Evaluation of Lake Curry Operations and Development of a Re-operation Schedule to Benefit Threatened Steelhead Trout in Suisun Creek

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Introduction

Lake Curry is an impoundment on Suisun Creek in Napa County. The Gordon Valley Dam that created Lake Curry was built in 1926. The dam is an earthen embankment approximately 107 feet high and 572 feet long. The dam crest is at elevation 392 ft. Seventeen square miles of the upper watershed of Suisun Creek drains into Lake Curry (Figure 1). The lake has a maximum surface area of 377 acres and volume of 10,700-acre feet as originally designed.

The original purpose of Lake Curry was to supply drinking water to the City of Vallejo. Water from the lake was treated at a water treatment plant at the dam. With changes in federal drinking water standards in the 1990's the treatment plant was closed and since then Lake Curry water has not been used as municipal water supply.

This study reviewed the potential for Lake Curry to be reoperated to release water to support an existing population of threatened steelhead trout (*Oncorhynchus mykiss*) in Suisun Creek downstream of the lake. Steelhead require relatively cold water of less than 70^{o} F throughout the summer for optimal juvenile growth. When temperatures exceed 70^{o} F for many days, steelhead become lethargic and do not feed adequately. If temperatures exceed 80^{o} F for 2.8 hours up to 10% of the steelhead population may die (Sullivan et al. 2002).

A prior study of Lake Curry completed in 2008 by Hydrologic Systems Inc. indicated that in most years there is adequate cold water to release into Suisun Creek to support steelhead trout. This study used two models to evaluate the lake temperatures and volumes under different climatic conditions. The study reviewed a limited number of release scenarios.

Another study completed in 2007 involved varying actual releases out of Lake Curry while measuring water and air temperatures with a network of instruments (Ca. Land Stewardship Institute et al. 2011). This study concluded that releases from Lake Curry could substantially cool temperatures in the three miles of Suisun Creek downstream of the lake outlet. However further downstream the cooler water from the dam mixed with warmer water in the low slope creek channel and could not significantly cool the reach of Suisun Creek more than 4 miles downstream of the lake.

In 2016 the Ca. Land Stewardship Institute (CLSI) applied for funding from the Wildlife Conservation Board to focus on improving instream flows in Suisun Creek for steelhead trout. This study uses a model to evaluate temperatures and volumes in Lake Curry. The model is used to analyze a set of recommended releases from Lake Curry to support a sustainable population of threatened steelhead trout in Suisun Creek.

Data Collection

There are a number of input parameters for the Lake Curry model that require collecting site specific data. Continuous water temperature monitoring is needed to calibrate the model for conditions at Lake

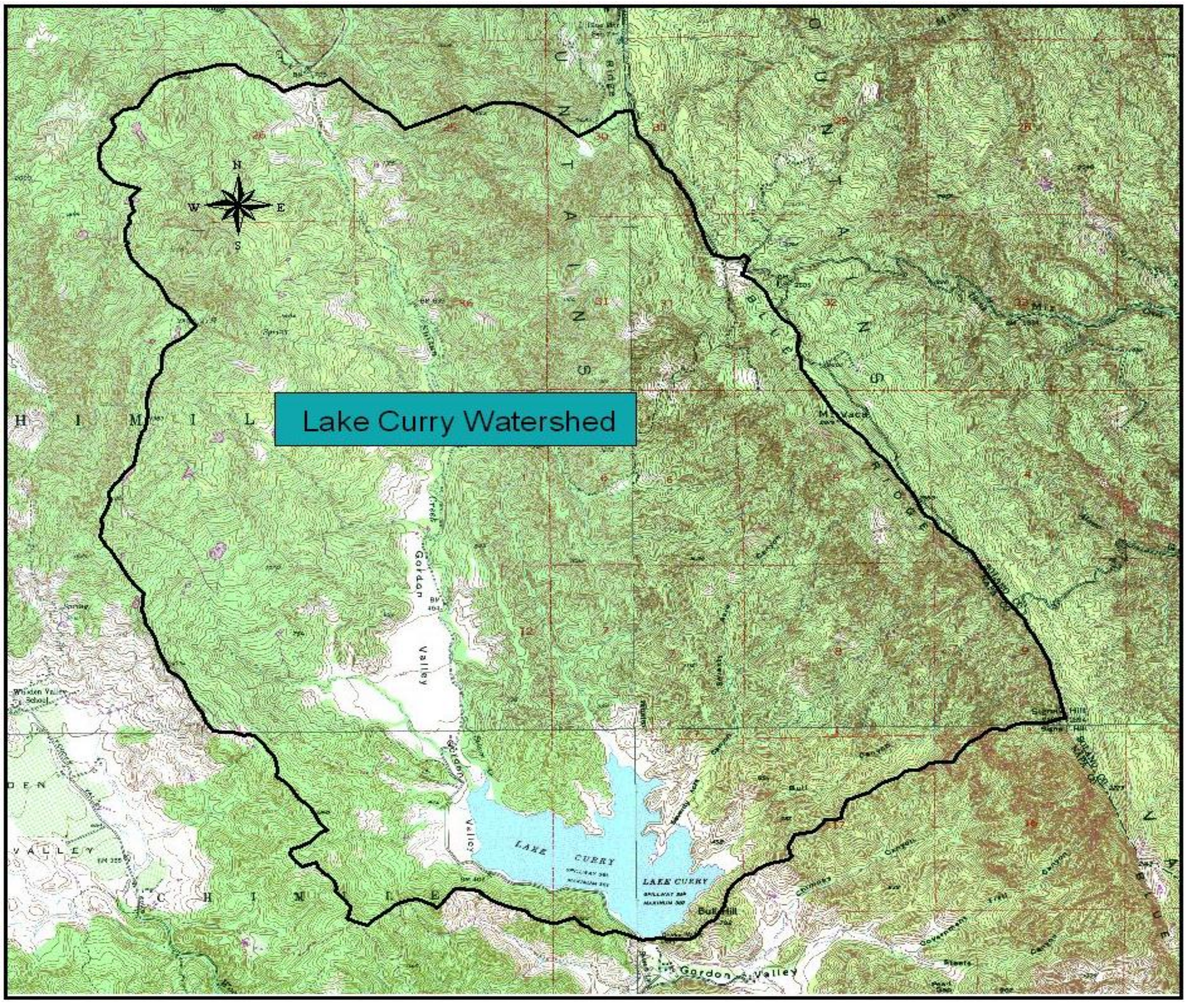


Figure 1. Lake Curry Watershed

Curry. To develop this calibration data, two water temperature monitoring campaigns were completed including: 1. the buoy-suspended approach and 2. the draped inboard embankment approach.

The first approach measured depth-dependent temperature using lines with temperature sensors attached to buoys (Figures 2, 3 and 4). Onset Hobotemp Pro v2 temperature dataloggers were used. The accuracy of each Hobotemp datalogger was checked by performing a comparison of each datalogger to a certified NIST thermometer for a room temperature water bath and an ice bath (Humboldt State University Forest Science Project 1997). The data loggers were set on the buoy line based on distance from the bottom of the lake. The lake bottom elevation was estimated based on spatial location and previous bathymetric survey elevations. The approach was employed to match previous onsite data collection protocols. Data were collected during the summer of 2017 into the fall of 2018 for all sensors except S1-14, which were removed after the first data collection campaign due to shallow water depths. The buoy suspended technique was determined to be problematic as a result of variable lake levels impacting the tension in the buoy line and, correspondingly, the datalogger elevations.

Figure 2: Use of buoys to suspend temperature data loggers (S-1, S-2, S-3).

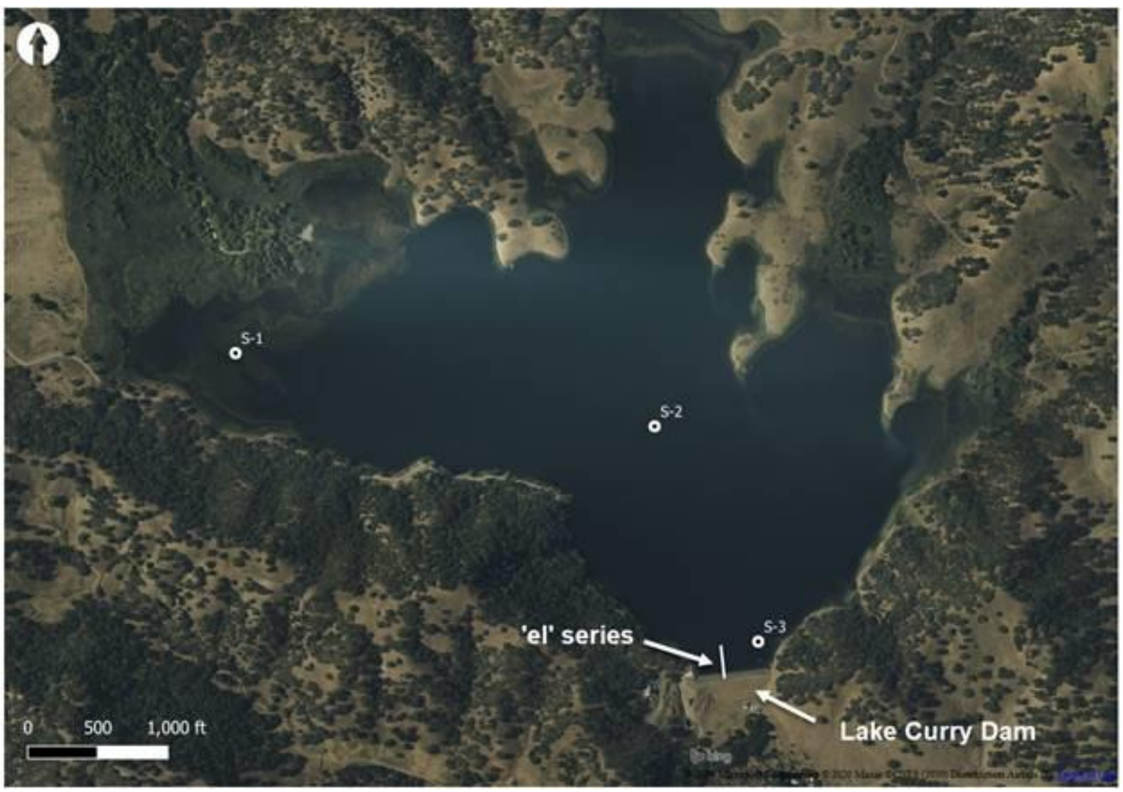


Figure 3. Water temperature instrument locations within Lake Curry and on the interior dam embankment.

The second campaign attached additional water temperature data loggers to an anchor line that was then draped on the inboard embankment, extending into the lake (Figure 4). The top of the line was set at the top of the embankment. Since the slope (slope of 2.5 horizontal to 1 vertical) of the inboard embankment was known (Figure 5), the data loggers could be pre-positioned on the line at target lake elevations. Data were collected during the summer and fall of 2018.

Figure 6 shows a plot of data collected using the two approaches. The “S” series data were collected using the buoy approach. The “el” series data was collected using the draping approach. Sensors el380 and el368 appear to have been out of the water measuring air temperatures for the entire data collection period and therefore were not included int the graph.

Both data collection approaches found that a distinguishable temperature gradient develops in Lake Curry during the summer months. A more uniform temperature profile then develops in the late fall, winter, and early spring.

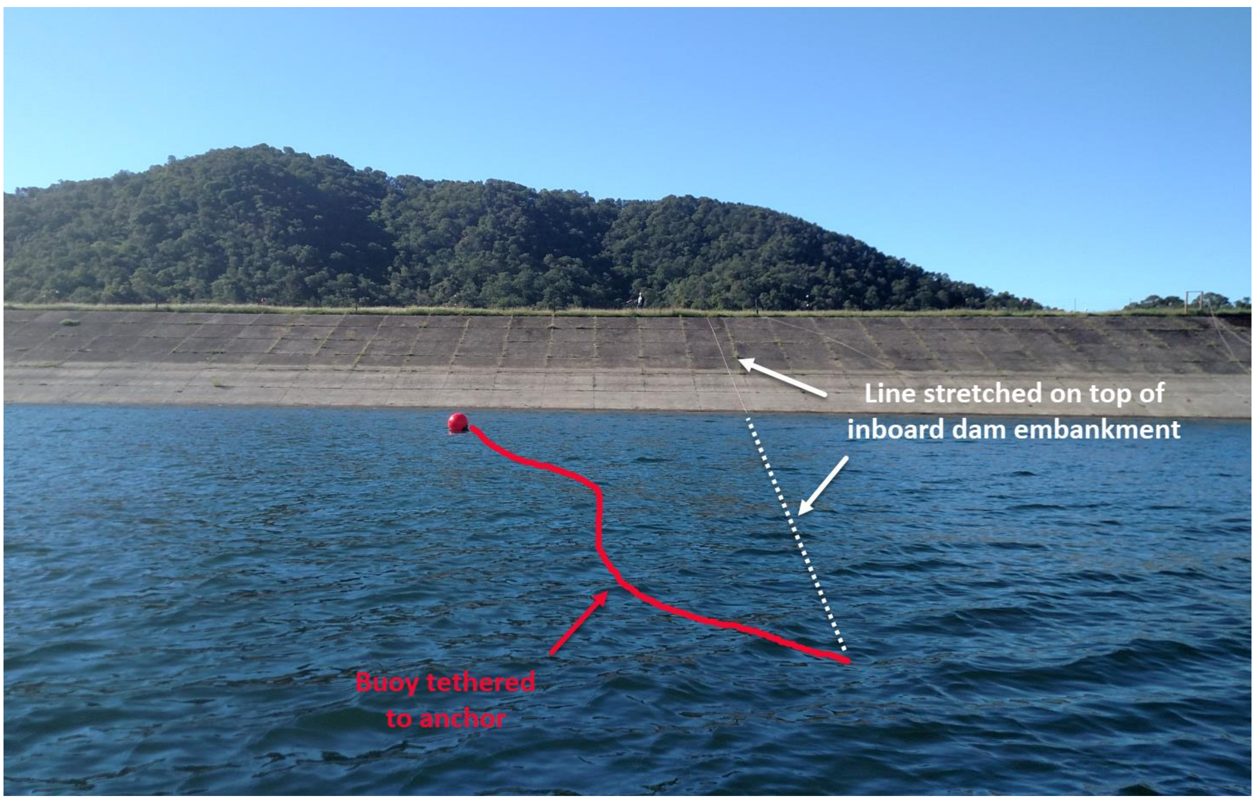


Figure 4. Temperature data loggers attached to anchor line and draped on inboard dam embankment to establish measurement elevation.

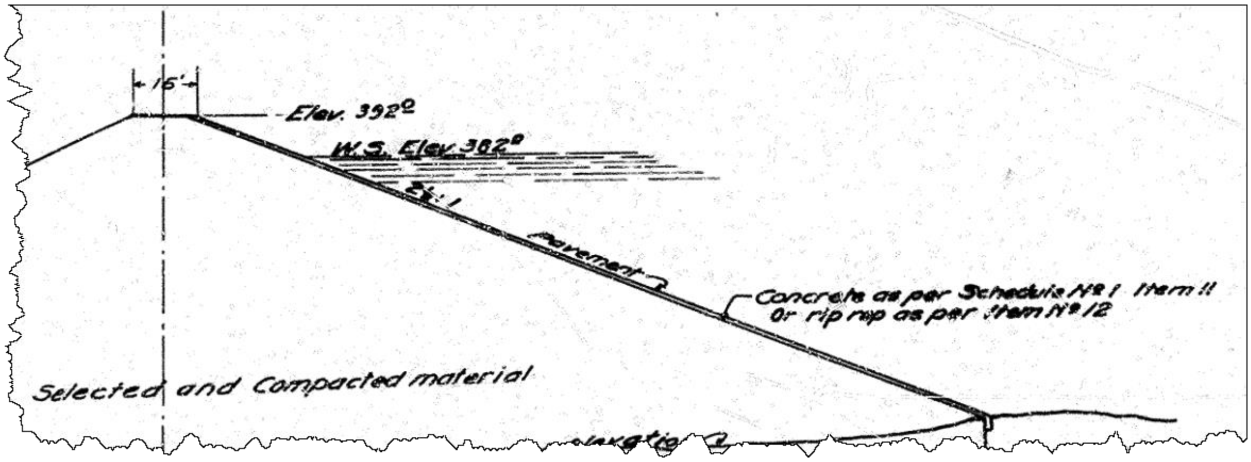


Figure 5. Geometry of the interior embankment for Lake Curry.

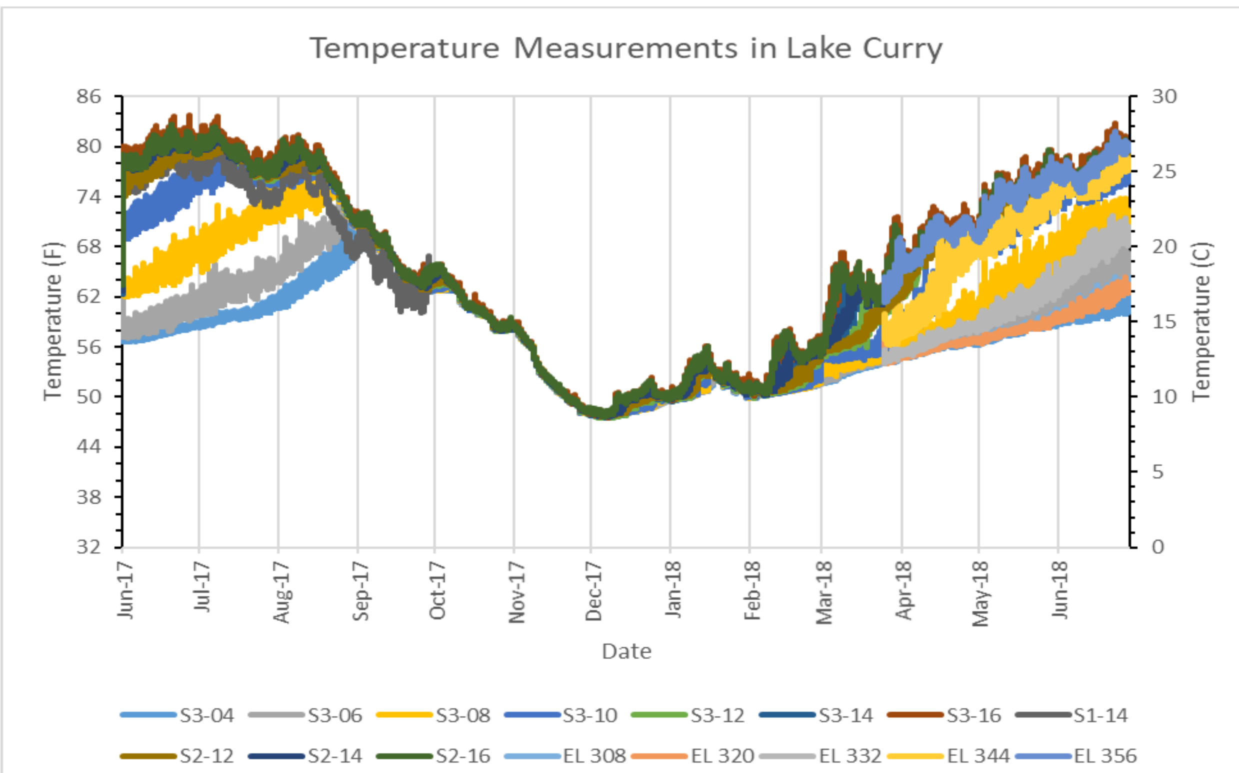


Figure 6. Water temperature data recorded within Lake Curry.

A series of temperature sensors were also installed by CLSI in Suisun Creek from 2017-2020 (Figure 7). Station 10.0 is located in a pool at the outlet pipe of Lake Curry. For prior studies water temperatures were monitored at station 10.0 in 2003, 2005-2006 and 2009. These data were also used in the current model.

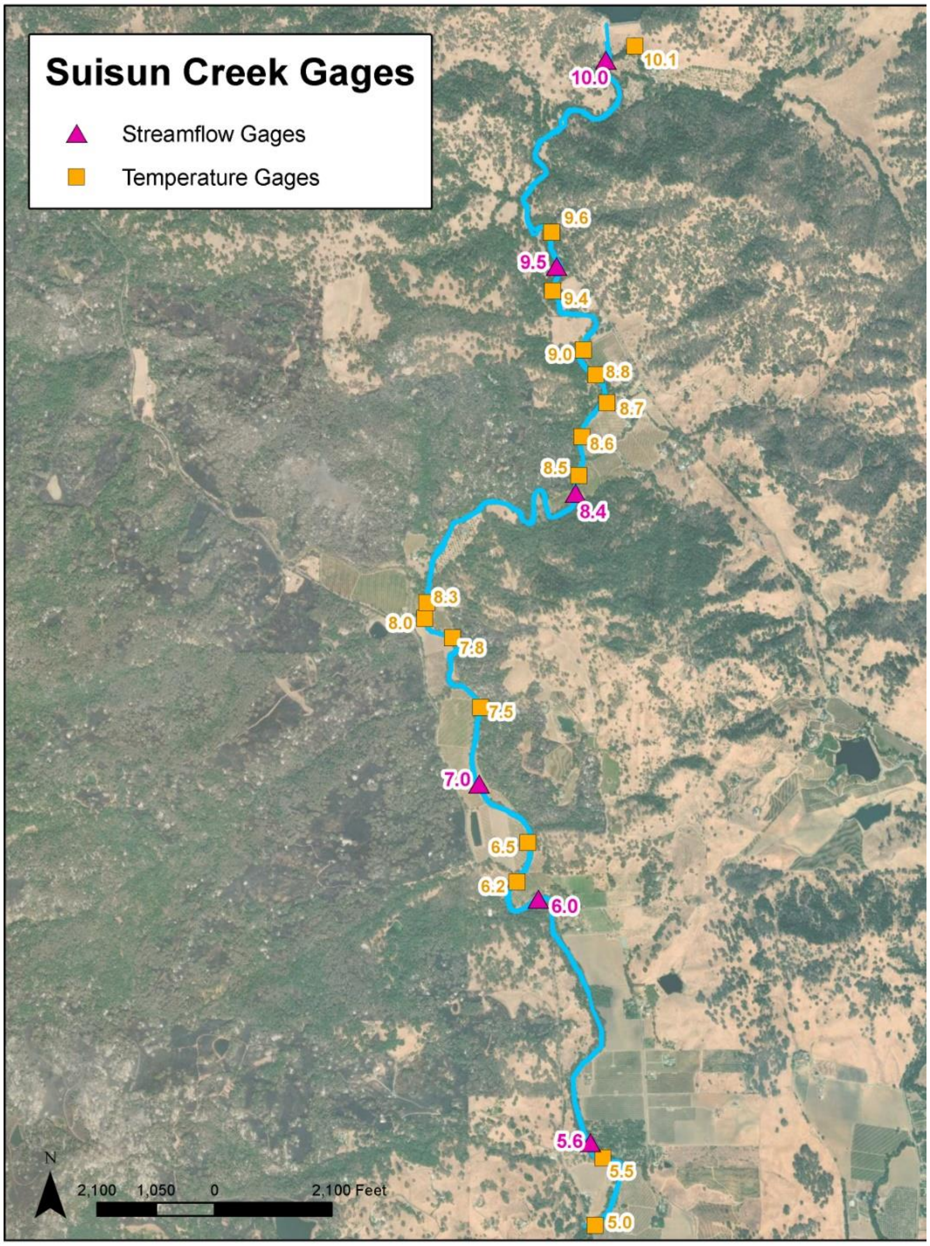


Figure 7. Temperature and streamflow gages deployed in Suisun Creek 2017-2020. The streamflow gages also measure water temperature.

Modeling

This study uses the Army Corps of Engineers CE-QUAL-W2 model V4 to analyze lake levels and temperatures. The CE-QUAL-W2 model is a two-dimensional, laterally averaged, hydrodynamic and water-quality model typically used for small reservoirs. CE-QUAL-W2 is appropriate for modeling the Lake Curry system since it contains the following elements:

• Two-dimensional, dynamic hydrodynamics and water quality capable of replicating temperature and water quality in a density stratified waterbody

- CE-QUAL-W2 has a proven track-record of being capable of modeling complex stratified reservoir systems in the US and abroad
- The code is open source and is readily available for peer-review
- The model code is easily modified for custom output or input features as required by the user
- Depending on model set-up and complexity, the model can be run for long-term simulations (e.g., 100 year simulations) within a reasonable time period
- The CE-QUAL-W2 model has been extensively applied to stratified systems undergoing eutrophication. It is the model of choice by many US federal agencies for stratified reservoir systems.

The model requires definition of branches, segments and depth layers of the reservoir and input of the data for the following parameters: air temperature, dewpoint temperature, wind speed, wind direction, cloud cover, solar radiation daily inflows for each branch, temperature inflows for each branch, daily inflows from each tributary, temperature inflows from each tributary, daily outflows from the dam, distributed tributary inflow and distributed tributary inflow temperature.

The CE-QUAL-W2 modeling was completed by Prof. Scott Wells at Portland State University. Dr. Wells and his group have been the primary developers of this model for the ERDC (Engineer Research and Development Center), Environmental Laboratory, Waterways Experiment Station Corps of Engineers for over 15 years. Since 2000, this model has been used extensively throughout the world in 116 different countries. There have been well-over 1000 applications of CE-QUAL-W2. The applications include reservoirs, estuaries, lakes, and river systems. A report of the model setup, calibration, and outputs is presented in Appendix 1, CE-QUAL-W2 Modeling Results. The original bathymetry and model resolution were greatly refined and parameters were modified to achieve greater correlation between model outputs and recorded data. A user guide was developed for CE-QUAL-W2 by Prof. Wells for this project and is presented in Appendix 2, CE-QUAL-W2 Modeling User Guide.

Model Development

Bathymetry

Model segments of the updated bathymetry for Lake Curry are shown in Figure 8. There are 14 segments in the updated model grid with a vertical resolution at 1 m. A side view of model cells is shown in Figure 9. The updated model bathymetry was developed using bathymetric data collected in 2005 (HSI Hydrologic Systems, 2008) combined with an integrated digital elevation map (DEM) of the area. The Lake Curry grid included 2 branches, with one branch modeling the mainstem of the reservoir and the other branch modeling a side arm. Figure 10 compares the model volume-elevation curve with the volume-elevation curve developed from data measured in the 2005 bathymetric survey. This plot shows excellent agreement between the model volume-elevation curve and data.

Meteorological Inputs

The original Lake Curry model (HSI Hydrologic Systems, 2008) used on-site meteorological data, but data summaries were only graphical in the report and consisted of daily averages except for 15 min wind speed and air temperature. The daily average graphs were not used since we required finer time resolution, and the 15-minute plots were too difficult to resolve and digitize. Hence, for the updated model, meteorological data were obtained from the California Department of Water Resources Suisun

Valley CIMIS weather station No. 123 for 2005-2007 and the Oakville CIMIS station for the 2017-2019 period.

Air and Dew Point Temperature

Air and dew point temperatures measured at the Suisun Valley station in 2005-2007 are shown in Figures 11 and 12. The figure of 15-minute air temperature from HSI Hydrologic Systems (2008) from an on-site weather station at Lake Curry was compared to the hourly data from Suisun Valley in Figure 13. A visual comparison shows that the two stations had similar air temperatures and that the Suisun Valley CIMIS station is a reasonable surrogate for air temperature at Lake Curry. The Suisun Valley CIMIS station stopped recording in 2010 so another CIMIS station in Oakville was selected for use. Air and dew point temperatures measured at the Oakville CIMIS station for 2017-2018 are shown in Figures 14 and Figure 15.

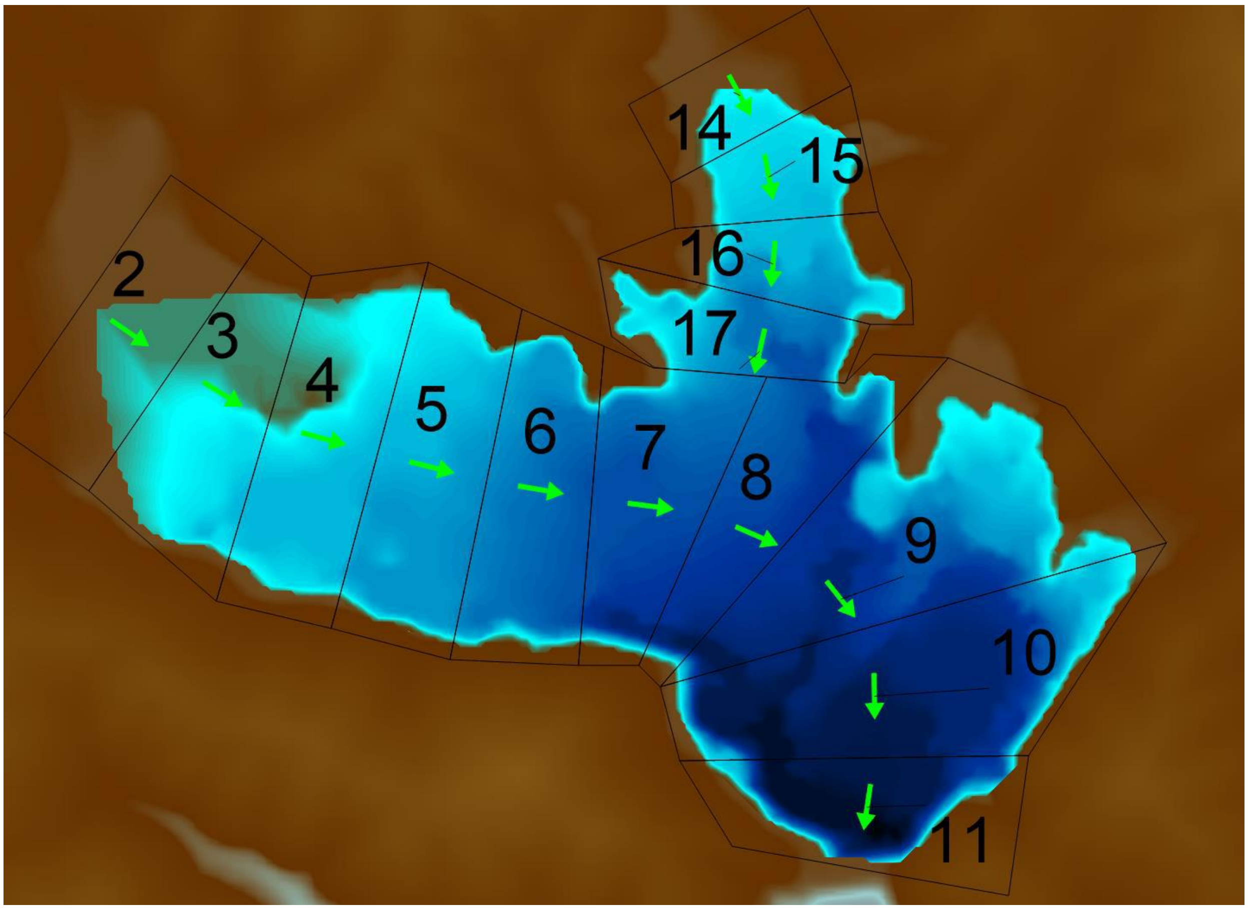


Figure 8. Updated Lake Curry model grid showing segment numbers.

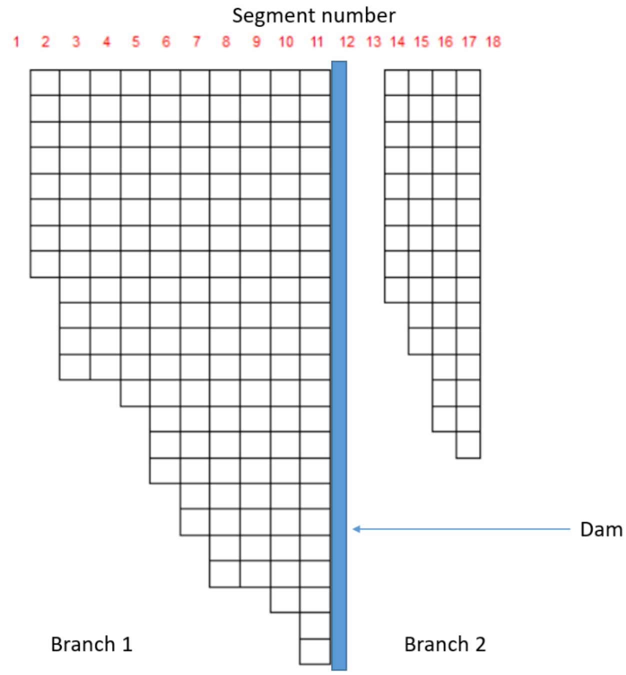


Figure 9. Profile view of Lake Curry grid showing model segments (horizontal) and vertical layers. Each layer was 1 m thick and every segment was 218.61 m (branch 1) or 173.88 m (branch 2) long.

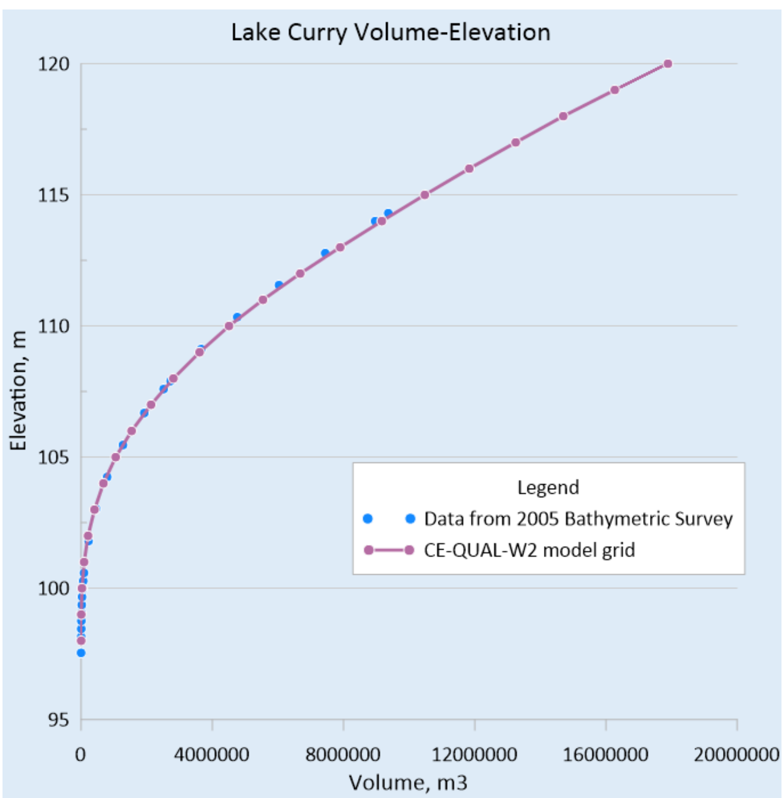


Figure 10. Model volume-elevation curve compared with bathymetric data.

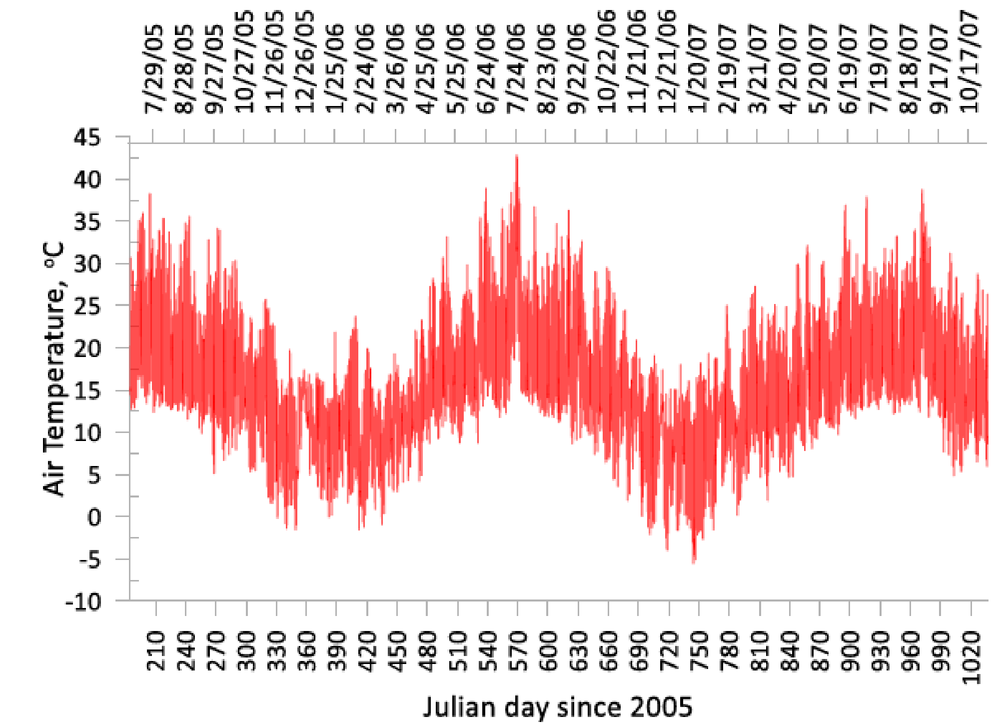


Figure 11. Air temperature at Suisun Valley CIMIS station between 2005 and 2007.

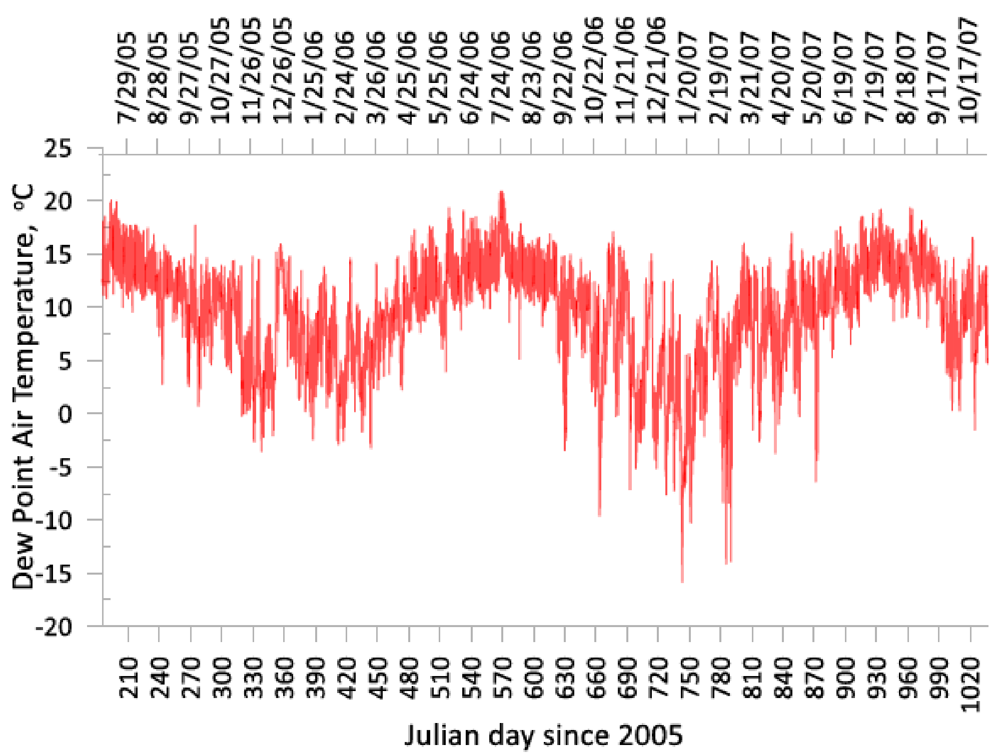


Figure 12. Dew point temperature at Suisun Valley CIMIS station between 2005 and 2007.

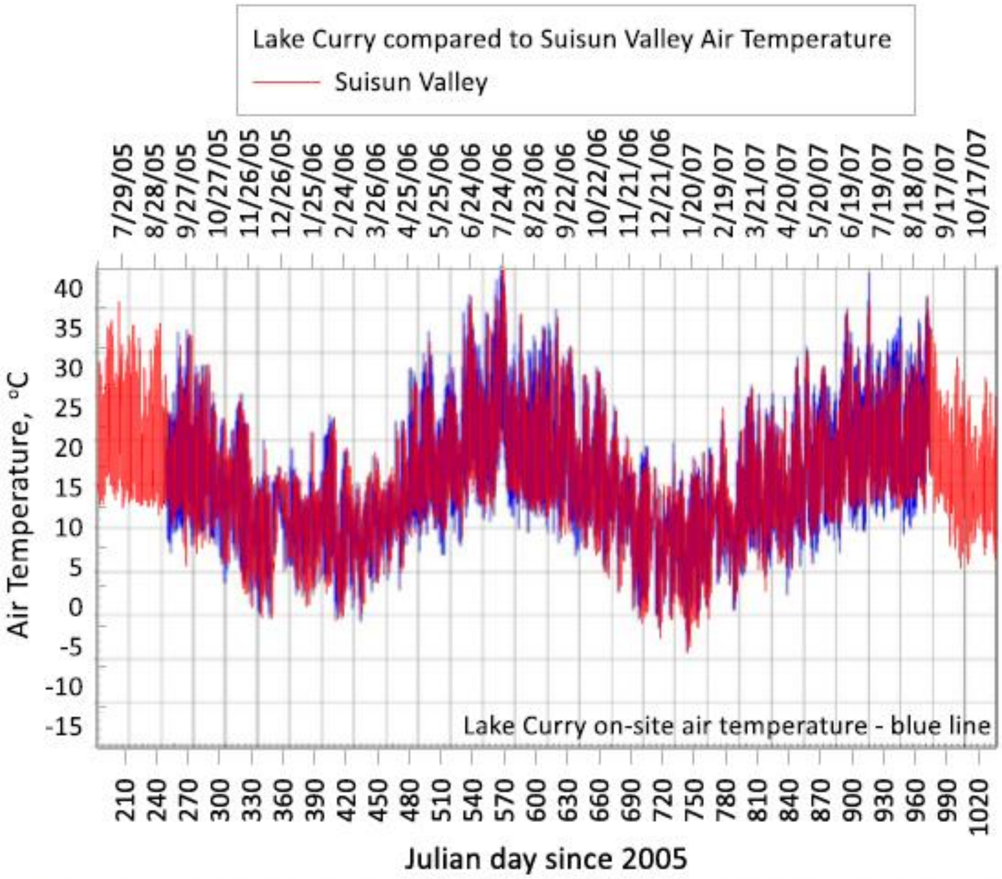


Figure 13. Comparison of air temperature measured on-site at Lake Curry compared to Suisun Valley CIMIS station between 2005 and 2007.

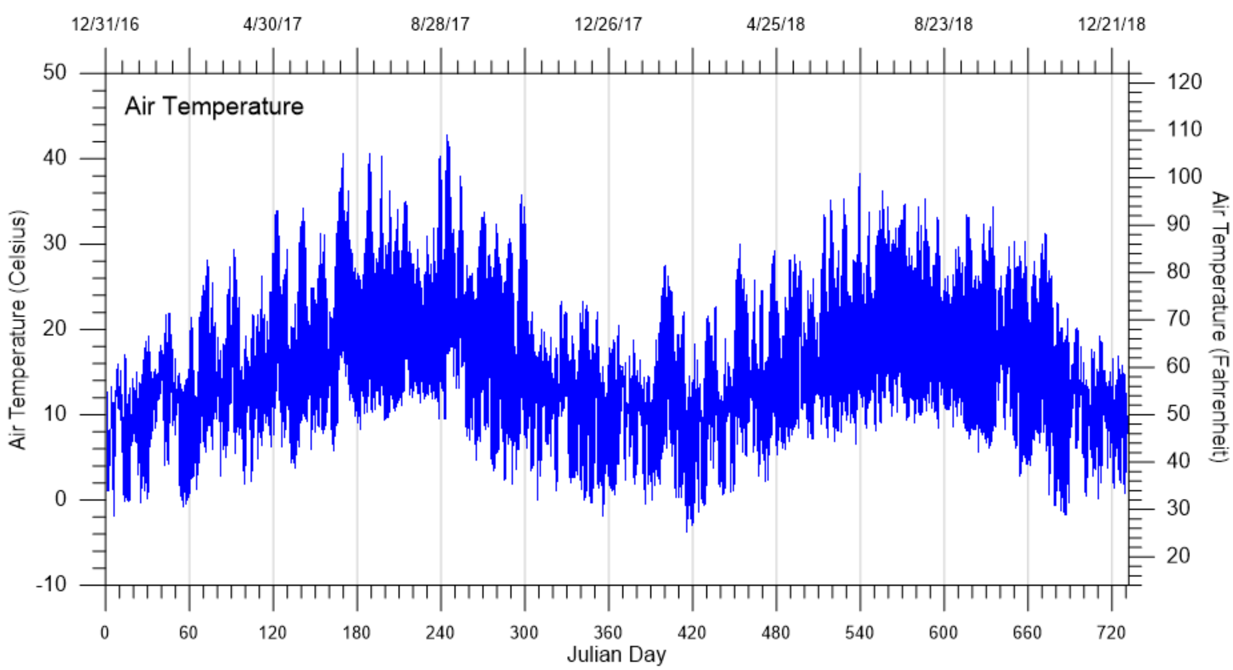


Figure 14. Air temperature for 2017-2018 measured at the Oakville CIMIS station.

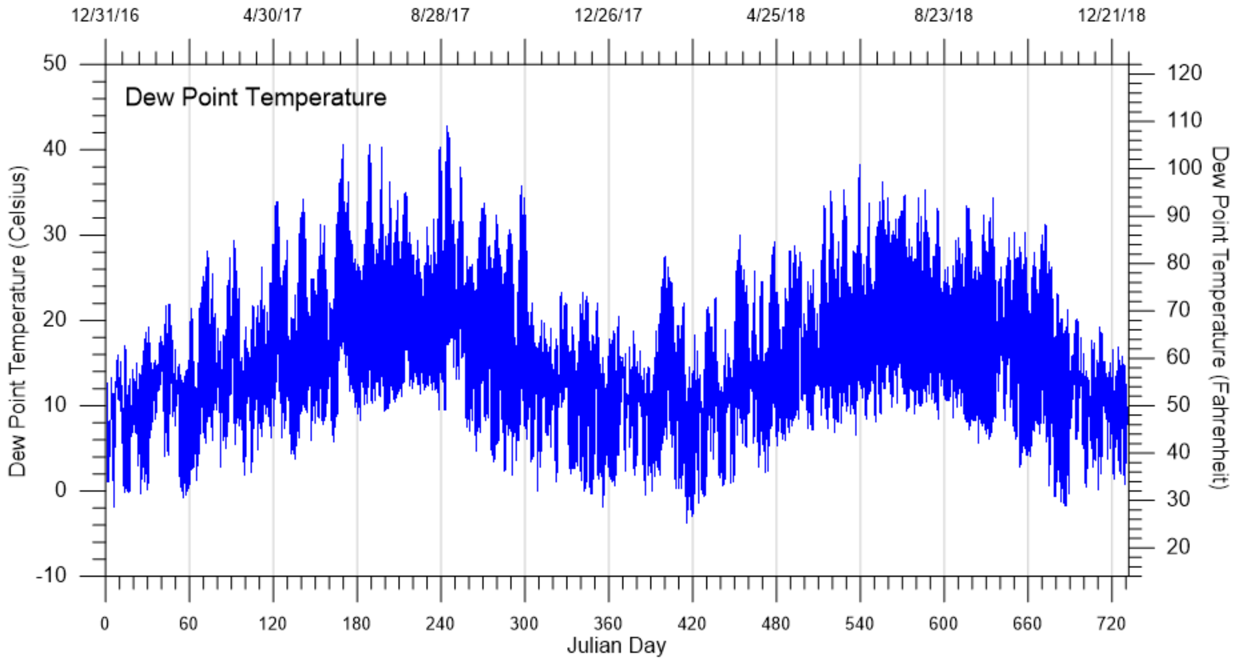


Figure 15. Dew point temperature for 2017-2018 measured at the Oakville CIMIS station.

Wind Speed and Direction

Measured wind speeds from the Suisun Valley CIMIS station are shown in Figure 16 (2005-2007) and from the Oakville CIMIS station in Figure 17 (2017-2018).

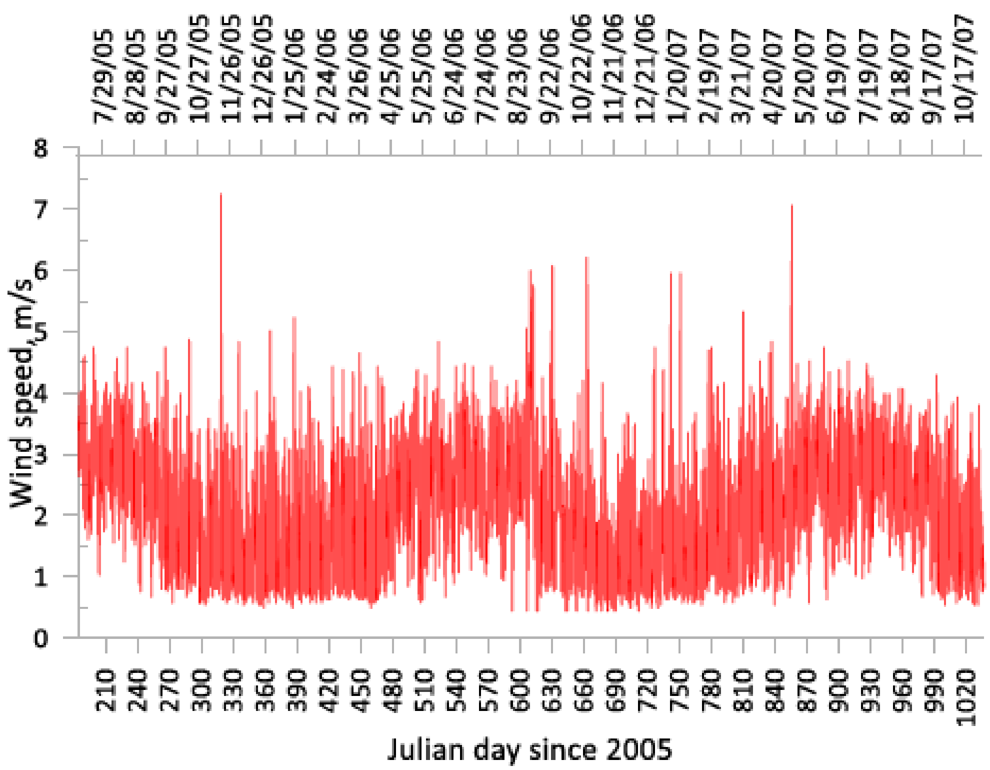


Figure 16. Wind speed measured at Suisun Valley CIMIS station between 2005 and 2007.

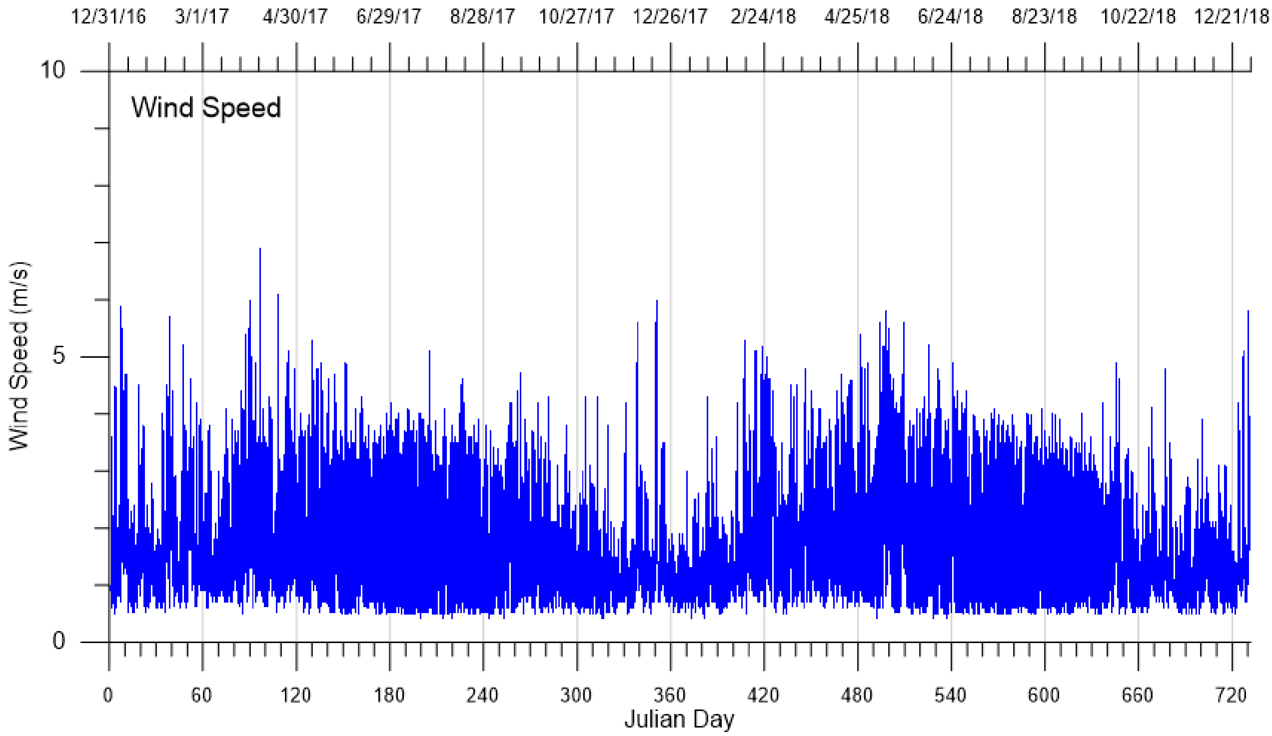


Figure 17. Wind speed measured at Oakville CIMIS station between for 2017-2018.

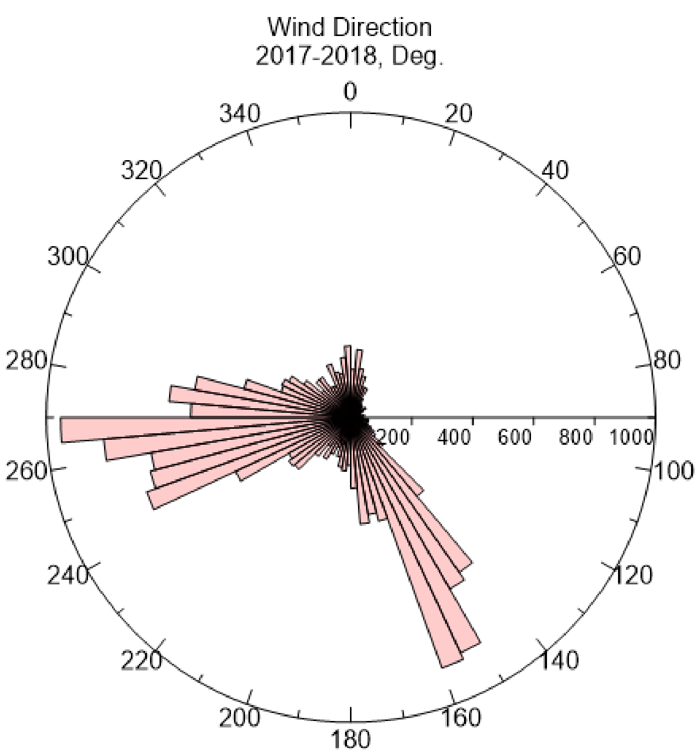


Figure 18. Wind direction measured at Oakville CIMIS station between for 2017-2018.

Short Wave Radiation and Cloud Cover

Short wave radiation data measured at the Suisun Valley CIMIS station in 2005-2007 are plotted in Figure 19. Short wave radiation data measured in 2017-2018 at the Oakville CIMIS station are plotted in Figure 20.

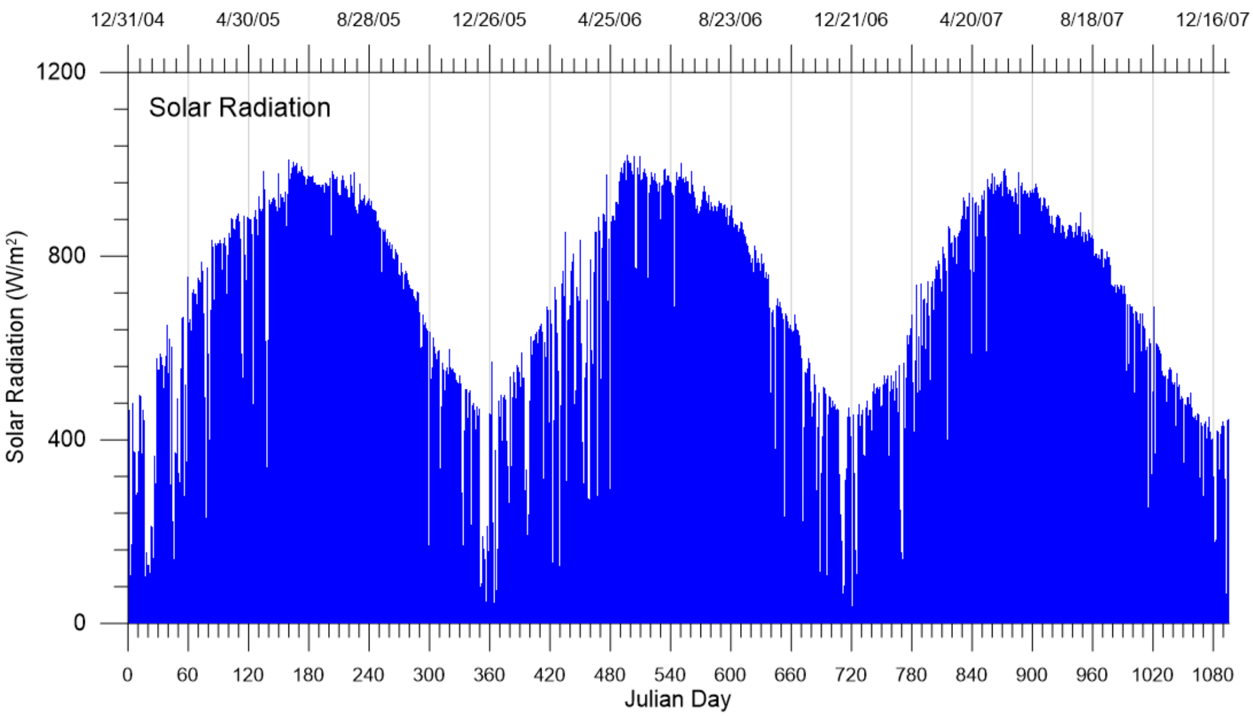


Figure 19. Radiation data measured at Suisun Valley CIMIS station between 2005 and 2007.

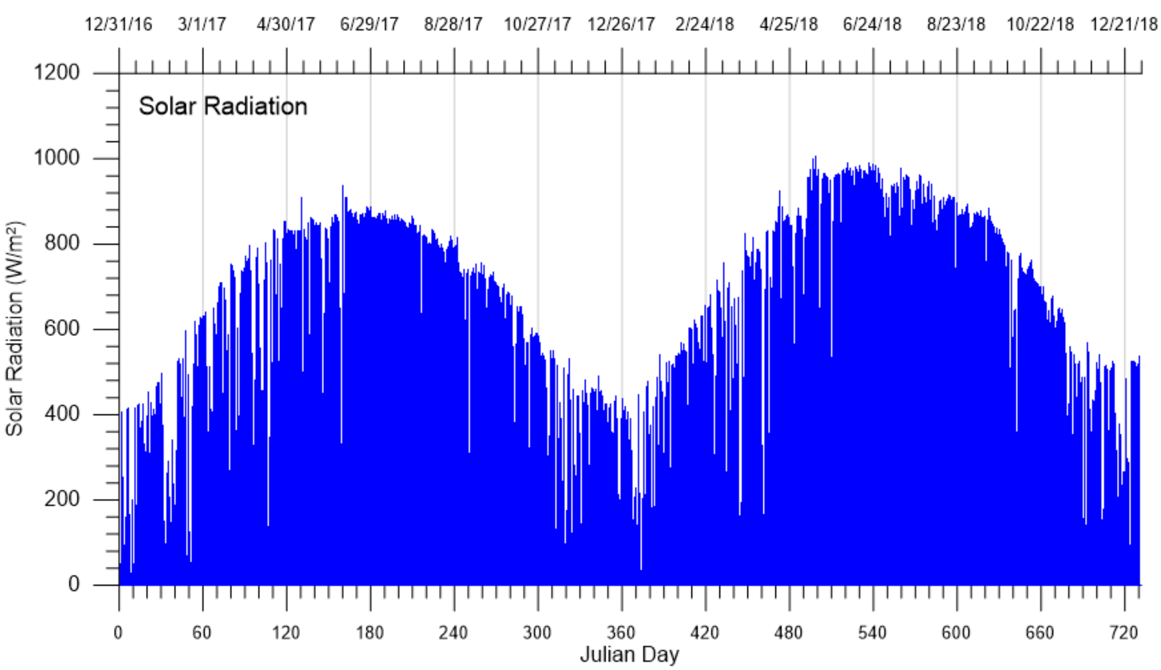


Figure 20. Radiation data measured at Oakville CIMIS station between 2017 and 2018.

Cloud cover inputs for the model were back calculated from short wave solar data. CE-QUAL-W2 uses cloud cover data and air temperature data to calculate long wave radiation. In the absence of measured cloud cover data, cloud cover data were back calculated (Cole and Wells 2018). Theoretical clear sky solar radiation was calculated based on the geographic location of the meteorological station. The ratio between the measured value and the theoretical clear sky radiation was used to calculate cloud cover a value ranging from 0 (no clouds) to 10 (complete cloud cover):

$$C = \sqrt{\frac{1}{0.0065}\left(1 - \frac{\varphi_{measured}}{\varphi_{theoretical\,clearsky}}\right)}$$

where C: cloud cover in tenths
$^{\phi}$measured: measured short-wave solar radiation
$^{\phi}$theoretical clear sky: computed from theoretical formulae with no cloud cover

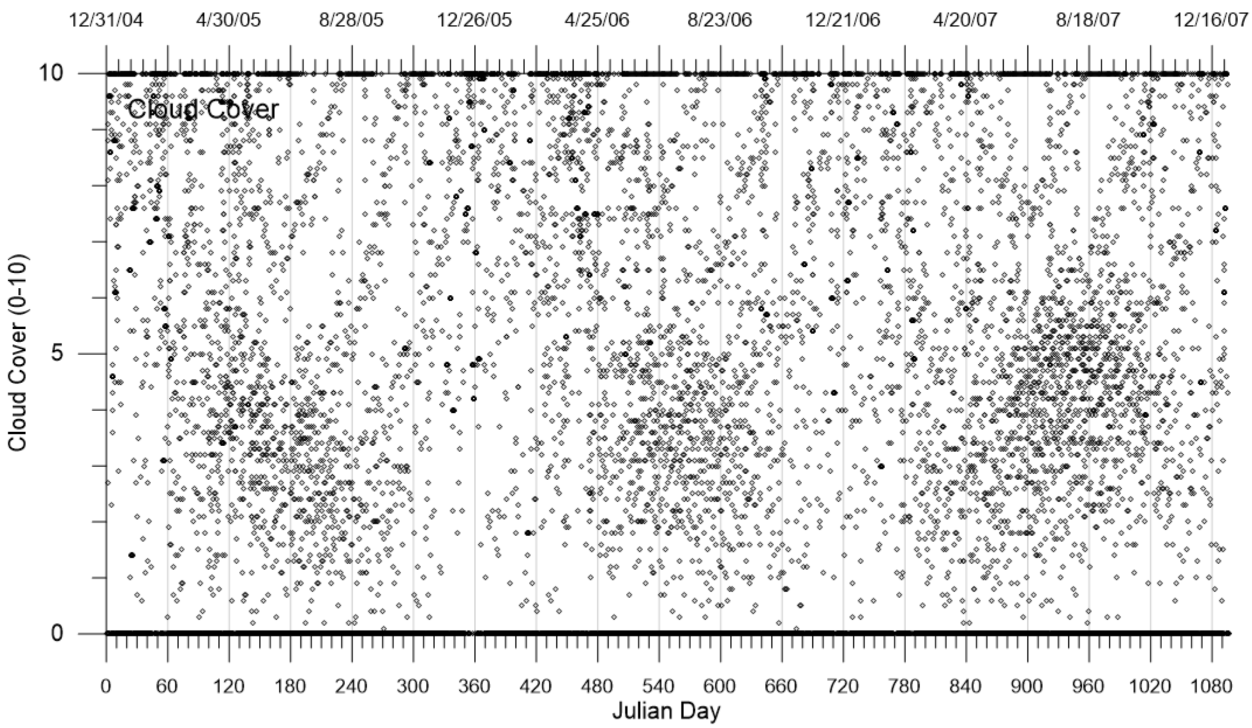


Figure 21. Cloud cover for the Lake Curry model from 2005-2007.

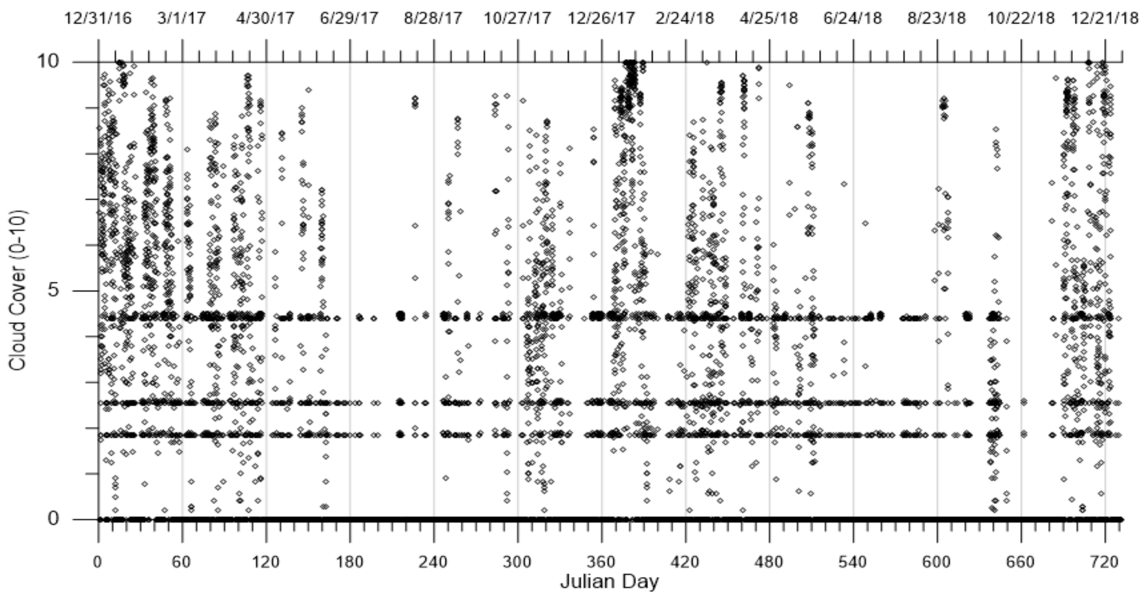


Figure 22. Cloud cover for Lake Curry model from 2017-2018.

Outflows

Water passing through the Lake Curry dam can flow over the spillway or flow through its outlet port. Modeled outflows for Lake Curry are plotted in Figure 23 for 2005-2007 and Figure 24 for 2017-2018. Documentation showing a spillway rating curve was available from historical dam drawings from the City of Vallejo (2018) and are shown in Appendix 1. The rating curve was digitized and fitted with a polynomial curve and spillway flow rates were estimated (Figure 25).

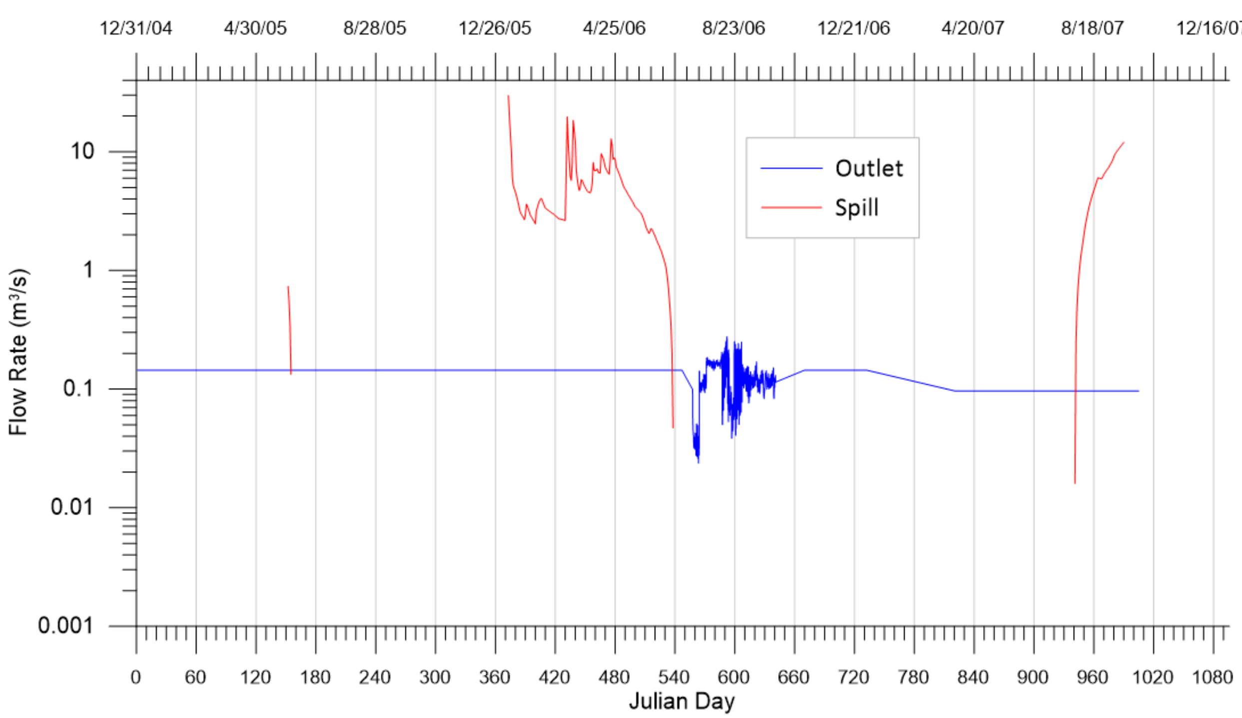


Figure 23. Lake Curry Dam outlet port and spill flow rates for 2005-2007.

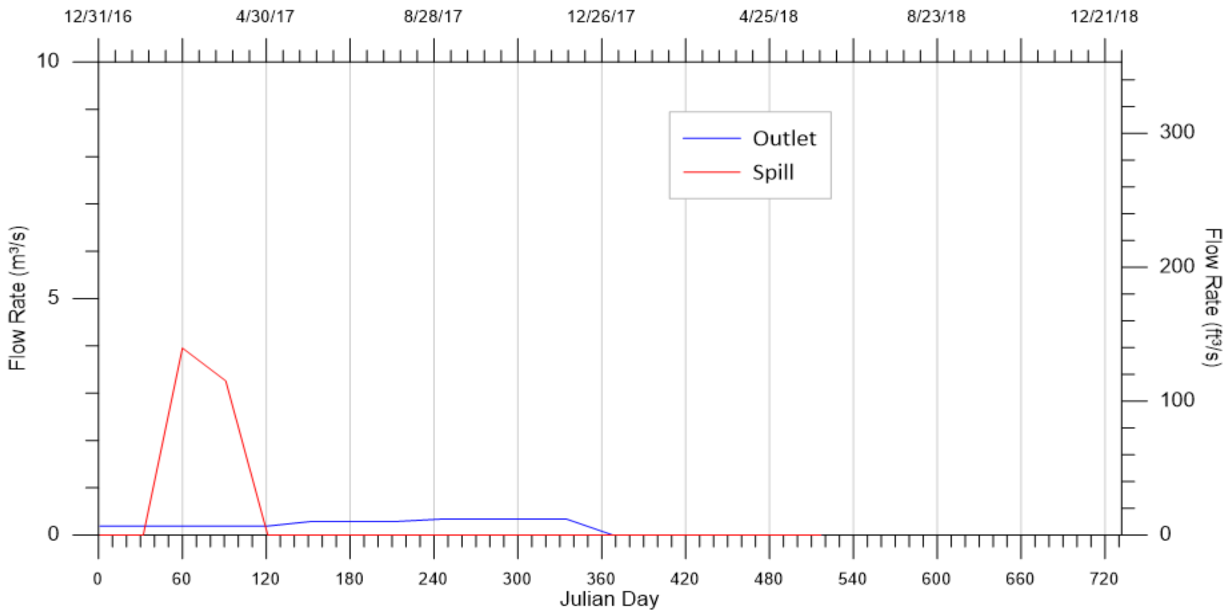


Figure 24. Lake Curry Dam outlet port and spill flow rates for 2017-2018. Outlet flow rates dropped to zero on 1/3/2018.

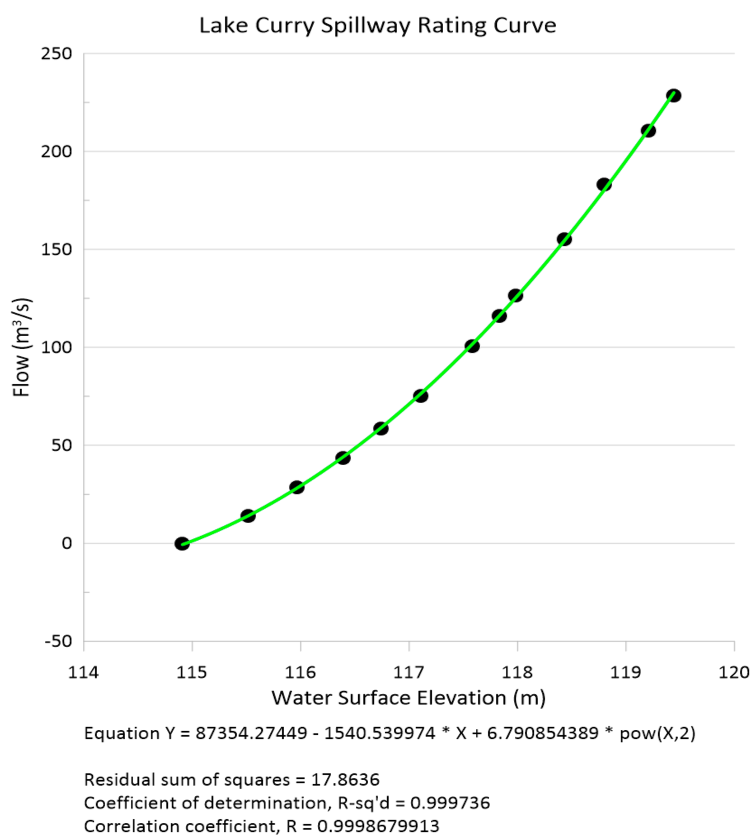


Figure 25. Spillway rating curve and fitted equation.

Inflows

Flow Rates

The CE-QUAL-W2 model was also used to model lake inflows by back-calculating required water inflow volumes in order to match the recorded lake stage over the course of the calibration period, as offset by outflows and evaporation/infiltration. The model was set up with 3 inflows: branch 1 and 2 inflows and a distributed inflow for branch 1 as shown in Figure 26. The distributed inflow distributes the flows to each model segment in the branch according to surface area. The inflow rates were estimated by performing a water balance using water level data and dam outflows. The flows from the water balance utility were disaggregated to the 3 inflows based on an assumed drainage basin contribution fraction of each basin. The fraction of total flows was 0.66, 0.09, and 0.25 for the branch 1 inflow, branch 2 inflow, and the distributed flow to branch 1, respectively. When the water balance predicted negative flows, these were only taken from the distributed tributary inflows.

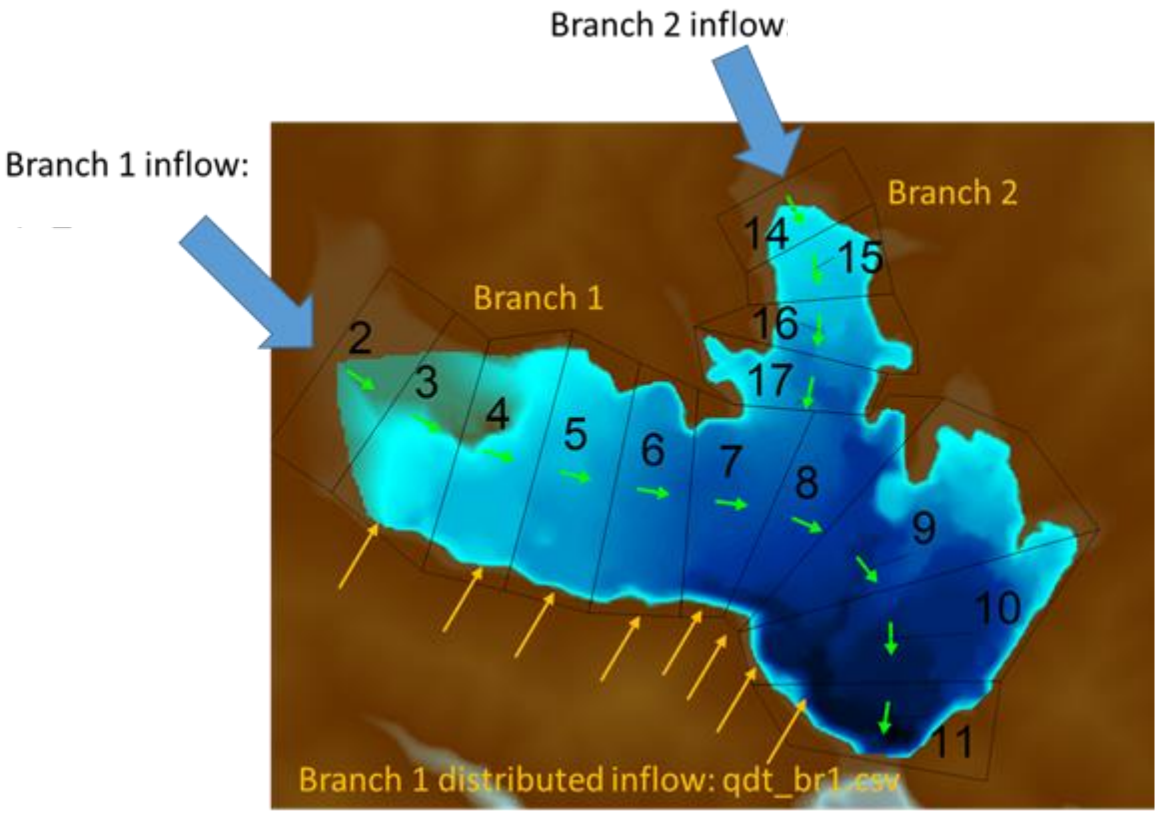


Figure 26. Model configuration for inflows, two branches and sheet flow from the Southwest.

Inflow Temperatures

Lake Curry inflow temperatures were estimated by calculating the 30-day average equilibrium temperature from the meteorological input data (Figure 27). The equilibrium temperature is a theoretical temperature based on the hourly meteorological file that represents the temperature the water is seeking, or when the net heat flux in and out is zero. An exponentially weighted average of the equilibrium temperature over a 30-day period was used.

During development of this model, Prof. Wells identified that the temperature of inflows to Lake Curry have a measurable impact to the temperature of the overall lake. No instrumentation was installed during the original model development nor during this most recent data collection phase to measure temperature in inflowing tributary streams. We recommend for future modeling that inflow rates and temperature be measured to evaluate the assumptions used in this model to further refine the accuracy of temperature predictions using CE-QUAL-W2.

It was noted though that the inflow temperature using just the meteorological data made the winter temperatures in the lake too cool when there was high inflow. The winter and fall temperatures were adjusted by Dr. Scott limiting winter temperatures to a minimum of 11° C and increasing temperatures by 1° C between October and April of each year from the computed equilibrium temperature as shown in Figure 28 for 2005-2007. A similar approach was taken for the 2017-2018 data based on Oakville meteorological data in Figure 29.

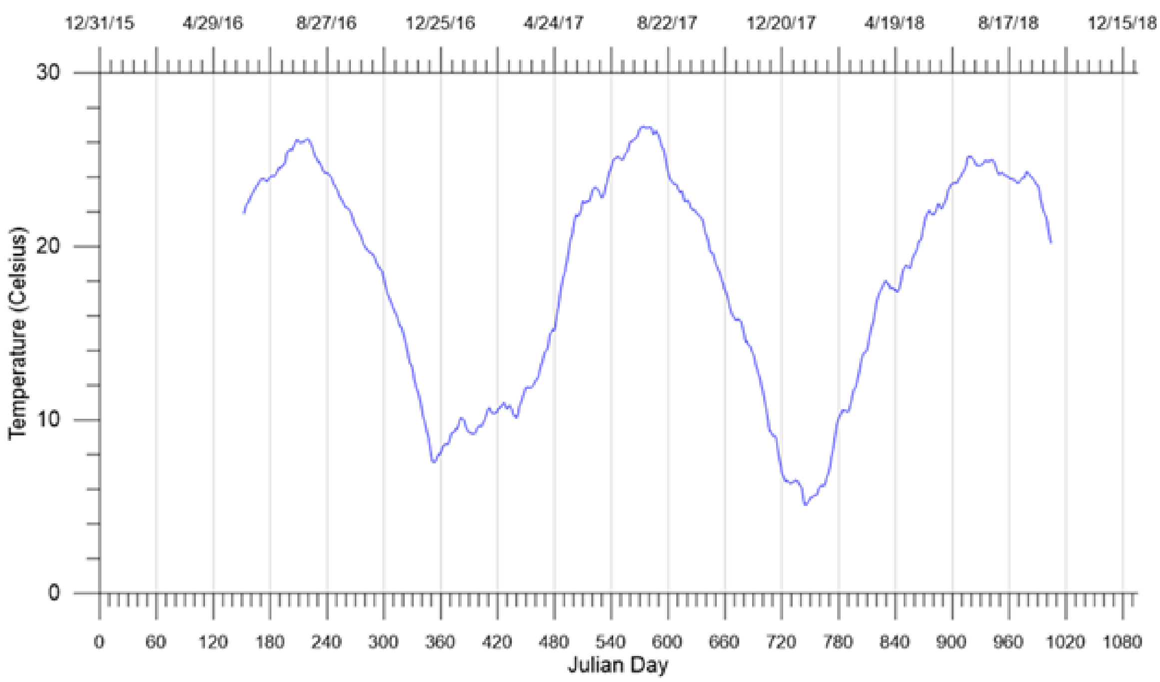


Figure 27. Estimated Lake Curry inflow temperatures using 30-day averages of equilibrium temperatures.

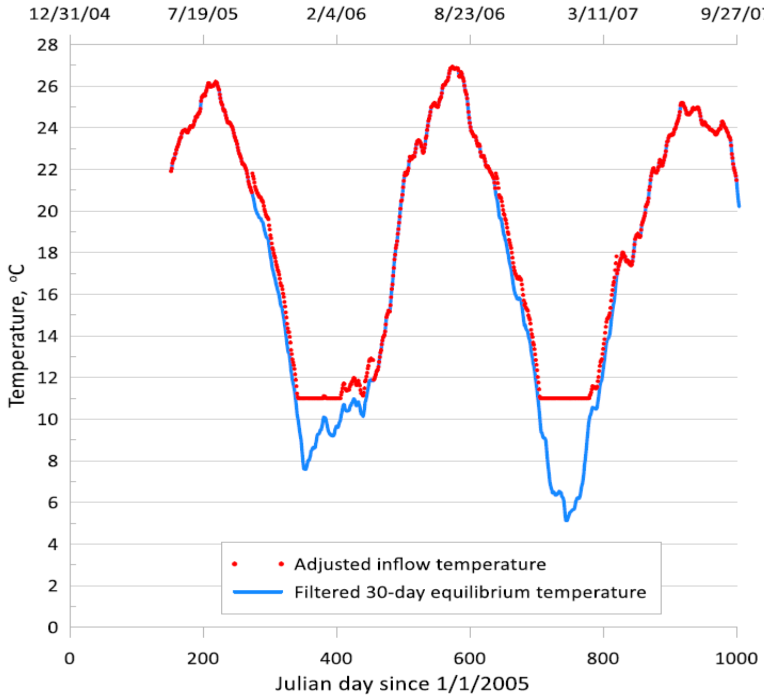


Figure 28. Adjusted inflow temperature for 2005-2007.

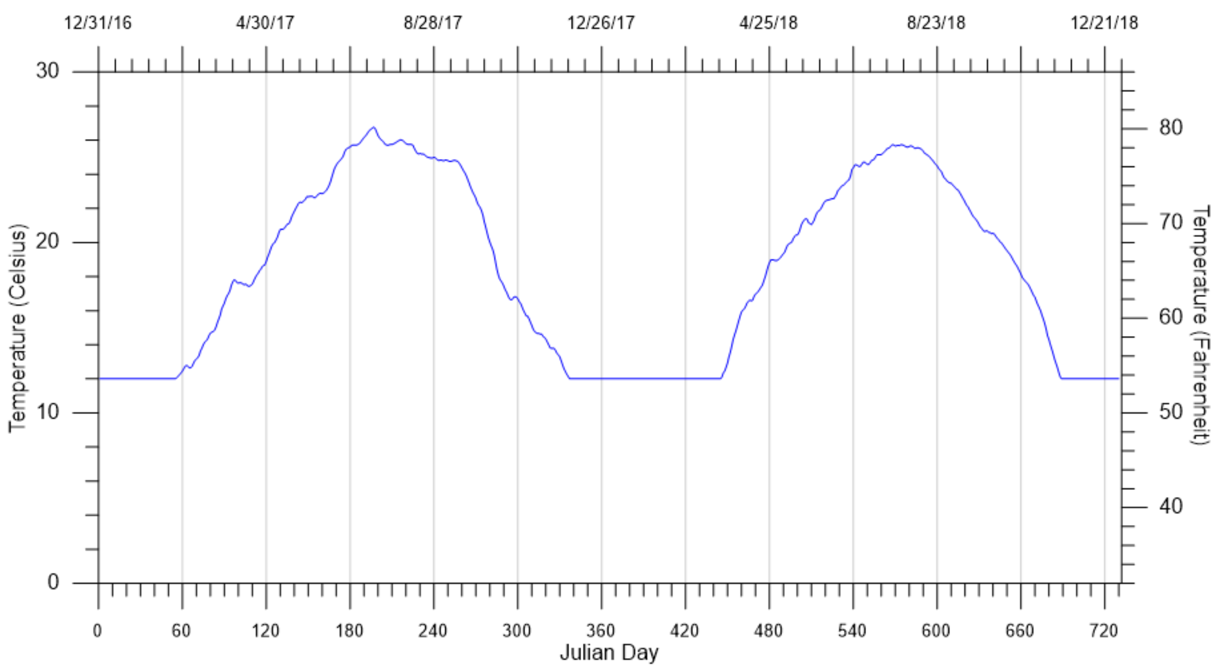


Figure 29. Estimated Lake Curry inflow temperatures 2017-2018.

Model Calibration

Approach

The model calibration periods were June 1, 2005 through September 17, 2007 and January 1, 2017 through December 30, 2018. This first period is consistent with the simulation period of the original model, and the second calibration period corresponds to times when additional water temperature data were collected. Calibration of the model included the following steps:

A. Development of model boundary conditions including meteorological inputs; boundary conditions, flows, temperature inputs; and dam operation data;
B. Hydrodynamic and temperature calibration to ensure correct water levels and flow rates are being simulated;
C. Development of draft model development and calibration report for peer review and comments;
D. Final model development and calibration report incorporating peer review comments.

Hydrodynamics were calibrated first. Once water levels and flows are being predicted adequately, temperature was then calibrated.

Our calibration approach is summarized in Figure 30. Instead of relying just on parameter adjustment to match measured field data, we also looked carefully at the measured inputs to the system as we performed the calibration. In order to demonstrate the prediction capability of the calibrated model, graphical comparisons and error statistics of model predictions compared to measured field data were developed. Model predictions were compared to field data for water level and temperature.

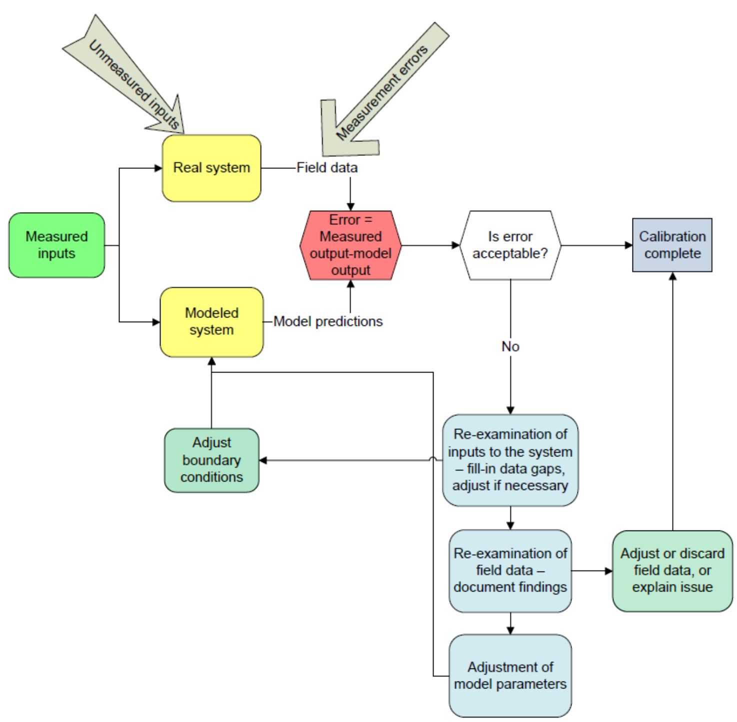


Figure 30. Calibration approach.

Results

Water Level

Lake Curry water level predictions are compared with data in Figures 31 and 32. Mean error (ME) for water level predictions was -0.004 to -0.002 m and mean absolute error was 0.005 to 0.002 m.

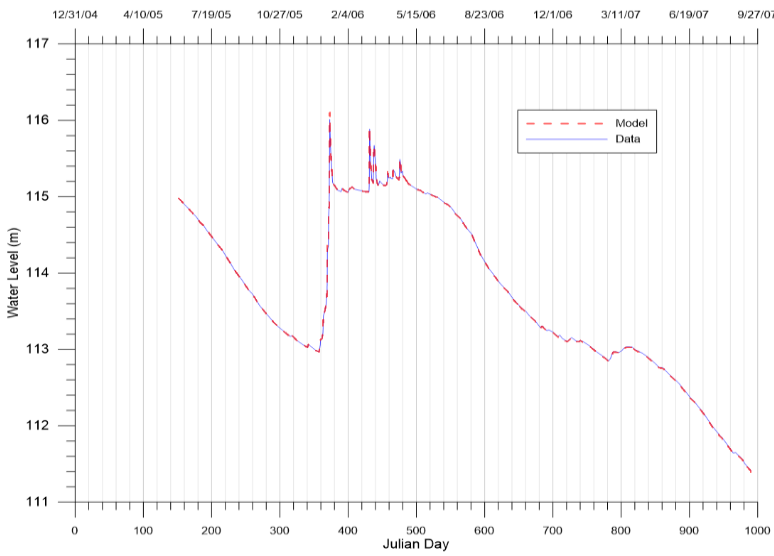


Figure 31. Model predicted water surface elevations compared with 2005-2007 Lake Curry data.

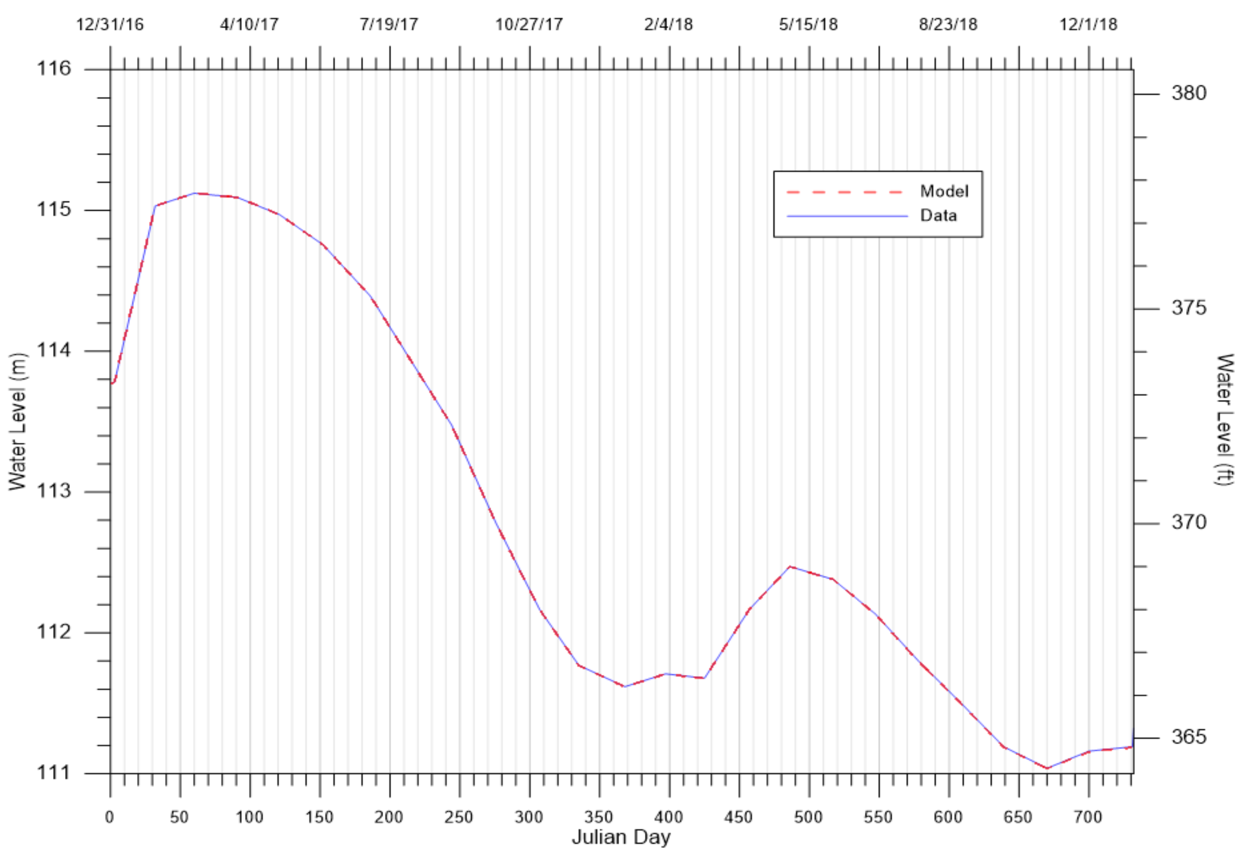


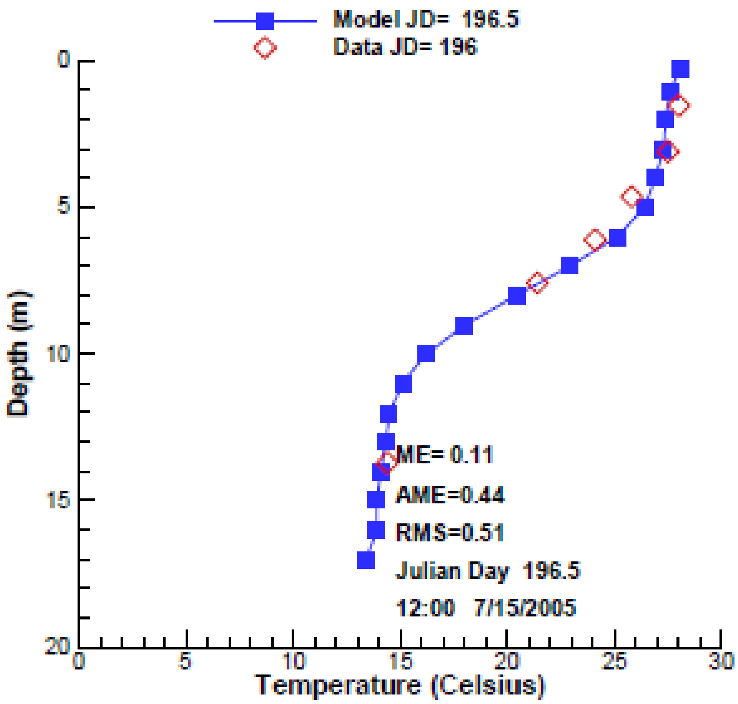
Figure 32. Model predicted water surface elevations compared with 2017-2018 Lake Curry data.

Temperature 2005-2007

Temperature vertical profile data digitized from the original report were used to compare to model predictions. Data were available from site Buoy A (S-3 on Figure 2), located just upstream of the dam. The mean error (ME) of the temperature predictions was 0.08 °C and the mean absolute error (MAE) was 0.80 °C. Model predicted temperature vertical profiles are compared with data in Figure 33 and 34 as well as additional figures in Appendix 1. Surface temperatures at Buoy A were compared to model predictions in Figure 35 showing that the model predictions followed well the heating and cooling trend of the data.

Temperature 2017-2018

Continuous data were available from several sites and at multiple depths in 2017-2018 (Figure 7). The buoy sensor data (S1, S2, and S3 stations) were inconsistent with the line sensor data collected in 2018 (stations el308, el320, el332, etc.). The buoy sensor elevations were measured at deployment, but as the lake level dropped sensor elevation changed and converged. The elevations of the line sensors were fixed because the line was attached to the dam face. Because the elevations of the sensors attached to the buoys were unknown, these data were not included in the temperature calibration. Figure 36 depicts the model predictions and measured data for one of the line sensors. Additional graphs are included in Appendix 1.



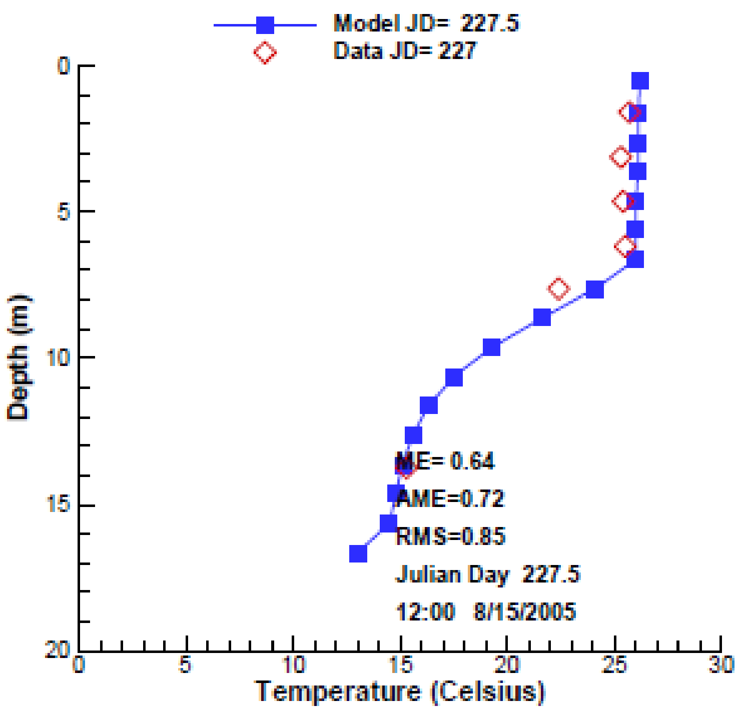


Figure 33 and 34. Vertical profile of modeled temperature compared with data for 7/15/2005 and 8/15/2005. Additional graphs of this comparison are in Appendix 1.

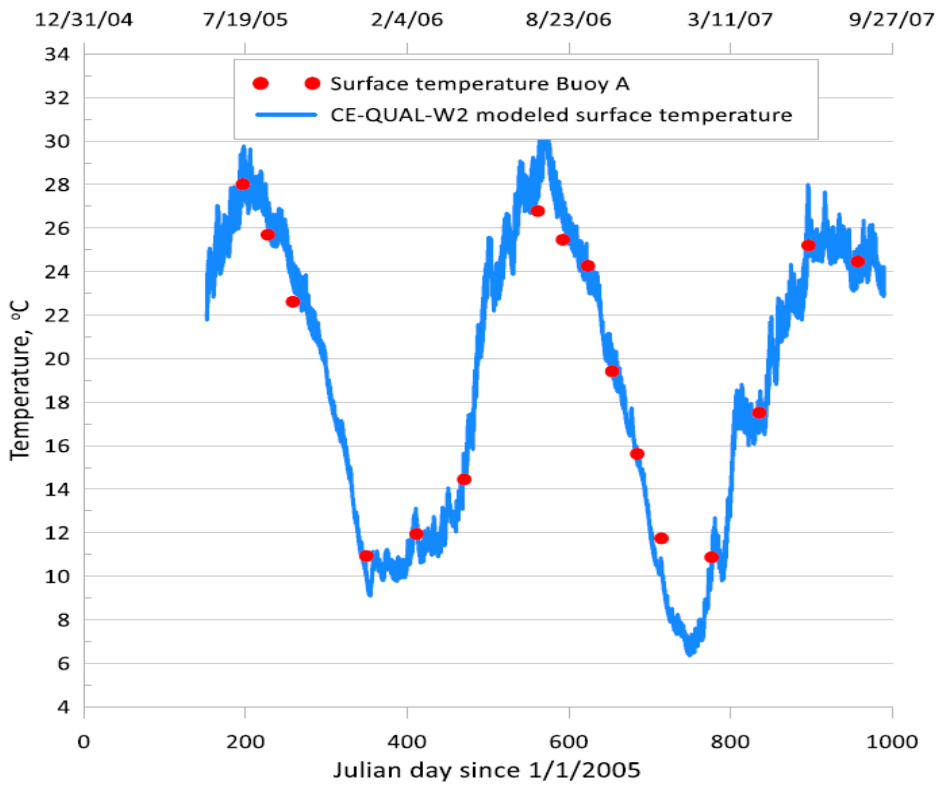


Figure 35. Comparison of Lake Curry surface temperature to model predictions between 2005-2007. Additional graphs of this comparison are in Appendix 1.

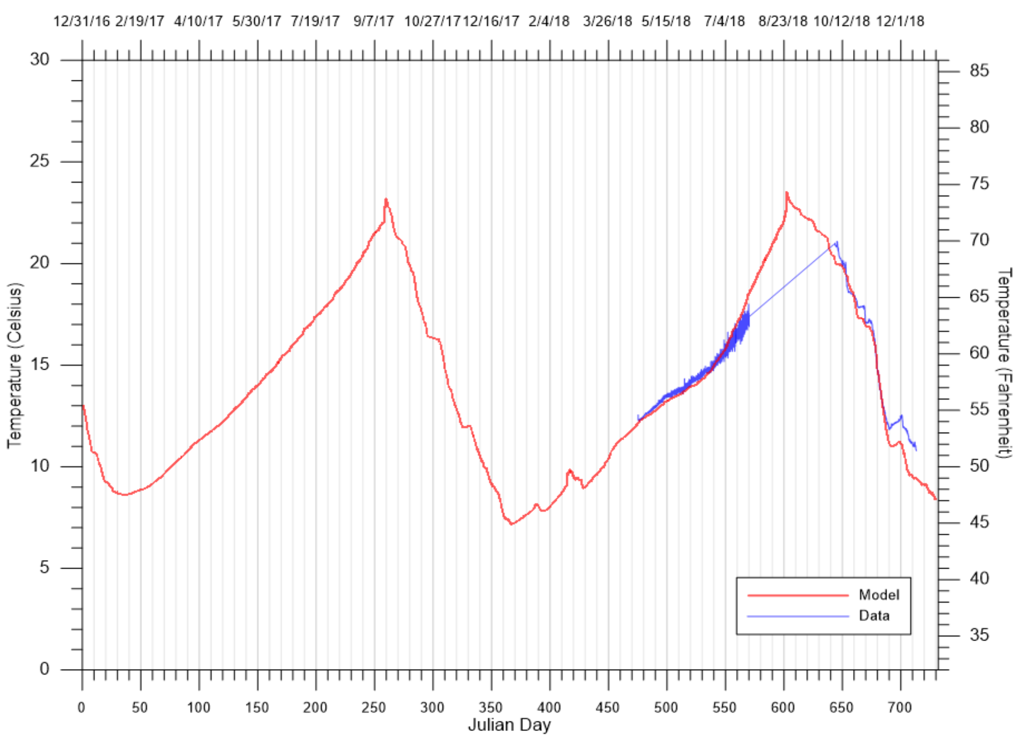


Figure 36. Model predicted temperatures compared with data measured at station el320 (320 ft.). Additional graphs of this comparison are in Appendix 1.

Model Results: Lake Curry Temperatures

Figures 37-46 depict modeled water temperatures at various depths of Lake Curry for a normal rainfall year (2016) assuming a full reservoir in January. As would be expected Jan.-April water temperatures are cold between 46.4^{o} F to 57.2^{o} F (Figure 37-41). In May the lower depths of the lake are 68^{o} F to 57.2^{o} F with surface layers reaching 71.6^{o} to 75.2^{o} F (Figure 41). Figures 42 and 43 depict modeled lake temperatures in June and July with cool water < 68^{o} F remaining at the bottom of the lake while surface water heats up. This shows the lake stratifies by temperature over the summer. August (Figure 45) has the smallest cold water pool of the summer months. In September the cooler water area rapidly expands as the lake turns over losing the temperature stratification as solar inputs are reduced with the change in season (Figure 46). As solar inputs continue to decrease through the fall (October-December) the lake water continues to cool.

Figures 37-46 also show the approximate elevation of the outlet pipe that discharges to Suisun Creek. For the modeling we are assuming a single elevation outlet but the City of Vallejo did some work on the outlet in 2019 which could have changed this elevation. Our request to the City about what was changed was not answered. Throughout the months depicted cool water is available for release from this outlet to sustain steelhead habitat in Suisun Creek.

We have found that the model slightly over estimates outlet temperatures by up to 3^{o}F when compared to water temperatures measured at the outlet pipe from 2017-2020. This means the model is conservative in determining the benefit of reservoir releases for steelhead in Suisun Creek.

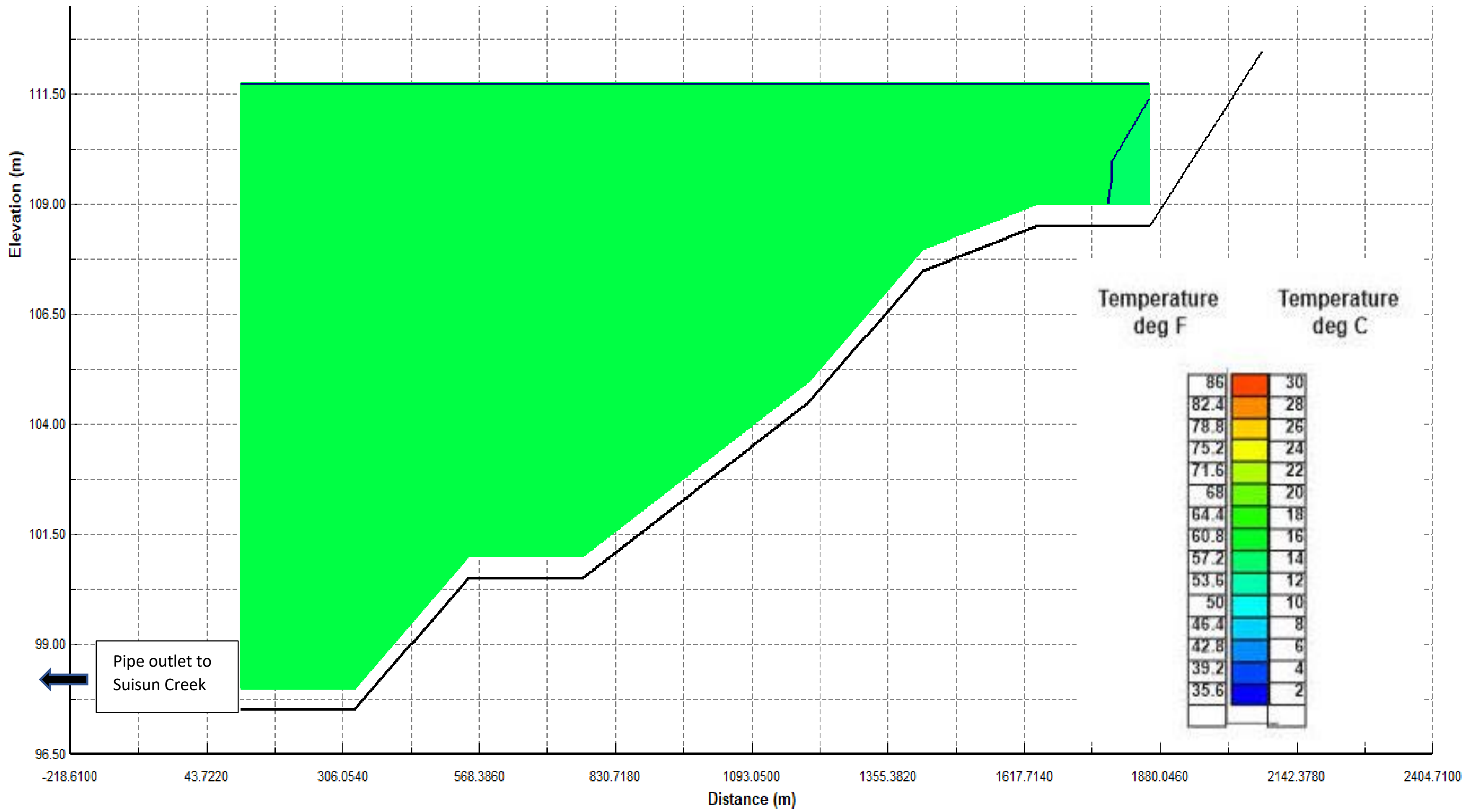


Figure 37. Profile of modeled temperature distribution on January 1, 2016 (normal rainfall year) in Lake Curry.

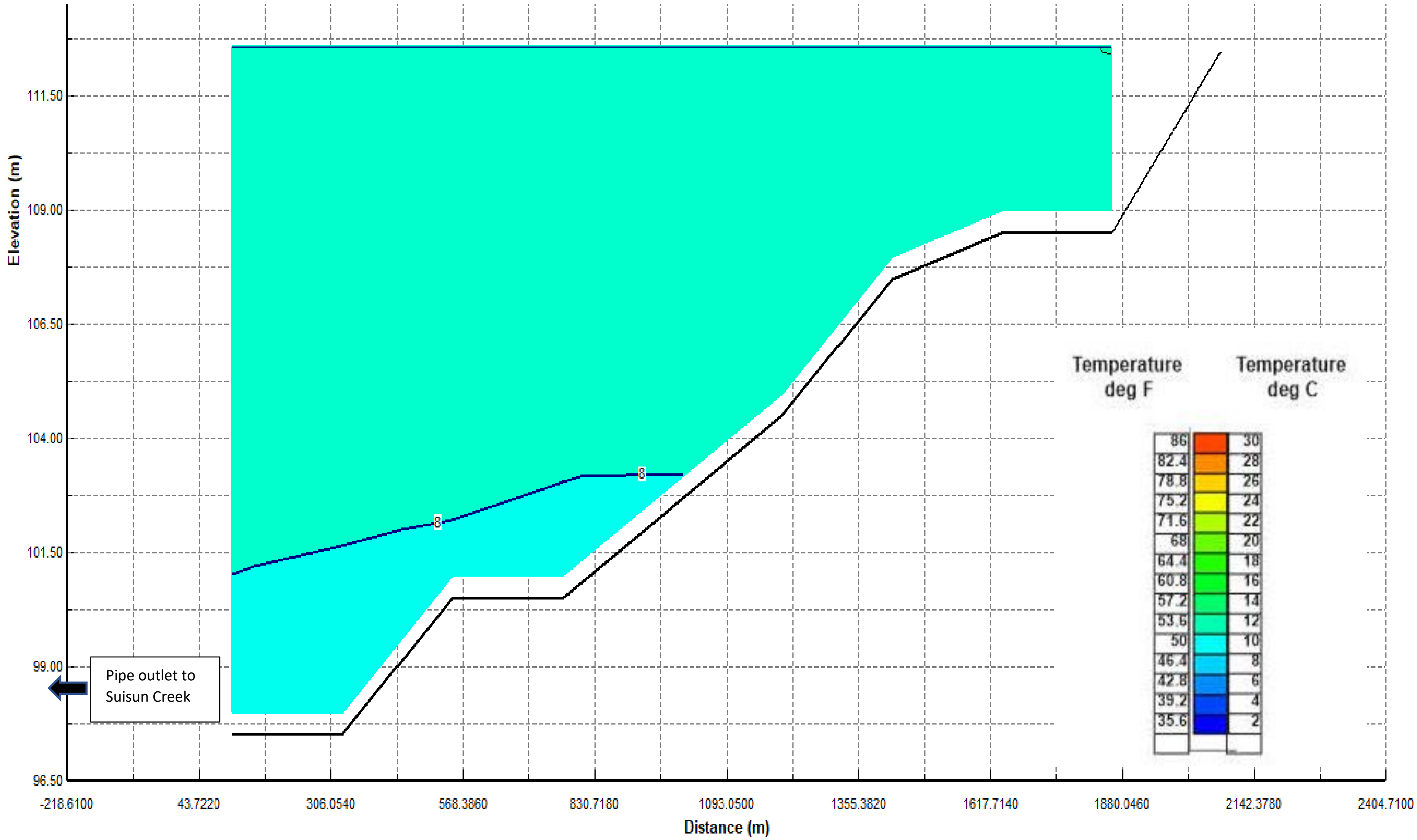


Figure 38. Profile of modeled temperature distribution on January 31, 2016 (normal rainfall year) in Lake Curry.

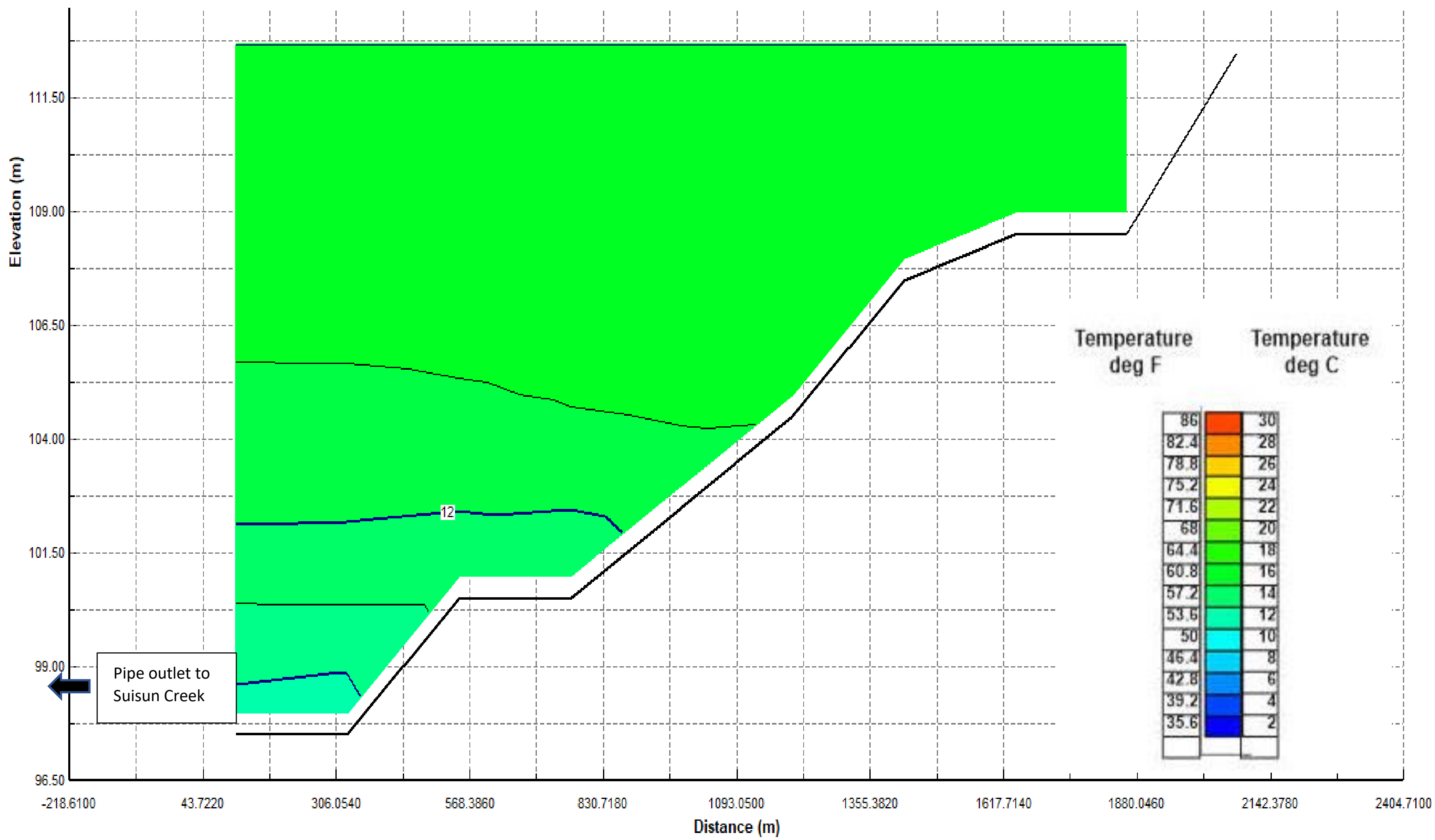


Figure 39. Profile of modeled temperature distribution on March 1, 2016 (normal rainfall year) in Lake Curry.

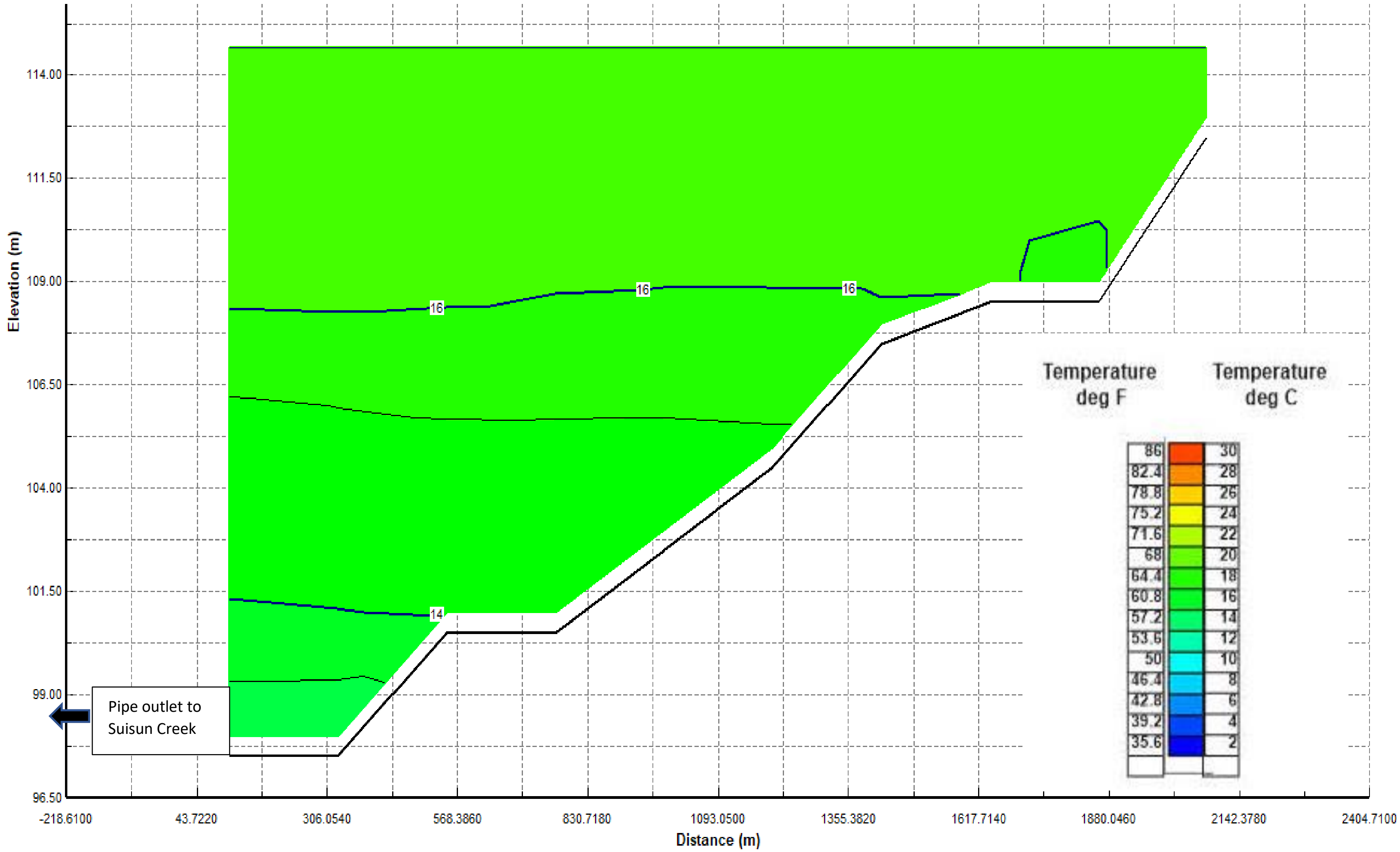


Figure 40. Profile of modeled temperature distribution on March 31, 2016 (normal rainfall year) in Lake Curry.

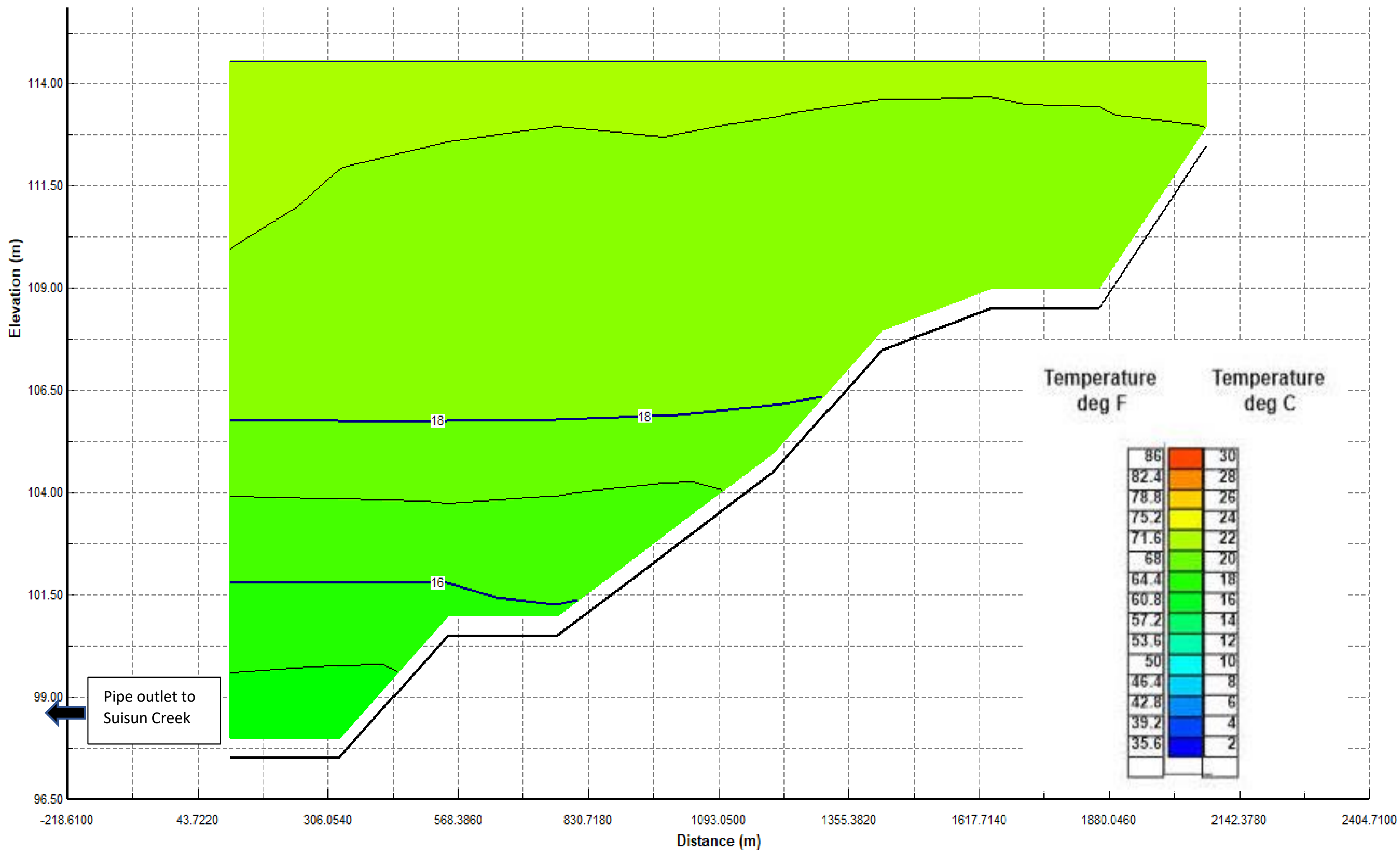


Figure 41. Profile of modeled temperature distribution on April 30, 2016 (normal rainfall year) in Lake Curry.

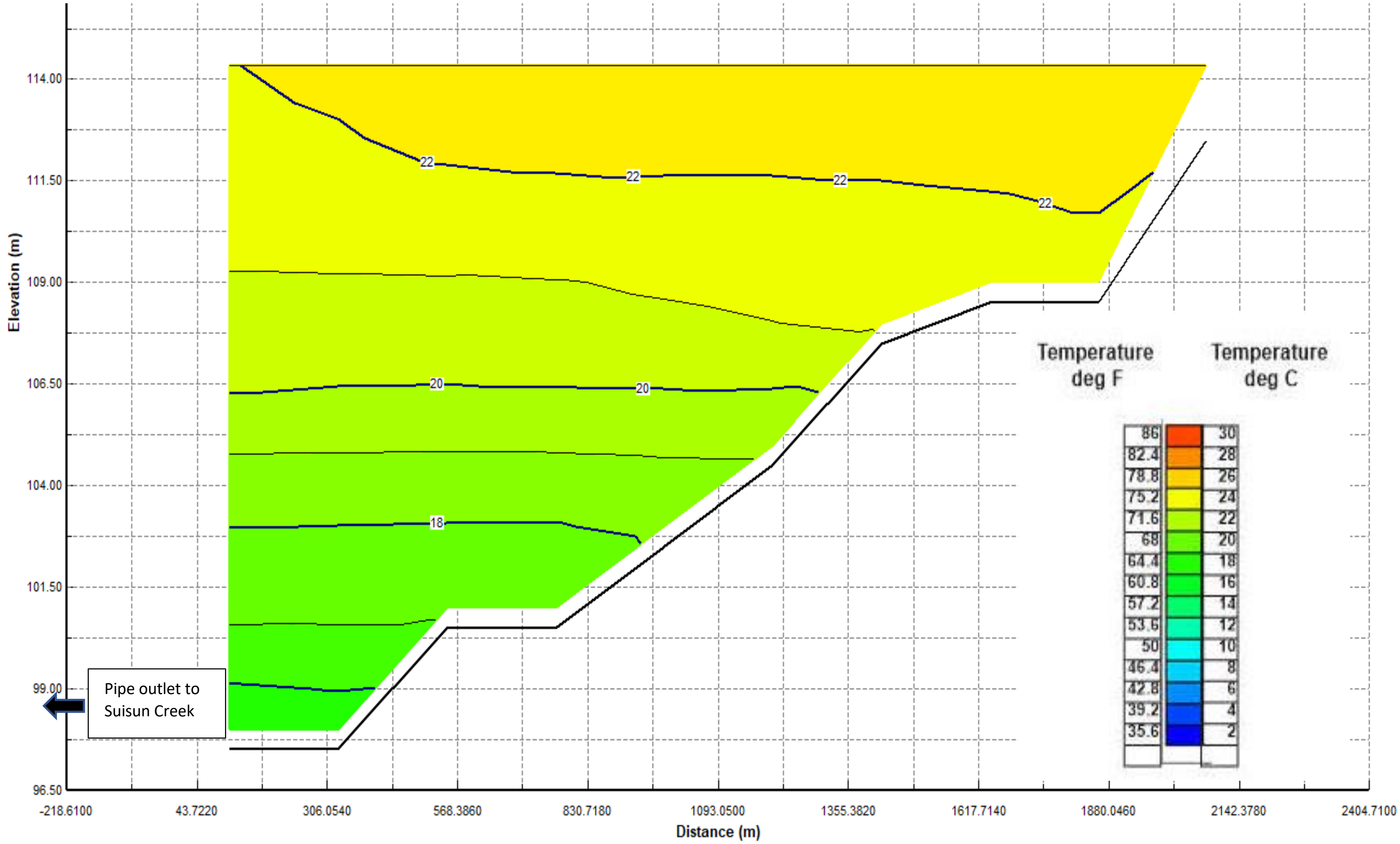


Figure 42. Profile of modeled temperature distribution on May 30, 2016 (normal rainfall year) in Lake Curry.

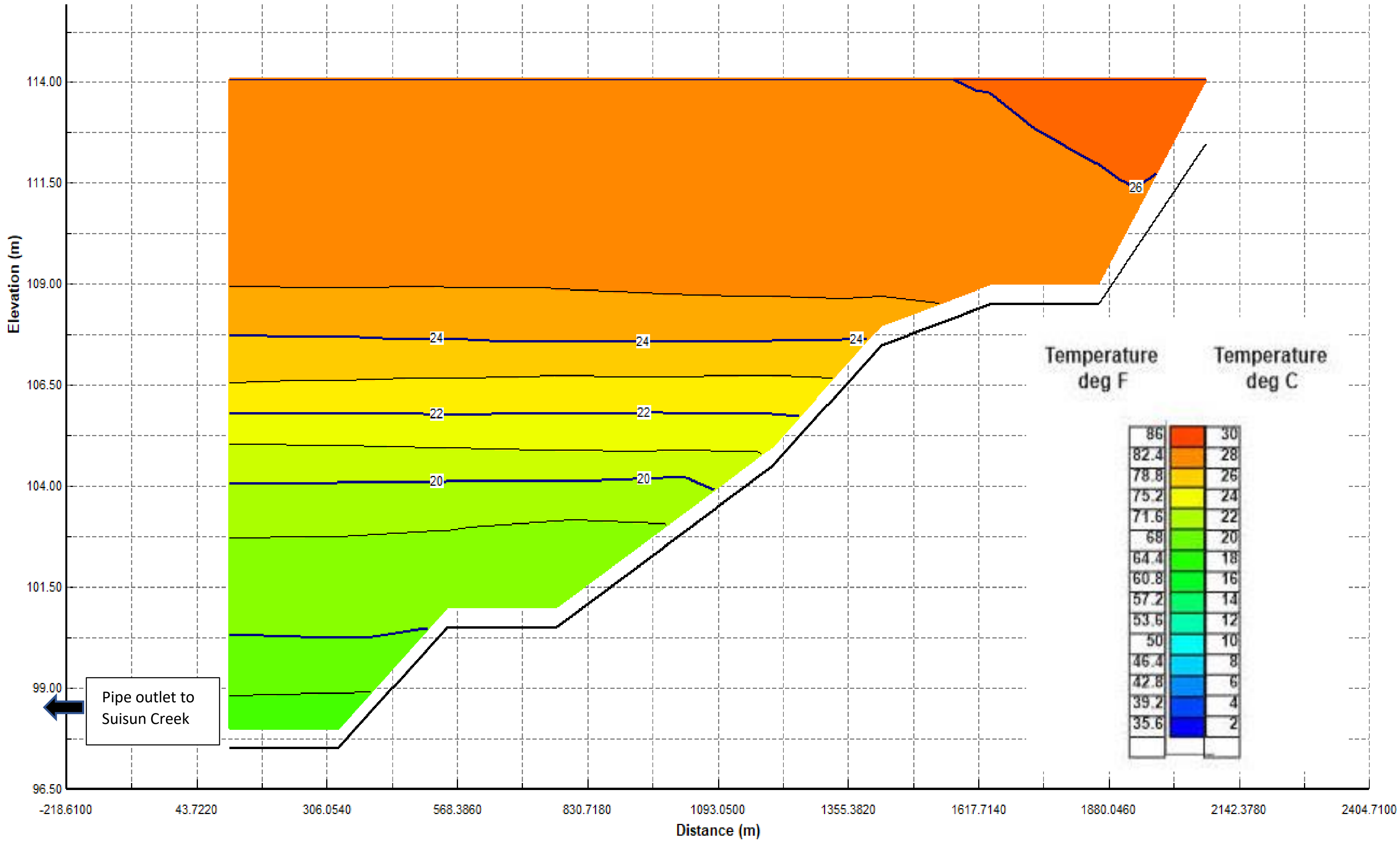


Figure 43. Profile of modeled temperature distribution on June 29, 2016 (normal rainfall year) in Lake Curry.

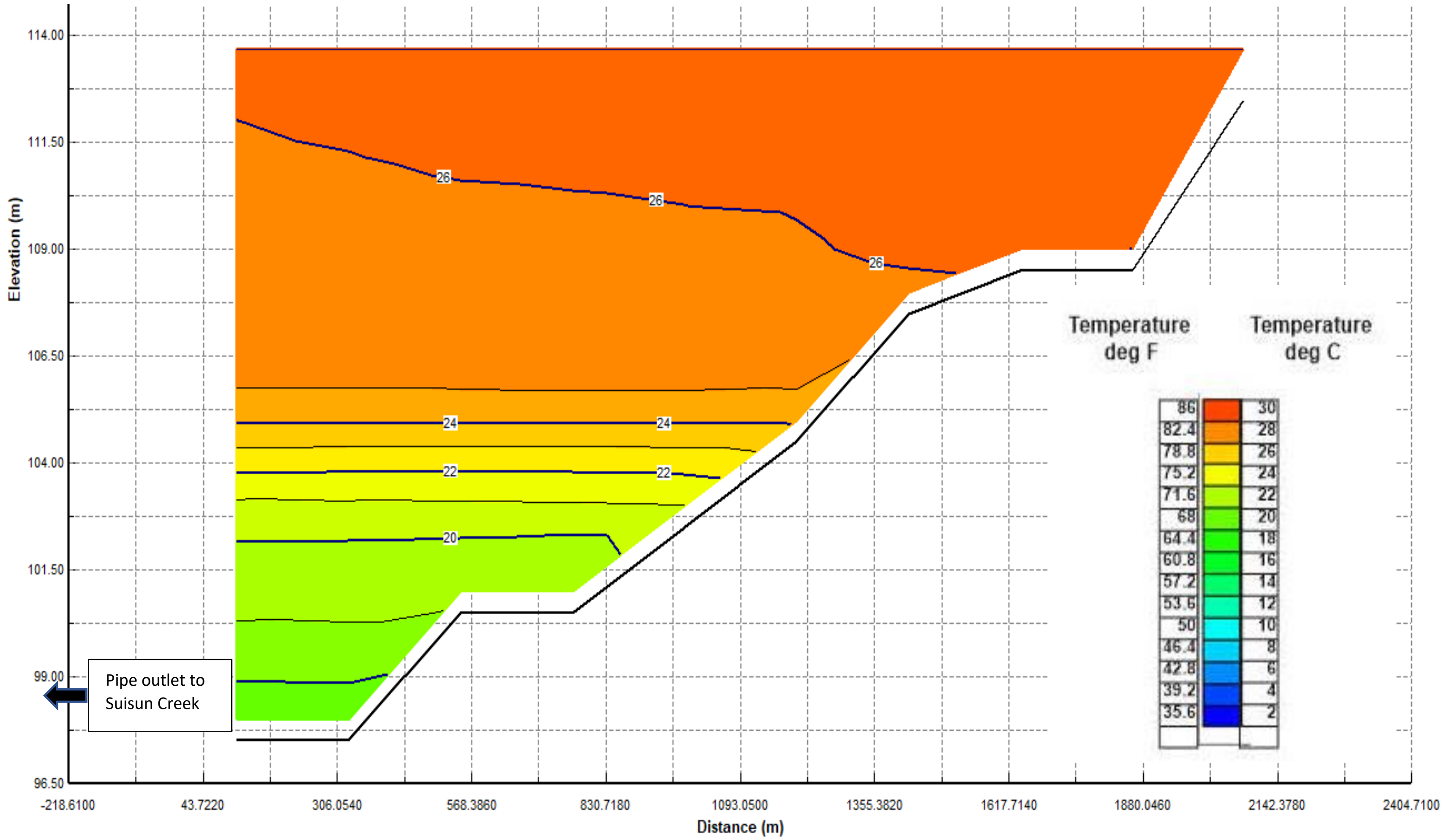


Figure 44. Profile of modeled temperature distribution on July 29, 2016 (normal rainfall year) in Lake Curry.

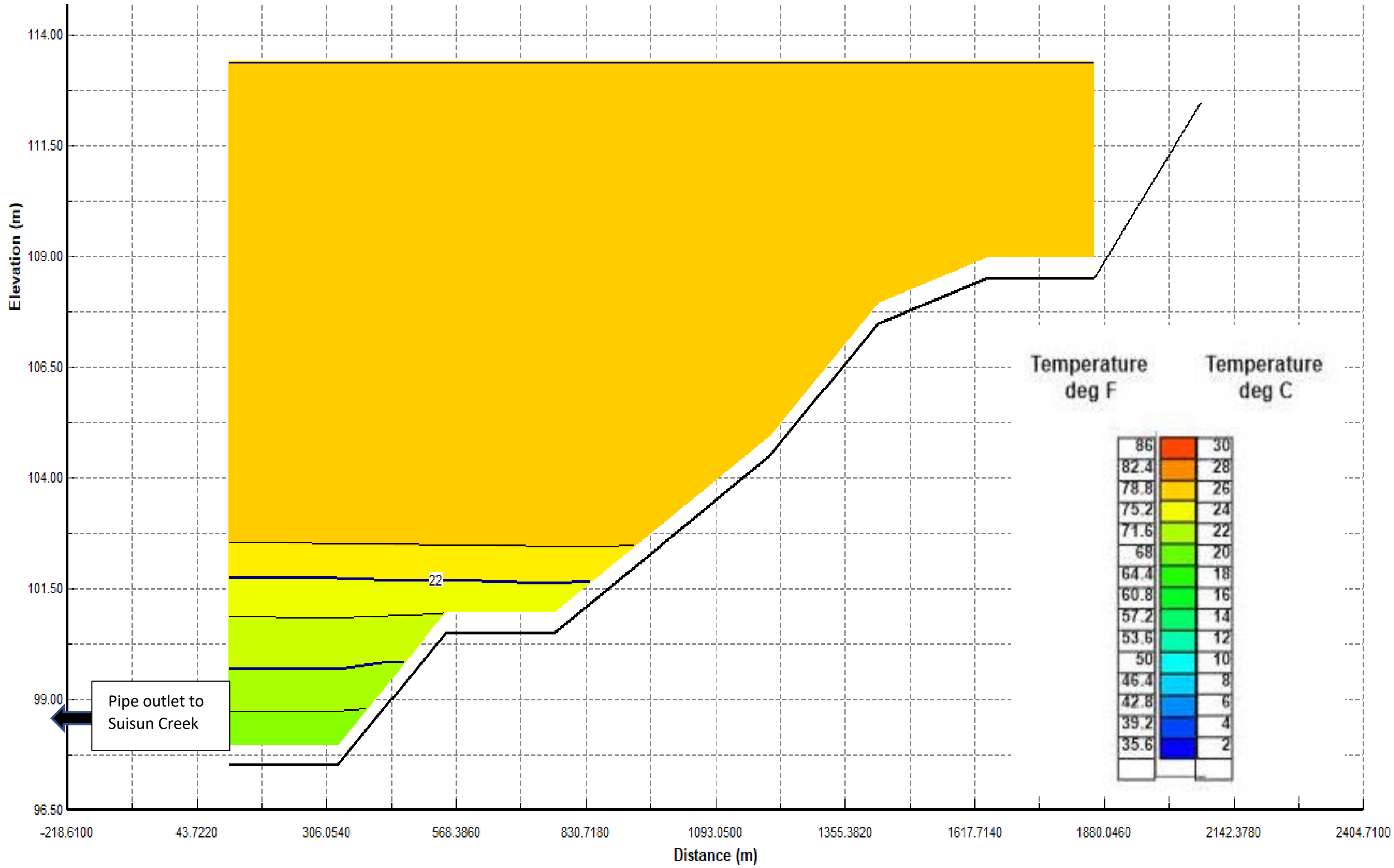


Figure 45. Profile of modeled temperature distribution on August 28, 2016 (normal rainfall year) in Lake Curry.

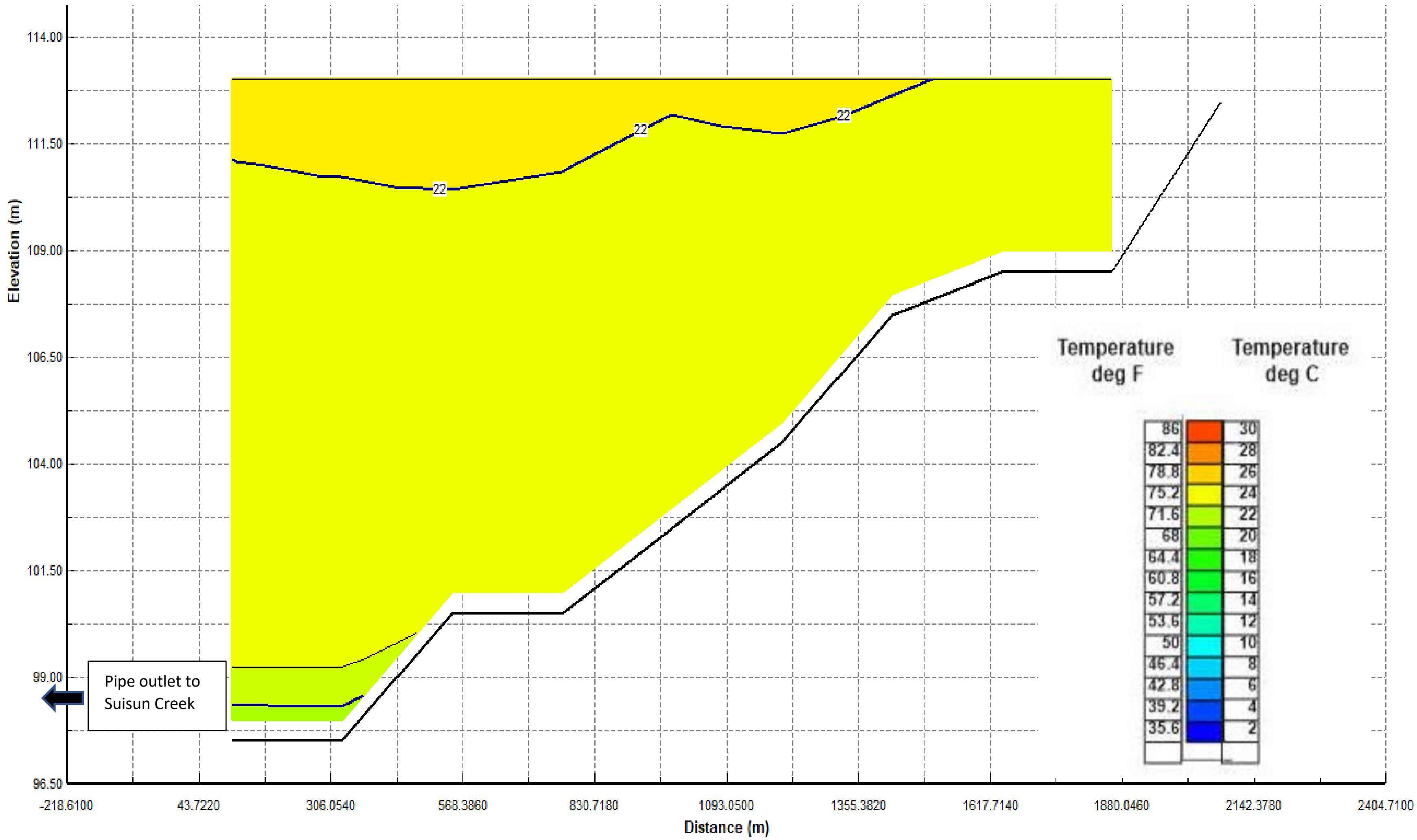


Figure 46. Profile of modeled temperature distribution on September 27, 2016 (normal rainfall year) in Lake Curry.

Modeled Release Scenarios

In the grant a number of lake release scenarios are defined for evaluation. Most of these scenarios were evaluated using the CE-QUAL-W2 model as calibrated for Lake Curry. All modeled scenarios were completed for a dry, normal and wet rainfall year. We selected three different years to represent these 3 rainfall conditions (Table 1). The year 1983 was selected as a wet year. This was an El Nino year with numerous atmospheric rivers and had total rainfall of 173% of normal levels. The year 2016 was used as the normal year as average amounts of rainfall occurred. The year 2013 was used as the dry year when rainfall was 13% of normal.

The model provides outputs of the temperature at the lake outlet (325 ft. elevation) and the water level in the lake over the year. We developed the scenarios through conversations with the National Marine Fisheries Service and Ca. Dept. of Fish and Wildlife, the City of Vallejo, our consultants and our stakeholder group.

Table 1. Summary of rainfall years used in model

Climatic Year	Meteorological year data used	Starting reservoir level used in model
Wet	1983	Starting reservoir water level of 377.0 ft.
Normal	2016	Starting reservoir water level of 377.0 ft.
Dry	2013	Starting reservoir water level of 370.0 ft.

The scenarios we evaluated include:

Scenario 1

From the grant: "Provide a nominal release of 2.5 cfs and maintain Lake Curry level at full for dry years. Release 5.5 cfs from April 1 to November 1 under dry, normal and wet years." We modified this alternative to include 3 different base flow levels of 2.5, 4 and 6 cfs released from the lake 24 hrs. a day from May 1 to Sept 30 (Table 2). We applied these baseflows to all three rainfall years. The 2.5cfs release is the minimal release level that can sustain connected flow from the reservoir outlet to station SC 6.0 or slightly further downstream depending on the climatic year. A lower release of 1-2 cfs will result in intermittent pools that can have low dissolved oxygen but would conserve water for consecutive dry years

Table 2. Scenario Set #1

Year	Scenario	Base Flow #1	Scenario	Base Flow #2	Scenario	Base Flow #3	Time period for each base flow 1-3
Dry	1A	2.5 cfs	1B	4 cfs	1C	6 cfs	May 1-Sept 30
Normal	1D	2.5 cfs	1E	4 cfs	1F	6 cfs	May 1-Sept 30
Wet	1G	2.5 cfs	1H	4 cfs	1I	6 cfs	May 1-Sept 30

From the grant: "Evaluate the relationship of the rainfall and summer water temperatures through comparisons of long-term records of these data sets. This evaluation will determine if dry winters are correlated with hot summers and therefore if conservation of reservoir water for release in dry years is important." We were not able to include Lake Curry levels in this analysis as we don't have long term records of lake levels. As Figure 47 shows there is no clear relationship between low rainfall winters and high summer temperatures.

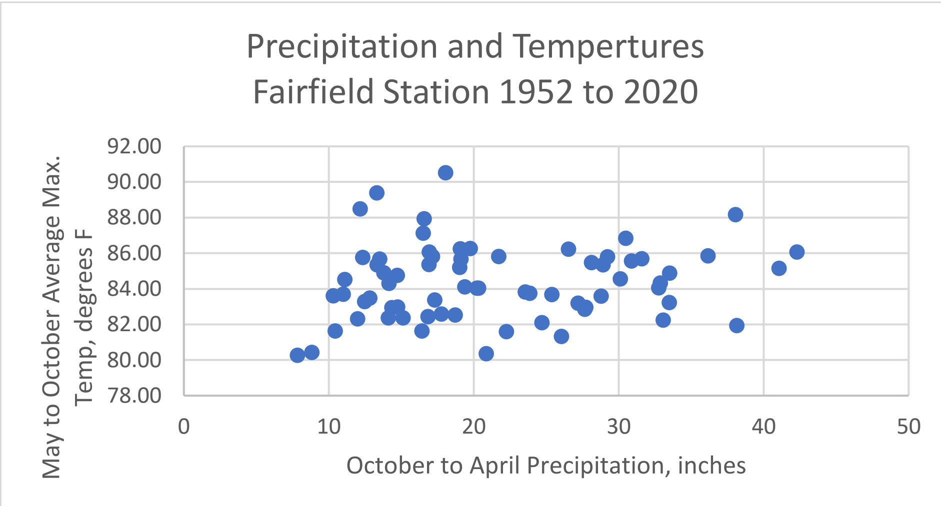


Figure 47. Winter precipitation and summer air temperatures as recorded at Fairfield Station. There is no clear relationship between low rainfall winters and high summer temperatures.

<u>Scenario 2</u>

From the grant: "Release nominal amounts (2.5 cfs) until the hottest months of the summer—July/August—then increase releases to 6 or 8 cfs unless air temperatures are abnormally mild." This scenario varies flow levels for different weeks over the summer. Releases are 24 hours a day. Relative low levels (2-4 cfs) are released in May when air temperatures tend to be lower. Releases are increased to 4-6 cfs for the month of June. For July when the highest air temperatures occur releases are increased to 6 cfs. For August releases are reduced to 4 cfs and for September to 2-4 cfs (Table 3). Changes between flow levels would be made slowly by changing 0.5 cfs/day

Table 3. Scenario Set #2

Year	Scenario	Flow week 1-4 starting May 1	Flow week 5-8 starting June 1	Flow week 9-12 starting July 1	Flow week 13-16 starting August 1	Flow week 17-21 starting Sept. 1
Dry	2A	2	4	6	4	2
Normal	2B	2	6	6	4	4
Wet	2C	4	6	6	4	4

<u>Scenarios 3 and 4</u>

From the grant: "Evaluate the long-term air temperature record from gages in the Lake Curry area. Define an air temperature that triggers the maximum water temperature objectives and therefore changes the release rate. This scenario would provide for a nominal release (2.5 cfs) until weather predictions forecast that air temperatures will reach the trigger air temperature and as a result water releases are increased to 6 or 8 cfs from 10 am to 6 pm over the heat wave period." We evaluated the occurrence of three temperatures (90, 95 and 110^{o} F) using the air temperatures used in the model for each climatic year (Table 4). Two trigger temperatures were defined at 90^{o} F and 95^{o} F. The base flow was defined as 1-3 cfs based on the climatic year (Table 5 and 6). The pulse releases from 10 am to 6 pm evaluated were 4-6 cfs depending on the climatic year.

Table 4. Evaluation of Trigger Temperatures

Maximum Air Temperature	Number of days when maximum air temperatures are exceeded		
	Wet year 1983	Normal year 2016	Dry year 2013
90^{o} F	52	66	61
95^{o} F	28	35	29
110^{o} F	19	16	10

Table 5. Scenario Set #3

Year	Scenario	Base flow	Pulse amount	Air temperature trigger	Pulse period
Dry	3A	1 cfs	4 cfs	90^{o} F	10 am-6 pm
Normal	3B	2.5 cfs	6 cfs	90^{o} F	10 am-6 pm
Wet	3C	3 cfs	6 cfs	90^{o} F	10 am-6 pm

Table 6. Scenario Set #4

Year	Scenario	Base flow	Pulse amount	Air temperature trigger	Pulse period
Dry	4A	1 cfs	4 cfs	95^{o} F	10 am-6 pm
Normal	4B	2.5 cfs	6 cfs	95^{o} F	10 am-6 pm
Wet	4C	3 cfs	6 cfs	95^{o} F	10 am-6 pm

<u>Scenario 5</u>

An additional alternative evaluated the ability to release water from Lake Curry during the October 1-April 30 period along with the May-Sept. period. This alternative was suggested to assure a dedicated year-round base flow to support all parts of the steelhead lifecycle in the Upper Suisun Creek. Three base flows were evaluated. For the migration/spawning period of Oct. 1-Dec 31, 2.5 cfs would be released 24 hours a day. From Jan. 1-March 31, 4 cfs would be released 24 hours a day to support spawning and egg incubation. For the month of April, 3 cfs would be released 24 hours a day to support rearing and outmigration of juveniles (Table 7, Figure 48). These releases would be in addition to natural runoff. It has been suggested although we did not model a release of 2.0 cfs from Oct 1-Dec 31, 3 cfs from Jan1-March 31 and 2 cfs from April 1-30 to further conserve water. Changes to flows would be made by reducing/increasing flows by 0.5/day.

A study of the frequency of water discharging over the Lake Curry spillway found that during the 12-year period of 1991 through 2002, Lake Curry spilled in 8 years or 66% of the years (Jackson 2003). This frequency indicates that winter flows in Suisun Creek are likely adequate for fish habitats at least 66% of years. These seasonal releases were applied in combination with scenarios 1A-I, 2A-C, 3A-C and 4A-C. Table 8 lists the numbers for the combined scenarios.

Table 7. Scenario Set #5

Year	Migration/spawning		Spawning incubation		Rearing/outmigration	
Dry	Oct 1- Dec. 31	2.5 cfs	Jan 1-March 31	4 cfs	April 1- 30	3 cfs
Normal	Oct 1- Dec. 31	2.5 cfs	Jan 1-March 31	4 cfs	April 1- 30	3 cfs
Wet	Oct 1- Dec. 31	2.5 cfs	Jan 1-March 31	4 cfs	April 1- 30	3 cfs

Figure 48. Hydrograph of Scenario 5 releases from October to April.

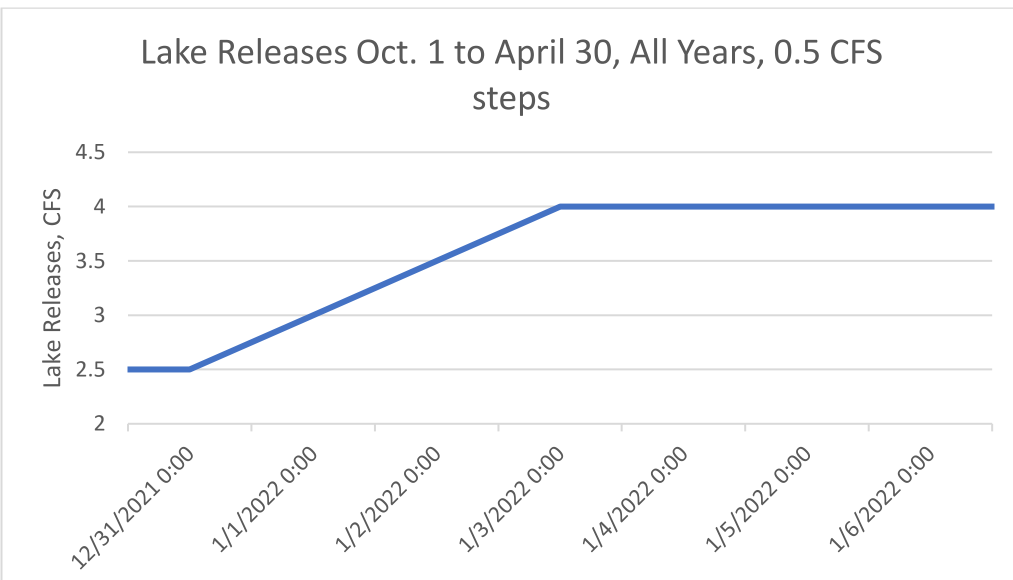


Figure 49. Hydrograph of Scenario 5 releases showing ramping or .05 cfs steps between flow changes.

Table 8. Scenario Numbers Combining Scenarios 1-4 with Scenario Set 5

Scenarios 1-4	Scenario number when combined with Scenario 5
1A	5A
1B	5B
1C	5C
1D	5D
1E	5E
1F	5F
1G	5G
1H	5H
1I	5I
2A	5J
2B	5K
2C	5L
3A	5M
3B	5N
3C	5O
4A	5P
4B	5Q
4C	5R

<u>Scenario 6</u>

From the grant: "Release of 2 cfs, 4 cfs, and 6 cfs for 1-2 weeks each to set a baseline of temperature and flow level along the creek." This scenario was field simulated in the summer 2017. In 2017 we collaborated with the City of Vallejo on releases from Lake Curry. The City had to complete some repairs to the Lake Curry spillway so releases were increased above the 6 cfs level. The final release schedule showed a 4 cfs release from 6/13-6/21/17 then releases were gradually increased to 8 cfs on 7/15/17 and then abruptly decreased. A release of 4 cfs was maintained 7/20-8/2/17. The 2 cfs release was restricted to 8/5-8/14/17. On 8/15/17 releases were abruptly increased to 14 cfs until 9/29/17 and then gradually reduced to 6 cfs on 10/23/17. The hydrograph in Figure 50 shows these releases at our stream flow gage just downstream of the Lake curry outlet pipe (SC 10). A network of temperature sensors (Figure 7) was used to record temperatures while particular levels of water were released.

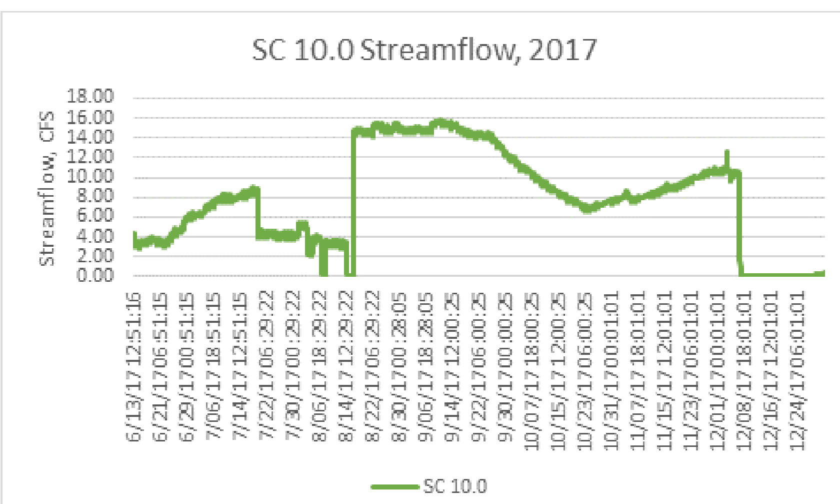


Figure 50. Hydrograph of Lake Curry releases for Scenario 6 measured at stream flow gage at SC 10.0.

Scenario 7

Natural groundwater flows may provide cooler water than reservoir releases can. Stopping releases should be timed with water temperature and flow monitoring. The effects of this scenario were field monitored from January to June, 2018 and throughout the study. The network of streamflow gages and temperature sensors (Figure 7) were used during a period of time when the City of Vallejo reduced and turned off the release from Lake Curry to Suisun Creek. This action was not done in coordination with this study. The water releases from the lake water were stopped from January to June when temperatures would generally be low. Releases from Lake Curry in 2019 and 2020 were also very low.

Evaluation of Modeling Results

For each scenario 1-4 and its corresponding scenario 5 we have graphed both the modeled changes in water temperature at the Lake Curry outlet and the surface water elevation of the lake over time. There is also a hydrograph for each scenario showing the rate of the release over time. For each scenario for each rainfall year, we have calculated the number of days that temperatures will exceed 70^{o}, 75.2^{o}and 80^{o} F. These temperatures represent different effects on steelhead trout.

The 70^{o}F temperature is tolerated temporarily by steelhead trout, but if the fish are exposed to this temperature for prolonged periods of time the fish will feed poorly and survival rates will decline. It should also be noted that the model predicts higher water temperatures than those measured at the lake outlet and therefore many of the scenarios with only a few days of modeled 70^{o}F water releases likely will have few deleterious effects on steelhead.

The 75.2^{o} F temperature represents a threshold that can create lethal conditions for a percentage of the fish population in the creek (Sullivan et al 2002). The 80^{o} F threshold creates lethal conditions for a much larger percentage of the steelhead in the creek. The effects of release of water of these temperatures on steelhead also depends upon the amount of groundwater and other sources of surface water entering each pool location along the creek during the summer months.

We have also reviewed the period of time when the water surface elevation of Lake Curry drops below the 365 ft. elevation. The City of Vallejo has informed us that water quality problems have occurred in Lake Curry during summers when the lake surface was at 365- 355 ft. Cramer Fish Science completed a survey of the fish in Lake Curry in October 2017. Two nonnative species were found - Sunfish (*Lepomis* sp.) and Black bass (*Micropterus* sp.). Black bass have a high tolerance for warm water easily surviving temperatures of 86-96^{o} F with dissolved oxygen levels of 1 mg/L. By comparison steelhead trout are cold water fish which survive best at temperatures below 70^{o} F and dissolved oxygen levels of 7 mg/L.

Dry Year Scenarios

Figures 51 to 64 depict the modeled results for each dry year scenario with and without the Oct-April releases from Scenario 5 and a hydrograph of each release level.

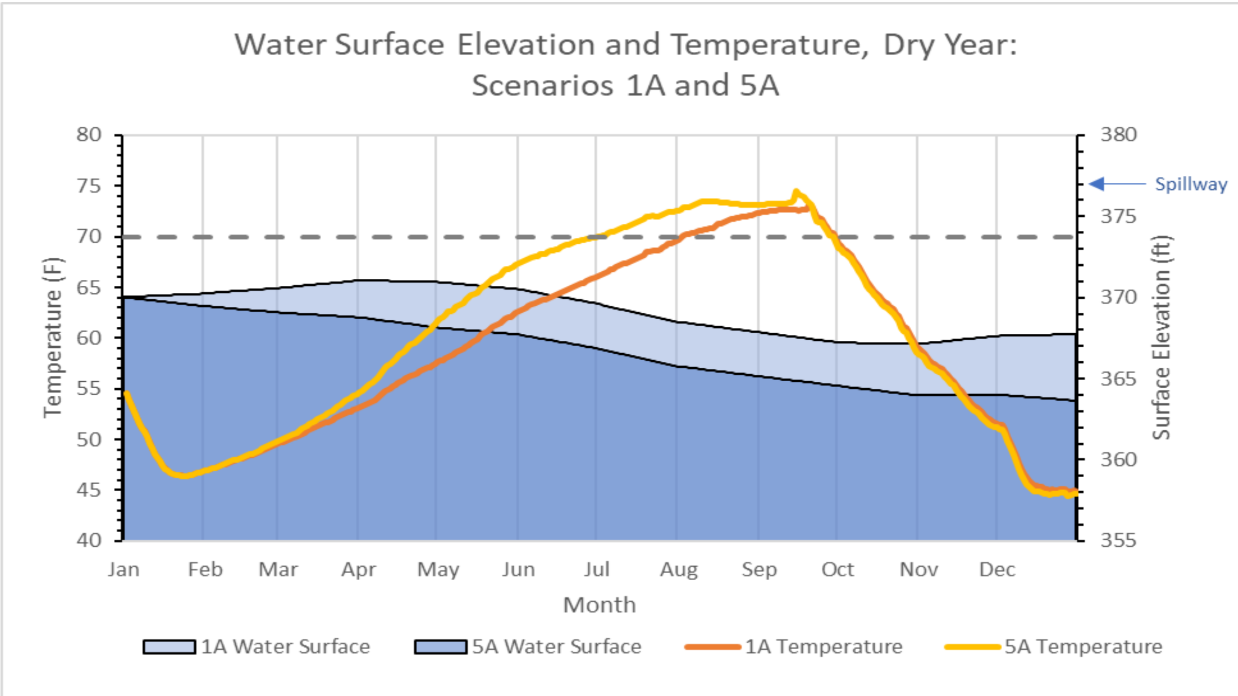


Figure 51. Scenario 1A would release 2.5 cfs from May 1 to Sept 30. Scenario 5A would include Scenario 1A and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

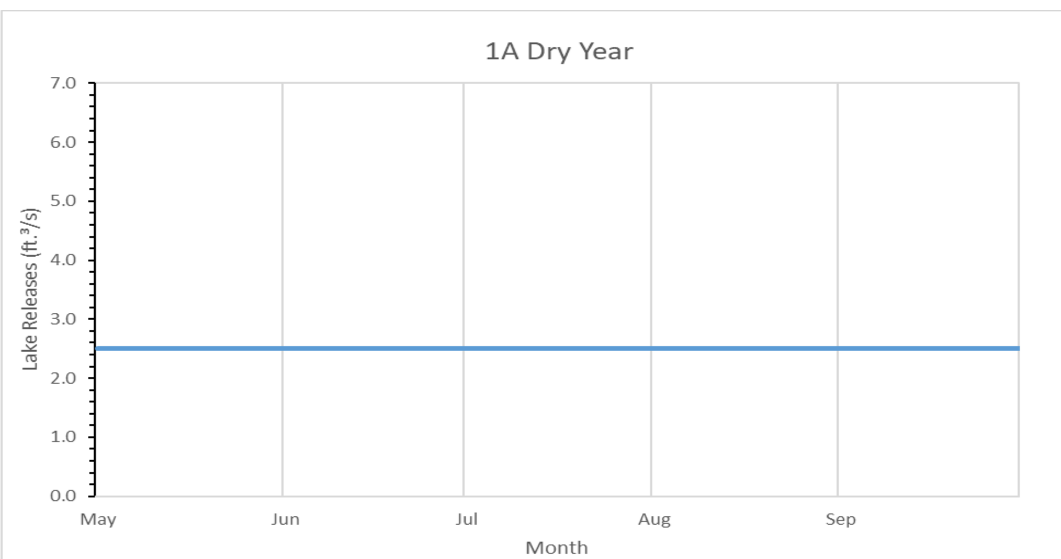


Figure 52. Hydrograph for Scenario 1A for May-Sept.

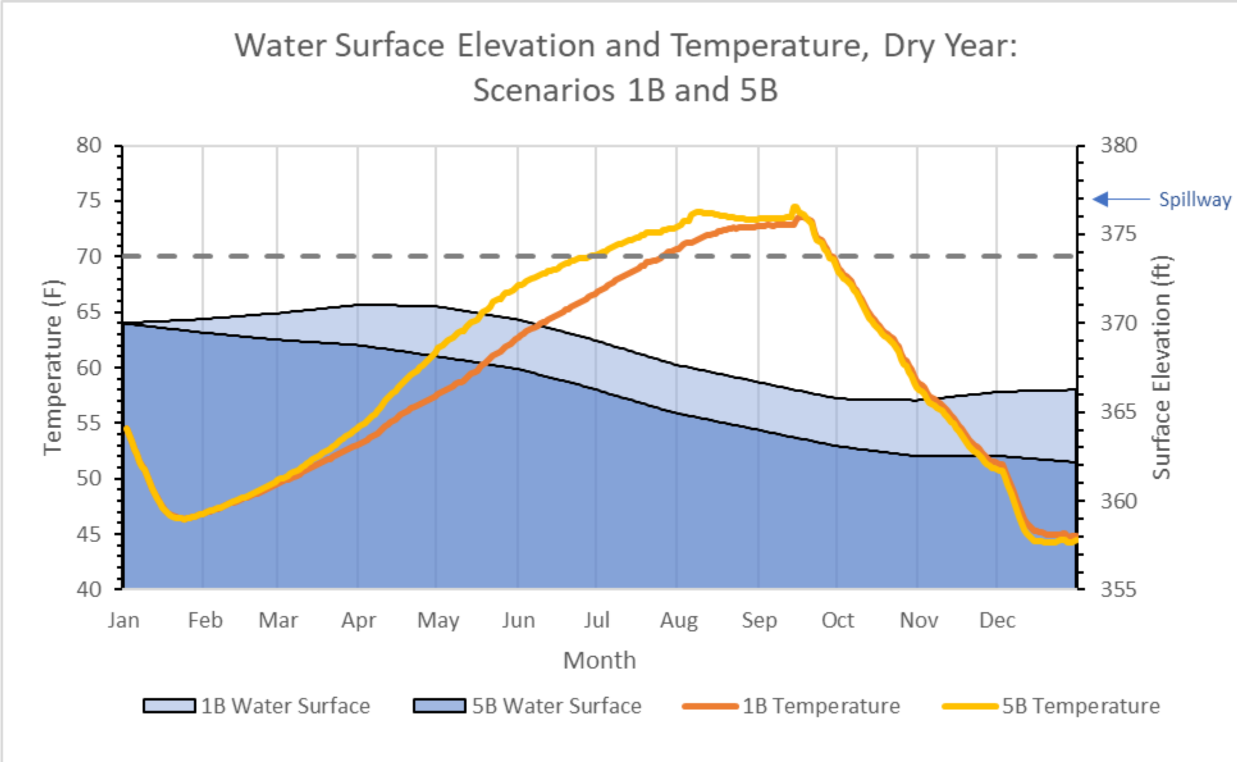


Figure 53. Scenario 1B would release 4 cfs from May 1 to Sept 30. Scenario 5B would include Scenario 1B and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

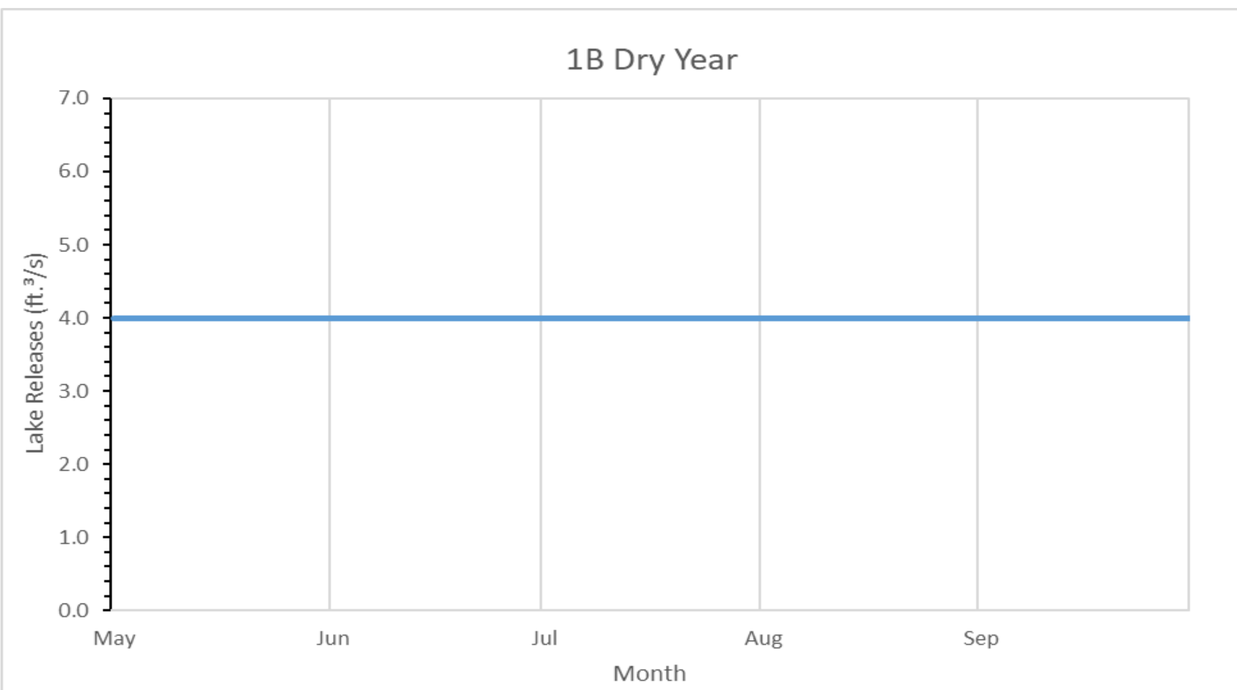


Figure 54. Hydrograph for Scenario 1B for May-Sept.

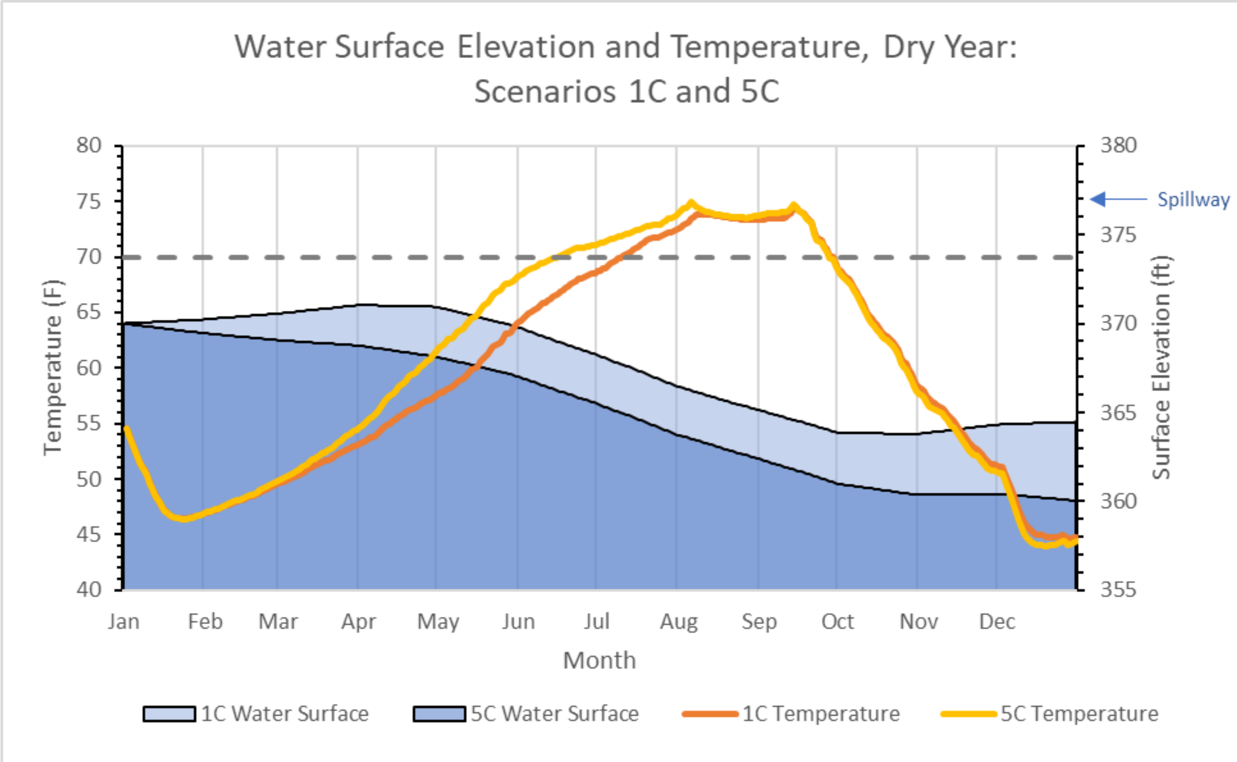


Figure 55. Scenario 1C would release 6 cfs from May 1 to Sept 30. Scenario 5C would include Scenario 1C and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

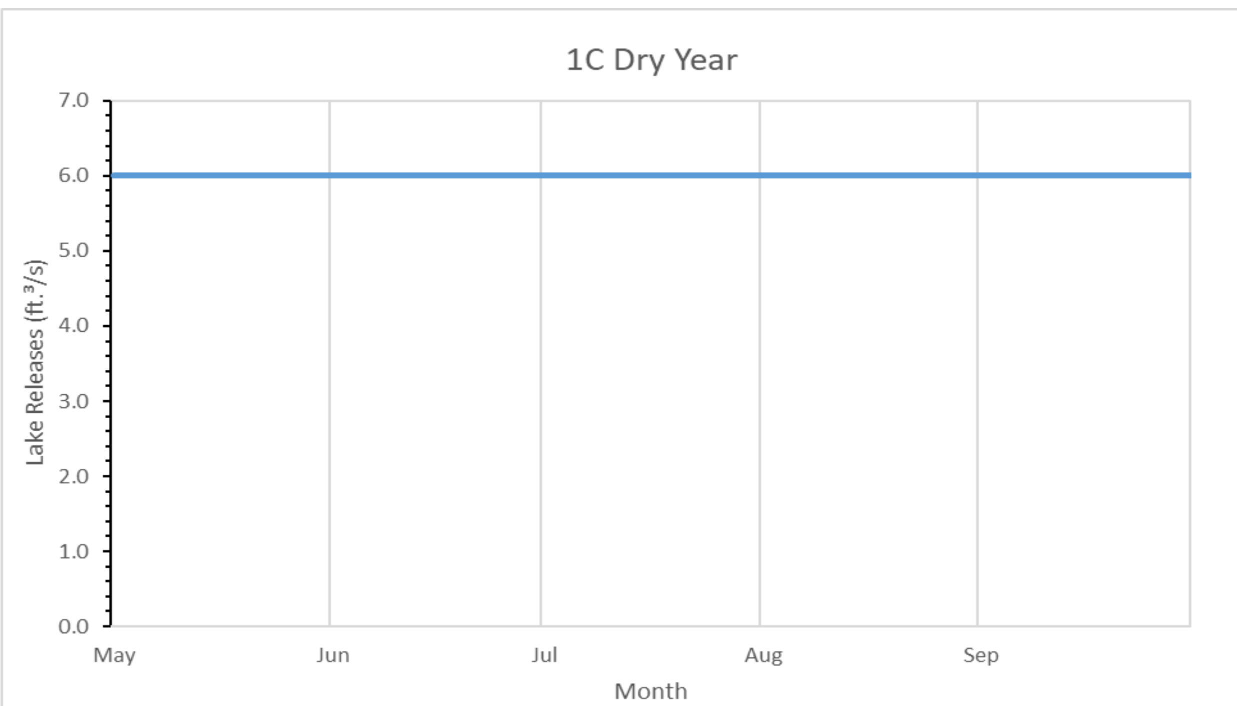


Figure 56. Hydrograph for Scenario 1C for May-Sept.

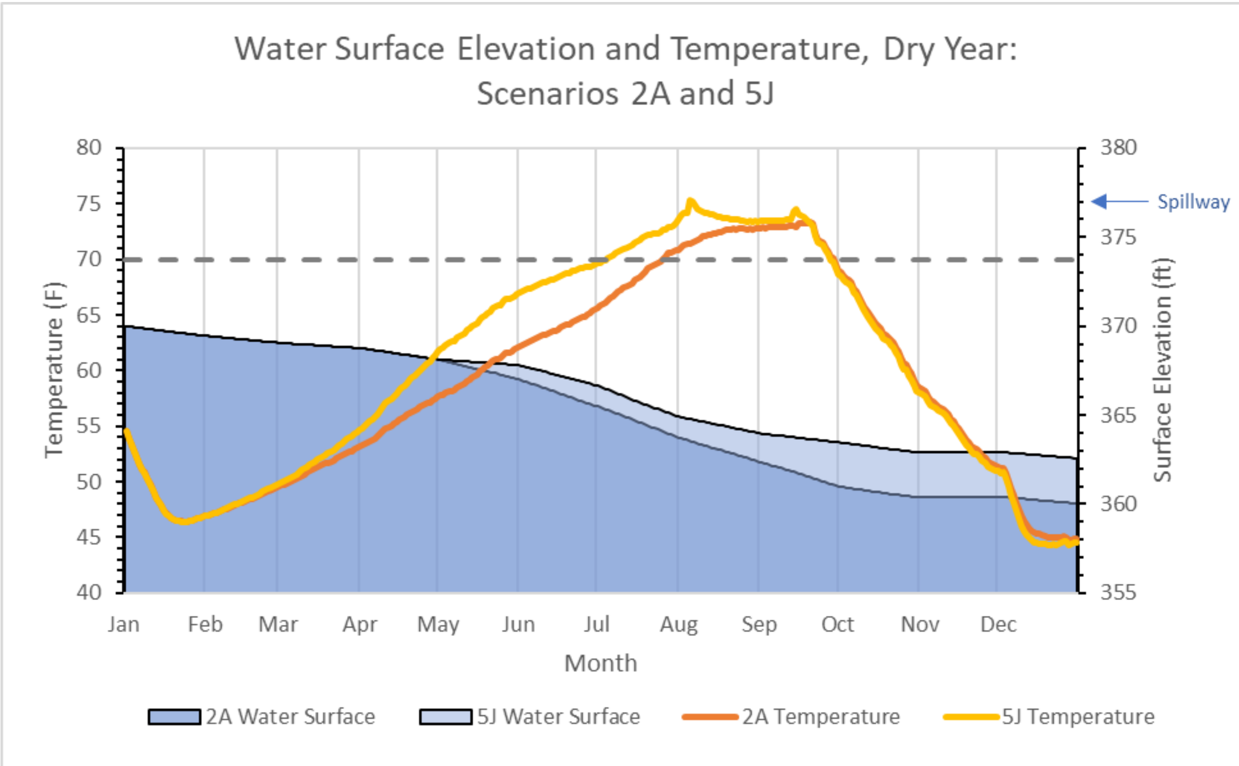


Figure 57. Scenario 2A would release 2 cfs in May, 4 cfs in June, 6 cfs in July, 4 cfs in August and 2 cfs in Sept. Scenario 5J would include Scenario 2A and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

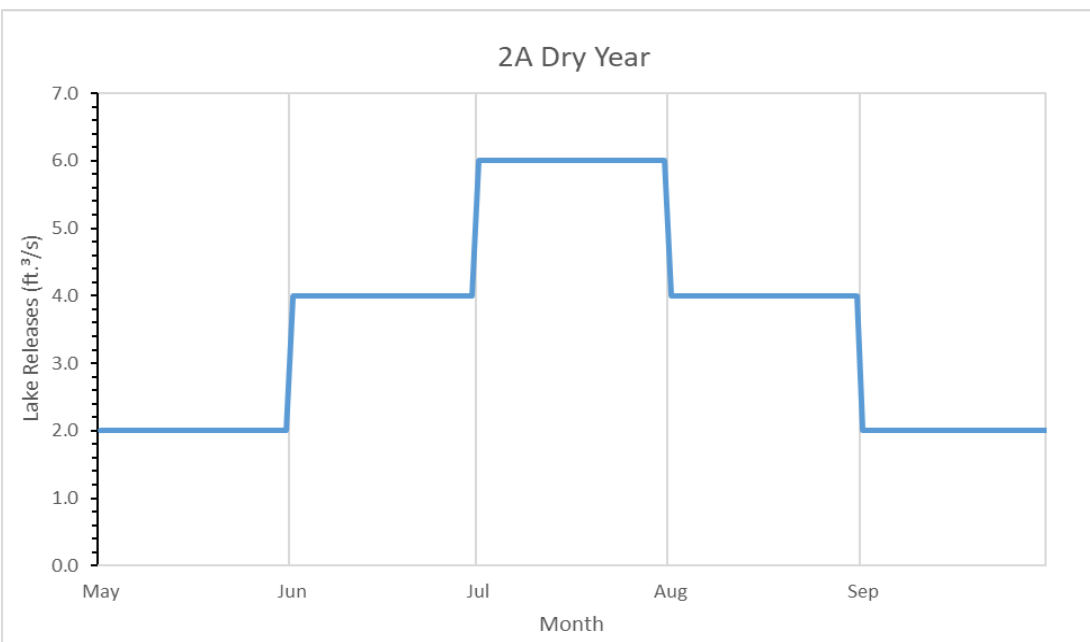


Figure 58. Hydrograph for Scenario 2A for May-Sept. Changes between release levels will be made at 0.5 cfs/day.

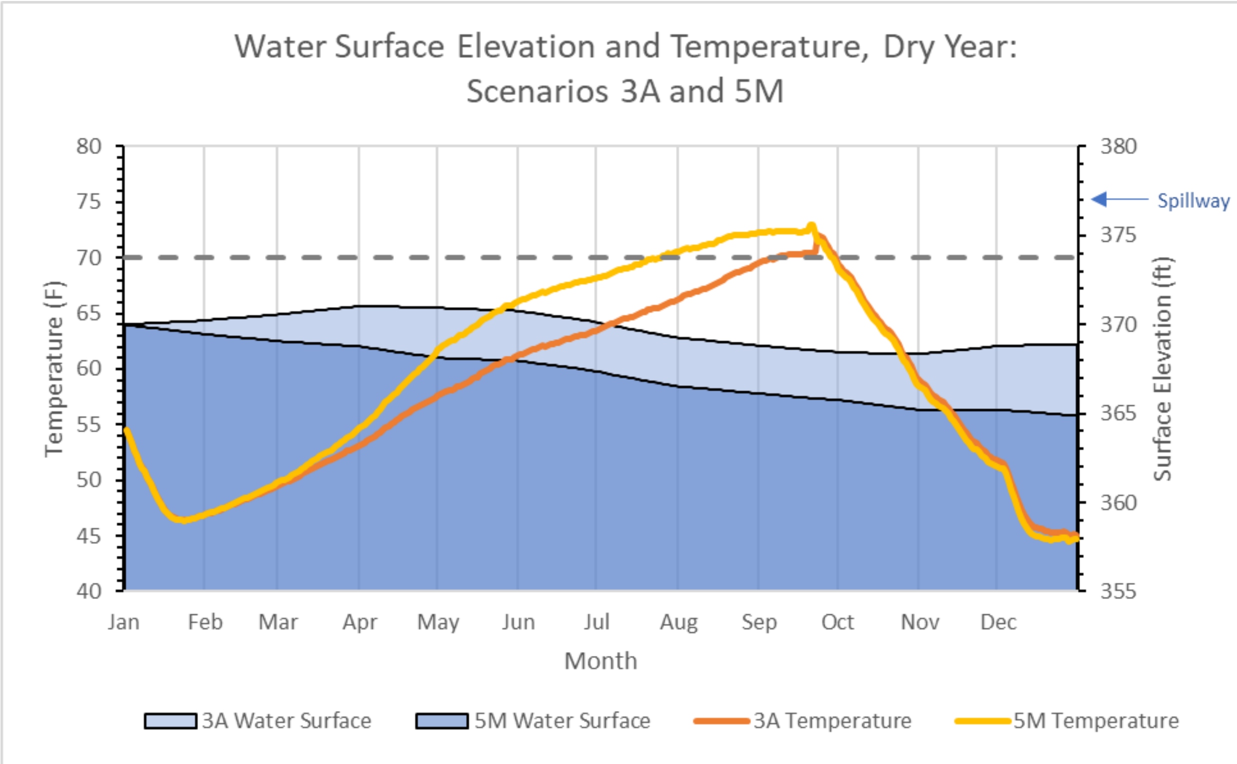


Figure 59. Scenario 3A would release 1 cfs from May through September. When air temperatures are predicted to reach 90^0 F a pulse of 4 cfs from 10 am to 6 pm is released. Scenario 5M would include Scenario 3A and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

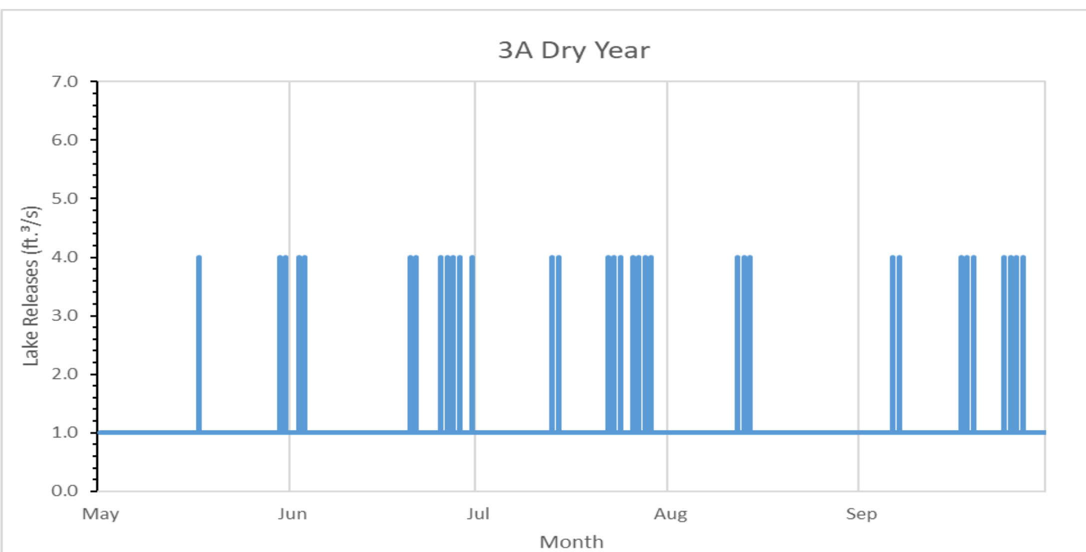


Figure 60. Hydrograph for Scenario 3A for May-Sept. It is important to note that this graph shows pulses on the dates when air temperatures exceeded 90^0 F in 2013. The timing of the pulses will vary from year to year.

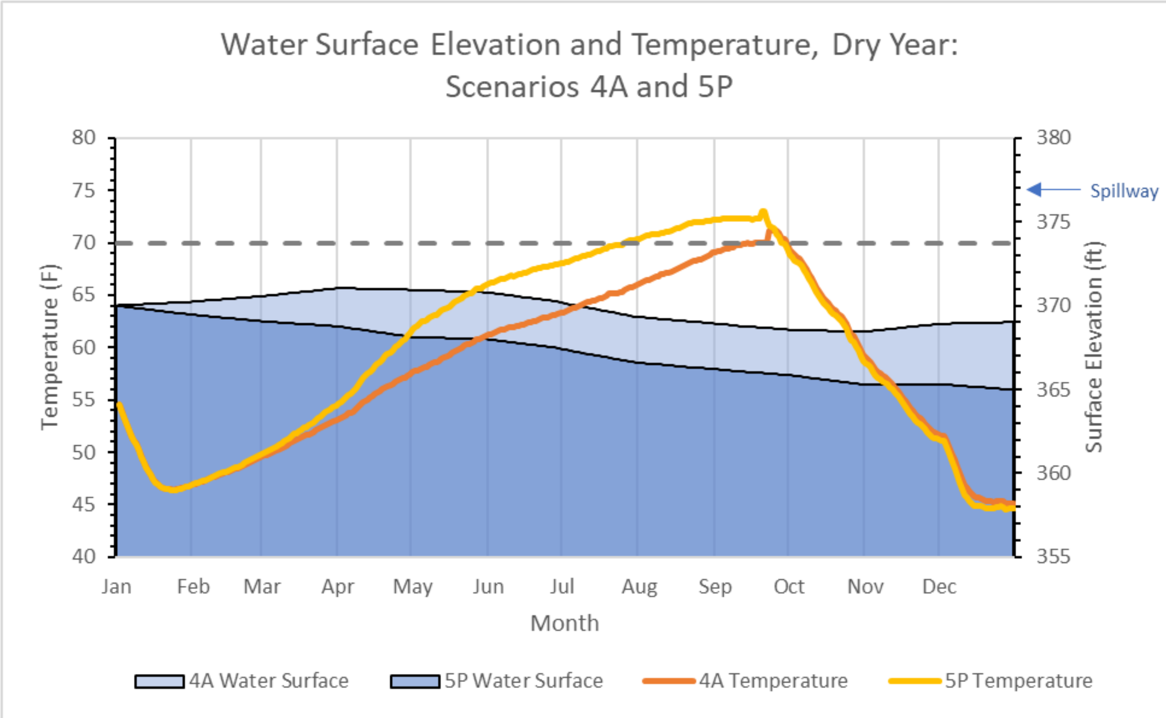


Figure 61. Scenario 4A would release 1 cfs from May through September. When air temperatures are predicted to reach 95⁰ F a pulse of 4 cfs from 10 am to 6 pm Scenario 5P would include Scenario 4A and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

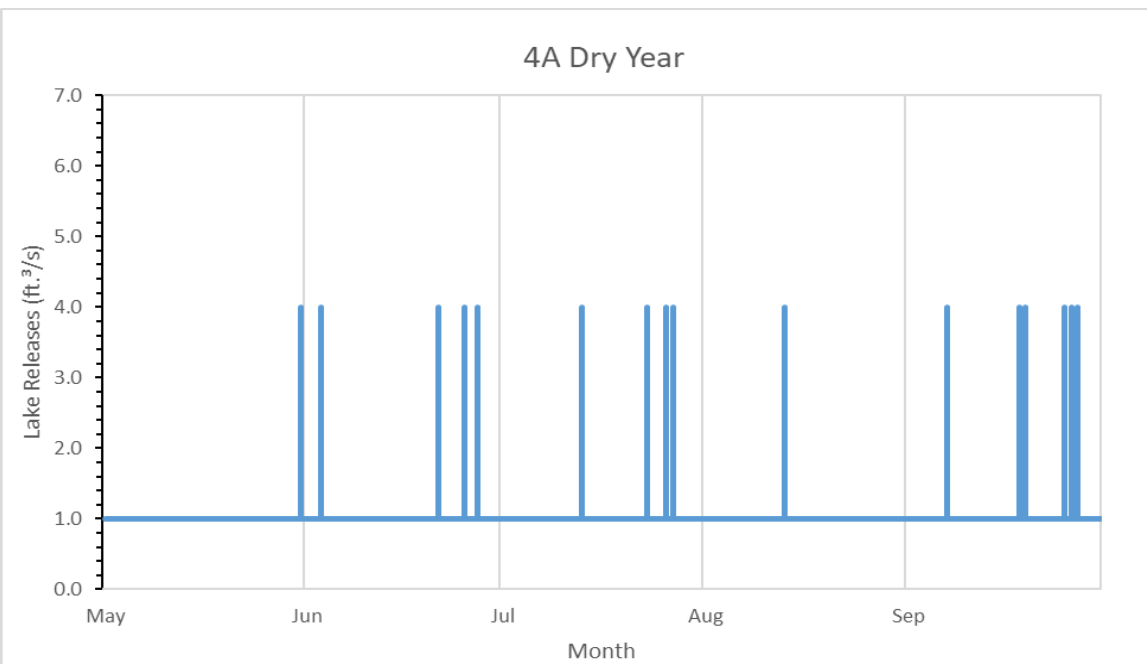
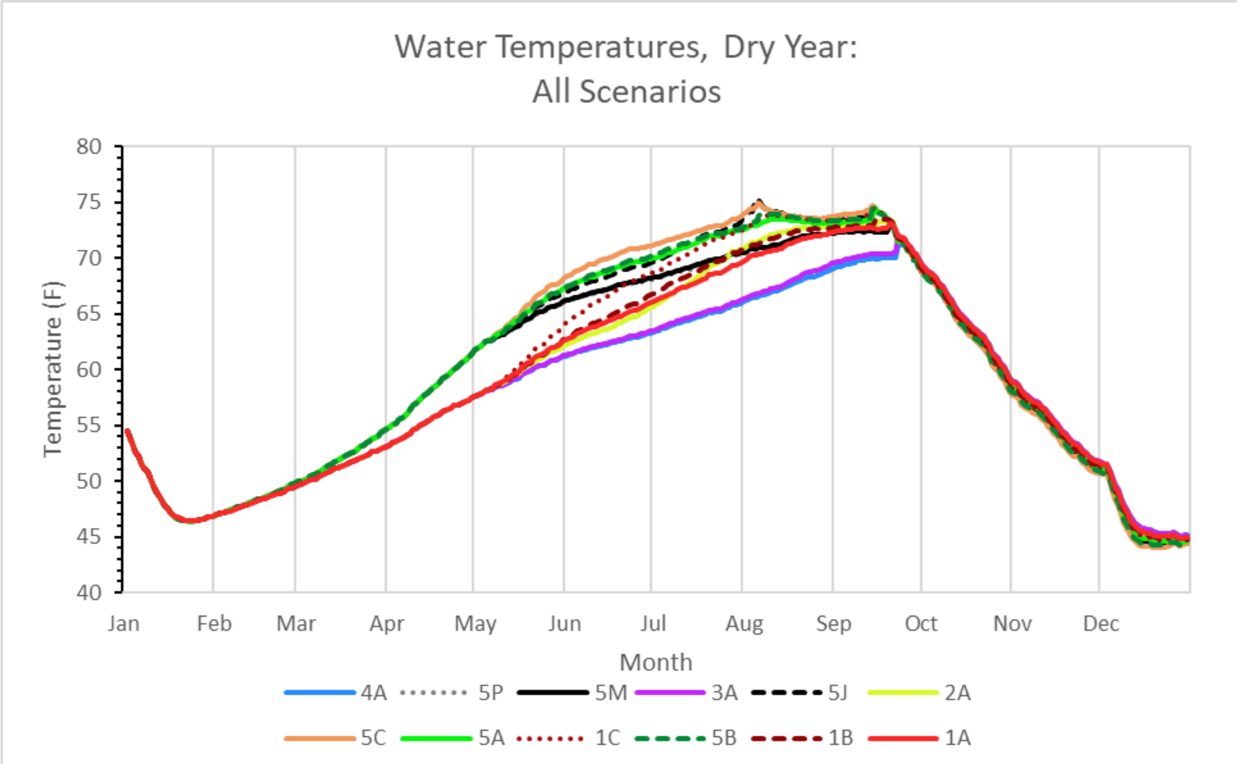
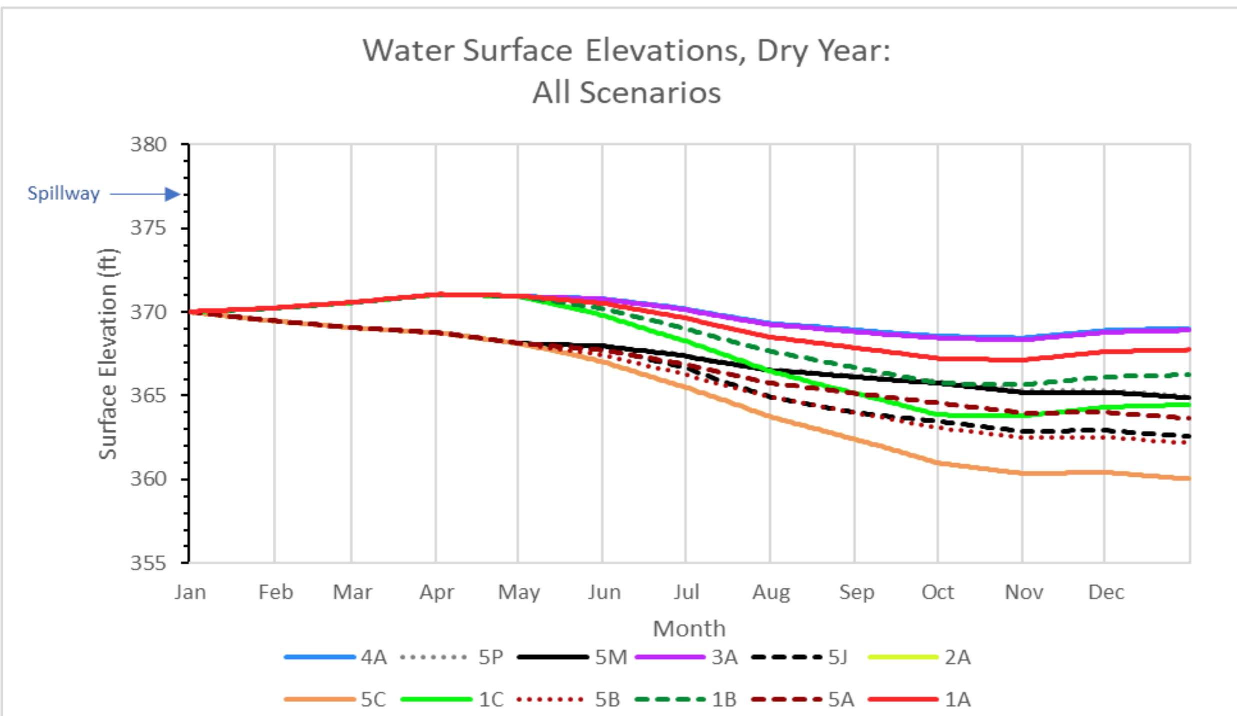


Figure 62. Hydrograph for Scenario 4A for May-Sept. It is important to note that this graph shows pulses on the dates when air temperatures exceeded 95⁰ F in 2013. The timing of the pulses will vary from year to year.





Figures 63 and 64. Modeled temperature changes over the summer for all the dry year scenarios and changes in the water surface elevation in Lake Curry for all dry year scenarios.

Table 9. Summary of days of high-water temperature releases and low lake levels in Lake Curry for Scenarios 1-4 for a dry year.

Dry Year Scenarios (1 - 4)					
Scenario	**Description**	**Days > 70° F**	**Days > 75.2° F**	**Days > 80° F**	**Days < 365 ft.**
1A*	2.5 cfs release 24 hrs. a day, May 1-Sept. 30	58 (Aug. - Sep.)	0	0	0
1B	4 cfs release 24 hrs. a day, May 1-Sept. 30	66 (Jul. - Sep.)	0	0	0
1C	6 cfs release 24 hrs. a day, May 1-Sept. 30	81 (Jul. - Sep.)	0	0	119 (Sep. - Dec.)
2A	Release 2 cfs in May, 4 cfs in June, 6 cfs in July, 4 cfs in August and 2 cfs in Sept.	66 (Jul. - Sep.)	0	0	175 (Jul. - Dec.)
3A	Release 1 cfs from May through September. When air temperatures are predicted to reach 90º F a pulse of 4 cfs from 10 am to 6 pm is released	22 (Sep.)	0	0	0
4A	Release 1 cfs from May through September. When air temperatures are predicted to reach 95º F a pulse of 4 cfs from 10 am to 6 pm is released	11 (Sep.)	0	0	0

*Recommended

Table 10. Summary of days of high-water temperature releases and low lake levels in Lake Curry for the Scenario 5's associated with Scenarios 1-4 for a dry year.

Dry Year Scenarios 5					
Scenario	**Associated Scenario**	**Days > 70° F**	**Days > 75.2° F**	**Days > 80° F**	**Days < 365 ft.**
5A*	1A	89 (Jul. - Sep.)	0	0	114 (Sep. - Dec.)
5B	1B	91 (Jun. - Sep.)	0	0	155 (Jul. - Dec.)
5C	1C	103 (Jun. - Sep.)	0	0	175 (Jul. - Dec.)
5J	2A	85 (Jul. - Sep.)	1 (Aug.)	0	154 (Jul. - Dec.)
5M	3A	65 (Jul. - Sep.)	0	0	11 (Dec.)
5P	4A	64 (Jul. - Sep.)	0	0	3 (Dec.)
For each Scenario 5 these releases are added to the associated summer release scenario: for the steelhead migration/spawning period of Oct. 1-Dec 31, 2.5 cfs would be released 24 hours a day. From Jan. 1-March 31, 4 cfs would be released 24 hours a day to support spawning and egg incubation. For the month of April, 3 cfs would be released 24 hours a day to support rearing and outmigration of juveniles. Changes in flows would be made at 0.5 cfs/day.					

* Recommended

Discussion: Dry Year Scenarios

Dry year scenarios 1-4 do not release water greater than 75.2^{o}and 80^{o} F and would not create lethal conditions for steelhead in Suisun Creek. However, release water temperatures exceed 70^{o} F on 11-81 days over the summer. Of these scenarios 3A and 4A have the lowest number of days of releasing 70^{o} F with 22 and 11 days respectively all in September. It is important to note that the modeled outflow temperatures are several degrees higher in comparison to measured, so the actual number of days > 70^{o}F degrees is probably lower than the model predicts.

All of the scenario 5's for dry year conditions would release 70^{o} F water from either June or July to September and are not recommended. National Marine Fisheries Service (NMFS) has suggested that scenario 5A will provide releases over the entire year which may be needed in a dry year.

Scenarios 5B, 5C, 5J and 2A reduce the level of the water in Lake Curry to 365 ft. from July to Dec. and could result in water quality problems. In many years, rainfall during winter would provide adequate flows for steelhead migration, spawning, and rearing. Fish habitats in Suisun Creek are not totally dependent on the lake during the winter for flows as they are in the summer.

We recommend scenarios 1A and 5A as the best release options in dry years. These scenarios provide a minimum flow to Suisun Creek that is high enough to create connected flow. National Marine Fisheries Service (NMFS) has suggested that scenario 5A will provide releases over the entire year which may be needed in a dry year. NMFS has also suggested that a lower release of 1-2 cfs during summer might be needed. Based on field studies a 1 cfs release does not produce connected flow and may result in low dissolved oxygen in intermittent pools. However, a 2 cfs release could provide viable habitat while conserving water for consecutive years of dry conditions.

Normal Year Scenarios

Figures 65 to 78 depict the modeled results for each dry year scenario with and without the Oct-April releases from Scenario 5 and a hydrograph of each release level.

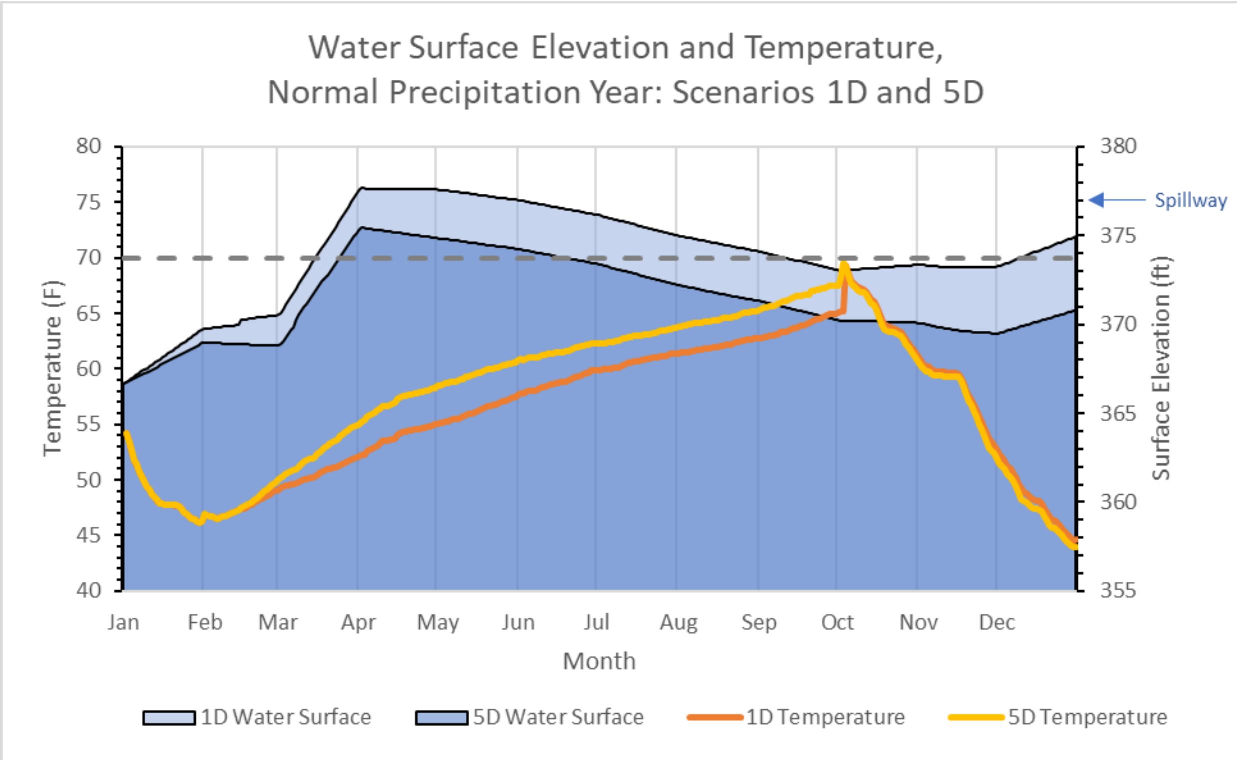


Figure 65. Scenario 1D would release 2.5 cfs from May 1 to Sept 30. Scenario 5D would include Scenario 1D and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

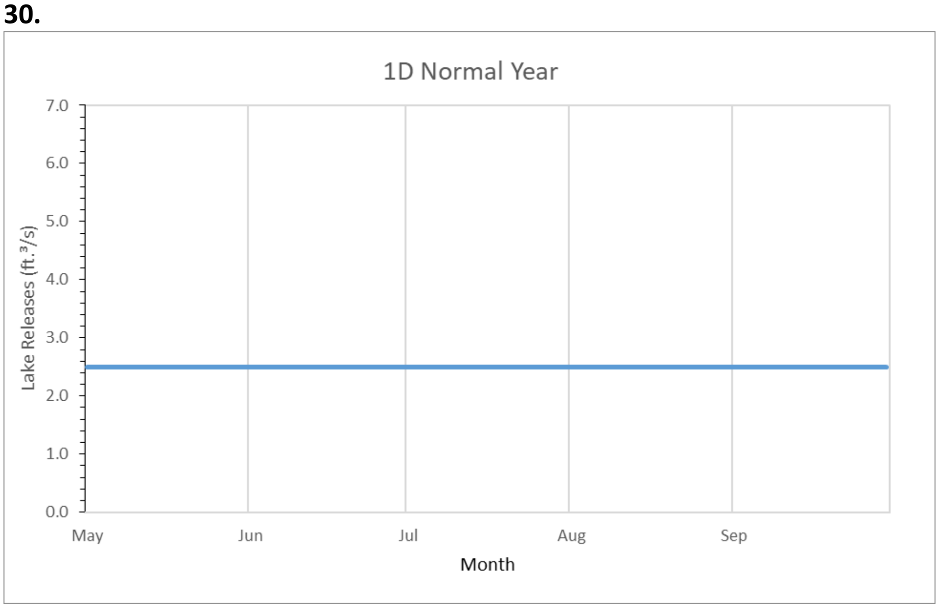


Figure 66. Hydrograph for Scenario 1D for May-Sept.

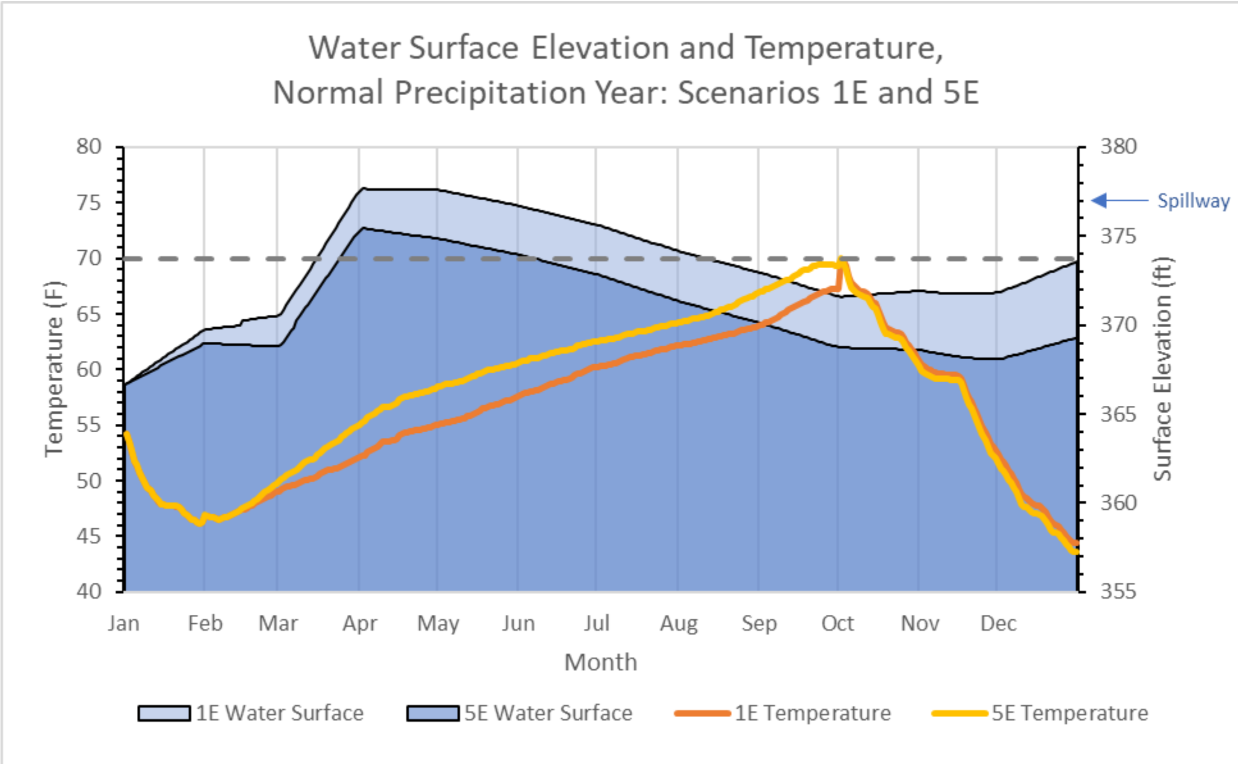


Figure 67. Scenario 1E would release 4 cfs from May 1 to Sept 30. Scenario 5E would include Scenario 1E and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

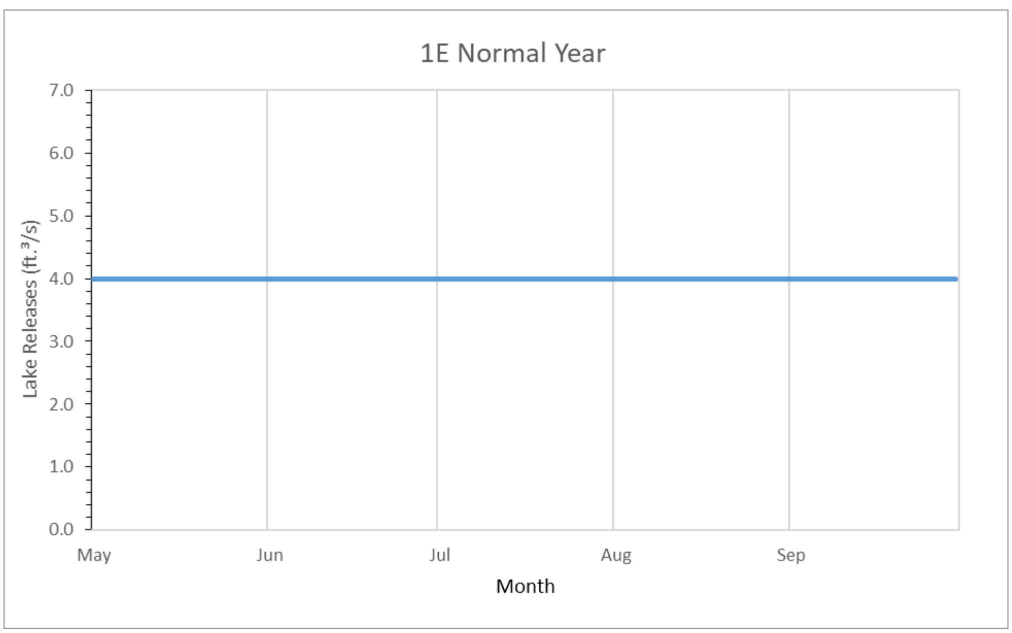


Figure 68. Hydrograph for Scenario 1E for May-Sept.

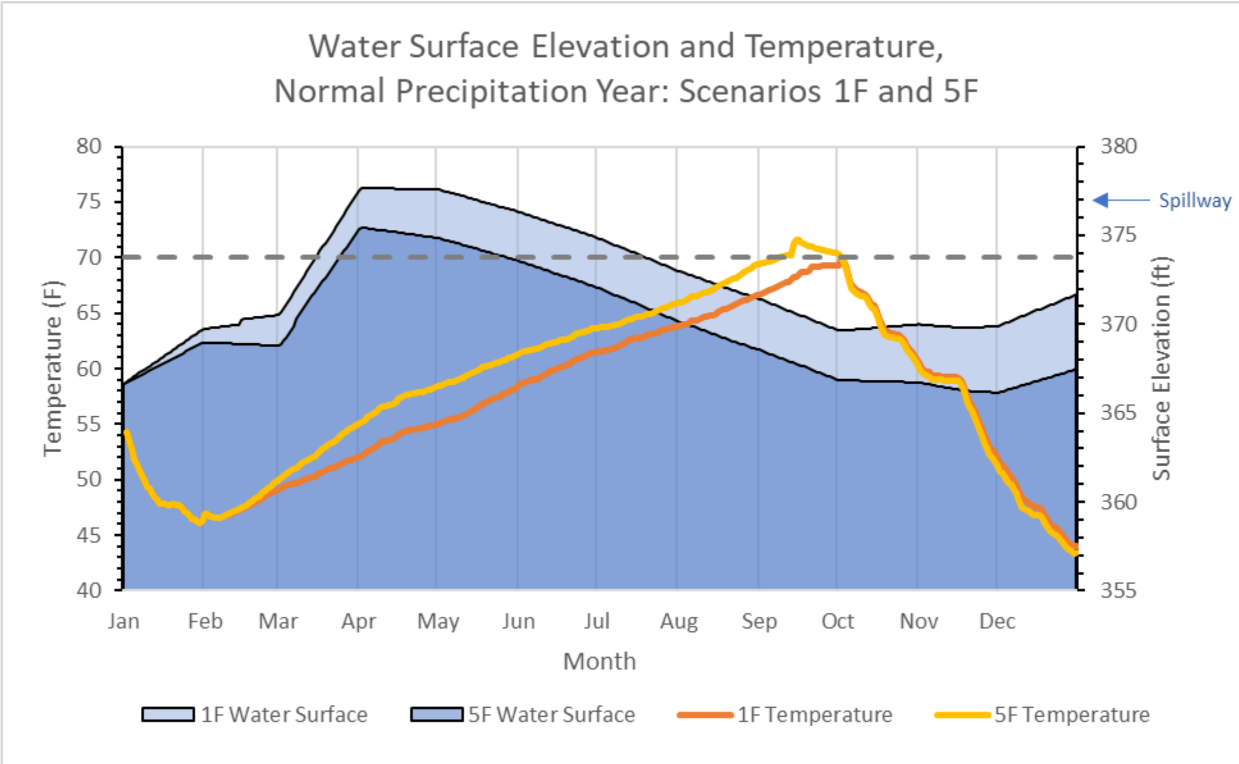


Figure 69. Scenario 1F would release 6 cfs from May 1 to Sept 30. Scenario 5F would include Scenario 1F and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

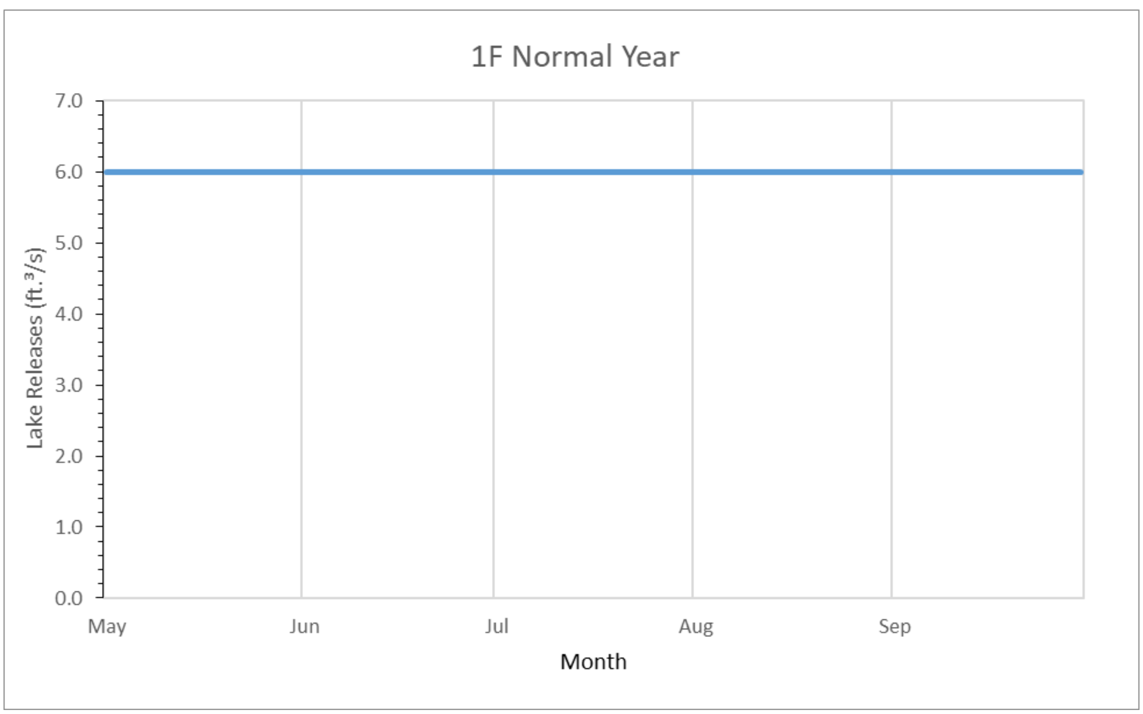


Figure 70. Hydrograph for Scenario 1F for May-Sept.

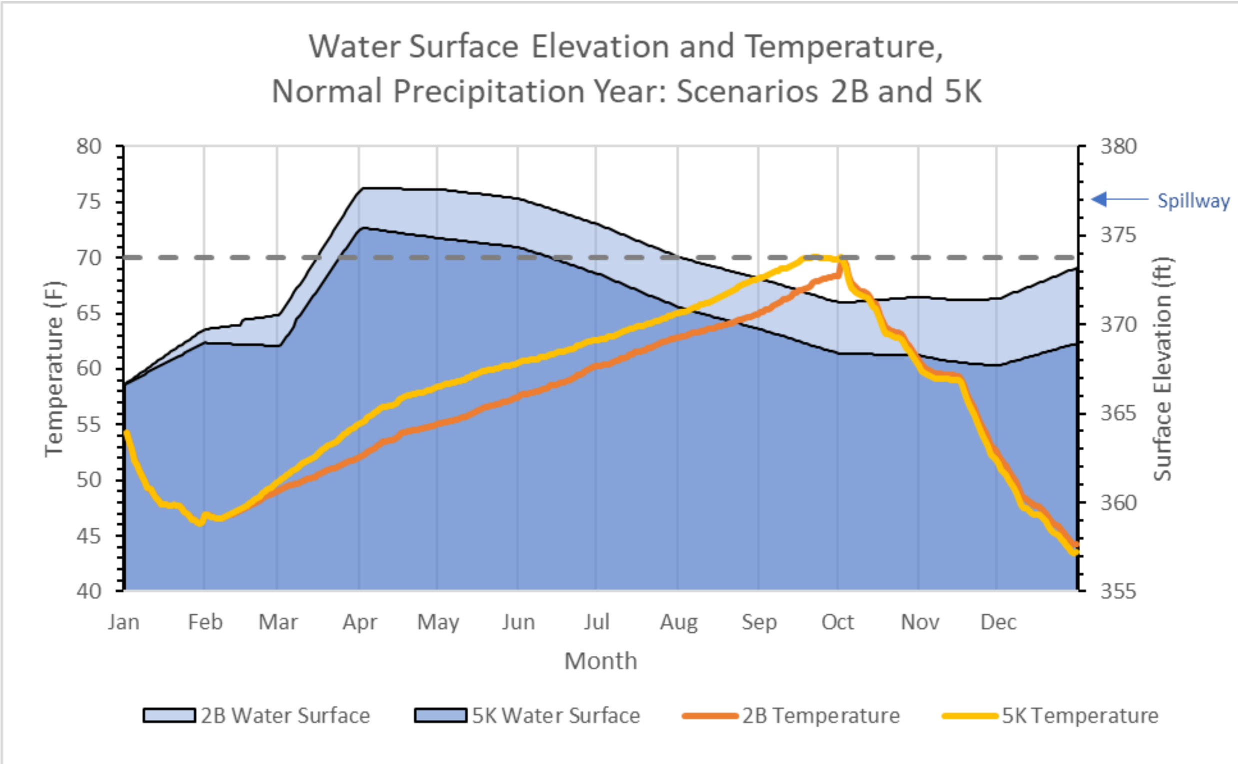


Figure 71. Scenario 2B would release 2 cfs in May, 6 cfs in June, 6 cfs in July, 4 cfs in August and 4 cfs in Sept. Scenario 5K would include Scenario 2B and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

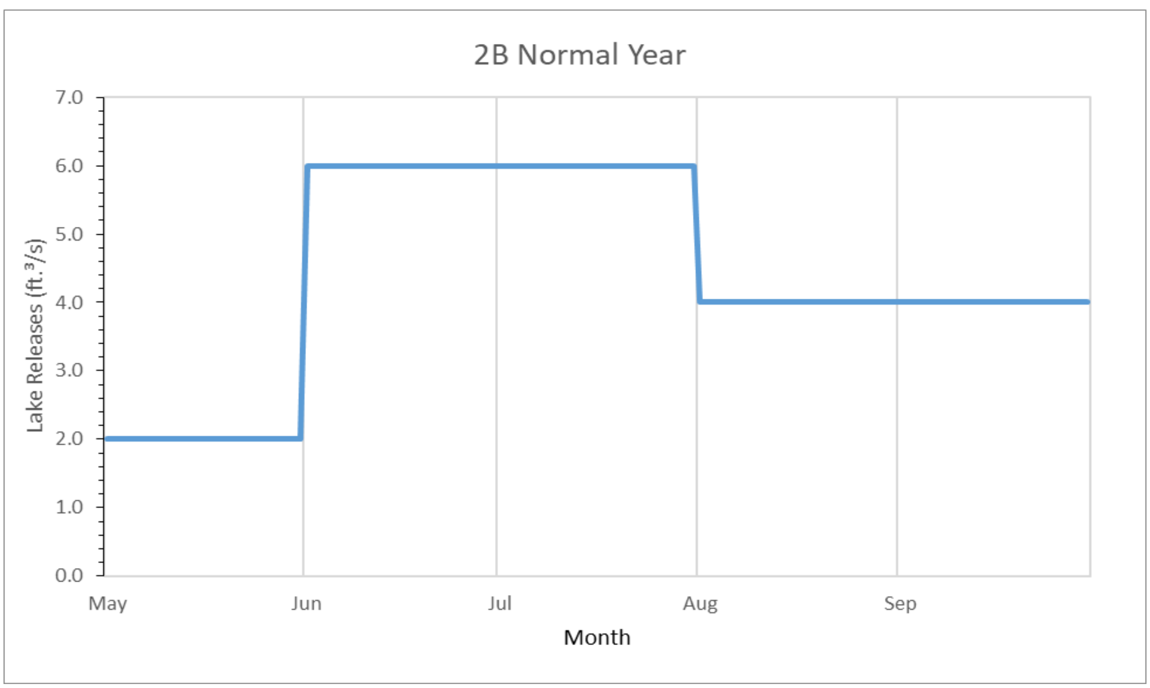


Figure 72. Hydrograph for Scenario 2B for May-Sept. Changes between release levels will be made at 0.5 cfs/day.

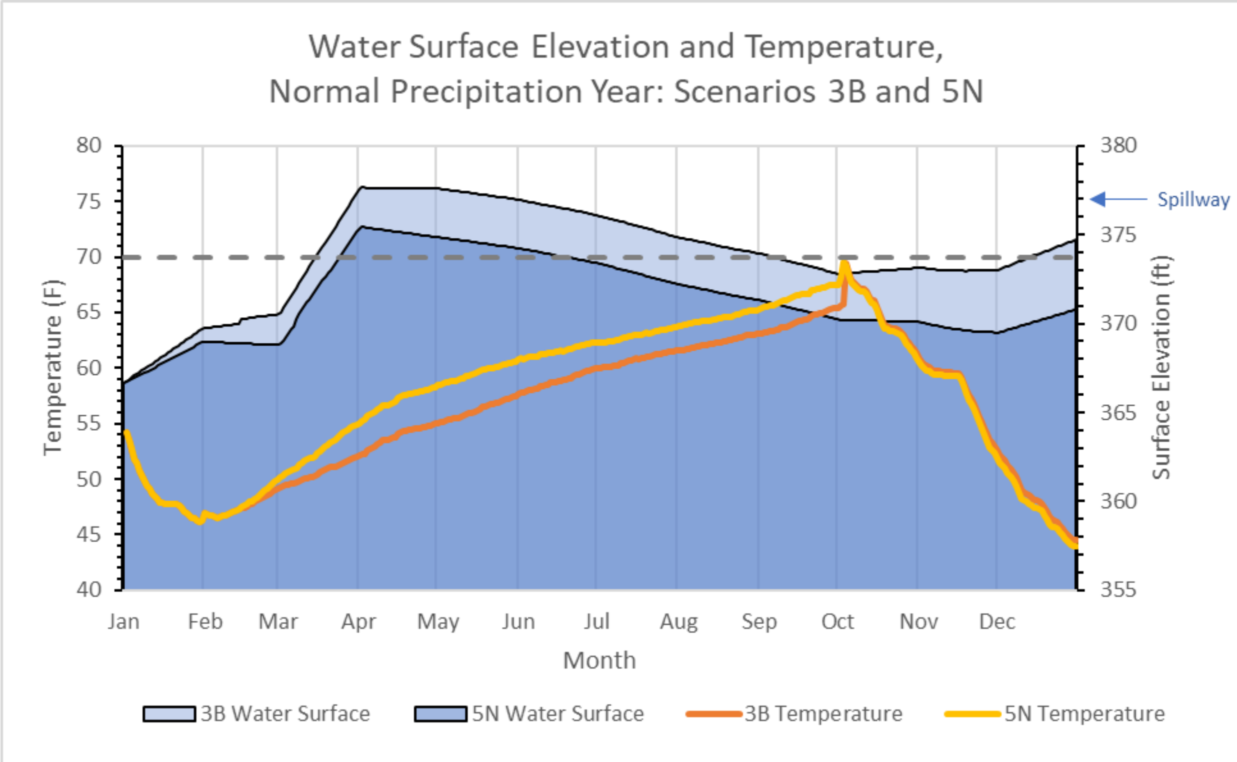


Figure 73. Scenario 3B would release 2.5 cfs from May through September. When air temperatures are predicted to reach 90⁰ F a pulse of 6 cfs from 10 am to 6 pm is released. Scenario 5N would include Scenario 3B and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

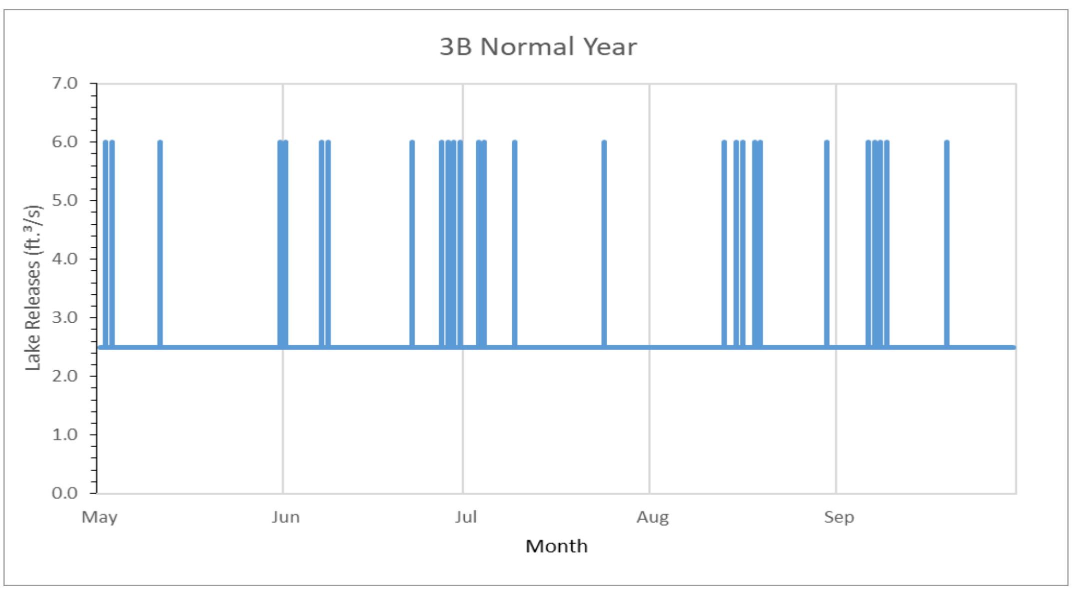


Figure 74. Hydrograph for Scenario 3B for May-Sept. It is important to note that this graph shows pulses on the dates when air temperatures exceeded 90⁰ F in 2016. The timing of the pulses will vary from year to year.

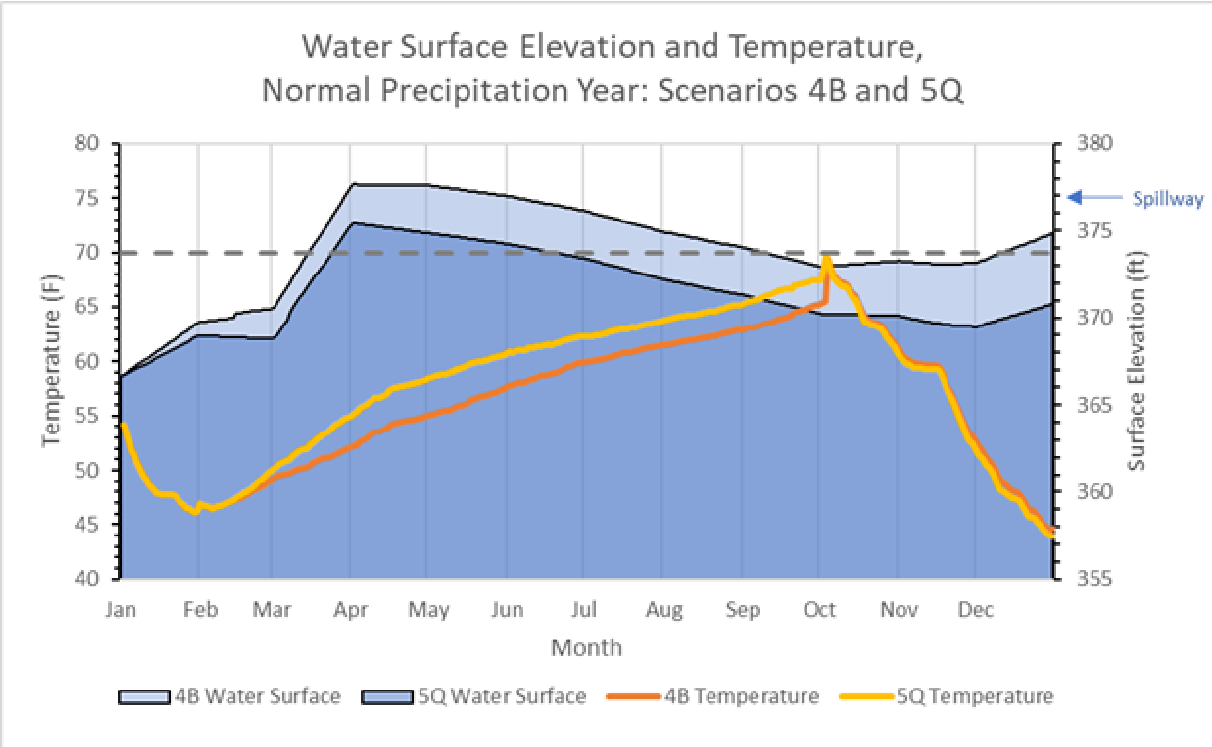


Figure 75. Scenario 4B would release 2.5 cfs from May through September. When air temperatures are predicted to reach 95⁰ F a pulse of 6 cfs from 10 am to 6 pm is released. Scenario 5Q would include Scenario 4B and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

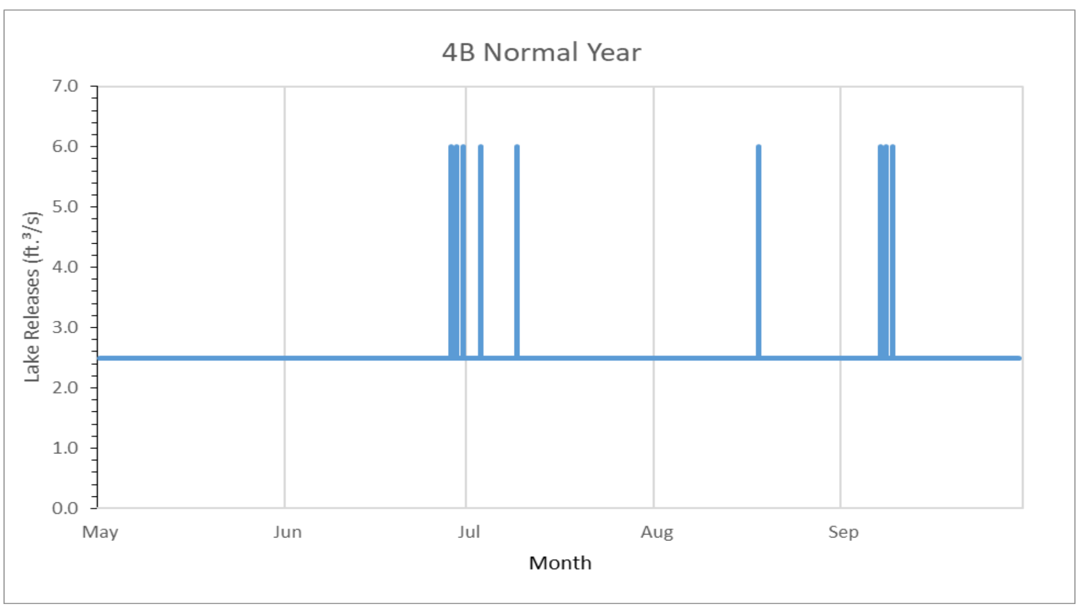
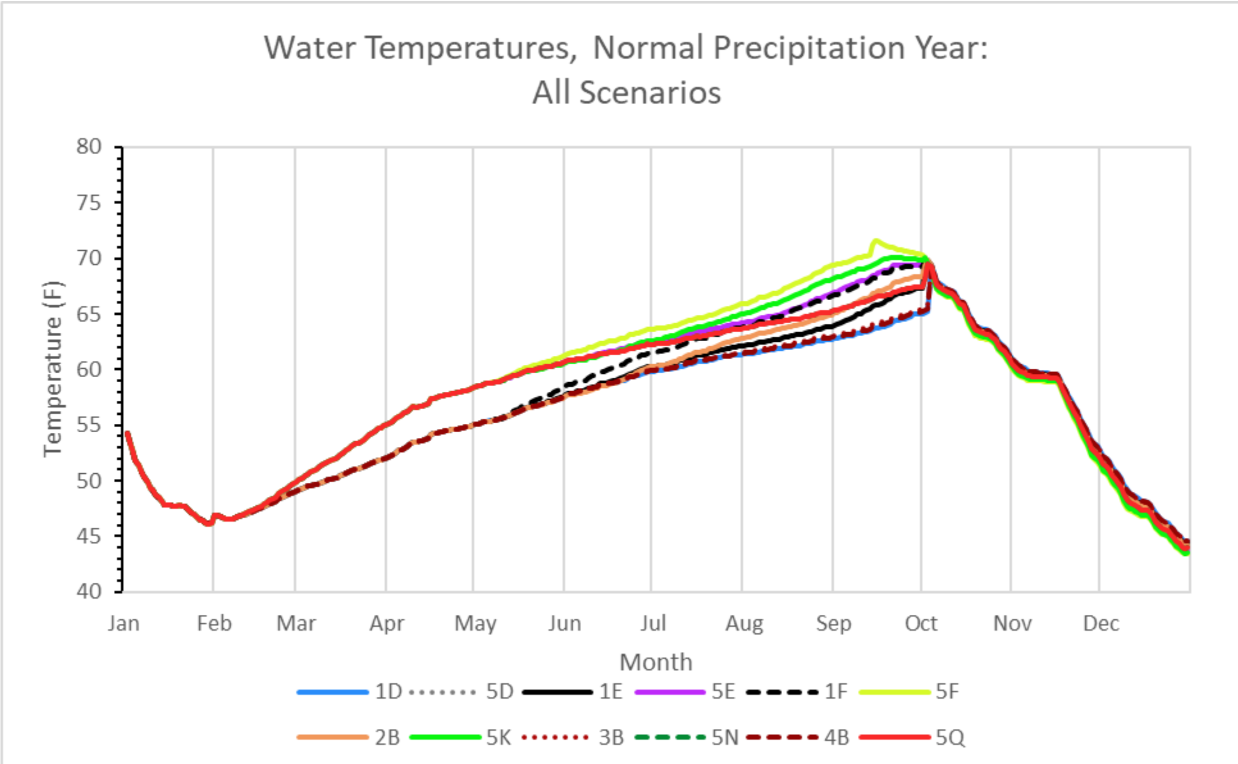
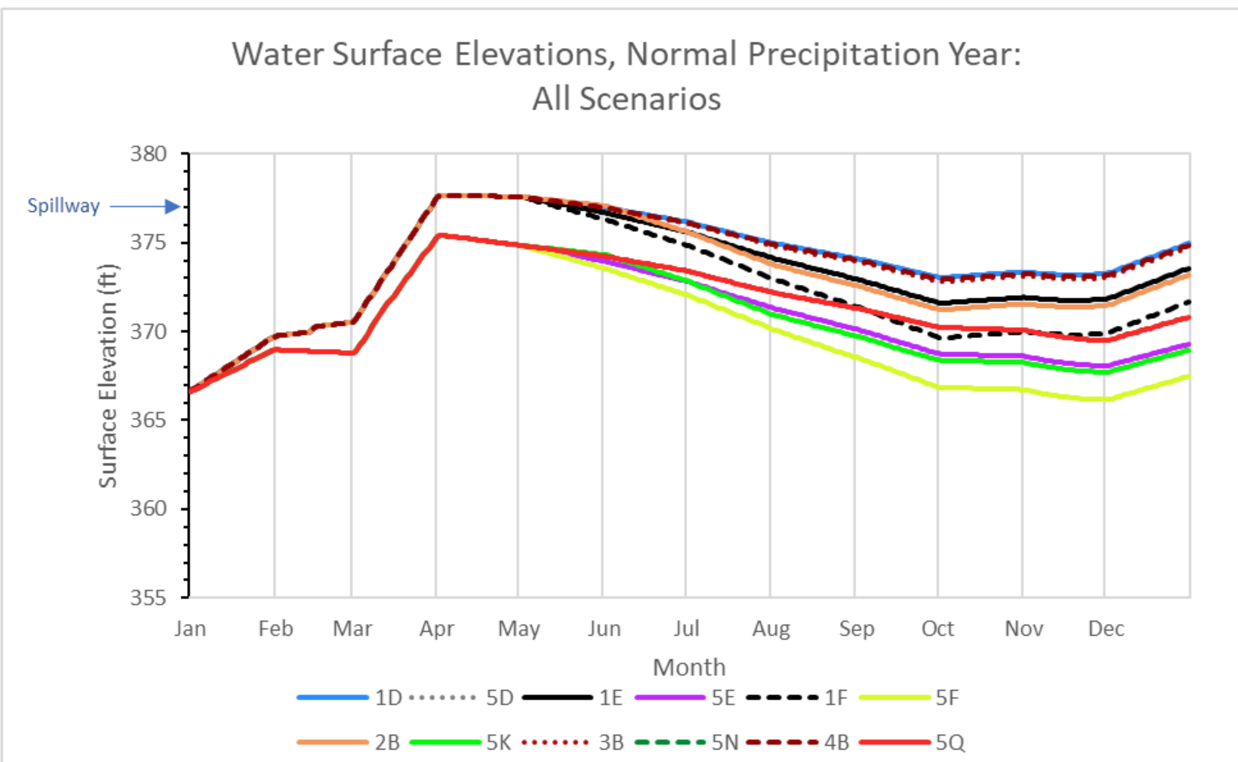


Figure 76. Hydrograph for Scenario 4B for May-Sept. It is important to note that this graph shows pulses on the dates when air temperatures exceeded 95⁰ F in 2016. The timing of the pulses will vary from year to year.





Figures 77 and 78. Modeled temperature changes over the summer for all the normal year scenarios and changes in the water surface elevation in Lake Curry for all normal year scenarios

Table 11. Summary of days of high-water temperature releases and low lake levels in Lake Curry for Scenarios 1-4 for a normal year.

Normal Year Scenarios (1 - 4)						
Scenario	**Description**	**Days > 70° F**	**Days > 75.2° F**	**Days > 80° F**	**Days < 365 ft.**
1D*	2.5 cfs release 24 hrs. a day, May 1-Sept. 30	0	0	0	0
1E*	4 cfs release 24 hrs. a day, May 1-Sept. 30	0	0	0	0
1F	6 cfs release 24 hrs. a day, May 1-Sept. 30	0	0	0	0
2B	Release 2 cfs in May, 6 cfs in June, 6 cfs in July, 4 cfs in August and 4 cfs in Sept.	0	0	0	0
3B	Release 2.5 cfs from May through September. When air temperatures are predicted to reach 90⁰ F a pulse of 4 cfs from 10 am to 6 pm is released	0	0	0	0
4B	Release 2.5 cfs from May through September. When air temperatures are predicted to reach 95⁰ F a pulse of 4 cfs from 10 am to 6 pm is released	0	0	0	0

*Recommended

Table 12. Summary of days of high-water temperature releases and low lake levels in Lake Curry for the Scenario 5's associated with Scenarios 1-4 for a normal year.

Normal Year Scenarios (5)					
Scenario	**Associated Scenario**	**Days > 70° F**	**Days > 75.2° F**	**Days > 80° F**	**Days < 365 ft.**
5D*	1D	0	0	0	0
5E*	1E	0	0	0	0
5F	1F	24 (Sep. - Oct.)	0	0	0
5K	2B	6 (Sep. - Oct.)	0	0	0
5N	3B	0	0	0	0
5Q	4B	0	0	0	0
For each Scenario 5 these releases are added to the associated summer release scenario: for the steelhead migration/spawning period of Oct. 1-Dec 31, 2.5 cfs would be released 24 hours a day. From Jan. 1-March 31, 4 cfs would be released 24 hours a day to support spawning and egg incubation. For the month of April, 3 cfs would be released 24 hours a day to support rearing and outmigration of juveniles. Changes in flows would be made at 0.5 cfs/day.					

*Recommended

Discussion: Normal Year Scenarios

Scenarios 1-4 do not release water that exceeds 70^{o} or higher temperatures and do not lower the level of Lake Curry below the 365 ft. elevation. Two of the scenarios, 5Fand 5K, result in releases of >70^{o} F water for a portion of the Sept.-Oct. period.

We recommend Scenarios 1D and 1E which would provide a constant release of 2.5 cfs and 4 cfs respectively. We also recommend Scenarios 5D and 5E to implement year-round water releases. When the flow changes under 5D and 5E are made they should be adjusted in 0.5 cfs increments/day to avoid stranding any juvenile steelhead along stream margins. In many years, rainfall during winter would provide adequate flows for steelhead migration, spawning, and rearing. Fish habitats are not totally dependent on the lake during the winter for flows in normal years as they are in summer. None of the scenarios reduces water levels in Lake Curry below 365 ft. elevation and are not likely to result in water quality problems in the lake.

Wet Year Scenarios

Figures 79 to 92 depict the modeled results for each dry year scenario with and without the Oct-April releases from Scenario 5 and a hydrograph of each release level.

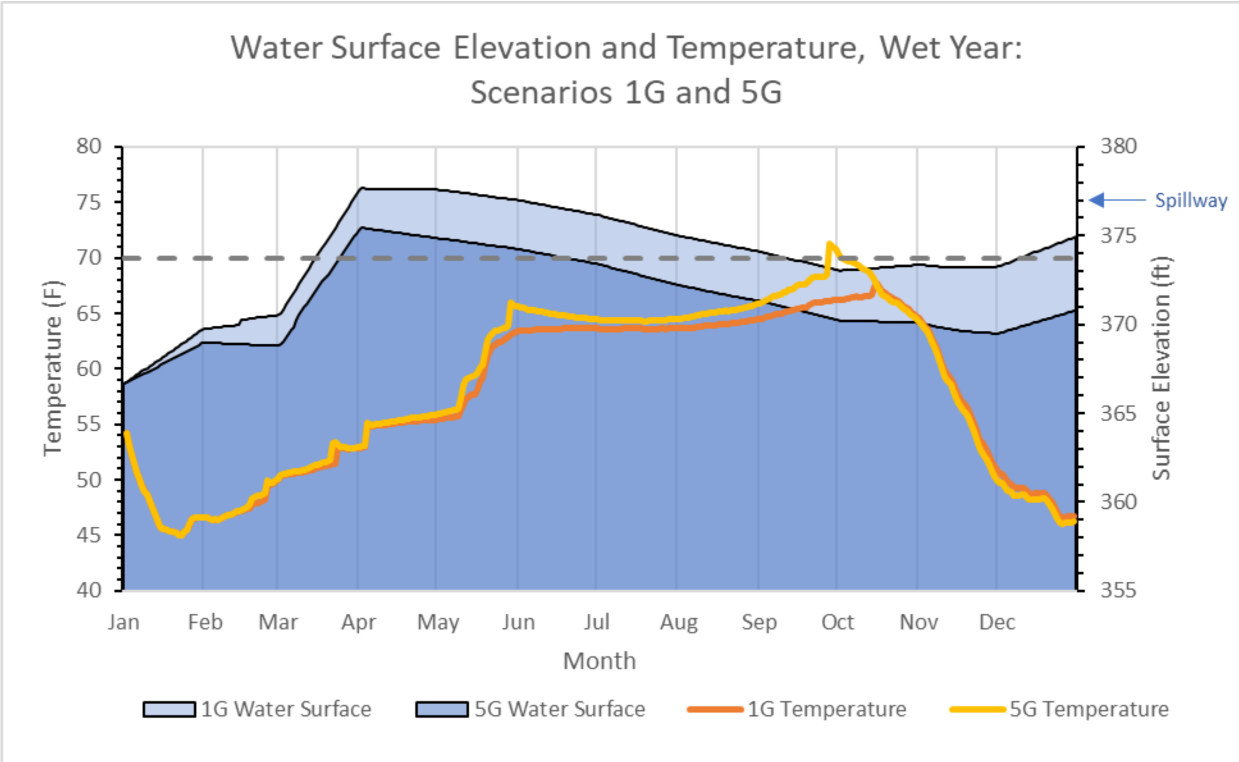


Figure 79. Scenario 1G would release 2.5 cfs from May 1 to Sept 30. Scenario 5G would include Scenario 1G and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

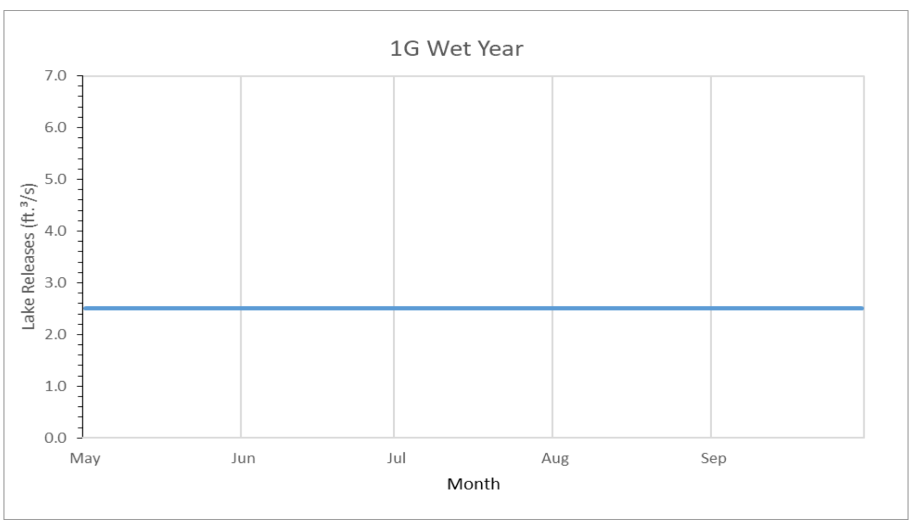


Figure 80. Hydrograph for Scenario 1G for May-Sept.

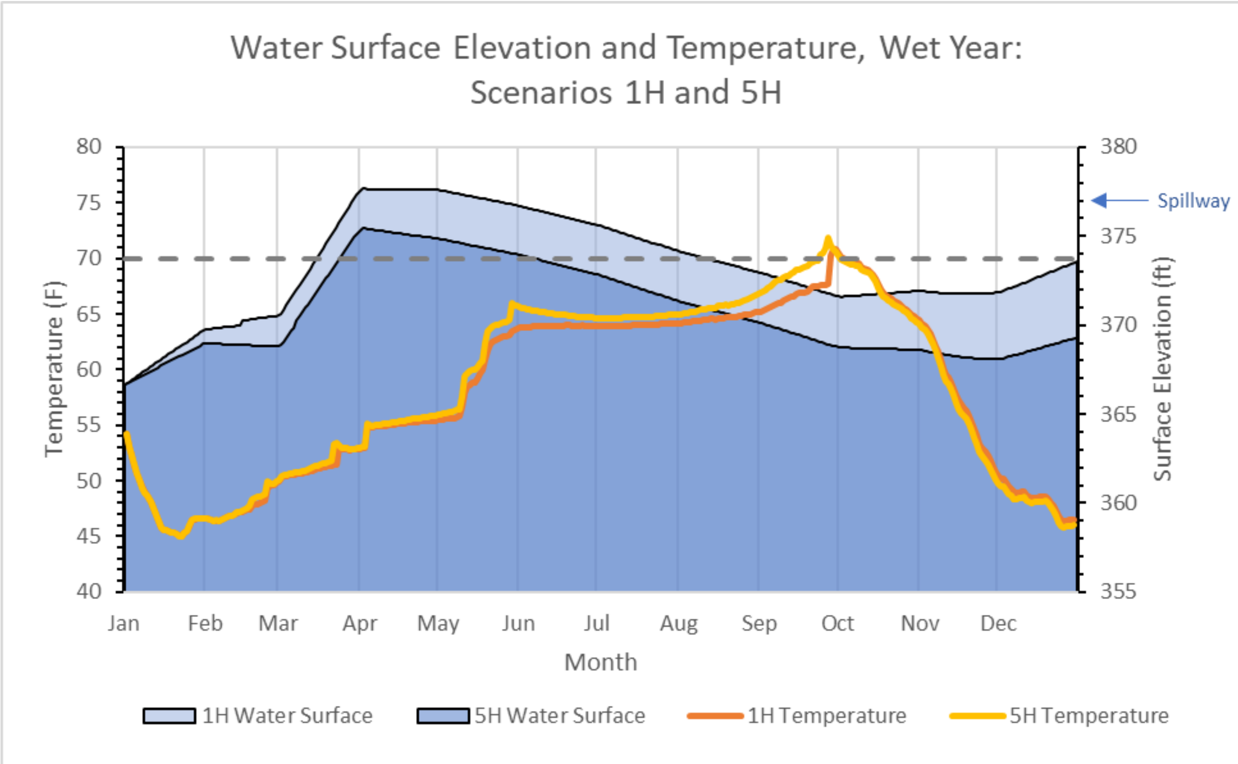


Figure 81. Scenario 1H would release 4 cfs from May 1 to Sept 30. Scenario 5H would include Scenario 1H and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

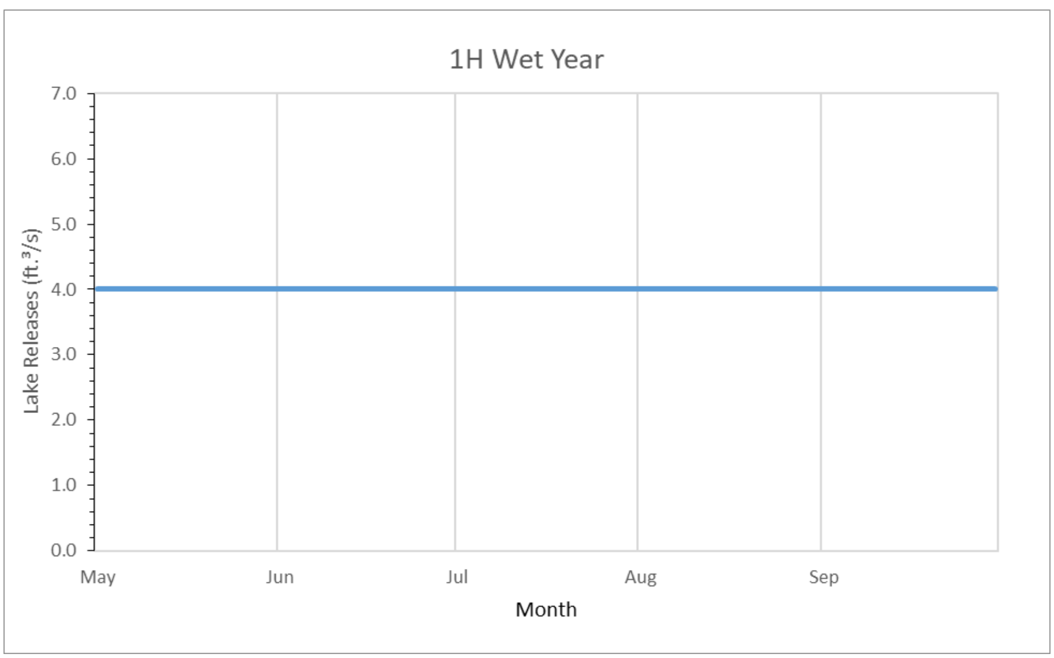


Figure 82. Hydrograph for Scenario 1H for May-Sept.

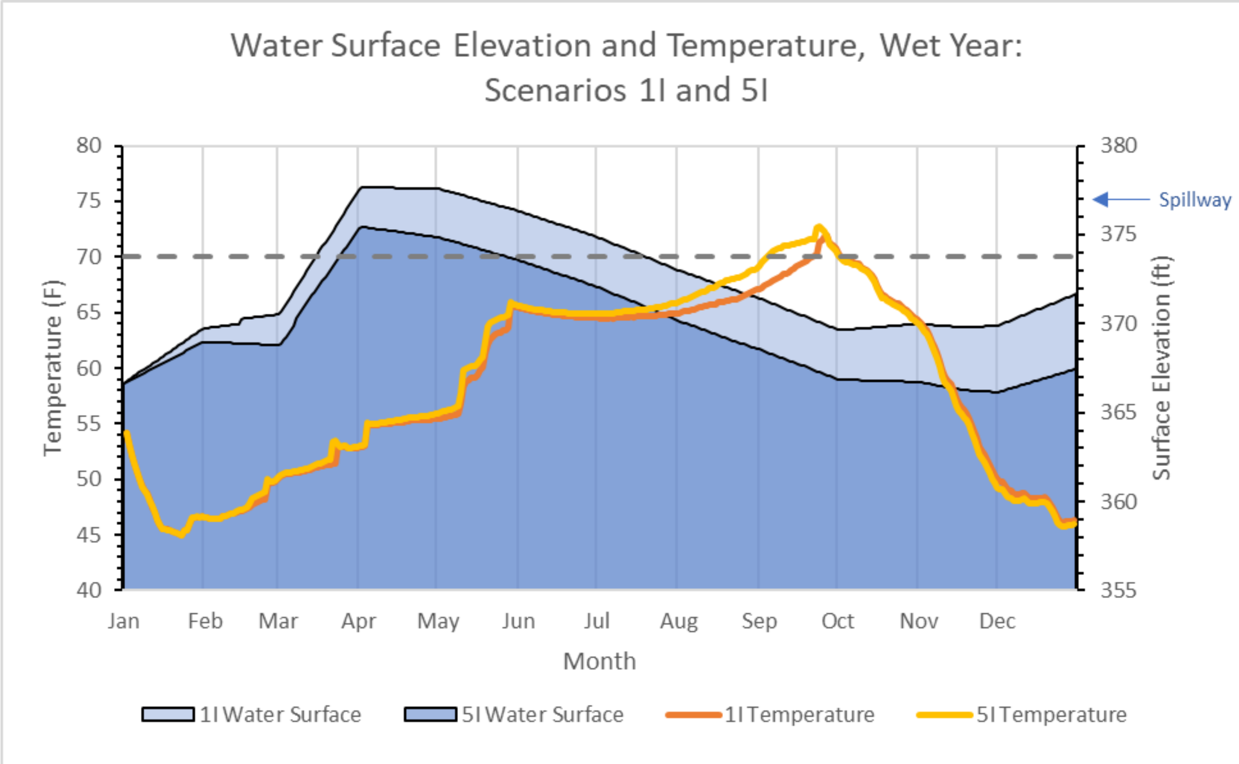


Figure 83. Scenario 1I would release 6 cfs from May 1 to Sept 30. Scenario 5I would include Scenario 1I and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

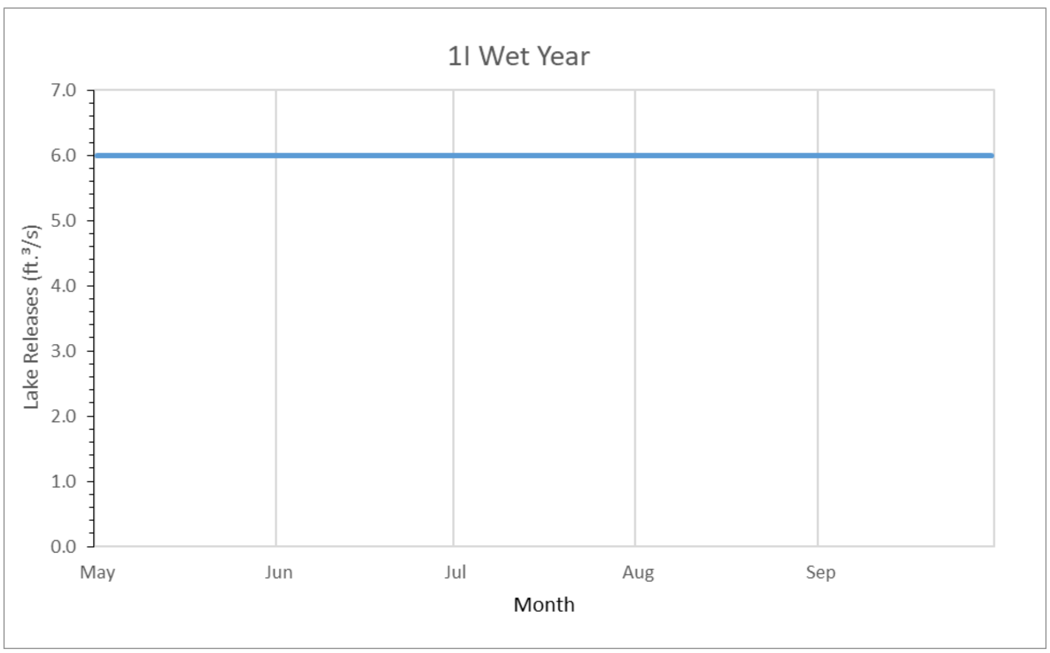


Figure 84. Hydrograph for Scenario 1I for May-Sept.

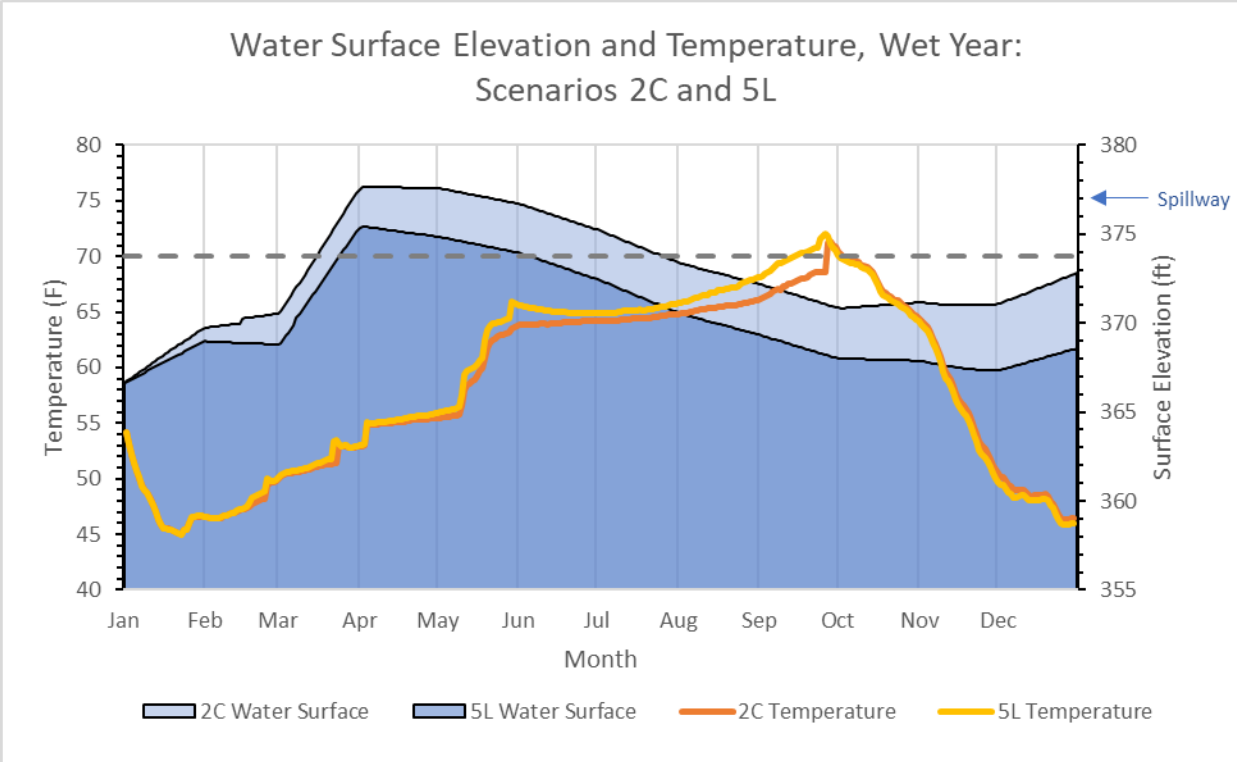


Figure 85. Scenario 2C would release 4 cfs in May, 6 cfs in June, 6 cfs in July, 4 cfs in August and 4 cfs in Sept. Scenario 5L would include Scenario 2C and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

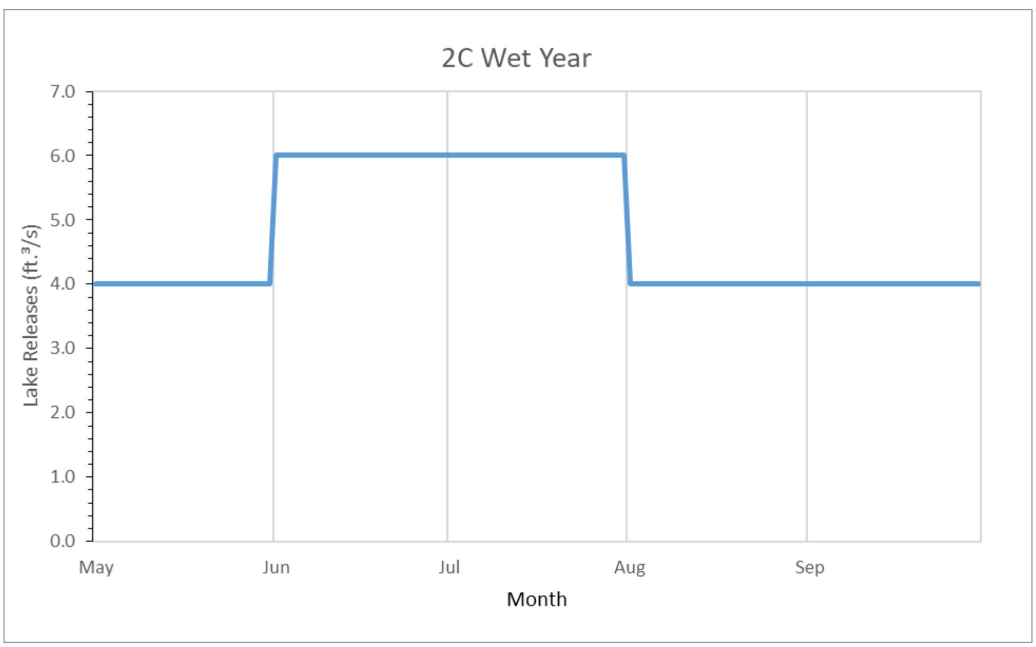


Figure 86. Hydrograph for Scenario 2C for May-Sept. Changes between release levels will be made at 0.5 cfs/day.

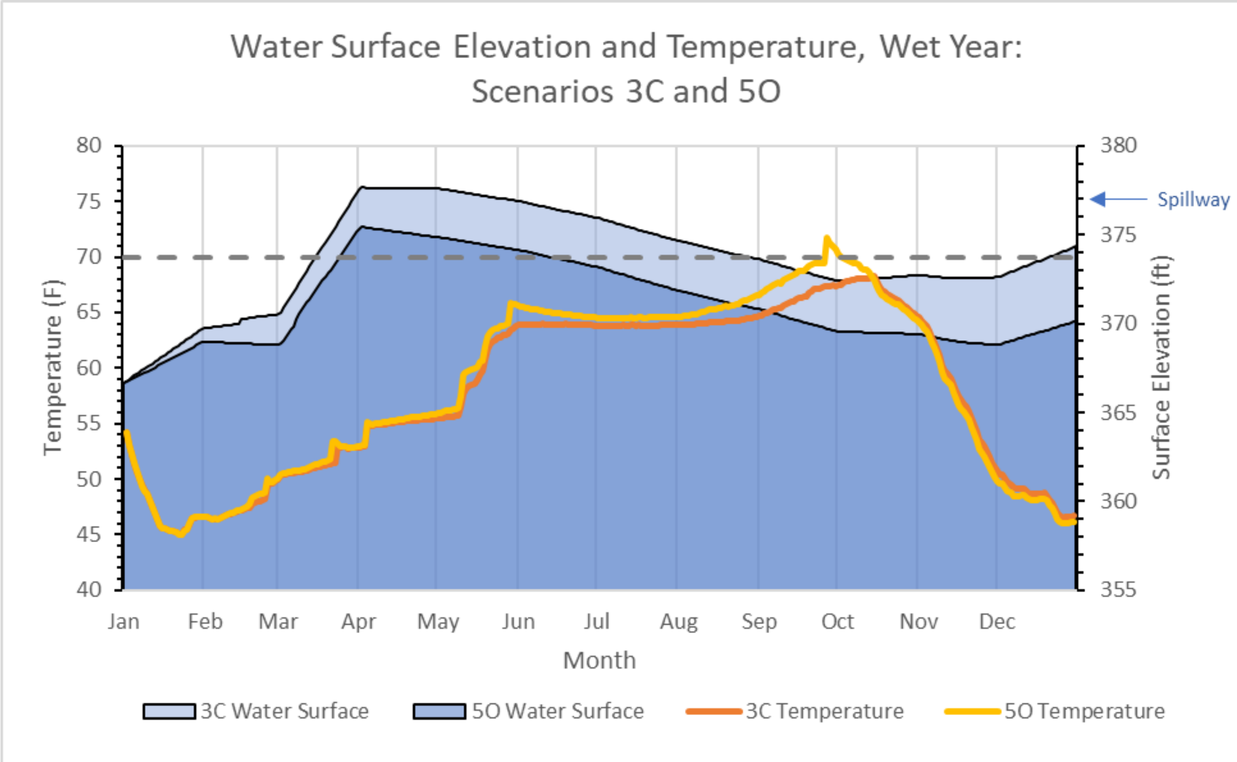


Figure 87. Scenario 3C would release 3 cfs from May through September. When air temperatures are predicted to reach 90^{0} F a pulse of 6 cfs from 10 am to 6 pm is released. Scenario 5O would include Scenario 3C and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

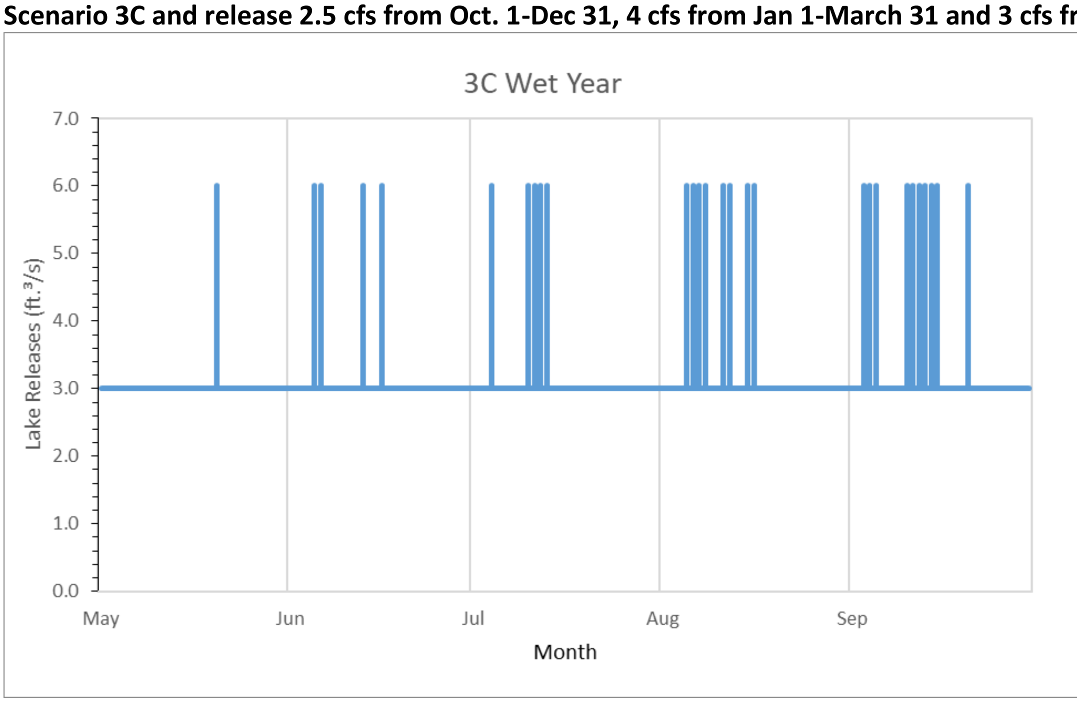


Figure 88. Hydrograph for Scenario 3C for May-Sept. It is important to note that this graph shows pulses on the dates when air temperatures exceeded 90^{0} F in 1983. The timing of the pulses will vary from year to year.

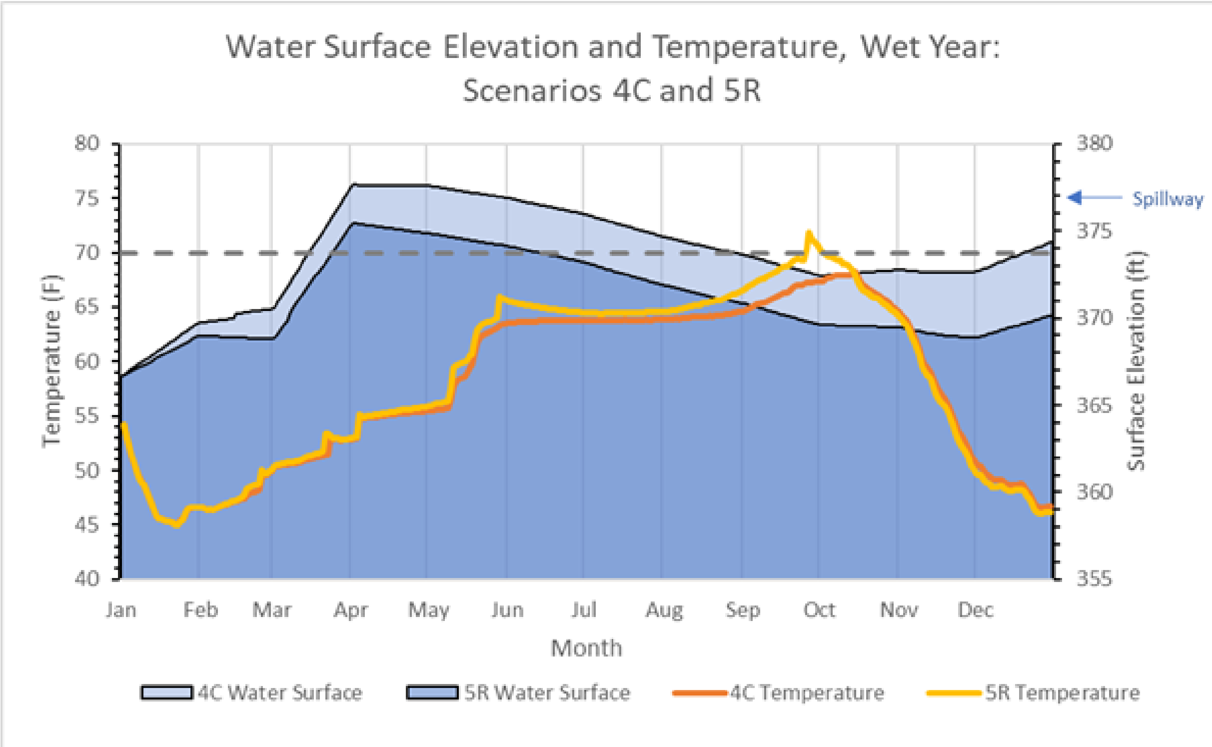


Figure 89. Scenario 4C would release 3 cfs from May through September. When air temperatures are predicted to reach 95⁰ F a pulse of 6 cfs from 10 am to 6 pm is released. Scenario 5R would include Scenario 4C and release 2.5 cfs from Oct. 1-Dec 31, 4 cfs from Jan 1-March 31 and 3 cfs from April 1-30.

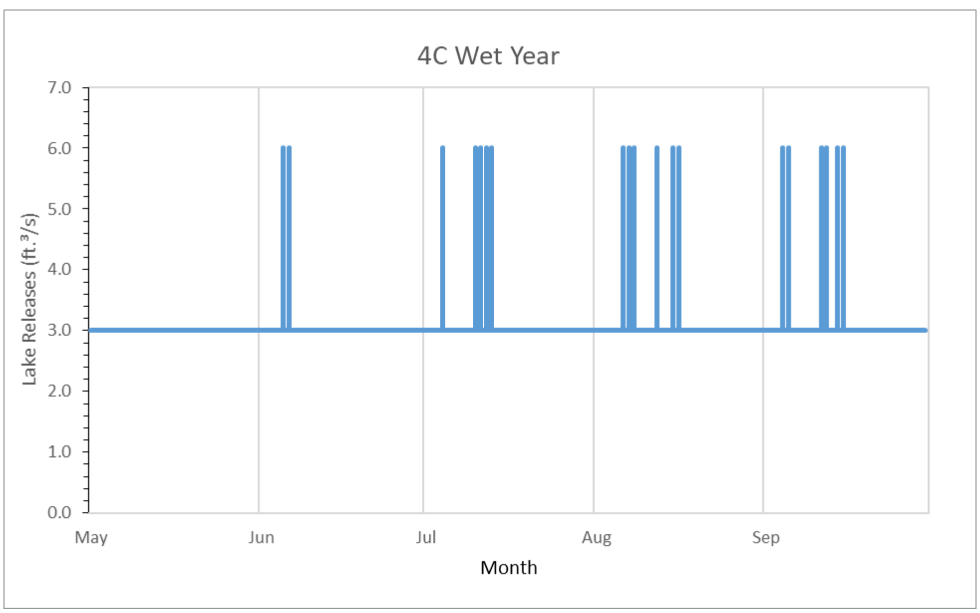
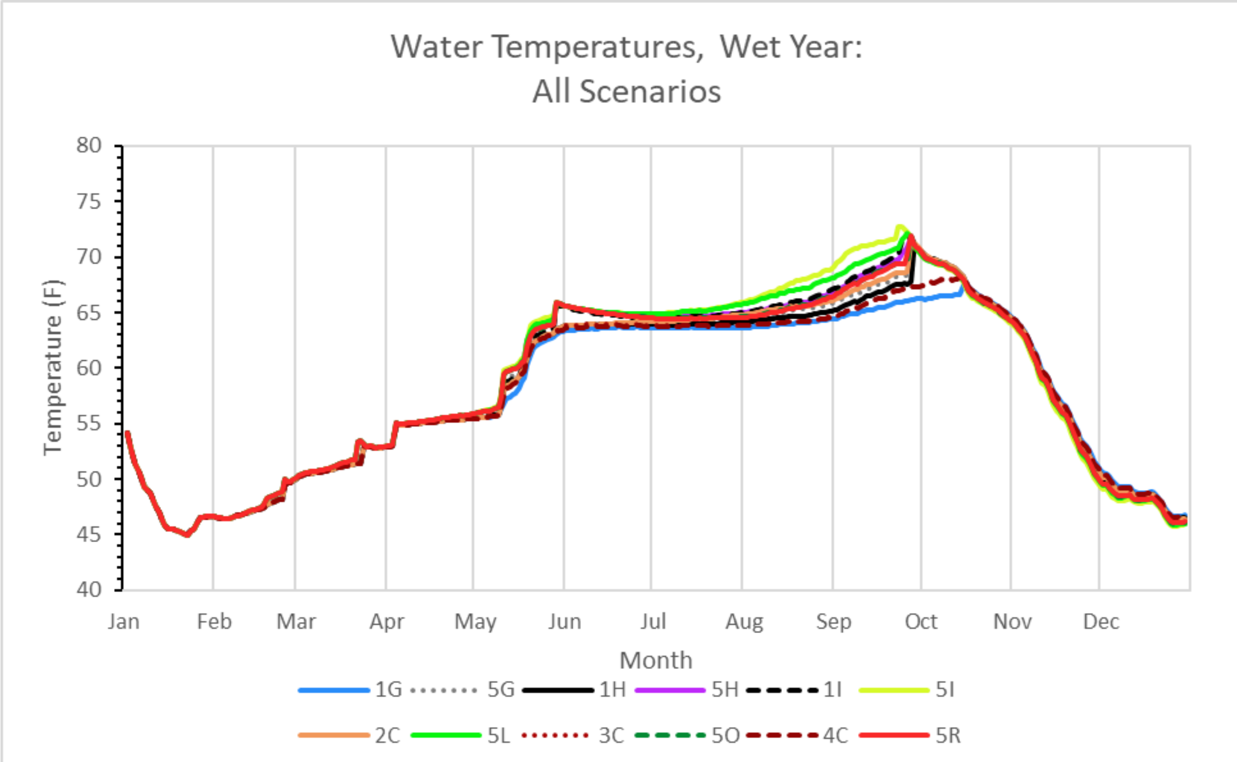
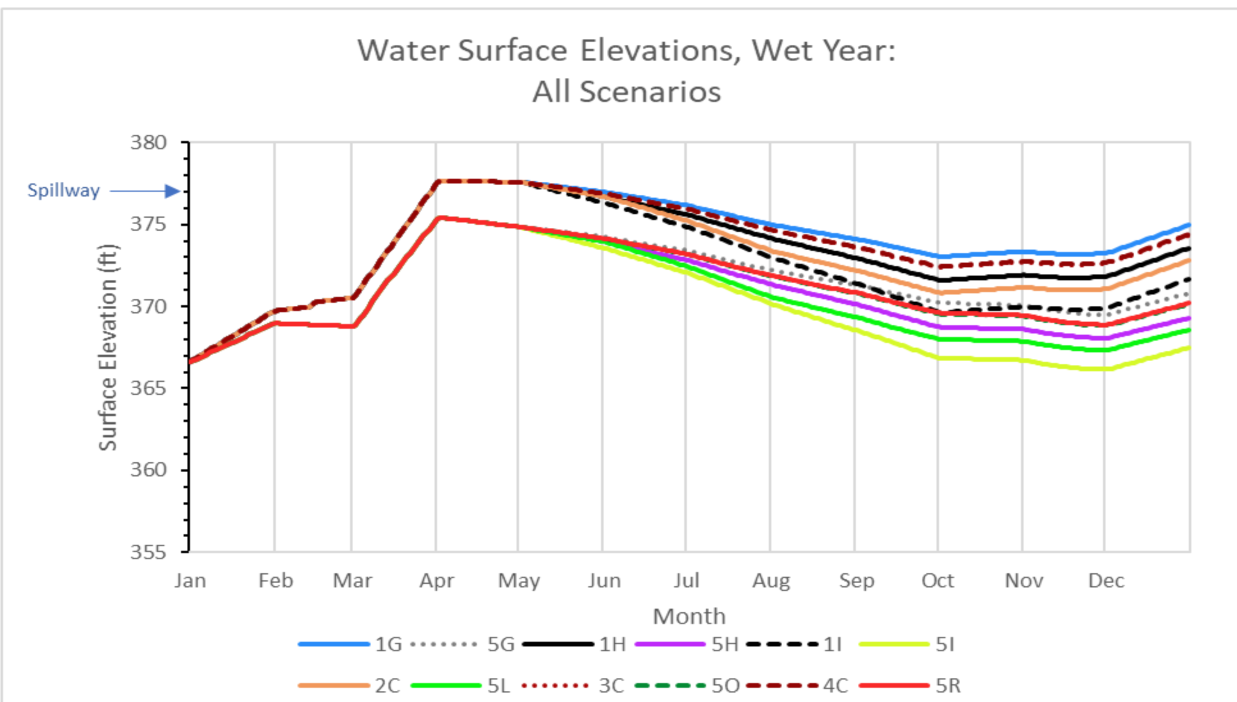


Figure 90. Hydrograph for Scenario 4C for May-Sept. It is important to note that this graph shows pulses on the dates when air temperatures exceeded 95⁰ F in 1983. The timing of the pulses will vary from year to year.





Figures 91 and 92. Modeled temperature changes over the summer for all the wet year scenarios and changes in the water surface elevation in Lake Curry for all wet year scenarios

Table 13. Summary of days of high-water temperature releases and low lake levels in Lake Curry for Scenarios 1-4 for a wet year.

Wet Scenarios (1 - 4)					
Scenario	**Description**	**Days > 70° F**	**Days > 75.2° F**	**Days > 80° F**	**Days < 365 ft.**
1G*	2.5 cfs release 24 hrs. a day, May 1-Sept. 30	0	0	0	0
1H*	4 cfs release 24 hrs. a day, May 1-Sept. 30	6 (Sep. - Oct.)	0	0	0
1I*	6 cfs release 24 hrs. a day, May 1-Sept. 30	11 (Sep. - Oct.)	0	0	0
2C	Release 4 cfs in May, 6 cfs in June, 6 cfs in July, 4 cfs in August and 4 cfs in Sept.	7 (Sep. - Oct.)	0	0	0
3C	Release 3 cfs from May through September. When air temperatures are predicted to reach 90° F a pulse of 4 cfs from 10 am to 6 pm is released	0	0	0	0
4C	Release 3 cfs from May through September. When air temperatures are predicted to reach 95° F a pulse of 4 cfs from 10 am to 6 pm is released	0	0	0	0

*Recommended

Table 14. Summary of days of high-water temperature releases and low lake levels in Lake Curry for the Scenario 5's associated with Scenarios 1-4 for a wet year.

Wet Scenarios (5)					
Scenario	**Associated Scenario**	**Days > 70° F**	**Days > 75.2° F**	**Days > 80° F**	**Days < 365 ft.**
5G*	1G	5 (Sep. - Oct.)	0	0	0
5H*	1H	8 (Sep. - Oct.)	0	0	0
5I	1I	27 (Sep. - Oct.)	0	0	0
5L	2C	17 (Sep. - Oct.)	0	0	0
5O	3C	5 (Sep. - Oct.)	0	0	0
5R	4C	6 (Sep. - Oct.)	0	0	0
For each Scenario 5 these releases are added to the associated summer release scenario: for the steelhead migration/spawning period of Oct. 1-Dec 31, 2.5 cfs would be released 24 hours a day. From Jan. 1-March 31, 4 cfs would be released 24 hours a day to support spawning and egg incubation. For the month of April, 3 cfs would be released 24 hours a day to support rearing and outmigration of juveniles. Changes in flows would be made at 0.5 cfs/day.					

*Recommended

Discussion: Wet Year Scenarios

The wet year scenarios include a slightly greater number of days with lake release water temperatures above 70° F than do the normal year scenarios. The wet year days with high water temperatures are all during September. September air temperature data used to model the wet year scenarios were higher than the September air temperatures used to model the normal year scenarios; the wet year air temperature data included 10 days above 90 degrees F in September, whereas the normal year data included only 5 such days. Although lake levels were higher for the wet year scenarios, the increased temperatures during September raised water temperatures briefly above 70° F. Air temperature data from other representative wet and normal years might produce slightly different results. As shown in Figure 49, years of high rainfall are not well correlated with low summer temperatures.

For wet year scenarios 1-4 several show releases of water warmer than 70° F for a few days (6-11) at the end of September. These are fairly short time frames that should not cause problems with steelhead in Suisun Creek. None of the scenarios 1-4 results in releases of water warmer than 72.5° F and none lowers the lake level below 365 ft. Scenarios 1G, 3C and 4C have a fairly low baseflow release of 2.5-3 cfs which limit the extent of aquatic habitats in the creek when there is sufficient stored water for a higher release. It is important to note that based on our streamflow data, flows downstream of the Wooden Valley Creek confluence with Suisun Creek often decrease to zero during the summer when lake releases remain at or below 1 cfs for extended periods. If a release of 4-6 cfs is possible it will provide improved steelhead habitat. We recommend scenarios 1H, 1I. However, we also recommend scenario 1G to conserve water in the reservoirs should a dry year follow a wet year. For scenarios 2C and 5L as flow changes are made, they should be adjusted in 0.5 cfs increments/day to avoid stranding any juvenile steelhead along stream margins. All of the scenario 5's release > 70^{o} F water for a few days (5-8) to nearly a month. Taking this into account we recommend scenarios 5G and 5H which allows a steady summer release of 2.5 or4 cfs but only results in a few days of > 70^{o} F water releases. Scenario 5G provides a minimal release but would conserve water in the reservoir should a dry year follow the wet year.

Evaluation of Field-Tested Scenarios

Scenario 6

The final release schedule showed a 4 cfs release from 6/13-6/21/17 then releases were gradually increased to 8 cfs on 7/15/17 and then abruptly decreased. A release of 4 cfs was maintained 7/20-8/2/17. During the 4 cfs release water temperatures were measured at the lake outlet varied from 58 -62^{o} F. The 2 cfs release was restricted to 8/5-8/14/17 and temperatures were 58-62^{o} F. The releases were not maintained at 6 cfs long enough to record water temperature. On 8/15/17 releases were abruptly increased to 14 cfs until 9/29/17 and then gradually reduced to 6 cfs on 10/23/17 (Figure 94).

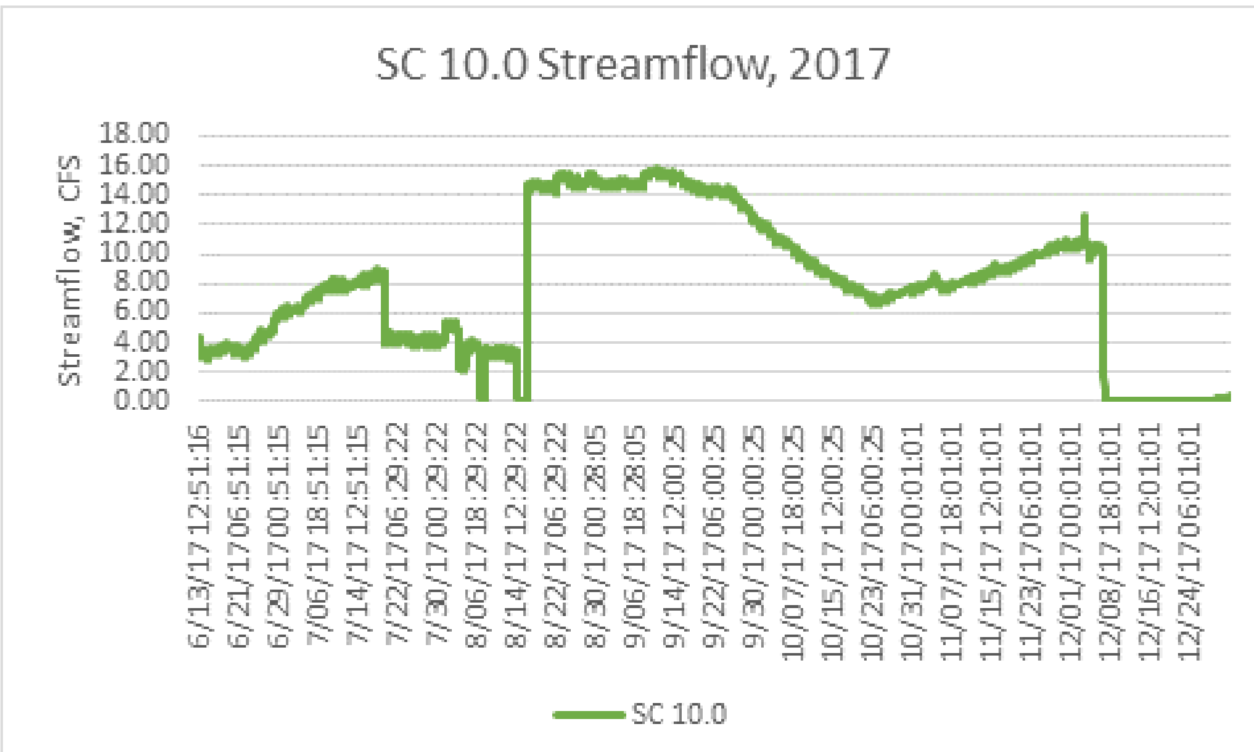


Figure 93. Hydrograph of releases from Lake Curry for Scenario 6 measured at stream flow gage at SC 10.0.

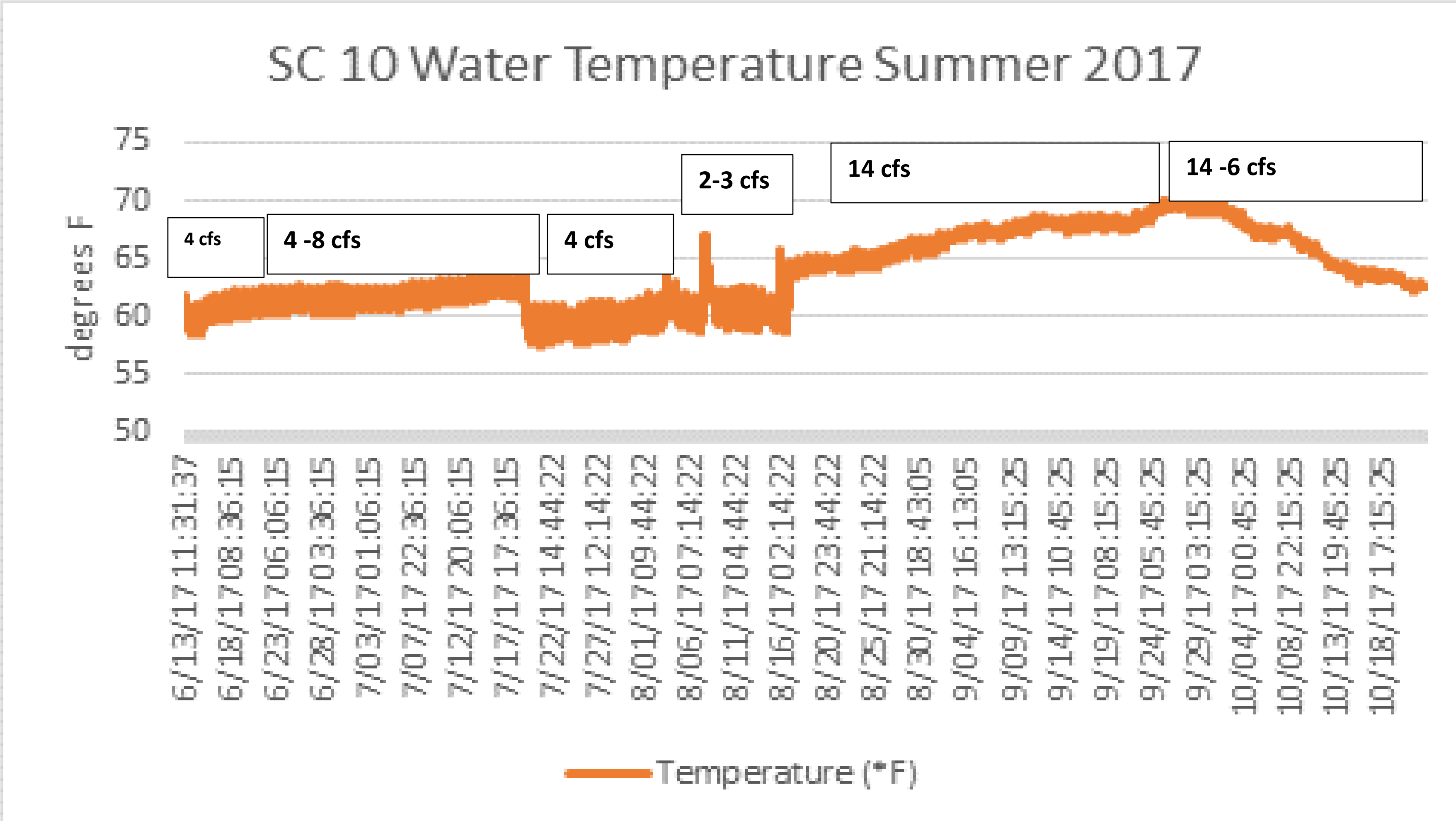


Figure 94. Measured water temperatures just downstream of Lake Curry outlet at SC 10 in 2017 during listed water release rates. 2017 was a wet year.

Discussion: Scenario 6

Scenario 6 shows that releases of 4-6 cfs maintain release temperatures of 60-65^{o} F from June through mid-August. However, when the release was increased to 14 cfs in August through October temperatures gradually rose to 70^{o} F likely due to the subsequent decline in lake water surface elevation of over 6.5 ft. (City of Vallejo 2019). This field monitored release shows that actual releases of 2-4-6 cfs maintain water temperatures below 70^{o} F.

Scenario 7

Natural groundwater flows may provide cooler water than reservoir releases can. The effects of this scenario were field monitored when the City of Vallejo reduced and turned off the release from Lake Curry to Suisun Creek. This action was not done in coordination with this study. The water releases from the lake were stopped from January to June 2018 when temperatures would generally be low. 2018 was a dry year (Ca. Dept of Water Resources 2021). Additionally, in 2019 and 2020 releases from Lake Curry were very low and stream flow gaging does not show flows augmented by groundwater. 2019 was a wet year and 2020 was a dry year (Ca. Dept of Water Resources 2021)

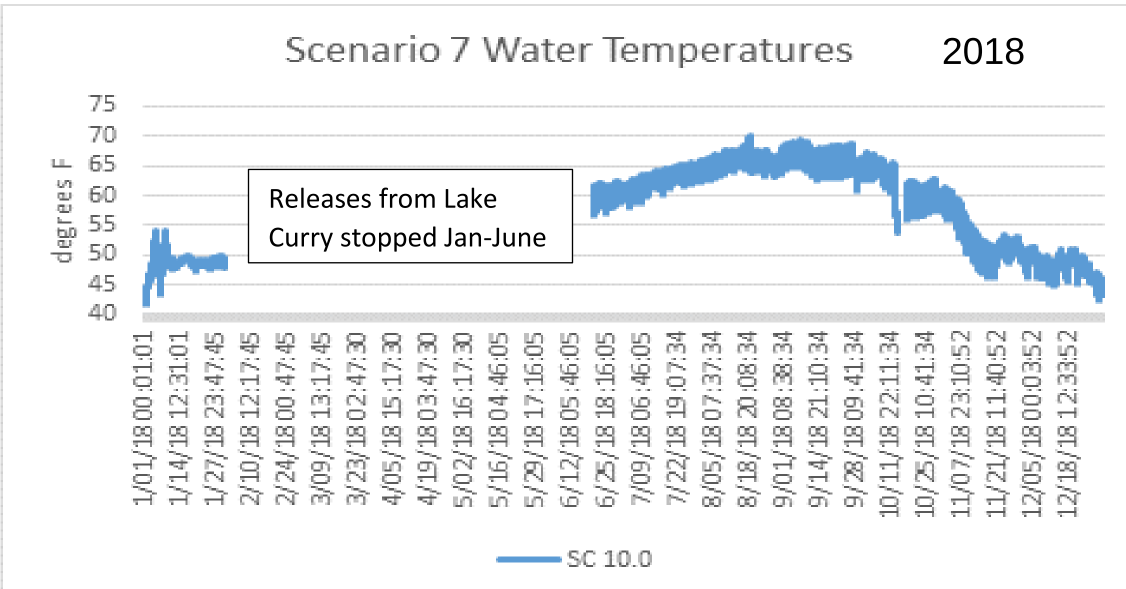
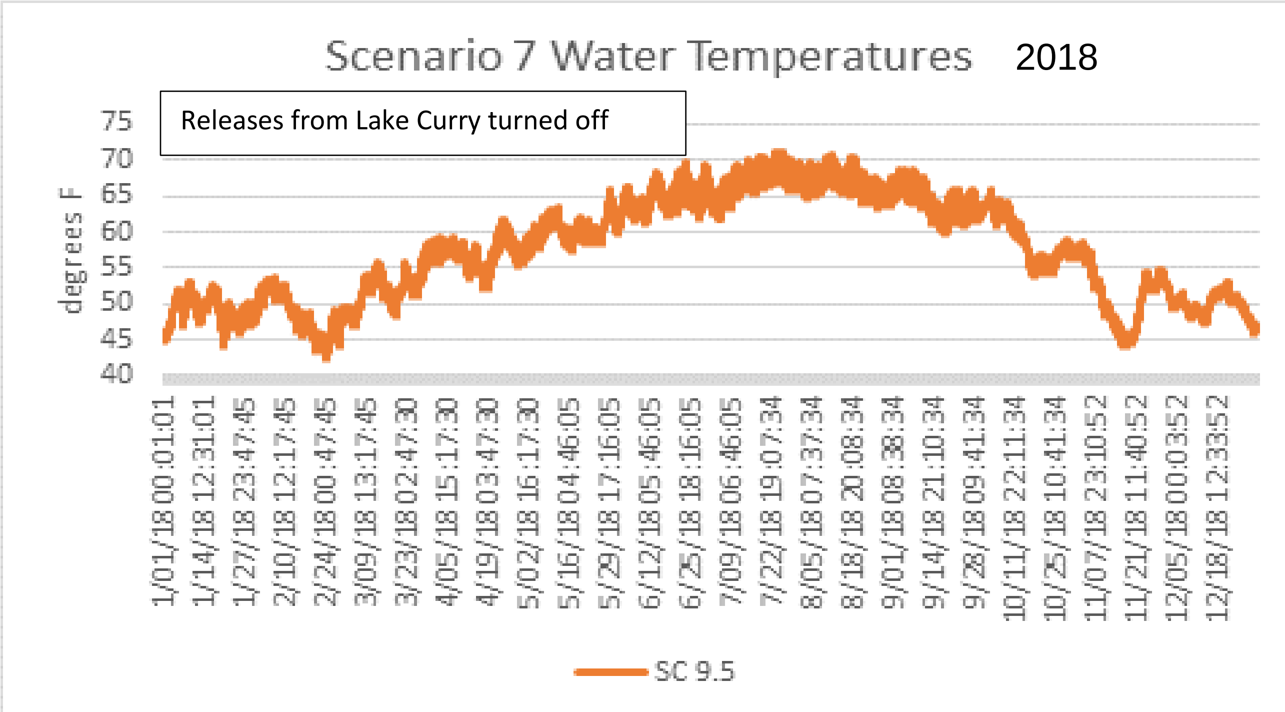
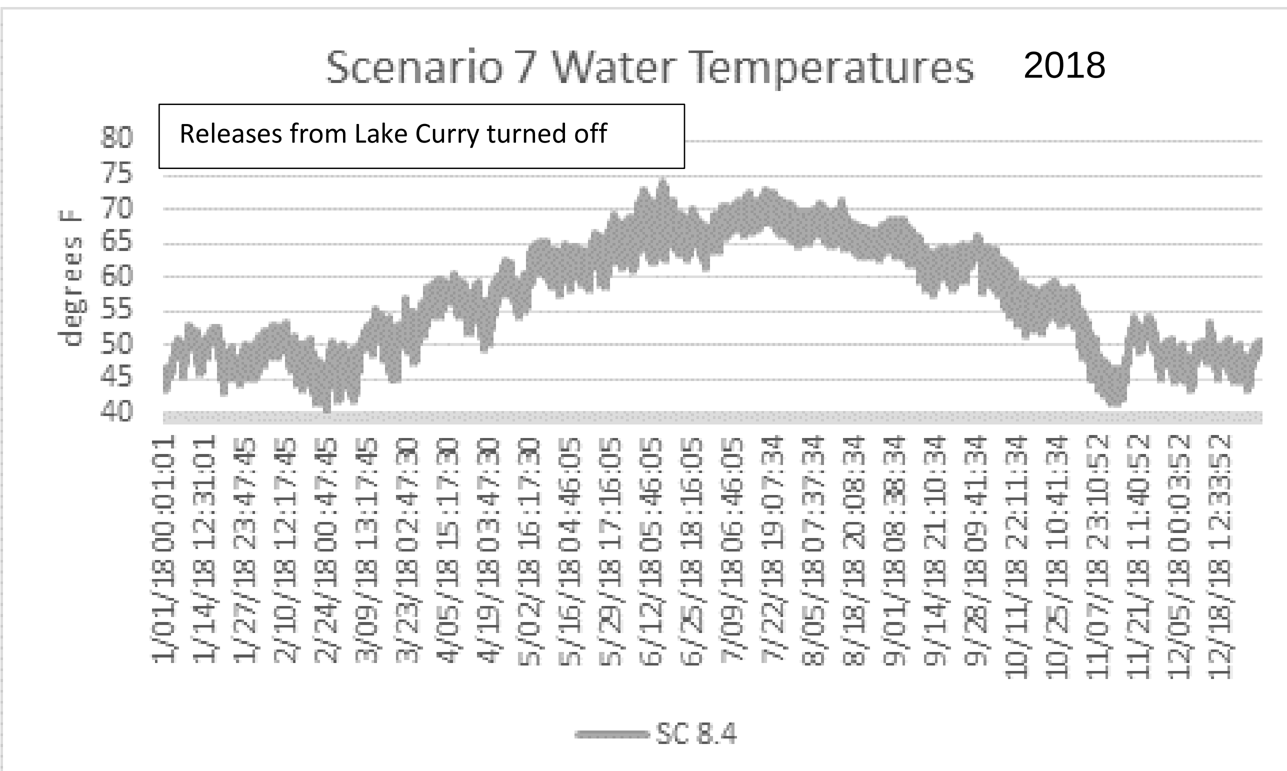


Figure 95. Water releases from Lake Curry to Suisun Creek were stopped from January to June 2018

Figure 96. Photographs of the Upper Suisun Creek in June 2018 when releases from Lake Curry were turned off. Previous locations with steelhead trout presence were either completely dry, or if wet, devoid of fish.





Figures 97 and 98. Water temperatures for two stations downstream of the lake outlet in 2018.

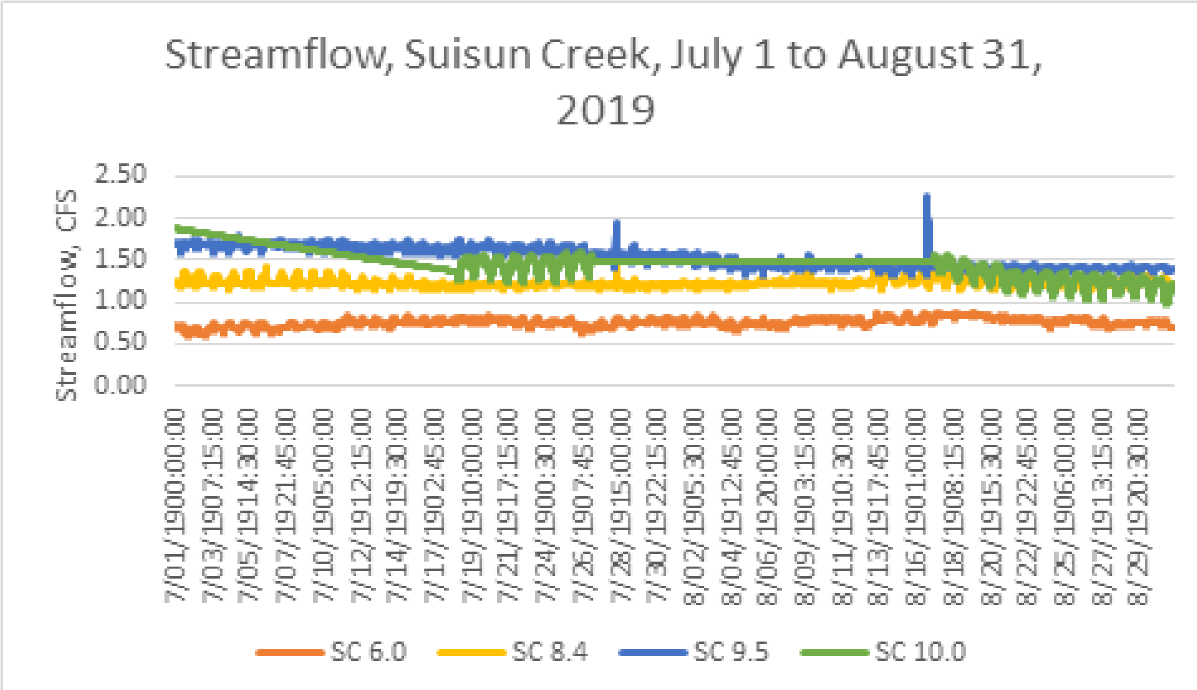


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Figure 99. Stream flows at four stations on Suisun Creek. Station 10 is at the outlet of Lake Curry and shows a reduction in flow from 1.5 cfs in July to 1.0 in August. Lower flows at downstream stations demonstrated water seeping into the streambed as it flows downstream rather than augmentation of flows from groundwater. 2019 was a wet year.

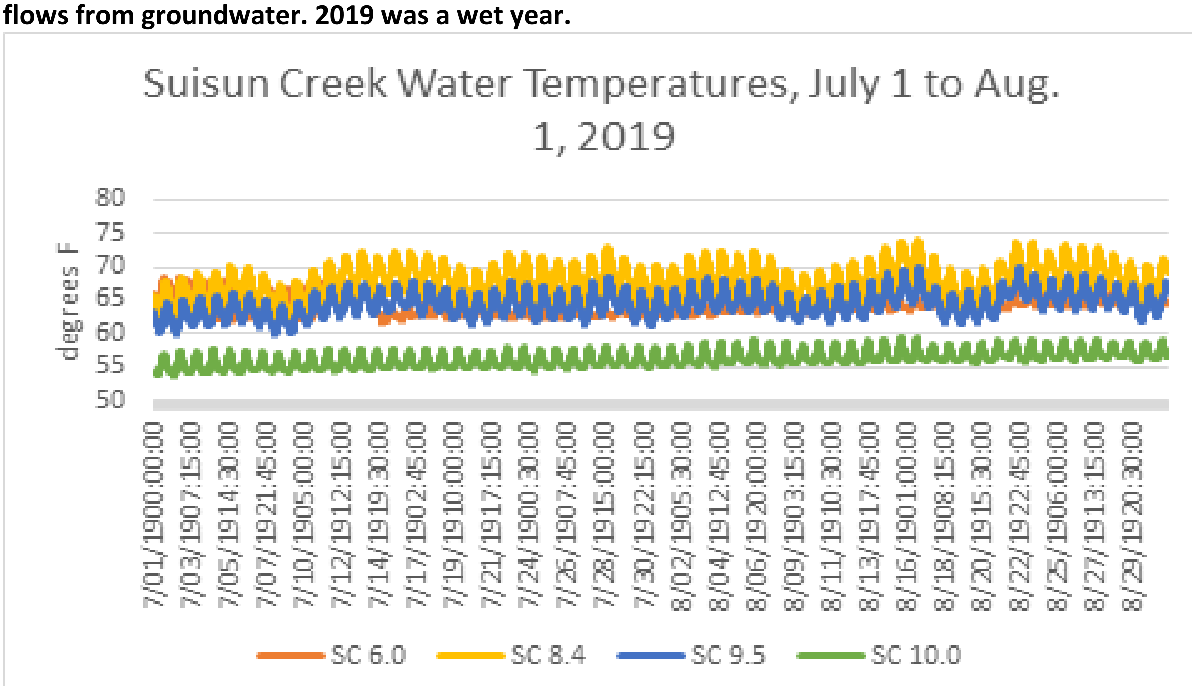

Figure 100. Monitored water temperatures in 2019 during low flows. While water at the lake outlet stays cool downstream station show much higher water temperatures.

Discussion: Scenario 7

The releases from Lake Curry were stopped between Jan.-June 2018. This time period does not have warm air temperatures and was not a good test of whether groundwater in the creek alone can maintain >70^{o} F water in Suisun Creek. Streamflow data collected between 2017 and 2021 by CLSI indicate that groundwater is not a major source of water for Suisun Creek during dry seasons, and therefore groundwater seepage to the creek is not likely to reduce stream temperatures during summers.

Summary

Table 15 summarizes the recommended Lake Curry scenarios by climatic year. Warm water and low dissolved oxygen conditions which may occur at Lake Curry at low lake levels will not harm the fish species in the lake. However not releasing cool water from the bottom of Lake Curry to Suisun creek will harm steelhead trout in Suisun Creek.

Table 15. Recommended Lake Curry release scenarios

	Recommended Dry Year Scenarios
1A*	2.5 cfs release 24 hrs. a day, May 1-Sept. 30
5A*	2.5 cfs release 24 hrs. a day, May 1-Sept. 30, release 2.5 cfs 24 hrs. a day from Oct. 1-Dec 31, 4 cfs 24 hrs. a day from Jan 1-March 31 and 3 cfs 24 hrs. a day from April 1-30. Changes in flows would be made at 0.5 cfs/day
	Recommended Normal Year Scenarios
1D*	2.5 cfs release 24 hrs. a day, May 1-Sept. 30
1E*	4 cfs release 24 hrs. a day, May 1-Sept. 30
5D*	Release 2.5 cfs release 24 hrs. a day, May 1-Sept. 30, release 2.5 cfs 24 hrs. a day from Oct. 1-Dec 31, 4 cfs 24 hrs. a day from Jan 1-March 31 and 3 cfs 24 hrs. a day from April 1-30. Changes in flows would be made at 0.5 cfs/day
5E*	Release 4 cfs 24 hrs. a day, May 1-Sept. 30, release 2.5 cfs 24 hrs. a day from Oct. 1-Dec 31, 4 cfs 24 hrs. a day from Jan 1-March 31 and 3 cfs 24 hrs. a day from April 1-30. Changes in flows would be made at 0.5 cfs/day
	Recommended Wet Year Scenarios
1G*	2.5 cfs release 24 hrs. a day, May 1-Sept. 30
1H*	4 cfs release 24 hrs. a day, May 1-Sept. 30
1I*	6 cfs release 24 hrs. a day, May 1-Sept. 30
5G*	Release 2.5 cfs release 24 hrs. a day, May 1-Sept. 30 May 1-Sept. 30, release 2.5 cfs 24 hrs. a day from Oct. 1-Dec 31, 4 cfs 24 hrs. a day from Jan 1-March 31 and 3 cfs 24 hrs. a day from April 1-30. Changes in flows would be made at 0.5 cfs/day
5H*	Release 4 cfs 24 hrs. a day, May 1-Sept. 30, release 2.5 cfs 24 hrs. a day from Oct. 1-Dec 31, 4 cfs 24 hrs. a day from Jan 1-March 31 and 3 cfs 24 hrs. a day from April 1-30. Changes in flows would be made at 0.5 cfs/day

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Evaluation of Lake Curry Operations and Development of a Re-operation Schedule to Benefit Threatened Steelhead Trout in Suisun Creek
APPENDIX 1

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Lake Curry Water Quality and Hydrodynamic Model: User Manual

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Chris J. Berger, Ph.D., P.E.

Prepared for Storesund Consulting

Table of Contents

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Introduction

This technical report documents the files used in the Lake Curry CE-QUAL-W2 model discussed in Berger and Wells (2018). The primary User Manual for the model is the CE-QUAL-W2 User Manual (Cole and Wells, 2018) for Version 4.1.

This report itemizes the model input files and the model output files and general guidelines for running the CE-QUAL-W2 model.

Model Grid and Inflows/Outflows

The model grid and inflows and inflows and outflows are shown in Figure 1.

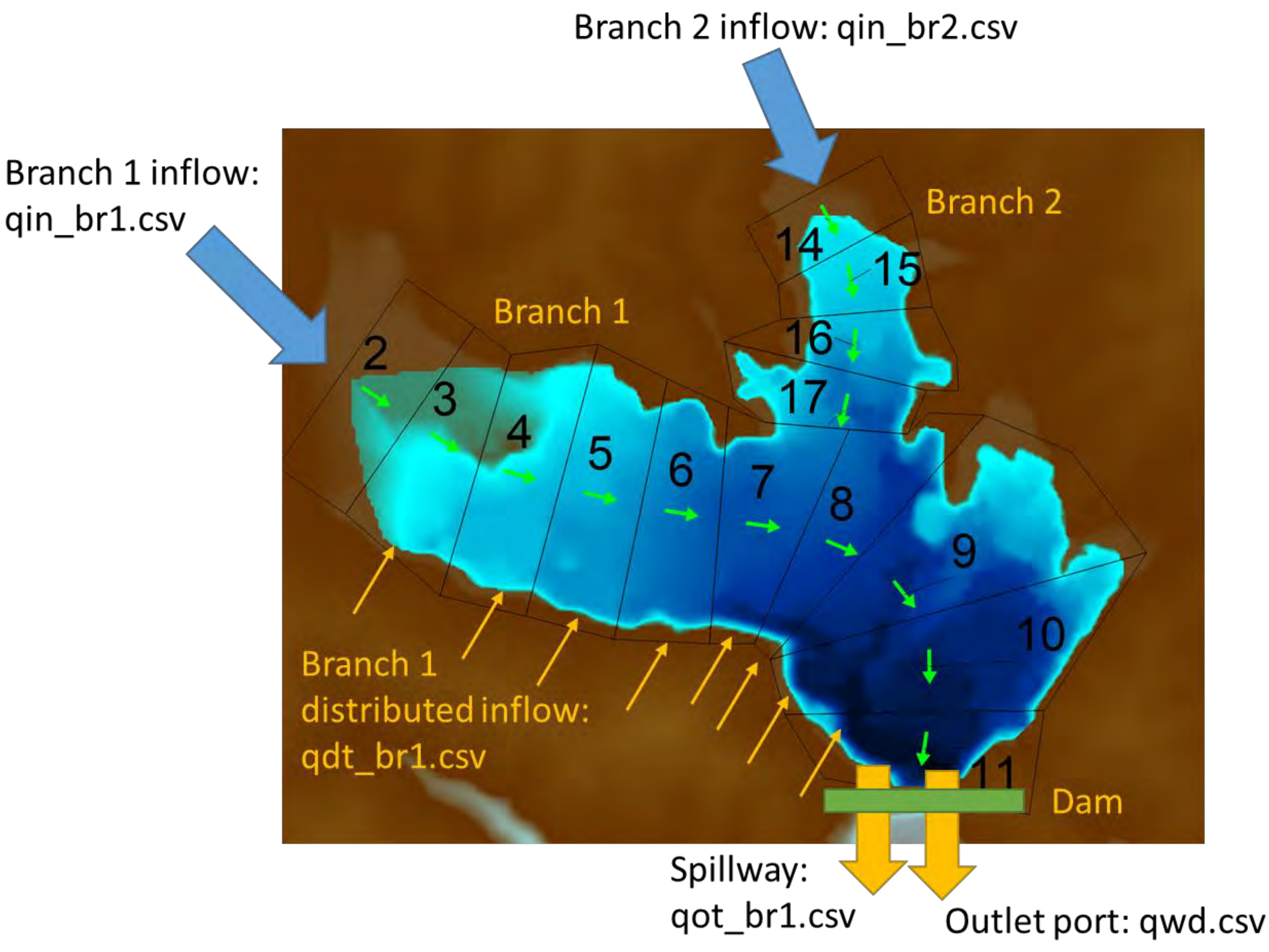

Figure 1. Inflows and outflows of the Lake Curry Model. File names of flow files are shown next to each inflow or outflow.

The grid characteristics are shown in Table 1 and Table 2.

Table 1. Lake Curry grid characteristics.

Parameter	Reservoir
Grid length	2186.1 m (branch 1)
Number of active segments	14
Longitudinal grid spacing	218.61 m (branch 1) or 173.88 m (branch 2)
Number of branches/waterbodies	2/1
Vertical layer thickness	1 m

Table 2. Lake Curry branch segments and descriptions.

Branch	Upstream Active Segment	Downstream Active Segment	Description
1	2	11	Mainstem
2	14	17	Side Arm

Model Files and Running the Model

A summary of model files for the Lake Curry model is shown in Table 3. This section provides an overview of running the model and examining output files.

Table 3: Lake Curry Model Input files

File Type	File Name	Description
Control file	w2_con.npt	Model control file
Bathymetry file	bth_wb1.csv	Segment lengths, initial water surface elevation, segment orientation, layer thickness and cell widths
Meteorological file	met.csv	Time series file containing temperature, dew point temperature, wind speed, wind direction and cloud cover data (based on solar radiation)
Graph file	graph.npt	This file controls input and output format
Wind sheltering file	wsc.csv	Wind sheltering coefficient for each segment and variable over time
Shade file	shade.csv	Shade file for characterizing vegetative and topographic shade or static shade values
Branch inflow files	qin_br1.csv	Flow rate file for branch 1 inflow
	tin_br1.csv	Temperature file for branch 1 inflow

File Type	File Name	Description
	qin_br2.csv	Flow rate file for branch 2 inflow
	tin_br2.csv	Temperature file for branch 2 inflow
Branch distributed inflow files	qdt_br1.csv	Distributed flow rate file for branch 1 inflow
	tdt_br1.csv	Distributed temperature file for branch 1 inflow
Branch outflow files	qot_br1.csv	Outflow flow rate file for branch 1 outflow – spillway flow
Withdrawal file	qwd.csv	Outflow flow rate through the outflow structure at the dam
Precipitation inflow files	pre_br1.npt	Flow rate file for precipitation
	tpr_br1.npt	Temperature file for precipitation
	cpr_br1.npt	Concentration file for precipitation
Aerator input file	w2_aerate.npt	Input parameters for using aeration mass input
Environmental Performance Criteria Input File	w2_envirprf.npt	Input parameters for specifying environmental performance criteria
Habitat volume input file	w2_habitat.npt	Input parameters for calculating habitat volumes
Selective withdrawal input file	w2_selective.npt	Input parameters for selective withdrawal feature
Preprocessor executable	preW2-4_64.exe, prew2-4_32.exe	Model preprocessor compiled code (32 or 64 bit)
Model executable	w2_v4_64.exe w2_v4_32.exe	CE-QUAL-W2 compiled code (32 or 64 bit)

The control file for the simulation is **w2_con.npt** and the bathymetry file is **bth_wb1.csv**.

The first step after all model files are put together is to run the model preprocessor. You can execute the model preprocessor by double-clicking on the **preW2-4_64.exe (**or **preW2-4_32.exe)** file and examine the output files generated.

The preprocessor catches errors in the input files and is essential to use before running the model. The preprocessor generates 2 or 3 files: **pre.opt** (this is an echo of the input data, useful information about input files, and a volume-area-elevation table of your model grid), **pre.wrn** (a list of warnings that are nonfatal that may or may not be issues with the model set-up), and if there were "fatal" errors: **pre.err** (a listing of errors that need to be corrected). There is also a file, **PREW2CodeCompilerVersion.opt,** that shows when the preprocessor code was compiled – it is useful for tracking version numbers of the code you are using.

If the results are OK (i.e., no fatal errors), then run the model by double clicking on the executable **w2_v4_64.exe (**or **w2_v4_32.exe)** and examine the output files generated after the model execution. A typical model naming convention is that output files are have the file type 'opt' even though many output files are in 'csv' format for ease of opening the file directly in Excel. Table 4 shows a list of the model output files. The model is set-up to run from June 1, 2005 through September 17, 2007.

Table 4: Lake Curry Model Output files

File Type	File Name	Description
Snapshot file	snp_wb1.opt	Snapshot output information for specific model segments. One file is output for each water body and includes model time parameters, meteorological parameters, inflow and outflow parameters, balances, geometry, water surface temperature and water quality information
Time series files	tsr_1_seg11.csv	Time series output files, each specific to model segment and vertical location. This one is located at the surface adjacent to the dam. Included in this file are water level predictions at segment 11, which is adjacent to the dam.
Vertical profile file	spr.opt	Vertical profile time series output for easy graphing in spreadsheets, specific to model segment
Combined Outflow file	qwo_11.csv	Outflow time series for segment 11 (at lake exit) combining spill and outlet flows
Combined Outflow temperature file	two_11.csv	Outflow temperature time series for segment 11 (at lake exit) combining spill and outlet temperatures.
Contour plotting output file	cpl.opt	TECPLOT software specific output file for contour plots – currently OFF
Flow balance file	flowbal.csv	Model flow balance summary – currently OFF
Water level output	wl.opt	Water level at all model segments over time
Output File used by W2_Post	LakeCurry.w2l	Binary output file for W2_Tool Post-Processor

File Type	File Name	Description
W2 code compile date	W2CodeCompilerVersion.opt	Compiler version of W2 code executable

The executable was developed using Intel Visual FORTRAN. During execution there is a graphical box showing pertinent run parameters (Figure 2).

As Figure 2 shows, one can use the "Stop" button and the “Restart” button to pause the simulation if one wants to examine the other windows in more detail, to print, to change run parameters in the control file, or to exit the simulation before it concludes.

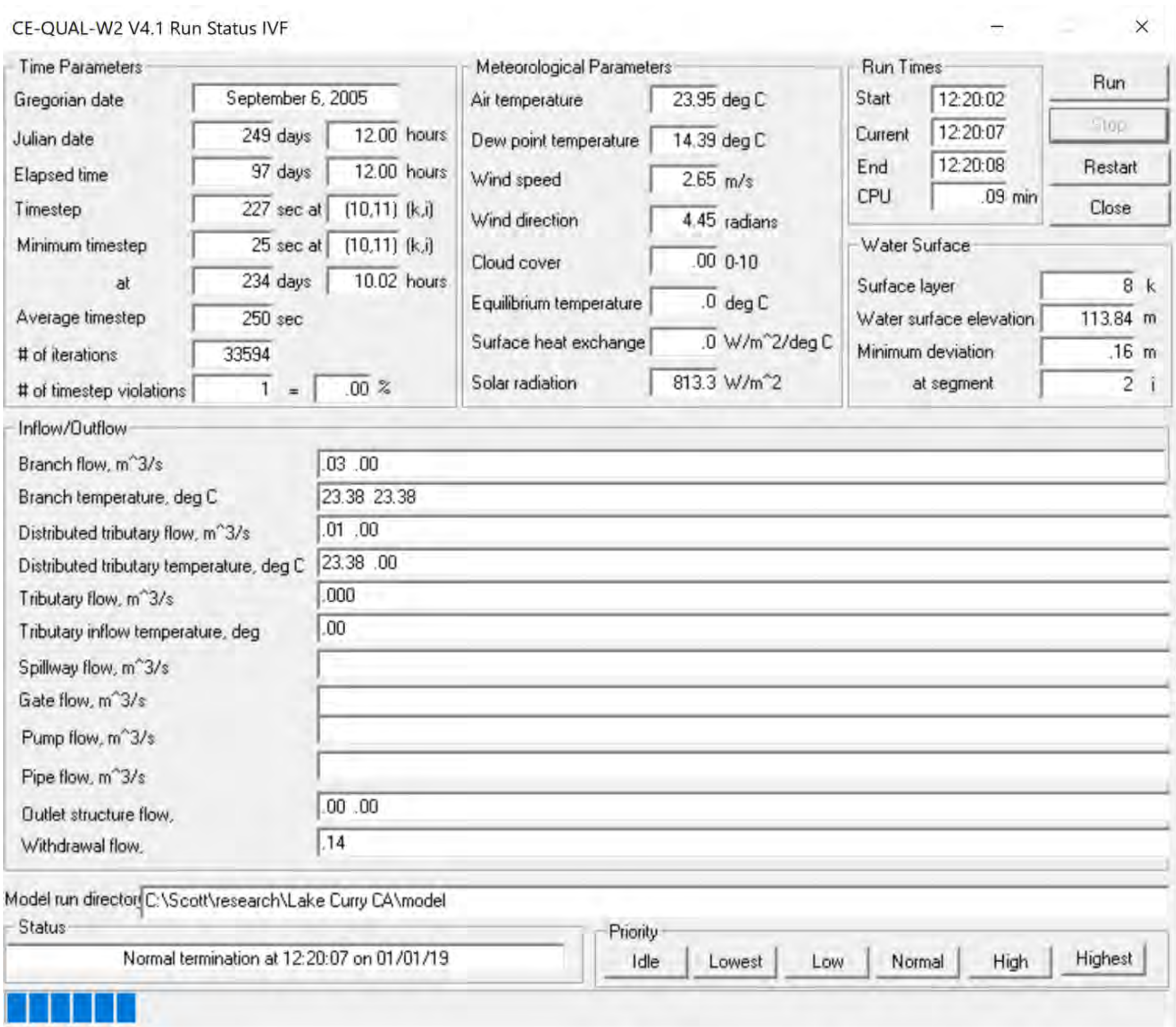

Figure 2: Model simulation run parameters

As shown in Table 4, the model generates output files (that were specified in the **w2_con.npt** control file) with the file extension ‘opt’ or ‘csv’. Browse through the output from the snapshot file, **snp.opt,** using Notepad or Notepad++.

This file contains information on mass and energy balances, inflows, and model predictions of water surface, velocity, and water quality parameters as specified in the control file. This is not used for plotting since other output files are set up specifically for that purpose. The file **spr.opt** is useful for model-data comparisons of vertical profiles and can easily be brought into Excel for plotting. The time series files**, tsr_X_segY.csv,** are easily graphed in Excel and are often used for model-data comparisons.

The file, **LakeCurry.w2l**, is to be used with the post-processing package **w2post**. Install the w2post program on your computer using the installation routine from the CE-QUAL-W2 web site (http://www.cee.pdx.edu/w2). Look over the instructions for the W2Post program downloaded files. You will open this program and open the file ‘**LakeCurry.w2l**’ (see Figure 3).

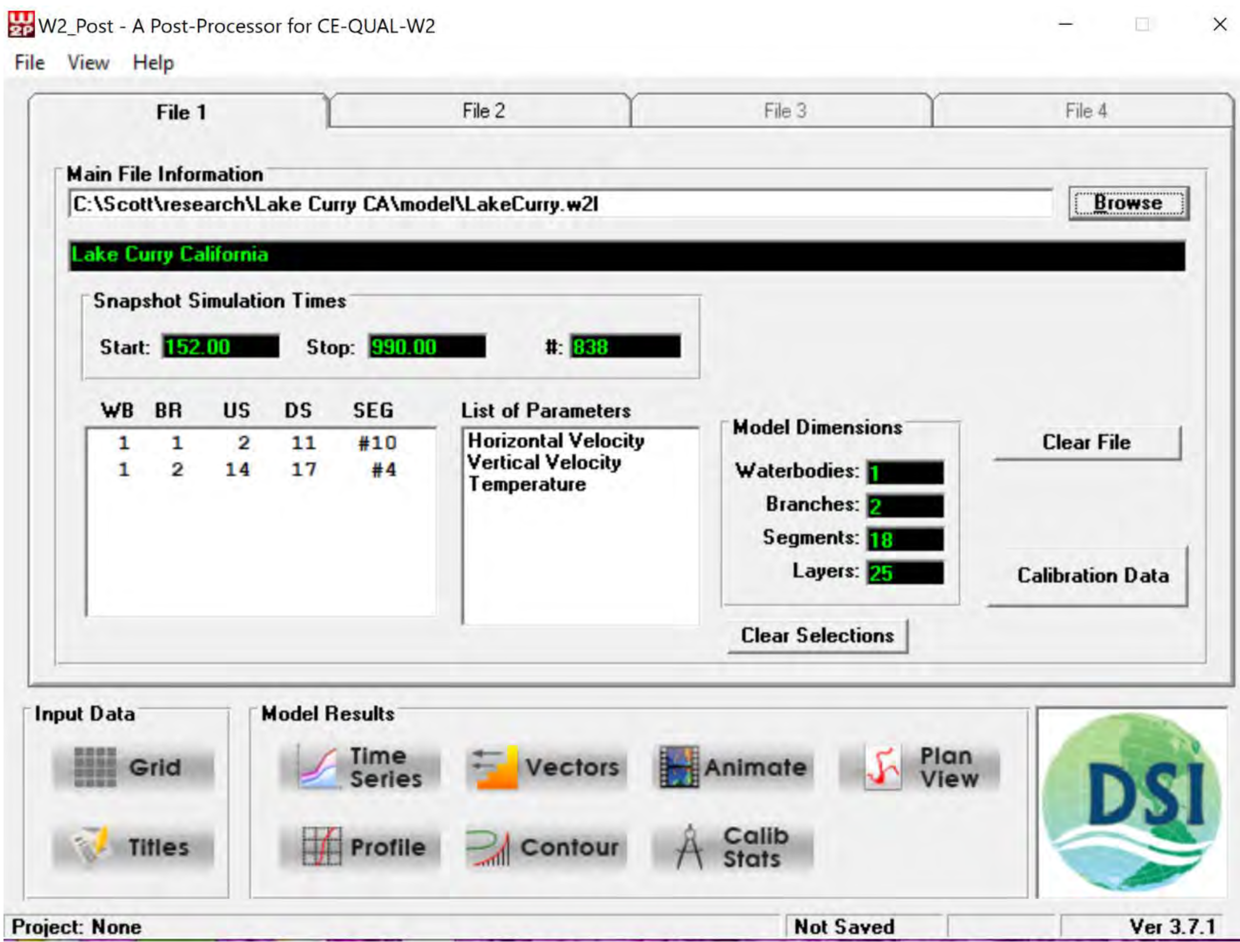

Figure 3. Opening screen of the w2post program.

Please explore the various features of this post-processor. It provides a quick way to evaluate model results such as contours as shown below:

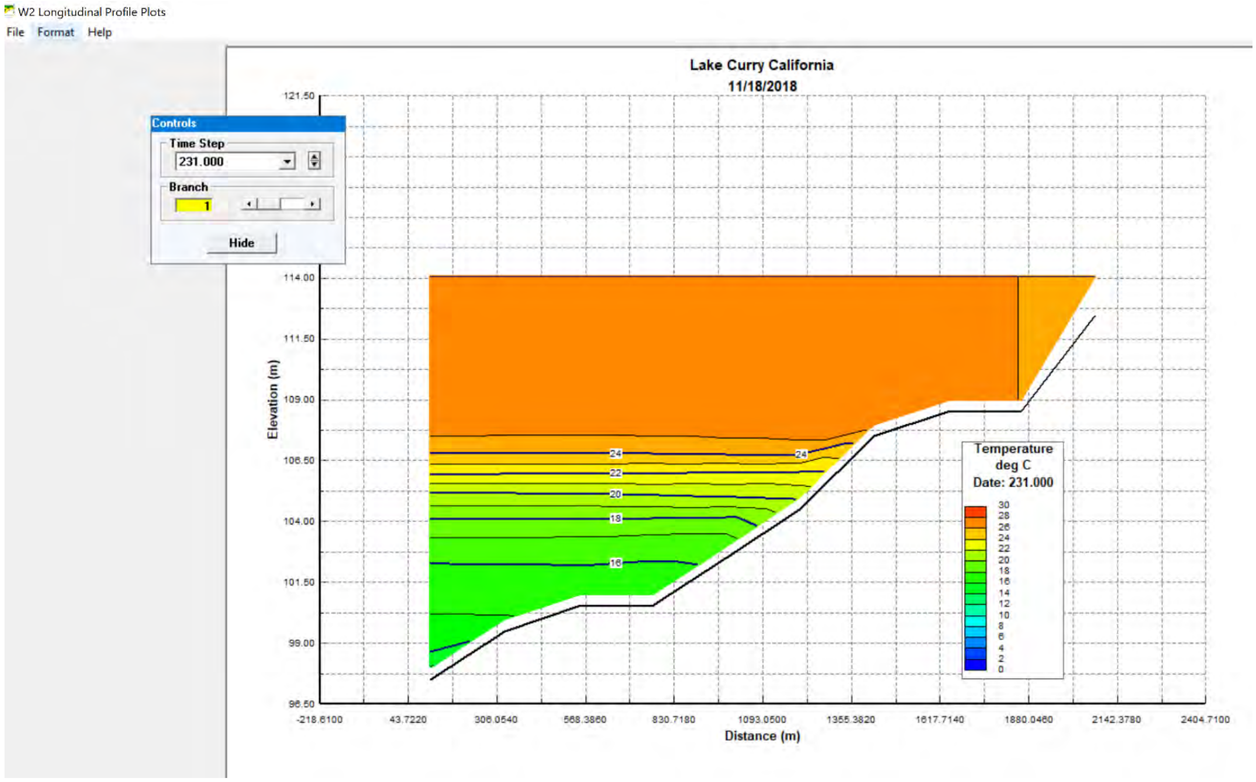

Figure 4. W2post temperature contours.

One can also show how the temperatures in the reservoir change longitudinally over time by using the Plan View of Model Results control. Figure 5 shows an example of the surface temperature in the reservoir predicted by the model on July 24, 2005.

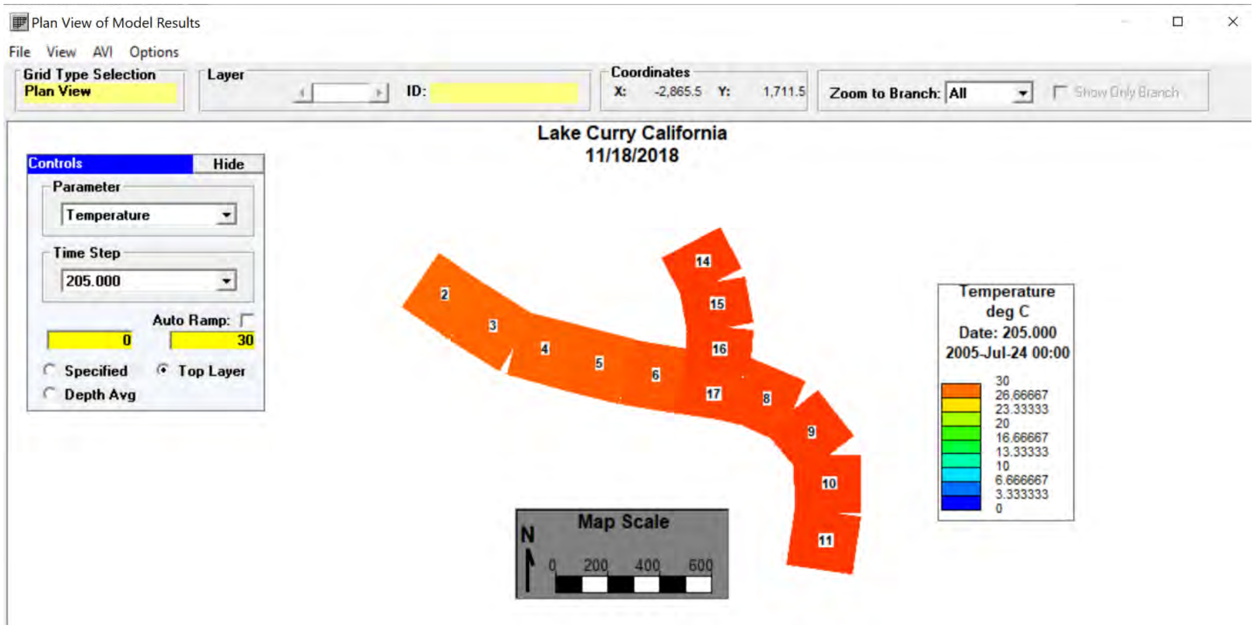

Figure 5. Plan view of model results on Julian day 205 or July 24, 2005.

The post-processor W2_Post can also be used to view contour animations and model-data vertical profile graphs. To view a temperature animation:

1. Start W2_Post
2. Load the model output file LakeCurry.w2l by clicking on 'Browse'
3. In the "List of Parameters" window select temperature
4. Click on 'Animate' and in the W2 Parameter Animation window click "Go|Restart"
5. To control the speed of the animation, use the arrow control 'Animation Speed'

Vertical profile predictions can also be compared with data with this program. Instructions are provided in the download files.

Setting up the Model for Other Years of Simulation

The current model is set up for the period June 1, 2005 through September 17, 2007. Hence, in order to set up the model for other time periods the following steps need to be performed:

1. Develop new meteorological files for the period of simulation. This includes air temperature, dew point temperature, wind speed and direction, cloud cover and short wave solar radiation (if available). Using hourly values is recommended. The meteorological station used for 2005-2007 was based on HSI Hydrologic Systems (2008) recommendation. Unfortunately, this station Suisun Valley, Solano, was only active between 8/18/1994 and 7/11/2010. Berger and Wells (2018) compared on-site meteorological data between 2005-2007 to Suisun Valley, and they were reasonably close except for wind direction. One would need to choose a new meteorological station and ensure that data gaps are filled and that it is a reasonable surrogate for Lake Curry.
2. Develop new outflow files for the spillway and dam outlet. Data on water level was used to estimate spill based on a rating curve in Berger and Wells (2018). The outlet flow was based on estimates provided by the City of Vallejo.

3. Perform a water balance on the reservoir to estimate inflow volumes. The water balance utility is used determine the inflow necessary given the outflow and water surface elevation. Then the inflow volume is spilt between the inflow for branch 1, branch 2 and the distributed inflow around the lake based on drainage basin areas (see Berger and Wells, 2018). Alternatives to this include using the SWMM model to estimate inflows. But the water balance utility would still need to be performed in order to correct for volume errors in the inflow and outflow. Note that if the model is being used for future scenarios, then the spillway would be set up in the model as a spillway and outlet flows would be known and there would be no need to perform a water balance since the model is predicting the water balance directly.
4. Estimate inflow temperatures from meteorological data. The inflow temperatures were estimated in Berger and Wells (2018) using a filtered equilibrium technique. This was just an estimate of inflow temperature. Knowing inflow temperatures is important to predict in-situ lake temperatures.
5. The main control file, w2_con.npt, would have to be adjusted for setting the correct reference year, tie period of simulation and file names for the new boundary conditions files. Then the model can be run with the preprocessor to assess if all the files are constructed properly before running the simulation.

Summary

This technical memorandum summarizes the model files and generally how to run the Lake Curry model developed in Berger and Wells (2018). The User Manual (Cole and Wells, 2018) and web download provide more details on how to run the model and the model options.

References

Berger, C, and Wells, S. (2018) "Lake Curry Hydrodynamic and Temperature Model: Development and Calibration," Prepared for Storesund Consulting, CA.

Cole, T. and Wells, S.A. (2018) "CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 4.1" Department of Civil and Environmental Engineering, Portland State University, Portland, OR., USA.

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