Yakima River Basin Integrated Water Resource Management Plan

Technical Memorandum: Wymer Reservoir Temperature Study

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1.0 Introduction

This technical memorandum describes the development of a temperature model for the proposed Wymer Reservoir and its application to evaluate the effects of different operational scenarios on the temperature of the water released from the reservoir, and on the water temperature in the Yakima River downstream of the reservoir. Wymer Reservoir is one of the projects proposed in the Yakima River Basin Integrated Water Resource Plan (Integrated Plan) (Reclamation and Ecology 2011a). Wymer Reservoir is located in central Washington State within the Yakima River Basin (see Figure 1).

The goals of the Integrated Plan are to protect, mitigate, and enhance fish and wildlife habitat; provide increased operational flexibility to manage instream flows to meet ecological objectives; and improve the reliability of the water supply for irrigation, municipal supply, and domestic uses (Reclamation and Ecology 2011a).

A CE-QUAL-W2 model of the proposed reservoir was developed previously by the Bureau of Reclamation (Reclamation) to evaluate the effect of releases from the water reservoir on the Yakima River (Reclamation 2008). This memorandum describes the development of a new CE-QUAL-W2 model for the proposed reservoir that uses more recent bathymetry data and applies the model to operational scenarios presently under consideration as part of the Integrated Plan.

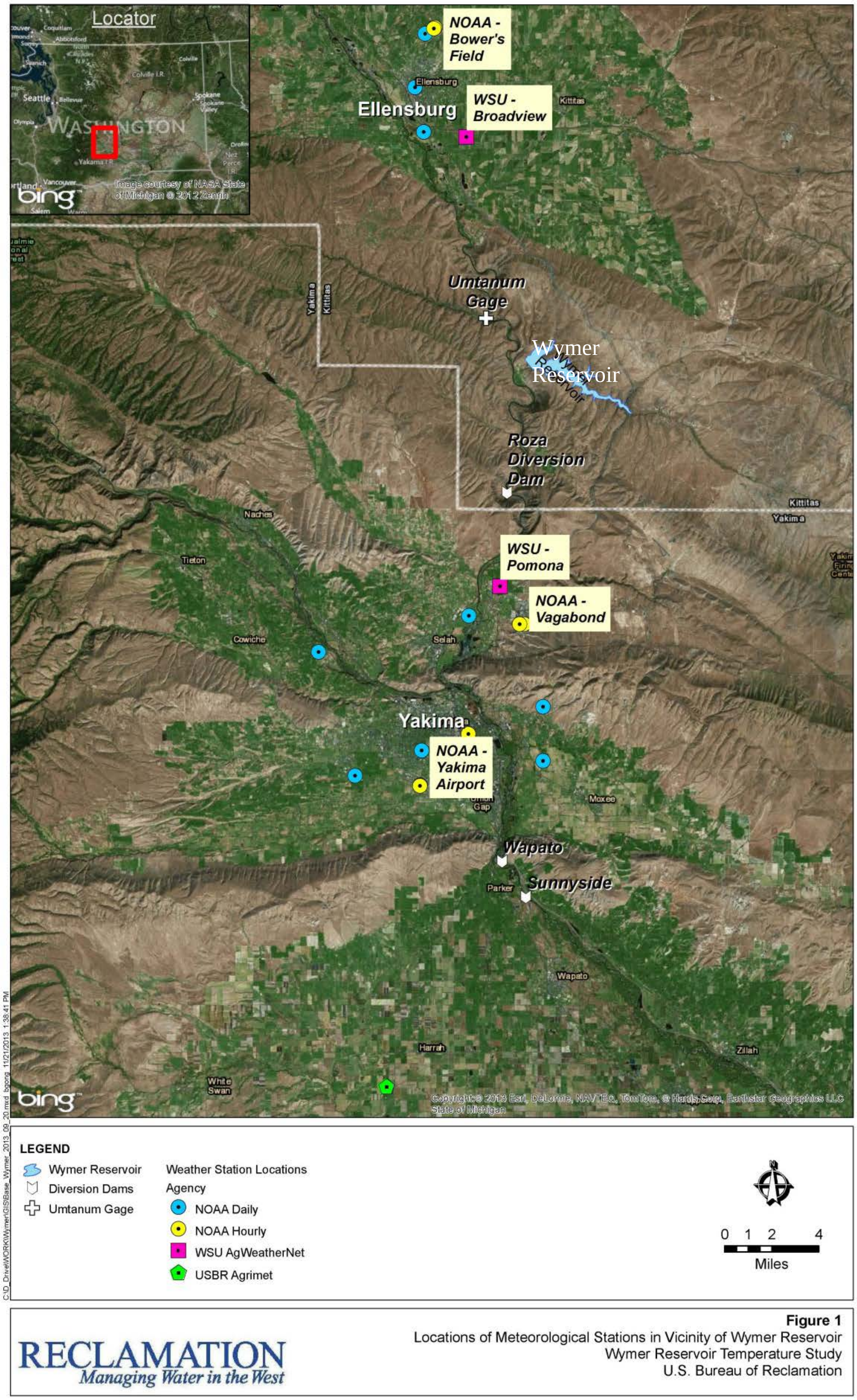

Figure 1. Location Map of Wymer Reservoir and Meteorological Stations

2.0 Model Development

The model domain was defined within the boundary line of the reservoir pool. The reservoir pool boundary specifies the area of inundation and is defined by the 1,730-foot-elevation contour (NGVD29 datum), consistent with the proposed normal water surface elevation provided in the Wymer Dam and Reservoir Appraisal Report (Reclamation 2007a). Figure 2 depicts the pool boundary line and model segmentation.

The model grid was defined by three geometric parameters, which ultimately define the storage volume of each water body: 1) segment length, 2) layer widths defined at regular vertical increments, and 3) layer thicknesses that specify the magnitude of the vertical increments. The area defined by the reservoir pool was divided into 28 longitudinal segments (on Figure 3, active model segments are shown in blue; gray segments are boundary segments required by CE-QUAL-W2 between branches and at the boundaries). The mainstem (Branch 1) and the north fork (Branch 2) were developed with 20 and 8 segments, respectively. The lengths of model segments were variable and ranged from approximately 925 to 2,500 feet. The segments were oriented longitudinally in the direction of surface water flow.

To develop cross sections for each segment, 3.28-foot (1-meter) resolution Light Detection and Ranging (LiDAR) data collected in 2009 by the U.S. Army Corps of Engineers were used. LiDAR coverage did not extend to a few segments toward the southeastern edge of Branch 1 (see Figure 2). For these segments, U.S. Geological Survey's National Elevation Dataset (USGS NED) at a resolution of 32.8 feet (10 meters) was used. ArcGIS® was used to establish elevation-volume relationships for each segment at 3.28-foot increments. Overall, 126 vertical segments were specified in the model adjacent to the dam (deepest segment in the model) under full storage. The cumulative volume represented at each elevation is shown on Figure 4. The model segment widths ranged from approximately 200 feet at the bottom to 1,700 feet, corresponding to the 1,730-foot contour.

Figure 4 also presents the elevation-to-storage relationship from the Appraisal Report (Figure 9 in Reclamation 2007a). A comparison of the two elevation-to-storage relationships shows they closely agree, which verifies the representation of storage in the model for this study.

2.1 Boundary Conditions

The CE-QUAL-W2 model requires several inputs for simulating hydrodynamics and water temperature, including specification of inflows and outflows or water surface elevations, or both, at model boundaries. Temperature simulation requires meteorological data, including wind speed, air temperature, cloud cover (or shortwave solar radiation), and dew point temperature. Surface heat fluxes are estimated from this information. In addition, the model requires specification of inflow temperatures.

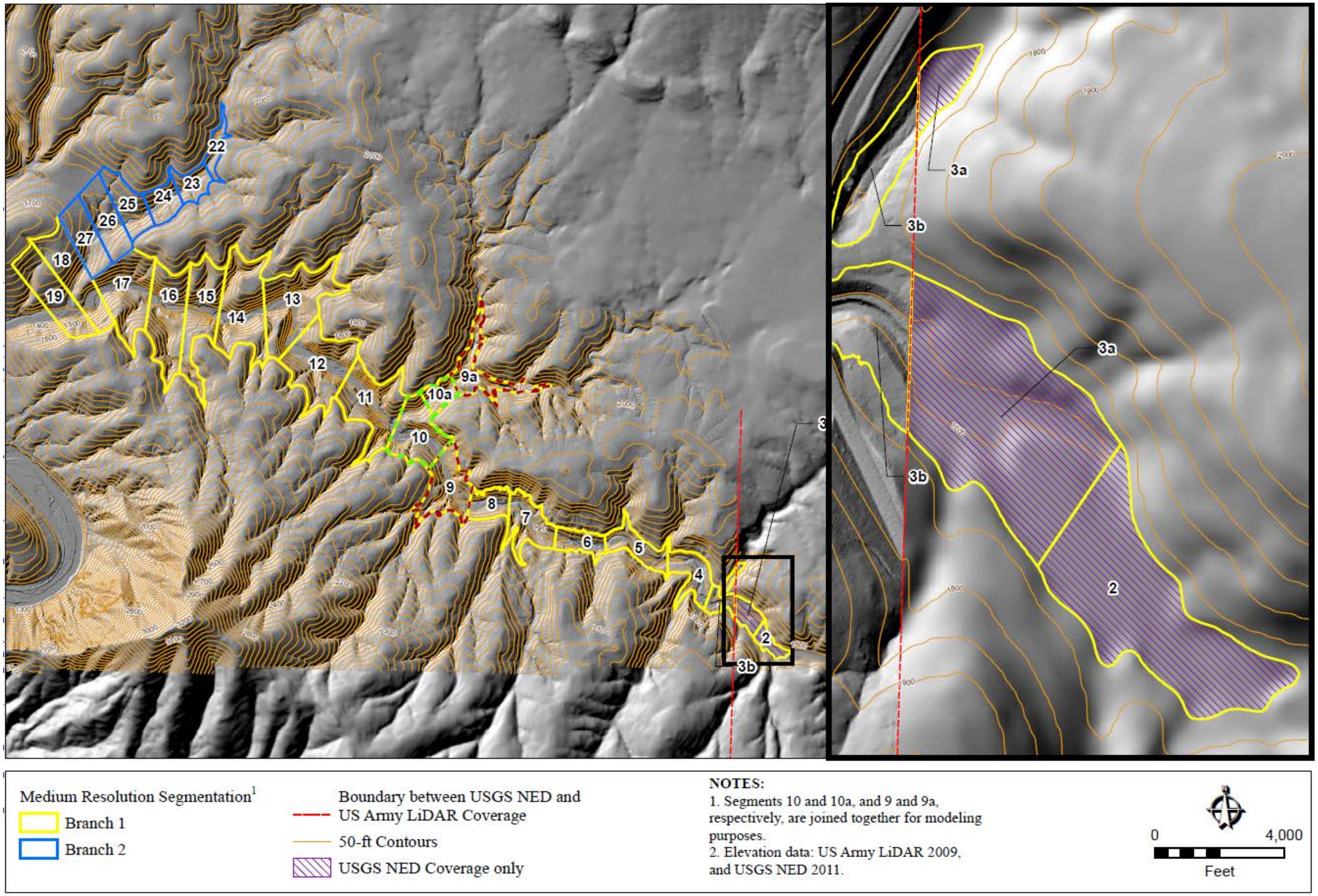

Figure 2. Wymer Reservoir Pool Boundary Line and Model Segmentation

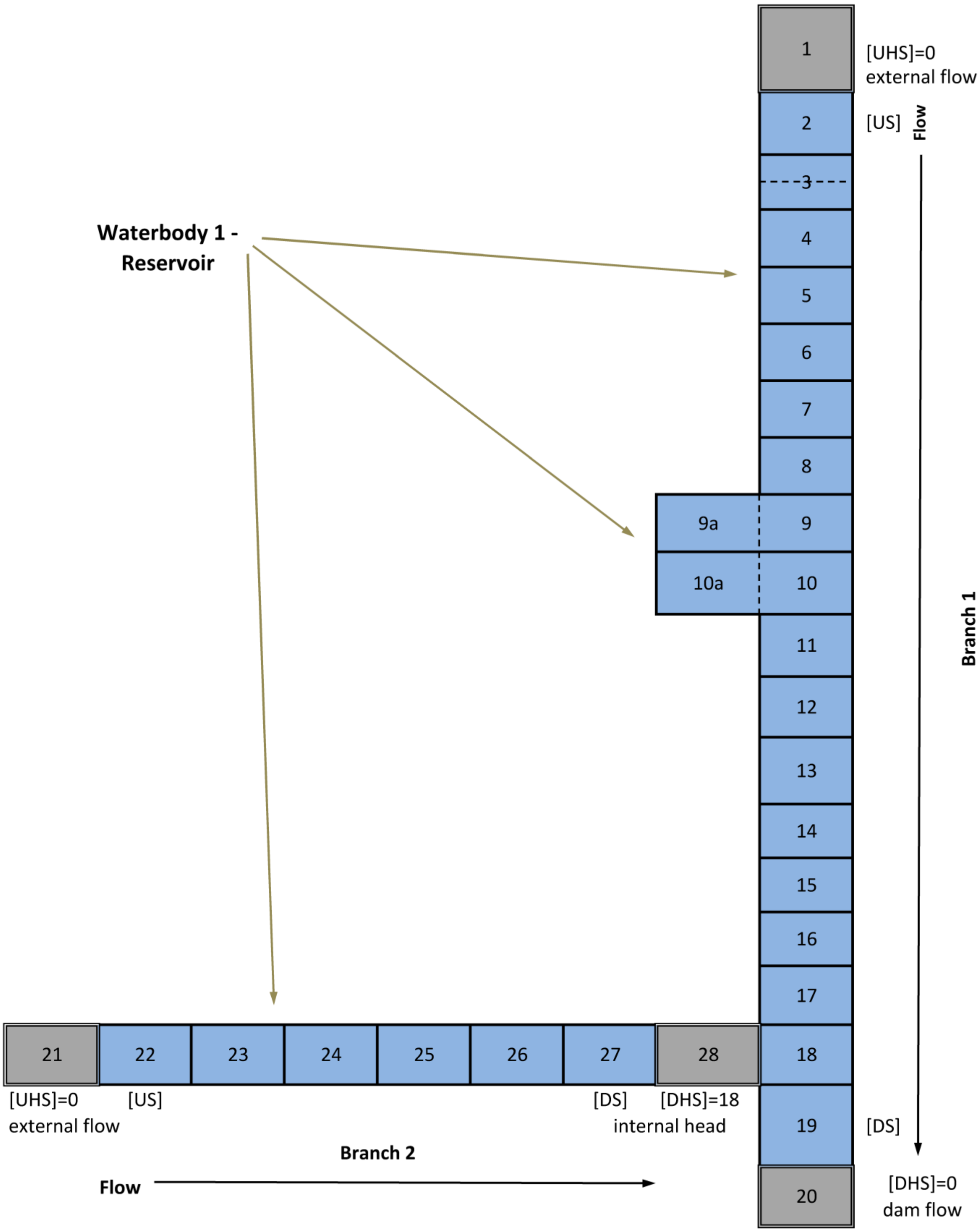

Figure 3. Segmentation Scheme Used in the CE-QUAL-W2 Model

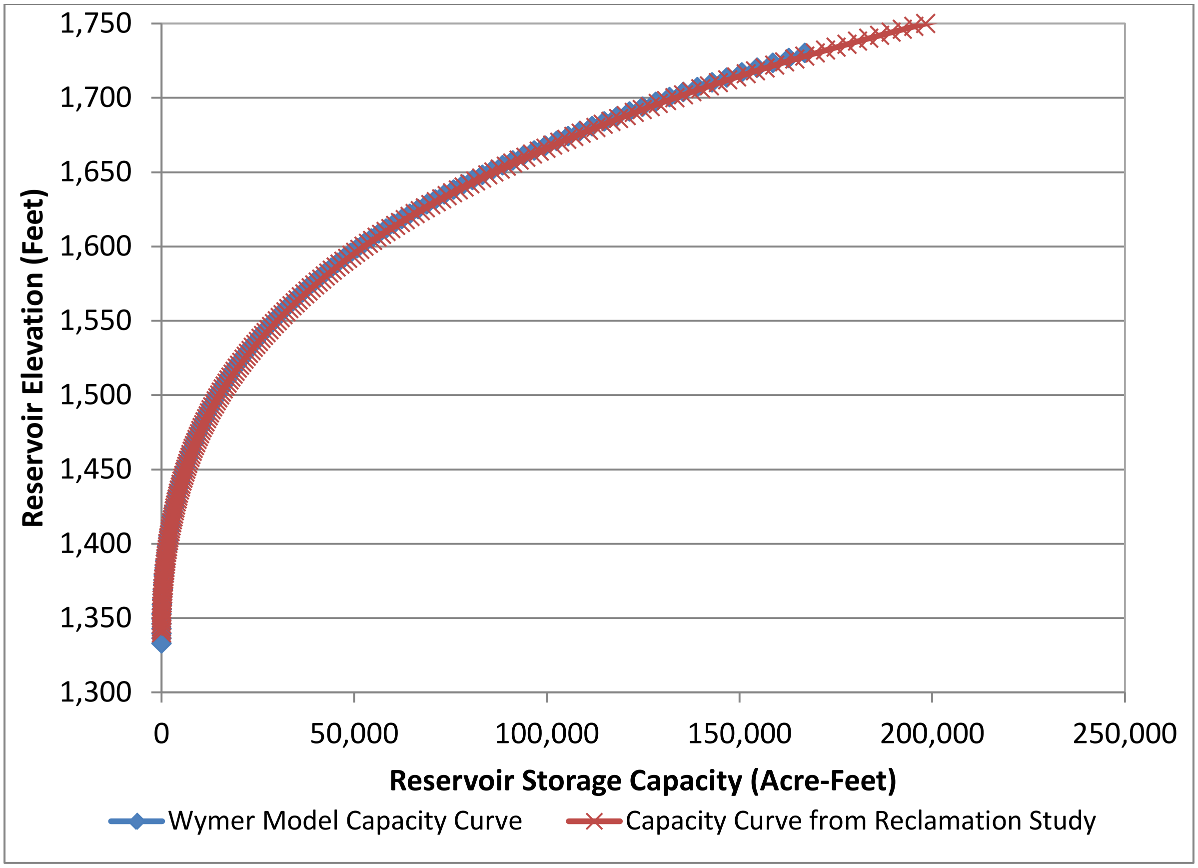

Figure 4. Elevation-Storage Relationship

Note: Capacity Curve from Figure 15 in Wymer Reservoir Appraisal Report (Reclamation 2007a).

2.1.1 Simulation Periods

Model simulation periods were selected to represent a range of conditions encountered in the Yakima River basin. Wet, dry, and average years established by Reclamation based on total water supply available for each year were reviewed for the period of 1977 through 2005 (Reclamation and Ecology, 2011a). The highest water supply available was in 1997, and the lowest was in 2001. Thus, these years were selected as the wet and dry years for the study to represent the range of conditions likely to occur in the Yakima River basin. In addition, 2002 was selected to represent an average year following a dry year.

2.1.2 Meteorological Inputs

Various sources of meteorological data were considered to provide the information needed for model development. Two National Oceanic and Atmospheric Administration (NOAA) stations south of the reservoir (at Yakima Airport and Vagabond) and one north at Bowers Field (Figure 1) provide hourly data for all meteorological parameters. Washington State University (WSU) AgweatherNet stations at Broadview (to the north) and Pomona (to the south) provide hourly data for all parameters except cloud cover. Reclamation has a station at Harrah, farther south of the cluster of NOAA and WSU stations, near Yakima. In addition, statistics on daily minimum, maximum, and average temperatures and precipitation are available at other NOAA stations in the area (Figure 1).

Figure 1 shows that NOAA stations and WSU stations to the south are closest to the site. Moreover, the stations to the north generally are at a higher elevation, are known to be in a high-wind area, and may not be fully representative of the conditions at the reservoir. The NOAA station at Vagabond, one of the three stations south of the reservoir with hourly data, did not have data for the study years.

The WSU station at Pomona and the NOAA station at the Yakima Airport provided the longest data set for the period of interest. The WSU station at Pomona is the closest to the reservoir and provided all inputs needed for the model, including incident solar radiation. Therefore, it was used for specifying the meteorological inputs in the model.

Figure 5 shows the entire suite of meteorological forcing functions specified for the wet and dry years.

2.1.3 Model Inflows and Outflows

Inflows and outflows for the CE-QUAL-W2 model were obtained from the output of the Yakima Basin RiverWare (Yak-RW) Model, which was used to evaluate Yakima River basin operating scenarios in the Integrated Plan. The Yak-RW model was applied to simulate Wymer Reservoir inflows from a pump station on the Yakima River near the reservoir and withdrawals developed for the Integrated Plan proposed in the Yakima River Basin Study (Reclamation and Ecology, 2011c). Minor adjustments (lower maximum outflow and revised inflows) were made to the Integrated Plan flows used in the Yak-RW model to account for recent changes being considered for the proposed operation. These changes were based on a change in the Wymer pump location (from Thorp to the Wymer Reservoir inlet/outlet location) and a change in the proposed maximum capacity of Wymer Reservoir outlet works.

Figure 6 shows the inflows and outflows from the Integrated Plan scenario used in the temperature model from November 1996 to May 1999 and from November 2000 to May 2003, which includes wet year (1997) and dry year (2001) followed by the average year (2002), respectively. Inflows from the Yakima River from the Yak-RW model were specified to enter the temperature model at Segment 19 at the surface, and the option for allowing the model to route the inflows to the appropriate elevation based on density was selected.

Inflows from natural flow in Lmuma Creek (the canyon where Wymer Reservoir is proposed) were not accounted for in this model. However Lmuma Creek is an intermittent stream with flows very small relative to the inflow from the pump station. Most all of that flow occurs in winter or early spring when temperatures are still low. No effect on the model results is expected if Lmuma Creek flows and temperatures were incorporated.

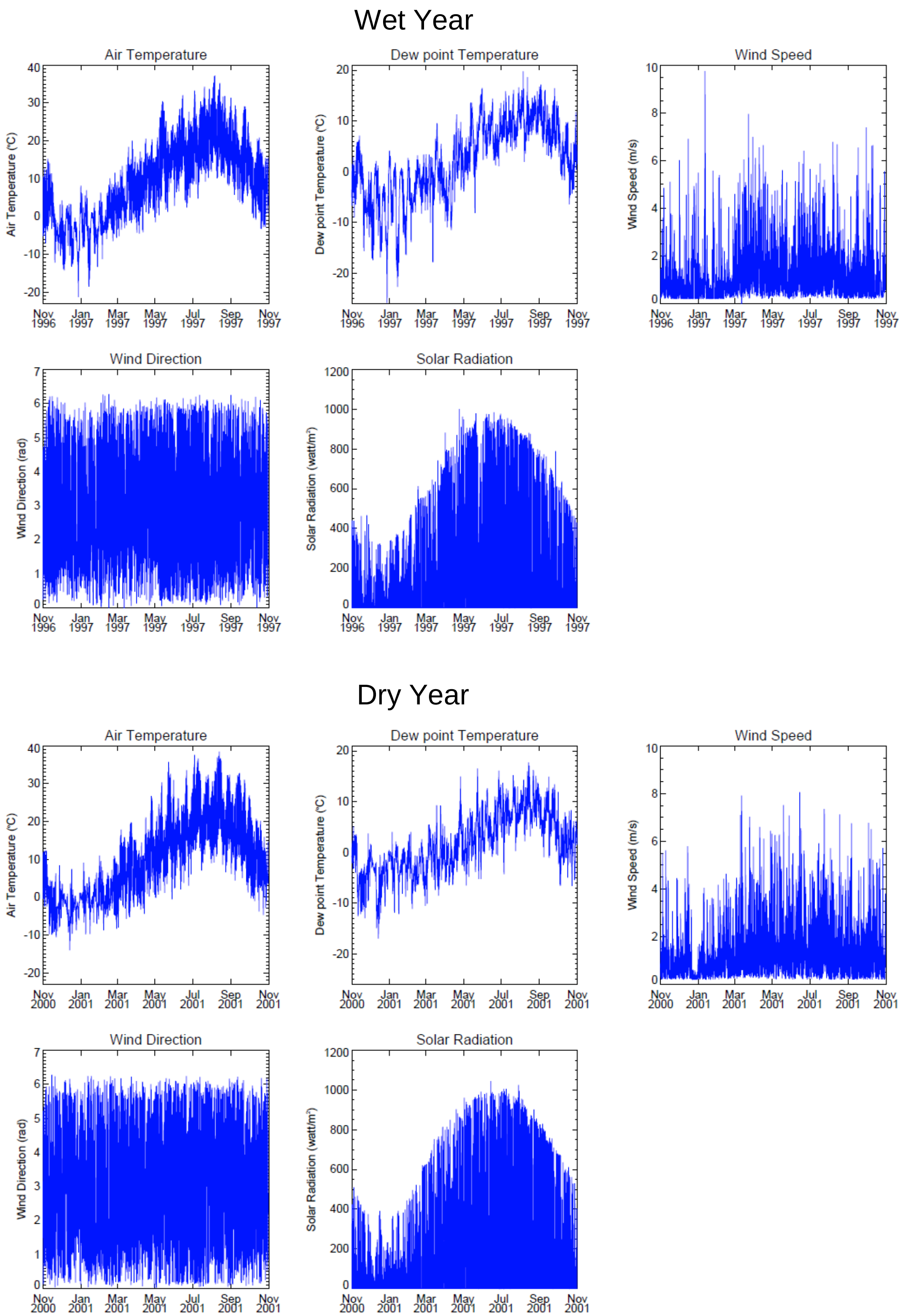

Figure 5. Meteorological Forcing Functions Used for Wet (1996-1997) and Dry (2000-2001) Years

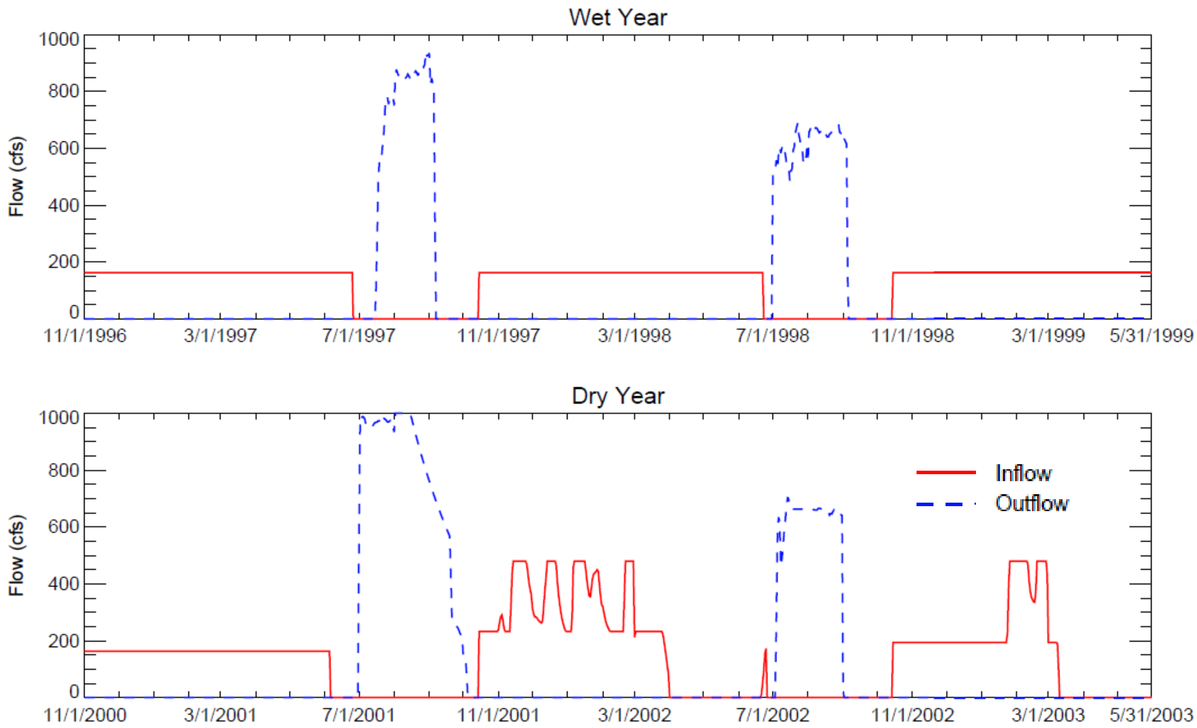

Figure 6. Inflows and Outflows Specified for the Integrated Plan Scenario

To specify inflow temperature, measured temperatures in the Yakima River at Umtanum (upstream of the reservoir) and at Roza Diversion Dam (downstream of the reservoir) were compared. Changes in Yakima River temperature between these two locations were not noteworthy, which suggests that there is little solar heating or cooling as the water travels through this reach. Thus, for purposes of this model, it was assumed that the temperatures recorded at Umtanum were representative of the inflow temperature to the reservoir.

2.2 Model Parameterization

Hydrodynamics and heat exchange are physically based processes, and are well simulated from first principles of energy, mass, and momentum conservation. Nonetheless, both processes require specification of some parameters within the CE-QUAL-W2 model. As the reservoir does not exist yet, it is not feasible to collect all the information needed to calibrate unknown model parameters, so default values recommended in the CE-QUAL-W2 model manual (Cole and Wells 2008) were used for hydrodynamic and heat simulations.

The most important parameters affecting hydrodynamics and temperature in the model are the Chezy coefficient for simulating bottom friction in hydrodynamics, light extinction coefficient and topographic shading that affect penetration of down-welling solar radiation, and wind-sheltering coefficient for momentum transfer at the air-water interface. The light extinction coefficient was set to the default value of 0.25 per meter as recommended in the manual. Topographic shading was determined from the ground surface elevation contours per methods provided in the manual (Cole and Wells 2008). Parameters that control wind forcing were selected based on the recommendations in the manual for small reservoirs. The wind-sheltering coefficient was set to 0.9 for all segments, based on suggestions in the manual and sensitivity analysis.

The uncertainty in the simulated temperature due to the unknown values of the true parameters was determined through sensitivity analysis. Among the parameters described above, the model was most sensitive to the light extinction coefficient. When the light extinction coefficient was set to the upper bound of the recommended range (0.45 per meter) in the CE-QUAL-W2 manual, simulated temperatures in the upper layers remained relatively similar to the baseline value (0.25 per meter). However, the extent of thermal stratification differed considerably (stratification was stronger at the upper bound of light extinction) and produced significantly cooler temperatures at the outflow, particularly later in the year, thereby having a greater cooling effect on the Yakima River temperature. If the project moves forward, subsequent phases of modeling should aim to establish this parameter more definitively. Temperature predictions were relatively insensitive to changes in other uncertain parameters over the ranges recommended in the manual.

Another unknown parameter is the temperature of the water in the reservoir at the start of the wet and dry year simulations. This is an important parameter because it specifies the initial heat energy contained in the reservoir. To determine the appropriate initial condition, model simulations were set up over a 3-year period, and repeated by re-initializing the temperature predicted at the end of each 3-year period several times. After two cycles, the model-predicted temperature stabilized at approximately 5 degrees Celsius (°C) (41 degrees Fahrenheit [°F]), which was specified as the initial temperature on November 1, the start of the simulation period for the wet and dry years.

2.3 Model Verification

Considering that the model cannot be calibrated to actual field measurements of temperature, model performance was verified by evaluating the predicted temperature patterns and comparing it to similar reservoirs. The average of the temperatures simulated in the top 5 meters and the bottom 5 meters of the model for the wet and dry years are shown in Figure 7. Upon comparing to air temperatures shown in Figure 5, it is evident that the model-predicted temperatures in the upper waters are consistent with the patterns in the air temperature. The bottom waters remain stable between 4 to 5 °C (39 to 41°F), which is the temperature at which water has the greatest density at atmospheric pressure.

The depth profiles at Segment 19 (adjacent to dam and at deepest part of reservoir) simulated at mid-month are shown grouped by season for the wet and dry year simulations on Figure 8. The temperature depth profiles simulated by the model show a typical pattern of onset and breakup of stratification in temperate lakes and reservoirs: onset of stratification over late spring and early summer; stable thermal stratification from mid-summer through early fall; a progressively-declining thermocline with cooling air temperature in mid-fall; and complete turnover in late fall through early winter. Moreover, the winter depth profiles show that the cooler air temperatures would cause a reverse stratification over winter, which breaks up in spring, suggesting that the reservoir, if constructed as designed, will likely stratify twice between two successive fall seasons (i.e. it will be dimictic).

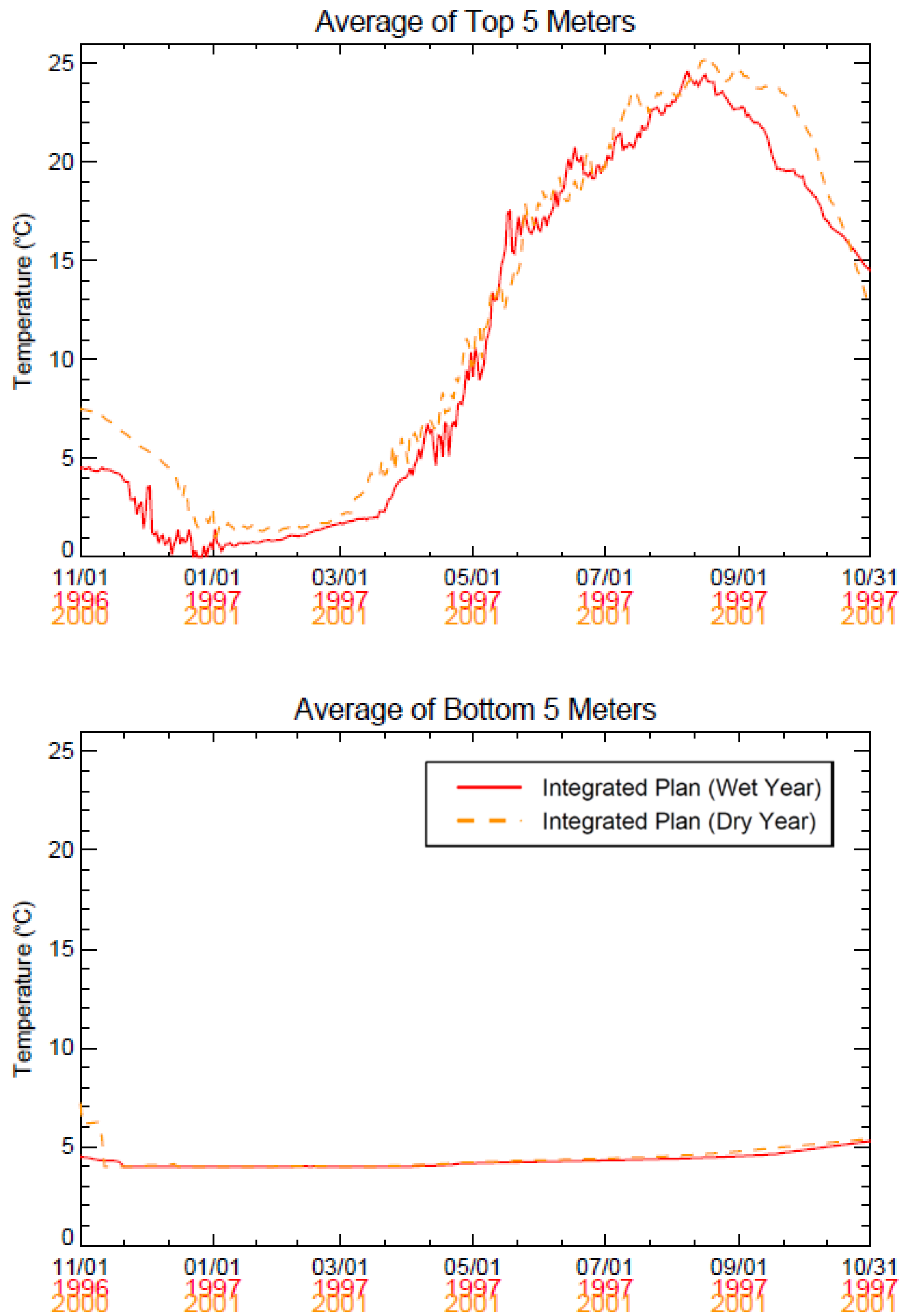

Figure 7. Time Course of Simulated Reservoir Water Temperature at Segment 19

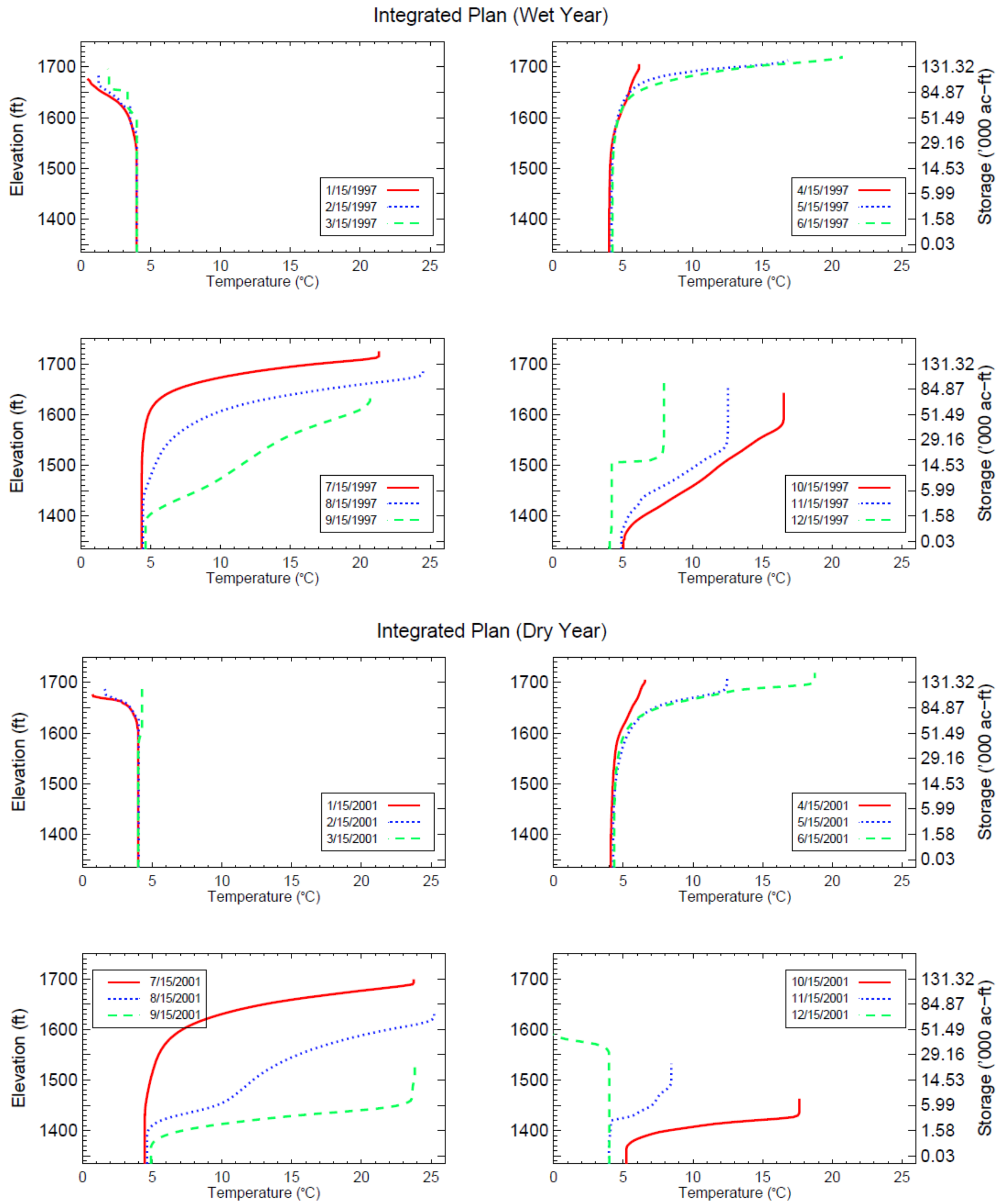

Figure 8. Depth Profiles of Simulated Water Temperature at Segment 19

Since Wymer Reservoir is not constructed and the temperature model cannot be calibrated, a literature search for water temperatures in reservoirs with similar characteristics was performed. The depth profiles of temperature measured at Shasta Lake (USGS 1983), a 500-foot-deep reservoir with a similar bottom withdrawal (at a time when temperature controls that currently are in place were not present) are shown on Figure 9. Measured and CE-QUAL-W2-simulated temperature depth profiles at the 350-foot-deep Blue Mesa Reservoir in Colorado (Boyer and Cutler 2004) are shown on Figure 10. Comparisons were also made to Cle Elum Reservoir, which is located approximately 45 miles north-northwest of the proposed Wymer Reservoir. Despite its proximity, the Cle Elum Reservoir is located in an area subject to much higher winds, and has a different configuration. Withdrawals occur from the south end of the reservoir which is not the deepest part of the reservoir. The deepest part of the reservoir is located about 1.2 miles north of the outlet, where a natural lake was located. Wymer Reservoir would have a different configuration with releases from the deepest (and coldest) area of the reservoir. Nonetheless, comparison to this reservoir was also included to provide a regional reference.

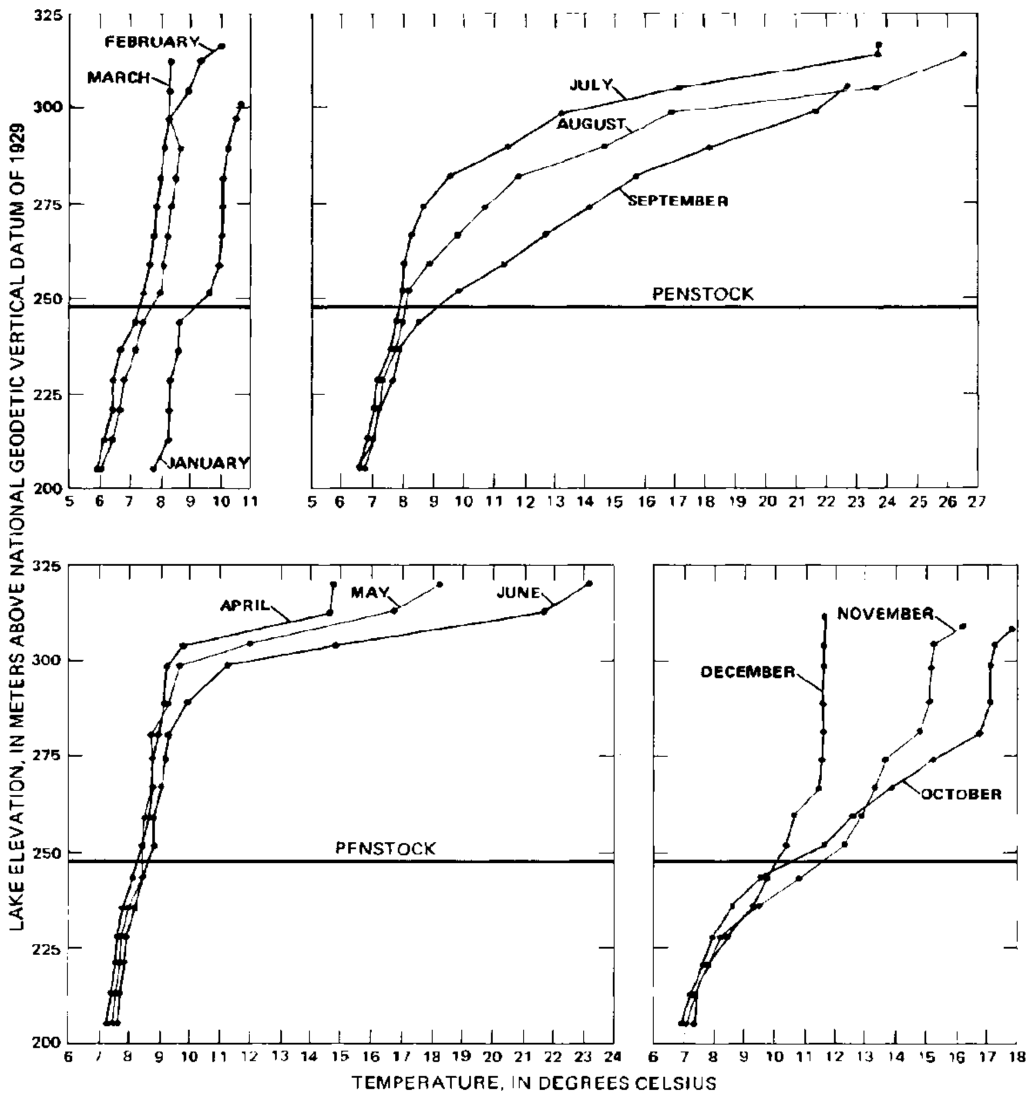

Figure 9. Temperature Profiles Recorded at Shasta Lake in 1962

Note: Adapted from USGS (1983)

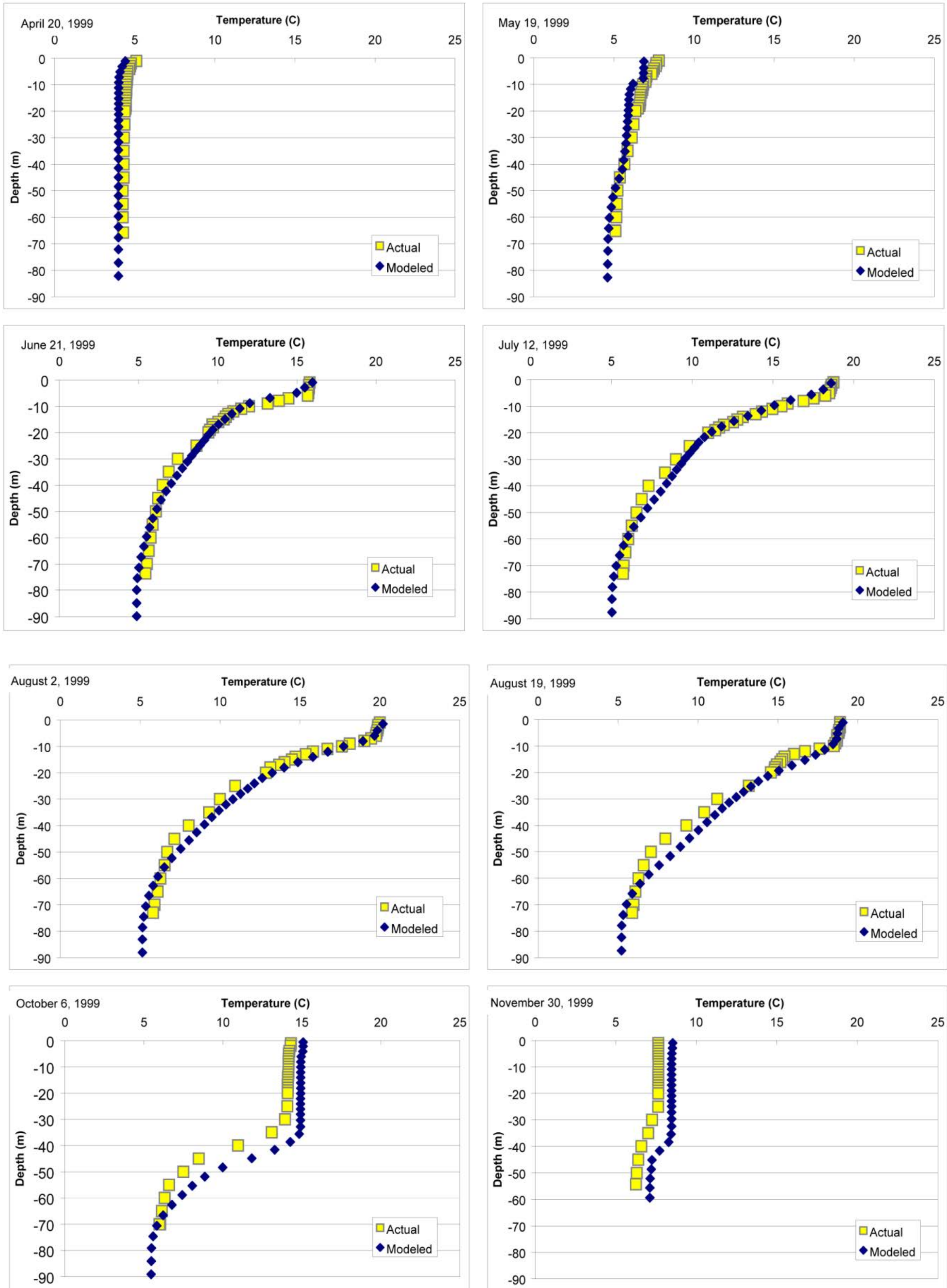

Figure 10. Measured and Simulated Temperature Profiles at the Blue Mesa Reservoir

Note: Adapted from Boyer and Cutler (2004)

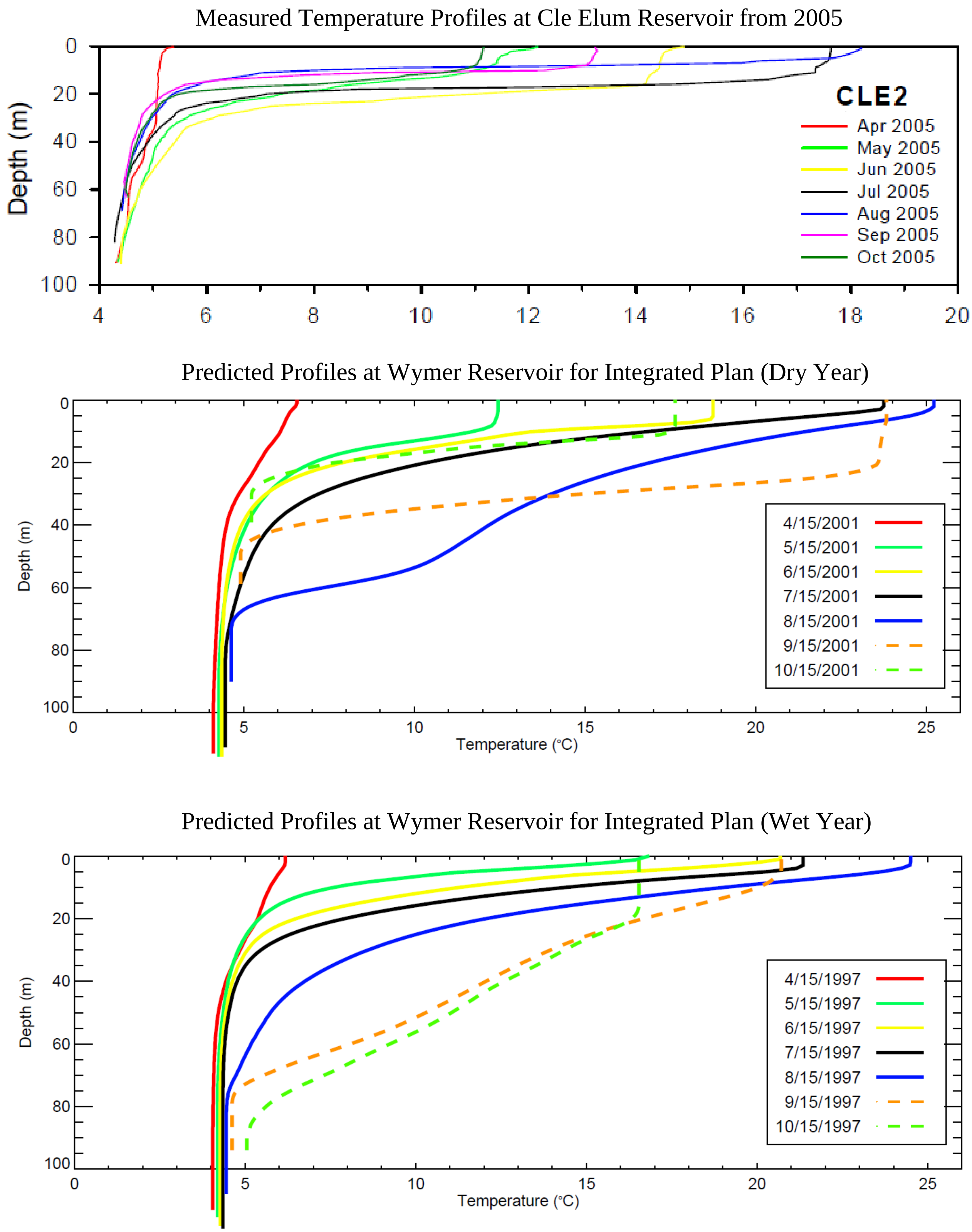

Figure 11. Measured Temperature Profiles at Cle Elum Reservoir in 2005 Shown Compared to Simulated Profiles at Wymer Reservoir for Dry and Wet Years

Note: Cle Elum Lake Temperature Profiles Adapted from Reclamation (2007b)

The simulated patterns for Wymer Reservoir shown in Figure 8 are comparable both in extent (vertically and over time) and in magnitude to Shasta Lake and Blue Mesa Reservoir that are shown in Figures 9 and 10. In comparison to Cle Elum Reservoir, shown in Figure 11, the temperature profiles in Wymer Reservoir are comparable prior to releases which start in August for Wymer Reservoir. The onset of stratification, and the extent and depth of stratification are all comparable to Cle Elum Reservoir. However, following the release period, the simulated profiles for both the dry and wet years are different, reflecting the differences in the withdrawal locations between Cle Elum Reservoir and Wymer Reservoir (as indicated earlier).

The results above show that while an actual calibration cannot be performed for the Wymer Reservoir model, its performance is consistent with expectations for temperate lakes and reservoirs and is comparable to observations and model simulations at similar reservoirs.

3.0 Model Application

The temperature model was used to simulate several scenarios to determine how various Wymer Reservoir operating schemes would affect temperature. Table 1 describes the modeling scenarios simulated. The scenarios include different timing of releases from Wymer Reservoir and also different configurations of release. The Integrated Plan scenario releases water in accordance with the operations of Wymer Reservoir as described in the Integrated Plan (Reclamation 2011a, 2011c) and as shown in Figure 6. The early release scenario aimed to release water earlier in the year to reduce the reservoir pool subject to warming over summer during a dry year. Two flip-flop reduction scenarios were designed to evaluate the effect of a later release on Yakima River temperature. Flip-flop is the procedure of reducing flows from upper Yakima Basin reservoirs (Keechelus and Kachess) to reduce instream flow in the upper Yakima River to a level suitable for spawning Chinook salmon. That reduced flow is offset by increased flow discharged from Rimrock Lake into the Tieton River. Yakima Basin fish biologists generally agree that the increased flow in the Tieton River is harmful to fish. The inflows and outflows used for the early release and flip-flop scenarios are shown on Figure 12.

Three configurations were tested: a single low-level outlet at the base of the dam; a multi-level outlet with three outlets; and a multi-level outlet with two outlets. These scenarios were selected based on discussion with Reclamation and its partners.

Table 1. Scenarios Simulated by Temperature Model

Scenario	Description	Type of Year Simulated
Integrated Plan	Integrated Plan with updated inflows/outflows, single low-level outlet	Wet and Dry
Early Release	Release water 2 weeks earlier than Updated Integrated Plan scenario during dry year, single low-level outlet	Dry only
Multi-Level Release 3	Release water with three outlets located at 1,600 feet, 1,500 feet and 1,456 feet. Release started at the topmost level, and was switched to the next lower level as water surface elevations dropped to 10 feet above the top of each outlet	Dry Only
Multi-Level Release 2	Release water with two outlets located at 1,630 feet and 1,456 feet. Release started at the topmost level, and was switched to the lower level at mid-August	Wet and Dry
Reduce Flip-Flop – 80 KAF	Release water during September to reduce the amount of water released from Rimrock Lake into Tieton River (~80 KAF)	Wet only
Reduce Flip-Flop – 110 KAF	Same as Reduce Flip-Flop – 80 KAF except additional water released (~110 KAF)	Wet only
KAF = 1,000 acre-feet		

For all scenarios other than the multi-level releases, withdrawals were simulated to occur from the bottom portion of the reservoir at an elevation of 1,456 feet. For Multi-Level Release 3, withdrawal was specified to occur at one of three elevations (1,600 feet, 1,500 feet, and 1,456 feet). Starting with a full reservoir, withdrawal was simulated from the topmost outlet until water surface elevation dropped to 10 feet above the top of the outlet, at which time it was moved to the next lower outlet. For Multi-Level Release 2, withdrawal was specified to occur at 1,630 feet through mid-August and switched to 1,456 feet from thereon.

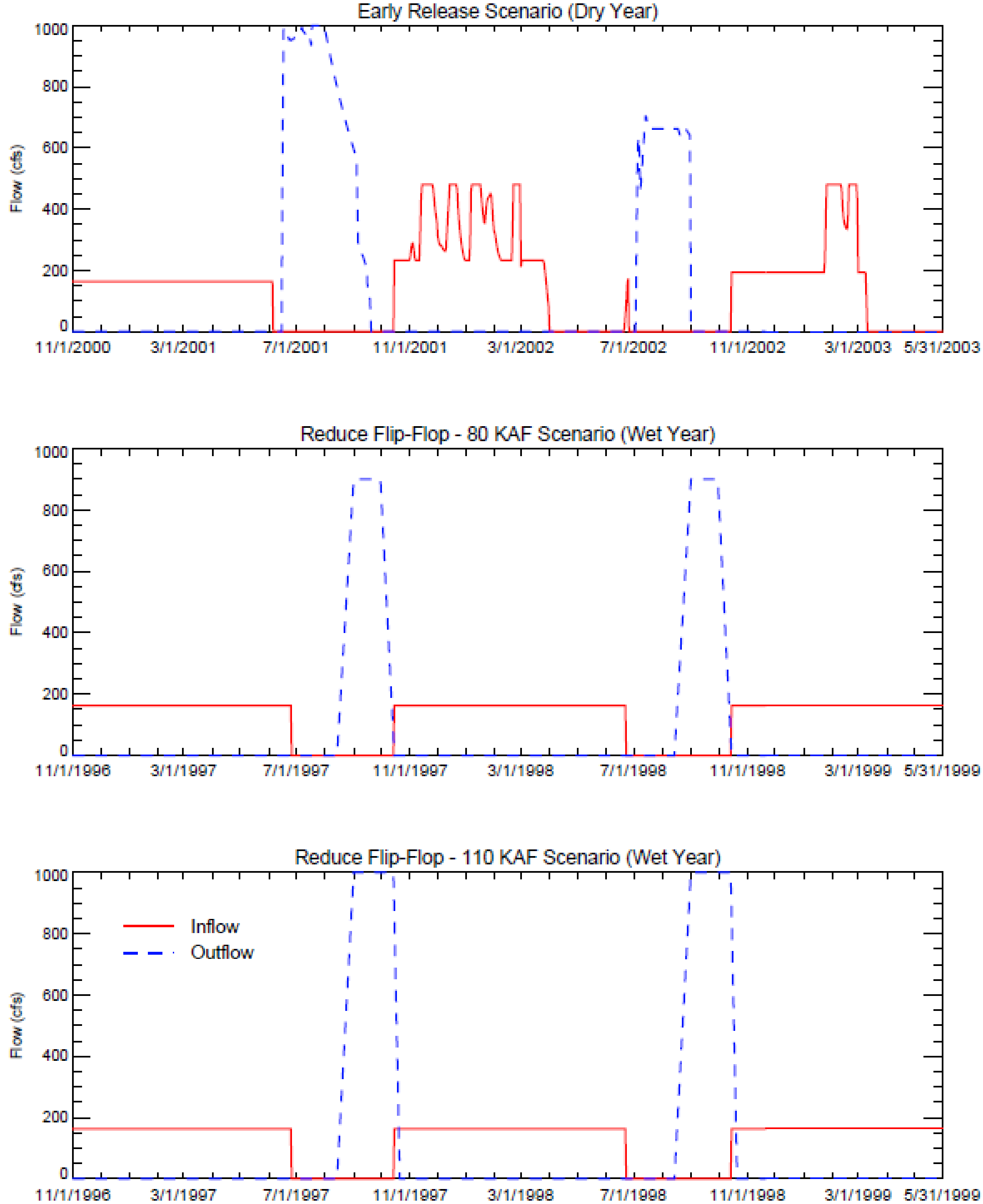

Figure 12. Inflows and Outflows Used in Wymer Temperature Model for Simulating the Operational Scenarios

3.1 Yakima River Temperature Downstream of the Reservoir

The temperature of the Yakima River downstream of the mixing zone from the reservoir outflow was determined through an energy budget calculation. For the purposes of this calculation, it was assumed that the Yakima River is sufficiently turbulent to mix with the reservoir outflow completely within a short distance, so that stratified flows or solar heating are not significant factors in affecting the river's temperature in the mixing zone. Furthermore, it was assumed that the temperature of the Yakima River at the Umtanum Gage, which is located approximately 5 river miles upstream of the reservoir, was representative of the conditions in the river immediately before mixing with the reservoir outflow.

Temperature changes in the Yakima River downstream of the reservoir are dependent on the ambient conditions in the river as well the temperature and flow rate of the reservoir outflow. For scenarios with a single outlet at the bottom, the temperature of the reservoir outflows will be cooler through summer because of the effects of thermal stratification (as described in Section 2.3). However as water is withdrawn from the reservoir through the summer, a smaller pool of water is subject to warming and can heat up quickly if the reservoir levels are drawn down. Furthermore, the heat stored in the smaller pool of water is not lost until later in the year, following the onset of cooler meteorological conditions over an extended period in fall and winter. On the other hand, the Yakima River undergoes heating and cooling that are more closely linked to changes in meteorological conditions because of the smaller and shallower body of water that is subject to heating and cooling. Thus, the reservoir temperature in fall could exceed the ambient Yakima River temperature. As a result, when the Yakima River receives the reservoir outflow that is warmer than the ambient conditions in the river in late summer and fall, it can result in warmer temperature downstream of the mixing zone.

Water Quality Standards promulgated by the State of Washington (Chapter 173-201A WAC; Ecology 2011) designate the reach of the Yakima River that Wymer Reservoir would discharge into as having the aquatic life use of Salmonid Spawning, Rearing and Migration. For this use, the water quality regulations require that the 7-day average of the daily maximum (7-DADmax) temperature not exceed 17.5 °C (63.5 °F) from September 16 through June 14. For this project, two possible cases apply under applicable standards:

1. When the background 7-DADmax temperature exceeds the applicable criterion (i.e. goes above 17.5 °C (64 °F) from September 16 through June 14) due to natural conditions, then cumulative human actions cannot produce a measurable change above the natural condition. The regulations define measurable change as temperature changes above 0.3 °C (0.5 °F).
2. When the background 7-DADmax temperature does not exceed the applicable criterion, the increase in 7-DADmax temperature at the edge of the mixing zone from a point source such as Wymer Reservoir outflow should not exceed 28/(T+7) where T is the background temperature prior to the introduction of the point source.

3.2 Wet Year Scenarios

Figure 13 through Figure 16 show the predicted 7-DADmax temperature for the wet year scenarios in the Yakima River downstream of the mixing zone based on the calculations described above. The background Yakima River temperature without reservoir release is expected[1] to be compliant with the applicable aquatic life use criterion described previously, for the time period between September 16 and June 14 that the temperature criterion applies[2]. For the Integrated Plan scenario, the model predicts a decrease in 7-DADmax temperature of about 2 to 3 °C (4 to 5 °F) from mid-July to mid-September, but more importantly no increases are predicted during the critical period of mid-September through mid-June (Figure 13). The reduction in Yakima River temperature downstream of the reservoir in the summer is primarily a result of releasing cooler water from the reservoir. A similar range of cooling is also predicted for the flip-flop reduction scenarios, but it extends from mid-August through mid-October (Figures 14 and 15). The shift in cooling follows the delayed release from Wymer Reservoir.

A small increase (less than 1 °C [1.8 °F]) in 7-DADmax temperature is predicted for the 110 KAF flip-flop reduction scenario (Figure 15) in October. As the river temperatures are expected[1] to be cooler at this time of the year, this increase is not predicted to cause any exceedances over the applicable temperature criterion.

The Multi-Level Release 2 scenario does not provide any benefits beyond what is already simulated for the Integrated Plan scenario with a single low-level outlet (Figure 16). The difference in the predicted temperature changes primarily reflect the temperature of the water at the upper level from which water is simulated to be withdrawn through mid-August (compare Figure 13 and Figure 16; also, see depth profiles from August 15 through October 15 in Figure A-2b in Appendix A).

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[1] Temperatures shown are "expected" values rather than measured values because the calculations use the flow output of the Yak-RW model rather than the true flows in the river for the corresponding years. The recorded temperature in the Yakima River was used for the corresponding time period and the assumption made is the temperatures would be the same under Integrated Plan scenarios. The Yak-RW flows were determined based on water releases and other operational parameters that are assumed in the Integrated Plan.

[2] On the graphs the horizontal line showing the regulatory limit of salmon spawning/rearing temperature is shown only in the months in which the limit applies.

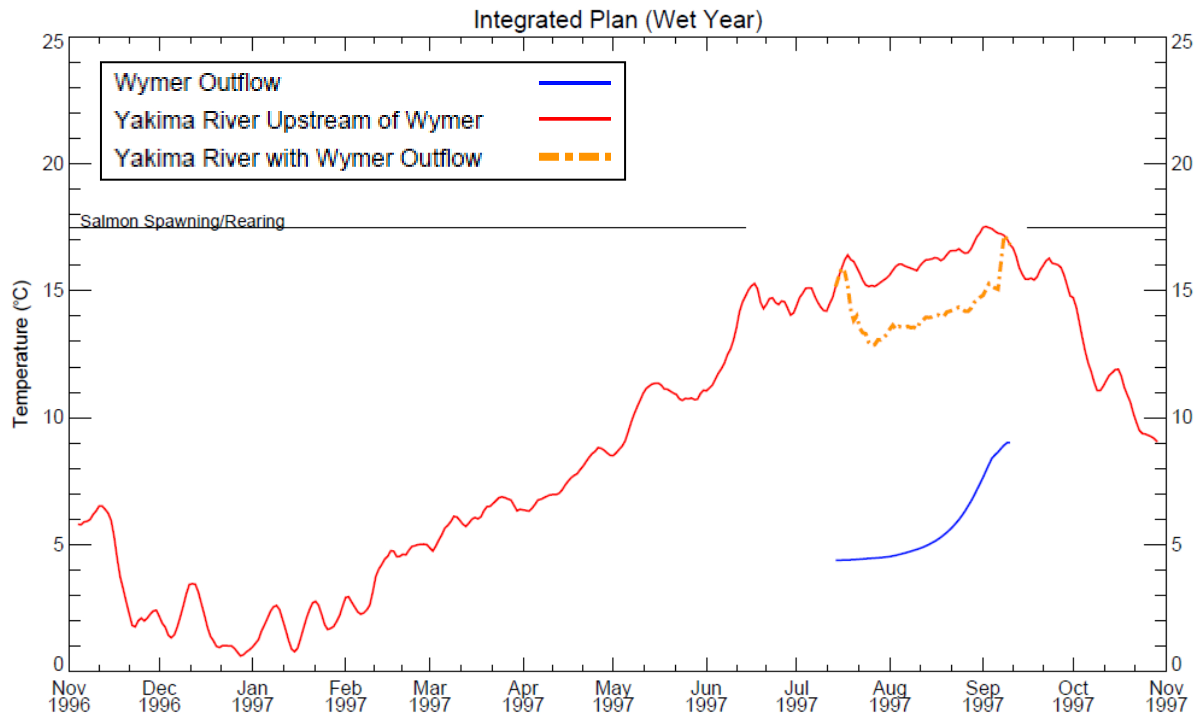

Figure 13. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Integrated Plan Scenario, Wet Year, Single Low-Level Outlet

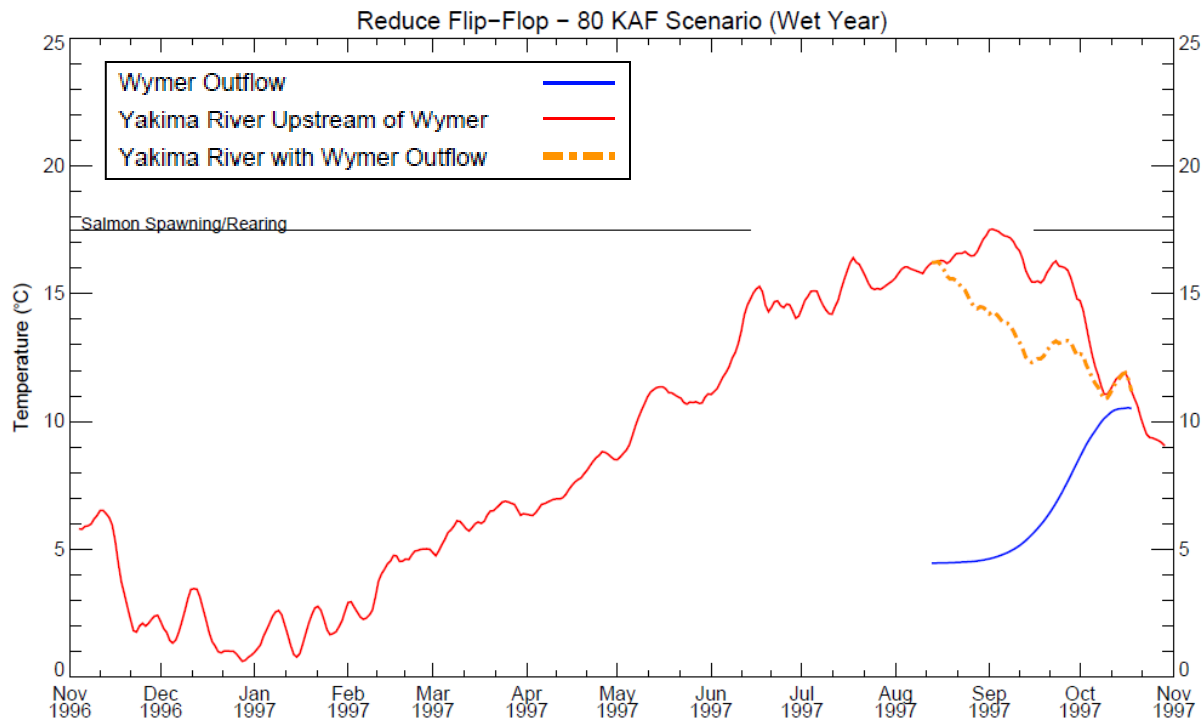

Figure 14. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Flip-Flop Reduction – 80KAF Scenario, Wet Year, Single Low-Level Outlet

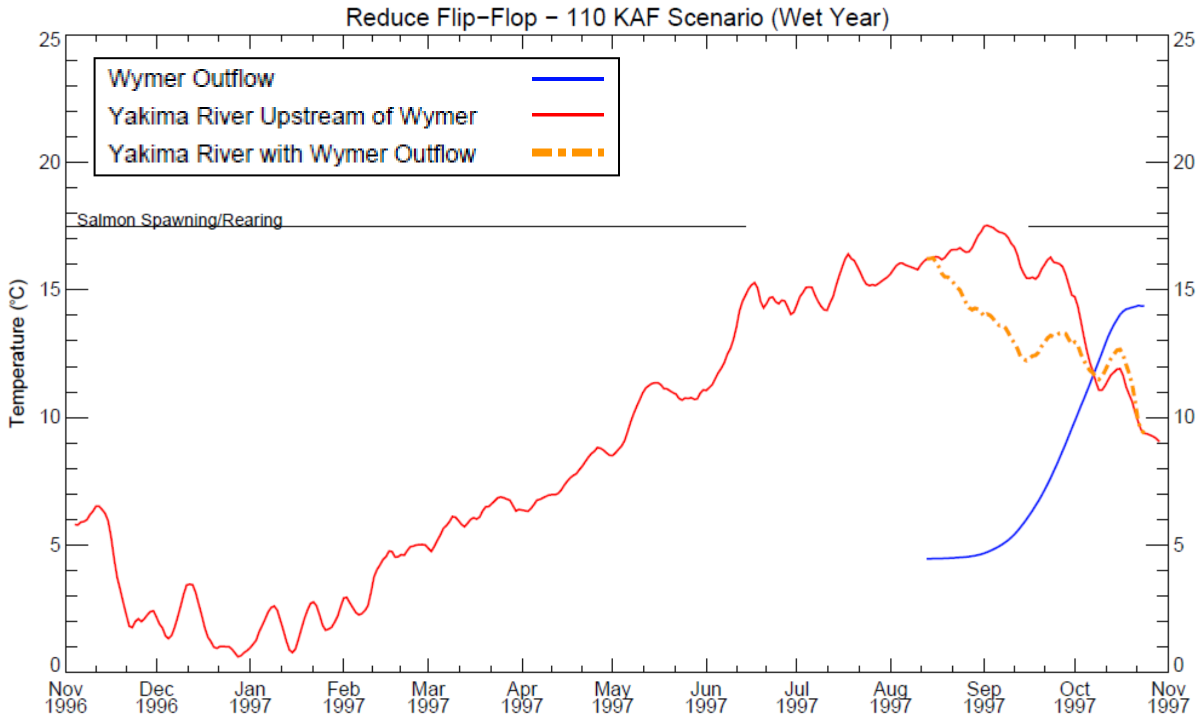

Figure 15. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Flip-Flop Reduction – 110KAF Scenario, Wet Year, Single Low-Level Outlet

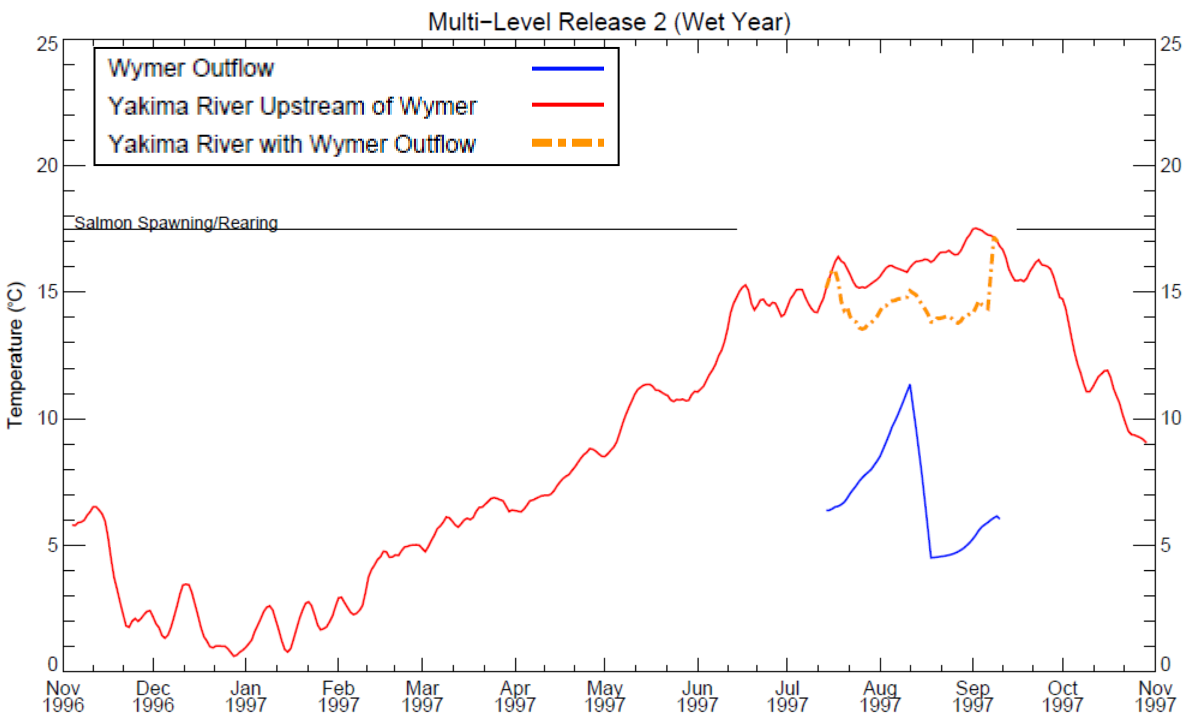

Figure 16. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Multi-Level Release 2 Scenario, Wet Year

3.3 Dry Year Scenarios

During dry years, flows in the Yakima River are lower and warmer compared to other years and releases from the reservoir are much greater to supply drought year water supplies. Under background conditions without Wymer Reservoir discharge, the 7-DADmax in the Yakima River is expected[3] to exceed the applicable standard from mid-September through early October.

The Integrated Plan scenario, in which a single low-level outlet is simulated, is predicted to cause river temperatures to decrease through August (Figure 17). Modest increases in temperature (less than 1 °C [1.8 °F]) are predicted to occur in September through mid-October when the water temperature in the reservoir is predicted to increase due to a falling water column that can warm up more rapidly through summer (see Figure A3-b in Appendix A). Moreover, flows in the Yakima River are low during this time of the year. An earlier release is predicted to contribute to temperature reductions earlier in the summer, but does not improve it in fall (Figure 18). Both multi-level release scenarios (Figure 19 and Figure 20) do contribute to improvement in temperatures from July through September, but the Multi-Level Release 3 is predicted to provide the greatest benefit. The Multi-Level Release 2 scenario is predicted to increase background temperatures slightly (less than 1 °C [1.8 °F]) during part of the critical time period (in late September and early October). No increases are predicted relative to the background conditions for Multi-Level Release 3 during the critical time period of mid-September to mid-June.

The temperature changes predicted for the dry year simulations relative to ambient temperatures in the Yakima River are summarized in Table 2. The findings are that with the exception of the Multi-Level Release 3 scenario all other scenarios cause modest increases in the number of days during which 7-DADmax temperature does not meet the applicable criterion during the critical time period (i.e. mid-September through mid-June).

The temperature increases described earlier relative to background conditions (in mid-September and October) were compared to the applicable thresholds stipulated in Washington State's water quality regulations (see Section 3.1). Among the three scenarios that cause an exceedance over the applicable criterion, the changes predicted for the Integrated Plan Scenario with a single low-level outlet have the greatest duration (of 10 days) over the critical period followed by the Early Release Scenario with a single low-level outlet (5 days). The Multi-Level Release 2 scenario is predicted to have exceedances over 3 days while the Multi-Level Release 3 scenario is predicted to meet water quality regulations for temperature increases during dry years.

As discussed in Section 3.1 releases occurring over fall invariably include reservoir water that is significantly warmer than the background conditions in the Yakima River upstream of the reservoir. In this temperature modeling study only a preliminary optimization was performed of the outlet levels and release rates for the multi-level outlet scenarios. It was found that a three-level outlet would be adequate to ensure the temperature of Wymer Reservoir releases would not exceed water quality criteria. Additional analyses and optimization are recommended to assist in the design of a multi-level outlet for the reservoir and determine how many outlets are needed, at

[3] See prior footnote 1 on "expected" values.

what reservoir elevation they should be constructed and how the outlets should be managed to minimize or even improve temperature effects on the Yakima River.

Table 2. Summary of Temperature Impacts on the Yakima River Predicted in the Dry Year Scenarios

Scenario	Year Type	Number of Days from September 16 to June 14 when Temperature does not meet Criterion		Number of days when Yakima River Temperature Increase is > 0.3 °C (0.5 °F) from September 16 to June 14
		Without Wymer Release	With Wymer Release	
Integrated Plan, single low-level outlet	Dry	10	16	10
Early Release Scenario, single low-level outlet	Dry	8	8	5
Multi-Level Release 3	Dry	10	3	0
Multi-Level Release 2	Dry	10	16	5

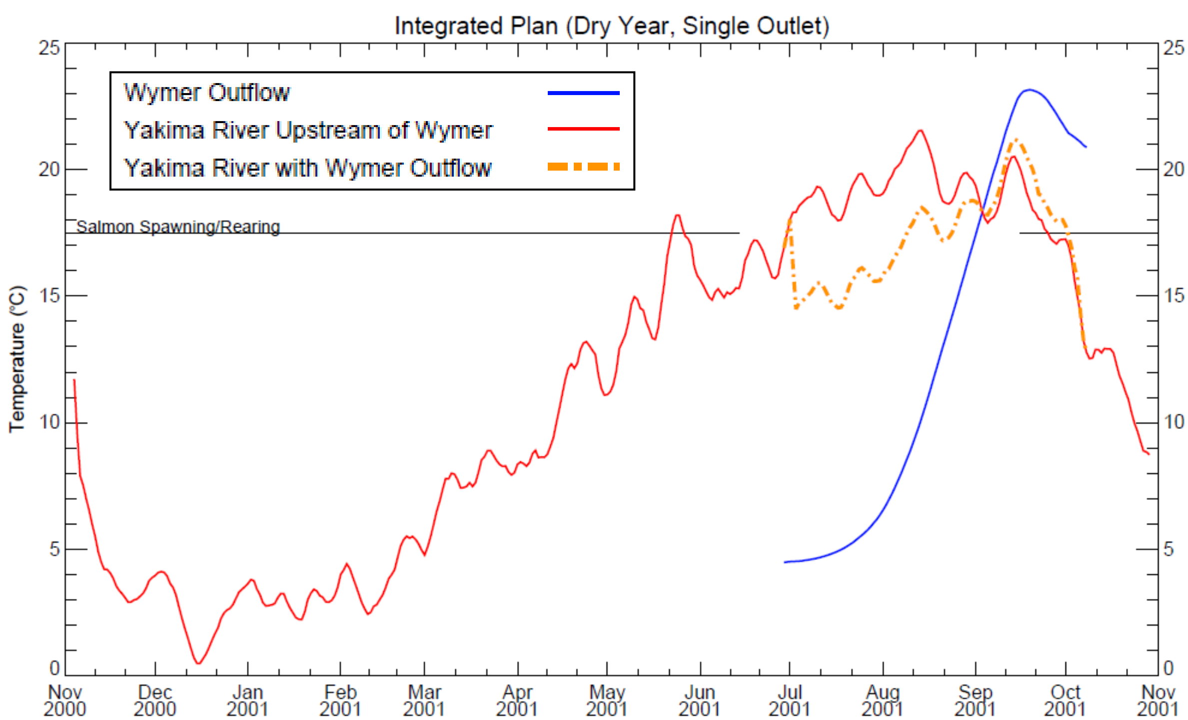

Figure 17. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Integrated Plan Scenario, Dry Year, Single Low-Level Outlet

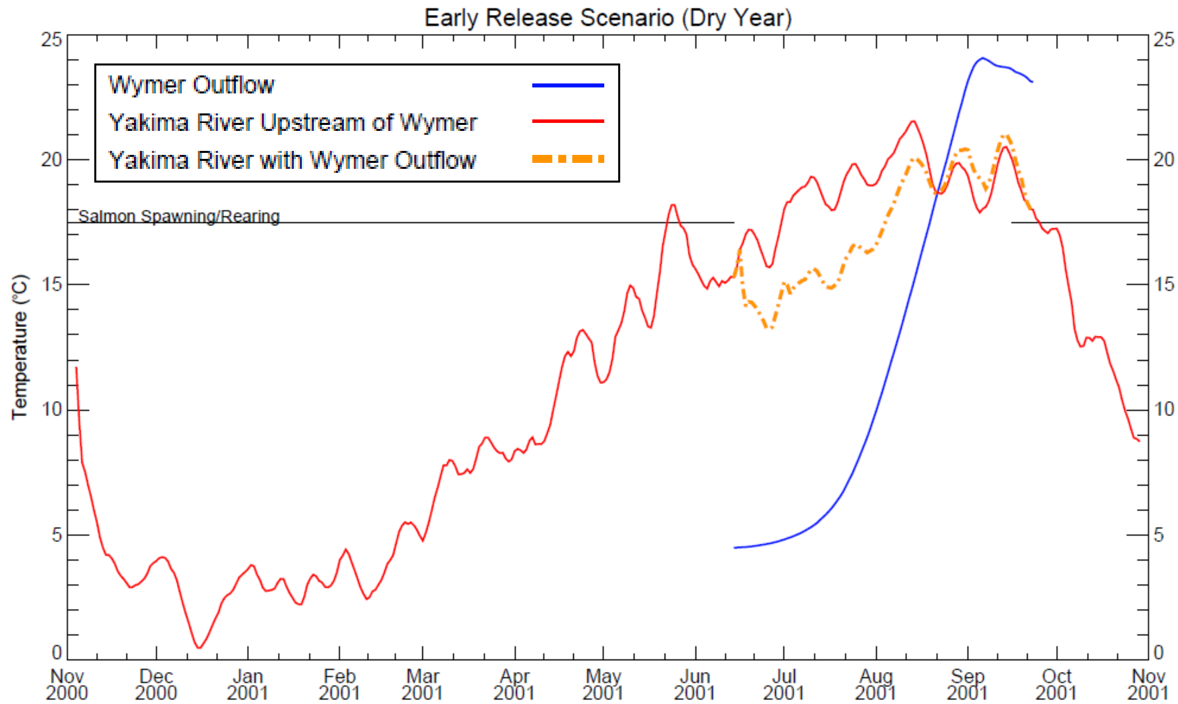

Figure 18. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Early Release Scenario, Dry Year, Single Low-Level Outlet

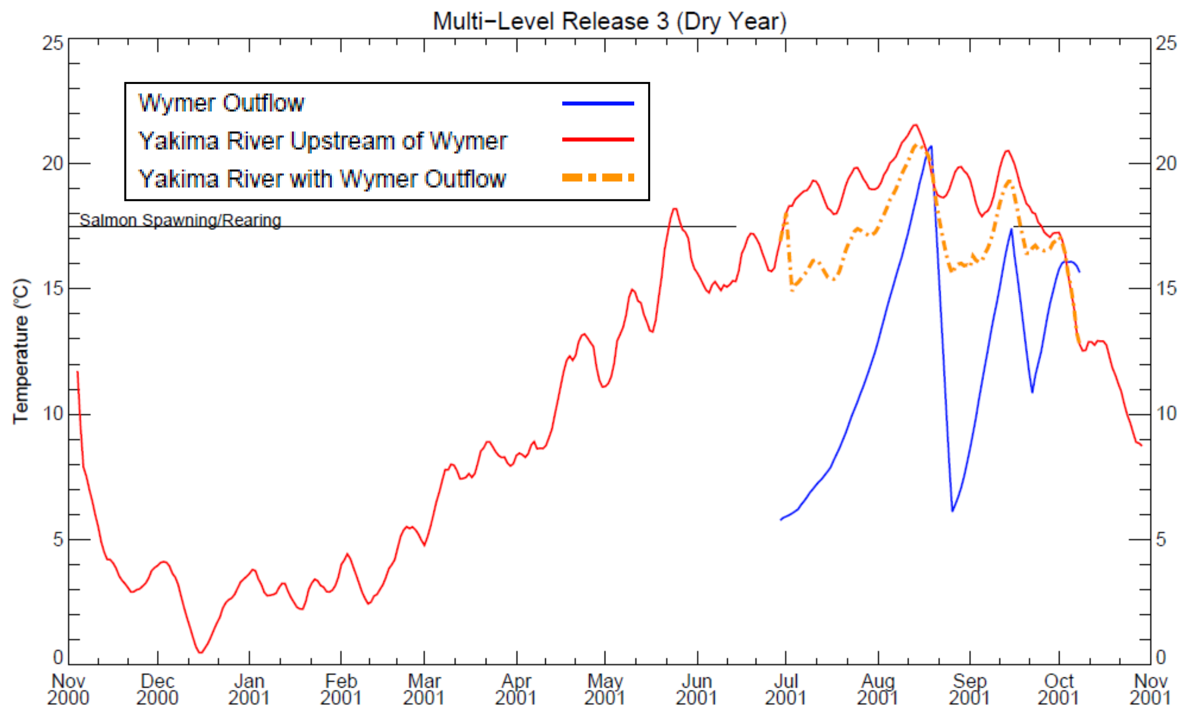

Figure 19. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Multi-Level Release 3 Scenario, Dry Year

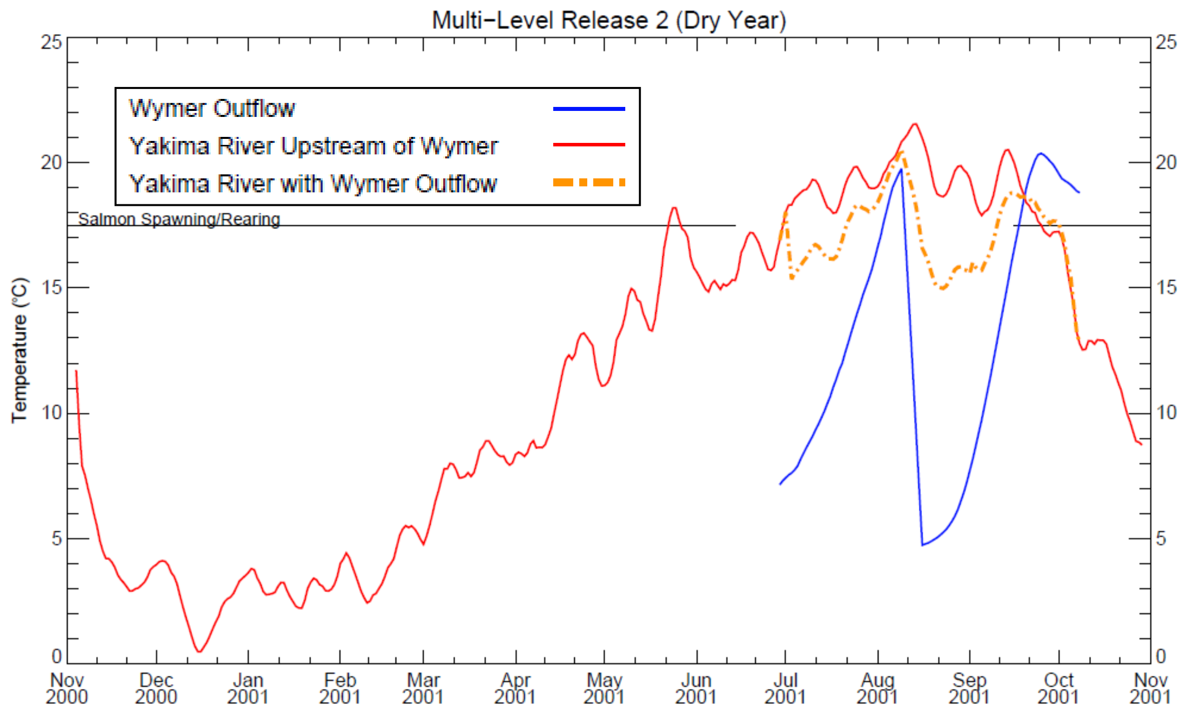

Figure 20. Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River Downstream of Wymer Reservoir Release: Multi-Level Release 2 Scenario, Dry Year

3.4 Sensitivity Analysis

The HDR team performed a sensitivity analysis based on feedback received from Reclamation and in order to better evaluate the robustness of the model predictions to uncertainty in over-winter temperatures estimated by the model. The sensitivity analysis runs were set up to determine whether the estimated temperature effects in the Yakima River resulting from the Wymer Reservoir would warrant a different conclusion if the temperature regime simulated in the model were initiated with reasonably worst-case starting temperatures prior to stratification, relative to those presented in the previous sections. Specifically, two sets of runs were set up for the Integrated Plan Single-Level and Multi-level 3 Dry Year Scenarios to start on March 1st with uniform temperature profiles of 5.5 °C and 7.5 °C. These runs are about 1 °C and 3 °C warmer respectively[4] relative to the corresponding dry year scenarios presented earlier. The reservoir pool elevation was based on the filling schedule in the Integrated Plan Scenario for the dry year. The release schedule remained unchanged from what was used in the runs presented previously. Thus, the two sensitivity runs start out with more heat stored in the reservoir prior to the onset of stratification. The anticipated effect of the introduction of greater heat prior to the onset of thermal stratification is that it will produce a thermocline with a weaker thermal gradient and will likely extend over a greater depth due to greater mixing of upper and lower waters.

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[4] These are approximately the differences in the model predicted temperatures below the thermocline (at roughly 20 to 40 meters below surface) for the Multi-level 3 dry year (2001) scenario relative to the observed profiles in Cle Elum Reservoir in 2005

Figures 21 and 22 show the Yakima River temperatures predicted for the integrated scenario dry year run with single low-level and three-level outlets presented earlier, which were started in November, along with corresponding sensitivity runs with the warmer temperature profiles starting in March. It is evident that artificially starting at a warmer temperature profile in March diminishes the relative improvement in Yakima River temperature once releases begin in summer, albeit only by a minor extent. As shown in Table 3, the changes are not large enough to appreciably change the number of days with detrimental (for the Single Low-level Outlet Scenario) or beneficial impacts (for the Multi-level 3 Scenario), indicating that the estimated temperature effect on the Yakima River downstream of the reservoir is robust within the anticipated bounds of uncertainty in the overwinter temperature predictions of the model.

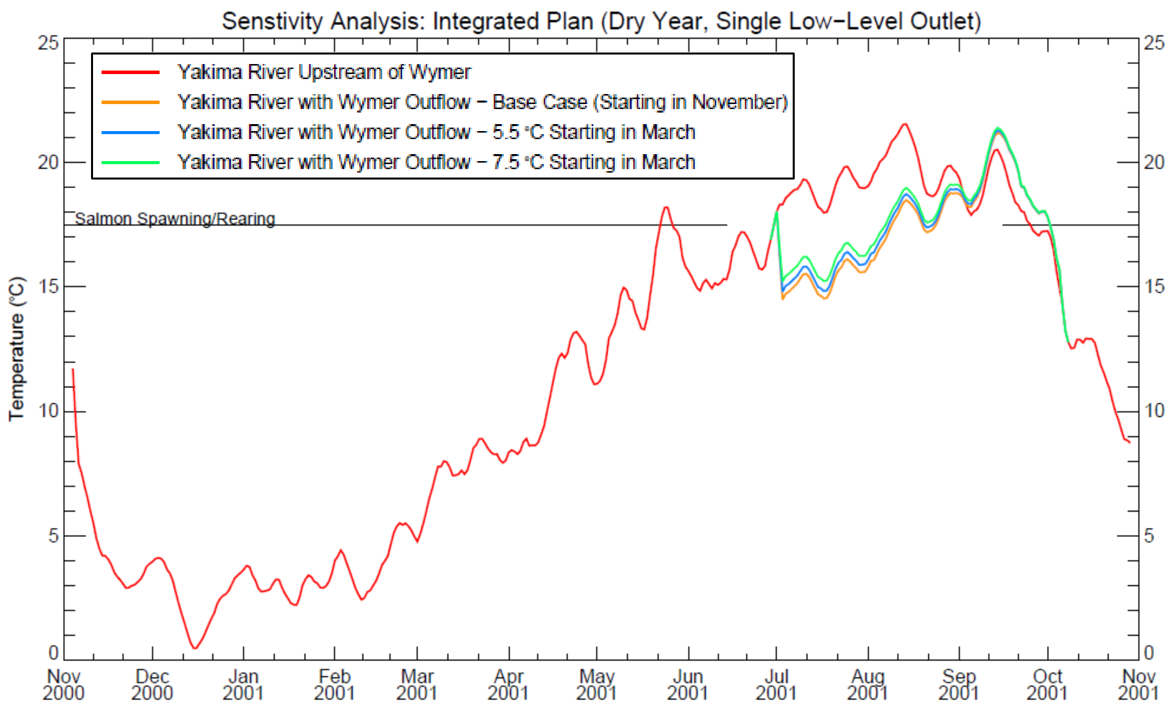

Figure 21. Sensitivity of Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River to Starting Temperature Profiles Prior to Stratification: Integrated Scenario with Single Low-Level Outlet, Dry Year

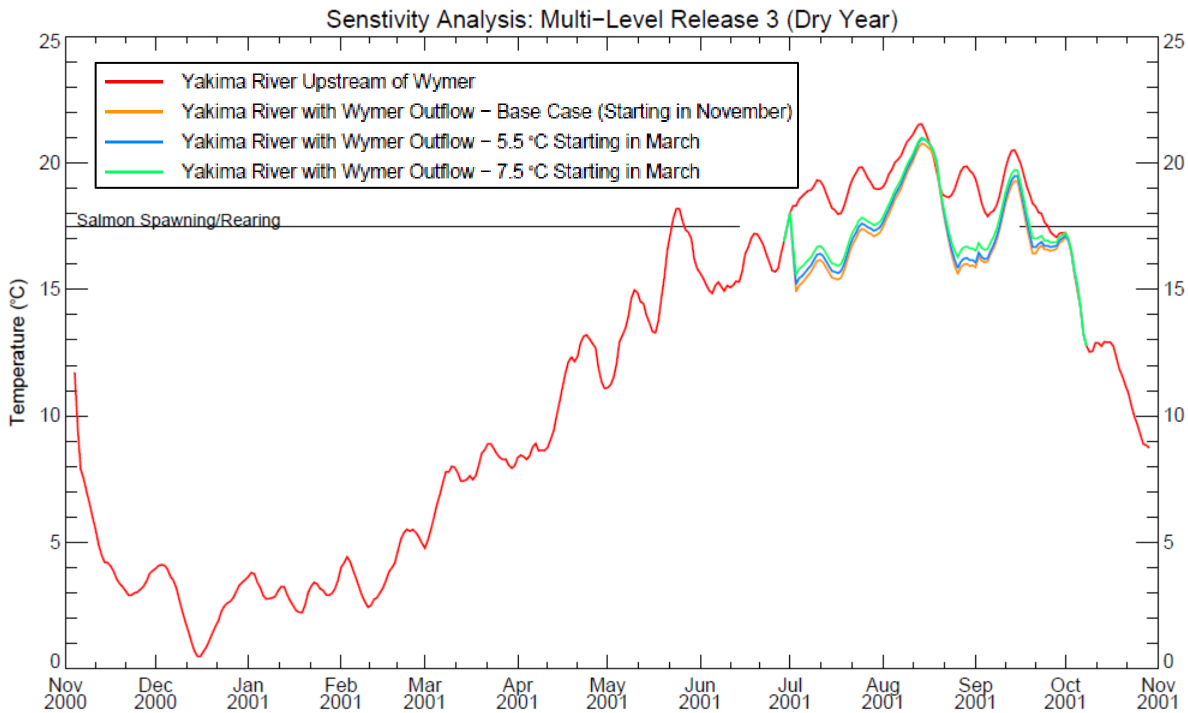

Figure 22. Sensitivity of Estimated 7-Day Average of Daily Maximum Temperature in the Yakima River to Starting Temperature Profiles Prior to Stratification: Integrated Scenario with Multi-Level Release 3, Dry Year

Table 3. Results of Sensitivity Analysis Using Warmer Temperature Settings Prior to Stratification

Scenario	Year Type	Number of Days from September 16 to June 14 when Temperature does not meet Criterion		Number of days when Yakima River Temperature Increase is > 0.3 °C (0.5 °F) from September 16 to June 14
		Without Wymer Release	With Wymer Release	
Integrated Plan, single low-level outlet: Starting in November 2000	Dry	10	16	10
Integrated Plan, single low-level outlet: Starting in March 2001 at 5.5 °C	Dry	10	16	10
Integrated Plan, single low-level outlet: Starting in March 2001 at 7.5 °C	Dry	10	16	10
Multi-Level Release 3: Starting in November 2000	Dry	10	3	0
Multi-Level Release 3: Starting in March 2001 at 5.5 °C	Dry	10	3	0
Multi-Level Release 3: Starting in March 2001 at 7.5 °C	Dry	10	4	0

4.0 Summary and Recommendations

A preliminary application of the temperature model to simulate conditions in the proposed Wymer Reservoir and in the Yakima River immediately downstream of the reservoir outflow indicated that significant reductions in the Yakima River temperature downstream of the reservoir outlet are possible over summer with releases from a lower-level outlet. Modest temperature exceedances are predicted in mid-fall when the temperatures of the reservoir releases are greater than Yakima River temperatures. That occurs during drought years when most of the reservoir contents are released and Yakima River flows are lower and ambient temperatures greater. A multi-level outlet is helpful as the warmer, upper level waters in the reservoir can be released sooner in the year before they can increase to a level that could increase downstream Yakima River temperatures. With a three-level outlet, no temperature increases are predicted in the Yakima River for any of the scenarios analyzed.

Based on the findings of this study, we recommend that additional operational scenarios be evaluated to optimize the release of water from Wymer Reservoir and assist in the design of outlet works for the reservoir. In addition, it may be worth examining the temperature conditions in the Yakima River downstream from Wymer Reservoir and simulate operations of Wymer Reservoir to determine if its operation could improve downstream temperatures. The operations of other reservoirs in the basin might also be brought into the analysis if there is the potential to optimize the temperature of releases for downstream benefits. In addition, design considerations, such as sizing of the outlet structure and pipes, and method of release into the river (for example, the effect of using diffusers at the end of the pipe), should be evaluated further to determine potential effects on the Yakima River in the area near the outfall.

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6.0 List of Preparers

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Nicholas Kim	Hydrodynamic Modeler	Quality Control Review
	RECLAMATION	
Joel Hubble	Fisheries	Review of technical analyses
Chris Lynch	Hydrology, water resources engineering	Review of technical analyses

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Appendix A

Depth Profiles of Temperature Simulated for the Modeling Scenarios

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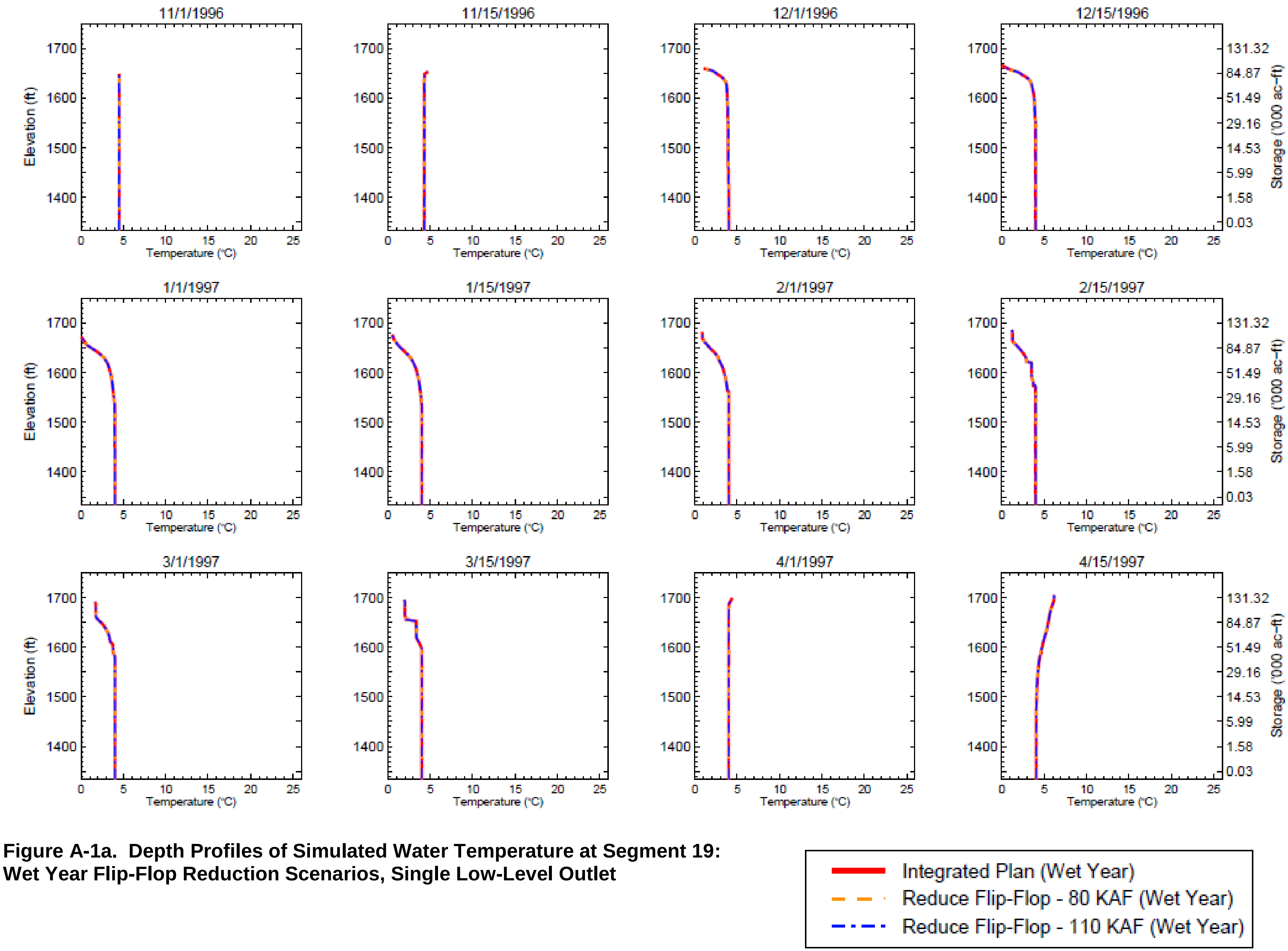

Figure A-1a. Depth Profiles of Simulated Water Temperature at Segment 19: Wet Year Flip-Flop Reduction Scenarios, Single Low-Level Outlet

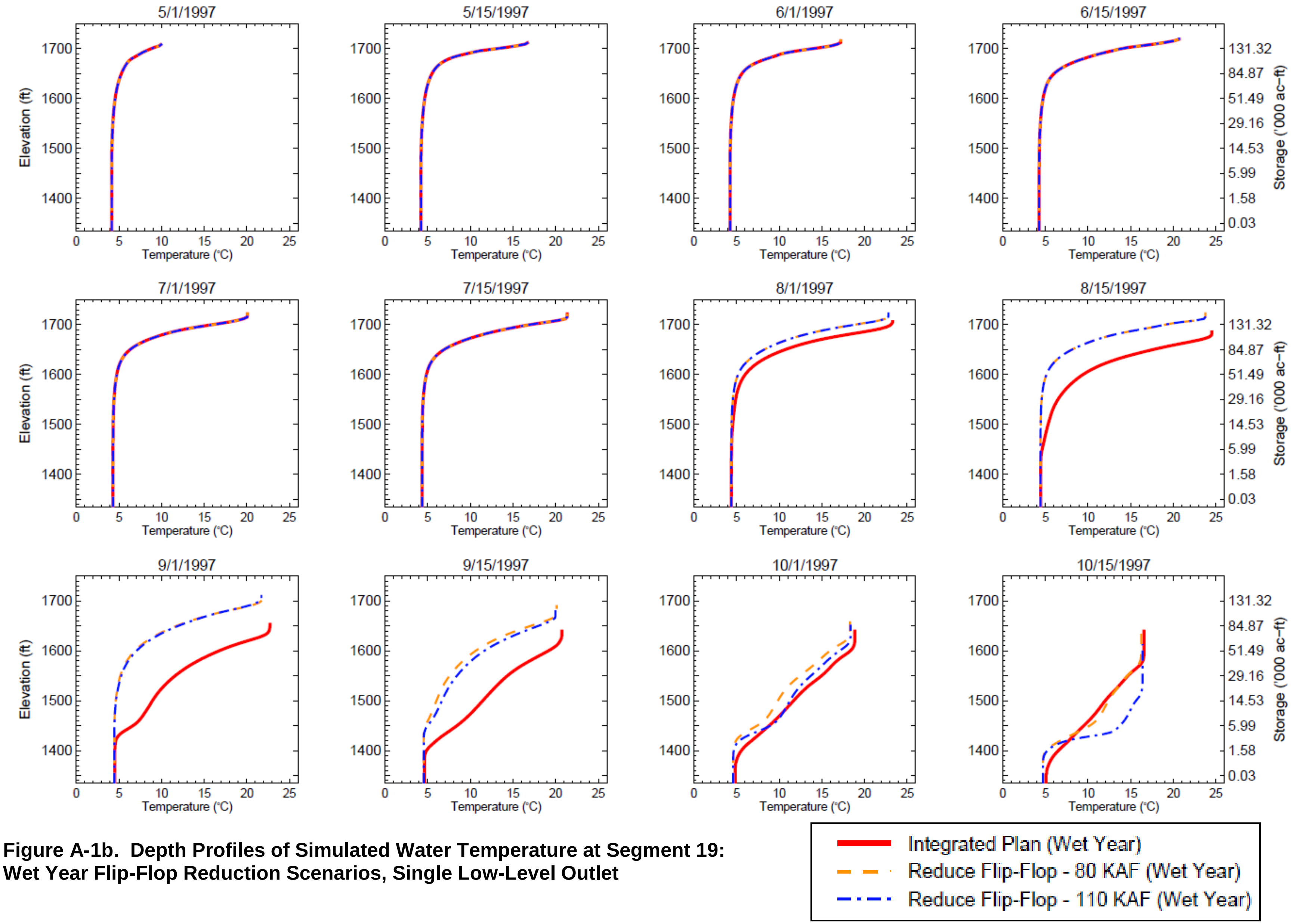

Figure A-1b. Depth Profiles of Simulated Water Temperature at Segment 19: Wet Year Flip-Flop Reduction Scenarios, Single Low-Level Outlet

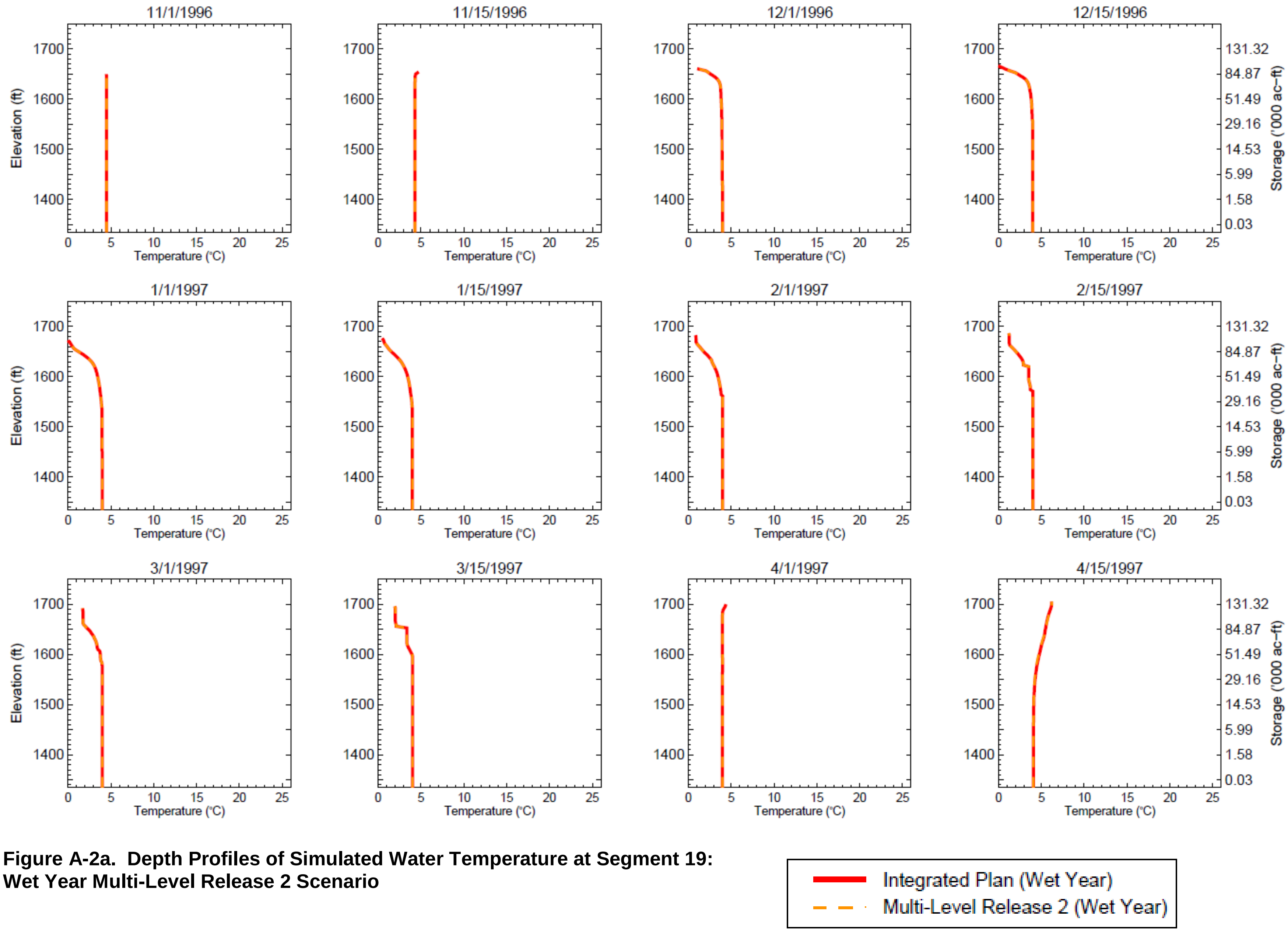

Figure A-2a. Depth Profiles of Simulated Water Temperature at Segment 19: Wet Year Multi-Level Release 2 Scenario

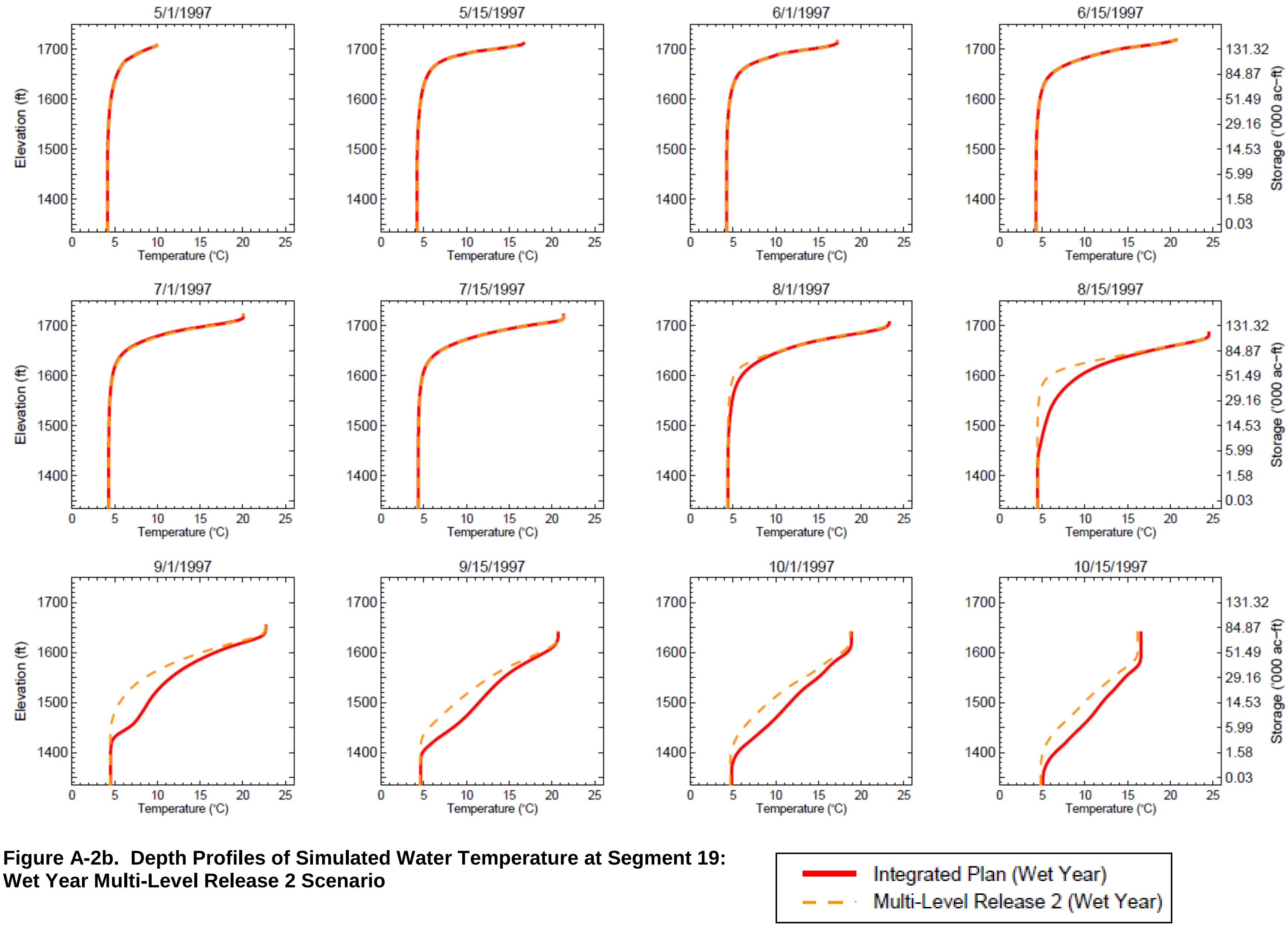

Figure A-2b. Depth Profiles of Simulated Water Temperature at Segment 19: Wet Year Multi-Level Release 2 Scenario

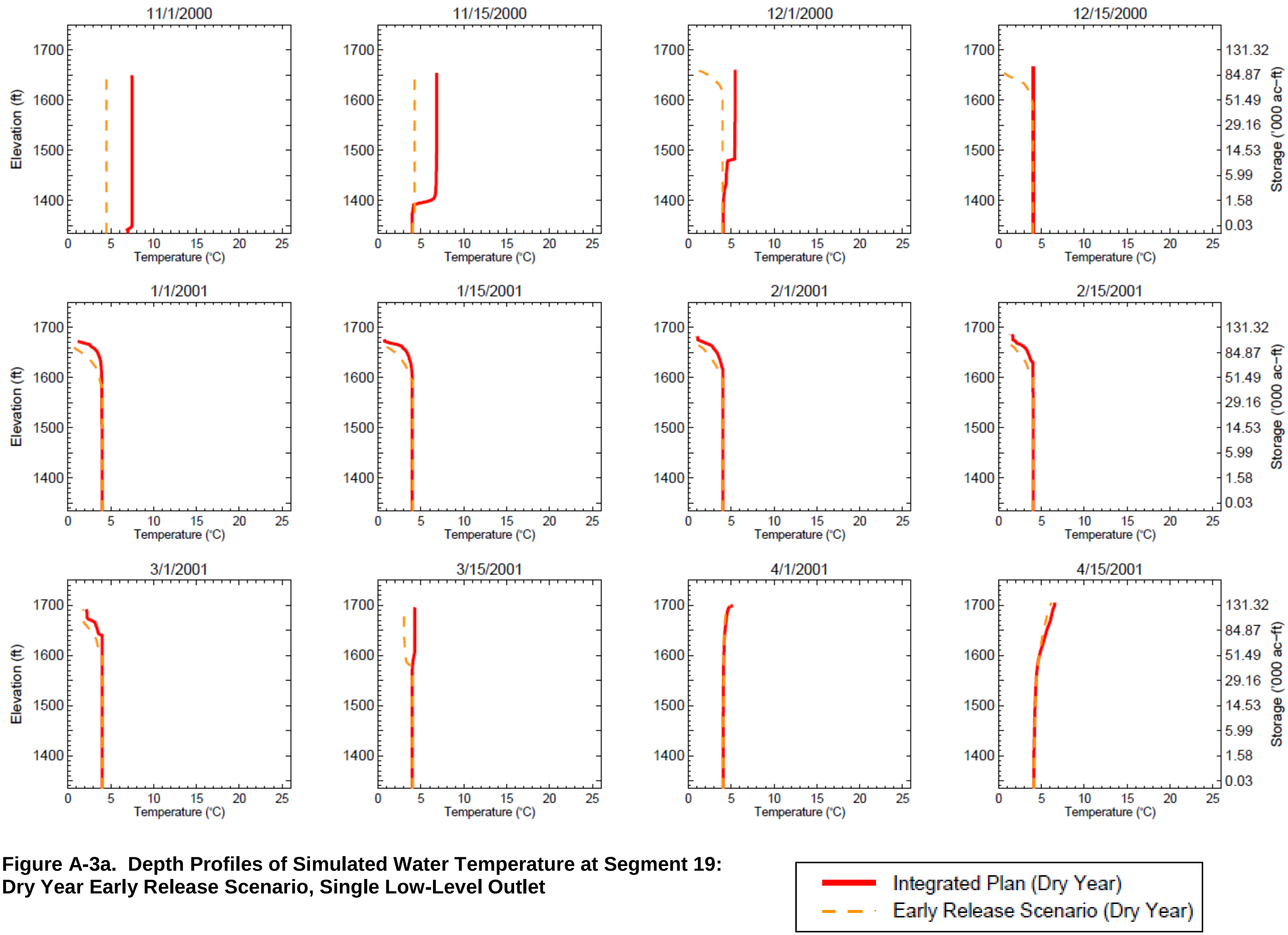

Figure A-3a. Depth Profiles of Simulated Water Temperature at Segment 19: Dry Year Early Release Scenario, Single Low-Level Outlet

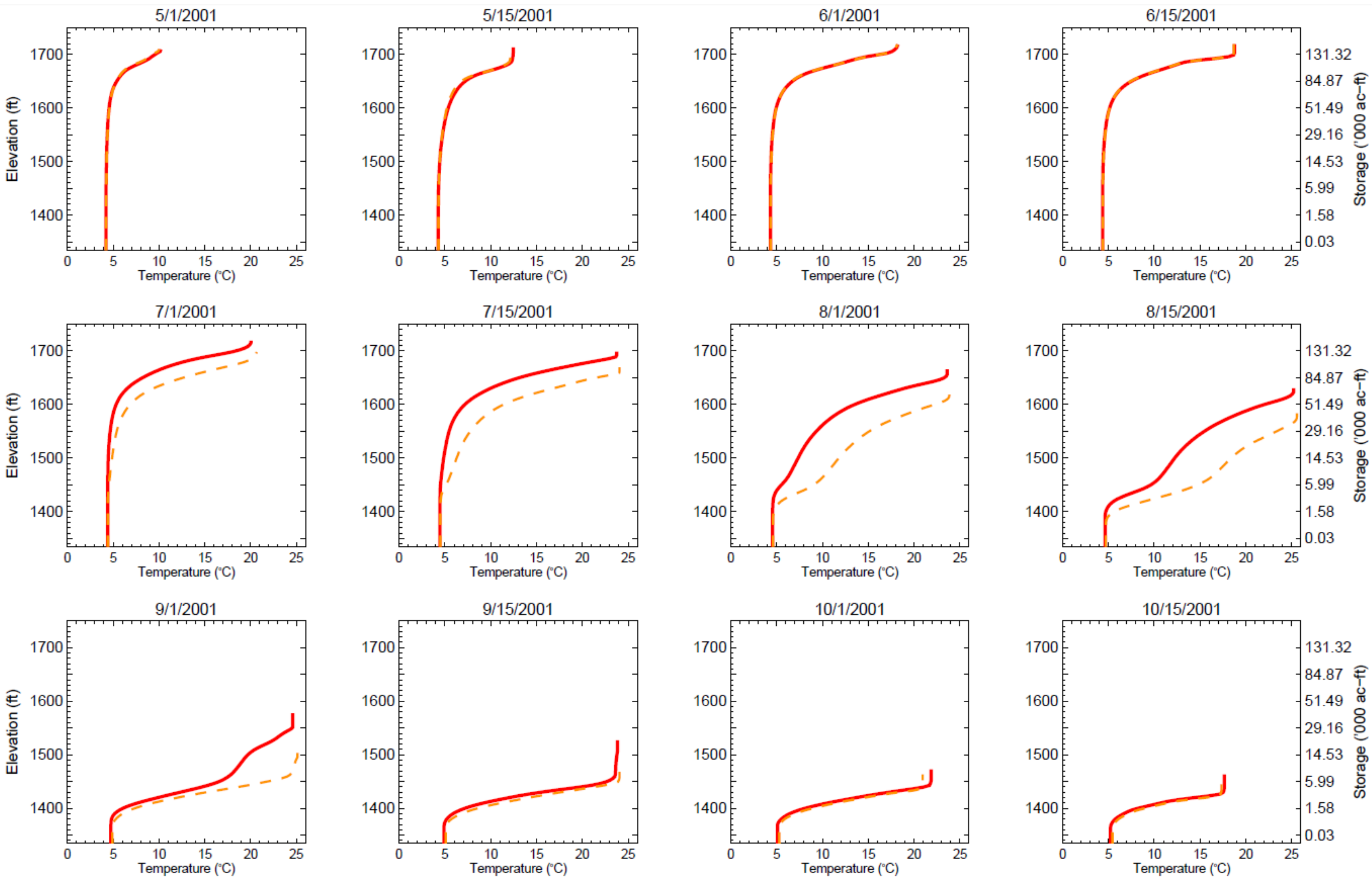

Figure A-3b. Depth Profiles of Simulated Water Temperature at Segment 19: Dry Year Early Release Scenario, Single Low-Level Outlet

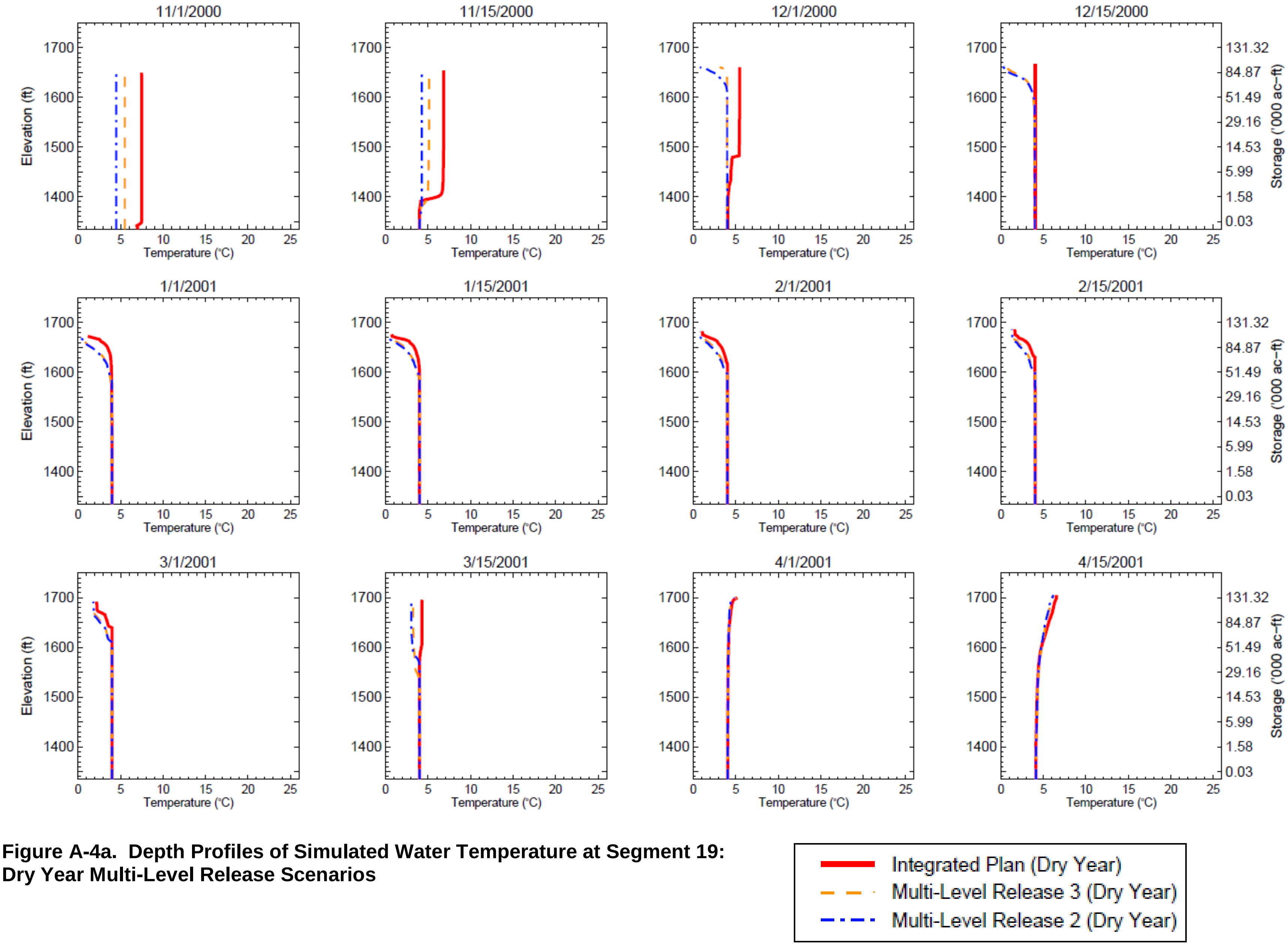

Figure A-4a. Depth Profiles of Simulated Water Temperature at Segment 19: Dry Year Multi-Level Release Scenarios

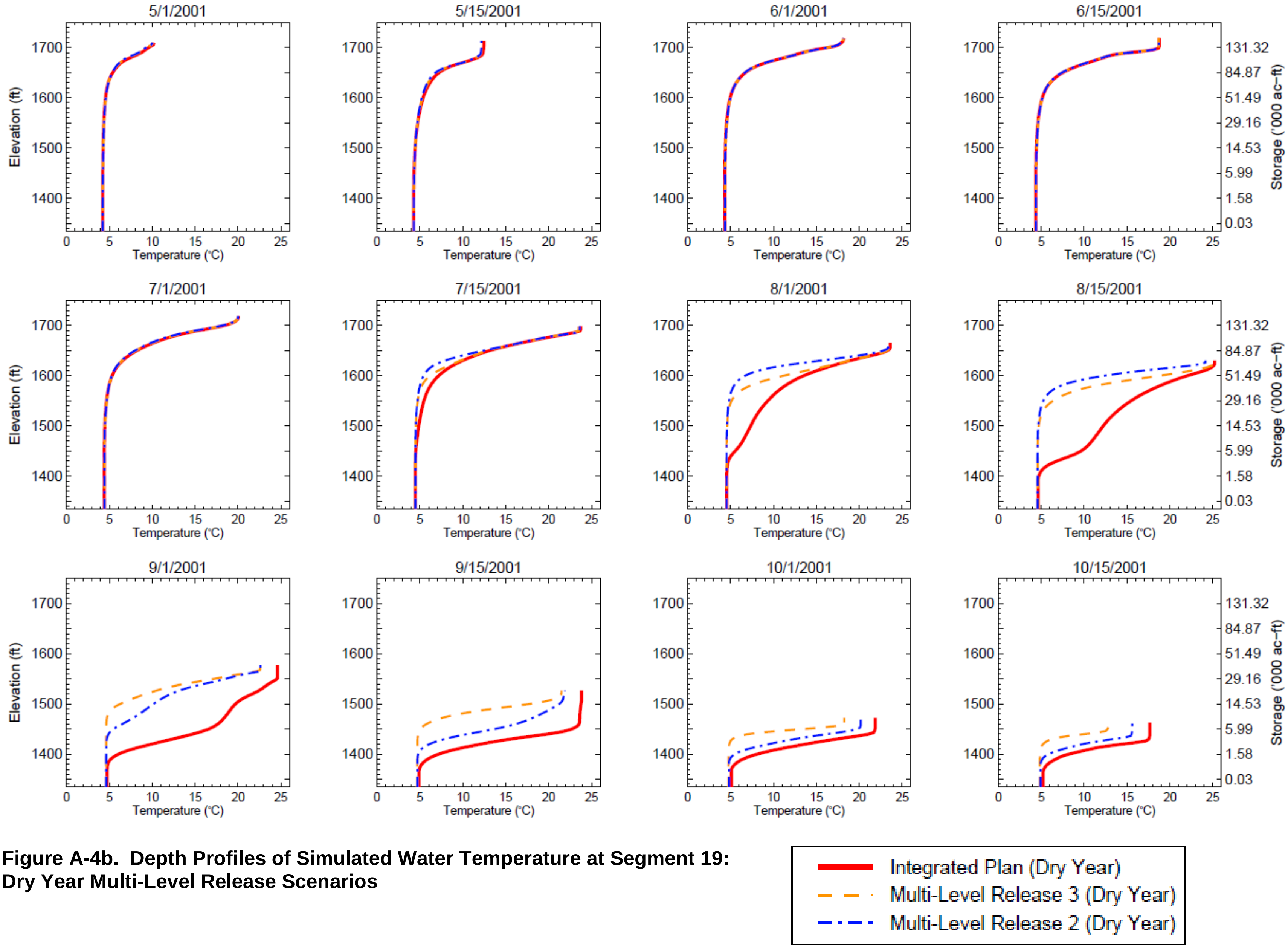

Figure A-4b. Depth Profiles of Simulated Water Temperature at Segment 19: Dry Year Multi-Level Release Scenarios