Grant County
PUBLIC UTILITY DISTRICT

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April 14, 2016

Mr. Pat McGuire
Washington Department of Ecology
Eastern Region
4601 N. Monroe
Spokane, WA 99205-1295

Re: Public Utility District No. 2 of Grant County, Washington Temperature Modeling Report for the Priest Rapids Project

Dear Mr. McGuire,

Attached please find Public Utility District No. 2 of Grant County, Washington's (Grant PUD's) Temperature Modeling Report for the Priest Rapids Project (Project) consistent with the requirement and associated obligations and mandates of the Washington State Department of Ecology (WDOE) 401 water quality certification (WQC). Section 6.5.2 of the WQC requires Grant PUD to perform temperature modeling of the Project to evaluate compliance with temperature standards. Section 6.5.2 of the WQC states:

> *In the sixth year after new license takes effect, Grant PUD shall run the MASS1 model to evaluate the Project compliance with temperature standards, with the data collected in the first five years of the license. Grant PUD shall evaluate, as feasible, the causes of any modeled exceedances. The PUD shall provide a report to Ecology summarizing the results of the ten years of monitoring and modeling (first five years of the license plus the five previous years). The input data, modeling, and results shall be subject to peer review and review by Ecology in a draft report submitted six months prior to the final draft is due. Grant PUD shall provide the final report to Ecology in Year Seven.*

The WQC stipulates that a one-dimensional MASS1 temperature model be employed for this investigation. On July 28, 2014, Grant PUD requested approval for using a two-dimensional CE-QUAL W2 (W2) model as Grant PUD believes it constitutes the best available science for modeling. On September 2, 2014, WDOE approved and supported the use of the W2 model. This report constitutes documentation of the W2 modeling effort and evaluation of the Project's compliance with water temperature standards.

This Temperature Modeling Report was distributed to WDOE on October 30, 2015 for a review and comment period. WDOE provided comments on December 4, 2015 and are included in Appendix H with Grant PUD responses. The Temperatures Modeling Report was also distributed for review and comments to members of the Priest Rapids Fish Forum (PRFF) including WDOE, U.S. Fish & Wildlife Service, Washington Department of Fish & Wildlife, Colville Confederated Tribes, Yakama Nation, the Columbia

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River Inter-Tribal Fish Commission, Bureau of Indian Affairs, Wanapum People and the Confederated Tribes of the Umatilla Indian Reservation on December 29, 2015. No comments were received from the PRFF.

If you have questions, please contact John Monahan at 509-754-5088 Ext. 2976 or at Jmonahan@gcpud.org.

Sincerely,

Ross Hendrick
License Compliance Manager

Cc: PRFF

TEMPERATURE MODELING FOR THE PRIEST RAPIDS PROJECT

FINAL REPORT

Prepared for:

Grant PUD

Public Utility District No. 2 of Grant County, Washington

Ephrata, WA

March 2016

NHC Project No. 2000460

nhc

northwest hydraulic consultants

water resource specialists

Temperature Modeling for the Priest Rapids Project

Final Report

Prepared for:

Public Utility District No. 2 of Grant County, Washington
Ephrata, WA

Prepared by:

Northwest Hydraulic Consultants Inc.
Seattle, WA

March 2016

NHC Project No. 2000460

nhc

Prepared by:

Derek Stuart
Associate

Reviewed by:

Todd Bennett
Principal

DISCLAIMER

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EXECUTIVE SUMMARY

Public Utility District No. 2 of Grant County, Washington (Grant PUD) owns and operates the Priest Rapids Hydroelectric Project (Project), including Wanapum and Priest Rapids dams located on the mid-Columbia River in central Washington. The Project is authorized by the Federal Energy Regulatory Commission (FERC) under Project No. 2114.

A 401 Water Quality Certification (WQC) for the operation of the Project was issued by the Washington State Department of Ecology (WDOE). Section 6.5.2 of the 401 WQC requires Grant PUD to perform temperature modeling of the Project to evaluate compliance with temperature standards. This report documents the modeling effort and evaluation of the Project's compliance with water temperature standards. The temperature criteria for this analysis are described in Section 173-201A-602 of the Washington State Administrative Code (WAC). The WAC includes two separate sets of criteria, one set applying upstream of Priest Rapids Dam, and a second set applying downstream of the dam. The applicable WAC criteria are restated for this report as the following five metrics:

- Metric 1, 7-day Average Daily Maximum (7-DADMax) Temperature Threshold Upstream of Priest Rapids Dam
- Metric 2, Maximum 7-DADMax Temperature Increase Upstream of Priest Rapids Dam
- Metric 3, Daily Maximum Temperature Threshold Downstream of Priest Rapids Dam
- Metric 4, Maximum Temperature Increase Downstream of Priest Rapids Dam, Part 1
- Metric 5, Maximum Temperature Increase Downstream of Priest Rapids Dam, Part 2

Evaluation of the maximum temperature increase metrics requires temperature modeling of two separate Project scenarios. One, the "with-Project" scenario, represents the existing condition and the second, the "without-Project" scenario, represents a condition with the Project dams (Wanapum and Priest Rapids) removed but Rock Island Dam and all upstream dams in-place.

The primary tool used to evaluate the Project was CE-QUAL-W2 (W2), a laterally averaged two-dimensional hydrodynamic water quality model developed by the U.S. Army Corps of Engineers (Corps). The "with-Project" model was calibrated to observed water surface elevations and water temperature data. The calibrated model matched observed data well, resulting in an absolute mean error statistic of 0.2 °C, a magnitude comparable to other Columbia River W2 modeling efforts (e.g. upstream Rocky Reach and Wells dams).

Following calibration, Project compliance was evaluated for a 10-year simulation of the period 2003 through 2012 (five years pre-license, five years post-license). Relative to the temperature impact from upstream reservoirs in the Columbia River system (i.e. Grand Coulee dam), the Project was found to have a relatively small impact on water temperatures as a whole. Metrics 1 and 3, the 17.5 degree C and 20.0 degree C temperature thresholds, could not be met because the inflow temperatures to the Project exceed these criteria. It was demonstrated by a sensitivity test that lowering upstream inflow temperatures outright would result in a comparable temperature decrease at the downstream end of the Project. Metrics 2 and 4 (an allowed 0.3 degree temperature differential between "with Project" and "without Project" conditions) resulted in a small number of exceedances at two sites. Metric 5, Part 2 of the maximum temperature increase criterion, is never exceeded.

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1 INTRODUCTION

Public Utility District No. 2 of Grant County, Washington (Grant PUD) owns and operates the Priest Rapids Hydroelectric Project (Project), including Wanapum and Priest Rapids dams located on the mid-Columbia River in central Washington. The Project is authorized by the Federal Energy Regulatory Commission (FERC) under Project No. 2114. A 401 Water Quality Certification (WQC) for the operation of the Project was issued by the Washington Department of Ecology (WDOE) on April 3, 2007 (WDOE 2007), amended on March 6, 2008, and directly incorporated into the FERC license to operate the Project on April 17, 2008 (FERC 2008). Section 6.5.2 of the 401 WQC requires Grant PUD to perform temperature modeling of the Project to evaluate compliance with temperature standards.

Section 6.5.2 of the 401 WQC states:

> *In the sixth year after the new license takes effect [2014], Grant PUD shall run the MASS1 model to evaluate the Project compliance with temperature standards with the data collected in the first five years of the license. Grant PUD shall evaluate, as feasible, the causes of any modeled exceedances. The PUD shall provide a report to Ecology summarizing the results of the ten years of monitoring and modeling (first five years of the license plus five previous years* [i.e. 2003 – 2012]*). The input data, modeling, and results shall be subject to a peer review and review by Ecology in a draft report submitted six months* [i.e. June 2015] *prior to the final report is due. Grant PUD shall provide the final report to Ecology in Year Seven* [2015]*. Ecology may order further modeling or accuracy analysis be done in additional years. Any further temperature modeling of waters within the Project area shall use the best available scientific information, methods, and analysis that are generally accepted in the scientific community for modeling impounded and open-river conditions.*

The 401 WQC stipulates that a one-dimensional MASS1 temperature model be employed for this investigation. However, Grant PUD believes that a two-dimensional CE-QUAL W2 (W2) model constitutes the best available science for modeling an impounded and open-river system, such as that within the Project. Therefore, a letter was sent to Ecology on July 28, 2014 (Hendrick 2014) requesting approval for using a W2 model versus a MASS1 model for the temperature modeling effort. Ecology approved and supported the use of the W2 model in its response letter dated September 2, 2014 (McGuire 2014). After receiving the Ecology approval letter, Grant PUD moved forward with the design and implementation of the W2 model and contracted Northwest Hydraulic Consultants (NHC) to perform the W2 temperature modeling efforts.

This report constitutes documentation of the W2 modeling effort and evaluation of the Project's compliance with water temperature standards. This report is subject to review/comment by Ecology, with a final report incorporating all review comments due to Ecology by December 31, 2015.

1.1 Project Background

The Project is located on the Columbia River in central Washington. From its headwaters in Canada, the

Columbia River extends for 1,214 miles, with 460 miles in Canada and 754 miles in the United States. The Columbia River watershed drains an area of approximately 258,500 square miles upstream of its mouth to the Pacific Ocean. Most of the states of Washington, Oregon, and Idaho, the western portion of Montana, the southeastern portion of British Columbia, and small areas of Wyoming, Nevada, and Utah lie within the Columbia River basin.

The portion of Central Washington where the Project is located is remote and the Columbia River dominates the landscape. The climate is arid and receives about 7 inches of rain in an average year. The Columbia River forms part of the western boundary of Grant County, and touches again at the county's most northern corner at Grand Coulee Dam. The Project is located on that portion of the Columbia River that makes up the western boundary of Grant County. The Project also forms partial boundaries of Benton, Yakima, Kittitas, Douglas, and Chelan counties. In all, the Project encompasses 58 miles of the Columbia River from River Mile (RM) 395 to RM 453. The Project remains today in a largely undeveloped and undisturbed region. Development along the river is limited to a few very small communities and scattered tracts of irrigated orchard land.

Two hydroelectric developments are included in the Project: Wanapum and Priest Rapids. Each development consists of a dam, powerhouse, fishways, reservoir, 230 kilovolt (kV) transmission lines, structures used in connection with the dam, water rights, rights-of-way, lands, and interests in lands necessary for the operation and maintenance of the Project. Wanapum Reservoir is 38 miles long, extending from the tailwater of Rock Island Dam (RID) to Wanapum Dam while Priest Rapids Reservoir is 18 miles long, extending from the tailwater of Wanapum Dam to Priest Rapids Dam (Figure 1). The Project ends approximately 2 miles downstream of Priest Rapids Dam.

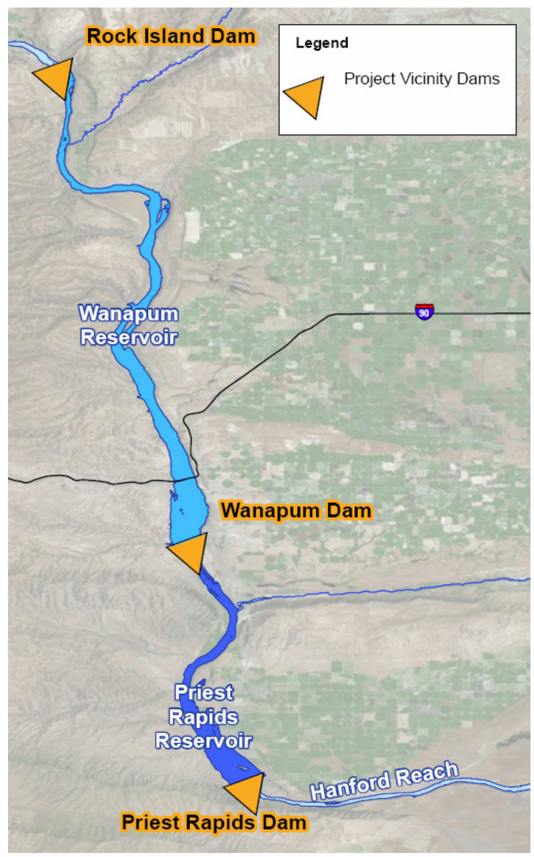


Figure 1: Project Vicinity

Wanapum Dam consists of a 8,637-foot-long by 186.5-foot-high dam spanning the river. The dam consists of left and right embankment sections; left and right concrete gravity dam sections; a left and right fish passage structure, each with an upstream fish ladder; a gated spillway; a downstream fish passage structure (the Wanapum Fish Bypass (WFB)); and a powerhouse containing ten vertical shaft integrated Kaplan turbine/generator sets with a total authorized installed capacity (best gate) of 735 MegaWatts (MW).

Priest Rapids Dam consists of a 10,103-foot-long by 179.5-foot-high dam spanning the river. The dam consists of left and right embankment sections; left and right concrete gravity dam sections; a left and right fish passage structure, each with an upstream fish ladder;

a gated spillway section; a downstream fish passage structure (the Priest Rapids Fish Bypass (PRFB)); and a powerhouse containing ten vertical shaft integrated Kaplan turbine/generator sets with a total authorized installed capacity (best gate) of 675 MW.

1.2 Project Operations

The Project is an integral part of the seven dam, 13,600 MW, Mid-Columbia River Hydroelectric System which extends 351 RM from near the U.S./Canada border to the beginning of the Hanford Reach. Project operations are complicated by the Project's location at the downstream end and can best be understood within the context of the entire system. The two developments of the Project, along with the next five dams upstream, constitute the seven developments operated in concert under the Hourly Coordination Agreement. The furthest upstream facility in this chain is the Grand Coulee Project. With a turbine hydraulic capacity exceeding 280kcfs and an active storage volume of 5.2 million acre-feet (MAF) or greater than 90% of the total storage volume, Grand Coulee operation dominates the mid-Columbia River flow regime. The two developments of the Project, each with a current turbine hydraulic capacity of roughly 175kcfs and a combined active storage capacity of about 0.20 MAF, are the furthest downstream facilities in the chain. Specific details on Project operations can be reviewed in Section 4.2 of Exhibit A of Grant PUD's Final License Application to the Federal Energy Regulatory Commission (Grant PUD 2003).

1.3 Regulatory Framework

The primary outcome of this analysis is an evaluation of the Project's compliance with the temperature criteria described in Section 173-201A-602 of the Washington State Administrative Code (WAC). The WAC includes two separate sets of criteria applicable to the Project reach of the Columbia River, one set applying upstream of Priest Rapids Dam and a second set applying downstream of the dam. The reach upstream of Priest Rapids Dam is designated as salmonid spawning, rearing, and migration habitat with a maximum temperature threshold, described as the seven day average of the daily maximum temperature (7-DADMax), of 17.5°C identified in Table 173-201A-200 (1) (c). Downstream of Priest Rapids Dam, the WAC stipulates that the maximum daily temperature shall not exceed 20.0°C due to human activities. Furthermore, in addition to these maximum temperature thresholds, the WAC also identifies maximum temperature increase thresholds that are intended to limit the Project's impacts on water temperature relative to "natural conditions".

The maximum temperature increase thresholds require that the evaluation of the Project include two separate simulation scenarios. One of the "natural condition" and the other of the existing condition with the Project in place. Due to the highly regulated nature of the Columbia River system, it is not meaningful to compare the Project to a condition with no dams. Instead the "natural condition" is represented by a scenario with the Project dams (Wanapum and Priest Rapids) removed but RID and all upstream dams in-place. Rather than refer to this as the "natural condition", this is referred to as the "without Project" scenario in this report. The existing condition is referred to as the "with Project" scenario.

The applicable WAC criteria are restated as the following five metrics for the purposes of this evaluation. These metrics include both maximum temperature thresholds and maximum temperature increase criteria.

a. **Metric 1, 7-DADMax Threshold Upstream of Priest Rapids Dam:** Do the 7-DADMax temperatures simulated for the "with Project" scenario at locations between the upstream extent of the Project (RID) and Priest Rapids Dam exceed 17.5°C?

    i. **Metric 2, Maximum 7-DADMax Temperature Increase Upstream of Priest Rapids Dam:** On days when the 7-DADMax temperature simulated for the "with Project" scenario exceeds 17.5°C is the 7-DADMax temperature simulated for the "without Project" scenario also greater than 17.5°C, and if so, are the "with Project" 7-DADMax temperatures more than 0.3°C higher than those simulated the "without Project" scenario within the Project? This only applies upstream of Priest Rapids Dam for the purpose of this analysis.

b. **Metric 3, Daily Maximum Threshold Downstream of Priest Rapids Dam:** Do instantaneous daily maximum temperatures simulated for the "with Project" scenario at locations between Priest Rapids Dam and the downstream terminus of the Project (RM 395) exceed 20.0°C?

    i. **Metric 4, Maximum Temperature Increase Downstream of Priest Rapids Dam, Part 1:** On days when the instantaneous daily maximum temperature simulated for the "with Project" scenario exceeds 20.0°C , does the instantaneous daily maximum temperature simulated for the "without Project" scenario also exceed 20.0°C, and if so are the "with Project" instantaneous daily maximum temperatures more than 0.3 °C higher than those simulated by the "without Project" scenario? This is only applied downstream of Priest Rapids Dam for the purpose of this analysis.

    ii. **Metric 5, Maximum Temperature Increase Downstream of Priest Rapids Dam, Part 2:** Are instantaneous maximum temperatures simulated for the "with Project" scenario at any time greater than 34/(T+9)°C relative to those simulated with the "without Project" scenario? The WAC states that "T" represents the background temperature as measured at a point or points unaffected by the discharge. In this case, the discharge is the Priest Rapids Project so "T" is the water temperature discharged from RID at the upstream end of the Project. This is only applied downstream of Priest Rapids Dam.

Portions of the Columbia River upstream, and within the Project, are currently classified as impaired for temperature under Section 303(d) of the Clean Water Act.

1.4 Temperature Modeling Approach

The primary tool used to evaluate the Project was W2, a laterally averaged two-dimensional hydrodynamic water quality model developed by the U.S. Army Corps of Engineers (Corps) Engineer Research and Development Center and currently maintained by Portland State University. Version 3.71 of the W2 model was used for this analysis.

The primary objectives of the modeling effort include:

- Capability of evaluating Project impacts to temperature for the period of 2003 – 2012 (five years pre-license, five years post-license).
- The model must be able to handle the operational complexities of mid-Columbia operations (as noted in Section 1.2 above).
- A scientifically defensible simulation of temperature. The model should simulate water-temperatures within an acceptable level of match to observed data.

The application of W2 described herein was designed to meet or exceed these objectives. The following steps outline the model development and application process:

1) Developed a W2 model for the entirety of the Project. The Project extends from the RID tailrace at RM 453 to the FERC boundary described as a point downstream of Priest Rapids Dam approximately 1 mile along the west (right-bank) side and 2 miles along the east (left-bank) side of the river, or approximately RM 395, including Wanapum and Priest Rapids Dams at RM 415.8 and 397.1, respectively. The W2 model was extended an additional seven miles downstream of the project to the Vernita Bridge (the location of observed temperature data downstream of Priest Rapids Dam) at RM 388.

2) Developed a complete hourly time-series of flow and temperature at inflow and outflow locations, water-levels, and meteorological conditions for the period 1998 to 2012.

3) Calibrated the model to observed water-level data for the full simulation period, and observed temperature data from 2001, and 2008 through 2012.

4) Applied the model to simulate water-temperatures within, and immediately downstream of, the Project for the period 2003 to 2012, <u>with</u> both Wanapum and Priest Rapids Dams in place. This is referred to as the "with Project" scenario.

5) Developed a W2 model of the Project reach without Wanapum or Priest Rapids Dams in place.

6) Applied the model to simulate water-temperatures within, and immediately downstream of, the Project for the period of 2003 to 2012, <u>without</u> both Wanapum or Priest Rapids Dams in place. This is referred to as the "without Project" scenario.

7) Evaluate the Project's compliance with Washington State temperature criteria based on the five identified temperature metrics as stated in Section 1.3 of this report.

1.4.1 Previous Studies

Several reports reviewed or applied Columbia River water temperature data associated with the Project. These included the following:

- Water-quality data reviews:
    - Normandeau et al. (2000) was a Grant PUD limnological investigation of the reservoirs that measured over 21 parameters including temperature.
    - Juul (2003) examined temperature, TDG, pH, DO, and turbidity data from five fixed-site monitoring (FSM) stations, historical scrollcase data, thermistor arrays, and water-column profile data at eight transects.
    - Grant PUD (2003) provides a summary of Normandeau et al. (2000) and Juul (2003).
    - Grant PUD (2009), the Project monitoring Quality Assurance Project Plan, provides much of the background included here and additional discussion about water-quality concerns associated with the project.
- Temperature modeling of the Project was performed by Perkins et al. (2002). That study evaluated the Project's impacts on water temperatures by simulating temperatures with and without the Project dams on the river, similar to the W2 analysis described in the current report. A third scenario also included in the Perkins et al. study was a simulation without any dams downstream of the Canadian border. The three scenarios were evaluated through application of a one-dimensional reservoir model called Modular Aquatic Simulation System 1D (MASS1). The developed model, which extended from the Canadian border downstream to McNary dam, was used to simulate hourly water temperatures at multiple analysis locations for the period 1973 through 2000.

  The primary difference between MASS1 and W2 is that the W2 model calculates hydrodynamic and temperature results for individual horizontal layers of the reservoir, but MASS1 only calculates depth averaged results. Both models laterally average across the river. The primary benefit of the W2 model is the ability to simulate vertical variations within the reservoir such as vertical stratification. A comparison of MASS1 and W2, performed by Cook et al. (2005), found that the MASS1 and W2 models developed for the Rocky Reach project matched within 0.1°C for the "without Project" scenario and 0.2°C for the "with Project" scenario. The difference between the "without-Project" results was considered small and the slightly larger difference between the "with Project" results was attributed to a minor amount of vertical stratification in the reservoir that was not captured by the MASS1 model. Additional documentation describing the formulation of MASS1 can be found in Appendix B of Richmond et al. (2000).

The Perkins et al. study found that the Project caused what was considered by the author to be a "very small effect" on peak daily temperatures, particularly relative to Grand Coulee Dam. The temperature increase was visible in temperature data as a seasonal shift in the annual rise and fall of water temperatures. The following is an excerpt, summarizing the finding from that report:

> *"The PRP was shown to have a very small effect on mid-Columbia temperatures. If all PRP* [Priest Rapids Project] *thermal impacts to the Columbia River were somehow eliminated, the average daily mean temperature in August (the hottest month) at Priest Rapids Dam would drop 0.1°C (19.4 to 19.3°C), whereas the average daily maximum temperature would rise 0.2°C (19.5 to 19.7 °C). Also, the daily mean temperature at Priest Rapids Dam would exceed 18°C 3 fewer days per year on average than under current conditions (63 days per year under current conditions versus 60 with the PRP effects removed scenario). However, the daily maximum would exceed 18°C [three] more days per year than under current conditions (66 versus 69 days per year).*
>
> *The mid-Columbia River impoundments affect water temperature primarily by shifting the annual temperature rise and fall later in the year. Because there is more water mass in the impounded river, it is slower than the river at natural elevations to warm in the spring and cool in the fall. The Wanapum and Priest Rapids Pools produce very little of this seasonal shift, however. Based on the examination of the observed data, Grand Coulee is the primary driver of this seasonal shift."*

2 ENVIRONMENTAL INPUT DATA

Hydrodynamic and water-quality modeling relies heavily on available data. The existing data used in this evaluation were assembled from Grant PUD (including both operations records and FSM), Public Utility District No 1 of Chelan County (Chelan PUD) FSM data, the Columbia River DART (Data Access in Real Time) system, the National Oceanic and Atmospheric Association (NOAA), the United States Department of Energy, the Corps, and the United Stated Geological Survey (USGS). The data includes instantaneous and time-series data collected during field monitoring programs, and spatial data such as orthophotos and bathymetry. The following sections provide a summary of the available data evaluated for use in the W2 temperature analysis of the Project.

2.1 Time-Series Data

Simulation of reservoir temperature with W2 requires time-series of observed water level, flow, temperature and meteorology data for the period to be simulated (i.e. 2000-2012 including calibration period). An inventory of the identified datasets is provided in Table 1, Table 2, Table 3, Table 4, and Table 5 below. The locations of data collection sites are presented in Figure 2.

Table 1: Observed Water Level Data				
Location	**Source**	**Period of record Reviewed**	**Time-Step**	**Comment**
Rock Island Tailrace	COE Dataquery	1998 – 2012	Hourly	
Wanapum Forebay	Grant PUD	1998 – 2012	Hourly	
Wanapum Tailrace	Grant PUD	1998 – 2012	Hourly	
Priest Rapids Forebay	Grant PUD	1998 – 2012	Hourly	
Priest Rapids Tailrace	Grant PUD	2001 – 2012	Hourly	

Table 2: Observed Flow Data				
Location	**Source**	**Period of record Reviewed**	**Time-Step**	**Comment**
Rock Island Total Flow	DART	1998 – 2012	Hourly	Daily data used for January and February 1999
	Chelan PUD	2002 – 2005; 2009 – 2012	Hourly	
Wanapum Spill	DART	1998 – 2012	Hourly	
Wanapum Total Flow	DART	1998 – 2012	Hourly	
	Grant PUD	1998 – 2012	Hourly	Only used January – February 2012
Priest Rapids Spill	DART	1998 – 2012	Hourly	
Priest Rapids Total Flow	DART	1998 – 2012	Hourly	
	Grant PUD	1998 – 2012	15-minute	Used for QA/QC only
12472800 Columbia River below Priest Rapids	USGS	1987 – current (earlier data available)	15-minute	

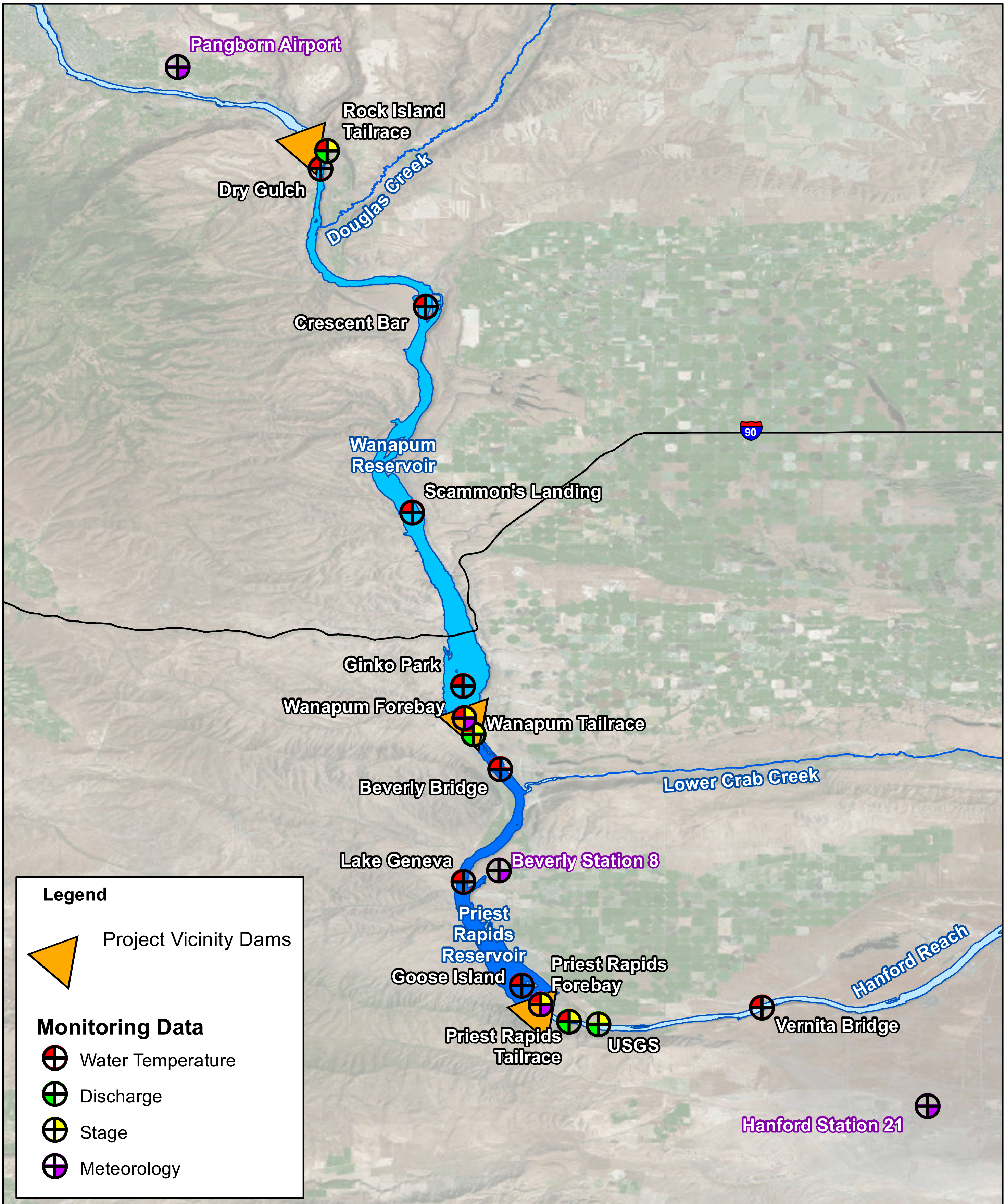
Table 3: Observed Water Temperature Data – Time-series				
Location	**Source**	**Period of record Reviewed**	**Time-Step**	**Comment**
Rock Island Tailrace (RM 451)	DART	1998 – 2012	Hourly	April – September only prior to 2012; except longer

Table 3: Observed Water Temperature Data – Time-series				
Location	**Source**	**Period of record Reviewed**	**Time-Step**	**Comment**
				collection periods in 2004 and 2005
	Chelan PUD	2002 – 2012	Hourly	April – September only prior to 2011
	Grant PUD	2003 – 2005	Hourly	
	U.S. Army Corps of Engineers	1997 – 2012	Hourly	Not Used
Wanapum Forebay, Fixed-Site Monitoring (FSM) Station (RM 415.8)	DART	2002 – 2010	Hourly	May – September only prior to 2011, except longer collection periods 2003, 2004, 2006, and 2007
	Grant PUD	1998 – 2000; 2002 – 2012	Hourly	Large gaps 1998, 1999, 2004, and 2005
Wanapum Forebay, Intake (RM 415.8)	Grant PUD	2001 – 2012	Hourly	Large gaps 2001, 2003, and 2007
Wanapum Tailrace FSM Station, Beverly Bridge (RM 412.2)	DART	1998 – 2010	Hourly	May – September only prior to 2010, except longer collection periods 2003, 2004, 2006, and 2007
	Grant PUD	1998 – 2000; 2002 – 2012	Hourly	Large gaps 1998, 1999, 2004, and 2005
Priest Rapids Forebay, FSM Station (RM 397.1)	DART	1998 – 2010	Hourly	May – September only prior to 2010, except longer collection periods 2003, 2004, 2006, and 2007
	Grant PUD	1998 – 2000; 2002 – 2012	Hourly	Large gap 2004 and 2005
Priest Rapids Forebay, Intake (RM 397.1)	Grant PUD	2001 – 2012	Hourly	
Priest Rapids Tailrace, FSM Station, Vernita Bridge (RM 388.1)	DART	1998 – 2010	Hourly	May – September only prior to 2010, except longer collection periods 2006 and 2007. This data is also hosted by the USCOE as station"PRXW".
	Grant PUD	1998 – 2000; 2002 – 2012	Hourly	Large gap 2004 and 2005

Table 4: Observed Water Temperature Data – Profiles				
Location (Site IDs)	**River-Mile (1999 or 2000/2011)[1]**	**Sampled Years**	**# of Profiles**	**Comment**
Wanapum Reservoir Sites				
Dry Gulch (DGRB/DGM/DGLB)	452.2 / 451	2000, 2011	93 days in 2000, 5 in 2011	
Crescent Bar (CBRB/CBM/CBLB)	440.4 / 440.5	1999, 2000, 2011	10 in 1999, 93 days in 2000, 16 in 2011	
Scammon's Landing (SLRB/SLM/SLLB)	427.5 / 428	1999, 2000, 2011	10 in 1999, 93 days in 2000, 22 in 2011	
Ginko Park (GPRB/GPM/GPLB)	419.0 / 417.5	1999, 2000, 2011	10 in 1999, 93 days in 2000, 21 in 2011	
Priest Rapids Reservoir Sites				
Wanapum Tailrace (WTRB/WTM/WTLB)	415.0 / 415.5	2000, 2011	93 days in 2000, 5 in 2011	
Hanson Creek / L. Geneva (LGRB/LGM/LGLB)	407.0 / 405.5	1999, 2000, 2011	10 in 1999, 93 days in 2000, 13 in 2011	
Goose Island (GIRB/GIM/GILB)	399 / 398.5	1999, 2000, 2011	9 in 1999, 93 days in 2000, 20 in 2011	
Hanford Reach Sites				
Priest Rapids Tailrace	395 / NA	2000	93 days in 2000	
[1] Sampling performed in 1999 was performed at a slightly different locations than sampling performed in 2000 and 2011. The same site names are used but the river-miles vary.				

Table 5: Observed Meteorology Data

Location	Parameter(s)	Source	Period of Record Reviewed	Time-Step	Comment
Wanapum Dam	wind speed and direction, air temperature	Grant PUD	2001 – 2012	Hourly	
Priest Rapids Dam	wind speed and direction, air temperature	Grant PUD	2001 – 2012	Hourly	
Beverly Station 8	wind speed and direction, air temperature	U.S. Department of Energy	1991 – 2012	Hourly	
Hanford Station 21	solar radiation and dew point temperature	U.S. Department of Energy	1991 – 2012	Hourly	
Hanford Airport	cloud cover and dew point temperature	NOAA	1998 – 2012	Hourly	
Pangborn Airport	cloud cover and dew point temperature	NOAA	1998 – 2012	Hourly	
Bowers Airport	cloud cover	NOAA	1998 – 1999; 2004 – 2009; 2011 – 2012	Hourly	Used only to fill small gaps in record
Desert Aire	wind speed and direction, air temperature, dew point temperature, solar radiation	WSU AgNet	2008 – 2012	Hourly	Used only as a check



	1 INCH = 7 miles 0 3.5 7 14 Miles N	*PRIEST RAPIDS WATER TEMPERATURE MODELING* *Monitoring Station Locations*
nhc northwest hydraulic consultants	*Coordinate System:* *Units: DECIMAL DEGREES*	
	Job: 2000460 / *Date: 07-March-2016*	*FIGURE 2*

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3 W2 MODEL FRAMEWORK AND EXTENTS

Two W2 models were developed for the study area extents, one representing “with Project” and another “without Project” conditions. Both use identical inflow discharge and temperatures from RID and the same bathymetry. However, because the “without Project” scenario is a much shallower riverine flow condition with a steeper water surface slope, the two models were assembled slightly differently from one another. These differences, in terms of W2 “Waterbodies”, “Segments” and “Layers”, are discussed in the following sections.

3.1 Waterbodies

For W2 modeling, a “waterbody” or a “branch” can be used to define a section with a relatively equal water-surface slope. For the “with Project” model, with relatively flat reservoir pools, 3 waterbodies and 4 branches were used to define the model grid (or domain). In the “with Project” W2 domain, two waterbodies were used to represent the two Project reservoirs, labeled as “Wanapum” between Rock Island and Wanapum dams, “Priest Rapids” between Wanapum and Priest Rapids Dam, and a third waterbody was used to represent the riverine reach below Priest Rapids Dam downstream to the Vernita Bridge, labeled as “Hanford Reach”. The Priest Rapids reservoir waterbody consists of two branches in series. For the “without Project” model, with a more varied riverine slope, 13 waterbodies and 13 branches were required to simulate a river environment through the Project (Figure 3). In Figure 3, the red lines correspond to the water surface slope for each “without Project” waterbody. The typical “with Project” pool elevations for Wanapum and Priest Rapids reservoirs are shown in blue for comparison.

Each waterbody is composed of segments that define the bathymetry and orientation of relatively short lengths of each waterbody. Segments are numbered starting at “2” and then increase in the downstream direction, skipping two numbers at each waterbody boundary. Though the “with Project” and “without Project” models have the same modeling extents, the segment numbers at a specific location can differ between the two models because of the different waterbody configuration. Furthermore, the “with Project” model was run in two pieces, thus requiring that numbering restart at 2 below Wanapum Dam. Figure 4 and Figure 5 show the different segment numbering used for calibration and reporting of output discussed later in this text.

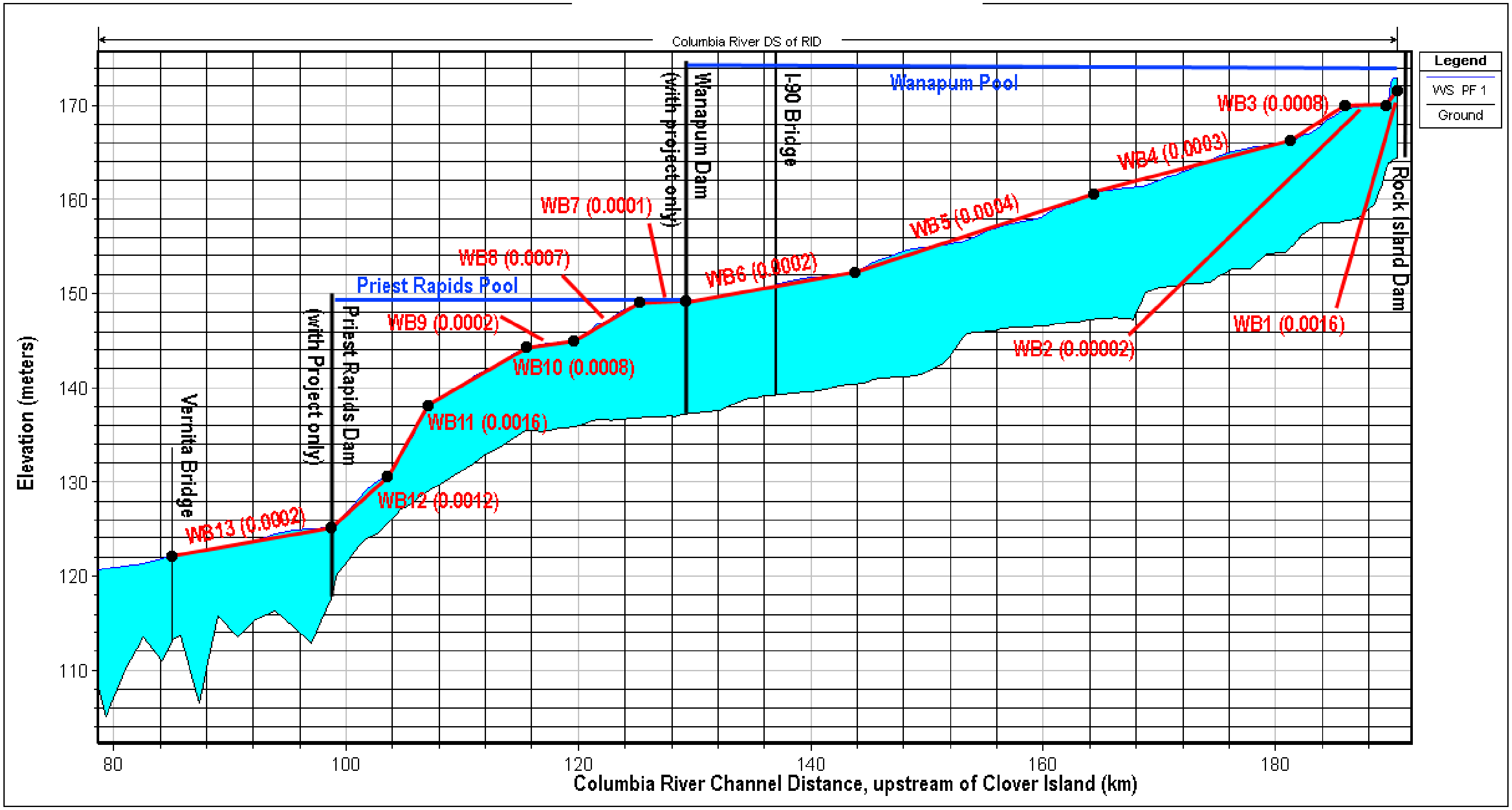
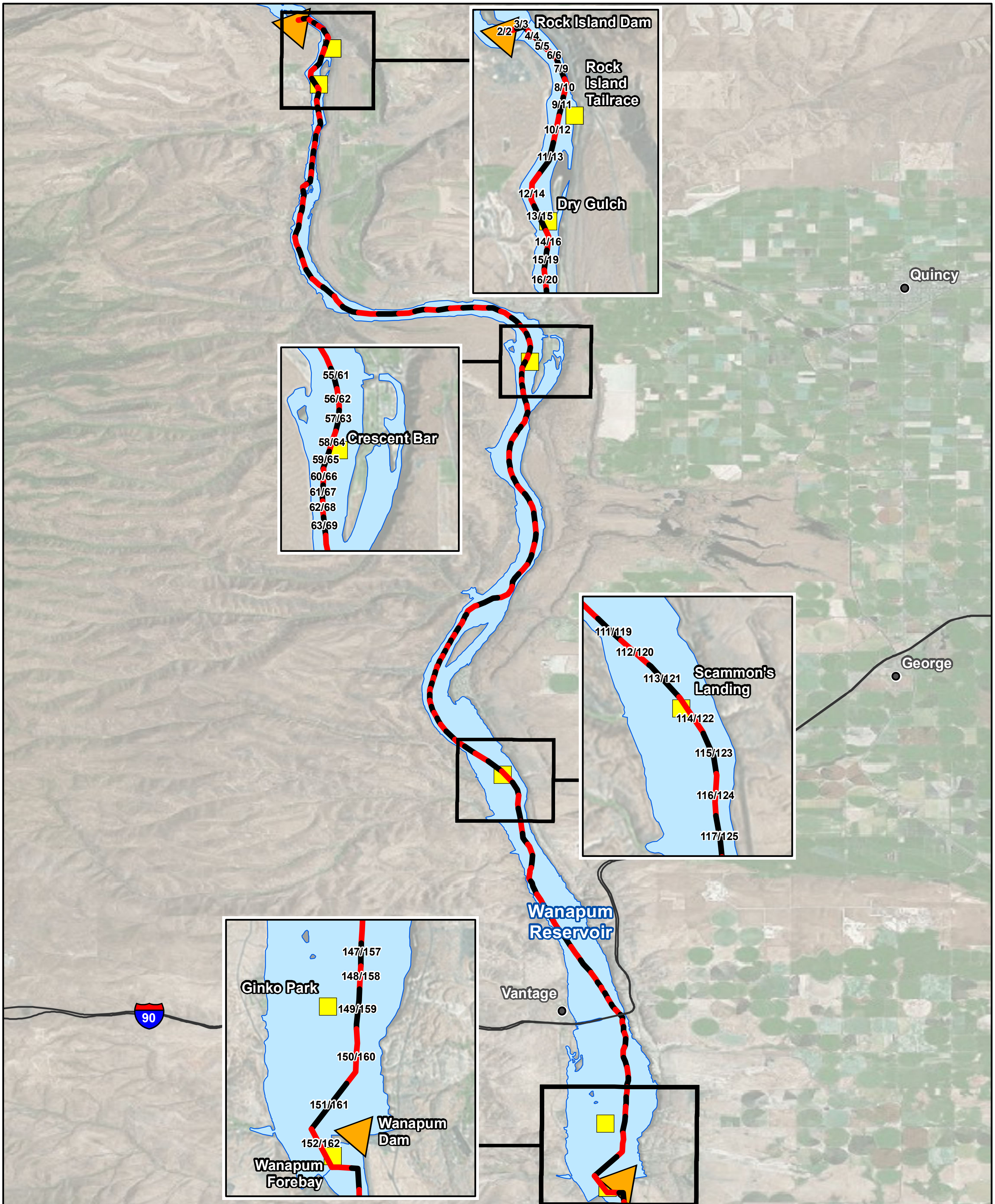


Figure 3: "Without Project" W2 Waterbody Slopes, RID to Vernita Bridge



Legend

Segment (Segment ID/Without Segment ID)

Sites

Dam

1 in = 4 miles

0 2 4 8 Miles

N

Coordinate System:
Units: DECIMAL DEGREES

Job: 2000460 | Date: 07-March-2016

PRIEST RAPIDS WATER TEMPERATURE MODELING

Segment Numbering at Monitoring Sites
Rock Island Dam to Wanatum Dam

FIGURE 4

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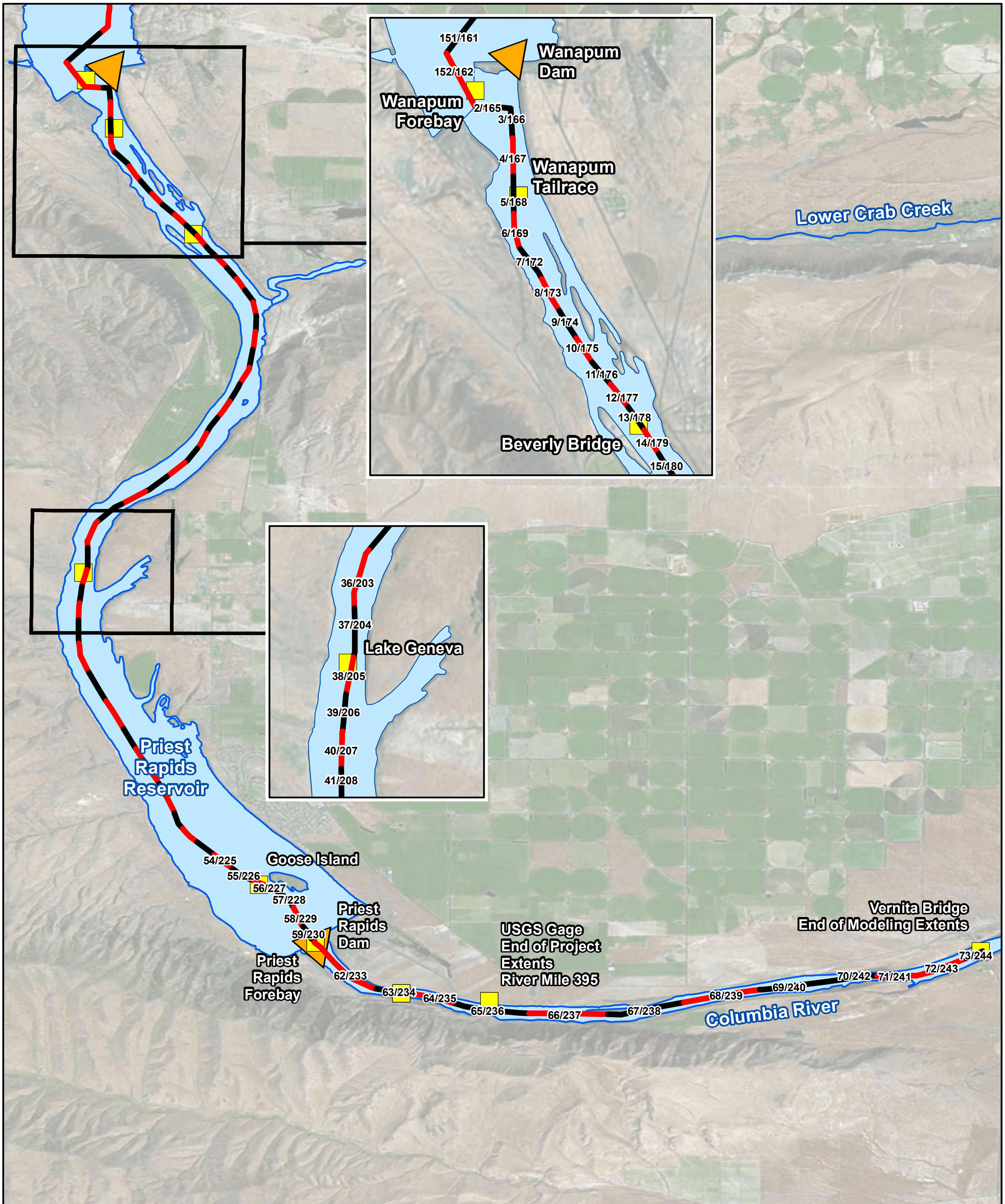

Legend

Segment (Segment ID/Without Segment ID)

Sites

Dam

1 INCH = 2 miles

0 1 2 4 Miles

N

Coordinate System:
Units: DECIMAL DEGREES

Job: 2000460 | *Date: 07-March-2016*

PRIEST RAPIDS WATER TEMPERATURE MODELING

Segment Numbering at Monitoring Sites
Wanatum Dam to Vernita Bridge

FIGURE 5

Q:\2000460_Priest_Rapids_Water_Temperature\GIS\MXD\Figure 5_ModelingExtents.mxd

3.2 Bathymetric Data

Bathymetric data used to define the W2 model geometry was based on four HEC-RAS models obtained from the Corps that are maintained as part of hydraulic modeling related to the ongoing Columbia River Treaty (CRT) review. The Corps CRT models (Corps, 2010a, 2010b, 2012a, and 2012b) were converted to W2 waterbody bathymetry data files using the waterbody slopes listed in Table 6 and Table 7 (and shown graphically in Figure 3 for the "without Project" model). With the exception of waterbody PR-1, all waterbodies have a single branch. Waterbody PR-1 has two branches, with unique slopes. The two right-most columns in the tables are labeled with the boundary HEC-RAS cross-section numbers that were used as the bathymetry data-source for each waterbody. With few exceptions, each W2 model segment ends and begins mid-distance between each cross-section in the CRT HEC-RAS model. A few segments also needed to be be split as part of W2 model development. A lookup table between W2 segment ID and HEC-RAS cross-section ID is provided in Table 22 of Appendix A.

Table 6: "With Project" Model Grid

Waterbody Number (Branch Number)	Reach Name	Slope	Segment Numbering		HEC-RAS Cross-Section (River-Mile)	
			Upstream	Downstream	Upstream	Downstream
WAN-1	Wanapum	0.0000001	WAN-2	WAN-152	453.47	415.19
PR-1 (1)	Priest Rapids	0.00003	PR-2	PR-20	415.10	410.26
PR-1 (2)	Priest Rapids	0.00001	PR-22	PR-59	410.01	397.11
PR-2	Hanford Reach	0.00030	PR-62	PR-73	395.6788	387.2501

Table 7: "Without Project" Model Grid

Waterbody Number	Reach Name	Slope	Segment Numbering		HEC-RAS Cross-Section (River-Mile)	
			Upstream	Downstream	Upstream	Downstream
1	Wanapum	0.00160	2	6	453.47	452.98
2	Wanapum	0.00002	9	16	452.80	451.09
3	Wanapum	0.00080	19	31	450.91	448.54
4	Wanapum	0.00030	34	73	448.35	438.58
5	Wanapum	0.00040	76	129	438.39	424.84
6	Wanapum	0.00020	132	162	424.47	415.19
7	Priest Rapids	0.00010	165	169	415.1	413.82
8	Priest Rapids	0.00070	172	185	413.51	410.26
9	Priest Rapids	0.00020	188	196	410.01	407.39
10	Priest Rapids	0.00080	199	210	407.09	402.56
11	Priest Rapids	0.00160	213	219	402.00	400.18
12	Priest Rapids	0.00070	222	230	399.87	397.11
13	Hanford Reach	0.00030	233	244	395.6788	387.2501

3.3 Model Segments

Each W2 model segment is composed of multiple laterally averaged model layers. It is these layers that allow simulated temperatures to vary vertically within a segment. The W2 code requires that the simulated water-surface be within a single layer within each water body, which can be problematic with 1 meter layer heights for riverine (e.g., “without Project”) conditions. To address this, riverine waterbodies (i.e. the entire “without Project” model and the Hanford Reach of the “with Project” model) were assigned 2 meter layer heights, while the reservoir waterbodies in the “with Project” model have smaller 1 meter layer heights. Example W2 model layer cross-sections for “without Project” Segment 155 and “with Project” Wanapum Segment 145, located at the same river station, are shown in Figure 6. The “with Project” model has 59 layers while the “without Project” model includes 52 layers.

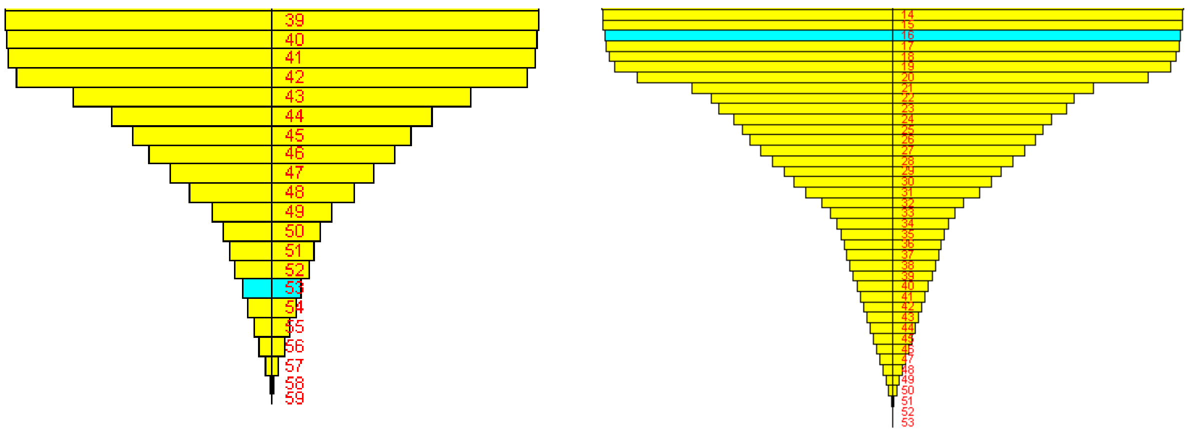

Figure 6: Example W2 Model Layers, (Left) Riverine "without Project" Segment 155, (Right) “with Project” Wanapum Segment 145

3.4 Boundary Conditions and Meteorological Data

Table 8 below provides a summary of the boundary condition datasets used with each of the W2 models. Similar boundary condition datasets were available for both Wanapum and Priest Rapids reservoirs, all of which were compiled and gaps filled to produce complete records for the period January 1998 through December 2012, though data prior to January 2000 was not used for calibration or scenario comparisons. Figure 2 showed the location of these data sources.

Table 8: Summary of W2 Model Input Data Sources

Data Need	**W2 Model**		
	"with Project" Waterbodies		**"without Project" Waterbodies**
	Wanapum	**Priest Rapids and Hanford Reach**	
Upstream Inflows	Rock Island Total Flow	Wanapum Total Flow	Rock Island Total Flow
Spillway Flows	Wanapum Spill	Priest Rapids Spill	No spillways modeled
Turbine Flows	Wanapum Total Flow - Spill	USGS 12472800 Flow - Spill	No turbines modeled
Downstream Stage		HEC-RAS simulated at Vernita Bridge	HEC-RAS simulated at Vernita Bridge
Upstream Water Temperature	Rock Island Tailrace	Wanapum Tailrace[1]	Rock Island Tailrace
Air Temperature	Wanapum Operations (located on Wanapum Dam)	Priest Rapids Operations (located on Priest Rapids Dam)	WB 1 – 6 = Wanapum; WB 7 – 13 = Priest Rapids Grant PUD Operations
Wind Speed and Direction	Beverly Station 8	Beverly Station 8	Beverly Station 8
Dew Point Temperature, Cloud Cover	Pangborn Memorial Airport (EAT)	Hanford Station 21	WB 1 – 6 = Pangborn Memorial Airport (EAT); WB 7 – 13 = Hanford Station 21
Shortwave Solar Radiation	Hanford Station 21	Hanford Station 21	Hanford Station 21

[1] Observed Wanapum intake temperatures from the Wanapum Operations Data were used for calibration and scenario model runs

3.4.1 Data Filling

For each of the datasets used, the record had to be reviewed and gaps filled. The following paragraphs individually discuss refinement of the meteorological, flow, and water temperature data.

3.4.1.1 Meteorological datasets

For the meteorological datasets, which were relatively complete, small gaps of missing data (typically shorter than 1 day) were filled using available data from a nearby station or linear interpolation if a nearby station were not available. Plots of the filled meteorological data used in the W2 modeling can be found in Figure 8 through Figure 15. It is noteworthy that cloud cover is more common at Hanford Station 21 than at Pangborn Memorial Airport (EAT). Also, while not visible at the scale of Figure 14 or Figure 15, the diurnal fluctuations in air temperatures recorded at Wanapum and Priest Rapids Dams are less extreme (i.e. lower highs and higher lows) than the air temperature data collected at the Beverly site. This is attributed to an insulating effect from the concrete dam mass but has not been confirmed.

3.4.1.2 Discharge/Flow datasets

Any gaps in the discharge/flow data, similar to the meteorological data, were filled with data from another gage, a longer time-step, or by linear interpolation. All of the total flow datasets had small gaps (typically shorter than 1 day) that were filled using linear interpolation. At RID, the total flow dataset was primarily hourly DART data with a gap in January and February of 1998 filled with daily data. The total flow dataset at Wanapum Dam was also composed primarily of DART hourly data with gaps longer than a day filled using Grant PUD operations data. The total flow record at Priest Rapids was developed using the USGS gage 12472800 filled with a small amount of Grant PUD operations data. The USGS data was used rather than the very similar Grant PUD operations data because the USGS gage had a slightly larger total volume which corresponded better with the Wanapum Dam flow dataset. The spill datasets were developed using DART data which was very similar to the Grant PUD operations data, but had a small amount of additional data. Plots of the total flow datasets are shown in Figure 16 through Figure 18.

3.4.1.3 Water Temperature datasets

All of the water temperature datasets required quality assurance/quality control (QA/QC) checks to ensure proper water temperature data was used in the modeling effort, both as input time-series and as calibration targets.

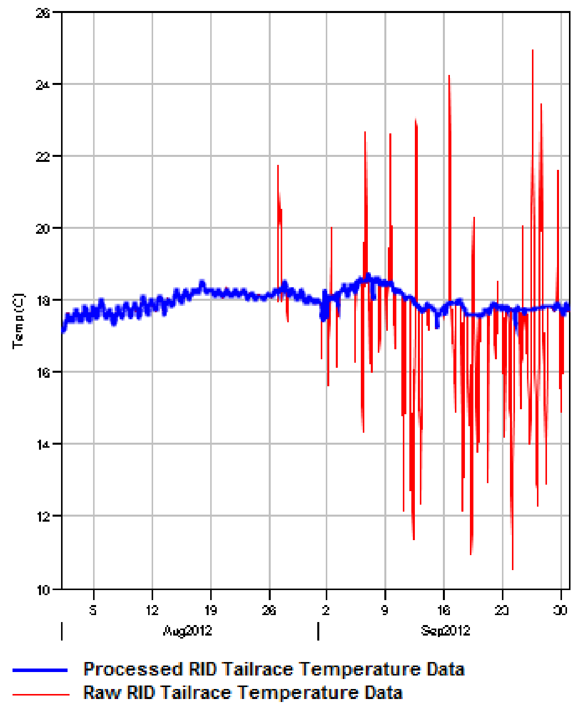

Figure 7: Example of Raw vs. Processed RID Temperature Data

The RID temperature dataset provides the upstream inflow temperatures used for all Wanapum Reservoir model simulations. This time-series was constructed by first filling hourly DART data with Chelan PUD data and editing discrepancies in the dataset. Next, daily averages were calculated using DART data to fill gaps where no temperature data was available, typically from mid-September to mid-April. The resulting dataset is shown in Figure 19.

Two observed temperature datasets are available at Wanapum dam: Project operations data collected at the turbine intake and FSM station data collected in the forebay near turbine unit 10. The turbine intake temperatures were used as the upstream inflow temperatures for calibration of the Priest Rapids Reservoir while both temperature datasets were used as calibration targets for the Wanapum Reservoir model.. The Wanapum FSM station data were highly variable, with frequent temperature spikes. As seen in Figure 20, the daily minimum of the FSM station data compared well with the daily averages of the turbine intake data. Based on this relationship, daily minimums of the FSM station data were used rather than the raw hourly data. All of the temperature datasets had small gaps that were filled using linear interpolation. The resulting Wanapum turbine intake temperature dataset, used as the upstream temperature boundary for the Priest Rapids model, are shown in Figure 21 and discussed further in Section 4.2.1.

Two temperature sensors similar to those operated at Wanapum Dam are also operated at Priest Rapids Dam. Similar to the Wanapum FSM station, data from the Priest Rapids Dam FSM station also had temperature spikes, though not to the same degree. The Priest Rapids turbine intake sensor looked reasonable, but a temperature differential was identified during model calibration that is discussed in more detail in Section 4.2.1. The Priest Rapids Dam was not used as a temperature boundary condition for either calibration or scenario simulation model runs, so some flaws such as small temperature spikes were left uncorrected unlike the Wanapum Dam data. Plots of observed Priest Rapids Dam temperatures are only provided with the calibration discussion in Section 4.2.1.

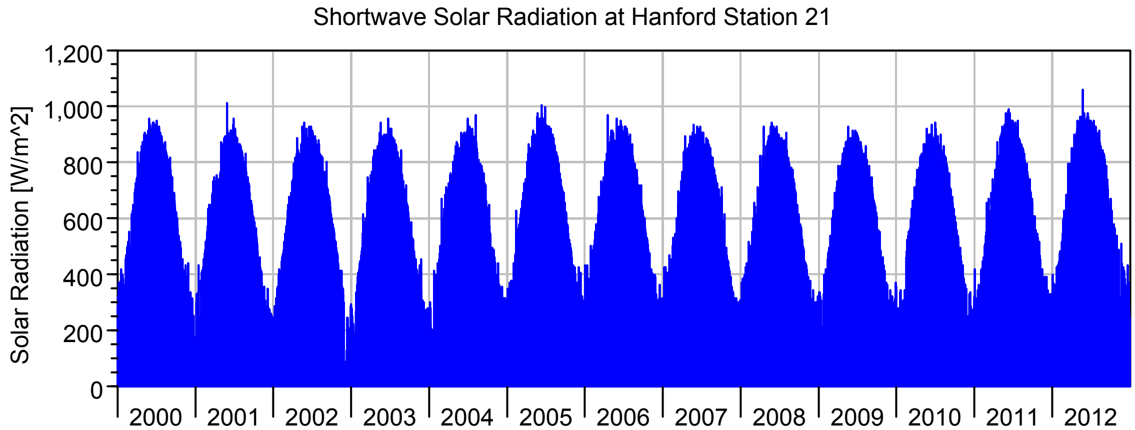

Figure 8: Short Wave Solar Radiation at Hanford Station 21

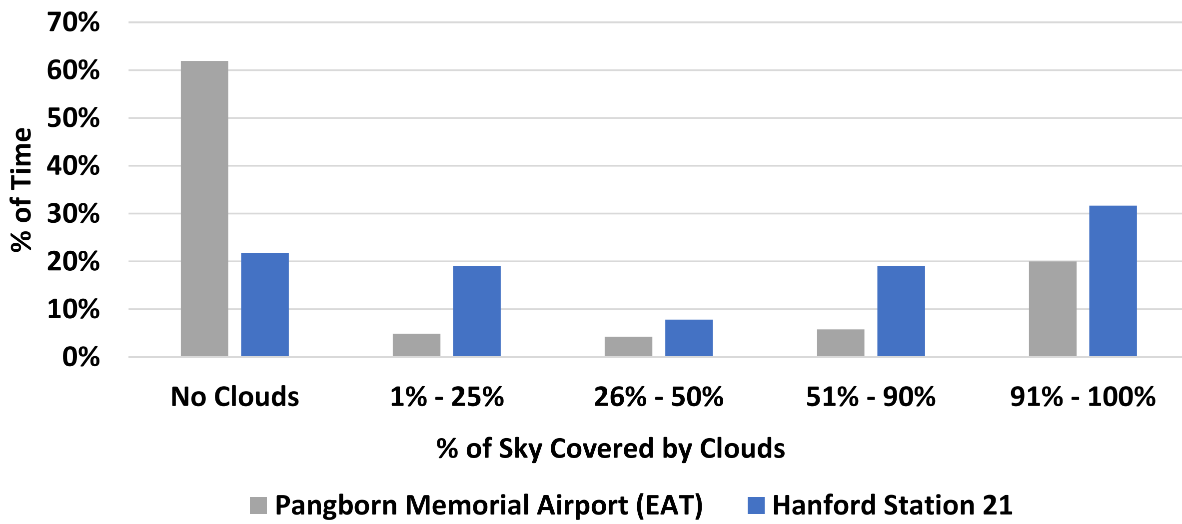

Figure 9: Cloud Cover at Pangborn Memorial Airport (EAT) and Hanford Station 21 (2006 – 2012)

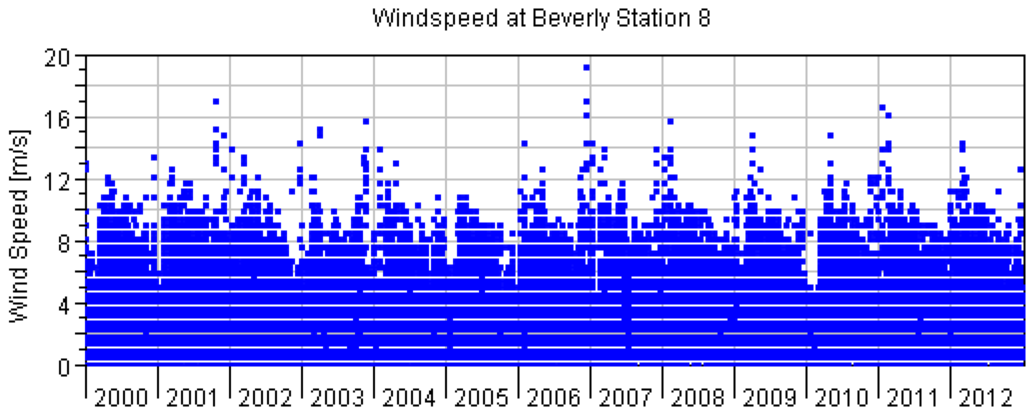

Figure 10: Wind Speed at Beverly Station 8

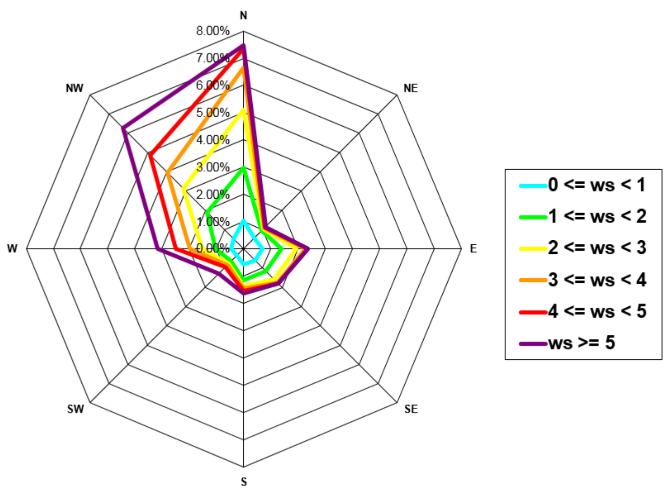

Figure 11: Wind Direction at Beverly Station 8 [colors indicate wind speed in m/s]

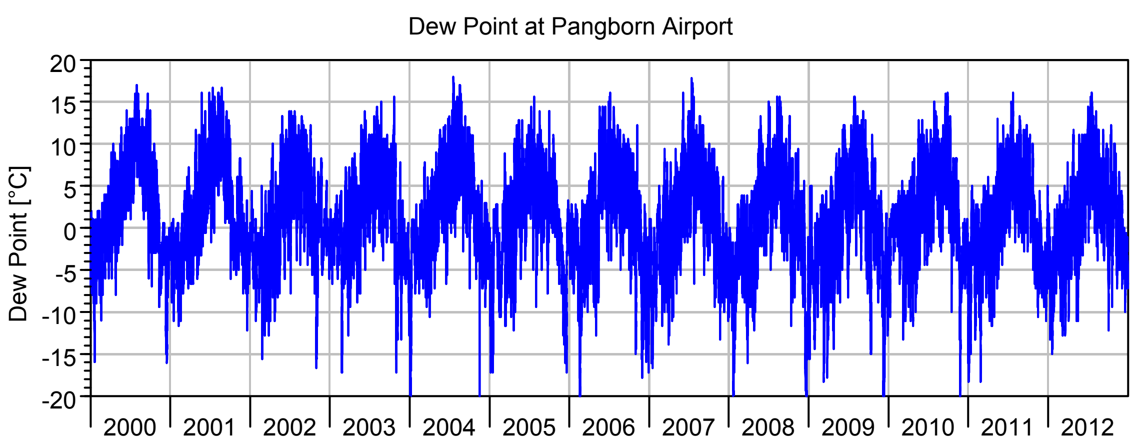

Figure 12: Dew Point Temperature at Pangborn Memorial Airport (EAT)

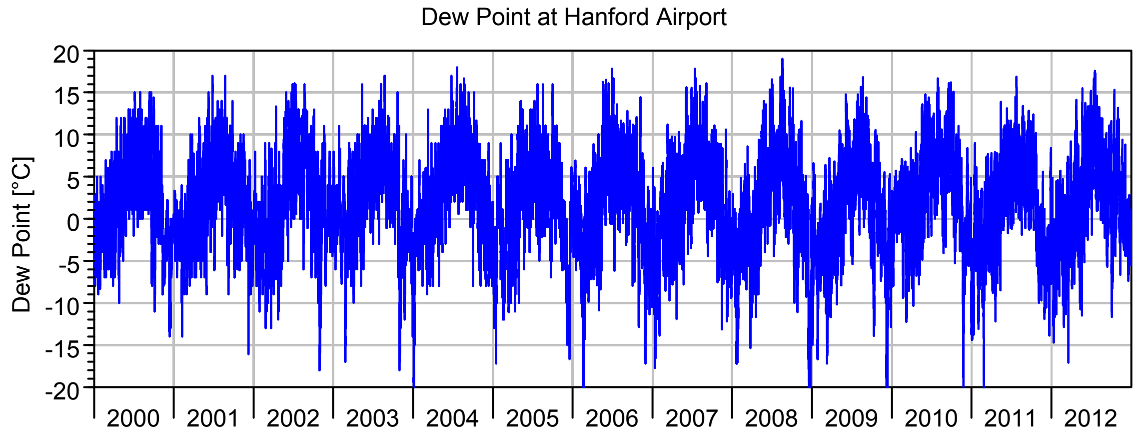

Figure 13: Dew Point Temperature at Hanford Station 21

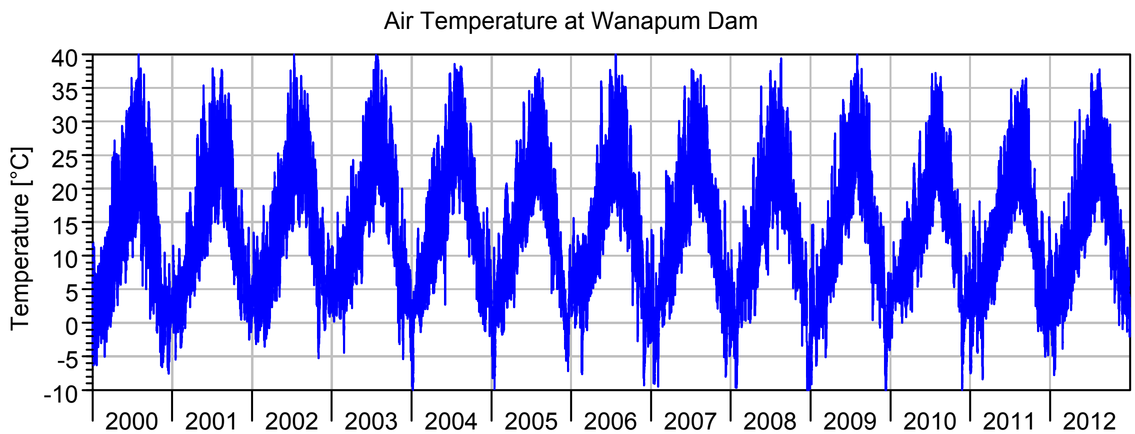

Figure 14: Air Temperature at Wanapum Dam

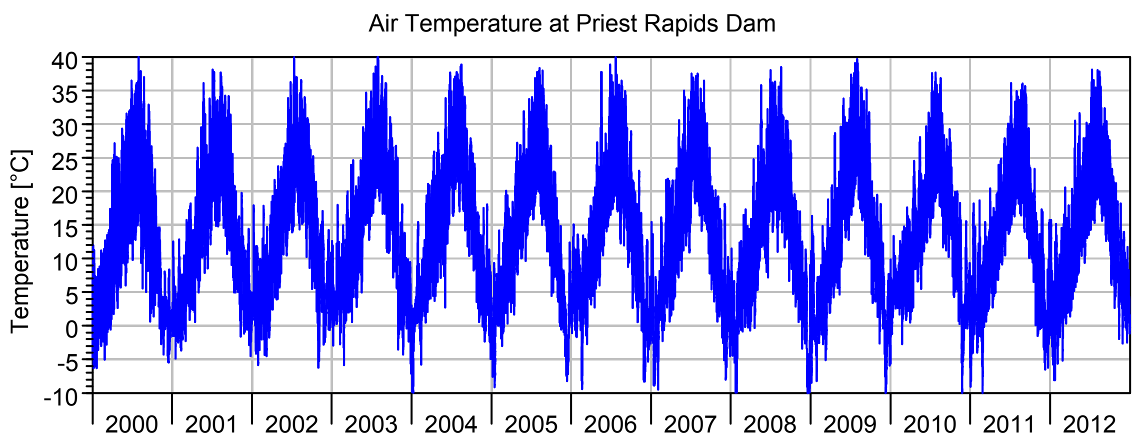

Figure 15: Air Temperature at Priest Rapids Dam

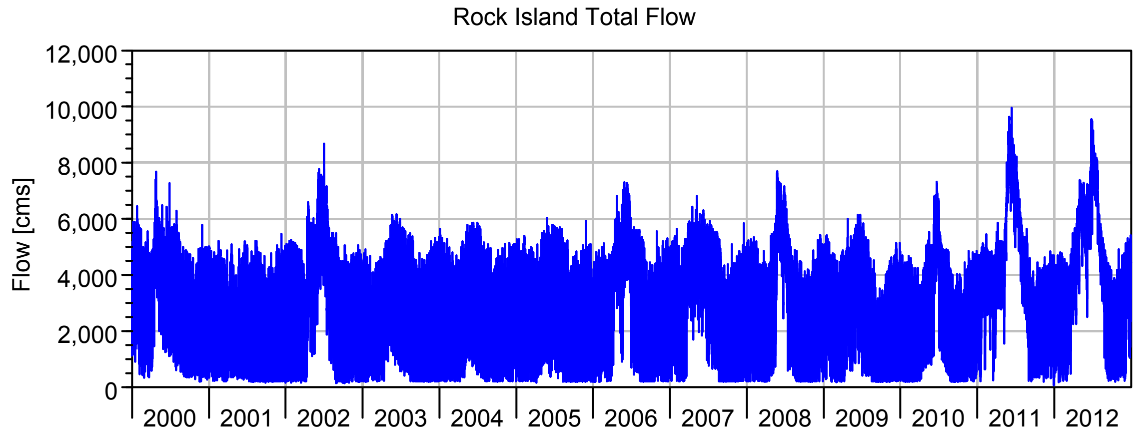

Figure 16: Rock Island Total Flow, Inflow to Wanapum Reservoir

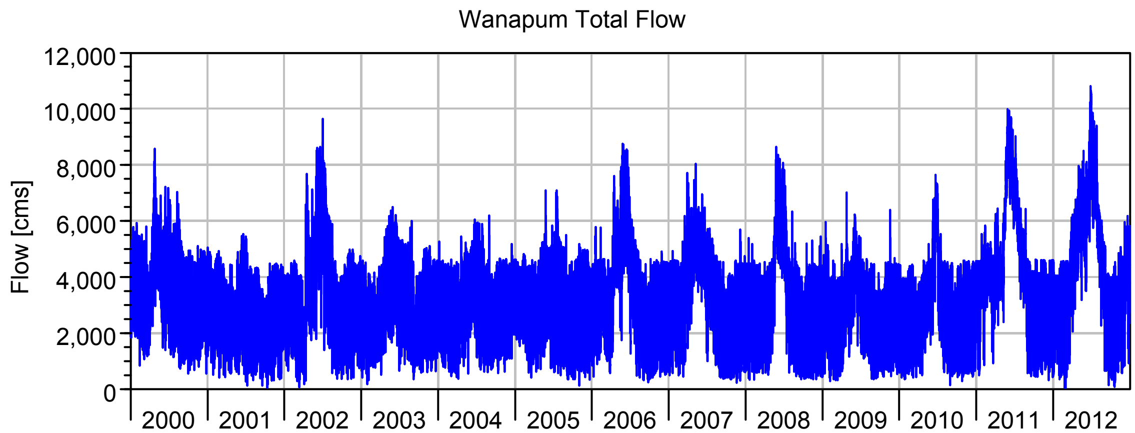

Figure 17: Wanapum Total Flow

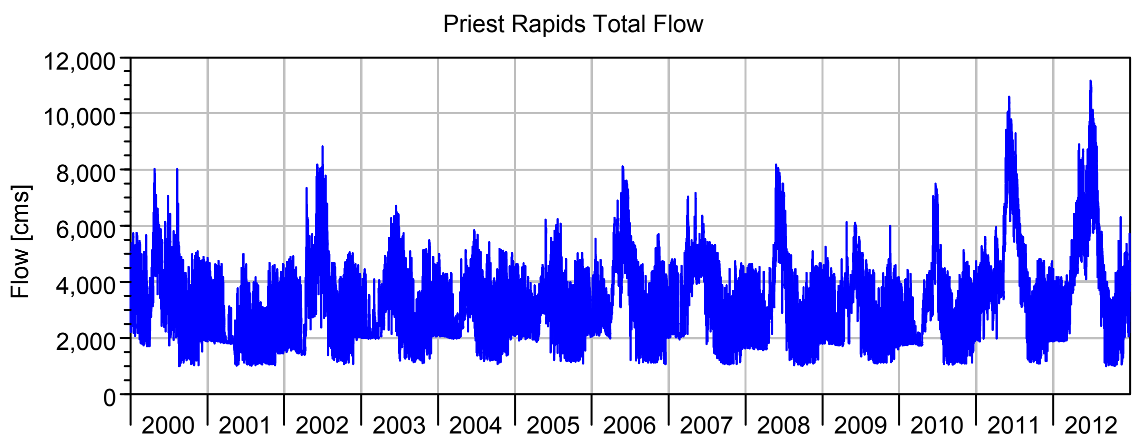

Figure 18: Priest Rapids Total Flow

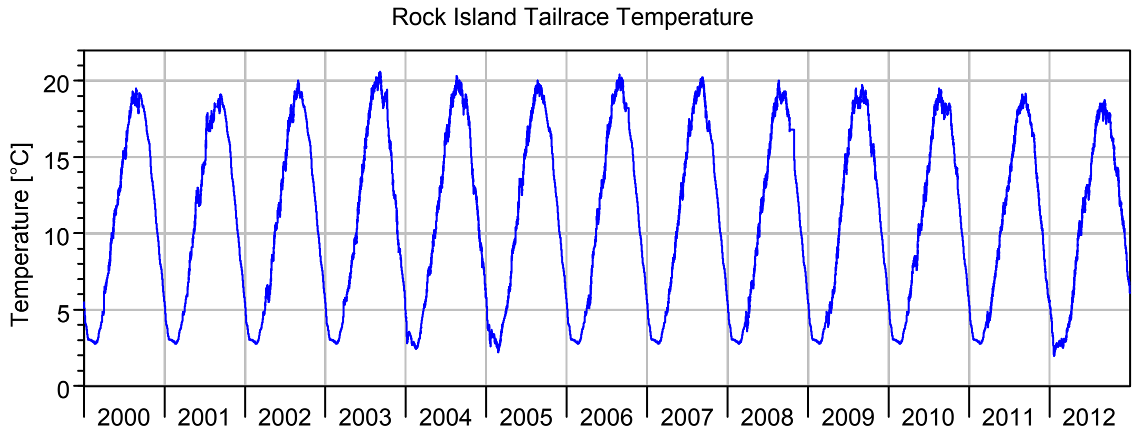

Figure 19: Rock Island Tailrace Water Temperature (Inflow to Wanapum Reservoir)

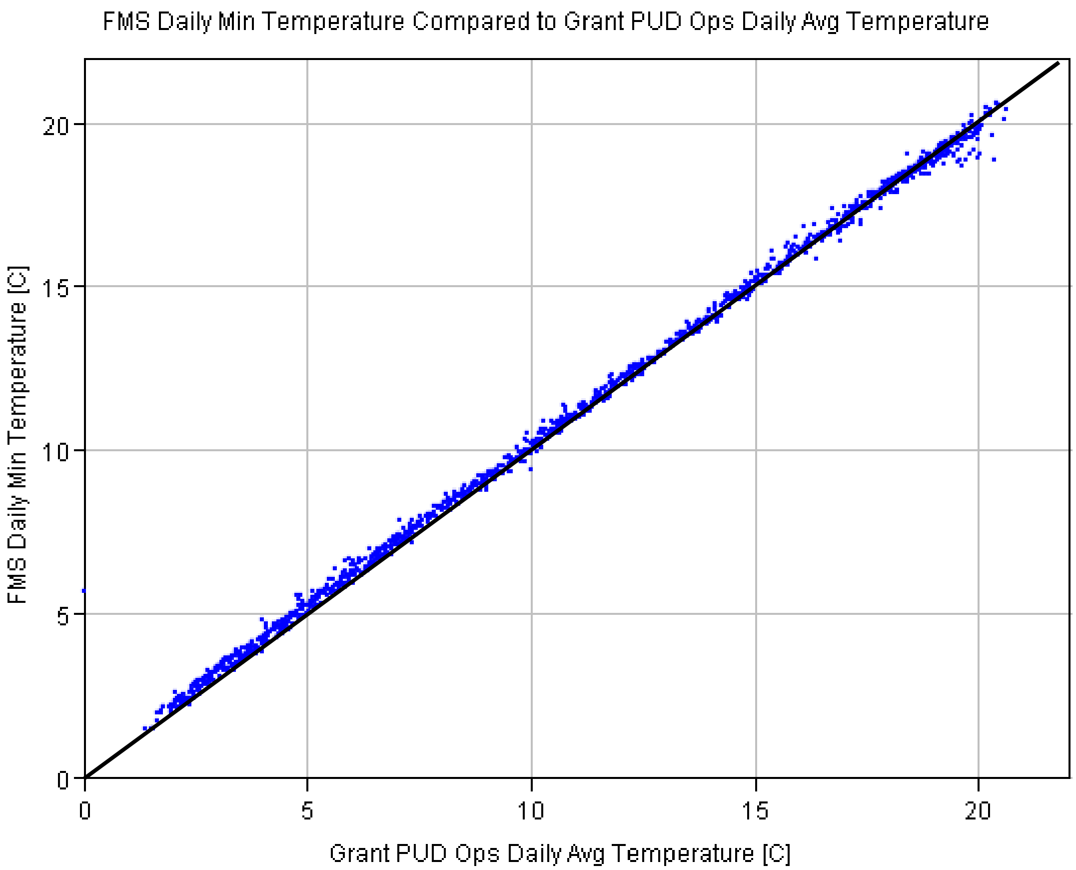

Figure 20: Daily Minimum of Wanapum fixed-site monitoring (FSM) station Water Temperature compared to Grant PUD Ops Daily Average Water Temperature Data

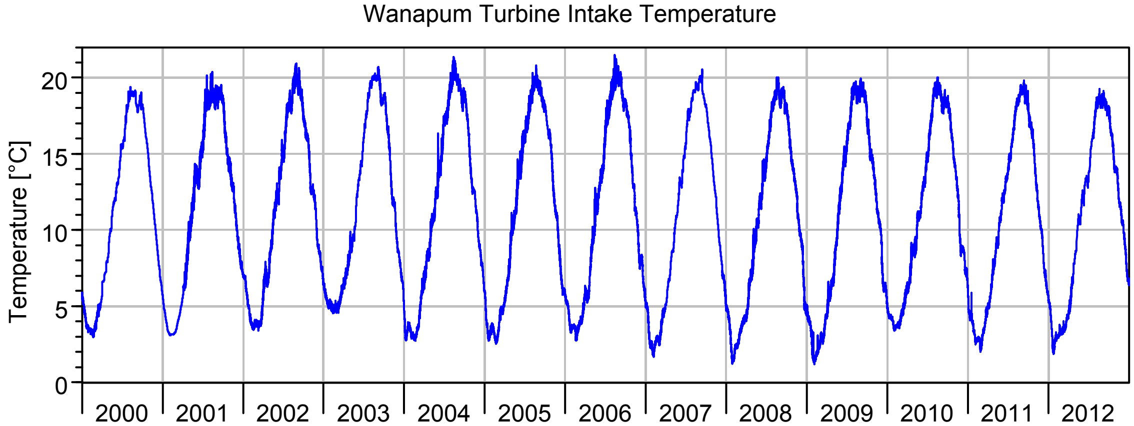

Figure 21: Wanapum Tailrace Temperature (Inflow to Priest Rapids Reservoir)

3.5 Topographic and Vegetative Shading

W2 requires topographic and vegetative shade angles to be defined for each model segment. Topographic shade inclination angles were calculated looking in 18 directions from each W2 model segment using a 30-meter Digital Elevation Model (DEM) of the region providing shade to the Project. Figure 22 shows an example of the topographic shade sampling lines (red), drawn radially from Segment 9 on Wanapum Reservoir. The purple "plus" symbols are the shade controlling topographic feature with the maximum inclination angle above the W2 segment for each sampling line. For this segment, the ridge 1000 - 2000 meters east, and the lower bank 250 meters west of the center of the river, provide shade for the segment. Similar calculations were performed for all W2 segments. It was assumed that there is limited vegetation within the Project vicinity that provides shade to the Columbia River.

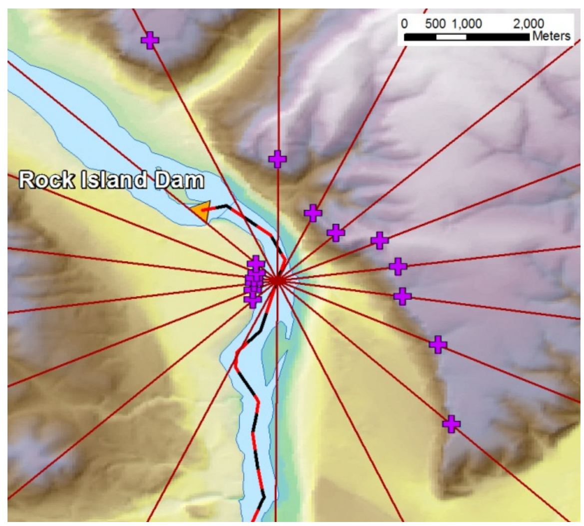

Figure 22: Example of Shade Controlling Topographic Features, Wanapum Segment 9

4 CALIBRATION AND SENSITIVITY ANALYSIS

The objective of model calibration is to achieve a scientifically defensible simulation of temperature by demonstrating an acceptable match to observed data. This means that the model should be accurate enough to make comparisons between "with" and "without Project" scenarios.

W2 has been used for hundreds of reservoir modeling applications since development began in 1975 and, as a result, a reliable set of default parameters are available to the user for use as an initial set prior to beginning model calibration. Initial model parameters for this analysis were all set to program defaults. Two exceptions being the vertical turbulent mixing method and wind speed height. The vertical turbulent mixing methods were set to "PARAB" for all riverine waterbodies (all "without Project" waterbodies and only the Hanford Reach for "with Project" models) and "W2" for all reservoir waterbodies (Wanapum and Priest Rapids for "with Project" models). The "PARAB" method was formulated for rivers while the default "W2" method was not. Wind speed height was set to the observed height of 10 meters, rather than the default of 2.

Data from 2000 to 2012 were used for calibration of the "with Project" model. The calibrated "with Project" parameter values were then used for the "without Project" scenario. Two exceptions are the vertical eddy viscosity method and channel roughness. As discussed previously, the "PARAB" vertical eddy viscosity method was used for riverine and the "W2" method was used for the reservoir waterbodies.

The water surface elevation was the first parameter calibrated to observed data. Without a good match to observed water surface elevations, there is no sense in looking at simulated temperatures, since these depend on water-level. After reasonable agreement is reached between simulated and observed water surface elevations, the water temperature was calibrated. Discussions of each of these calibration processes follow.

4.1 Water Surface Elevation Calibration and Flow Water Balance

Simulated water surface elevations were calibrated against observed water surface elevation data at six different locations: the Rock Island tailrace, the Wanapum forebay, the Wanapum tailrace, the Priest Rapids forebay, the Priest Rapids tailrace, and the USGS 12472800 gage.

First, the Wanapum and Priest Rapids forebay locations were calibrated using the water balance utility provided with W2 to create daily averaged distributed inflow files. The resulting inflow time-series, shown in Figure 23, include both positive and negative flow rates. The majority of the distributed inflow on any given time-step is associated with errors in the flow records provided for RID, Wanapum Dam, and the USGS gage below Priest Rapids Dam. Errors in the stage records at either forebay would also result in changes in the distributed inflow file; however, the accuracy of the stage records is higher than that of the reported flows. In addition to correcting for errors in the upstream and downstream flow gaging records, the distributed inflow may also correct for any ungaged inflow into the Project, though this is likely a small fraction of the flow on any given time-step.

Comparison plots of simulated and observed water surface elevations at each forebay can be found in Figure 24 and Figure 25. The match with observed stages are good overall, both matching within 0.1 meters on average, but individual hours have larger errors because the water-balance was performed on a daily time-step. Water-balances on an hourly time-step were also developed for use in sensitivity testing, but were not used for final model simulations because the magnitude of inflows needed to match reservoir stages were unreasonably high, exceeding 8,000 cms. The matches are comparable to other Columbia River W2 studies (e.g. Rocky Reach).

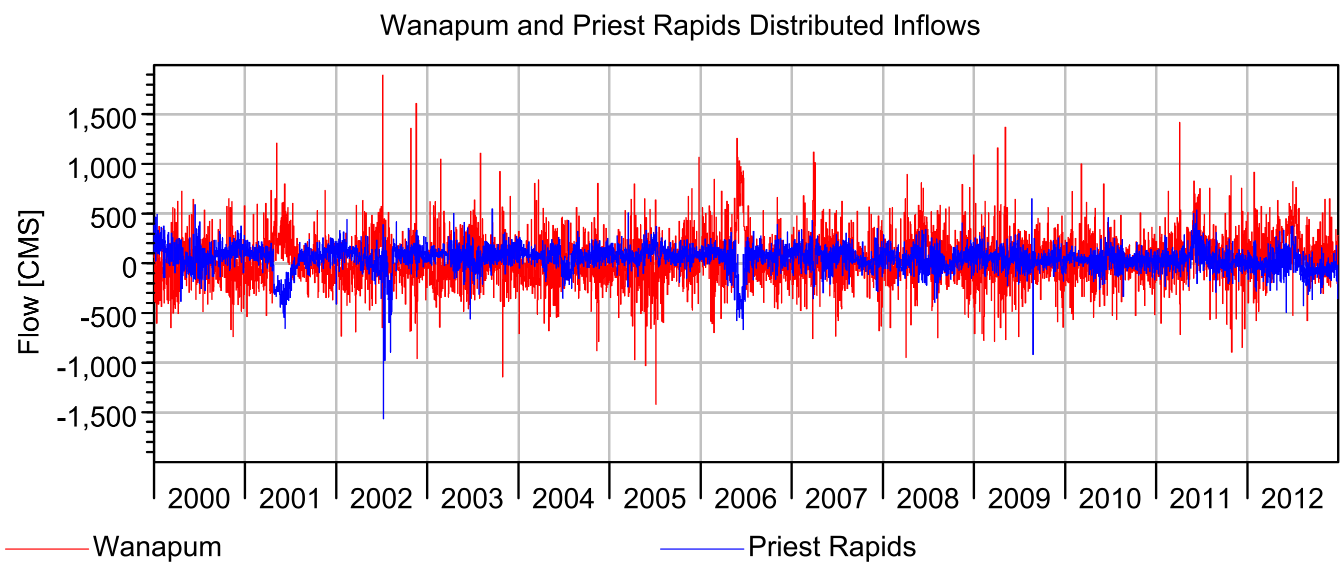

Figure 23: Daily Time-Step Distributed Inflow Files Developed to Match Observed Stages at Wanapum and Priest Rapids Reservoir Forebays

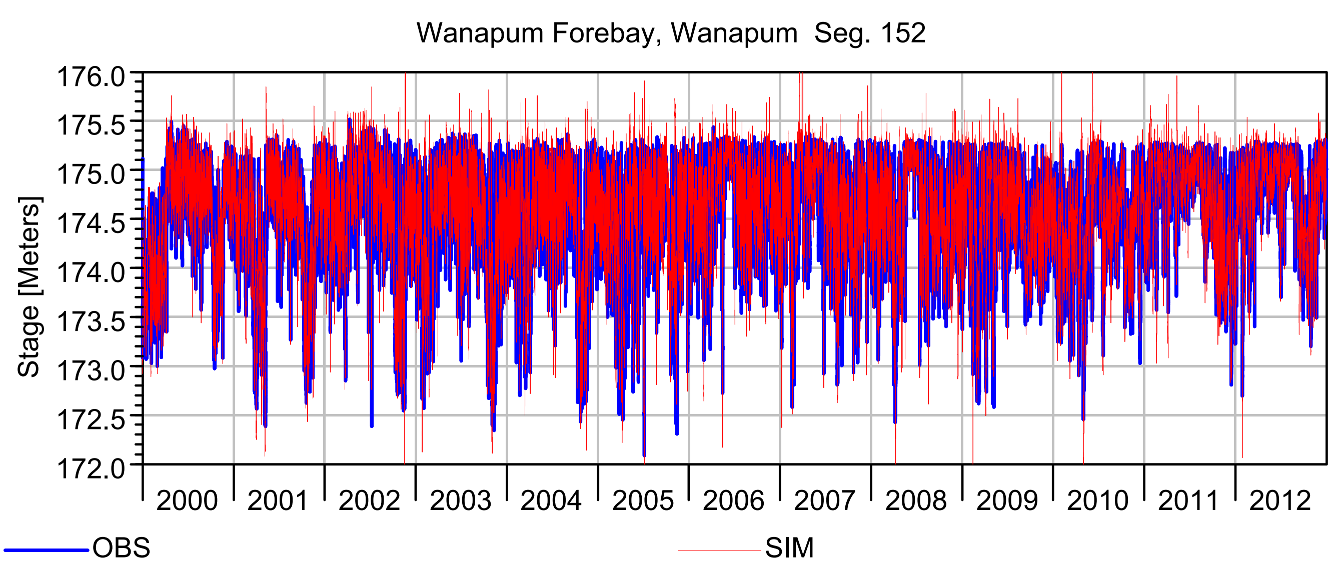

Figure 24: Comparison of Observed with W2 model Simulated Water Surface Elevation at Wanapum Forebay

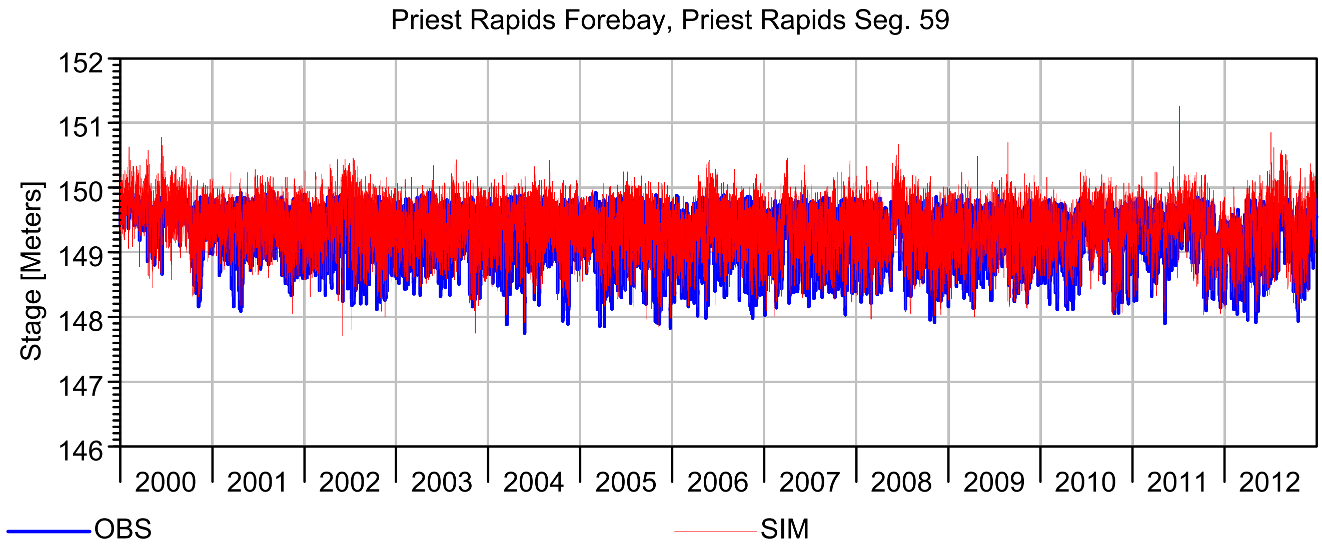

Figure 25: Comparison of Observed with W2 model Simulated Water Surface Elevations at Priest Rapids Forebay

Following completion of the water-balance, simulated water surface elevations were calibrated at the RID and Wanapum Dam tailwater stations by adjusting the Manning's roughness coefficients for each reservoir. Roughness coefficients of 0.035 and 0.030 were applied throughout the Wanapum and Priest Rapids reservoirs respectively. The resulting simulated water surface elevations at the RID and Wanapum Dam tailraces, which matched observed stages within 0.2 and 0.1 meters on average, can be found in Figure 26 and Figure 27.

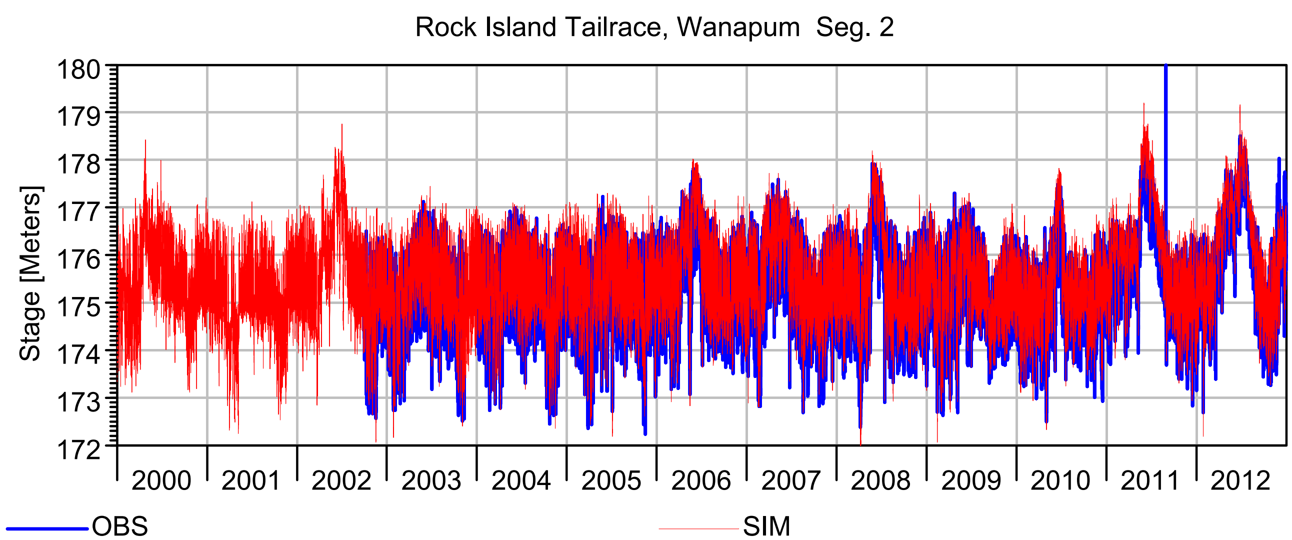

Figure 26: Comparison of Observed with W2 model Simulated Water Surface Elevation at RID Tailrace

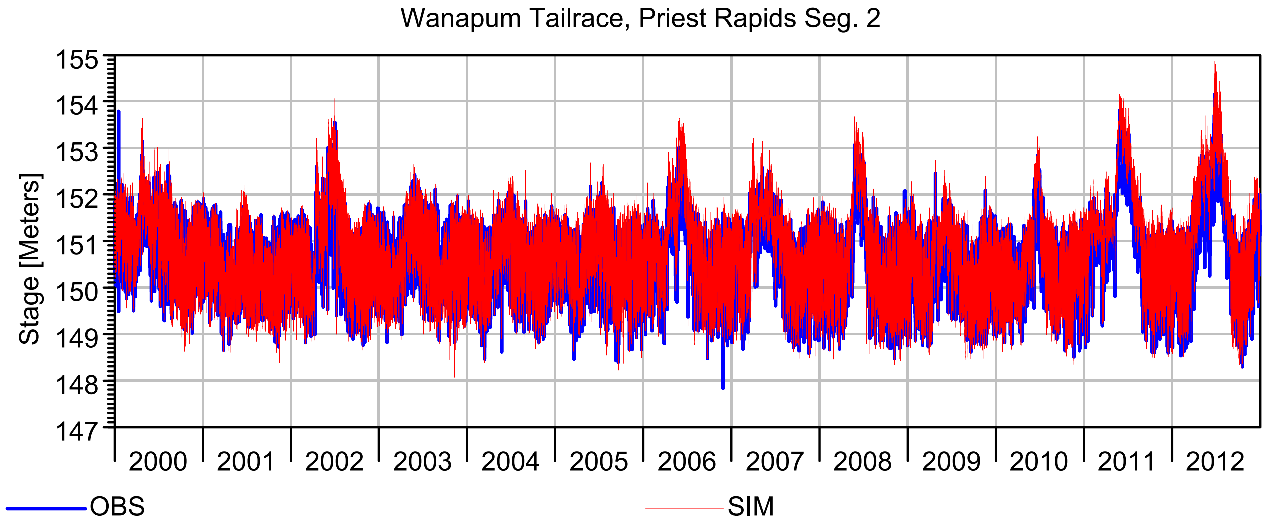

Figure 27: Comparison of Observed with W2 model Simulated Water Surface Elevation at Wanapum Tailrace

Finally, the water surface elevation was calibrated for the riverine reach downstream of Priest Rapids Dam. First, the HEC-RAS model of the Hanford Reach, which is used to establish stages at Vernita Bridge, the downstream boundary of the W2 model, was calibrated to stages at the USGS gage downstream of Priest Rapids Dam. With roughness coefficients of 0.030, the HEC-RAS model matched the stages at the USGS gage within 0.1 meters on average. Then, using the time-series of stages at Vernita Bridge as a downstream boundary condition, the W2 model reach downstream of Priest Rapids Dam was calibrated to match stages at the Priest Rapids tailrace and USGS gage. For this reach of the W2 model, a Manning's roughness coefficient of 0.030 produced the best match to observed stages across a range of high and low flow rates, also matching within 0.1 meters on average. Plots of final water surface elevations at the Priest Rapids tailrace and the USGS gage can be found in Figure 28 and Figure 29. Channel roughness for all riverine waterbodies were set equal to that calibrated for the Hanford Reach.

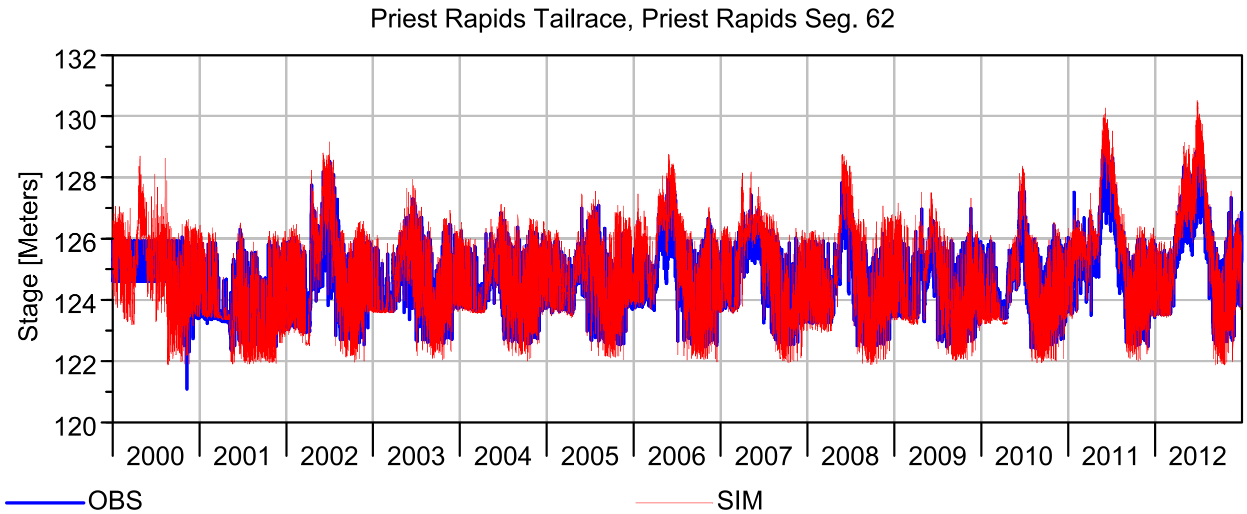

Figure 28: Comparison of Observed with W2 model Simulated Water Surface Elevation at the Priest Rapids Tailrace

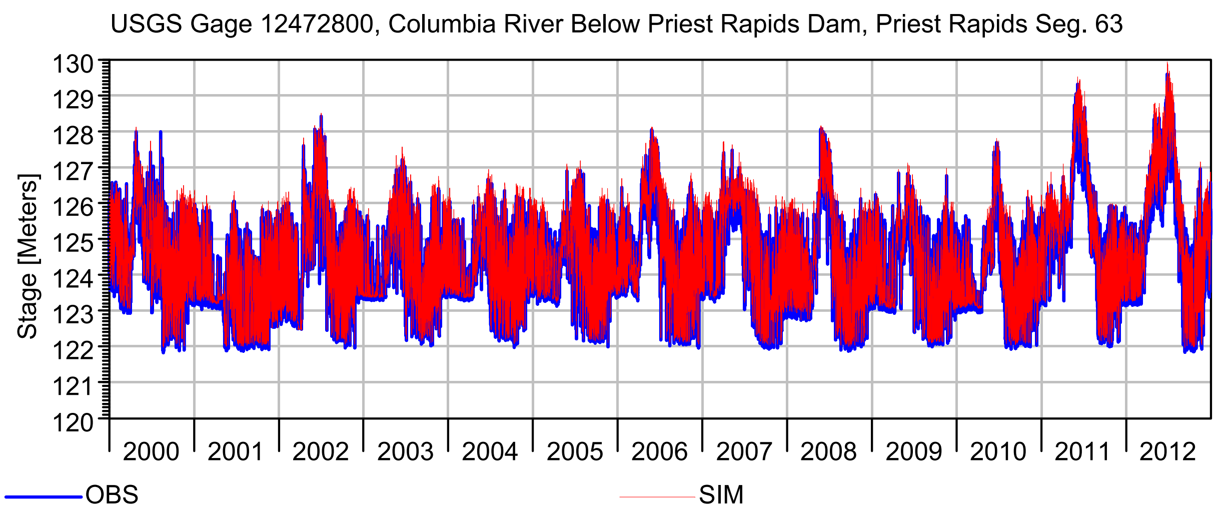

Figure 29: Comparison of Observed with W2 model Simulated Water Surface Elevation at USGS Gage 12472800

4.2 Water Temperature

The W2 model was calibrated to achieve an acceptable match between simulated and observed temperatures using three different sets of observed monitoring data:

- FSM station time-series collected at four Project locations (Wanapum forebay, Wanapum tailrace (Beverly Bridge), Priest Rapids forebay, and Priest Rapids tailrace (Vernita Bridge) from

2008 - 2012 (sites are listed in Table 3). Grant PUD operations temperature records at the Wanapum and Priest Rapids turbine intakes were also used at the two forebay locations.

- Time-series data collected at 1, 3, and 5 meter depths from June to September of 2000 at eight locations distributed throughout out the Project (sites are listed in Table 4).
- Temperature profiles collected by Grant PUD in 2011 (sites are listed in Table 4).

4.2.1 Temperature Time-series

Due to the relative large volume of data, the observed time-series data for the years 2008 through 2012 was the primary data-source used for temperature calibration of the W2 model. Observed time-series data also exist for the first five years of the 2003 – 2012 simulation period, but the calibration was limited to last five years of the modeled time period because the more recent data is believed to be more accurate. Figure 30 through Figure 32 show the modeled versus measured temperatures at the four Project locations from 2008 – 2012. Note that the model used to generate the output shown in these figures includes refinements adopted following sensitivity tests discussed in Section 4.3. Absolute Mean Error (AME) and Root Mean Square Error (RMSE) for the entire year are provided on each plot and a summary of the 2008 – 2012 summer (July – September) AME statistics are provided in Table 9. Error statistics for both the pre-and post-2008 simulation years are summarized for the summer and annual periods in Appendix C.

Table 9: Absolute Mean Error, "with Project", July through September 2008 – 2012 Calibration Period

Year	Absolute Mean Error, Simulated vs. Observed					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM [1]	Intake		FSM	Intake[1]	
2008	-	0.26	0.20	0.36	0.30	0.15
2009	-	0.29	0.22	0.34	0.30	0.17
2010	-	0.19	0.10	0.28	0.55	0.48
2011	-	0.12	0.09	0.21	0.49	0.15
2012	-	0.11	0.08	0.22	0.47	0.15
Average		0.19	0.14	0.28	0.42	0.22

[1] The Wanapum forebay FSM sensor and Priest Rapids forebay Turbine Intake sensors had some quality concerns and were not included as calibration time-series.

The match to observed temperature time-series data is similar to that achieved by other W2 modeling efforts (e.g. Rocky Reach, Wells dam, etc.). The Wanapum turbine intakes and the Beverly Bridge site have AME statistics below 0.3 °C while the Priest Rapids forebay FSM station AME statistic is below 0.4 °C. The AME statistic at the Vernita Bridge site was excellent, below 0.2 degrees, in all years but 2010. The error visible during the summer of 2010 is not visible in any of the other years, and is considered an outlier. In July/August of 2010, the model simulates temperatures greater than 1.0 degrees higher than the observed data. Therefore, assuming that the sensor data during this period is valid, the model is biased warm during the summer of 2010 and is more likely to show an artificial Project related impact.

While not a focus of this study, there is also some error during the winter (December – March) at the Vernita Bridge site, but winter periods are not of concern because temperatures are well below the temperature criteria of 20^{o}C.

The FSM station time-series at the Wanapum Dam forebay site had small spikes (Figure 33) that Grant PUD has determined to be associated with Project turbine operations. These spikes are not representative of the laterally averaged segment/layer temperatures simulated by the W2 model. An alternative dataset used for calibration at the site was the Wanapum turbine intake temperature time-series. The turbine intake sensor (actually multiple sensors) is located at a slightly deeper location and is void of these spikes (Figure 30).

The Priest Rapids FSM station time-series also had small temperature spikes similar to the Wanapum FSM station, but to a lesser degree (Figure 34 and Appendix B). This FSM station data was used for calibration but the AME error is higher as a result of the spikes in the observed data than would be the case if they were not in the observed data record. The Priest Rapids turbine intake temperature was also considered for use, however this data was found to be a half degree low during the summer months relative to the model simulation (Figure 35 and Appendix B). Various adjustments to the model were evaluated to improve the calibration, but none provided a good match. And those adjustments that provided some improvement in the match at the Priest Rapids turbine intake degraded the calibration at other locations. Similar to the Vernita Bridge site 2010 data, if the Priest Rapids intake sensor data is valid, then the "with Project" model could potentially be over predicting temperaures by up to 0.5 degrees in the Priest Rapids forebay.

In addition to the four long-term (2008 – 2012) temperature monitoring locations, the model was also calibrated to water temperature data collected from the beginning of June through the end of August 2000 at eight locations within the Project. These measurements were collected from the right-bank, left-bank, and middle of the reservoir channel at depths of 1, 3, and 5 meters. However, the left-bank and right-bank samples were not considered adequately representative of the laterally averaged model segment layer to be used for calibration. The W2 simulated temperature from the segment layer corresponding to a depth of 5 meters is compared to the 5 meter depth time-series in Figure 34 and Figure 32 (middle of channel only). The match to observed data at these sites is good, with AME error statistics of less than 0.3. Results from depths of 1 and 3 meters produced comparable matches.

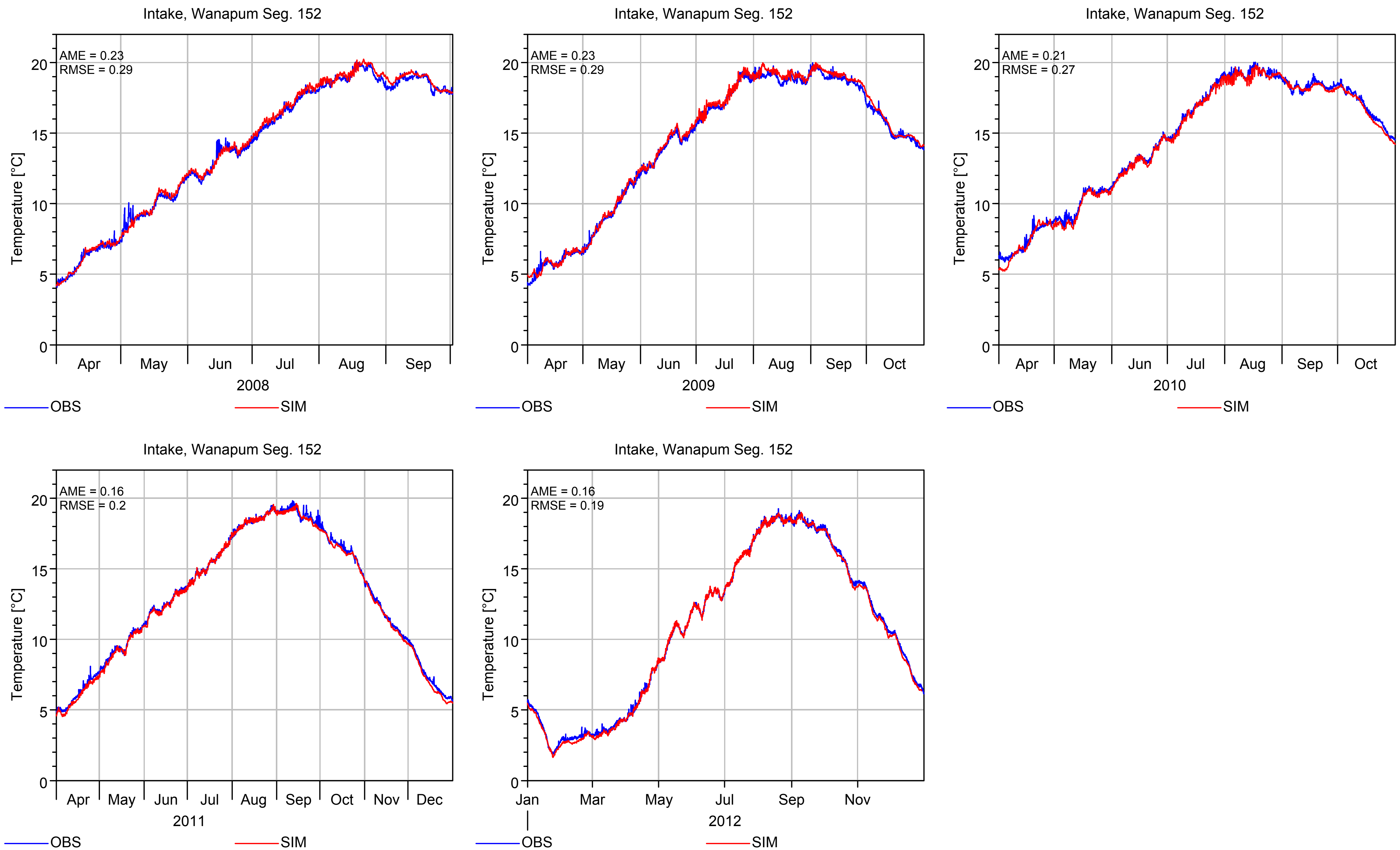

Figure 30: Simulated vs. Observed Water Temperature, Wanapum Forebay Intake, Wanapum Segment 152, 2008 – 2012

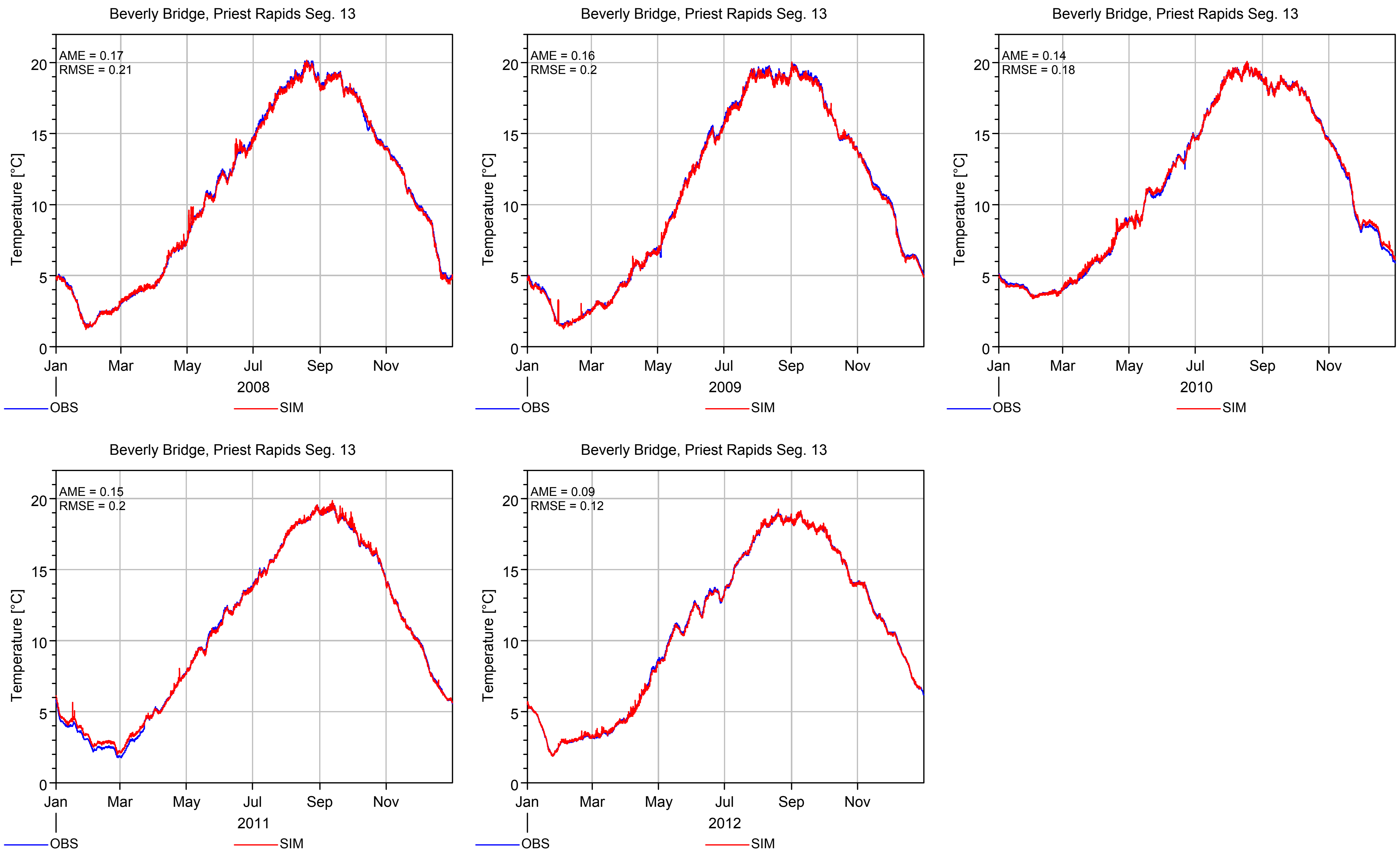

Figure 31: Simulated vs. Observed Water Temperature, Beverly Bridge, Priest Rapids Segment 13, 2008 - 2012

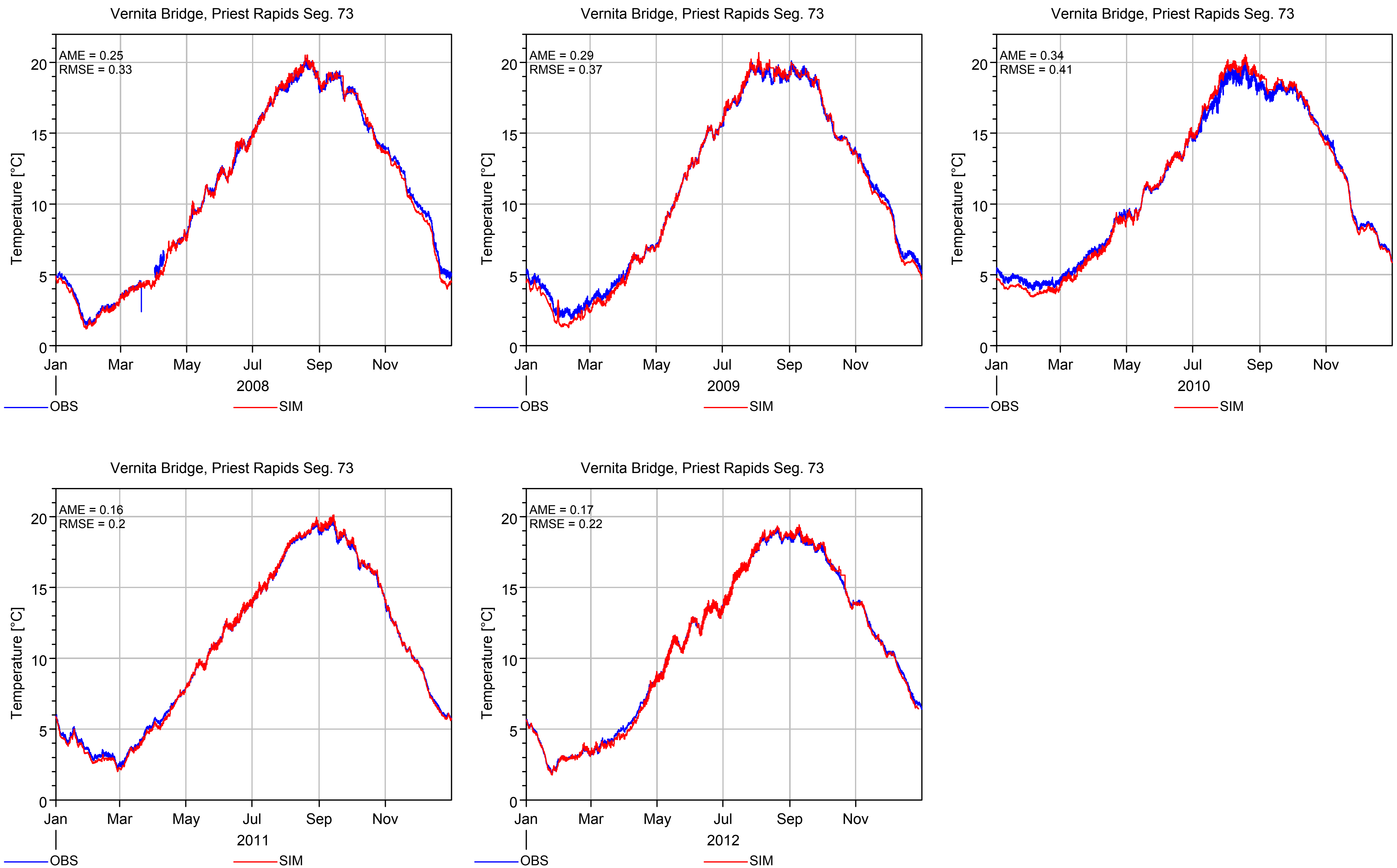

Figure 32: Simulated vs. Observed Water Temperature, Vernita Bridge, Priest Rapids Segment 73, 2008 – 2012

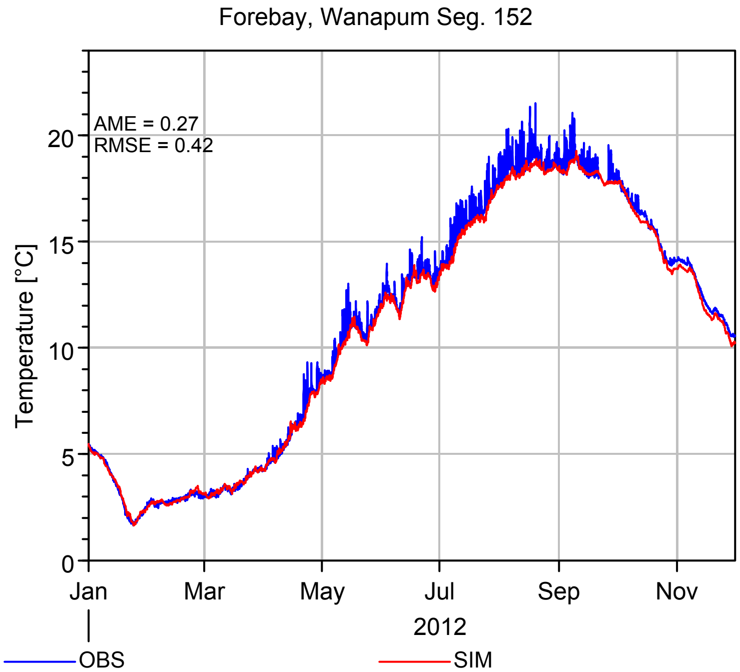

Figure 33: Example of Simulated vs. Observed Water Temperature, Wanapum Forebay FSM Sensor, Wanapum Segment 152, 2012

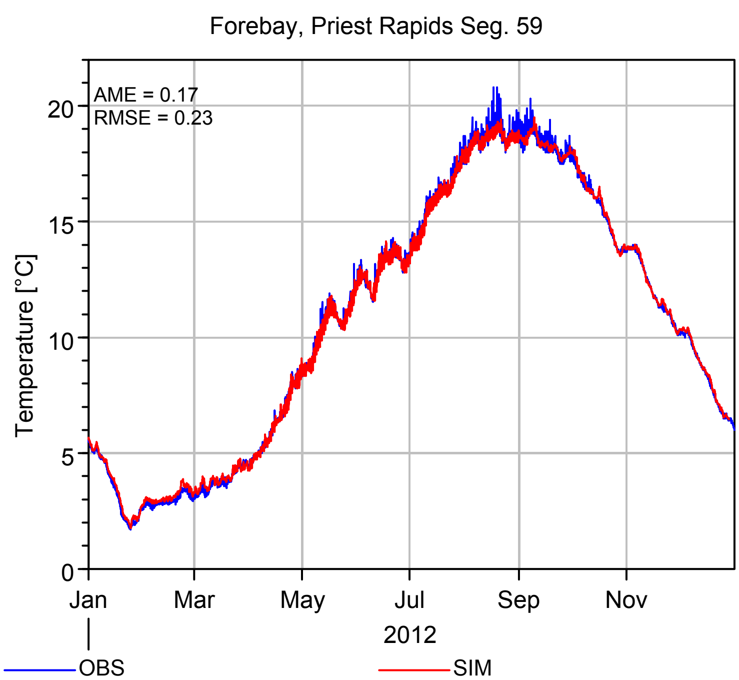

Figure 34: Example of Simulated vs. Observed Water Temperature, Priest Rapids Forebay FSM Sensor, Priest Rapids Segment 59, 2008 - 2012

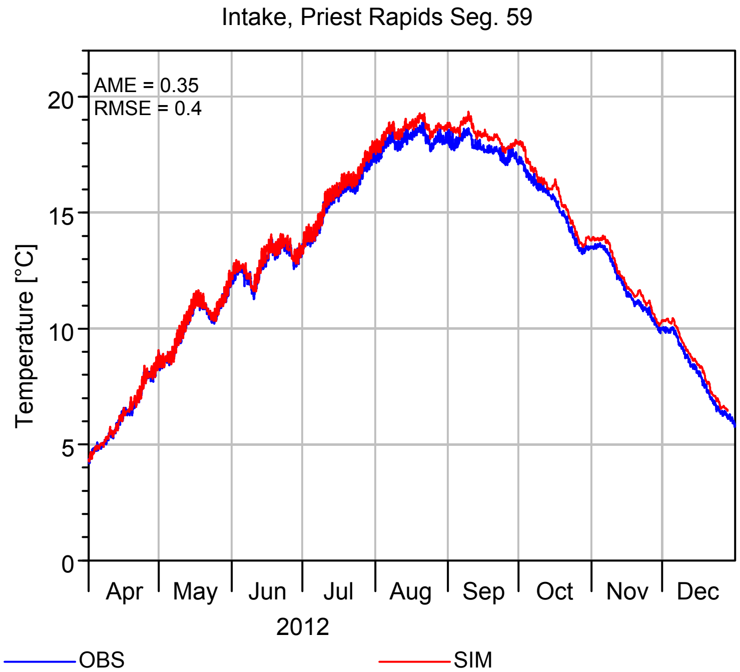

Figure 35: Example of Simulated vs. Observed Water Temperature, Priest Rapids Intake, Priest Rapids Segment 59, 2012

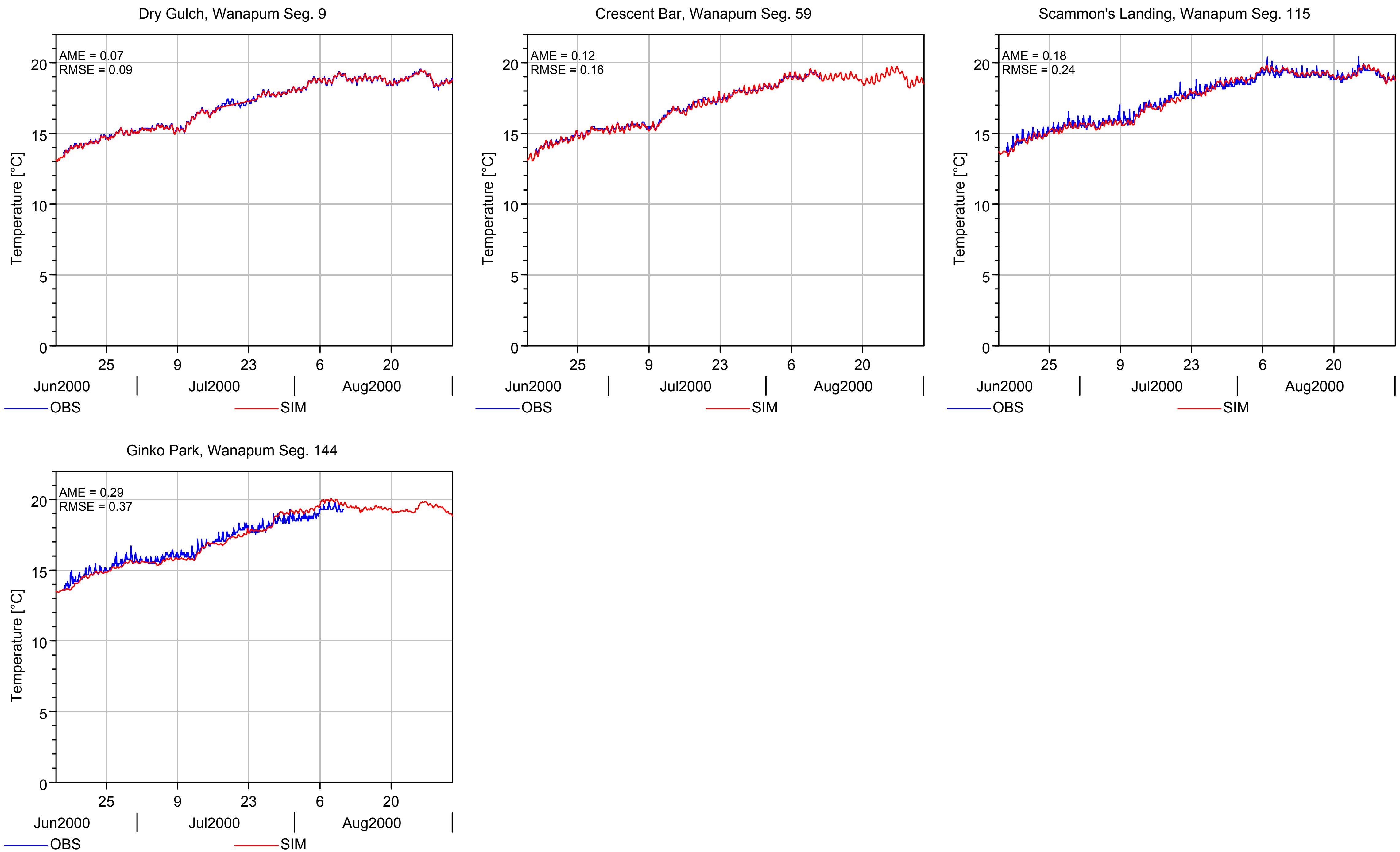

Figure 36: Wanapum Simulated vs. Observed Water Temperature, 2000, Middle of Channel 5 Meter Depth

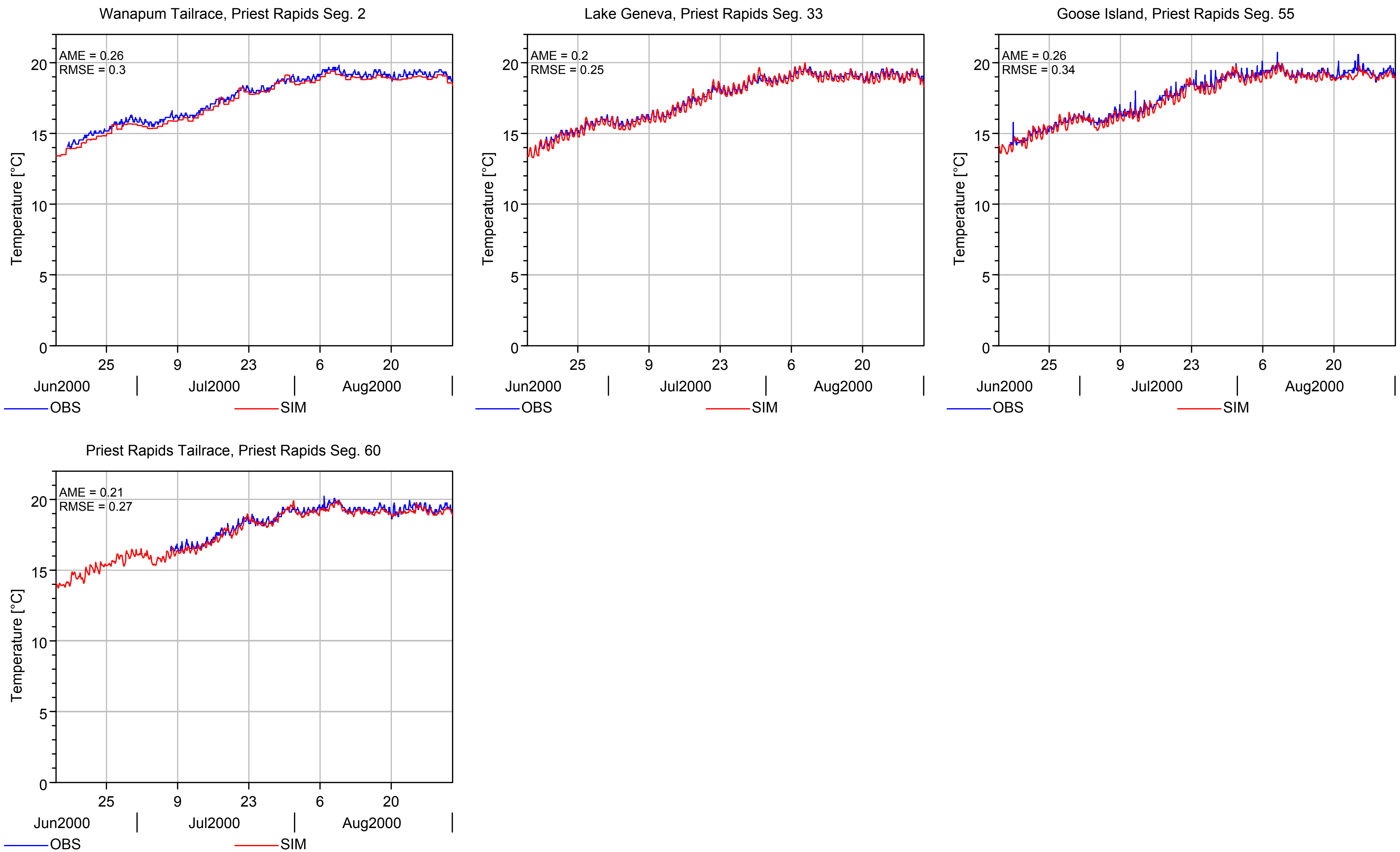

Figure 37: Priest Rapid Simulated vs. Observed Water Temperature, 2000, Middle of Channel 5 Meter Depth

4.2.2 Temperature Profiles

Temperature profiles were collected in 1999 and 2011 from May to September at seven locations within the Project (same as eight sights with time-series data in 2000, except the Priest Rapids tailrace site). For model calibration, only profiles located in the middle of the channel were used, thus limiting the calibration to 10 profiles collected in May and September of 2011 (no middle or channel profiles were collected in 1999). Results from the calibrated model are compared to the observed temperature profiles in Figure 38 and Figure 39. The x-axes have been provided with separate scales in spring and summer to aid the visual evaluation of small variations in temperature. As depicted in these figures, the calibrated model does a good job of matching the observed temperature profiles in both reservoirs with all but one simulated value being within 0.5 °C of observed data.

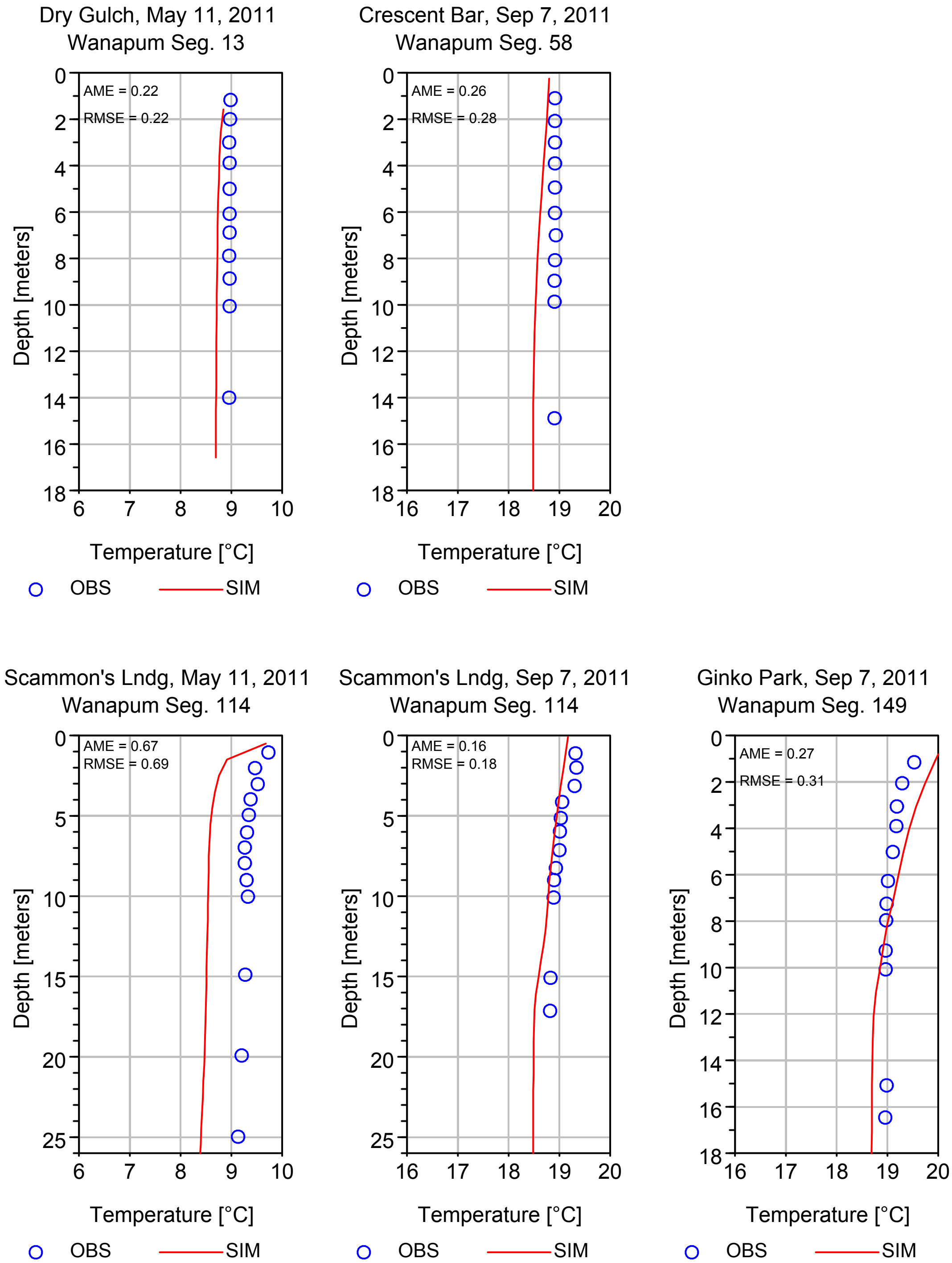

Figure 38: Wanapum Simulated vs. Observed Water Temperature Profiles, 2011

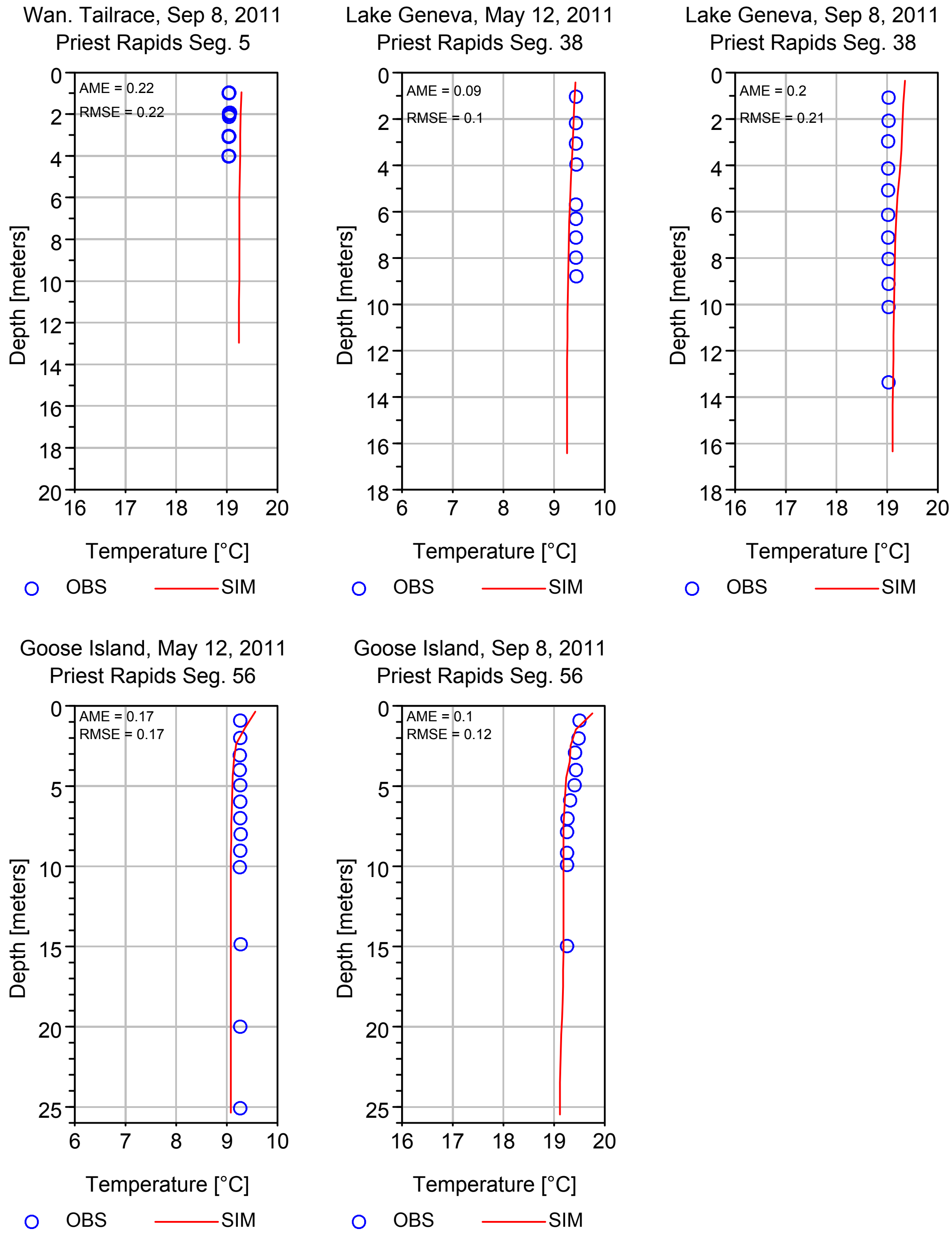

Figure 39: Priest Rapids Simulated vs. Observed Water Temperature Profiles, 2011

4.3 Sensitivity Analysis

Following the initial water balance procedure and calibration discussed above, more than 20 different datasets and parameters were varied in the "with" and/or "without Project" W2 models to determine how much variation resulted in the simulated temperatures. Those considered to have the most uncertainty or were the most likely to affect the result were evaluated.

A list of the sensitivity tests for which temperature statistics were calculated are as follows:

A. **Baseline Simulations –** A baseline simulation of the "with Project" and "without Project" models was used for comparison of sensitivity adjustments. For both models, the baseline simulation used daily water-balance distributed inflow files. Before using the original daily water-balance developed for the "with Project" model with the "without Project" model some considerations for the total net flow in the river reach had to be made. If distributed inflow files developed for the "with Project" W2 model were applied directly to the "without Project" model the model segments would dry up and terminate the model simulation. The model segments dry up when negative flows in the distributed inflow files are greater than the total discharge from RID; thus causing a net negative discharge in the riverine reach. Drying up of riverine segments was overcome in the baseline model runs by averaging adjacent days in the daily distributed inflow time-series to keep the total reach discharge above 200 cms, approximately the minimum observed in the observed RID flow record. The same adjusted daily water-balance was used for both the "with Project" and "without Project" baseline simulation. Other aspects of the baseline models are discussed in the context of each sensitivity test.

B. **Hourly Water-Balance ("with Project" only)** – The first sensitivity test compared temperatures simulated using distributed inflow files developed to achieve a water-balance that matched reservoir stages observed at Wanapum and Priest Rapids reservoirs on an <u>hourly time-step</u>. This differs from the daily time-step water-balance used to develop the distributed inflows used for the baseline simulations. The hourly water-balance produces a better match to observed reservoir stages, but also introduces larger negative flows needed to match stages on an hourly time-step. As stated previously, negative inflows are believed to result from errors in the flow records at the Projects bounding each reservoir.

C. **Daily Average of Hourly Water-Balance ("without Project" only) –** This test is very similar to the baseline model simulation, except the water-balance was developed as a daily average of an hourly water-balance instead of a daily-water balance. That is, the distributed inflow file was averaged from the flows used to match "with Project" stages on an hourly time-step rather than a daily time-step. It is the closest to the "with Project" hourly water-balance that could be run in the "without Project" model.

D. **No Distributed Inflow and Daily ("without Project" only)** – The screening of flows to prevent negative discharges from a distributed inflow file is moderately subjective due to the need to select a minimum allowed discharge threshold. This sensitivity test eliminated the use of any distributed inflow files in the "without Project" model. The long-term monthly average water-balances for the entire project account for only 2.5% of the total flow, so omission of distributed inflows results in only a small under-estimate of the overall project water-balance.

E. **5% Increase in Gaged Flows at Wanapum (“with Project” only) –** Upgrades to the turbines at Wanapum Dam have been implemented incrementally over the last decade but flow records for discharges through the turbines are calculated as a function of power generation using efficiency curves for the turbines that have since been replaced (personal communication Carson Keeler, Grant PUD). Total flows used for baseline simulations were corrected to reflect the newer more efficient turbines for the entire simulation period. However, because the turbines were installed incrementally during an approximately 10 year period, the applied Wanapum Reservoir turbine flows are likely under representing turbine flow releases at the beginning of the simulation period. This sensitivity test increased the turbine flows by 5% to evaluate if this error in the flow data could affect the simulation results. A new water-balance was developed using the adjusted flow rates.

   Note: The “without Project” W2 model does not directly use the turbine flow record at Wanapum, so this test does not apply directly to that model. However, a test was run using a daily water-balance developed from “with Project” simulations that used a 5% increase in the gaged turbine flows at Wanapum.

F. **RID Forebay Data for Wanapum Inflow Temperatures** – Simulated inflow temperature to the model at the upstream boundary condition are based on observed RID tailrace temperatures. And, as stated previously in Section 3.4.1.3, the raw time-series of temperatures recorded at the RID dam tailrace had a significant amount of noise during some years of the simulation that required manual editing. This sensitivity test used the RID forebay temperatures instead of the RID tailrace temperatures to see if the model results were sensitive to the data-source and the manual corrections that were applied to the tailrace data.

G. **Reduce Priest Rapids Inflows by 0.5 Degrees (“with Project” only) –** The sensitivity of the temperatures in Priest Rapids Dam to the water temperatures released from Wanapum Dam was evaluated by lowering the observed Wanapum Dam turbine intake temperatures by 0.5 degrees C.

H. **Increase AX and DX (Longitudinal Eddy Viscosity and Longitudinal Eddy Diffusivity) values to 10.0** – Two calibration parameters that can affect mixing and vertical stratification in the model are longitudinal eddy viscosity and longitudinal eddy diffusivity coefficients AX and DX. The sensitivity of the model to these parameters was evaluated by scaling them up from the baseline value of 1.0 to 10.0.

I. **Use Pangborn Cloud Cover for Priest Rapids Reservoir** – As stated previously, the NOAA data for cloud cover reports significantly more cloud cover at Hanford Station 21 than Pangborn Memorial Airport. This sensitivity of the model to the cloud cover dataset applied was tested by applying Pangborn Memorial Airport cloud cover data to the Priest Rapids Reservoir reach of the W2 models instead of the Hanford Station 21 data that was used in the baseline simulations.

J. **Use Air Temperature for Distributed Inflow –** This sensitivity test assigned air temperature to the distributed inflows instead of the observed reach inflow water temperature used in the baseline model simulations. The use of air temperature, or a function of air temperatures, to define the inflow temperatures to local inflows is common. However, the use of air temperature for the current project distributed inflows beyond sensitivity testing is not recommended because a large volume of the distributed inflow volume on any given time-step is actually associated with inflows from the upstream projects rather than local inflows. The observed upstream inflow temperatures provide a better representation of the inflow than air temperature.

K. **Use Line Instead of Point Withdrawals ("with Project" only) –** Spillway releases and turbine withdrawals are specified for both Project dams. The definition of these withdrawals includes the elevation of the structure outlet, but the amount of flow that is pulled to the outlet from each model layer can be adjusted by defining the outlet as a single horizontal location vs. a linear feature. These outlet geometries are referred to as points and lines in W2. If a relatively wide horizontal opening (i.e. a line) outlet is defined, then discharges will be pulled from only a few model layers near the outlet elevation. Conversely, if a narrow (point) outlet is defined, the total discharge needs to be pulled from a wider range of model layers.

L. **Outlet Structure Withdrawal Ranges ("with Project" only) –** In addition to changing the geometry of outlet structure withdrawals at each dam, the layers from which flow can be withdrawn can also be controlled. This test expanded the range of reservoir height from which spills and turbine intake discharges pull from.

M. **Vertical Eddy Viscosity Formulations** – The vertical eddy viscosity formulation selected to calculate the vertical shear stress in a waterbody can play a critical role in the simulation of flow patterns and vertical mixing by the model. The baseline models used the W2 and PARAB formulations for reservoir and riverine branches of the model, respectively. For these tests, reservoir branches in the "with Project" model were simulated using the RNG (Re-Normalization Group) formulation and riverine branches in the "without Project" model were simulated with the Nickuradse and W2 formulations.

N. **Use Theoretical Solar Radiation Data (SROC) –** Solar radiation plays an important role in the heat budget and dynamics of simulated water temperatures. For this test, the solar radiation dataset recorded at Hanford Station 21 was replaced with a theoretical solar radiation time-series calculated by W2 using the longitude and latitude coordinates for the project.

O. **Wind Sheltering Coefficients** – The sensitivity of the models to wind speed was evaluated by changing factors called wind sheltering coefficients. These coefficients are applied as multipliers on the wind data observed at the Beverly station that is used by the models. The baseline models use coefficients of 1.0 for all model segments. Coefficients of 0.75 and 1.25 were evaluated for sensitivity tests.

P. **Reduce Shading Factors ("with Project" only) –** The sensitivity of the model to topographic and vegetative shading was evaluated by changing the dynamic shading method that accounts for the position of the sun relative to obstructions to a simpler method that uses just a multiplier. A conservatively small multiplier of 0.3 was applied.

Q. **Priest Rapids Reservoir as Two Branches or Two Waterbodies –** The baseline Priest Rapids model was developed as a single branch with a nearly flat slope. Two alternative bathymetries were evaluated to see if breaking the reservoir into two branches or two waterbodies, each with a slightly steeper upper reach and a nearly flat lower reach, had any effect on simulated temperatures.

R. **Decreased Roughness Downstream of Vernita Bridge to 0.030 ("with Project" only) –** The sensitivity of the model to the downstream boundary water-levels assigned at Vernita was evaluated. This was performed by adjusting the roughness in the HEC-RAS model used to develop the time-series of stages at Vernita Bridge and then re-running the "with Project" W2 model with the updated stages. The Manning's roughness coefficients defining channel roughness in the HEC-RAS model were decreased from the baseline value of 0.035 to 0.030.

S. **Increase Channel Roughness to Mannings-N of 0.045 ("without Project" only)** – The sensitivity of the "without Project" model to flow depth was evaluated by increasing the channel roughness throughout the model domain.

4.3.1 Sensitivity Analysis Statistics and Results

The resulting sensitivity of each test was evaluated by calculating the following four statistics at key locations in the Project:

- Maximum Annual 7-DADMax
- Average Annual 7-DADMax
- Absolute Mean Error, relative to observed data ("with Project" simulations only)
- Root Mean Square Error, relative to observed data ("with Project" simulations only)

The results for the statistics are presented in Table 28 through Table 33 in Appendix D for the summer period of July through September 2012. This period was selected for sensitivity testing because it was a year that resulted in simulated temperature differences and it was within the simulation period with observed data considered to be the most reliable.

The first two statistics, the maximum and average annual 7-DADMax, are informative for evaluating the impact a parameter adjustment can have on temperature Metric 2, the 7-DADMax Maximum Temperature Increase threshold. Metric 2 and Metric 4 require the comparison of temperatures within a 0.3 degree margin, so both demand high precision results from the model relative to the other metrics. It should also be noted that the maximum annual 7-DADMax was found to occur during approximately the same seven day period for all of the sensitivity tests performed; that being the seven days prior to August 20, 2012. As a result, this statistic is effectively reporting the 7-DADMax for that period.

A measure of the change that resulted from each test is the change in the maximum annual 7-DADMax relative to the baseline simulation, tabulated in Table 10 and Table 11 for the "with Project" and "without Project" sensitivity tests, respectively. Negative values indicate that the test resulted in a decrease in the 7-DADMax temperature. It should be noted that some of these tests cause increases or decreases in both the "with Project" and "without Project" models. So, it should not be assumed that a simulated change in the "with Project" model 7-DADMax will correspond to a comparable change in the Metric 2 or 4 results if the test were adopted for use in evaluating Project compliance.

The sensitivity tests that resulted in the most significant decreases in simulated temperature were reducing Priest Rapids inflow temperature by 0.5 °C and reducing shading factors to 0.3. Both of these fairly extreme tests resulted in the reduction of temperatures at the Priest Rapids forebay by approximately 0.5 °C. While these are significant changes, they resulted in poorer calibration AME and RMSE statistics tabulated in Appendix D. The one exception being the Priest Rapids turbine intake sensor, but the sub-daily match to the temperature variation was still poor. And, as was previously discussed, the change degraded the calibration at the other calibration locations.

The test that caused the most significant increase in the 7-DADMax temperature was the use of air temperature for the distributed inflows rather than the observed Project inflow temperatures. This test resulted in a 0.18 degree increase at the Priest Rapids forebay FSM station sensor in the "with Project" model and a 0.28 degree increase in the "without Project" model at the same model segment. However, the AME and RMSE statistics decreased for the "with Project" model.

Based on the results of the sensitivity tests and further model review, four refinements were adopted for use in the final model simulations. Those changes included: the use of wide (line) withdrawals instead of narrow (point) withdrawals at the dam spillway and intake locations, increasing the range from which outlet structures withdraw to include the entire height of the reservoir, the Priest Rapids Reservoir was broken up into two branches, and the water-balance used for the "without Project" model simulations was applied as long-term monthly averages rather than a daily or hourly water-balance. The values for each month were calculated from "with Project" daily water-balance. The cumulative effect of these changes was small, on the same order as the individual sensitivity test results.

Table 10: Change in Simulated 7-DADMax, “with Project”, July through September 2012

Sensitivity Test	Change in Maximum Simulated 7-DADmax Relative to Daily Water-Balance					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
Baseline Simulation (Daily Water-Balance)	-	-	-	-	-	-
Hourly Water-Balance	-0.02	-0.02	0.00	-0.02	-0.01	-0.01
5% Increase in Turbine Flows at Wanapum	0.06	-0.02	0.00	0.05	-0.04	0.00
RID Forebay Data for Wanapum Inflow Temperatures	0.08	0.06				
Reduce Priest Rapids Inflows by 0.5 Degrees			-0.50	-0.29	-0.51	-0.47
Increase AX and DX values to 10.0			-0.01	0.18	-0.04	0.00
Use Pangborn Cloud Cover for Priest Rapids			0.00	-0.02	-0.03	0.00
Use Air Temperature for Distributed Inflow			0.00	0.18	0.00	0.04
Use Line Instead of Point Withdrawals	0.01	0.00	0.00	0.18	-0.03	0.00
Outlet Structure Withdrawal Ranges			0.00	-0.02	-0.02	-0.02
RNG Vertical Eddy Viscosity Formulation			-0.03	0.12	-0.05	-0.03
Use Theoretical Solar Radiation Data			0.01	0.14	-0.11	-0.04
Wind Sheltering Coefficient of 0.75			0.00	0.15	-0.01	0.01
Wind Sheltering Coefficient of 1.25			-0.01	0.01	-0.01	-0.05
Reduce Shading Factors to 0.3			-0.11	-0.41	-0.40	-0.42
Priest Rapids Reservoir as two Branches			-0.01	0.00	-0.04	-0.03
Priest Rapids Reservoir as two Waterbodies			0.00	0.01	-0.04	-0.01
Decreased Roughness Downstream of Vernita Bridge to 0.030			0.00	0.00	0.00	0.02

Table 11: Change in Maximum Simulated 7-DADMax, "without Project", July through September 2012

Sensitivity Test	Change in Maximum Simulated 7-DADmax Relative to Daily Water-Balance			
	Wanapum Forebay	Beverly Bridge	Priest Rapids Forebay	Vernita Bridge
Baseline Simulation (Daily Water-Balance)	-	-	-	-
Daily Average of Hourly Water-Balance	0.00	-0.01	0.00	0.02
No Distributed Inflows	0.00	0.01	0.00	0.02
Daily Water-Balance Developed with 5% Increase in Turbine Flows at Wanapum	0.01	0.01	0.01	0.03
RID Forebay Data for Wanapum Inflow Temperatures	0.00	0.00	0.03	0.02
Increase AX and DX values to 10.0	0.00	-0.01	0.00	0.02
Use Pangborn Cloud Cover for Priest Rapids	0.00	0.00	0.03	0.06
Use Air Temperature for Distributed Inflow	0.28	0.29	0.28	0.33
Nickuradse Vertical Eddy Viscosity Formulation	0.17	0.24	-0.02	0.01
W2 Vertical Eddy Viscosity Formulation	-0.01	0.00	0.00	0.01
Wind Sheltering Coefficient of 0.75	0.01	0.00	0.02	0.03
Increase Channel Roughness to Mannings 'n' of 0.045	-0.02	-0.05	-0.01	-0.03

4.4 Model Usefulness Based on Calibration and Sensitivity Analysis

The W2 model calibration and sensitivity analysis demonstrates that the model provides a robust simulation of measured water temperature within the Project. This observation is based on the calibration plots and associated statistics in Section 4.2 and the sensitivity tests completed in Section 4.3.

Visual examinations of the temperature time-series plots (Figure 30 through Figure 37) reveal that the model is not biased high or low. There is very little disagreement between simulated and observed temperatures at a majority of the sites. Table 12 and below provide summaries of AME, RMSE, maximum, average, and minimum value statistics for the temperature calibration. The statistics are similar, with relatively small average values below 0.21 and 0.27 degrees AME and RMSE, respectively, for time-series data comparisons. The maximum errors are slightly higher for the profile data plots, largely due to one outlier at Scammon's Landing on May 11, 2011 with both AME and RMSE values near 0.7. Without that May 11, 2011 profile, the maximum AME and RMSE statistics would have been significantly lower at 0.34 and 0.42, respectively. These calibration statistics are comparable to other W2 model calibrations used for similar purposes (e.g. Rocky Reach WQC, Wells Dam WQC, Pend Oreille TMDL, etc.). The maximum AME or RMSE statistics are on the order of the temperature differences being evaluated by Metric 2 and Metric 4. However, because the same input datasets are used for both the "with Project" and "without Project" models, many of the errors occurring in one simulation also occur in the other. If observed data for the "without Project" model existed, the accuracy of both models could be evaluated, but that data cannot be obtained. It has been shown that, based on the reported "with Project" calibration and sensitivity results, the "with Project" model provides an accurate match to observed data and there is little sensitivity in the "without Project" model results.

These water temperature calibration results demonstrate that the developed "with Project" W2 model is capable of simulating temperatures with adequate accuracy for the purposes of this analysis.

Table 12: Temperature Calibration Statistics (2008 – 2012)

Calibration Data Type		Absolute Mean Error (AME) (°C)	Root Mean Square Error (RMSE) (°C)
Time-Series Data (Annual)			
	Maximum	0.34	0.41
	Average	0.20	0.25
	Minimum	0.07	0.09
Time-Series Data (July - September)			
	Maximum	0.48	0.55
	Average	0.21	0.27
	Minimum	0.08	0.10
Profile Data			
	Maximum	0.67	0.69
	Average	0.24	0.25
	Minimum	0.09	0.10

Table 13: Simulated "with Project" and Observed Temperatures (July through September 2003 – 2012, Hourly Values)						
	Calibration Location					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
Simulated						
Max	21.9	20.8	21.4	21.3	21.2	21.3
Average	18.5	18.4	18.4	18.5	18.6	18.5
Min	13.4	13.4	13.2	13.2	13.2	13.2
Observed						
Max	-	21.5	21.0	21.9	21.6	21.2
Average	-	18.4	18.4	18.6	18.1	18.4
Min	-	13.2	13.5	13.6	13.3	13.6

5 EVALUATION OF PROJECT WITH TEMPERATURE CRITERIA

The primary outcome from this analysis is an evaluation of the Project's compliance with WDOE standards set forth in the 401 WQC (Section 6.5) for operation of the Project. The required criteria, described by five temperature metrics previously outlined in Section 1.3 of this report, are as follows:

1. 7-DADMax Threshold Upstream of Priest Rapids Dam
2. Maximum 7-DADMax Temperature Increase Upstream of Priest Rapids Dam
3. Daily Maximum Threshold Downstream of Priest Rapids Dam
4. Maximum Temperature Increase Downstream of Priest Rapids Dam, Part 1
5. Maximum Temperature Increase Downstream of Priest Rapids Dam, Part 2

The metrics were evaluated at four locations within the Project listed in Table 14, three upstream of Priest Rapids Dam and one downstream. Simulated output from these locations was analyzed for each day of calendar years 2003 – 2012.

Table 14: Project Locations Analyzed with Temperature Criteria			
Location Name	W2 Model Segment ID		River-Mile[1]
	"with Project"	"without Project"	
Wanapum Forebay	WAN-152	162	415.8
Beverly Bridge	PR-13	178	412.2
Priest Rapids Forebay	PR-59	230	397.1
Project Boundary	PR-65	236	395.1

[1] Analysis locations, and corresponding river-miles, match those reported previously by Grant PUD.

5.1 Methodologies for Calculating Simulated Temperature

The state water-quality criteria (WAC 173-201-200) does not specify how a laterally averaged two-dimensional model such as W2 should be queried when evaluating a Project's compliance with temperature criteria. The WAC criteria does state, "Temperature measurements should be taken to represent the dominant aquatic habitat of the monitoring site" and "be taken from well-mixed portions of rivers…and not be taken at the surface, or at the water's edge". The Project 401 WQC specified that a one-dimensional model, MASS1, be applied to evaluate the project's compliance with temperature criteria. Output from MASS1 would have been limited to a depth averaged solution but how a two-dimensional model would be applied was not specified when the required model was changed to CE-QUAL-W2.

Two methods were used to query simulated temperature data; flow and volume weighted averaging. Both methods target representing the overall water column condition, similar to that which would be reported by a one-dimensional model such as MASS1. These are also the same weighting methods used for the comparable analyses of Rock Reach Dam and Wells Dam (WEST Consultants, 2006 and 2008). The same methods are also routinely applied for similar studies more broadly in the Pacific Northwest (e.g. PSU, 2004) and are considered an industry standard. The two methods are described in further detail as follows:

- Flow weighted temperature – This is the primary method used to analyze the two scenarios. The flow weighted temperature is determined by multiplying the discharge of each segment layer by the temperature of each layer and then summing the products over the full depth of each model segment. The result is then divided by the total discharge of all of the layers in the segment to find the flow weighted temperature for the segment.
- Volume weighted temperature – This is the secondary method used to analyze the two scenarios. The volume weighted temperatures are determined using a similar method to the flow weighted, except the volume of each layer is used instead of discharge. Results for both flow and volume weighted temperature results are provided in the report, but discussion primarily focuses on flow weighted results because the two were found to be similar at the reported Project analysis locations.

The flow and volume weighted temperatures were calculated by modifying the W2 Fortran code and recompiling a new version of the program that exports the needed temperature data.

5.1.1 Different "with Project" and "without Project" Hydraulic Conditions

The hydraulic conditions in the Priest Rapids and Wanapum Reservoirs are significantly different in the "with Project" condition than they are in the "without Project" condition. The differences are important factors that influence the capacity of the Project to assimilate heat and the overall temperature dynamics of the system. A summary of typical hydraulic properties within the Project, sampled from a date in spring and another in summer of 2012, are shown in Table 15. The "with Project" geometry is approximately three times deeper and wider at Wanapum Forebay and Priest Rapids Forebay whereas the properties at Beverly Bridge and the Project Boundary are very similar between the two scenarios.

Table 15: Hydraulic Properties Comparison

Scenario	Date	Discharge (cfs)	Depth (m)	Top Width (m)	Average Velocity (m/sec)
Wanapum Forebay					
With Project	May 5, 2012	6,300	37.6	2,500	0.2
Without Project	May 5, 2012	6,500	15.9	490	1.4
With Project	August 8, 2012	5,200	37.9	2,500	0.2
Without Project	August 8, 2012	5,400	15.1	490	1.3
Beverly Bridge					
With Project	May 5, 2012	6,100	14.8	790	1.9
Without Project	May 5, 2012	6,500	16.4	890	1.9
With Project	August 8, 2012	5,100	14.9	790	1.5
Without Project	August 8, 2012	5,400	15.2	630	2.0
Priest Rapids Forebay					
With Project	May 5, 2012	6,500	28.4	2,430	0.2
Without Project	May 5, 2012	6,600	8.5	500	2.9
With Project	August 8, 2012	5,200	29.9	2,470	0.2
Without Project	August 8, 2012	5,500	7.3	400	3.1
Project Boundary					
With Project	May 5, 2012	6,600	14.5	380	2.0
Without Project	May 5, 2012	6,800	14.7	380	1.7
With Project	August 8, 2012	5,200	13.3	370	2.1
Without Project	August 8, 2012	5,500	13.6	370	1.6

5.1.2 Weighting Factors in Flow and Volume Weighted Methods

Vertical profiles are provided for the three locations located upstream of Priest Rapids Dam (Table 14) in Figure 40 through Figure 42 (note that x-axis scale on these figures is at a very small resolution, e.g. increment of only 0.2 - 0.4 °C , in order to magnify the little variation within the water column). The two dates presented in the figures, May 5, 2012 and August 8, 2012, were selected to represent spring and the peak of summer.

In addition to the vertical temperature profile, each figure provides a vertical profile of the flow and volume weighting factors used to calculate the flow and volume weighted temperatures corresponding to the profile simulated for that time-step. The weighting factor profiles show that temperatures in the upper half of the water column are weighted two to three times that of the temperatures in the lower half of the water column. This occurs because the widths of model layers are the smallest at the bottom of the reservoir and the largest at the top of the reservoir. Both the flow and volume weighted methods report similar temperatures from the "with Project" and "without Project" simulations as a result.

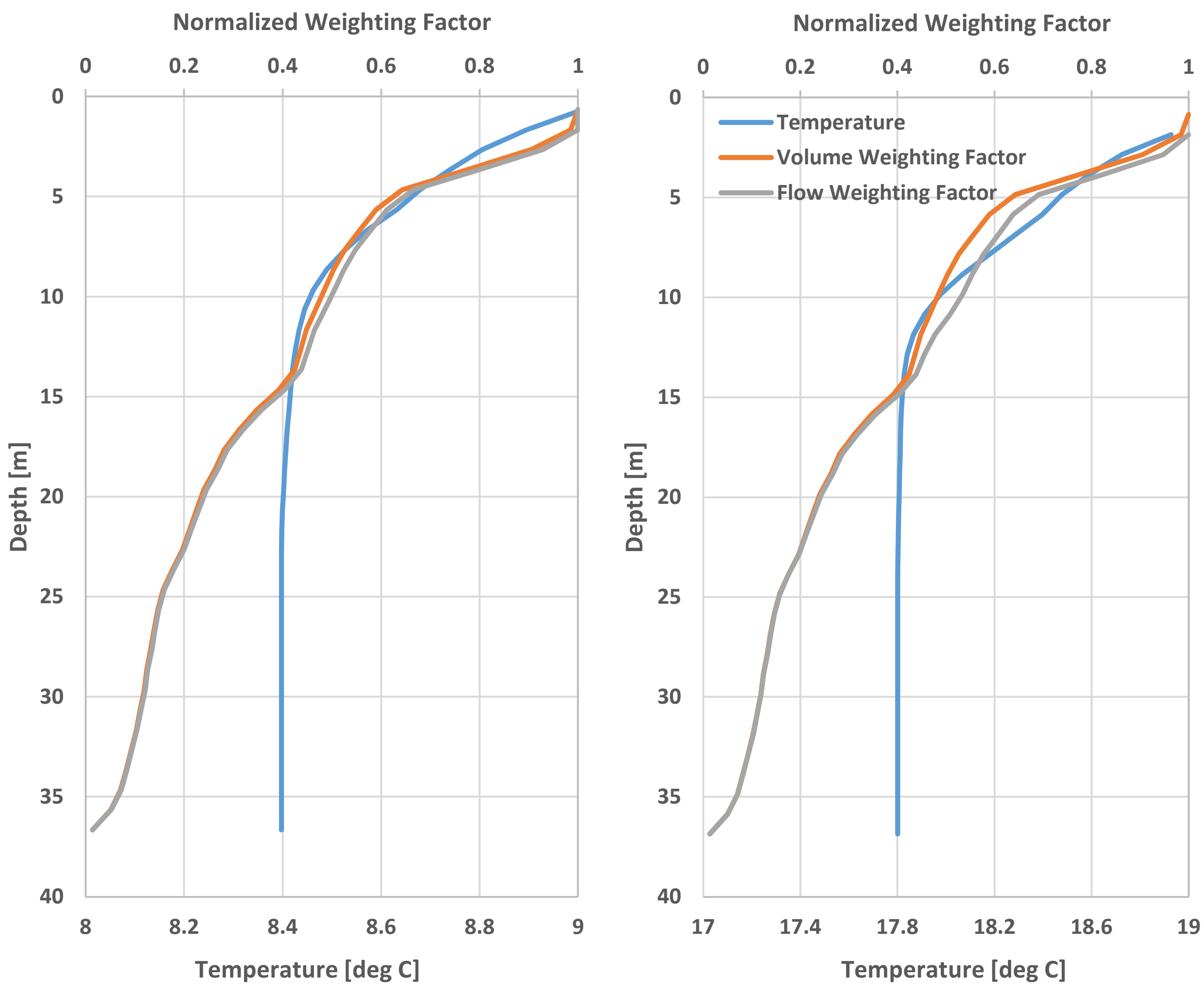

Figure 40: Temperature and Weighting Factors at Wanapum Forebay, May 5, 2012 (left) and August 8, 2012 (right)

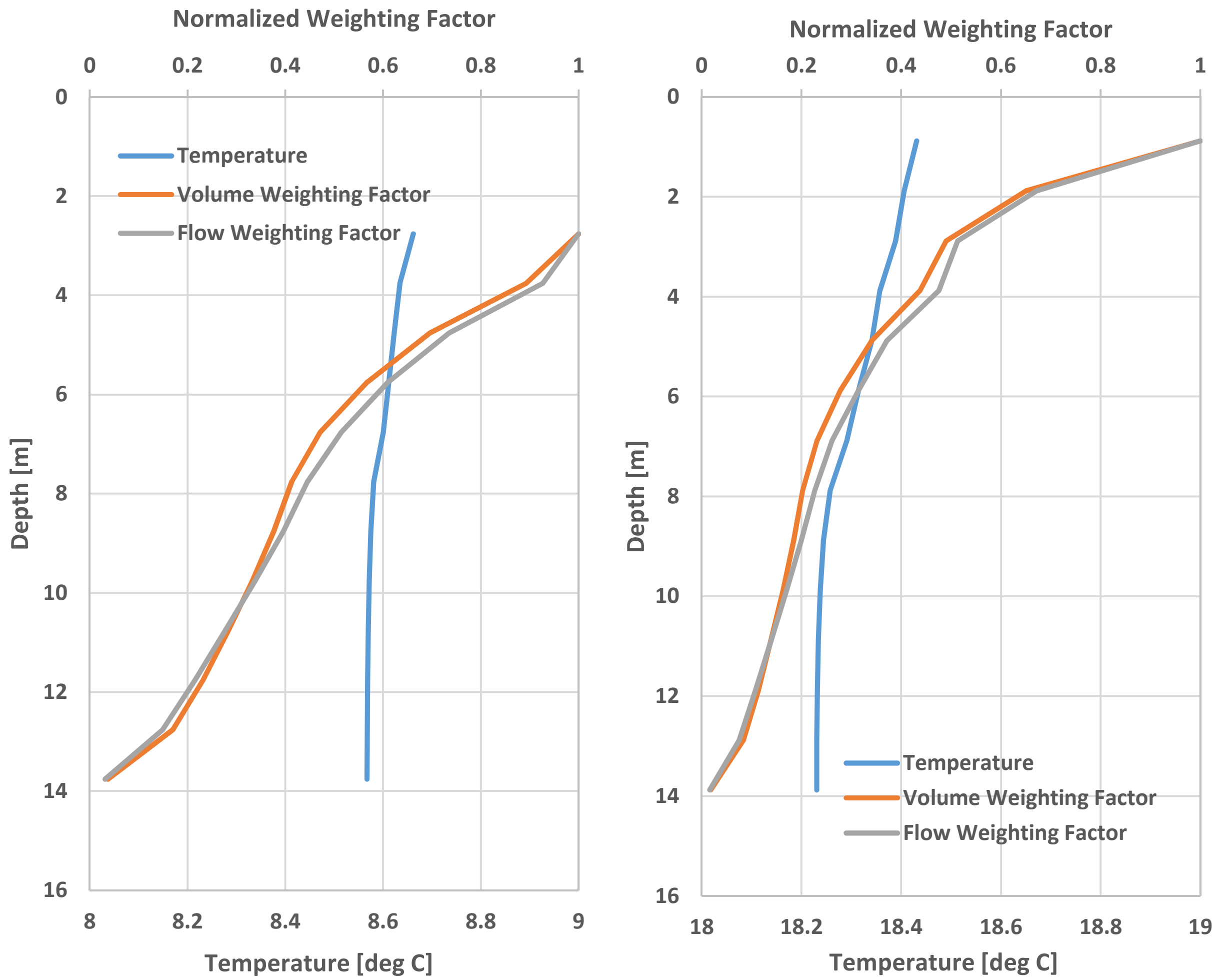

Figure 41: Temperature and Weighting Factors at Beverly Bridge, May 5, 2012 (left) and August 8, 2012 (right)

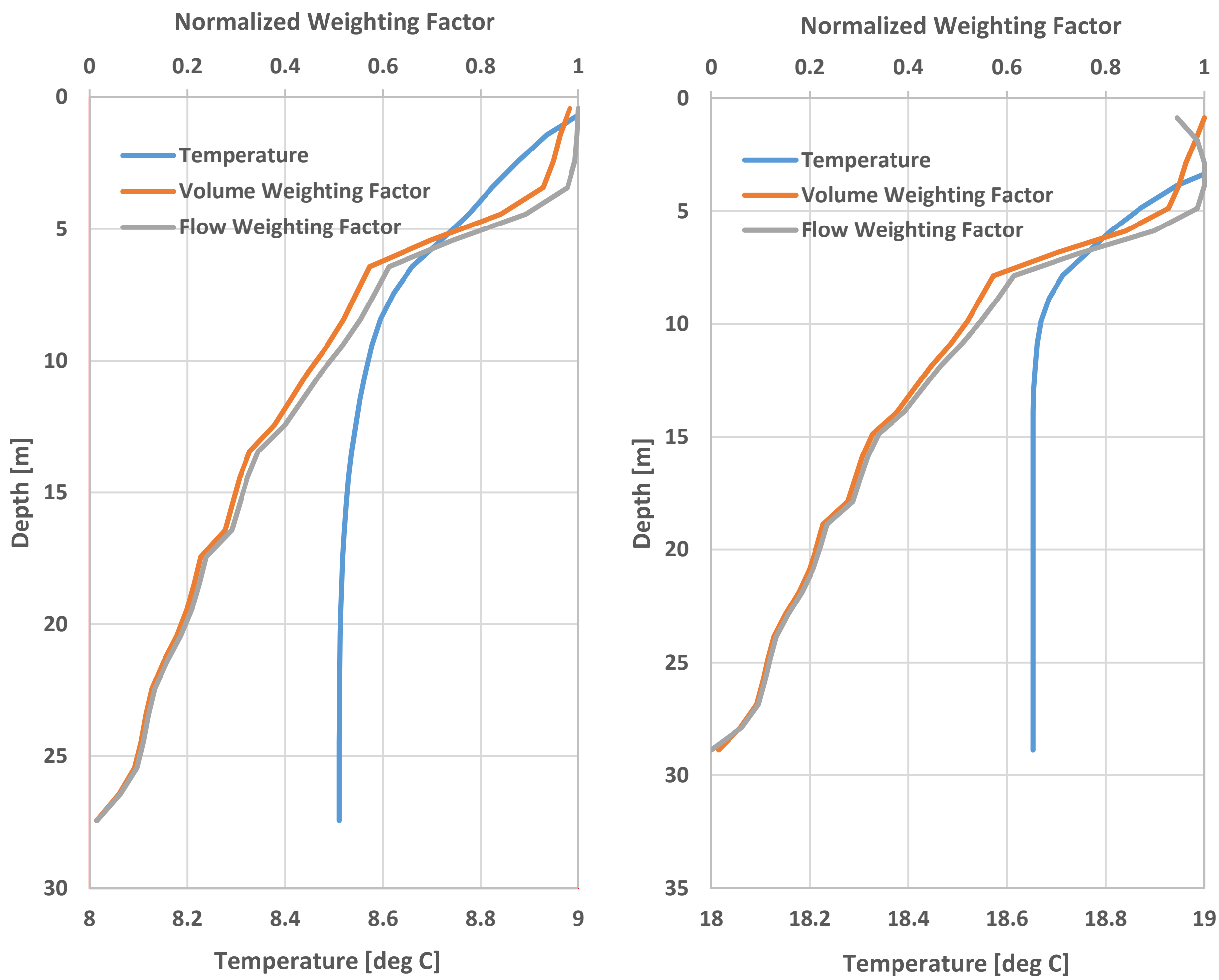

Figure 42: Temperature and Weighting Factors at Priest Rapids Forebay, May 5, 2012 (left) and August 8, 2012 (right)

5.1.3 Vertical Variation in Temperature Relative to Flow Weighted Average

Longitudinal profiles of 7-DADMax temperatures, queried at five depths along the length of the Project, are presented in Figure 43 through Figure 45 for 2003, 2008, and 2012 below. These plots show the range and variation in temperature with depth between "with Project" and "without Project" scenarios. Comparable plots for all years between 2002 and 2012 are presented in Appendix E. These plots present simulated "with Project" temperatures sampled at depths of 1, 3, 5, 10, and 20 meters (dashed lines) along with the "with Project" and "without Project" flow weighted temperatures (solid lines). Temperatures at 20 meters depth are not included for reservoir locations shallower than this depth (i.e. Dry Gulch, Beverly Bridge and L. Geneva, and downstream of Priest Rapids Dam). The plots show a similar degree of vertical stratification as the vertical profiles presented in Figure 40 through Figure 42. With the exception of the upper 1 meter of the water column, there is very little vertical stratification and the flow weighted average does a good job of reflecting the overall trend of temperature at each location. In the upper 1 meter, surface heating increases along the length of the reservoirs, reaching maxima at both the Wanapum and Priest Rapids Forebay locations.

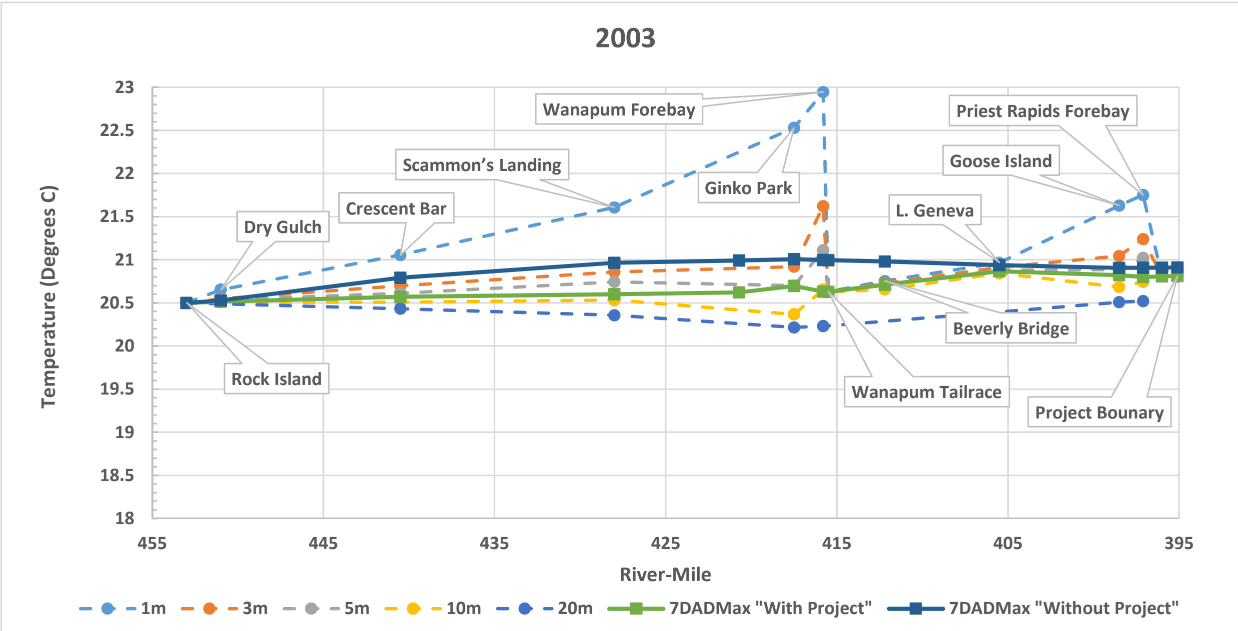

Figure 43: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2003

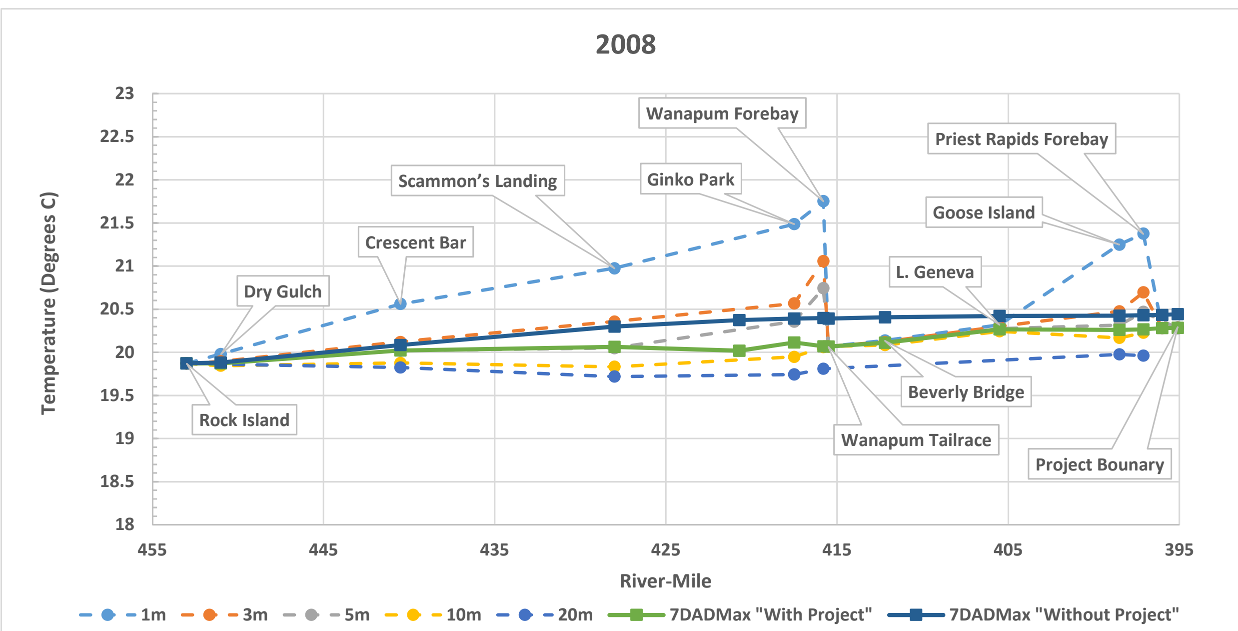

Figure 44: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2008

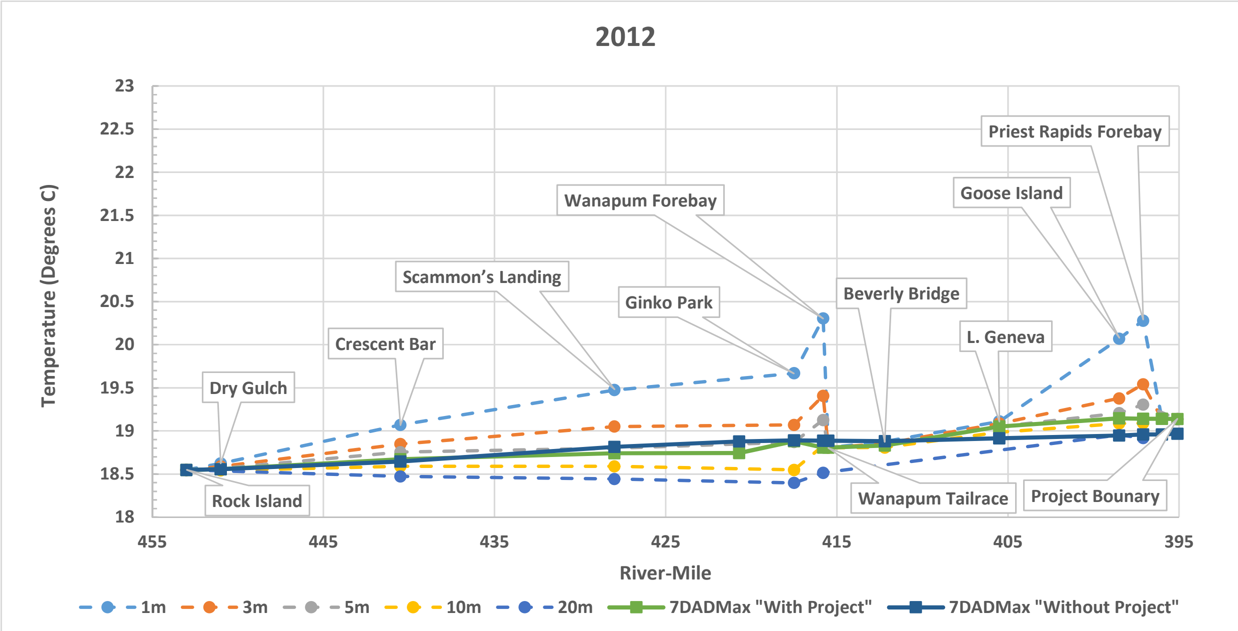

Figure 45: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2012

5.2 Metrics 1 and 3, Temperature Thresholds

Calculation of Metrics 1 and 3 are relatively simple because they are only dependent on the "with Project" temperatures. For Metric 1, applicable only upstream of Priest Rapids Dam, the 7-DADMax was calculated for each day of the analysis period at each analysis location. For Metric 3, applicable downstream of Priest Rapids Dam, the daily maximum temperature was calculated for each day of the analysis period at each analysis location. Tabulations of calculated Metric 1 and 3 results are summarized by calendar year in Table 16 through Table 19. All four sites are included in both tables, though Metric 1 only applies to the three sites upstream of Priest Rapids Dam and Metric 3 only applies to the Project area downstream of Priest Rapids Dam. It is not surprising that the temperature threshold for Metric 1, a 7-DADMax of 17.5°C, is exceeded at all sites in all years because the inflow temperatures from RID also exceed the criteria. It is also not surprising that the temperature threshold for Metric 3, a daily maximum temperature of 20.0°C, is exceeded at the Project Boundary site downstream of Priest Rapids Dam in years 2003 through 2010, but not in 2011 or 2012. The years 2003 through 2010 are time periods that inflow temperatures to the Project from RID were 19.5 °C or higher. It is also worth noting that the temperatures from RID trend downwards from 2003 to 2012.

A tabulation of flow weighted temperatures for the "without Project" simulation is provided in Table 18. A "without Project" conditions simulation is not required for Metric 1 or 2, but the information provides useful background on the conditions that would existing without the Project in place.

Table 16: Metric 1, Simulated "With Project" Maximum 7-DADMax Temperature, Flow Weighted

Year	Observed 7-DADMax Discharged from Rock Island Dam	Analysis Location [With Project Segment #s]			
		Wanapum Forebay [WAN-152]	Beverly Bridge [PR-13]	Priest Rapids Forebay [PR-59]	Project Boundary [PR-65]
2003	20.5	20.6	20.7	20.8	20.8
2004	20.1	20.5	20.6	20.9	20.9
2005	19.7	20.2	20.2	20.3	20.3
2006	20.2	20.3	20.4	20.5	20.5
2007	20.1	20.1	20.2	20.3	20.3
2008	19.9	20.1	20.1	20.3	20.3
2009	19.5	19.8	19.9	20.1	20.1
2010	19.2	19.7	19.7	19.9	19.9
2011	19.0	19.4	19.5	19.6	19.6
2012	18.5	18.8	18.8	19.1	19.1
Average	19.7	19.9	20.0	20.2	20.2

Table 17: Metric 1, Simulated "With Project" Maximum 7-DADMax Temperature, Volume Weighted

Year	Observed 7-DADMax Discharged from Rock Island Dam	Analysis Location [With / without Project Segment #s]			
		Wanapum Forebay [WAN-152]	Beverly Bridge [PR-13]	Priest Rapids Forebay [PR-59]	Project Boundary [PR-65]
2003	20.5	20.7	20.7	20.9	20.8
2004	20.1	20.6	20.6	20.9	20.9
2005	19.7	20.2	20.2	20.3	20.3
2006	20.2	20.3	20.4	20.5	20.5
2007	20.1	20.2	20.2	20.3	20.3
2008	19.9	20.1	20.1	20.3	20.3
2009	19.5	19.8	19.9	20.2	20.1
2010	19.2	19.7	19.7	19.9	19.9
2011	19.0	19.4	19.5	19.7	19.6
2012	18.5	18.9	18.8	19.2	19.1
Average	19.7	20.0	20.0	20.2	20.2

Table 18: Simulated "Without Project" Maximum 7-DADMax Temperature, Flow Weighted, (for informational purposes, not required as a temperature metric)

Year	Analysis Location [With / without Project Segment #s]			
	Wanapum Forebay [162]	Beverly Bridge [178]	Priest Rapids Forebay [230]	Project Boundary [236]
2003	21.0	21.0	20.9	20.9
2004	20.7	20.7	20.8	20.8
2005	20.2	20.2	20.2	20.2
2006	20.4	20.5	20.5	20.5
2007	20.4	20.4	20.4	20.3
2008	20.4	20.4	20.4	20.4
2009	20.0	20.0	20.0	20.0
2010	19.7	19.8	19.8	19.8
2011	19.4	19.4	19.4	19.4
2012	18.9	18.9	19.0	19.0
Average	20.1	20.1	20.1	20.1

Table 19: Metric 3, Simulated "With Project" Maximum Daily Temperature, Flow Weighted

Year	Observed Daily Maximum Temperature Discharged from Rock Island Dam	Analysis Location [With / without Project Segment #s]			
		Wanapum Forebay [WAN-152]	Beverly Bridge [PR-13]	Priest Rapids Forebay [PR-59]	Project Boundary [PR-65]
2003	20.6	20.8	21.0	21.1	21.1
2004	20.3	20.6	20.7	21.0	21.0
2005	20.0	20.4	20.3	20.5	20.5
2006	20.4	20.6	20.6	20.7	20.7
2007	20.2	20.3	20.5	20.5	20.6
2008	20.0	20.2	20.3	20.5	20.5
2009	19.7	20.0	20.1	20.2	20.2
2010	19.5	19.8	19.9	20.3	20.3
2011	19.1	19.6	19.7	19.8	19.8
2012	18.7	19.0	19.0	19.3	19.3
Average	19.9	20.1	20.2	20.4	20.4

Longitudinal profile plots showing the simulated maximum annual "with Project" and "without Project" 7-DADMax temperature are provided for simulation years 2003, 2008, and 2012 in Figure 46 through Figure 48, and for all ten simulation years in Appendix F. The data in these plots are duplicated from Figure 43 through Figure 45 but temperatures queried at depths have been omitted and a variable y-axis is used to increase resolution and to aid in the evaluation of the longitudinal trends in temperature at the evaluated locations as a function of Project river-mile. The data are also included in Table 16 and Table 18. In all of the simulated years, the "with Project" model results in lower maximum temperatures than the "without Project" simulation at the Wanapum Forebay and Beverly Bridge sites. However, downstream of Beverly Bridge this cooling trend is more variable. During some years, such as 2003 and

2008, the "with Project" simulation is cooler than the "without Project" at all analysis locations. While other years, such as 2012, the "with Project" simulation indicates a greater increase than the "without Project" simulation. There are multiple factors that make one year different from the next. These include meteorological conditions, releases from RID, temperature discharged from RID, and the total and relative discharge of spill and turbine intakes from Project dams.

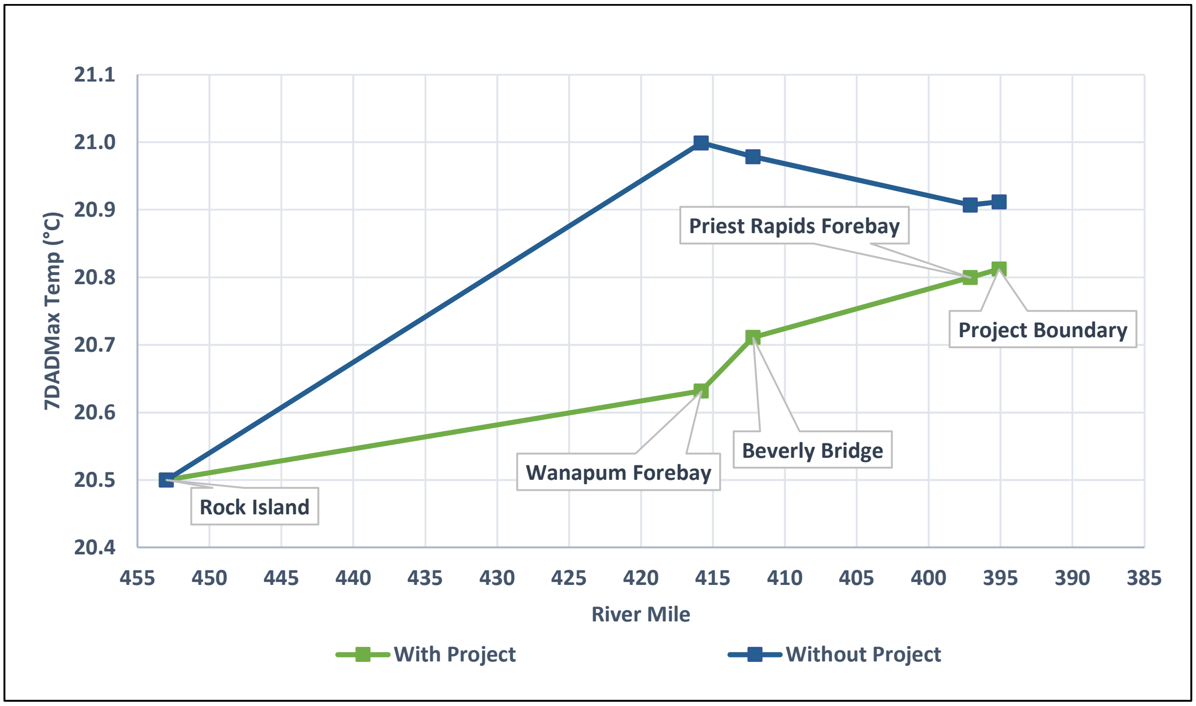

Figure 46: Maximum Annual 7-DADMax by River-Mile, 2003

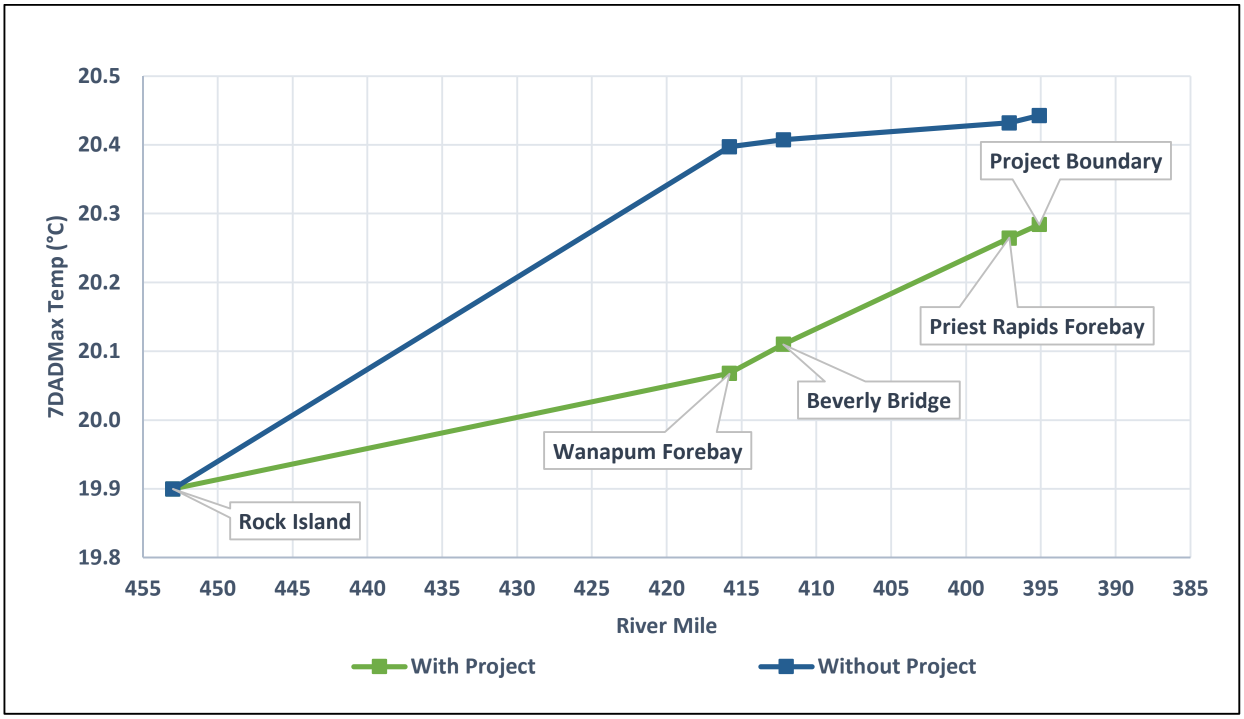

Figure 47: Maximum Annual 7-DADMax by River-Mile, 2008

Figure 48: Maximum Annual 7-DADMax by River-Mile, 2012

5.3 Metrics 2 and 4 Maximum Temperature Increase of 0.3°C

Calculation and evaluation of Metrics 2 and 4 is more complex than that of the two threshold metrics. This complexity is due to the effect that the operation of Wanapum and Priest Rapids Dams has on the timing and magnitude of flows through the mid-Columbia River relative to the "without Project" condition. These timing effects cause problems with metric calculation methods that simply compare day-to-day temperatures simulated with "with Project" and "without Project" scenarios. Figure 49 includes "with Project" and "without Project" simulated output at the Priest Rapids Forebay analysis location for the summer of 2007 as an example. A 2.5 day lag can be seen in mid to late September and elsewhere. This lag is particularly problematic when there are large swings in RID tailrace temperatures used as the model upstream boundary condition, causing out of phase temperature swings to be simulated throughout the Project. One such spike occurs in early October when the observed RID temperatures end and long-term average temperatures were used to fill the time-series. Without accounting for lags similar to this, a day-to-day comparison would incorrectly indicate an exceedance, but as a result of timing rather than increased heating due to the Project operations.

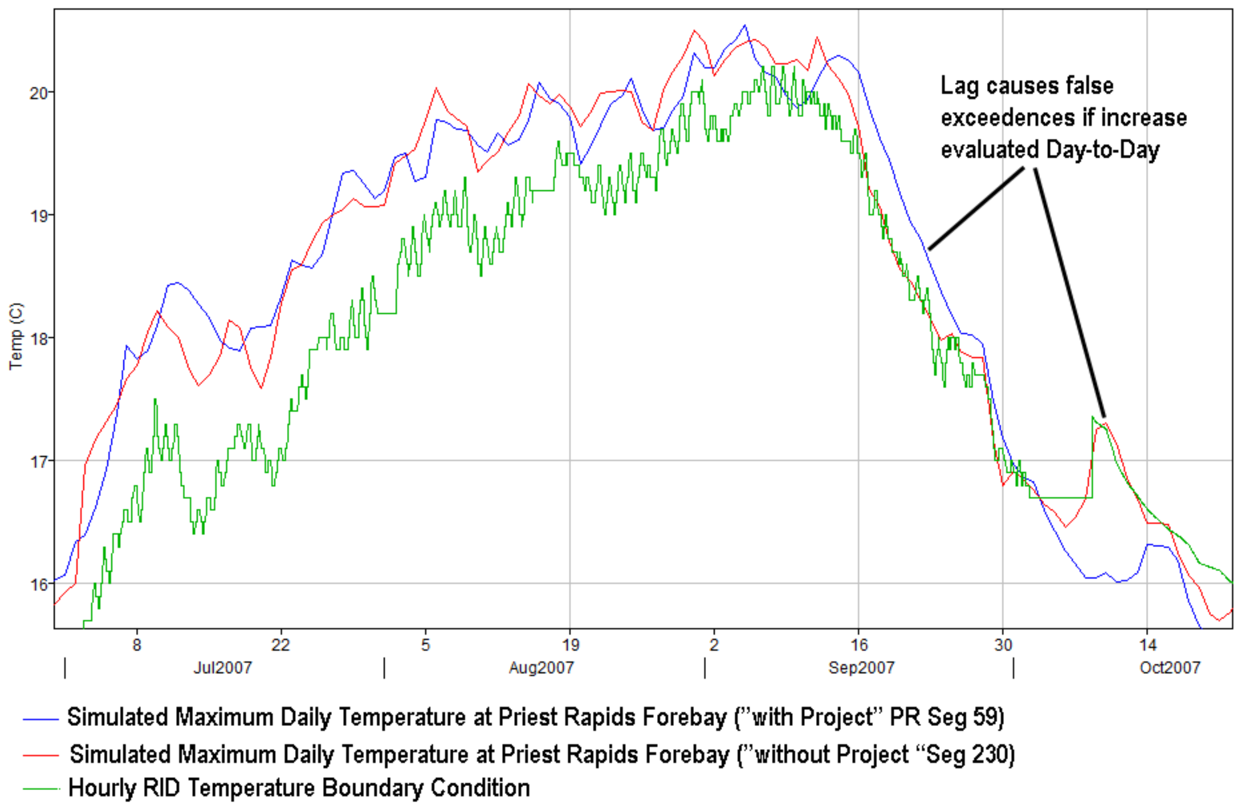

Figure 49: Example of Problems with Day-to-Day Temperature Comparisons Caused by Different Timing of Flows in the "with Project" and "without Project" Scenarios

The challenges associated with differences in timing of Columbia River flows was overcome by using a cumulative frequency distribution (CFD) analysis to calculate Metrics 2 and 4. A CFD analysis could also have been used for Metric 5, but no exceedances of that metric were calculated with a day-to-day comparison so CFD methods were determined unwarranted for the evaluation. The CFD method calculates the temperature differentials by subtracting the "without Project" temperature CFD from the corresponding "with Project" temperature CFD, at similar percentiles. By comparing temperatures at similar percentiles rather than day-to-day comparisons the issues with lag are avoided while still providing a temperature differential needed for the metrics. The temperatures compared for Metric 2 are the 7-DADMax temperatures and those for Metric 4 are the daily maximum temperatures. This method was implemented in the same manner as that used for the Pend Oreille River TMDL (Ecology 2011).

The steps used to apply the method for Metric 2 are as follows:

- Days with 7-DADMax temperatures less than 17.5°C simulated for the "with Project" scenario were removed from both the "with Project" and "without Project" time-series of 7-DADMax temperature values.
- A CFD of the 7-DADMax temperature values was created for each calendar year in the "with Project" and "without Project" time-series.
- Temperature differentials, calculated by subtracting the "without Project" 7-DADMax temperature from the "with Project" 7-DADMax temperature, at similar percentiles. This was only performed on percentiles when the "without Project" 7-DADMax temperature exceeded 17.5°C, consistent with the temperature criteria.
- Compare temperature differentials to maximum allowed temperature increase of 0.3°C.

A similar method was used to apply the CFD method to Metric 4, except that the daily maximum temperature was used instead of the 7-DADMax temperature.

Tabulations of calculated Metric 2 and 4 results for both flow and volume weighted temperatures are summarized by calendar year in Table 20 and Table 20. The tables show the maximum temperature differential and for the years when the maximum differential criterion of 0.3°C is exceeded, the number of days with exceedances can also be found in parenthesis. CFD curves and temperature differentials by percentile are provided for a single year for each site in Figure 76 through Figure 79 found in Appendix G. The year selected for plotting at each site was the year with the highest temperature differential reported in Table 20 at that site. Plots for sites upstream of Priest Rapids Dam reflect Metric 2 and that for the Project Boundary site located downstream of Priest Rapids Dam reflects Metric 4.

Table 20: Metrics 2 and 4, Maximum Temperature Differential by Year Derived by CFD Method, Calculated for days when “with Project” Temperature Exceeds 7-DADMax of 17.5°C (upstream of Priest Rapids) or Daily Maximum of 20.0°C (downstream of Priest Rapids) and the “without Project” also Exceeds the Same Criterion, Flow Weighted

Year	**Analysis Location** [With / without Project Segment #s]			
	Metric 2 Upstream of Priest Rapids dam, 7-DADMax Temperature Differential in °C (# of days Difference > 0.3 °C)			Metric 4 Downstream of Priest Rapids dam, Daily Maximum Temperature Criterion, (# of days Difference > 0.3 °C)
	Wanapum Forebay [152 / 162]	Beverly Bridge [13 / 178]	Priest Rapids Forebay [59 / 230]	Project Boundary [65 / 236]
2003	-0.02	0.00	0.29	0.16
2004	0.15	0.19	0.32 (1)	0.33 (5)
2005	0.05	0.11	0.17	0.13
2006	0.05	0.08	0.33 (1)	-0.02
2007	0.11	0.13	0.31	0.12
2008	-0.10	-0.02	0.17	0.11
2009	-0.02	0.09	0.27	0.05
2010	0.16	0.23	0.33 (3)	0.12
2011	0.04	0.09	0.26	NA[1]
2012	0.21	0.27	0.38 (9)	NA[1]
Average	0.06	0.12	0.28 (14)	0.12 (5)

[1] The 20 degree temperature threshold was not exceeded during 2011 or 2012.

Table 21: Metrics 2 and 4, Maximum Temperature Differential by Year Derived by CFD Method, Calculated for days when "with Project" Temperature Exceeds 7-DADMax of 17.5°C (upstream of Priest Rapids) or Daily Maximum of 20.0°C (downstream of Priest Rapids) and the "without Project" also Exceeds the Same Criterion, Volume Weighted

Year	Analysis Location [With / without Project Segment #s]			
	Metric 2, Upstream of Priest Rapids Dam, 7-DADMax Temperature Differential in °C (# of days Difference > 0.3 °C)			Metric 4 Downstream of Priest Rapids Dam, Daily Maximum Temperature Criterion, (# of days Difference > 0.3 °C)
	Wanapum Forebay [152 / 162]	Beverly Bridge [13 / 178]	Priest Rapids Forebay [59 / 230]	Project Boundary [65 / 236]
2003	0.07	0.00	0.31 (1)	0.16
2004	0.22	0.19	0.36 (16)	0.35 (5)
2005	0.10	0.11	0.21	0.11
2006	0.16	0.08	0.36 (1)	-0.02
2007	0.17	0.13	0.33 (3)	0.07
2008	-0.04	-0.02	0.21	0.10
2009	0.11	0.09	0.33 (5)	0.06
2010	0.22	0.23	0.41 (5)	0.08
2011	0.10	0.09	0.28	NA[1]
2012	0.25	0.28	0.40 (14)	NA[1]
Average	0.14	0.12	0.32 (45)	0.11 (5)

[1] The 20 degree temperature threshold was not exceeded during 2011 or 2012.

5.3.1 Considerations Regarding Simulated Temperature Difference

Two considerations that should be made when evaluating the significance of simulated temperature differences.

- Frequency that the difference threshold is exceeded, and
- Certainty in results from W2 model.

Frequency that Difference Threshold is Exceeded

Table 22 provides three measures of the frequency that the Metric 2 and 4 0.3 degree C difference threshold is exceeded. There are no exceedances at the Wanapum forebay or Beverly Bridge sites within the entire ten year simulation period and relatively few exceedances, occurring less than 0.5% of the time (0.4% and 0.1%, respectively) at the Priest Rapids forebay and Project Boundary. The total number of days and the percent of total simulation days are calculated by simply counting the days in the simulation that have differences greater than the threshold. If the total number of exceedance days at all four sites are added together, then Metric 2 and 4 are exceeded 0.1% of the time overall [i.e. 19 / (4 x 3652 days]). It is noted that this counting methodology overlooks that many of the days exceeding the criteria are in sequence with one another, and that when evaluated as temperature events, the number of occurrences drops approximately in half. Priest Rapids forebay location has only 7 exceedance events and the Project Boundary location has only 3 within the 10 year simulation period.

Table 22: Frequency that Metric 2 and 4, Maximum Flow Weighted Temperature Difference Threshold is Exceeded

Difference > 0.3 °C	Analysis Location				Total for all Project Analysis Locations
	Metric 2 Upstream of Priest Rapids Dam			Metric 4, Downstream of Priest Rapids Dam	
	Wanapum Forebay	Beverly Bridge	Priest Rapids Forebay	Project Boundary	
Total # of Days	0	0	14	5	19
% of All Days[1]	0%	0%	0.4%	0.1%	0.1%
# of Events[2]	0	0	7	3	9

[1] The 2003 – 2012 simulation includes 3652 days at each analysis location. And there are 14608 (4 x 3652) days analyzed project wide.
[2] Separate events do not share dates within the period used to calculate their 7-DADMax (Metric 2) and are not in sequence with one another (Metric 4)

Figure 50 and Figure 51 provide visual representations of the occurrence of exceedances at the Priest Rapids forebay and the Project Boundary in the context of the ten year simulation period. The grey time-series show the 7-DADMax and 1-DADMax for the two respective sites, the red dots correspond to individual exceedance events, and the green lines at the bottom of the plot show the total period that the threshold is exceeded. At the Priest Rapids forebay site, most of the exceedance events are clustered together during the summers of 2004 and 2012. These are not extreme high or low flow years, but the combination of operational and environmental conditions used as inputs to the model are such that exceedances occur. The Project Boundary site only had three simulated exceedance events, all of which occurred during the summer of 2004.

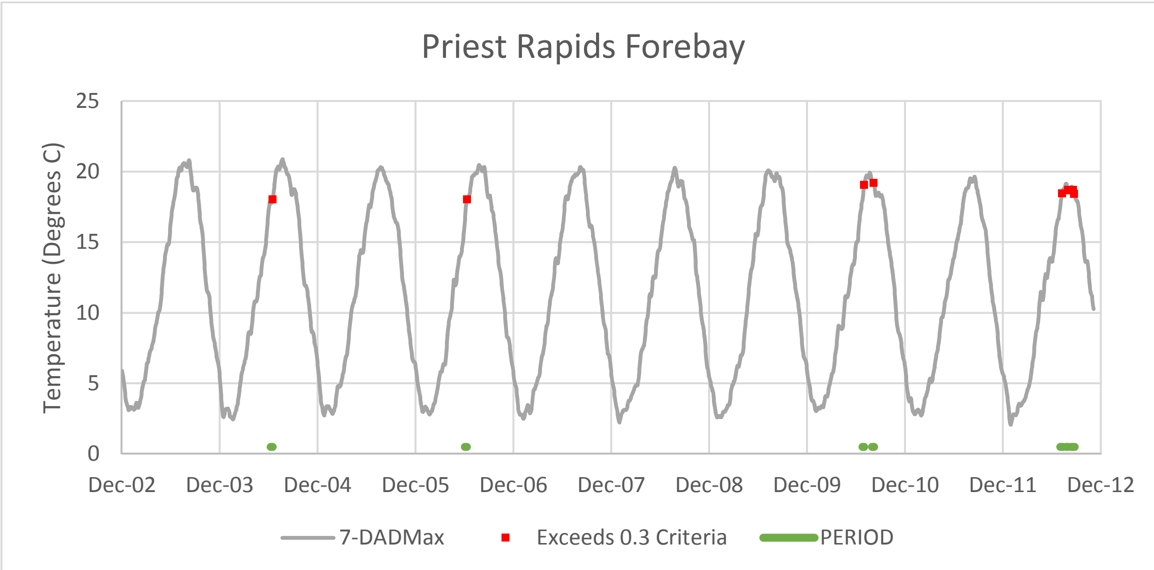

Figure 50: Simulated 7-DADMax with Exceedance Periods, Priest Rapids Forebay, Flow Weighted

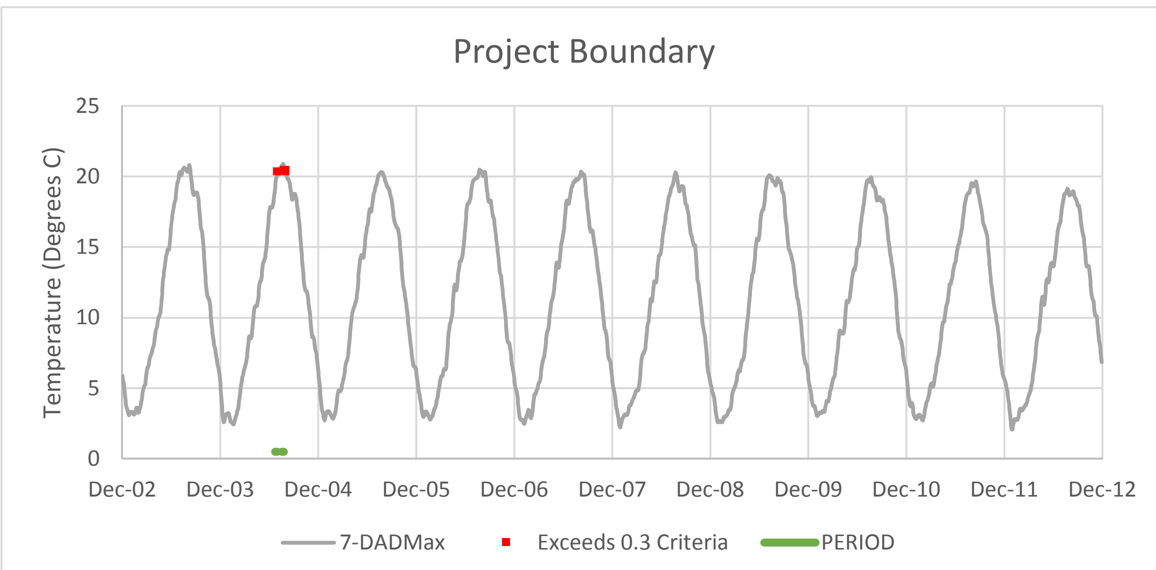

Figure 51: Simulated 7-DADMax with Exceedance Periods, Project Boundary, Flow Weighted

Certainty in Results from W2 models

The “with Project” model was shown to match available observed data well, as indicated by a small average AME value of 0.21 degrees C, which is comparable to that reported for the Rocky Reach and Wells Dam CE-QUAL-W2 models studies (WEST, 2006 and 2008). However, in order to obtain the acceptably low AME, measured data at the Priest Rapids turbine intake was excluded from the model calibration. If the measured data at the Priest Rapids turbine intake were found to be representative of real world conditions at that location, the “with Project” modeled temperatures in that reach could be up to 0.5 degrees C colder, resulting in far fewer exceedances of the 0.3 degree C threshold for Metric 2 and 4. Calibration efforts and sensitivity tests could not identify an explanation that validated both the observed intake and other temperature data provided, but it is difficult to completely disregard the lower observed data at this location.

5.4 Metric 5 Maximum Temperature Increase = 34 / (RID Temperature + 9)

Metric 5, part 2 of the maximum temperature increase criterion applicable downstream of Priest Rapids Dam, was calculated using two methods and neither exceeded the criteria. Those methods included the CFD method used for Metric 4 and also day-to-day temperature differentials, ignoring the lag effects between the two scenarios that were problematic for Metric 4. Like Metric 4, the Metric 5 criteria only apply to days when the "with Project" temperature is greater than 20 degrees C. The difference is that the allowable increase threshold varies as a function of the special equation 34 / (T + 9), rather than an absolute threshold of 0.3 degrees C. The resulting time-series of allowable temperature increases, calculated by inserting the RID tailwater temperature for T in the special equation, varied from 1.15 to 1.25°C between 2003 and 2012. The resulting time-series of day-to-day temperature differentials for days with a daily maximum temperature greater than 20 degrees C and the corresponding allowable temperature increase is shown in Figure 52.

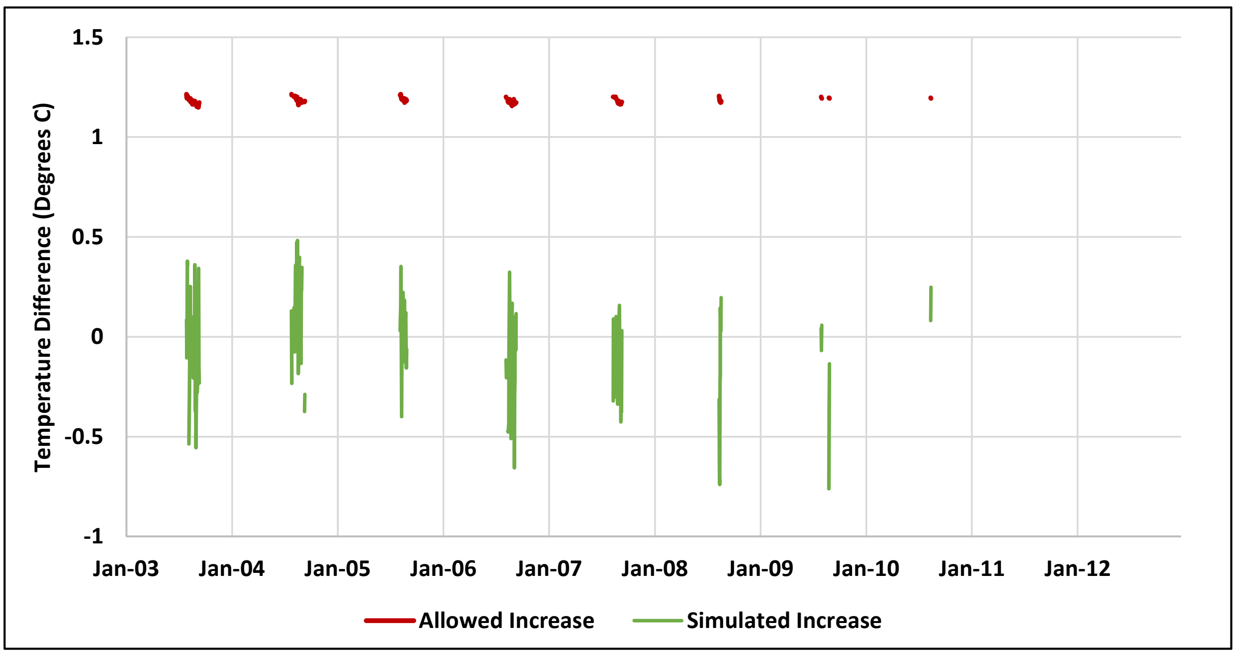

Figure 52: Metric 5, Simulated and Allowable Temperature Increase at Project Boundary, Day-to-Day Comparison Ignoring Lag Effects (2003 – 2012)

6 SUMMARY AND CONCLUSIONS

The prior sections of this report document the development, calibration, and application of W2 to evaluate the Project's compliance with five temperature metrics constituting the applicable water-quality criteria. The calibrated model matched observed data well, resulting in an absolute mean error statistic of 0.2 °C. Project compliance was evaluated with a 10-year simulation of the period 2003 through 2012 as determined by the Project's 401 WQC.

The "with Project" average flow weighted 7-DADMax temperature was 19.7 degrees C at the upstream boundary of the project (the RID tailrace) and increased gradually to 20.2 degrees C at the Priest Rapids forebay. The "without Project" 7-DADMax for the same period was simulated with the same upstream boundary condition but the resulting simulated temperature at the Priest Rapids forebay was slightly lower having a 7-DADMax of 20.1 degrees C. However, in some years the "with Project" model had a lower maximum 7-DADMax at the Priest Rapids forebay than the "without Project" model, while other years it was higher.

Simulated project temperatures at most Project sites did not show an increase of more than the 0.3 degree threshold. The only analysis locations with simulated temperature increases, calculated as flow weighted temperatures integrated across the depth of the reservoir, that exceeded 0.3 degrees were the Priest Rapids forebay and the Project Boundary. The threshold was exceeded for 7 and 3 events at the two respective sites and the total number of days with exceedances was less than 0.5% of the 10-year simulation period (Figure 50 and Figure 51) at each site and less than 0.1% as the total across all analysis locations and all years (i.e. 19 of 14,608 analysis days).

The Project has the effect of reducing the diurnal variation in temperature. Figure 53 shows example time-series of "with Project" and "without Project" temperatures simulated immediately downstream of Priest Rapids Dam for the month of August 2008. The "with Project" temperatures vary by less than 0.5 degrees C during each day, but the "without Project" temperatures vary by nearly a full degree.

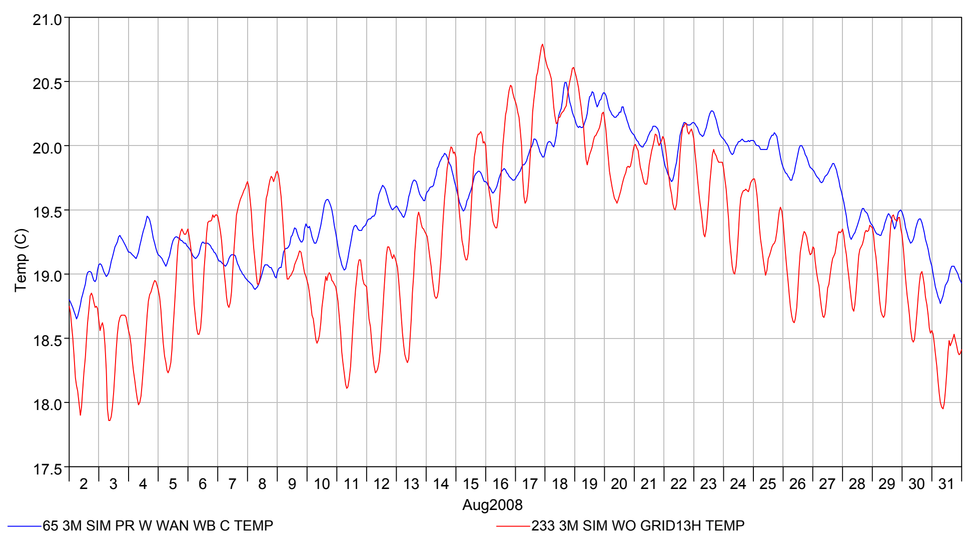

Figure 53: Example Illustrating Temporal Impact on Temperatures at the Priest Rapids Tailrace

In summary, relative to the temperature impact from upstream reservoirs in the Columbia River system (i.e. Grand Coulee dam as per Perkins et al. 2002), the Project was found to have a relatively small impact on water temperatures as a whole. Metrics 1 and 3, the 17.5 degree C and 20.0 degree C temperature thresholds, could not be met because the inflow temperatures to the Project exceed these criteria. It was demonstrated by a sensitivity test that lowering upstream inflow temperatures outright would result in a comparable temperature decrease at the downstream end of the Project. Metrics 2 and 4 (the 0.3 degree temperature differential between "with Project" and "without Project" conditions) resulted in a small number of exceedances at two sites. Metric 5, Part 2 of the maximum temperature increase criterion is never exceeded.

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APPENDIX A: SEGMENT LENGTH AND BATHYMETRY SOURCES

Table 23: Segment Length and Bathymetry Sources

Waterbody ID (Branch ID)		Waterbody Name	Segment #		Segment Length (meters)	HEC-RAS Station (River-Mile)
With Project	Without Project		With Project	Without Project		
1	1	Wanapum	1	1	0	
1	1	Wanapum	2	2	162.58	453.47
1	1	Wanapum	3	3	195.5	453.34
1	1	Wanapum	4	4	195.5	453.22
1	1	Wanapum	5	5	195.5	453.1
1	1	Wanapum	6	6	242.8	452.98
	1	Wanapum		7	0	
	2	Wanapum		8	0	
1	2	Wanapum	7	9	290.1	452.8
1	2	Wanapum	8	10	290.1	452.62
1	2	Wanapum	9	11	290.1	452.44
1	2	Wanapum	10	12	407.7	452.26
1	2	Wanapum	11	13	525.4	451.93
1	2	Wanapum	12	14	525.4	451.61
1	2	Wanapum	13	15	413.3	451.28
1	2	Wanapum	14	16	301.2	451.09
	2	Wanapum		17	0	
	3	Wanapum		18	0	
1	3	Wanapum	15	19	301.2	450.91
1	3	Wanapum	16	20	301.2	450.72
1	3	Wanapum	17	21	301.2	450.53
1	3	Wanapum	18	22	320.3	450.34
1	3	Wanapum	19	23	339.3	450.13
1	3	Wanapum	20	24	339.3	449.92
1	3	Wanapum	21	25	339.3	449.71
1	3	Wanapum	22	26	339.3	449.5
1	3	Wanapum	23	27	320.8	449.29
1	3	Wanapum	24	28	302.4	449.1
1	3	Wanapum	25	29	302.4	448.91
1	3	Wanapum	26	30	302.4	448.73
1	3	Wanapum	27	31	302.4	448.54
	3	Wanapum		32	0	
	4	Wanapum		33	0	

1	4	Wanapum	28	34	331.5	448.35
1	4	Wanapum	29	35	360.6	448.13
1	4	Wanapum	30	36	360.6	447.9
1	4	Wanapum	31	37	360.6	447.68
1	4	Wanapum	32	38	453.4	447.45
1	4	Wanapum	33	39	546.3	447.11
1	4	Wanapum	34	40	546.3	446.78
1	4	Wanapum	35	41	497.2	446.44
1	4	Wanapum	36	42	448.2	446.16
1	4	Wanapum	37	43	448.2	445.88
1	4	Wanapum	38	44	487.3	445.6
1	4	Wanapum	39	45	526.5	445.27
1	4	Wanapum	40	46	526.5	444.95
1	4	Wanapum	41	47	572.4	444.62
1	4	Wanapum	42	48	618.3	444.23
1	4	Wanapum	43	49	618.3	443.85
1	4	Wanapum	44	50	492.5	443.47
1	4	Wanapum	45	51	366.7	443.24
1	4	Wanapum	46	52	366.7	443.01
1	4	Wanapum	47	53	366.7	442.78
1	4	Wanapum	48	54	377.2	442.55
1	4	Wanapum	49	55	387.6	442.31
1	4	Wanapum	50	56	387.6	442.07
1	4	Wanapum	51	57	414.9	441.83
1	4	Wanapum	52	58	442.2	441.56
1	4	Wanapum	53	59	442.2	441.28
1	4	Wanapum	54	60	385.9	441.01
1	4	Wanapum	55	61	329.5	440.8
1	4	Wanapum	56	62	329.5	440.6
1	4	Wanapum	57	63	329.5	440.39
1	4	Wanapum	58	64	329.5	440.19
1	4	Wanapum	59	65	288.1	439.98
1	4	Wanapum	60	66	246.7	439.83
1	4	Wanapum	61	67	246.7	439.68
1	4	Wanapum	62	68	246.7	439.52
1	4	Wanapum	63	69	281.9	439.37
1	4	Wanapum	64	70	317	439.17
1	4	Wanapum	65	71	317	438.98
1	4	Wanapum	66	72	317	438.78
1	4	Wanapum	67	73	317	438.58

	4	Wanapum		74	0	
	5	Wanapum		75	0	
1	5	Wanapum	68	76	361.6	438.39
1	5	Wanapum	69	77	406.3	438.13
1	5	Wanapum	70	78	406.3	437.88
1	5	Wanapum	71	79	406.3	437.63
1	5	Wanapum	72	80	390	437.38
1	5	Wanapum	73	81	373.8	437.14
1	5	Wanapum	74	82	373.8	436.91
1	5	Wanapum	75	83	373.8	436.68
1	5	Wanapum	76	84	415	436.45
1	5	Wanapum	77	85	456.3	436.16
1	5	Wanapum	78	86	456.3	435.88
1	5	Wanapum	79	87	461.8	435.6
1	5	Wanapum	80	88	467.2	435.31
1	5	Wanapum	81	89	467.2	435.02
1	5	Wanapum	82	90	469.9	434.73
1	5	Wanapum	83	91	472.5	434.43
1	5	Wanapum	84	92	472.5	434.14
1	5	Wanapum	85	93	601.9	433.84
1	5	Wanapum	86	94	731.2	433.39
1	5	Wanapum	87	95	731.2	432.94
1	5	Wanapum	88	96	525.8	432.48
1	5	Wanapum	89	97	320.5	432.28
1	5	Wanapum	90	98	320.5	432.08
1	5	Wanapum	91	99	320.5	431.88
1	5	Wanapum	92	100	282	431.69
1	5	Wanapum	93	101	243.6	431.53
1	5	Wanapum	94	102	243.6	431.38
1	5	Wanapum	95	103	243.6	431.23
1	5	Wanapum	96	104	247.3	431.08
1	5	Wanapum	97	105	251.1	430.92
1	5	Wanapum	98	106	251.1	430.77
1	5	Wanapum	99	107	251.1	430.61
1	5	Wanapum	100	108	255.3	430.46
1	5	Wanapum	101	109	259.4	430.29
1	5	Wanapum	102	110	259.4	430.13
1	5	Wanapum	103	111	259.4	429.97
1	5	Wanapum	104	112	269.6	429.81
1	5	Wanapum	105	113	279.8	429.64

1	5	Wanapum	106	114	279.8	429.46
1	5	Wanapum	107	115	279.8	429.29
1	5	Wanapum	108	116	360.1	429.12
1	5	Wanapum	109	117	440.4	428.84
1	5	Wanapum	110	118	440.4	428.57
1	5	Wanapum	111	119	440.4	428.29
1	5	Wanapum	112	120	524.5	428.02
1	5	Wanapum	113	121	608.5	427.64
1	5	Wanapum	114	122	608.5	427.26
1	5	Wanapum	115	123	596.4	426.89
1	5	Wanapum	116	124	584.2	426.52
1	5	Wanapum	117	125	584.2	426.16
1	5	Wanapum	118	126	548.2	425.8
1	5	Wanapum	119	127	512.2	425.48
1	5	Wanapum	120	128	512.2	425.16
1	5	Wanapum	121	129	557.9	424.84
	5	Wanapum		130	0	
	6	Wanapum		131	0	
1	6	Wanapum	122	132	603.6	424.47
1	6	Wanapum	123	133	603.6	424.09
1	6	Wanapum	124	134	625.2	423.72
1	6	Wanapum	125	135	646.9	423.32
1	6	Wanapum	126	136	646.9	422.91
1	6	Wanapum	127	137	651.3	422.51
1	6	Wanapum	128	138	655.7	422.1
1	6	Wanapum	129	139	655.7	421.7
1	6	Wanapum	130	140	460.9	421.29
1	6	Wanapum	131	141	266	421.12
1	6	Wanapum	132	142	266	420.96
1	6	Wanapum	133	143	266	420.79
1	6	Wanapum	134	144	266	420.63
1	6	Wanapum	135	145	272	420.46
1	6	Wanapum	136	146	278	420.29
1	6	Wanapum	137	147	278	420.12
1	6	Wanapum	138	148	278	419.94
1	6	Wanapum	139	149	278	419.77
1	6	Wanapum	140	150	278	419.6
1	6	Wanapum	141	151	367.6	419.43
1	6	Wanapum	142	152	457.2	419.14
1	6	Wanapum	143	153	457.2	418.86

1	6	Wanapum	144	154	446.2	418.57
1	6	Wanapum	145	155	435.2	418.3
1	6	Wanapum	146	156	435.2	418.03
1	6	Wanapum	147	157	435.2	417.76
1	6	Wanapum	148	158	435.2	417.49
1	6	Wanapum	149	159	762.6	417.22
1	6	Wanapum	150	160	1089.9	416.54
1	6	Wanapum	151	161	1089.9	415.87
1	6	Wanapum	152	162	819.16	415.19
1	6	Wanapum	153	163	0	
2 (1)	7	Priest Rapids	1	164	0	
2 (1)	7	Priest Rapids	2	165	377.92	415.1
2 (1)	7	Priest Rapids	3	166	520.6	414.78
2 (1)	7	Priest Rapids	4	167	520.6	414.45
2 (1)	7	Priest Rapids	5	168	508.8	414.13
2 (1)	7	Priest Rapids	6	169	497	413.82
	7	Priest Rapids		170	0	
	8	Priest Rapids		171	0	
2 (1)	8	Priest Rapids	7	172	497	413.51
2 (1)	8	Priest Rapids	8	173	497	413.2
2 (1)	8	Priest Rapids	9	174	442.7	412.9
2 (1)	8	Priest Rapids	10	175	388.3	412.65
2 (1)	8	Priest Rapids	11	176	388.3	412.41
2 (1)	8	Priest Rapids	12	177	388.3	412.17
2 (1)	8	Priest Rapids	13	178	388.3	411.93
2 (1)	8	Priest Rapids	14	179	379.8	411.69
2 (1)	8	Priest Rapids	15	180	371.3	411.46
2 (1)	8	Priest Rapids	16	181	371.3	411.23
2 (1)	8	Priest Rapids	17	182	376.9	411
2 (1)	8	Priest Rapids	18	183	382.5	410.76
2 (1)	8	Priest Rapids	19	184	398	410.52
2 (1)	8	Priest Rapids	20	185	413.5	410.26
	8	Priest Rapids	21	186	0	
	9	Priest Rapids	22	187	0	
2 (2)	9	Priest Rapids	23	188	472.7	410.01
2 (2)	9	Priest Rapids	24	189	531.9	409.68
2 (2)	9	Priest Rapids	25	190	531.9	409.35
2 (2)	9	Priest Rapids	26	191	539.1	409.02
2 (2)	9	Priest Rapids	27	192	546.4	408.68
2 (2)	9	Priest Rapids	28	193	546.4	408.34

2 (2)	9	Priest Rapids	29	194	517.4	408
2 (2)	9	Priest Rapids	30	195	488.4	407.69
2 (2)	9	Priest Rapids	31	196	488.4	407.39
	9	Priest Rapids		197	0	
	10	Priest Rapids		198	0	
2 (2)	10	Priest Rapids	32	199	553.7	407.09
2 (2)	10	Priest Rapids	33	200	619	406.7
2 (2)	10	Priest Rapids	34	201	619	406.32
2 (2)	10	Priest Rapids	35	202	717.6	405.93
2 (2)	10	Priest Rapids	36	203	816.2	405.43
2 (2)	10	Priest Rapids	37	204	658	404.92
2 (2)	10	Priest Rapids	38	205	499.8	404.61
2 (2)	10	Priest Rapids	39	206	499.8	404.3
2 (2)	10	Priest Rapids	40	207	499.8	403.99
2 (2)	10	Priest Rapids	41	208	700.5	403.68
2 (2)	10	Priest Rapids	42	209	901.2	403.12
2 (2)	10	Priest Rapids	43	210	901.2	402.56
	10	Priest Rapids		211	0	
	11	Priest Rapids		212	0	
2 (2)	11	Priest Rapids	44	213	901.2	402
2 (2)	11	Priest Rapids	45	214	642.1	401.44
2 (2)	11	Priest Rapids	46	215	383	401.2
2 (2)	11	Priest Rapids	47	216	383	400.96
2 (2)	11	Priest Rapids	48	217	383	400.72
2 (2)	11	Priest Rapids	49	218	437	400.49
2 (2)	11	Priest Rapids	50	219	491	400.18
	11	Priest Rapids		220	0	
	12	Priest Rapids		221	0	
2 (2)	12	Priest Rapids	51	222	491	399.87
2 (2)	12	Priest Rapids	52	223	491	399.57
2 (2)	12	Priest Rapids	53	224	523.7	399.26
2 (2)	12	Priest Rapids	54	225	556.5	398.92
2 (2)	12	Priest Rapids	55	226	556.5	398.57
2 (2)	12	Priest Rapids	56	227	578	398.23
2 (2)	12	Priest Rapids	57	228	599.4	397.85
2 (2)	12	Priest Rapids	58	229	599.4	397.48
2 (2)	12	Priest Rapids	59	230	553.46	397.11
2 (2)	12	Priest Rapids	60	231	0	
3 (3)	13	Hanford Reach	61	232	0	
3 (3)	13	Hanford Reach	62	233	1913.5	395.6788

3 (3)	13	Hanford Reach	63	234	801.45	394.6967 (split)
3 (3)	13	Hanford Reach	64	235	801.45	394.6967 (split)
3 (3)	13	Hanford Reach	65	236	1623	393.6868
3 (3)	13	Hanford Reach	66	237	1608	392.6797
3 (3)	13	Hanford Reach	67	238	1598.3	391.6885
3 (3)	13	Hanford Reach	68	239	1605.1	390.6935
3 (3)	13	Hanford Reach	69	240	1626.2	389.6937
3 (3)	13	Hanford Reach	70	241	809.1	388.6725 (split)
3 (3)	13	Hanford Reach	71	242	809.1	388.6725 (split)
3 (3)	13	Hanford Reach	72	243	1144.6	387.6827
3 (3)	13	Hanford Reach	73	244	422.4	387.2501
3 (3)	13	Hanford Reach	74	245	0	

APPENDIX B: SUPPLEMENTAL CALIBRATION PLOTS FOR PRIEST RAPIDS FOREBAY

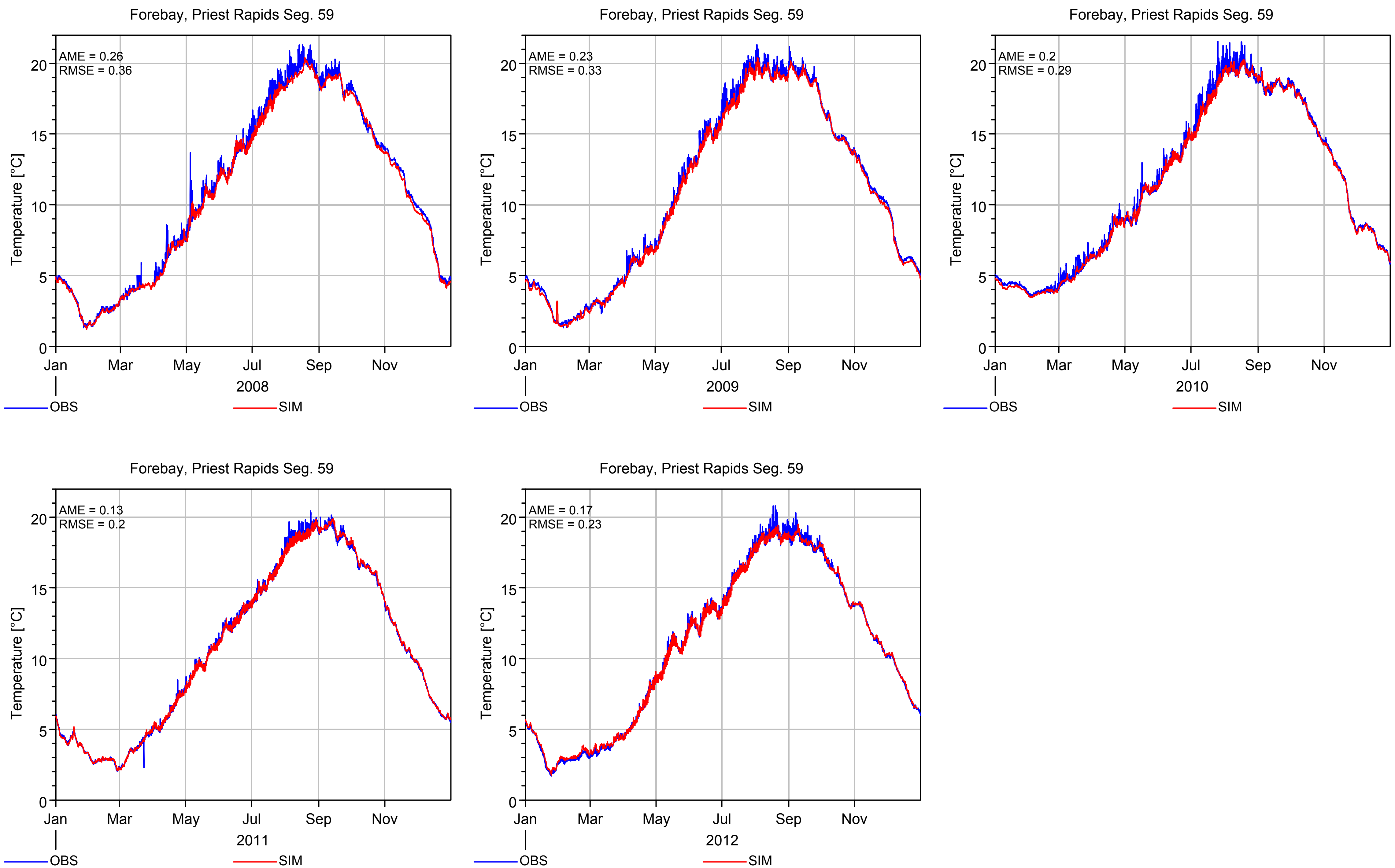


Figure 54: Simulated vs. Observed Water Temperature, Priest Rapids Forebay FSM Sensor, Priest Rapids Segment 59, 2008 – 2012

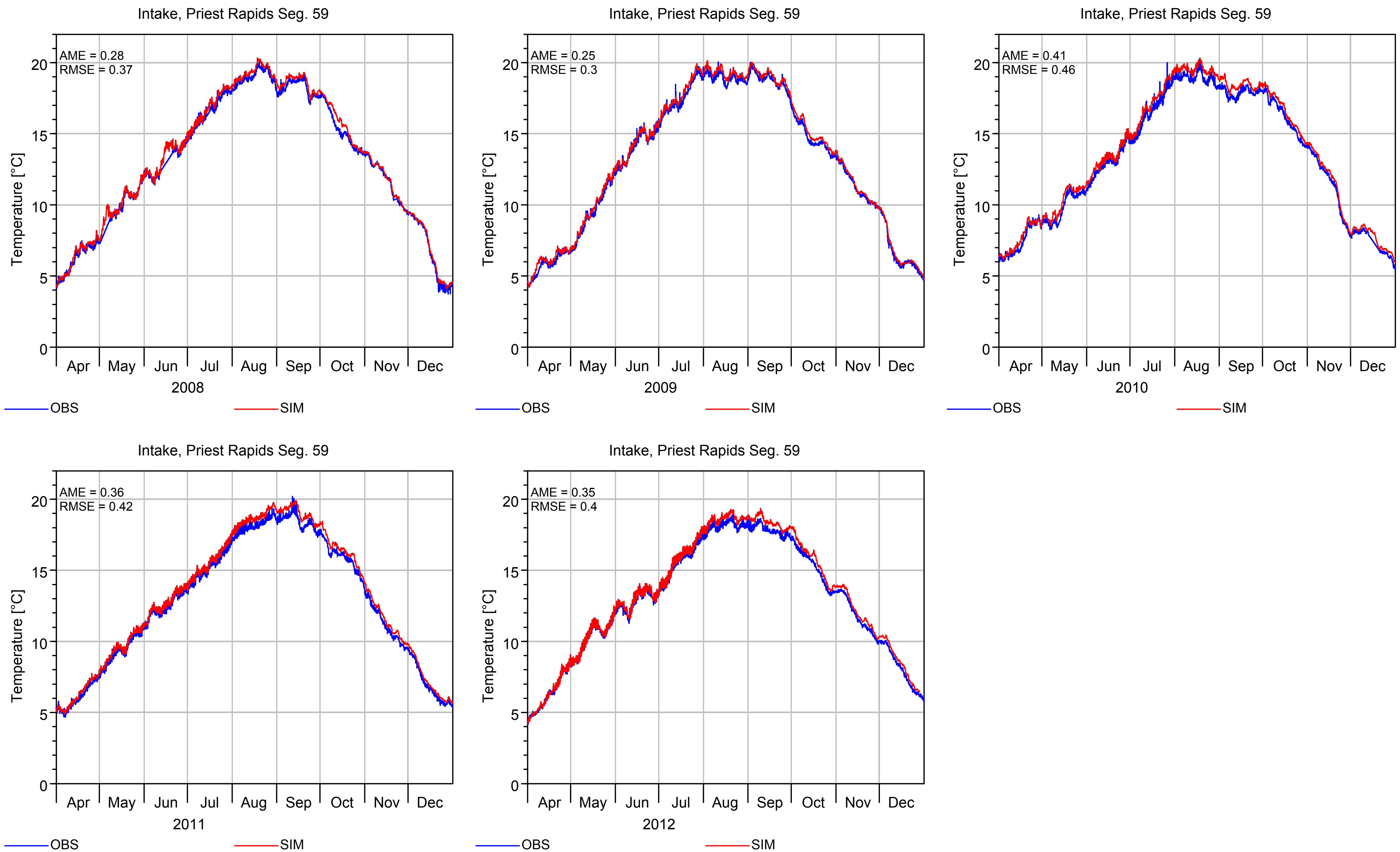


Figure 55: Simulated vs. Observed Water Temperature, Priest Rapids Forebay Intake, Priest Rapids Segment 59, 2008 – 2012

APPENDIX C: CALIBRATION ERROR STATISTICS

Table 24: Absolute Mean Error, "with Project", Annual

Year	Mean Absolute Error, Simulated vs. Observed					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
2003	-	-	0.20	0.26	0.39	0.34
2004	-	-	0.23	0.26	0.48	0.37
2005	-	-	0.16	0.28	0.27	0.16
2006	-	-	0.42	0.28	0.28	0.17
2007	-	-	0.12	0.31	0.36	0.16
2008	-	-	0.17	0.26	0.23	0.25
2009	-	-	0.16	0.23	0.22	0.27
2010	-	-	0.14	0.20	0.33	0.34
2011	-	-	0.15	0.13	0.33	0.16
2012	-	-	0.09	0.17	0.32	0.16

Table 25: Root Mean Square Error, "with Project", Annual

Year	Root Mean Square Error, Simulated vs. Observed					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
2003	-	-	0.26	0.41	0.45	0.49
2004	-	-	0.30	0.36	0.56	0.44
2005	-	-	0.21	0.38	0.35	0.23
2006	-	-	1.14	0.38	0.37	0.34
2007	-	-	0.16	0.40	0.52	0.21
2008	-	-	0.21	0.37	0.32	0.32
2009	-	-	0.20	0.33	0.28	0.35
2010	-	-	0.18	0.30	0.40	0.41
2011	-	-	0.20	0.20	0.38	0.19
2012	-	-	0.12	0.23	0.37	0.21

Table 26: Absolute Mean Error, "with Project", July through September

Year	Mean Absolute Error, Simulated vs. Observed					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
2003	-	0.17	0.13	0.34	0.55	0.15
2004	-	0.19	0.21	0.29	0.71	0.38
2005	-	0.20	0.14	0.31	0.44	0.12
2006	-	0.25	0.25	0.27	0.48	0.14
2007	-	0.22	0.13	0.32	0.51	0.13
2008	-	0.26	0.20	0.36	0.30	0.15
2009	-	0.29	0.22	0.34	0.30	0.17
2010	-	0.19	0.10	0.28	0.55	0.48
2011	-	0.12	0.09	0.21	0.49	0.15
2012	-	0.11	0.08	0.22	0.47	0.15

Table 27: Root Mean Square Error, "with Project", July through September

Year	Root Mean Square Error, Simulated vs. Observed					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
2003	-	0.21	0.16	0.51	0.59	0.19
2004	-	0.25	0.28	0.42	0.74	0.47
2005	-	0.25	0.17	0.40	0.47	0.17
2006	-	0.32	0.34	0.38	0.52	0.18
2007	-	0.33	0.17	0.46	0.58	0.21
2008	-	0.31	0.23	0.50	0.34	0.19
2009	-	0.35	0.24	0.48	0.34	0.22
2010	-	0.24	0.12	0.43	0.58	0.55
2011	-	0.18	0.14	0.29	0.53	0.18
2012	-	0.14	0.10	0.31	0.51	0.18

APPENDIX D: SENSITIVITY ANALYSIS STATISTICS

Table 28: Maximum Simulated 7-DADMax, "with Project", July through September 2012

Sensitivity Test	Maximum Simulated 7-DADmax					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
Baseline Simulation (Daily Water-Balance)	19.30	18.75	18.96	19.22	19.18	19.18
Hourly Water-Balance	19.29	18.73	18.96	19.21	19.17	19.16
5% Increase in Gaged Flows at Wanapum	19.37	18.73	18.96	19.27	19.14	19.17
RID Forebay Data for Wanapum Inflow Temperature	19.38	18.81				
Reduce Priest Rapids Reservoir Inflows by 0.5 Degrees			18.47	18.93	18.67	18.71
Increase AX and DX values to 10.0			18.96	19.41	19.15	19.18
Use Pangborn Cloud Cover for Priest Rapids			18.96	19.21	19.16	19.18
Use Air Temperature for Distributed Inflow			18.97	19.40	19.18	19.22
Use Line Instead of Point Withdrawals	19.32	18.75	18.96	19.41	19.15	19.18
Outlet Structure Withdrawal Ranges						
RNG Vertical Eddy Viscosity Formulation			18.93	19.34	19.14	19.15
Use Theoretical Solar Radiation Data			18.97	19.37	19.07	19.13
Wind Sheltering Coefficient of 0.75			18.97	19.37	19.17	19.18
Wind Sheltering Coefficient of 1.25			18.95	19.21	19.17	19.12
Reduce Shading Factors to 0.3			18.85	18.81	18.79	18.75
Priest Rapids Reservoir as two Branches			18.95	19.22	19.14	19.15
Priest Rapids Reservoir as two Waterbodies			18.96	19.23	19.14	19.17
Decreased Roughness Downstream of Vernita Bridge to 0.030			18.96	19.22	19.18	19.20

Table 29: Average Simulated 7-DADMax, “with Project”, July through September 2012

Sensitivity Test	Average Simulated 7-DADmax					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
Baseline Simulation (Daily Water-Balance)	18.00	17.49	17.69	18.07	17.92	17.99
Hourly Water-Balance	17.95	17.47	17.69	18.04	17.91	17.97
5% Increase in Gaged Flows at Wanapum	18.01	17.53	17.68	18.09	17.95	17.99
RID Forebay Data for Wanapum Inflow Temperature	18.02	17.51				
Reduce Priest Rapids Reservoir Inflows by 0.5 Degrees			17.19	17.66	17.45	17.52
Increase AX and DX values to 10.0			17.68	18.12	17.92	17.98
Use Pangborn Cloud Cover for Priest Rapids			17.68	18.06	17.91	17.98
Use Air Temperature for Distributed Inflow			17.69	18.21	17.97	18.05
Use Line Instead of Point Withdrawals	18.00	17.49	17.69	18.12	17.92	17.98
Outlet Structure Withdrawal Ranges						
RNG Vertical Eddy Viscosity Formulation			17.67	18.10	17.89	17.98
Use Theoretical Solar Radiation Data			17.69	18.08	17.88	17.94
Wind Sheltering Coefficient of 0.75			17.68	18.14	17.91	18.00
Wind Sheltering Coefficient of 1.25			17.68	18.06	17.89	17.98
Reduce Shading Factors to 0.3			17.64	17.55	17.52	17.51
Priest Rapids Reservoir as two Branches			17.67	17.97	17.93	17.99
Priest Rapids Reservoir as two Waterbodies			17.68	17.97	17.93	18.00
Decreased Roughness Downstream of Vernita Bridge to 0.030			17.69	18.07	17.92	17.99

Table 30: Absolute Mean Error, "with Project", July through September 2012

Sensitivity Test	Mean Absolute Error, Simulated vs. Observed					
	Wanapum Forebay FSM	Wanapum Forebay Intake	Beverly Bridge	Priest Rapids Forebay FSM	Priest Rapids Forebay Intake	Vernita Bridge
Baseline Simulation (Daily Water-Balance)	0.70	0.18	0.09	0.23	0.44	0.16
Hourly Water-Balance	0.74	0.20	0.09	0.22	0.43	0.15
5% Increase in Gaged Flows at Wanapum	0.68	0.15	0.09	0.23	0.43	0.16
RID Forebay Data for Wanapum Inflow Temperature	0.67	0.16				
Reduce Priest Rapids Reservoir Inflows by 0.5 Degrees			0.48	0.40	0.20	0.36
Increase AX and DX values to 10.0			0.09	0.24	0.43	0.16
Use Pangborn Cloud Cover for Priest Rapids			0.09	0.22	0.43	0.15
Use Air Temperature for Distributed Inflow			0.09	0.27	0.46	0.19
Use Line Instead of Point Withdrawals	0.69	0.17	0.09	0.24	0.43	0.16
Outlet Structure Withdrawal Ranges			0.09	0.22	0.48	0.15
RNG Vertical Eddy Viscosity Formulation			0.08	0.22	0.41	0.15
Use Theoretical Solar Radiation Data			0.09	0.24	0.38	0.15
Wind Sheltering Coefficient of 0.75			0.09	0.25	0.43	0.17
Wind Sheltering Coefficient of 1.25			0.09	0.22	0.42	0.14
Reduce Shading Factors to 0.3			0.09	0.31	0.19	0.26
Priest Rapids Reservoir as two Branches			0.08	0.22	0.47	0.16
Priest Rapids Reservoir as two Waterbodies			0.08	0.22	0.47	0.16
Decreased Roughness Downstream of Vernita Bridge to 0.030			0.09	0.23	0.44	0.16

Table 31: Root Mean Square Error, "with Project", July through September 2012

Sensitivity Test	Root Mean Square Error, Simulated vs. Observed					
	Wanapum Forebay		Beverly Bridge	Priest Rapids Forebay		Vernita Bridge
	FSM	Intake		FSM	Intake	
Baseline Simulation (Daily Water-Balance)	0.78	0.21	0.11	0.29	0.49	0.20
Hourly Water-Balance	0.79	0.21	0.11	0.28	0.48	0.19
5% Increase in Gaged Flows at Wanapum	0.75	0.17	0.11	0.30	0.47	0.20
RID Forebay Data for Wanapum Inflow Temperature	0.76	0.19				
Reduce Priest Rapids Reservoir Inflows by 0.5 Degrees			0.49	0.49	0.27	0.40
Increase AX and DX values to 10.0			0.11	0.31	0.48	0.19
Use Pangborn Cloud Cover for Priest Rapids			0.11	0.28	0.48	0.19
Use Air Temperature for Distributed Inflow			0.11	0.35	0.50	0.24
Use Line Instead of Point Withdrawals	0.77	0.21	0.11	0.31	0.48	0.19
Outlet Structure Withdrawal Ranges			0.11	0.31	0.52	0.19
RNG Vertical Eddy Viscosity Formulation			0.10	0.30	0.46	0.19
Use Theoretical Solar Radiation Data			0.11	0.31	0.43	0.18
Wind Sheltering Coefficient of 0.75			0.11	0.32	0.49	0.21
Wind Sheltering Coefficient of 1.25			0.11	0.28	0.47	0.18
Reduce Shading Factors to 0.3			0.11	0.40	0.23	0.29
Priest Rapids Reservoir as two Branches			0.10	0.32	0.52	0.19
Priest Rapids Reservoir as two Waterbodies			0.11	0.32	0.52	0.19
Decreased Roughness Downstream of Vernita Bridge to 0.030			0.11	0.29	0.49	0.20

Table 32: Maximum Simulated 7-DADMax, "without Project", July through September 2012

Sensitivity Test	Maximum Simulated 7-DADmax			
	Wanapum Forebay	Beverly Bridge	Priest Rapids Forebay	Vernita Bridge
Baseline Simulation (Daily Water-Balance)	18.93	18.92	18.94	18.99
Daily Average of Hourly Water-Balance	18.92	18.91	18.93	19.01
No Distributed Inflows	18.93	18.93	18.93	19.01
Daily Water-Balance Developed with 5% Increase in Turbine Flows at Wanapum	18.93	18.93	18.95	19.01
RID Forebay Data for Wanapum Inflow Temperature	18.92	18.93	18.97	19.01
Increase AX and DX values to 10.0	18.92	18.91	18.93	19.01
Use Pangborn Cloud Cover for Priest Rapids	18.92	18.92	18.96	19.04
Use Air Temperature for Distributed Inflow	19.21	19.21	19.21	19.31
Nickuradse Vertical Eddy Viscosity Formulation	19.10	19.16	18.92	19.00
W2 Vertical Eddy Viscosity Formulation	18.92	18.92	18.93	18.99
Wind Sheltering Coefficient of 0.75	18.94	18.93	18.95	19.01
Increase Channel Roughness to Mannings-N of 0.045	18.90	18.87	18.92	18.95

Table 33: Average Simulated 7-DADMax, "without Project", July through September 2012				
Sensitivity Test	**Maximum Simulated 7-DADmax**			
	Wanapum Forebay	**Beverly Bridge**	**Priest Rapids Forebay**	**Vernita Bridge**
Daily Water-Balance	17.69	17.70	17.75	17.78
Daily Average of Hourly Water-Balance	17.68	17.70	17.75	17.79
No Distributed Inflows	17.70	17.71	17.75	17.79
Daily Water-Balance Developed with 5% Increase in Turbine Flows at Wanapum	17.68	17.70	17.93	17.80
RID Forebay Data for Wanapum Inflow Temperature	17.71	17.72	17.77	17.81
AXDX	17.68	17.70	17.75	17.79
Cloud Cover	17.68	17.70	17.76	17.80
Use Air Temperature for Distributed Inflow	18.07	18.09	18.15	18.18
Use NICK Turbulence Scheme	17.79	17.82	17.76	17.82
Use W2 Turbulence Scheme	17.66	17.69	17.75	17.79
Wind Sheltering Coefficient of 0.75	17.69	17.70	17.76	17.80
Increase Channel Roughness to Mannings-N of 0.045	17.67	17.67	17.72	17.75

APPENDIX E: MAXIMUM ANNUAL 7-DADMAX QUERIED AT DEPTHS BY RIVER-MILE

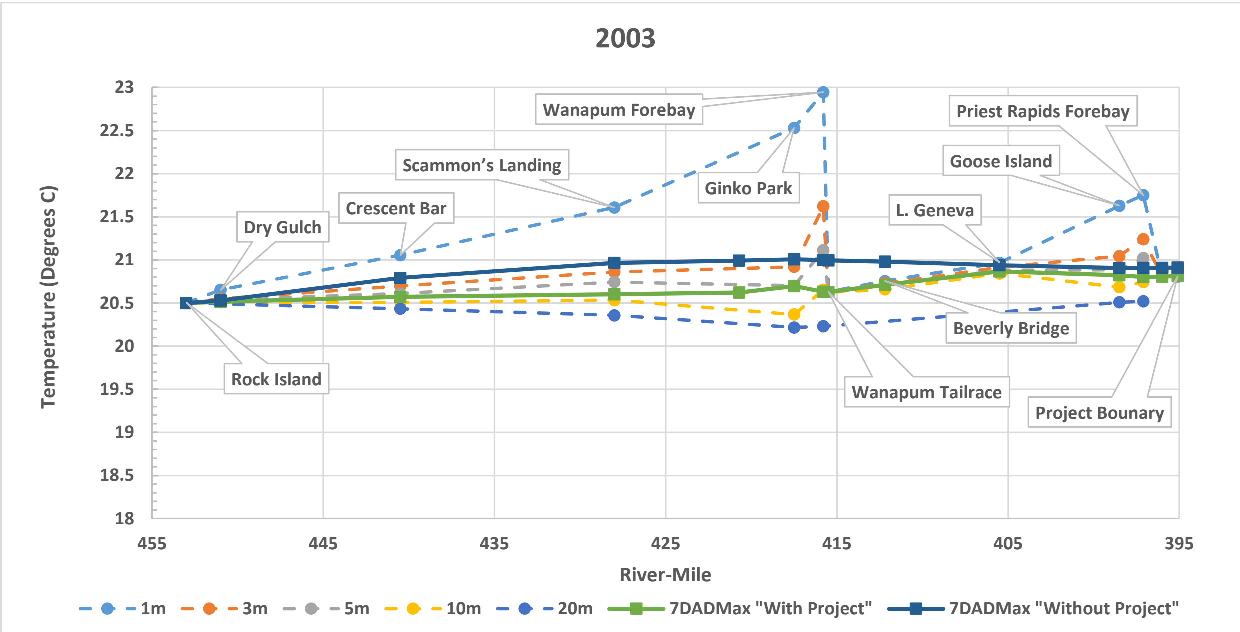


Figure 56: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2003

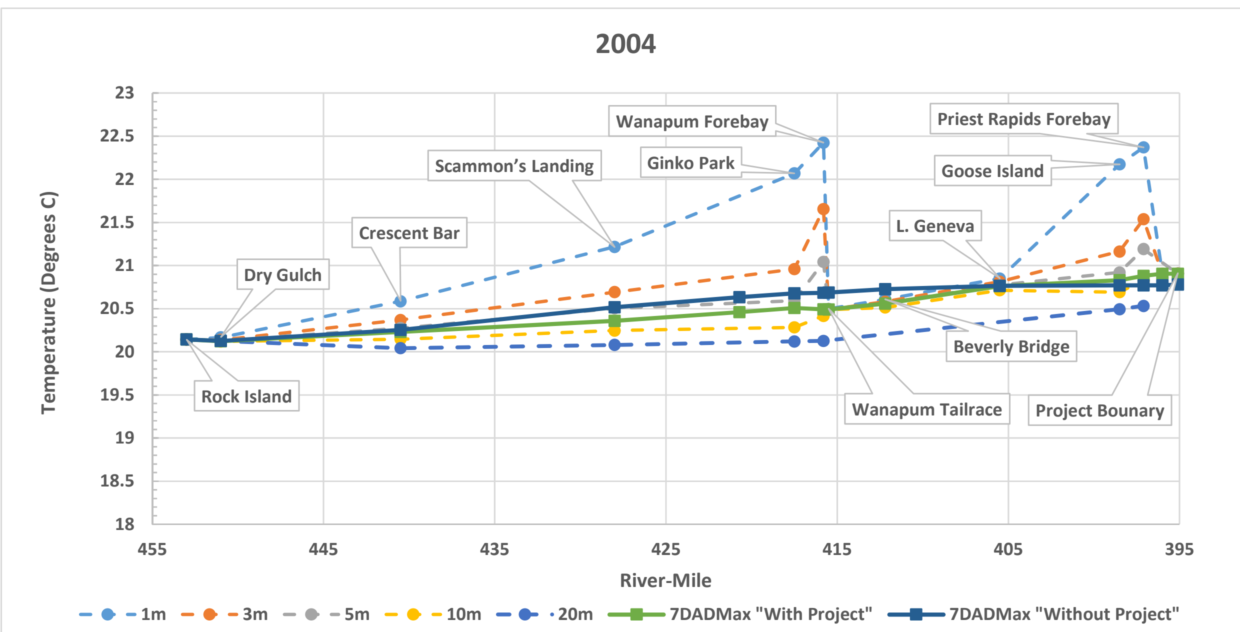


Figure 57: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2004

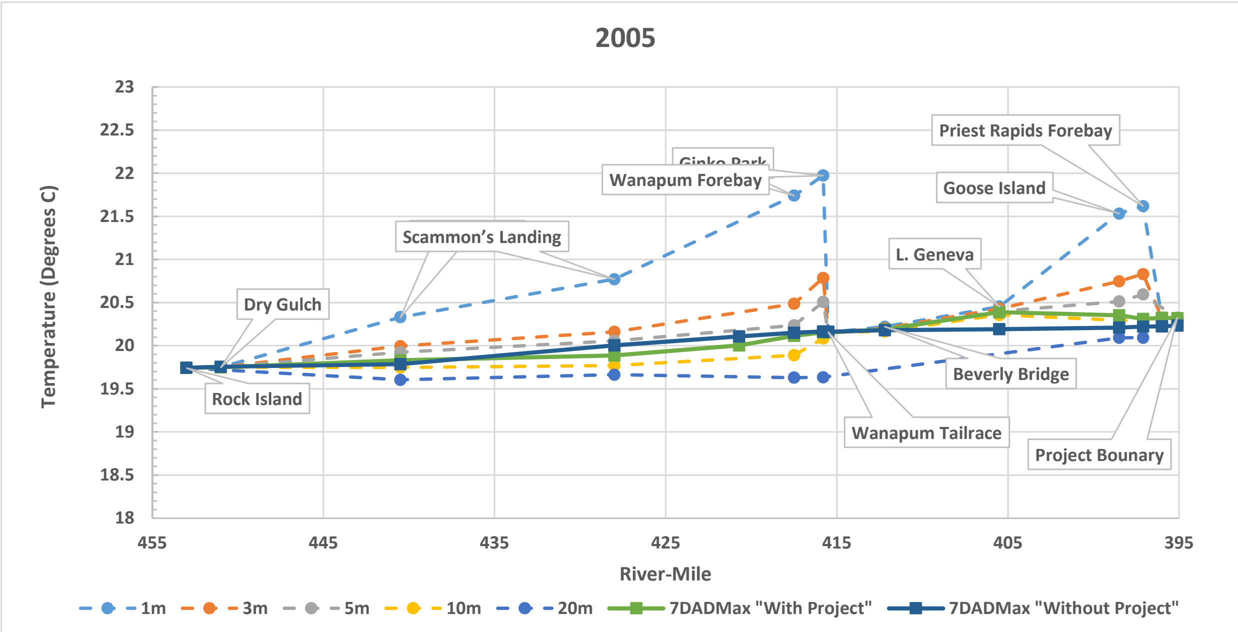


Figure 58: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2005

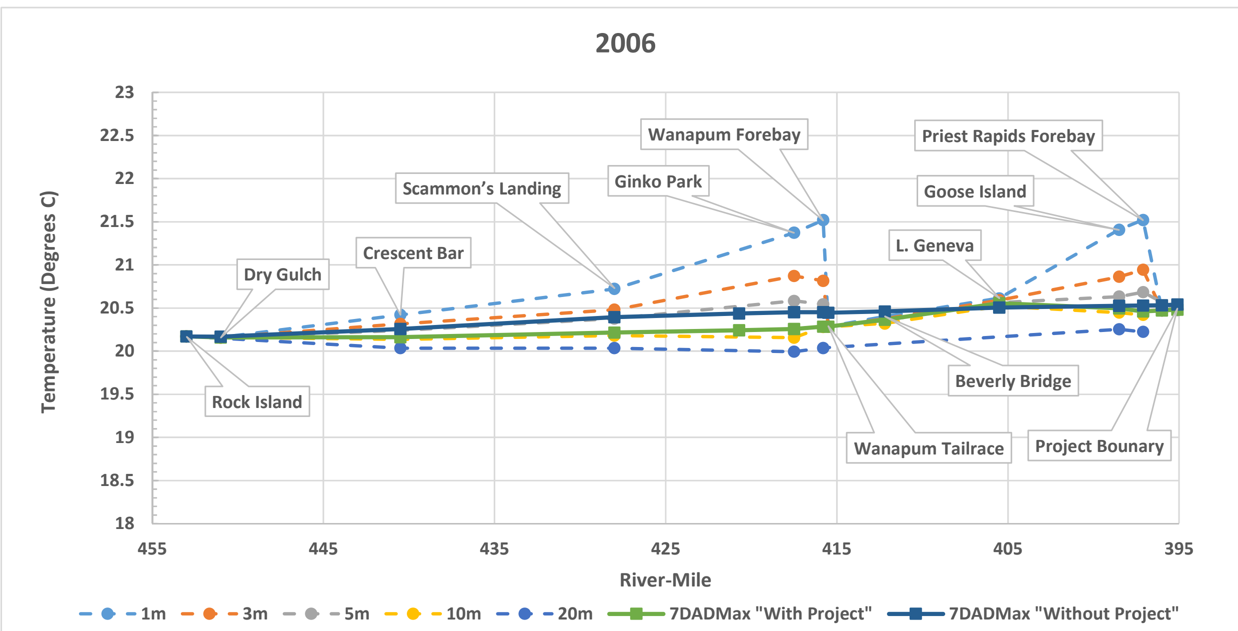


Figure 59: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2006

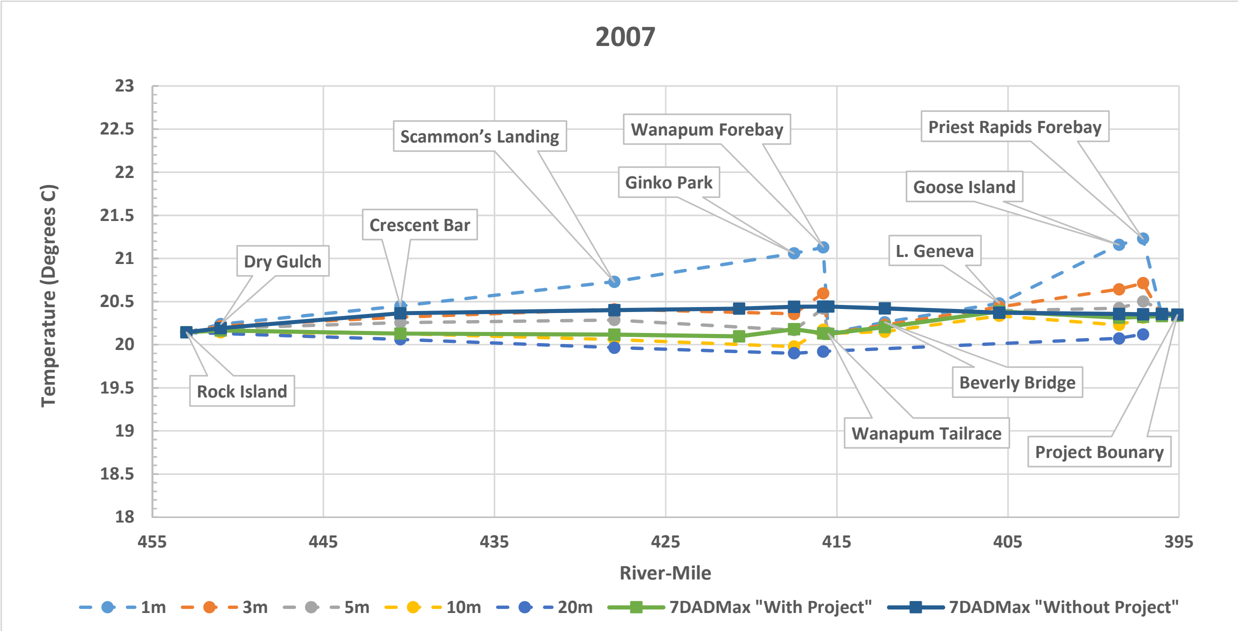


Figure 60: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2007

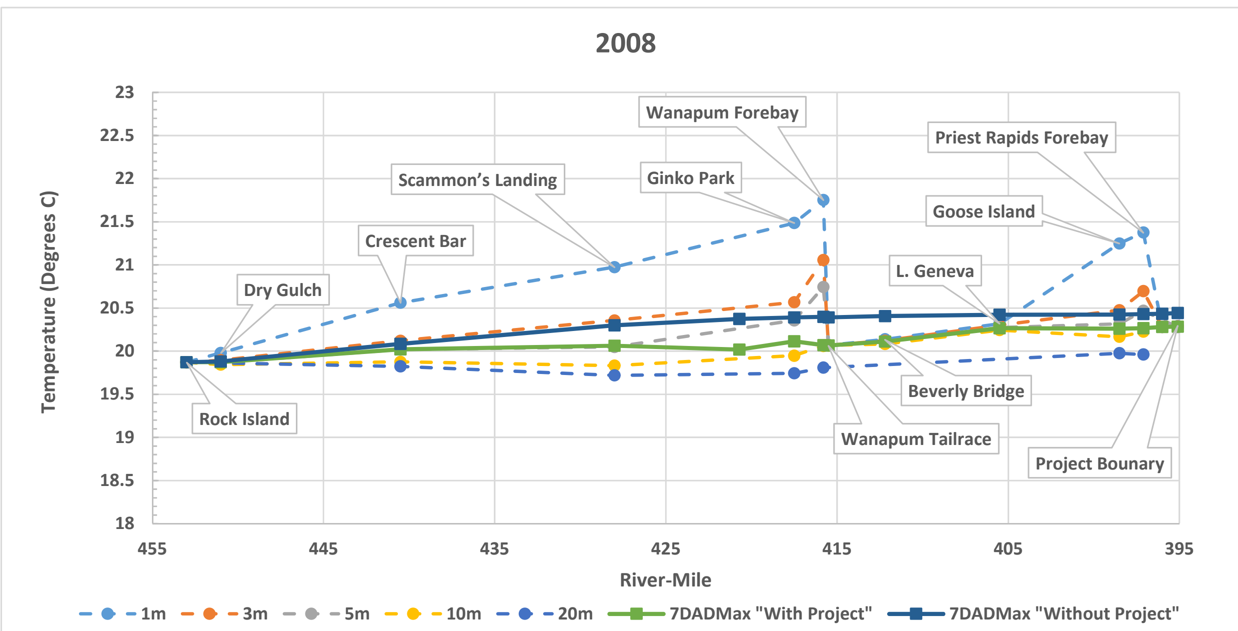


Figure 61: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2008

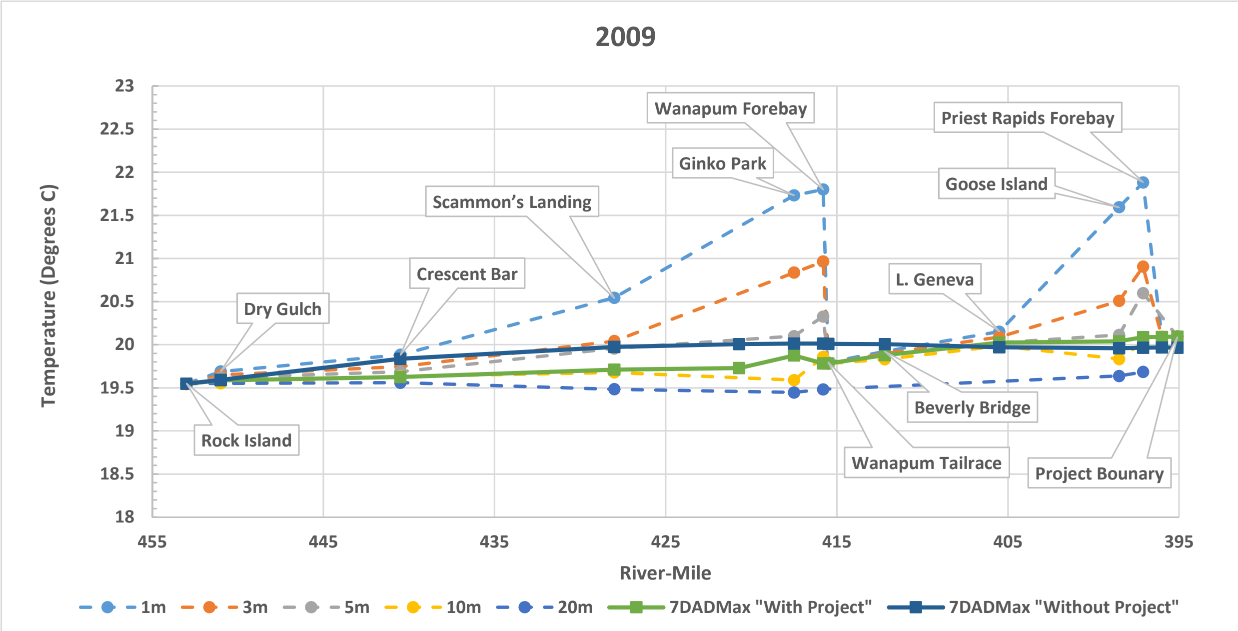


Figure 62: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2009

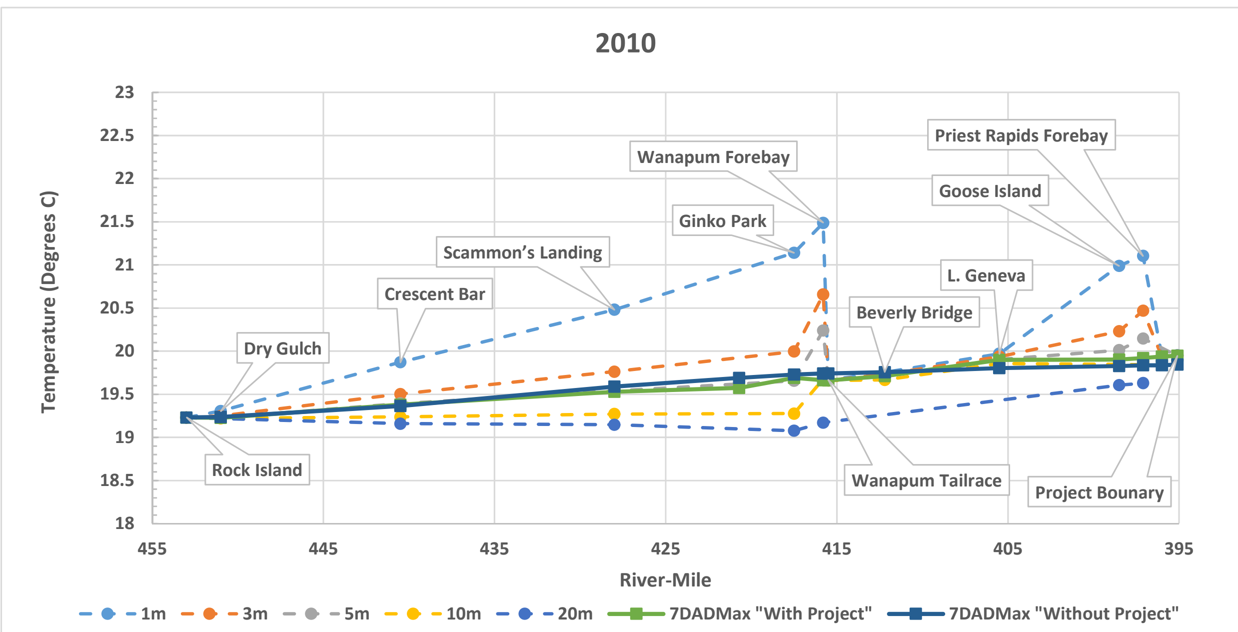


Figure 63: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2010

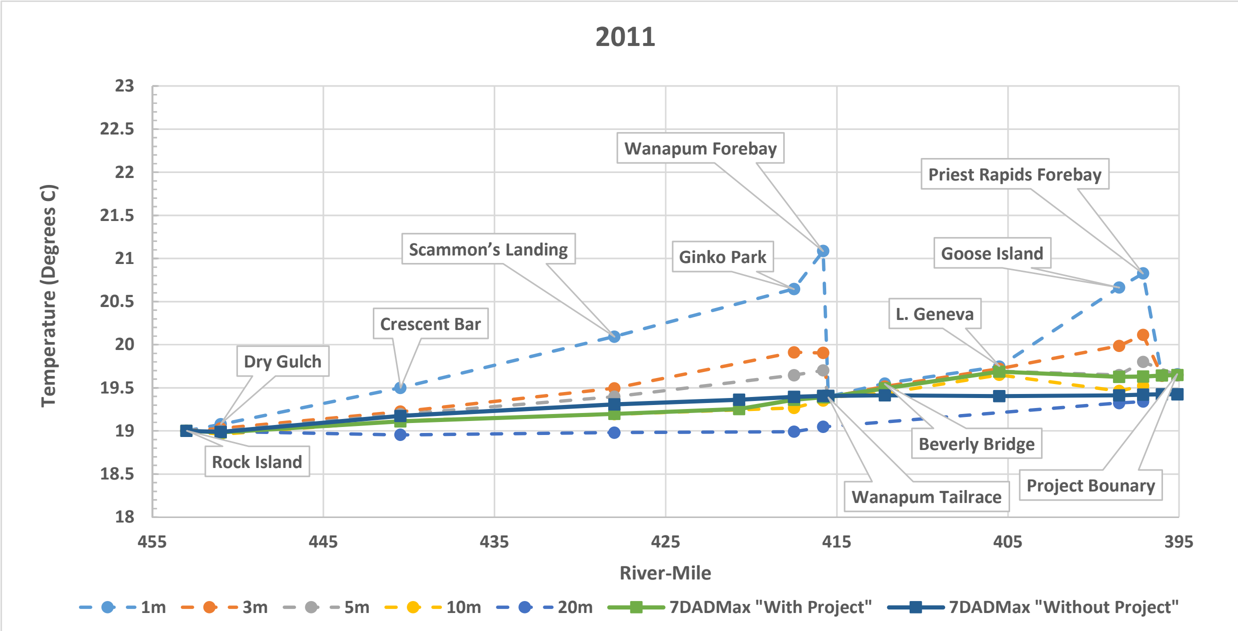


Figure 64: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2011

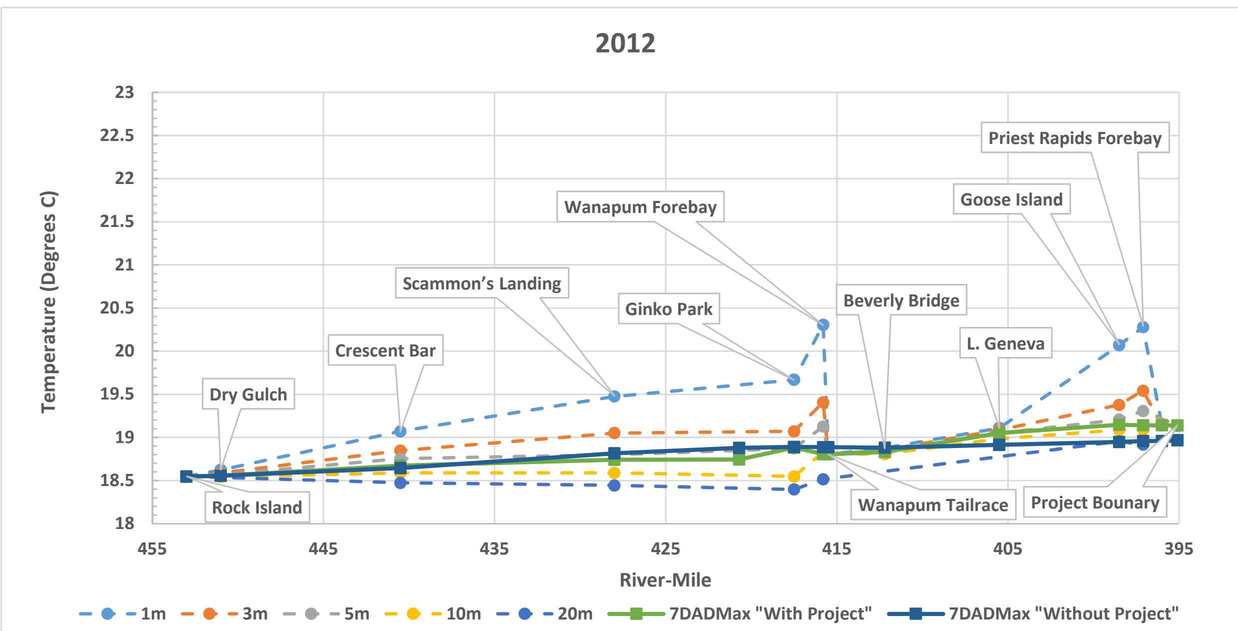


Figure 65: Maximum Annual 7-DADMax Queried at Depths by River-Mile, 2012

APPENDIX F: MAXIMUM ANNUAL FLOW WEIGHTED 7-DADMAX BY RIVER-MILE

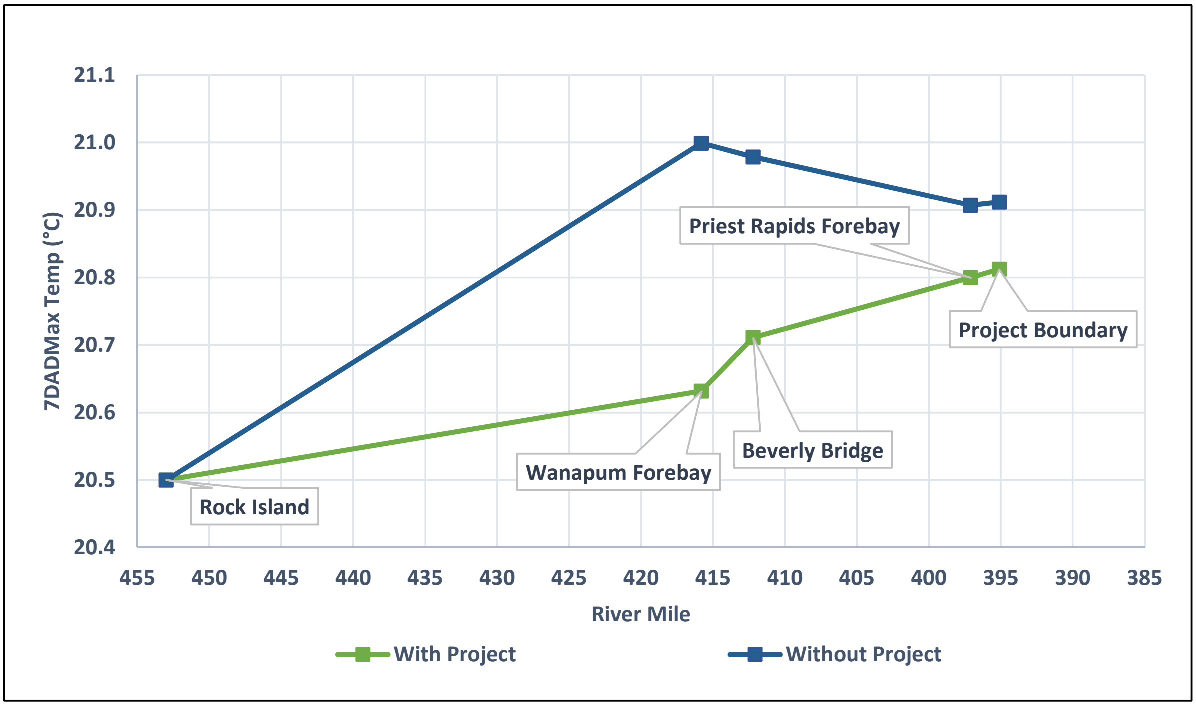


Figure 66: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2003

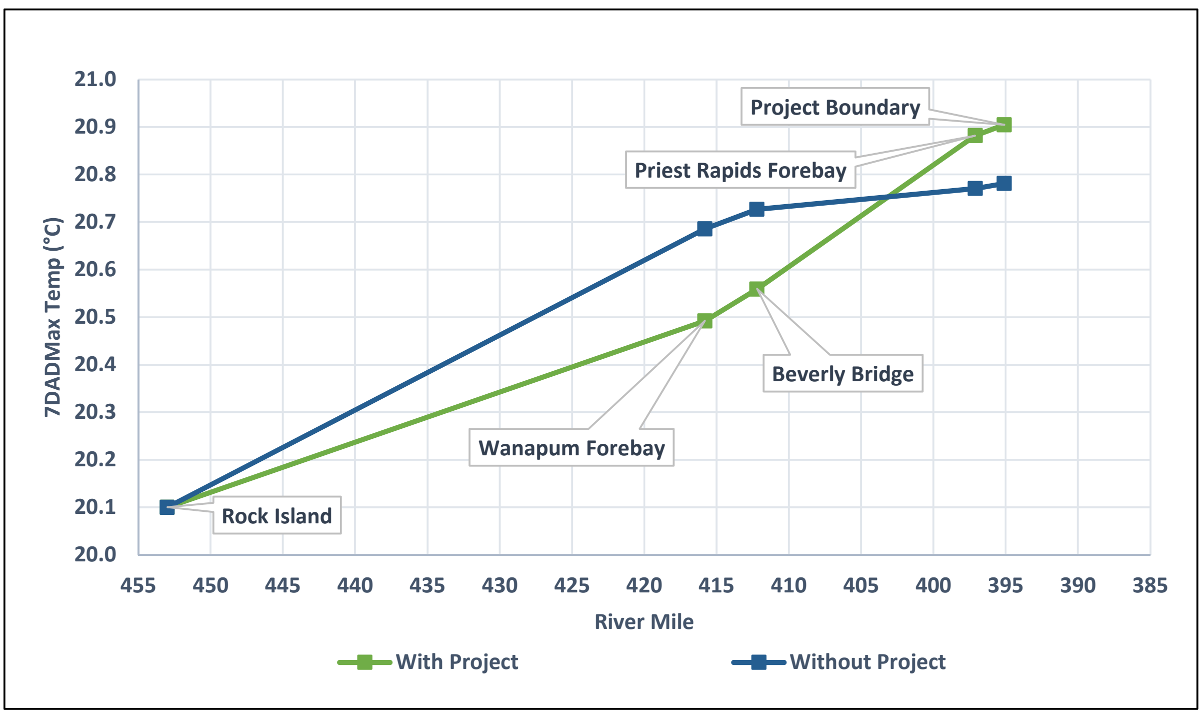


Figure 67: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2004

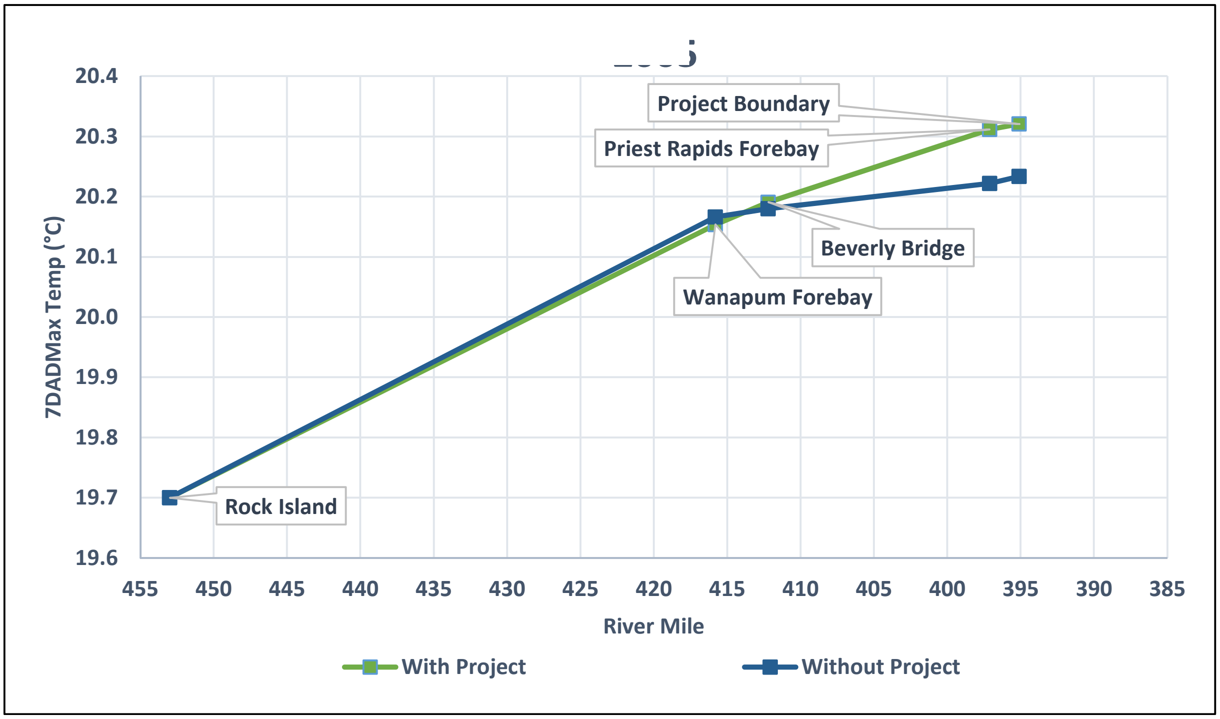


Figure 68: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2005

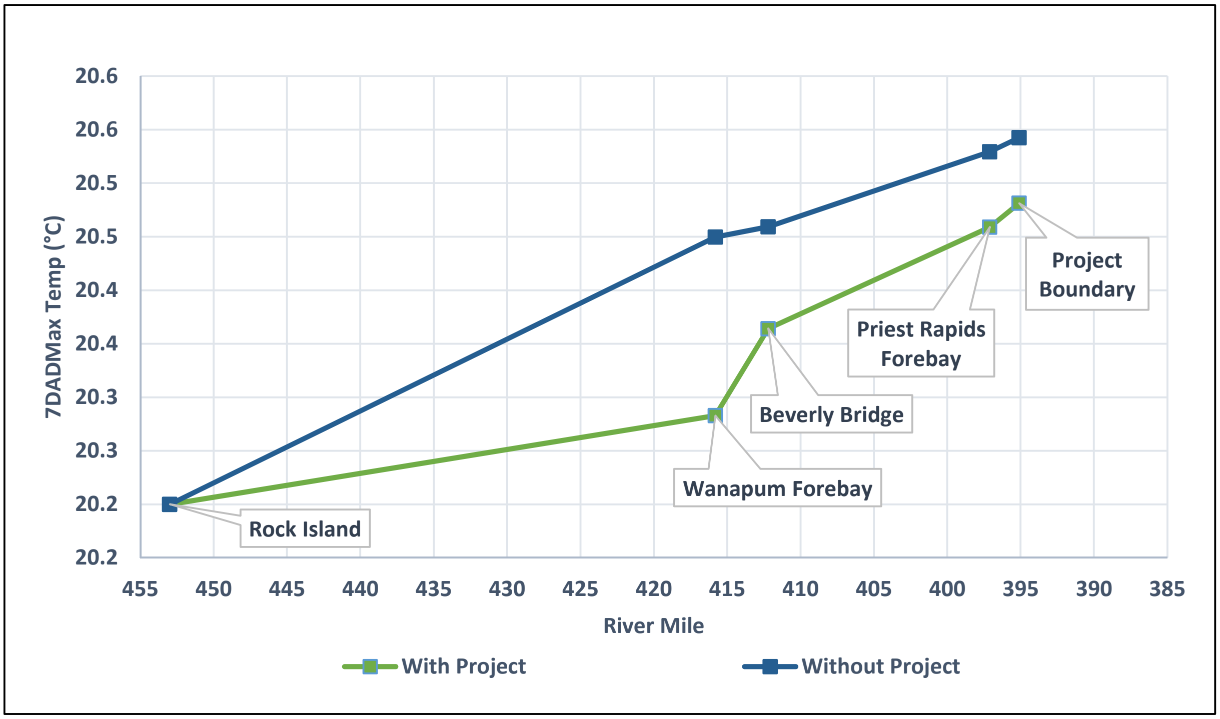


Figure 69: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2006

Figure 70: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2007

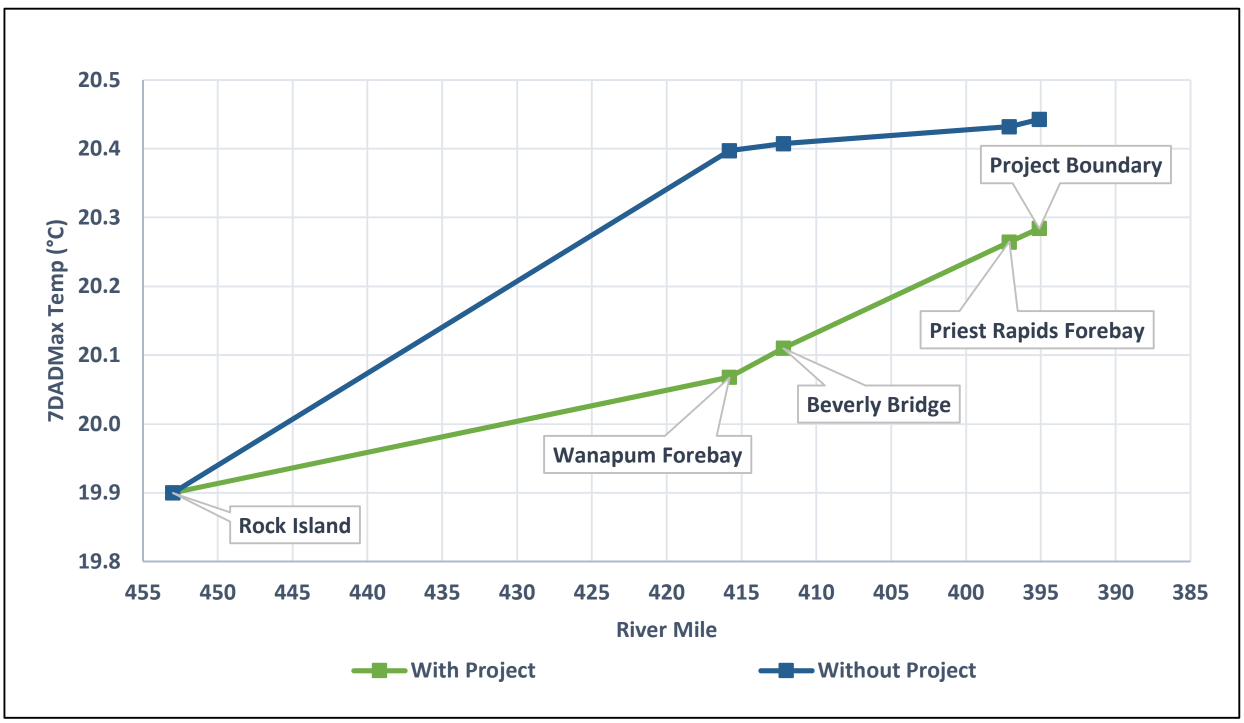


Figure 71: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2008

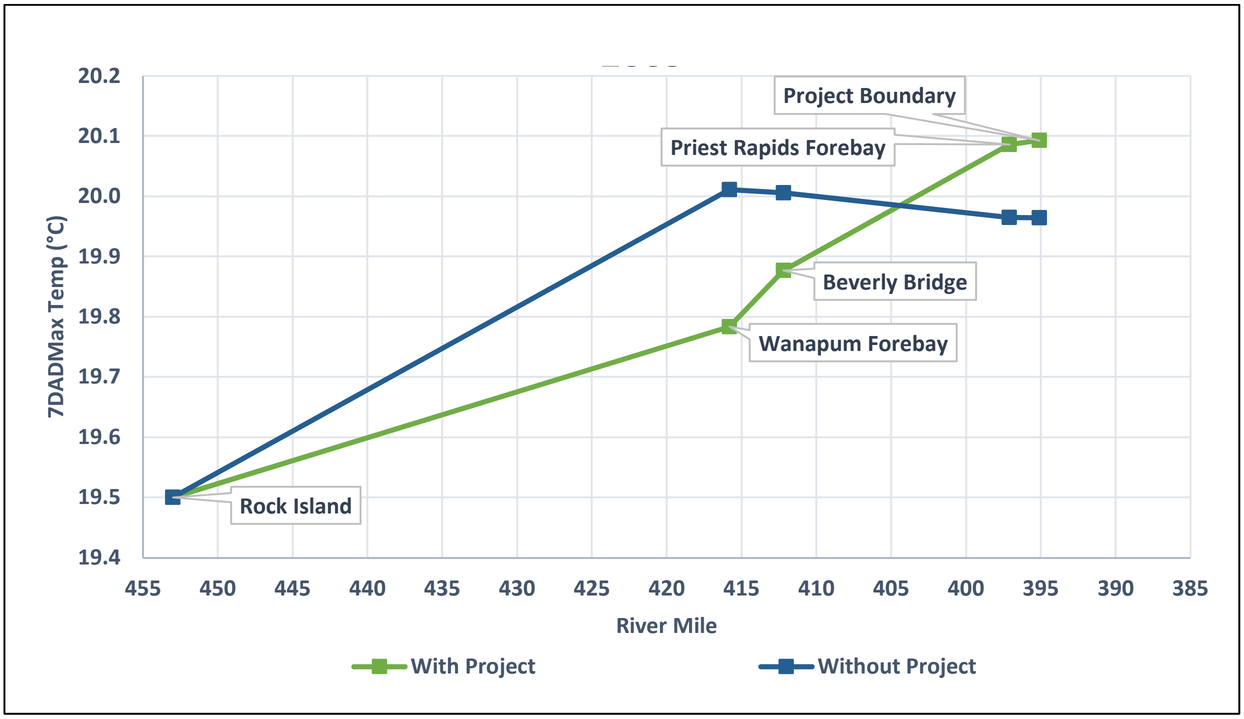


Figure 72: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2009

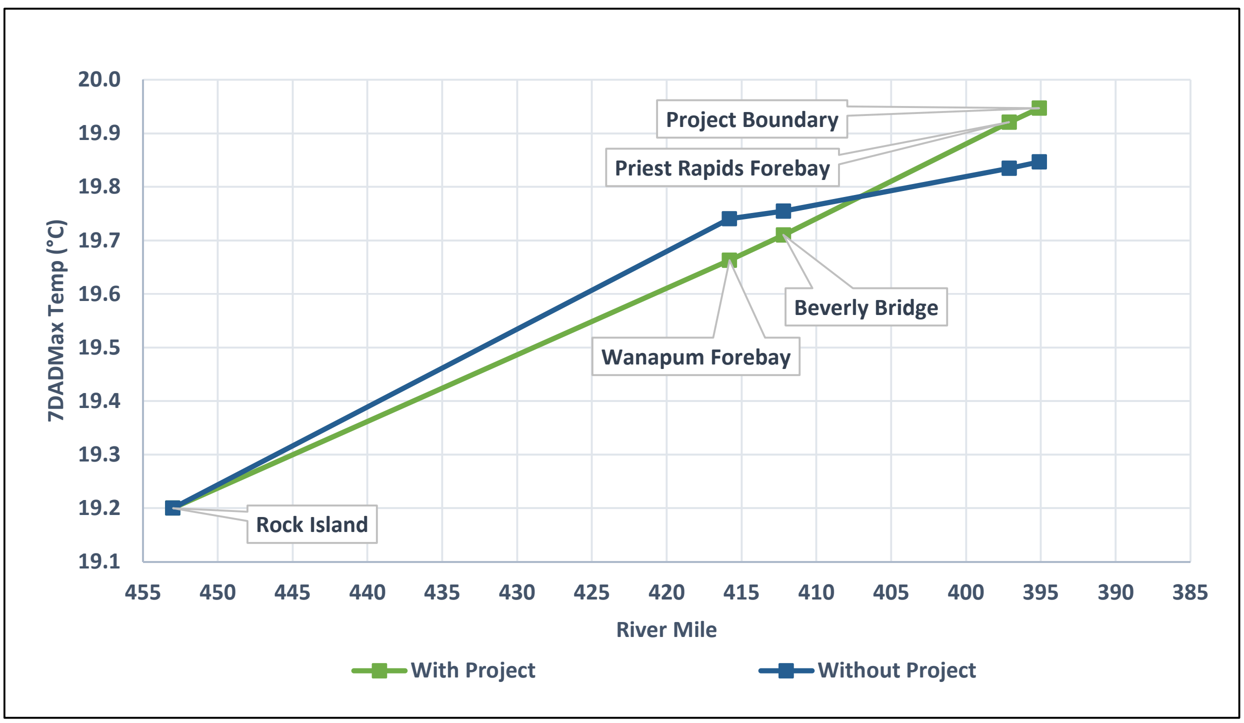


Figure 73: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2010

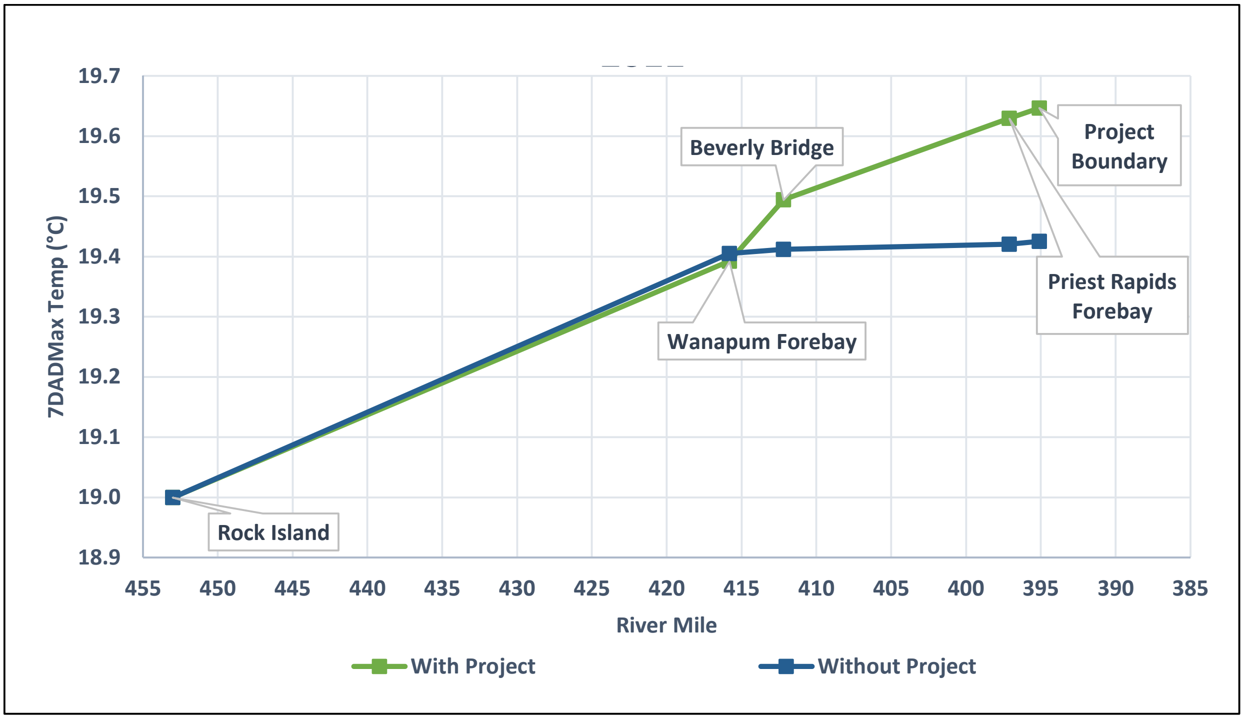


Figure 74: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2011

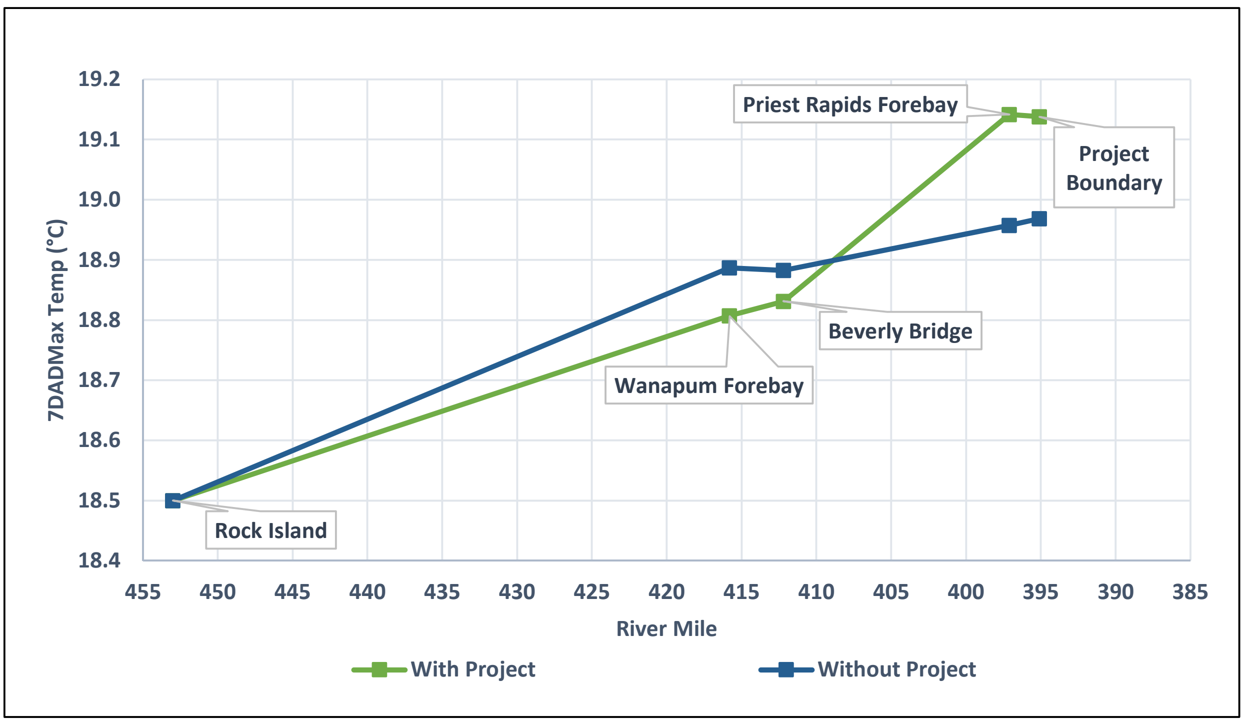


Figure 75: Maximum Annual Flow Weighted 7-DADMax by River-Mile, 2012

APPENDIX G: CFD CURVES USED FOR METRICS 2 AND 4

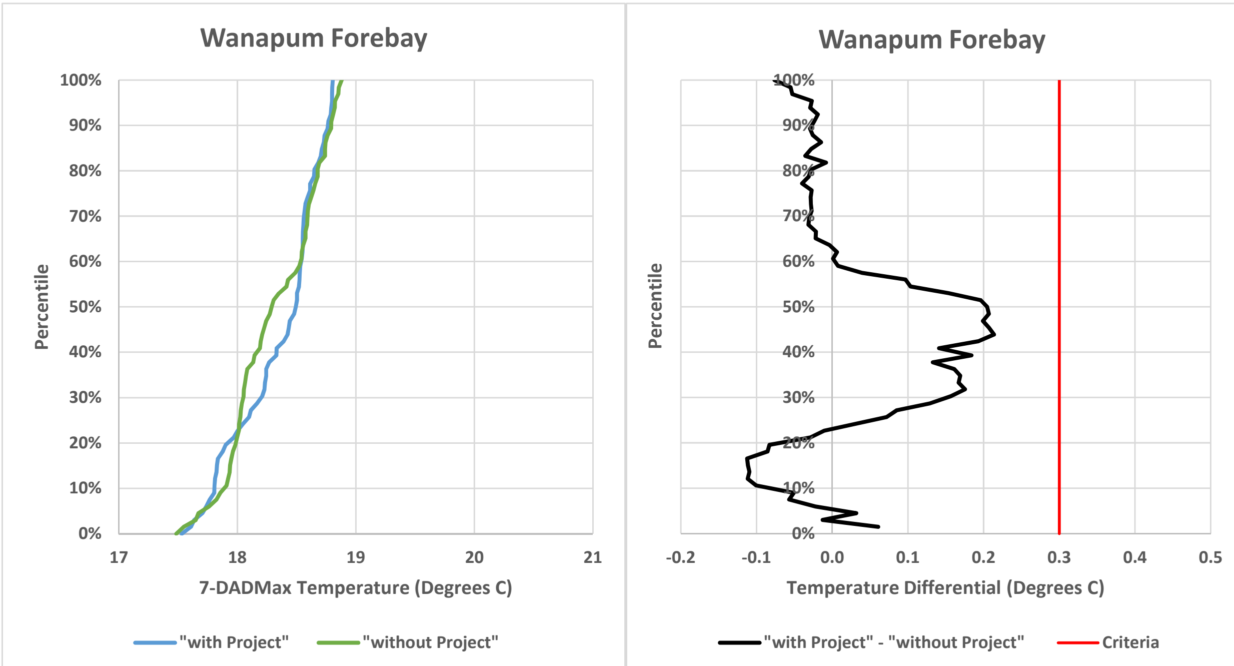


Figure 76: CFDs at Wanapum Forebay 7-DADMax flow weighted temperatures simulated for calendar year 2012, when the "with Project" 7-DADMax exceeds 17.5 °C (Left); temperature differential when the "without Project" scenario exceeds 17.5 °C (Right)

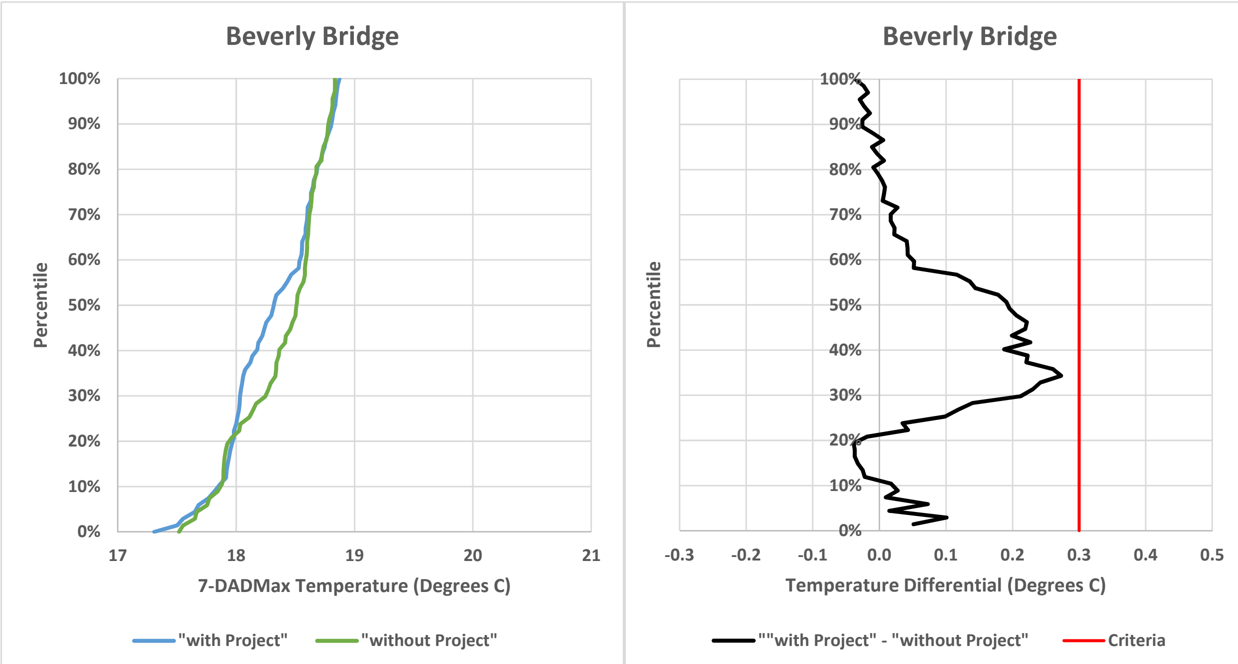


Figure 77: CFDs at Beverly Bridge 7-DADMax flow weighted temperatures simulated for calendar year 2012, when the "with Project" 7-DADMax exceeds 17.5 °C (Left); temperature differential when the "without Project" scenario exceeds 17.5 °C (Right)

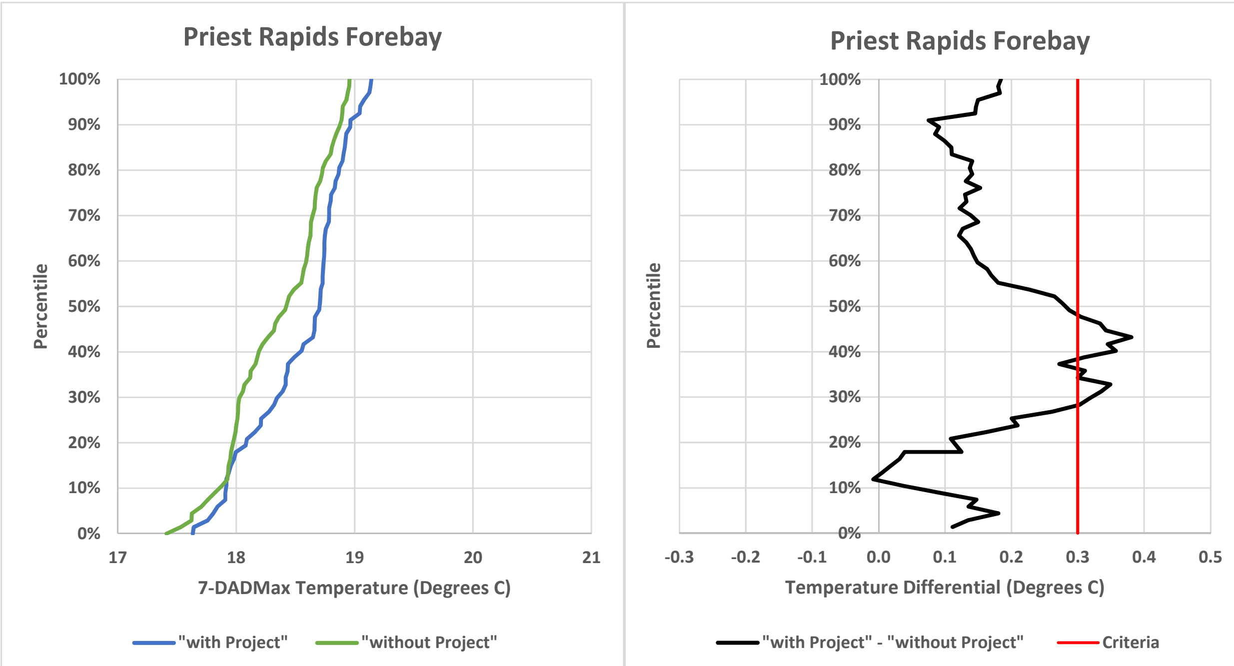
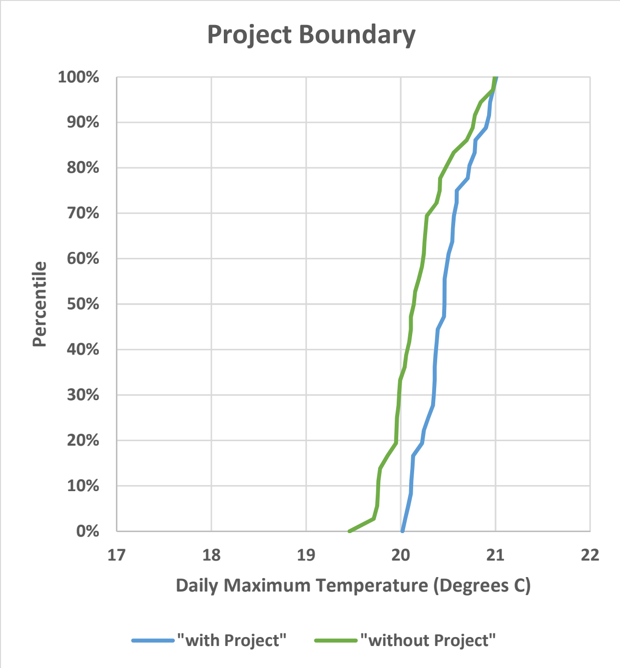


Figure 78: CFDs at Priest Rapids Forebay; 7-DADMax flow weighted temperatures simulated for calendar year 2012, when the "with Project" 7-DADMax exceeds 17.5 °C (Left); temperature differential when the "without Project" scenario exceeds 17.5 °C (Right)



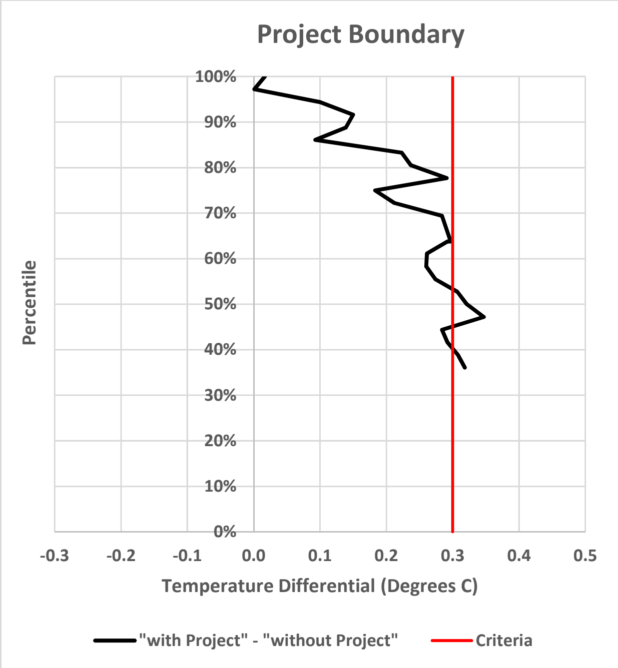


Figure 79: CFDs at Project Boundary; daily maximum flow weighted temperatures simulated for calendar year 2004, when the "with Project" daily maximum exceeds 20.0 °C (Left); temperature differential when the "without Project" scenario exceeds 20.0 °C (Right)

APPENDIX H: STAKEHOLDER COMMENTS ON REPORT AND MODEL

Submitting Entity	Date Received	Paragraph #	Agency Comment	Grant PUD Response
WDOE – (Memo. from A.J. Whiley attached to email from Pat McGuire)	12/4/15	1	The modelling methods and approaches used to evaluate potential Columbia River temperature impacts, associated with the Grant PUD hydroelectric projects, appear appropriate.	Grant PUD appreciates Ecology's review and coordination and collaboration on the development of the Water Temperature Model for the Priest Rapids Project in accordance with Section 6.5.2 of the 401 Water Quality Certificate to operate the Priest Rapids Project.
		2	While it would seem that the criteria serves as a bottom-line assessment of impact, in actual application, it's how the data are examined that really has the most significant effect on outcomes and conclusions. Recognizing this ambiguity, Ecology typically requires that reasonable assumptions are applied with criteria assessment while providing a clear justification to the analysis approaches taken. I'll indicate where the study falls short of providing a clear justification.	Grant PUD appreciates Ecology's careful review of the report, and recommendations for improvement. We interpret this statement and the first statement as support of Grant PUD's approach and assumptions, with the caveat that clear justification of approach and assumptions is requested. We have provided clarification in the Consultation Draft report.
		3	<u>Water Column Temperature Averaging</u> Because the use of the water column average method tends to provide the lowest possible maximum temperature, some justification for its application is warranted.	We have clarified in the Consultation Draft report the appropriateness of how flow and volume-weighted averaging were appropriately applied for this model effort.

		4	Water Column Temperature Averaging Some vertical profiles are presented in the report but there wasn't sufficient resolution to the scale obscuring the ability to properly evaluate variation in water column temperatures.	We have added illustrations with adjusted scales as requested. Please note that this has resulted in different scales for different months (e.g. May and September).
		5&6	Pre and Post Hydroelectric Hydraulics The greater volume that characterizes the current condition assimilates greater heating loads with relatively lower effective change in temperature – it provides a greater heat storage capacity. For this reason, the study needs to clearly present why the assessment approach taken is an appropriate one. The report should clearly provide hydraulic metrics (graphic and table form) for assessment points comparing the pre and post hydroelectric conditions.	We have add graphs and tables to the report, as requested, to clearly present why the assessment approach selected is appropriate.
		7	Application of the Cumulative Frequency Distribution In terms of the application of the cumulative frequency distribution, the report does not clearly state how the temperature data for the pre and post project model scenarios were selected for analysis.	Grant PUD's approach was consistent with the approach used on the Pend Oreille River TMDL. We have added text and references demonstrating consistency.
		8	Application of the Cumulative Frequency Distribution It appears that for the Grant PUD report Northwest Hydraulics Consultants (NHC) constructed the temperature comparison dataset from the pre-hydroelectric output ("natural condition") not from the existing condition.	Pre-hydroelectric output were created from the existing condition. We have provided clarifying text.

		9	Other Bits and Pieces • The report should provide a graphic(s) depicting longitudinal temperature profiles, for various depths, through the study area while also indicating the four assessment locations.	We have added longitudinal profiles as requested.
		9	Other Bits and Pieces • The calibration of the model for the Priest Rapids forebay appears to be challenged (figure 32). The calibrated model output is biased – routinely predicting lower temperatures than typically observed during each of the study years examined.	As stated in Section 4.4 the model is neither biased high or low. Figure 32 illustrates deviations of the model low during cold periods and high during hot periods. If anything, the model may be biased high for years like 2010 as illustrated in Figure 32.
		9	Other Bits and Pieces • In providing an argument for low project impact (section 5.2.1) the report points out that the criteria were only exceeded a minimal number of times but bases that on counting days outside of the critical July/August period (i.e. winter months etc.). Along this thinking, it can also be argued that at the Priest Rapids forebay that the criteria is exceeded 40% of the time (occurring at least once each year for 4 of the 10 year assessment period) – refer to figure 45.	No change was made in the report or model.

		9	• Cloaking the level of impact on the change in temperature within aquatic habitat is a weak argument (section 5.2.1). For starters fisheries habitat has completely changed with the dams now in place. Also fisheries habitat is not just based on temperature. For instance, a fish may prefer a certain range in temperature but it has to also coincide with a particular depth (likely not the bottom of the reservoir where food is minimal) and velocity. Water quality must also be compatible. For instance, the temperature may be right but there is no food available or the dissolved oxygen is not appropriate. So the argument presented is too simplistic to be of much value.	Thank you for your comment, no changes were made to the report or model. Indeed the comment appears to advocate for modeling and reporting on water temperatures throughout the project for the entire period given that aquatic organisms reside year round and may be distributed anywhere within the water column at any time given other ecological needs.
		9	• Section on the certainty of the model (also 5.2.1) is odd and the argument presented tends to undercut the appropriateness of the model to conduct this analysis.	Information presented in section 5.3.1 (formerly 5.2.1) is intended to document model and data limitations rather than dismiss the model altogether. In addition, this section points out that data were excluded from the modeling exercise that, if used, would have produced results with zero exceedances, but would have compromised model calibration.

		9	• The application of Metric 5 to the project area (which is the increase in temperature outside of the peak temperature period - tends to be most applicable late-August through fall) is not adequately addressed in the report. Further explanation of the analysis methods and results should be presented.	Further explanation was provided as requested.