



Two-Dimensional Water Quality Modeling of Arrowrock Reservoir, 2013-14

Technical Memorandum



**U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Regional Office**

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U.S. Department of the Interior

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Table of Contents

| | | |
|----------|--|-----------|
| 1 | Introduction | 1 |
| 1.1 | Background..... | 1 |
| 1.2 | Purpose and Scope | 1 |
| 2 | Methods | 1 |
| 2.1 | Model Description..... | 1 |
| 2.2 | Measured Data | 2 |
| 2.2.1 | Meteorology | 3 |
| 2.2.2 | Hydrology | 4 |
| 2.2.3 | Water Temperature and Water Quality..... | 7 |
| 2.3 | Model Development..... | 15 |
| 2.3.1 | Water Balance | 15 |
| 2.3.2 | Initial and Boundary Conditions..... | 15 |
| 2.3.3 | Model Sensitivity Analysis..... | 18 |
| 3 | Model Results..... | 25 |
| 3.1.1 | Water Temperature..... | 25 |
| 3.1.2 | Dissolved Oxygen and Chlorophyll-a | 40 |
| 4 | Scenario Modeling | 47 |
| 4.1 | Scenarios 1 and 2 | 47 |
| 4.2 | Scenario 3 | 52 |
| 4.3 | Scenario 4 | 55 |
| 5 | Conclusions..... | 58 |
| 6 | Other Resources | 59 |
| 7 | Appendix..... | 60 |

1 INTRODUCTION

1.1 Background

Questions regarding the effects of water quality on bull trout in Arrowrock Reservoir include a number of variables, but can be summarized into two categories: 1) do current operations affect bull trout migration, and 2) do current operations affect the bull trout prey base? Water quality is an important limiting factor with respect to these questions and two-dimensional water quality modeling has the potential to provide insight into the vertical and longitudinal distribution of suitable water quality conditions in the reservoir under various operations scenarios.

A two-dimensional water quality model was completed for Arrowrock Reservoir in 2003 (Reclamation 2003) and results from this model were used in the development of Reclamation's 2004 Biological Assessment for bull trout in the Boise Project and by USFWS in the 2005 BiOp. Since the 2003 model was completed, additional water quality data has been collected as a result of commitments in the 2005 BiOp.

1.2 Purpose and Scope

The goal of this effort is to expand upon the water quality modeling work completed in 2003; incorporating additional water quality parameters and newly collected data, and taking into account changes to dam operations with respect to the discontinued use of certain outlet structures. This work involves the recalibration of the 2003 model using 2013 and 2014 datasets (focusing on temperature, dissolved oxygen, and algae growth), sensitivity analysis to improve understanding of the key water quality drivers in the reservoir, and scenario modeling to evaluate the influence of June reservoir levels on reservoir productivity through the summer and early-fall.

2 METHODS

2.1 Model Description

The CE-QUAL-W2 (Version 4.0) model is a two-dimensional, laterally averaged hydrodynamic and water quality model. This particular implementation of the model on Arrowrock Reservoir builds upon a previous modeling effort conducted in 2003 using version 3.1 of CE-QUAL-W2 (USBR, 2003). The model consists of three branches (shown in Figure 1) and one tributary. This project involves recalibrating this model using updated 2013 and 2014 water quality data and reducing the input data time steps from daily to sub-daily where possible (15-minute, hourly,

or daily depending on the particular dataset). Use of a sub-daily time step is particularly important for capturing diurnal variation in temperature.

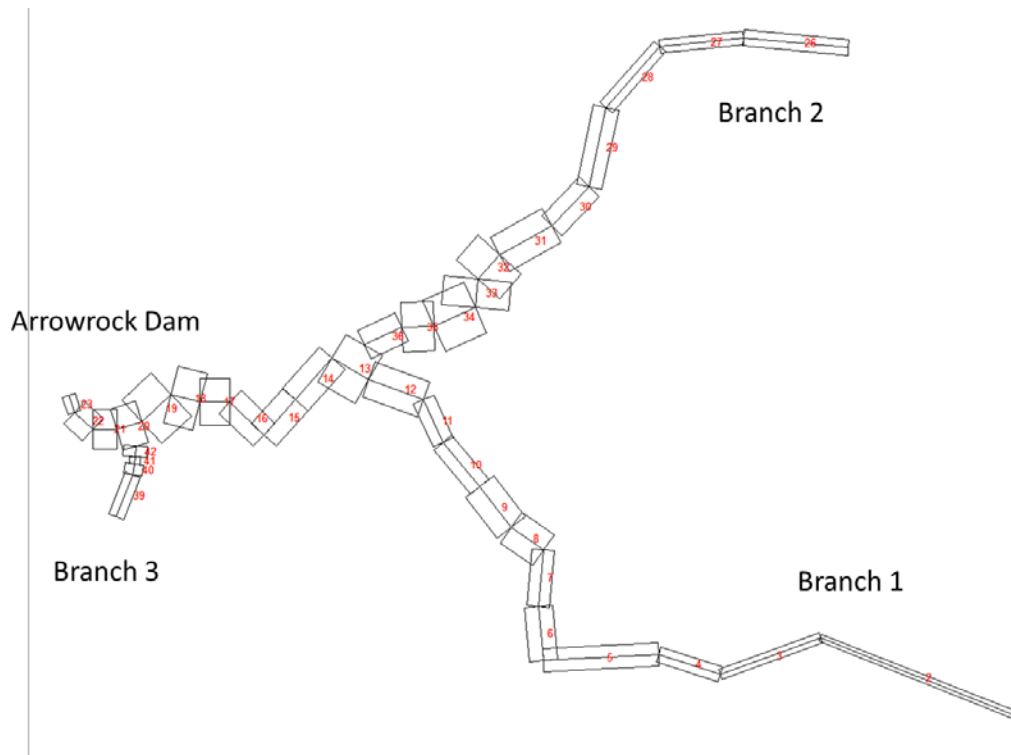


Figure 1: Arrowrock Reservoir model segments. Branch 1 represents the South Fork of the Boise River below SFNI (South Fork at Neal Bridge gage), Branch 2 represents the Middle Fork of the Boise River below BTSI (Boise River at Twin Springs gage), and Branch 3 represents Grouse Creek.

2.2 Measured Data

Inputs to the Arrowrock Reservoir CE-QUAL-W2 model include meteorological data, hydrologic data (inflows and outflows), and water quality data for the period spanning March 27, 2013 through December 15, 2014. These start and end dates were selected to coincide with the spring 2013 post-ice/pre-stratification and the fall 2014 turnover/destratification. Hydrologic and water quality data for the reservoir inflow and outflow points (or boundary conditions) drive the model simulation, while data collected at locations within the reservoir (including profile data) are used to initialize the model at the first-time step and to verify the model calibration in subsequent time steps. The following sections describe the meteorology, hydrology, and water quality data used for this study.

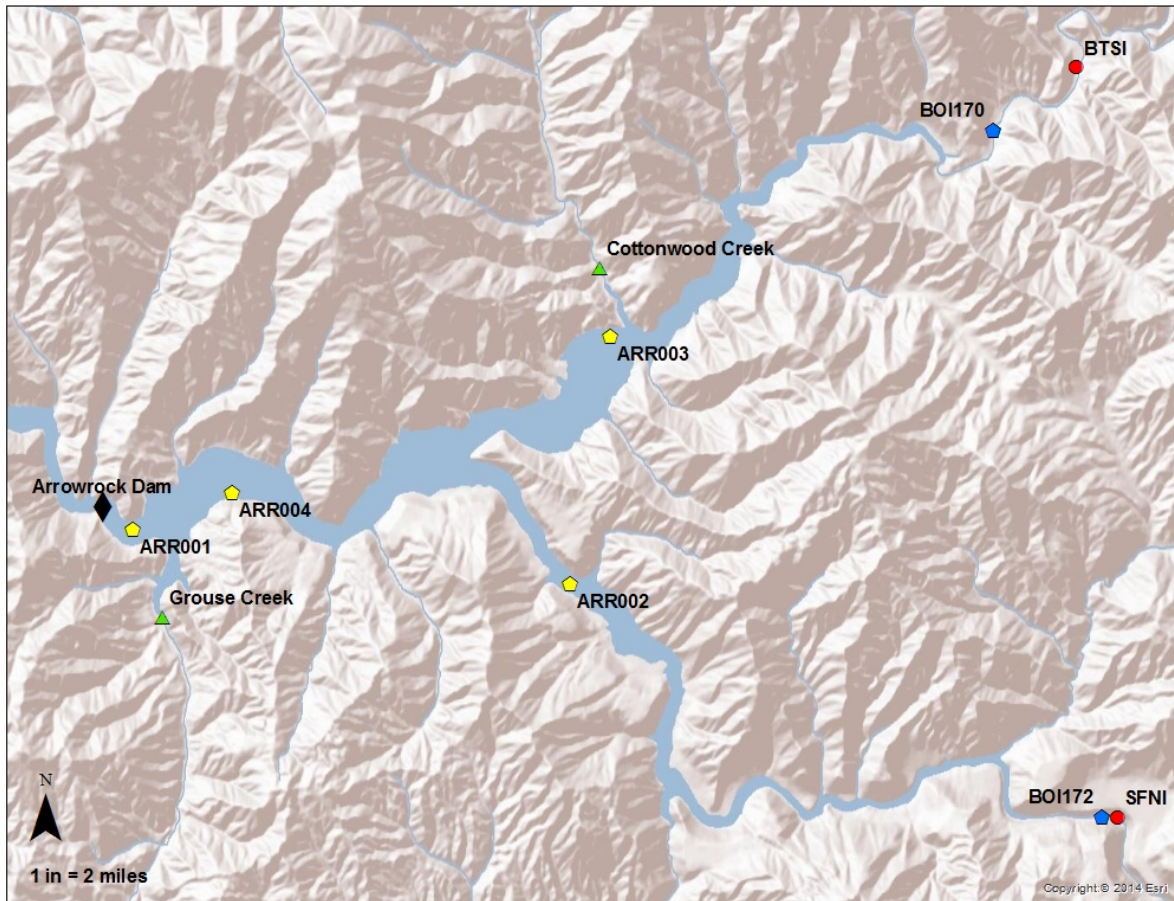


Figure 2: Map of 2013 and 2014 monitoring locations. Red circles represent locations with continuous flow and temperature data. Green triangles represent locations with continuous temperature data only. Hexagons represent locations where water quality constituents were measured at regular intervals (not continuous), with yellow indicating reservoir profile measurement locations and blue indicating grab sample locations.

2.2.1 Meteorology

The CE-QUAL-W2 model requires input time series for air temperature, dew point temperature, wind speed, wind direction, and cloud cover. This study used 15-minute air temperature, dewpoint temperature, wind speed, and wind direction data collected at the BOII Agrimet station (located east of downtown Boise off of Warm Springs Avenue). Cloud cover data was estimated using hourly “sky conditions” data collected at the Boise Air Terminal/Gown Field Airport National Weather Service station. Precipitation on the reservoir surface was not included as model input.

2.2.2 Hydrology

Reservoir inflows represented in the model include flows from the South Fork Boise River at Neal Bridge (SFNI), the Boise River near Twin Springs, Idaho (BTSI), Grouse Creek, and Cottonwood Creek. Arrowrock Reservoir outflows are represented by the Hydromet site Middle Fork Boise River at Arrowrock Dam (ARKI). Figure 3 illustrates the flows at BTSI, SFNI (which was adjusted to account for suspected gage error during and after debris flows), and ARKI. The following sections summarize how these datasets were prepared for use in the water quality model.

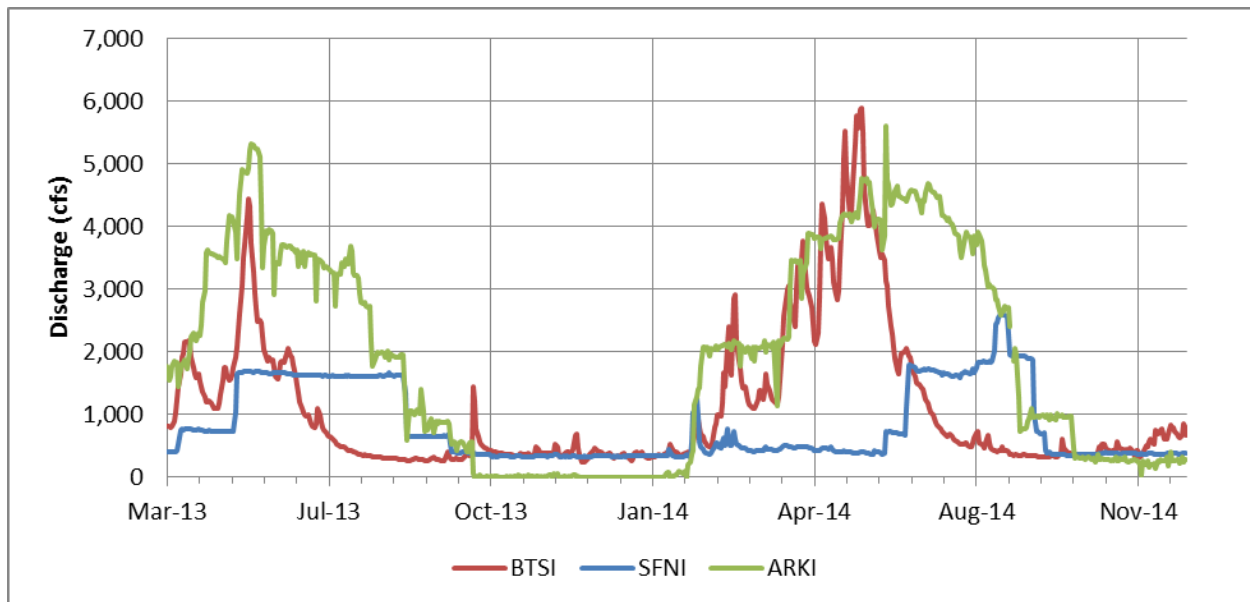


Figure 3: Hydrographs for the Boise River at Twin Springs (BTSI), corrected South Fork Boise River near Neal Bridge (SFNI), and the Middle Fork Boise River at Arrowrock Dam (ARKI). Corrections made to the SFNI timeseries are discussed in Section 2.2.2.2.

2.2.2.1 Middle Fork Boise River

The Boise River at Twin Springs (BTSI) Hydromet gage represents the inflow to Branch 2 in the model. Flows from the Middle Fork of the Boise River are uncontrolled and generally contribute the largest inflows to Arrowrock Reservoir. This is illustrated in Figure 3 where the red and blue lines represent the inflows from BTSI and the SFNI respectively.

2.2.2.2 South Fork Boise River

Inflows from the South Fork Boise River (Branch 1 in the model) are measured at the Hydromet gage South Fork Boise River at Anderson Ranch Dam (ANDI) and are largely dominated by Anderson Ranch releases. This is illustrated in Figure 4 where flows at SFNI exhibit a stair-step shaped hydrograph and closely resemble the flows measured at ANDI. In contrast to 2013, which was a relatively low runoff year, 2014 exhibited large runoff events along the South Fork of the Boise River between SFNI and ANDI. Heavy rains over burned areas (left behind from

the August 2013 wildfires) in August 2014 produced mudslides and debris flows along this stretch of river, dramatically changing the flow in several locations. In response to these events, the USBR (in coordination with Idaho Department of Fish and Game, USFS, Trout Unlimited, and the University of Idaho) temporarily increased flows from Anderson Ranch (starting August 18, 2014 and ending around August 29, 2014) to flush sediment and logs and help restore habitat for bull trout and other fish species.

Comparison of SFNI flows to flows out of Anderson Ranch following the large runoff events suggest that SFNI gage fouling may have occurred, causing lower than expected gage readings. Prior to the large runoff events, gains between ANDI and SFNI were consistently positive. However inspection of the calculated gains during the large debris flow periods revealed that the gain falls dramatically and becomes negative during the peak flushing flows. Since it is unlikely that this stretch of river would have transitioned from a gaining reach to a losing reach during these periods, the SFNI flow data was adjusted during the suspect periods and assumed to equal the flows measured at ANDI plus the estimated gains (with any negative gain values removed and replaced with interpolated values). The original and corrected SFNI flows are illustrated in Figure 4 along with the flows measured at ANDI.

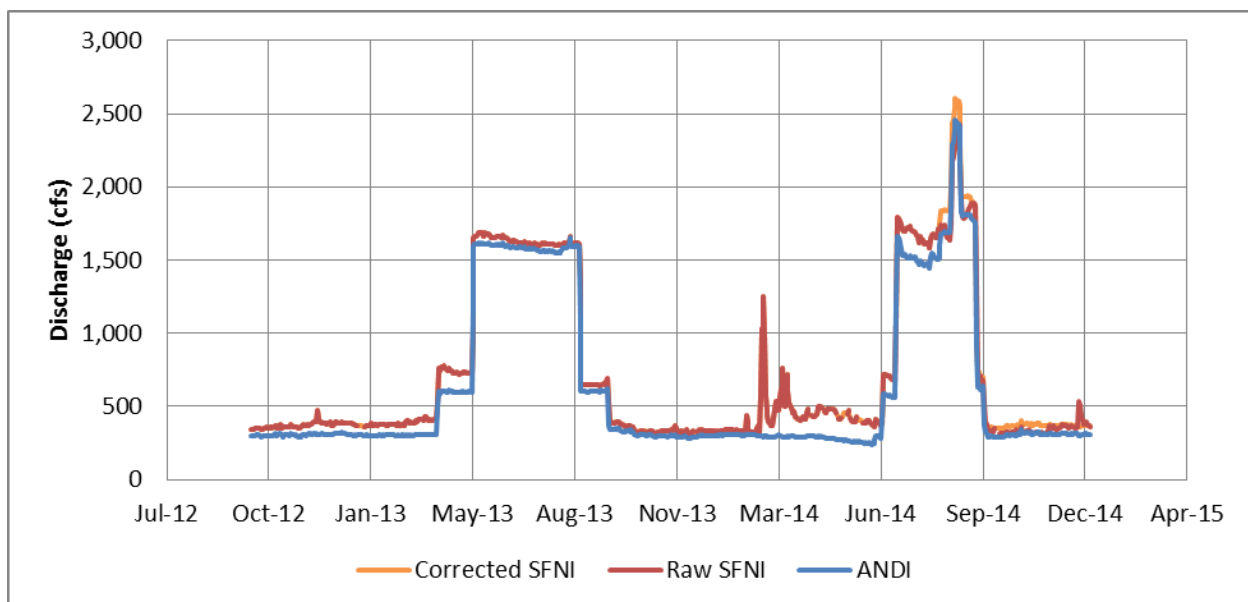


Figure 4: Raw and corrected flows for the South Fork Boise River at Neal Bridge (SFNI) and flows measured at the South Fork Boise River at Anderson Ranch gage (ANDI). The SFNI gage was adversely impacted by debris flows following 2013 wildfire and high runoff events in August 2014. Taking this into account, SFNI flows were adjusted using flows at ANDI and estimated gains between SFNI and ANDI.

2.2.2.3 Tributaries

Grouse and Cottonwood creeks were included in the model as tributaries. While each of these creeks do have continuous measured temperature data from TidBits (discussed in Section 2.2.3), flows from these tributaries had to be estimated. The estimated flows for each of these tributaries are illustrated in Figure 5.

Cottonwood Creek flows were estimated using a quantile mapping approach and historical flow data collected during the early 1900s. This approach involved developing exceedance plots of both the historical Cottonwood Creek data and the flows measured at BTSI. For each timestep, these paired exceedance plots were used to translate flows occurring at BTSI into the corresponding flow for Cottonwood Creek using percentile as the cross-reference value. Alternatively stated, for each timestep the exceedance percentile at BTSI was used to look up the Cottonwood Creek flow for that particular exceedance value.

Grouse Creek flows were also calculated using the quantile mapping approach, however due to limited data for Grouse Creek exceedance values were estimated using Idaho StreamStats. Comparison of the resulting dataset to the measurements made on Grouse Creek during the 1940s showed the estimated data to be much lower than the measured values. Since even the larger inflows in the constructed dataset make up such a small portion of the Arrowrock Reservoir water budget, the constructed dataset was left as is and it was assumed that further refinement would be inconsequential to the simulation.

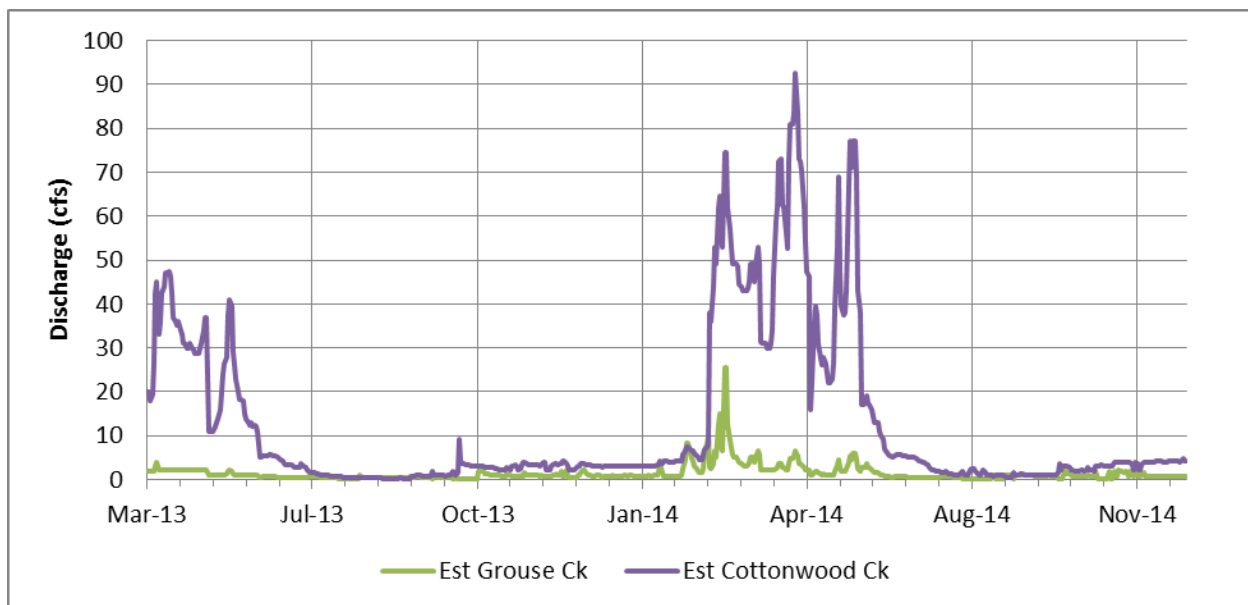


Figure 5: Estimated flow timeseries for Grouse Creek and Cottonwood Creek, tributaries to Arrowrock Reservoir. These flows were constructed using a quantile mapping approach to translate flows measured at BTSI into flows in each creek based on exceedance percentile and historical exceedance plots of creek flows.

2.2.2.4 Arrowrock Reservoir Outflow

Arrowrock Reservoir outflow is represented by a calculated “gage” (ARKI QD in Hydromet) and is considered to have a large amount of uncertainty. Flows at this location are calculated using the change in storage in Lucky Peak Reservoir minus the measured contributions from Mores Creek (MORI Q in Hydromet). To better understand the amount of uncertainty associated with this dataset, an additional Arrowrock outflow dataset was calculated based on Arrowrock Reservoir inflows minus Arrowrock Reservoir’s change in storage. Figure 6 illustrates the comparison of “Hydromet ARKI” (representing the calculated flows obtained

directly from Hydromet) and “Calculated ARKI” (representing the flows calculated from Arrowrock Reservoir storage and inflows). The two datasets are fairly similar with flows differing by no more than +/- 15% during most of the modeling period.

Recognizing that not all inflows to Arrowrock Reservoir are measured (meaning inflows, and calculated outflows, could be larger), and assuming that losses from Arrowrock Reservoir are small relative to the gains (i.e. outflows should be greater than or equal to inflows to Arrowrock Reservoir minus the change in storage), a new combined dataset was generated by taking the larger of the two calculated outflow values on each day. During the winter when outflow from Arrowrock Reservoir was shutoff, values in the outflow dataset were set to zero.

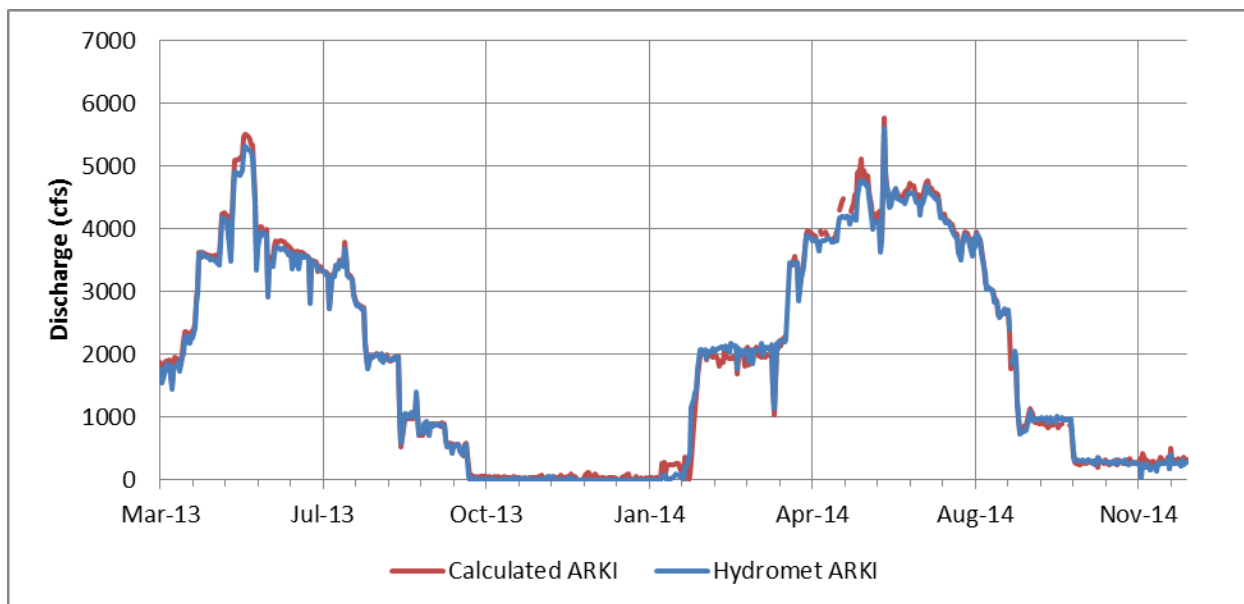


Figure 6: Arrowrock Reservoir outflow calculated from Arrowrock Reservoir inflows and change in storage (Calculated ARKI) and Middle Fork Boise River at Arrowrock Dam (Hydromet ARKI) data obtained directly from Hydromet. ARKI is a calculated gage in Hydromet and is based on change in storage in Lucky Peak Reservoir minus inflows from Mores Creek.

2.2.3 Water Temperature and Water Quality

Water temperature and water quality data were collected throughout the reservoir and at the major inflow points. Figure 2 illustrates the various measurement locations with symbols representing the type of sampling that occurred at each monitoring point (interval vs. continuous sampling and the range of parameters measured). The following sections provide a more detailed summary of the water temperature and water quality data used for the model simulations.

One reservoir profile was conducted using the Hydrolab. Water parameters measured include: water temperature, pH, dissolved oxygen, electrical conductivity, and turbidity at various depths. These water parameters were measured in 2-meter increments to 21-meter depth, then measured every 5 meters until the bottom of the reservoir is reached.

2.2.3.1 Water Temperature Data

Continuous water temperature measurements were collected at both the BTSI and SFNI Hydromet stations as well as by TidBits deployed on Grouse and Cottonwood creeks. Temperature regimes in Grouse and Cottonwood creeks were found to be very similar, therefore Grouse Creek TidBit measurements were used to fill in the November 2013 through April 2014 data gap on Cottonwood Creek. Other than the filling of data gaps, temperature measurement time series were used directly as model boundary input with no further correction. Figure 7 through Figure 10 illustrate the temperature and flow regimes at these four locations.

As shown in Figure 7 temperatures at SFNI range from almost zero degrees Celsius during the winter months to as high as 19.6 degrees Celsius during the summer. There is an interesting drop in temperature beginning in July of 2014 that appears to correspond to increased outflow from Anderson Ranch Reservoir, however such a drop was not observed in 2013. To ensure that this drop was not associated with fouling of the temperature sensor, measurements much further upstream at Danskin Bridge were also investigated and exhibited the same drop in temperature.

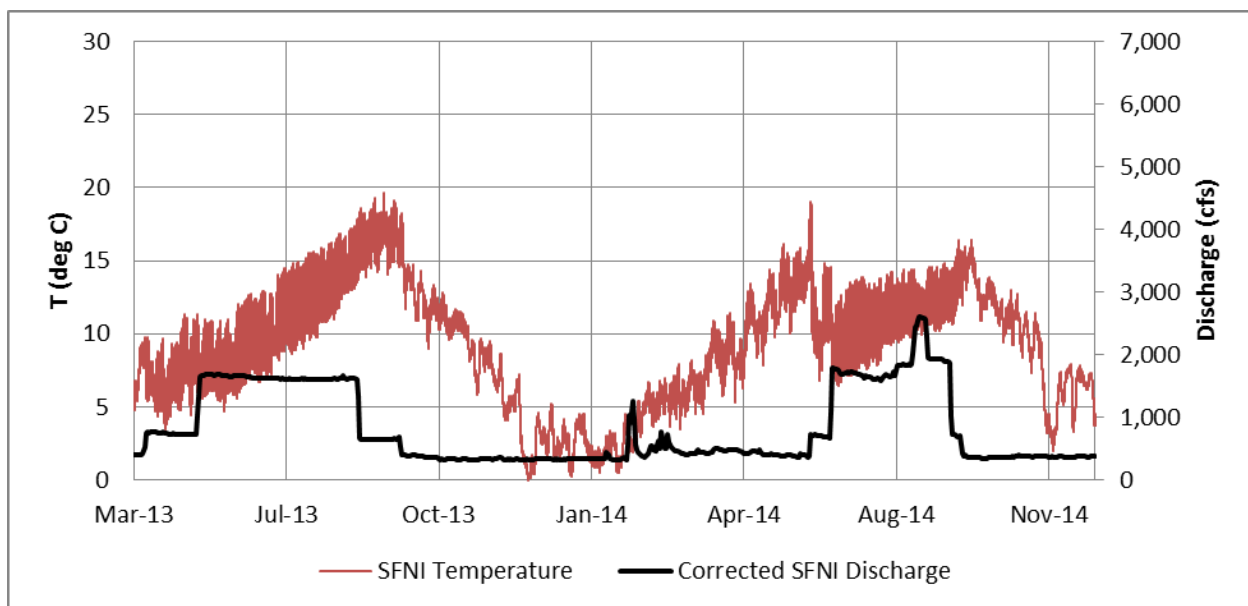


Figure 7: Corrected flow (cfs) and measured temperature (degrees Celsius) at SFNI (South Fork at Neal Bridge).

Water temperatures at BTSI are shown in Figure 8 along with the measured flow at this location. As seen in this figure temperatures at BTSI range from close to zero degrees Celsius during the winter months to as high as 25.8 degrees Celsius during the summer, with the highest temperatures occurring during the summer low flow period. These temperatures generally start to decline in September as the fall rainy season begins.

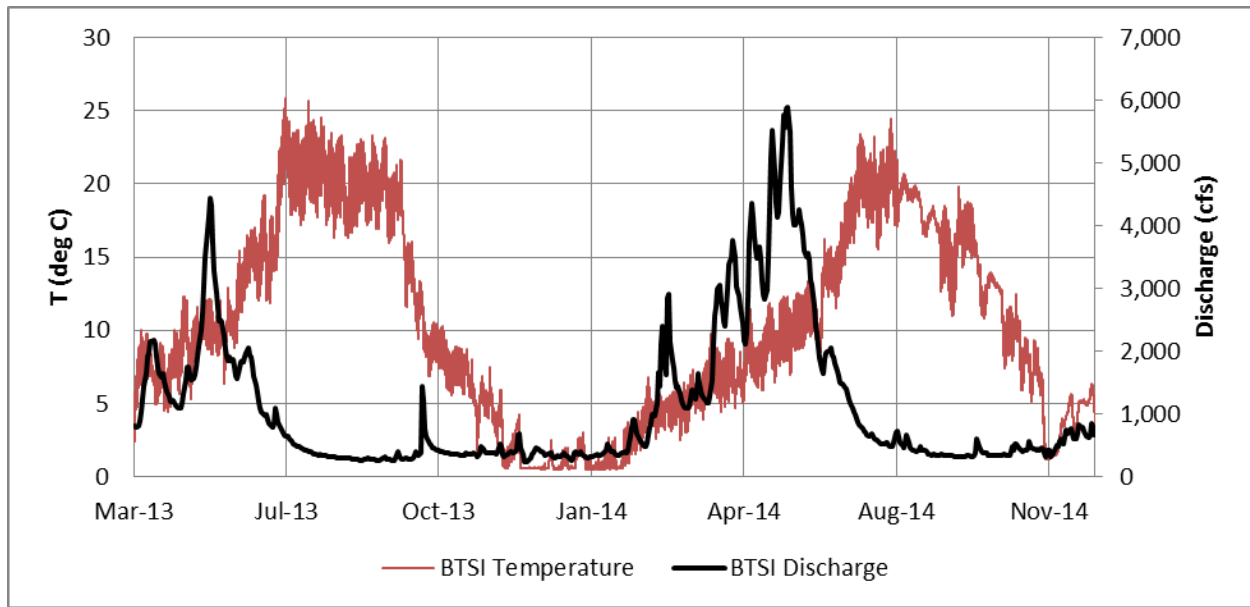


Figure 8: Measured flow (cfs) and temperature (degrees Celsius) at BTSI (Middle Fork Boise River at Twin Springs).

Water temperatures for Grouse and Cottonwood creeks are shown in Figure 9 and Figure 10 along with the estimated flow regimes for each location. Compared to the temperatures measured at SFNI and BTSI, measurements on Grouse and Cottonwood creeks exhibited higher diurnal fluctuations during portions of the summer and early fall periods. It is possible that the position of the TidBit sensors within the channel at these locations affected their outputs by being heavily influenced by air temperature and solar radiation during low water periods. Given the relatively small contribution of these creeks to the overall water budget, the decision was made to use the measurements as-is and rely on sensitivity analysis of inflow temperature to better understand the influence of these creeks on water temperatures within the reservoir.

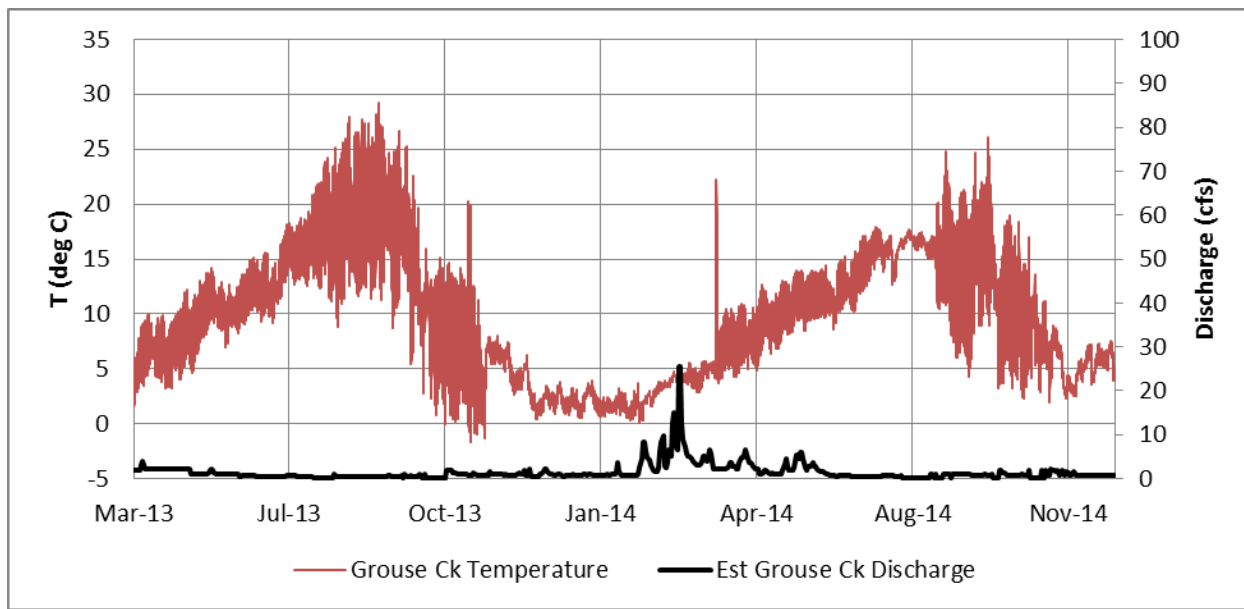


Figure 9: Estimated flow (cfs) and measured temperature (degrees Celsius) in Grouse Creek (tributary to Arrowrock Reservoir near Arrowrock Dam). Flows were estimated based on exceedance characteristics at BTSI during the model period and exceedance flows calculated from StreamStats flow estimates for Grouse Creek.

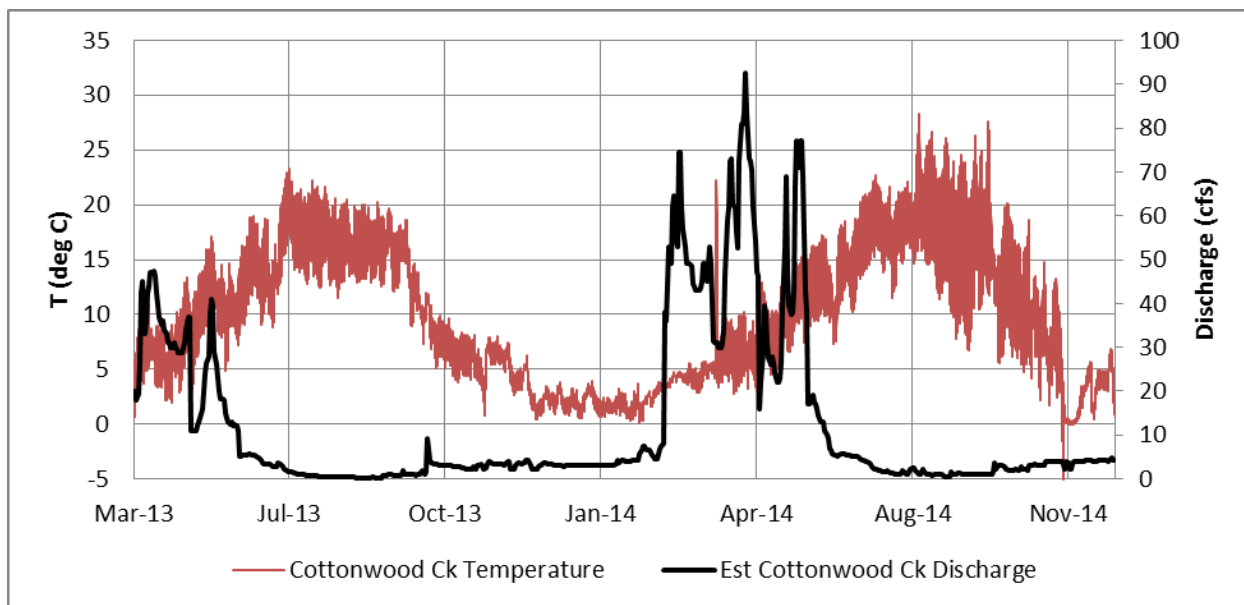


Figure 10: Estimated flow (cfs) and measured temperature (degrees Celsius) in Cottonwood Creek (tributary to the Middle Fork of the Boise River below BTSI). Flows were estimated based on exceedance characteristics at BTSI during the model period and exceedance flows calculated from historical (1914 - 1941) measurements on Cottonwood Creek.

Figure 11 is a comparison of the average monthly temperature and discharge occurring at SFNI and BTSI. This figure illustrates the relative flow contribution from each branch as well as the cooling effect that Anderson Ranch Reservoir has on downstream water temperatures (measured at SFNI).

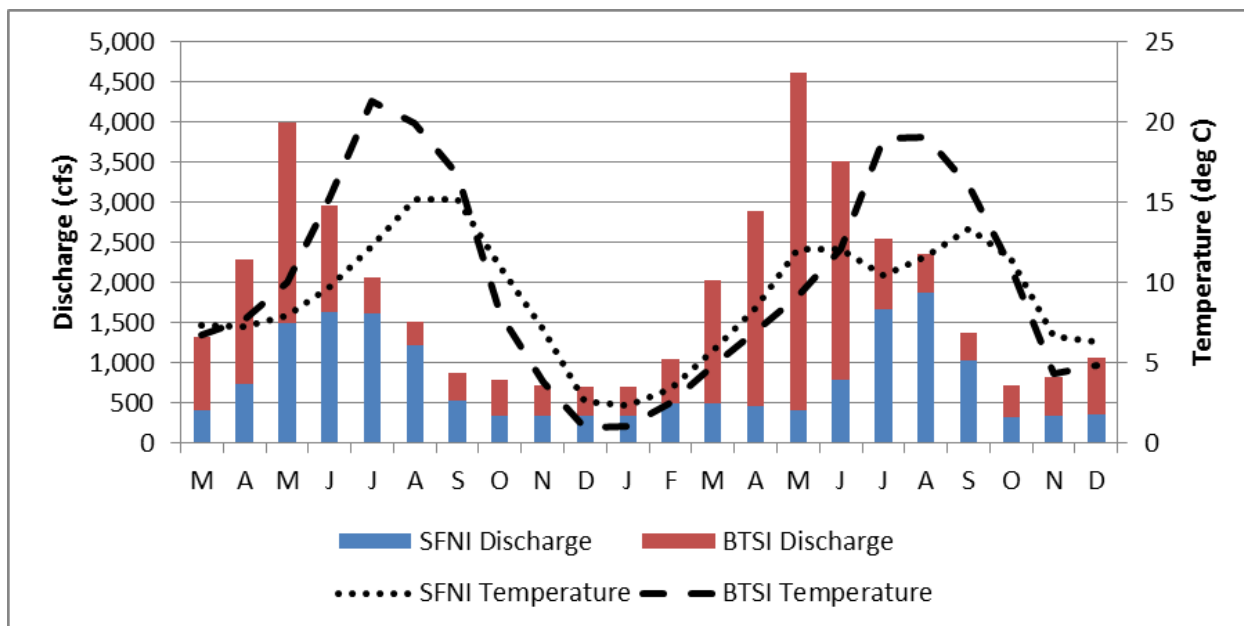


Figure 11: Stacked bar plot and line plot depicting monthly average inflows and temperatures from the South Fork (SFNI) and Middle Fork (BTSI) of the Boise River. The overall height of each bar represents the combined discharge of SFNI and BTSI, while the red and blue segments represent the contributions from the individual branches. Average inflows and temperatures from Grouse and Cottonwood creeks are not shown, but their combined contribution ranges from less than 1 cfs to a maximum of 110 cfs.

2.2.3.2 Water Quality Data

Water quality data were collected at BOI 170 and BOI 172 on seven occasions during the model period. Figure 12 and Figure 13 illustrate these dates relative to the hydrologic regime at each location. Unfortunately no water quality samples were collected during the large runoff and flushing events in August 2014. Water quality data were not collected on Grouse and Cottonwood creeks, therefore concentrations measured at BOI 170 were used as model input for these locations. Figure 14 through Figure 17 depict the constituent concentrations measured on each date and at each location.

Nutrients (PO_3 , NO_3 , and NH_4) were analyzed by the Bureau of Reclamation Water and Soils Laboratory in Boise, Idaho. The *Quality Assurance Plan Pacific Northwest Regional Laboratory* outlines specific quality assurance/quality controls methodology used by the laboratory such as sample replicates, spikes, blank samples, and standard reference materials. Nitrate (NO_3) and ammonium (NH_4) water samples were filtered using $0.45\ \mu\text{m}$ filter before analysis and phosphate (PO_3) water samples were unfiltered and preserved with sulfuric acid to a $\text{pH} < 2$ before analysis. Chlorophyll-a (Chl-a) was also analyzed by the Water and Soils Laboratory.

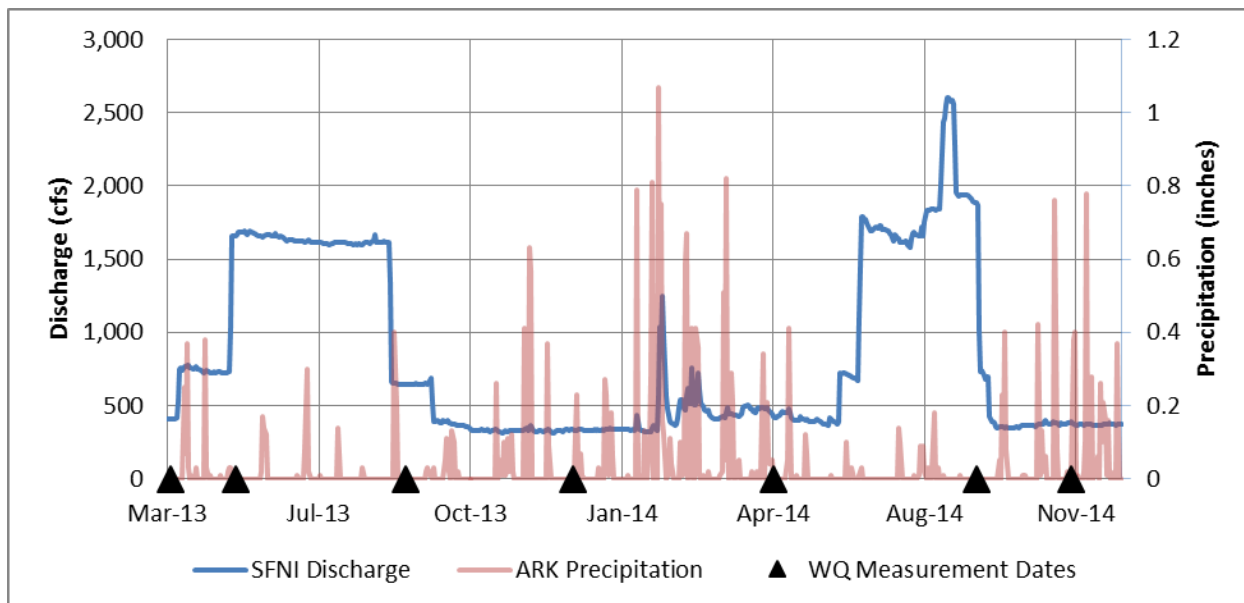


Figure 12: Seven water quality samples were collected on the South Fork of the Boise River (Branch 1) during the model period (black triangles). Precipitation and flow at SFNI are shown for hydrologic reference.

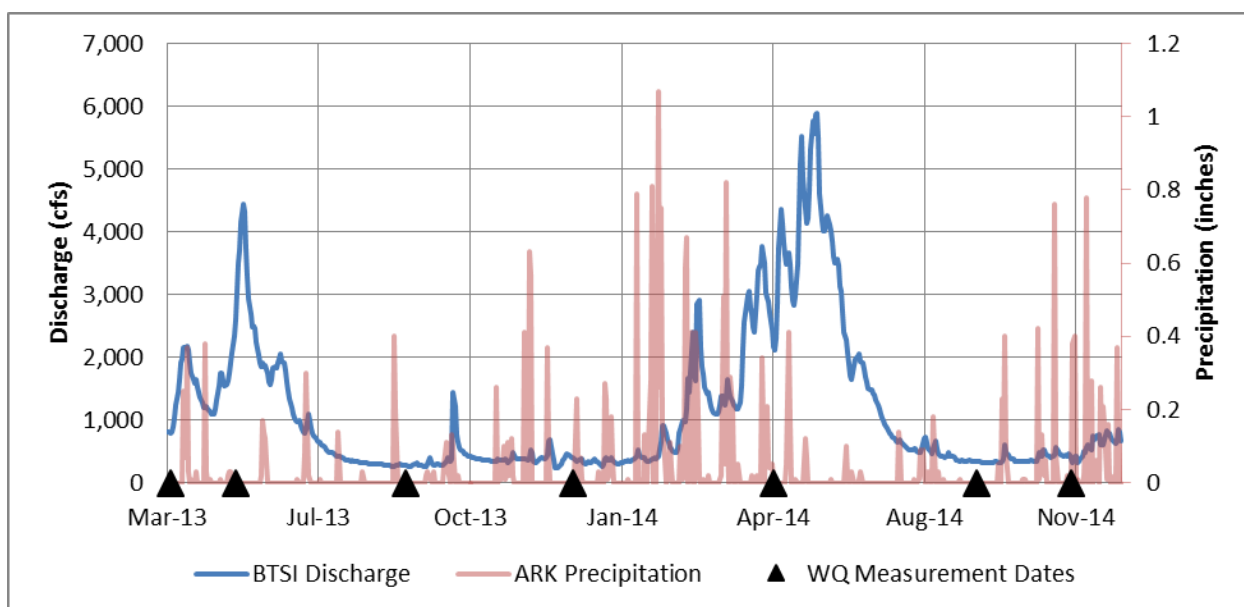


Figure 13: Seven water quality samples were collected on the Middle Fork of the Boise River (Branch 2) during the model period (black triangles). Precipitation and flow at SFNI are shown for hydrologic reference.

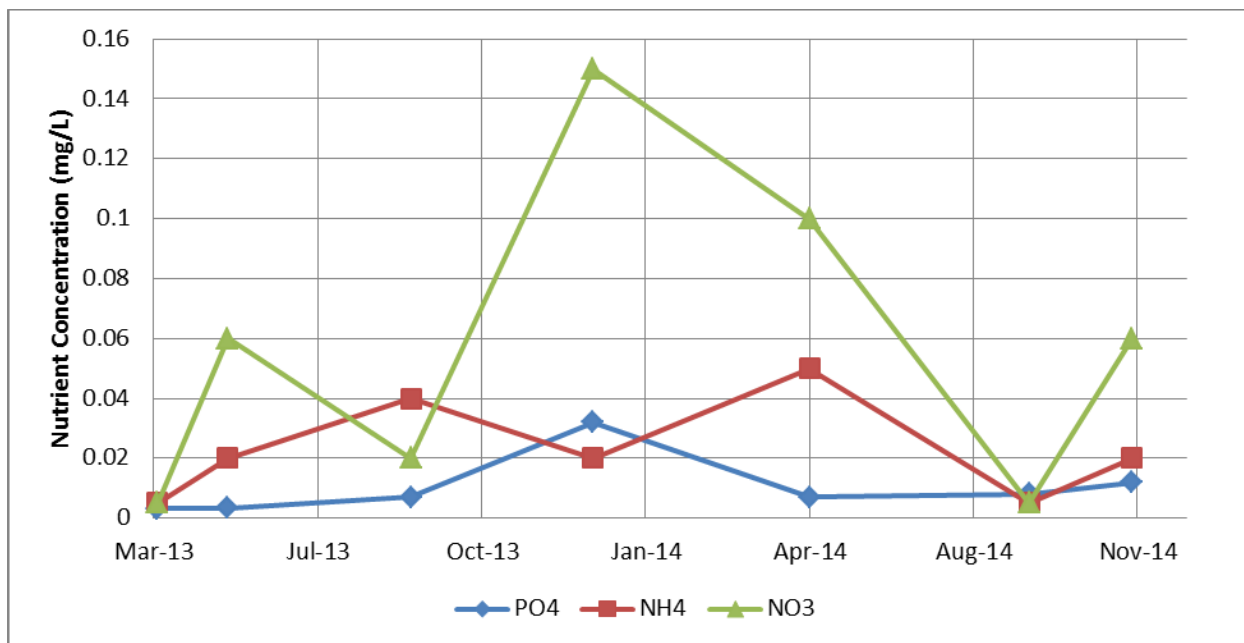


Figure 14: Nutrient concentrations in the South Fork Boise River at BOI 172. Where the concentration was found to be less than the detection limit, the value used in the model was assumed to be one-half of the detection limit.

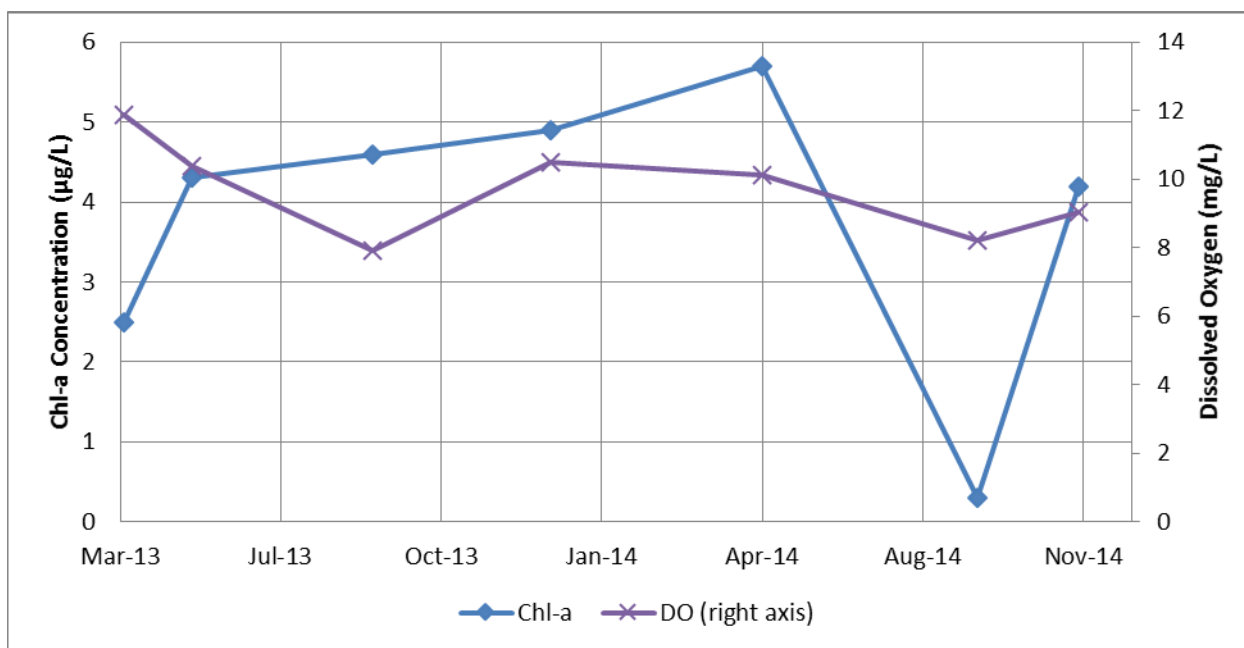


Figure 15: Chlorophyll-a and dissolved oxygen concentrations on the South Fork of the Boise River at BOI 172. Where the concentration was found to be less than the detection limit, the value used in the model was assumed to be one-half of the detection limit.

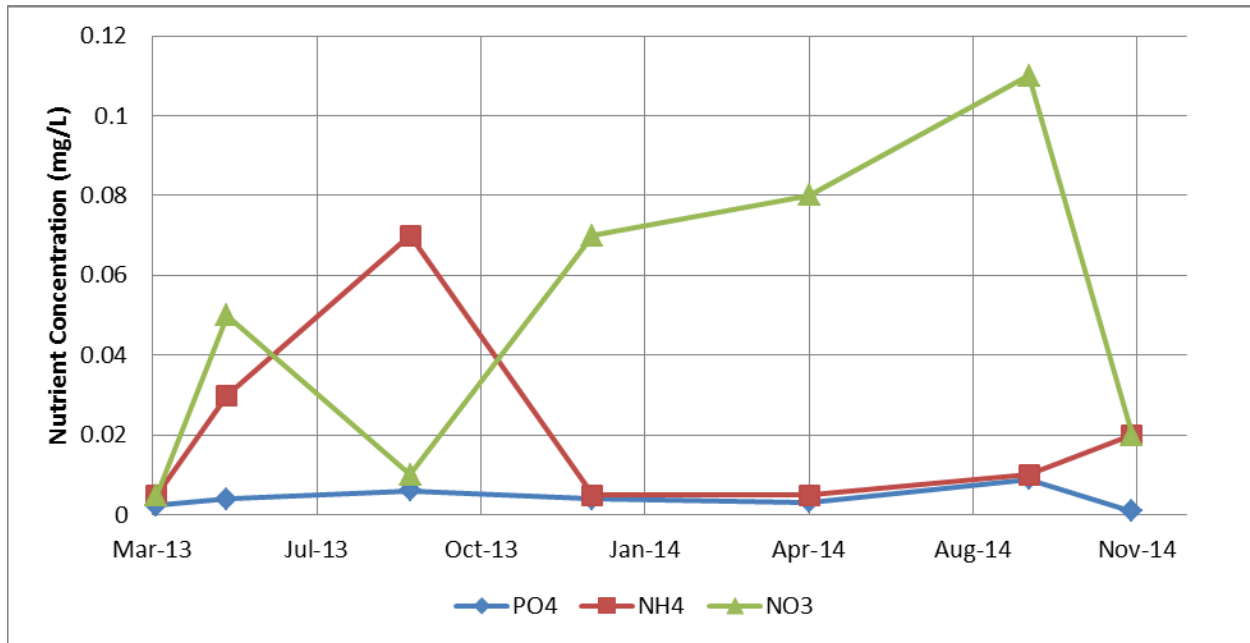


Figure 16: Nutrient concentrations in the Middle Fork Boise River at BOI 170. Where the concentration was found to be less than the detection limit, the value used in the model was assumed to be one-half of the detection limit.

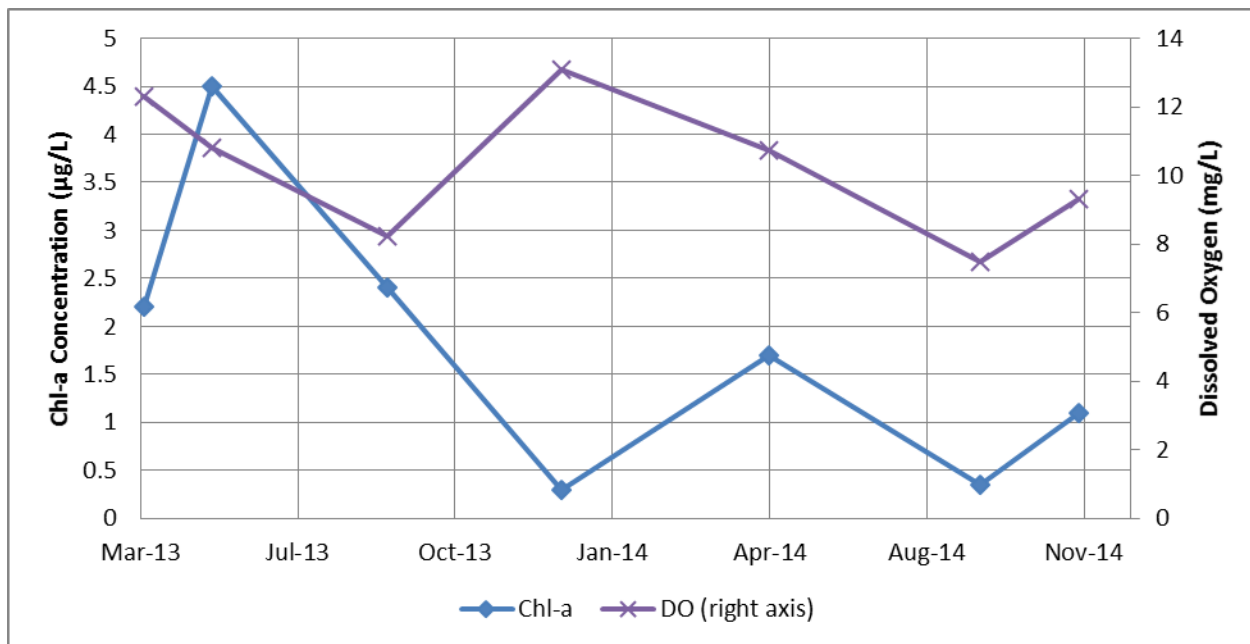


Figure 17: Chlorophyll-a and dissolved oxygen concentrations on the Middle Fork of the Boise River at BOI 170. Where the concentration was found to be less than the detection limit, the value used in the model was assumed to be one-half of the detection limit.

2.3 Model Development

2.3.1 Water Balance

Not all inflows and losses from Arrowrock Reservoir have been quantified or measured. Outflow calculations are highly uncertain, and gaged stations also have some uncertainty associated with their measurements. For this reason, it is not surprising that initial simulations of reservoir elevations (left panel of Figure 18) did not match observations. Hydrodynamic calibration involved several iterations using the mass balance utility provided with the CE-QUAL-W2 model. This utility identifies the amount of flow that must be added or subtracted in each timestep in order to achieve mass balance. These mass balance flows were distributed as adjustments to the various inflows and outflows, not to exceed the assumed measurement error at each site. The right-hand panel of Figure 18 shows the results of the balanced model.

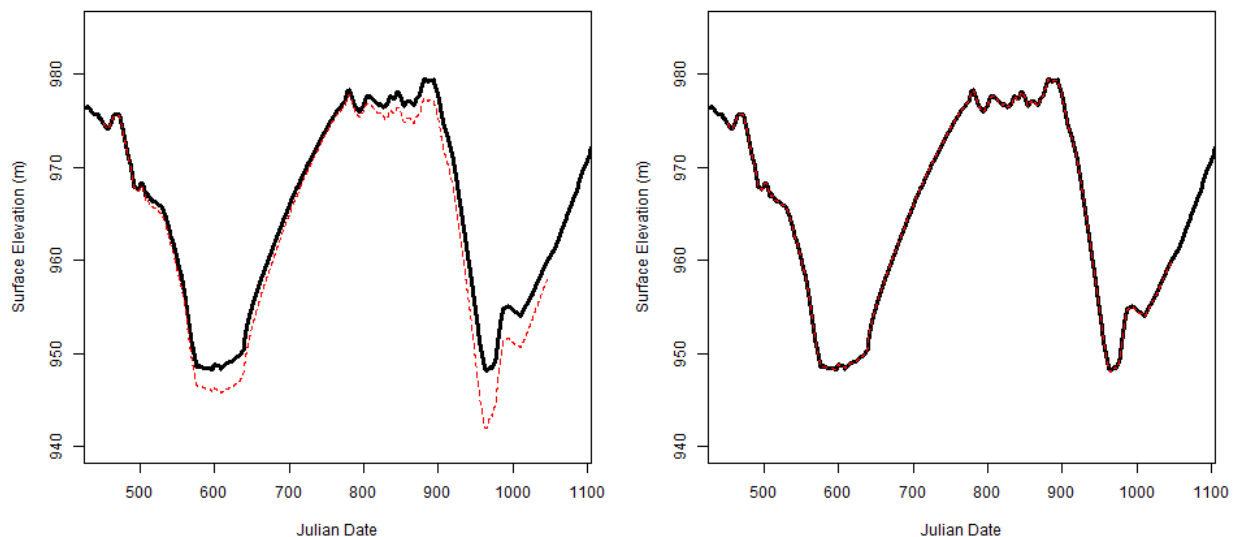


Figure 18: Measured reservoir surface elevations (black solid lines) and modeled reservoir elevations (dashed red lines) before mass-balance adjustments (left) and after mass-balance adjustments (right).

2.3.2 Initial and Boundary Conditions

Table 2.1 lists the temperature and water quality constituents required for initial condition and boundary condition input to the model and how values for those constituents were obtained. While many of the constituents were measured directly (including temperature, nitrate/nitrite, ammonia/ammonium, ortho-phosphate, and dissolved oxygen), others had to be estimated based on assumptions and correlations with other measured constituents. These assumptions and correlations include the following:

- Total Dissolved Solids (TDS) was estimated from Electrical Conductivity (EC) where $\text{TDS mg/L} = \text{EC dS/m} * 640$. (Gustafson and Behrman 1939; Essington 2004).
- Inorganic Suspended Solids (ISS) was estimated directly from turbidity measurements where 1 NTU turbidity was assumed to equal 1 mg/L ISS. The same assumption was used in the 2003 modeling effort.
- Organic matter compartments (labile dissolved organic matter, refractory dissolved organic matter, labile particulate organic matter, and refractory particulate organic matter) were not measured and were instead obtained directly from 2003 model estimates.
- Algal biomass was calculated based on a ratio of 0.05 mg algae/ μg chlorophyll-a.
- Total inorganic carbon was obtained from 2003 model estimates.
- Alkalinity was estimated based on a relationship between electrical conductivity and alkalinity obtained from an earlier dataset where both constituents were measured together ($R^2 = 0.9$). The equation for this relationship was $\text{alkalinity (mg/L)} = 2.9 + 0.4643 * \text{EC } (\mu\text{S/cm})$

Initial conditions within the reservoir at the start of the model period were based on measurements obtained from the most central reservoir monitoring point (ARR004) during March 2013. While only a single reservoir profile (one day and one location) was used for actual input into the model, the rest of the profile measurements were used extensively for comparison during the calibration and sensitivity analysis. Boundary conditions (which include water quality conditions at all inflow points) were based on water quality information (measured or estimated) obtained from BOI 170 and BOI 172. When possible, data gaps were filled in using information from the nearest in-reservoir location (ARR003 and ARR002).

Table 2.1: Model boundary condition constituents and the data source or method used to estimate values.

| Required Constituent | Recommended Frequency | Source/Method | Actual Frequency |
|--|------------------------------|--|-------------------------|
| Water Temperature | Daily or continuous | Measured | 15-minute to hourly |
| Total Dissolved Solids (TDS) | Daily or continuous | Calculated from Electrical Conductivity (EC) | 6- to 8-week intervals |
| Inorganic Suspended Solids (ISS) | Weekly w/ storm sampling | Estimated from Turbidity | 6- to 8-week intervals |
| Phosphate (PO ₄) | Weekly w/ storm sampling | Measured | 6- to 8-week intervals |
| Ammonia/Ammonium (NH ₄) | Weekly w/ storm sampling | Measured | 6- to 8-week intervals |
| Nitrate/Nitrite (NO ₃) | Weekly w/ storm sampling | Measured | 6- to 8-week intervals |
| Labile Dissolved Organic Matter (LDOM) | Weekly w/ storm sampling | 2003 estimates | 6- to 8-week intervals |
| Refractory Dissolved Organic Matter (RDOM) | Weekly w/ storm sampling | 2003 estimates | 6- to 8-week intervals |
| Labile Particulate Organic Matter (LPOM) | Weekly w/ storm sampling | 2003 estimates | 6- to 8-week intervals |
| Refractory Particulate Organic Matter (RPOM) | Weekly w/ storm sampling | 2003 estimates | 6- to 8-week intervals |
| Algae Biomass | Weekly w/ storm sampling | Calculated from Chlorophyll-a | 6- to 8-week intervals |
| Dissolved Oxygen (DO) | Daily or continuous | Measured | 6- to 8-week intervals |
| Total Inorganic Carbon (TIC) | Weekly w/ storm sampling | 2003 estimates | 6- to 8-week intervals |
| Alkalinity (ALK) | Weekly w/ storm sampling | Calculated from EC | 6- to 8-week intervals |

2.3.3 Model Sensitivity Analysis

Water quality calibration and sensitivity analysis involved adjustments to a wide range of model parameters including algae growth rates, temperature rate coefficients, and stoichiometry. The 2003 model included only one algal group (which appears to have been leveraged as a calibration parameter) and no zooplankton. This sensitivity analysis therefore explored the effect of including a diatom group as well as a zooplankton group in the model. Sensitivity analysis suggested the most improvement in model performance was with the addition of zooplankton to the model. While there was no zooplankton data available for the model simulation years, samples were collected later in 2016 to gain qualitative insight into the species and concentrations seen in the reservoir. Zooplankton were further evaluated through a sensitivity analysis with respect to their kinetic rates and algal feeding preferences, revealing little justification for adjusting these parameters away from their default values.

2.3.3.1 Zooplankton

Strong interactions exist between zooplankton and algae and the processes involved in those interactions vary seasonally. The temperature preferences of algae, diatoms, and zooplankton make them more/less active relative to one another at different times of the year. Model sensitivity to the addition of zooplankton had the most influence on model output when compared to all of the other sensitivity adjustments that were performed. Since no data was available for zooplankton for the model simulation years, inflow concentrations of zooplankton were assumed to be negligible and default zooplankton parameter rates were used. Reservoir starting concentrations for zooplankton were varied during the analysis, but had relatively little effect on simulated concentrations in the reservoir.

It should be noted that algal rates and stoichiometry were set to the model default values under the assumption that the calibrated parameter values in the 2003 model were likely compensating for a range of processes not accounted for in the older model, including the influence of zooplankton in the reservoir. A comparison of the output from the 2003 model with the output from a default parameter value model (both without zooplankton) was also conducted and supported this assumption, where the calibrated Baseline parameters exhibited higher performance than the default values.

The model appeared to improve temperature and chlorophyll-a estimates on many, but not all, of the observed dates. Figure 19 through Figure 24 illustrate the differences between the 2003 calibrated model (Baseline) and the “with Zooplankton” model.

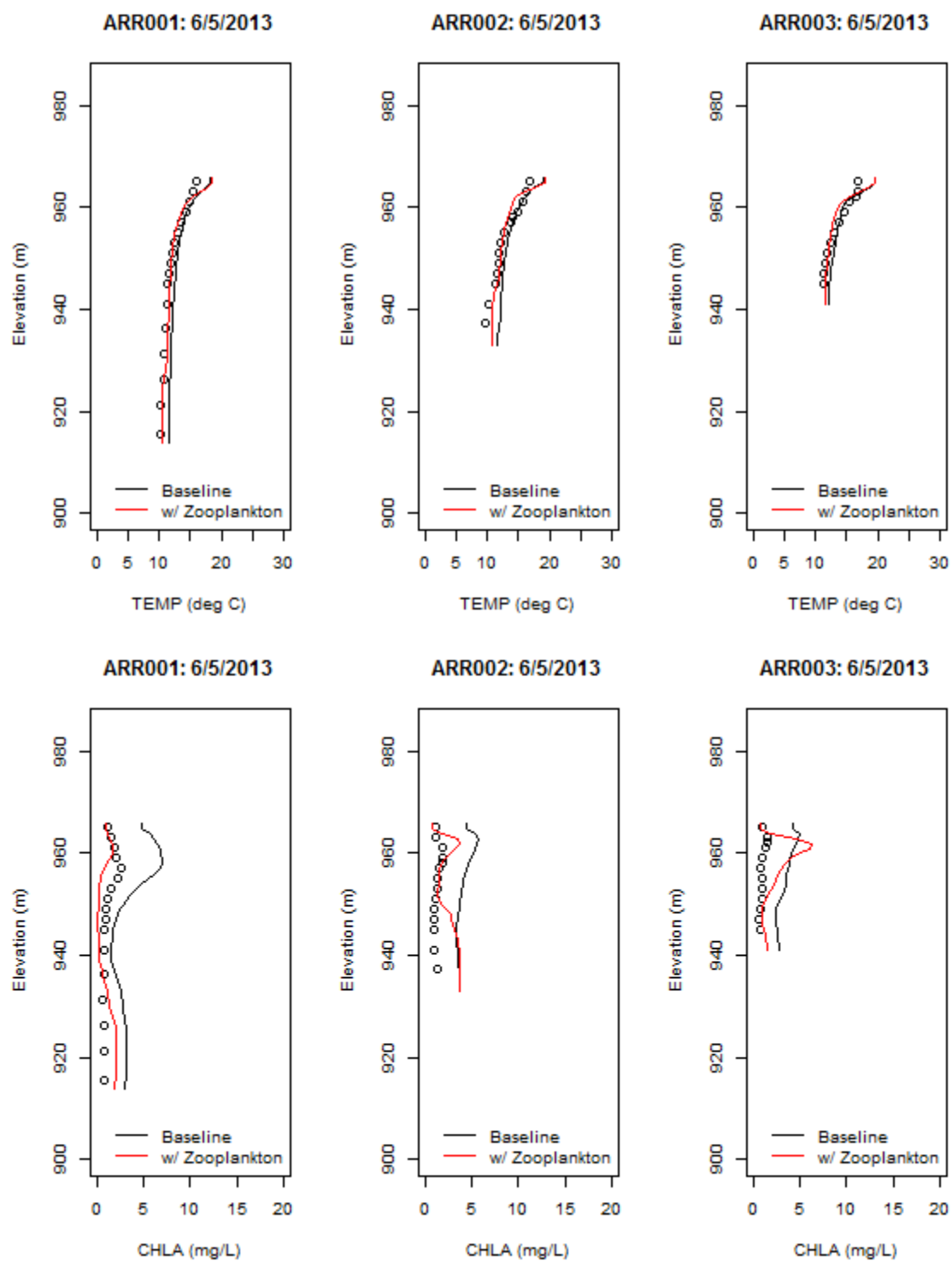


Figure 19: Observed (denoted by circles) and simulated (denoted by red and black lines) temperature and chlorophyll-a concentrations at ARR001, ARR002, and ARR003 on 6/5/2013.

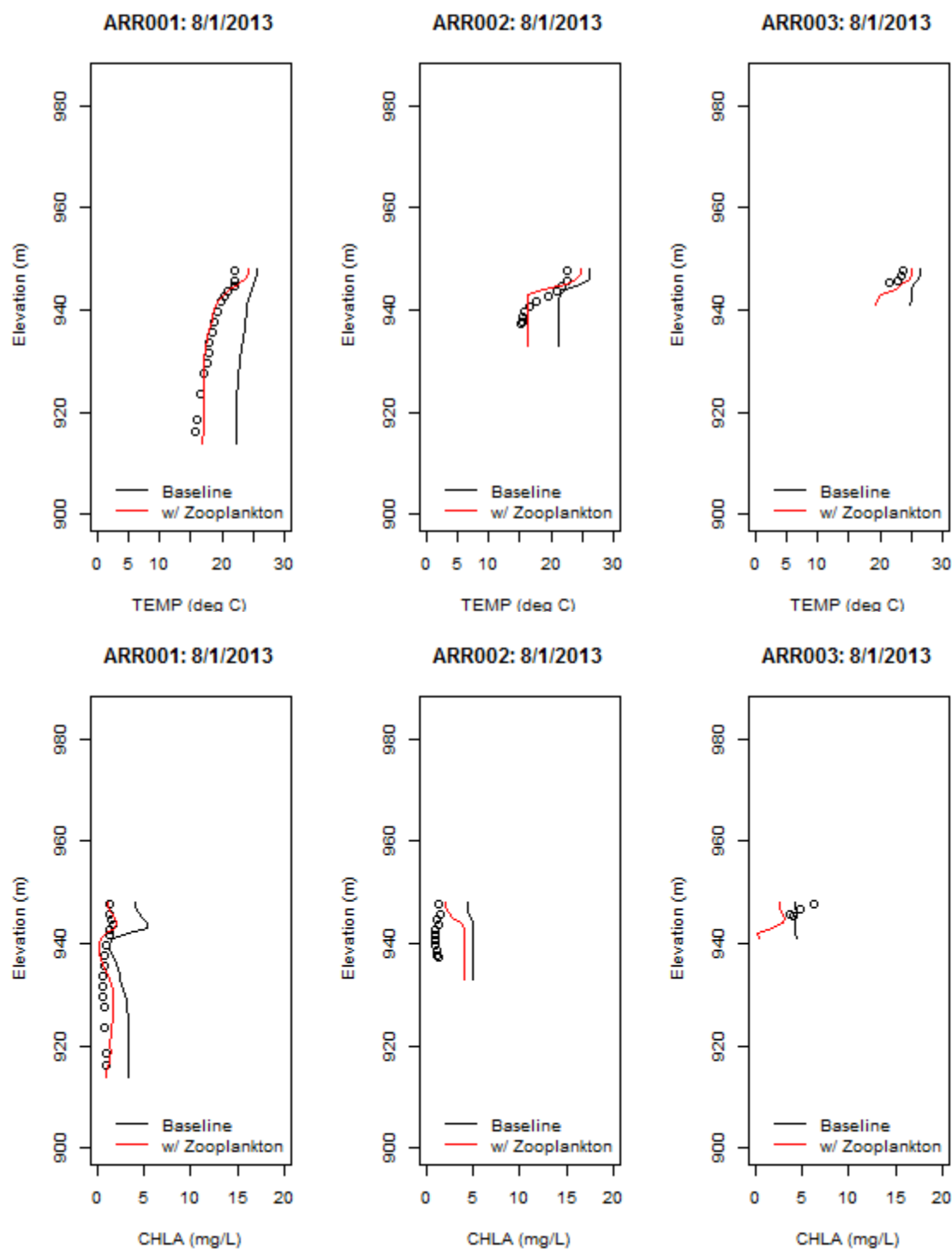


Figure 20: Observed (denoted by circles) and simulated (denoted by red and black lines) temperature and chlorophyll-a concentrations at ARR001, ARR002, and ARR003 on 8/1/2013.

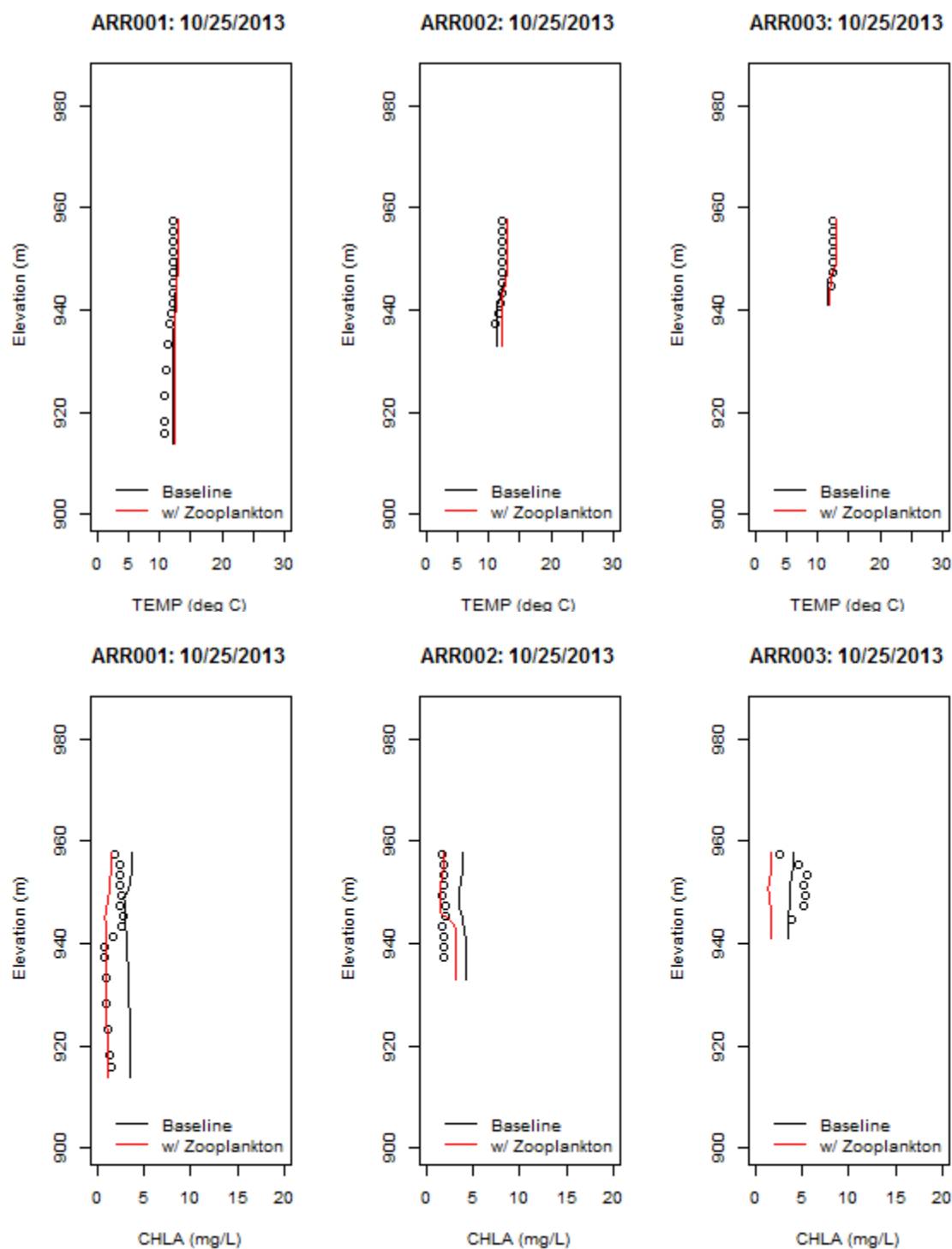


Figure 21: Observed (denoted by circles) and simulated (denoted by red and black lines) temperature and chlorophyll-a concentrations at ARR001, ARR002, and ARR003 on 10/25/2013.

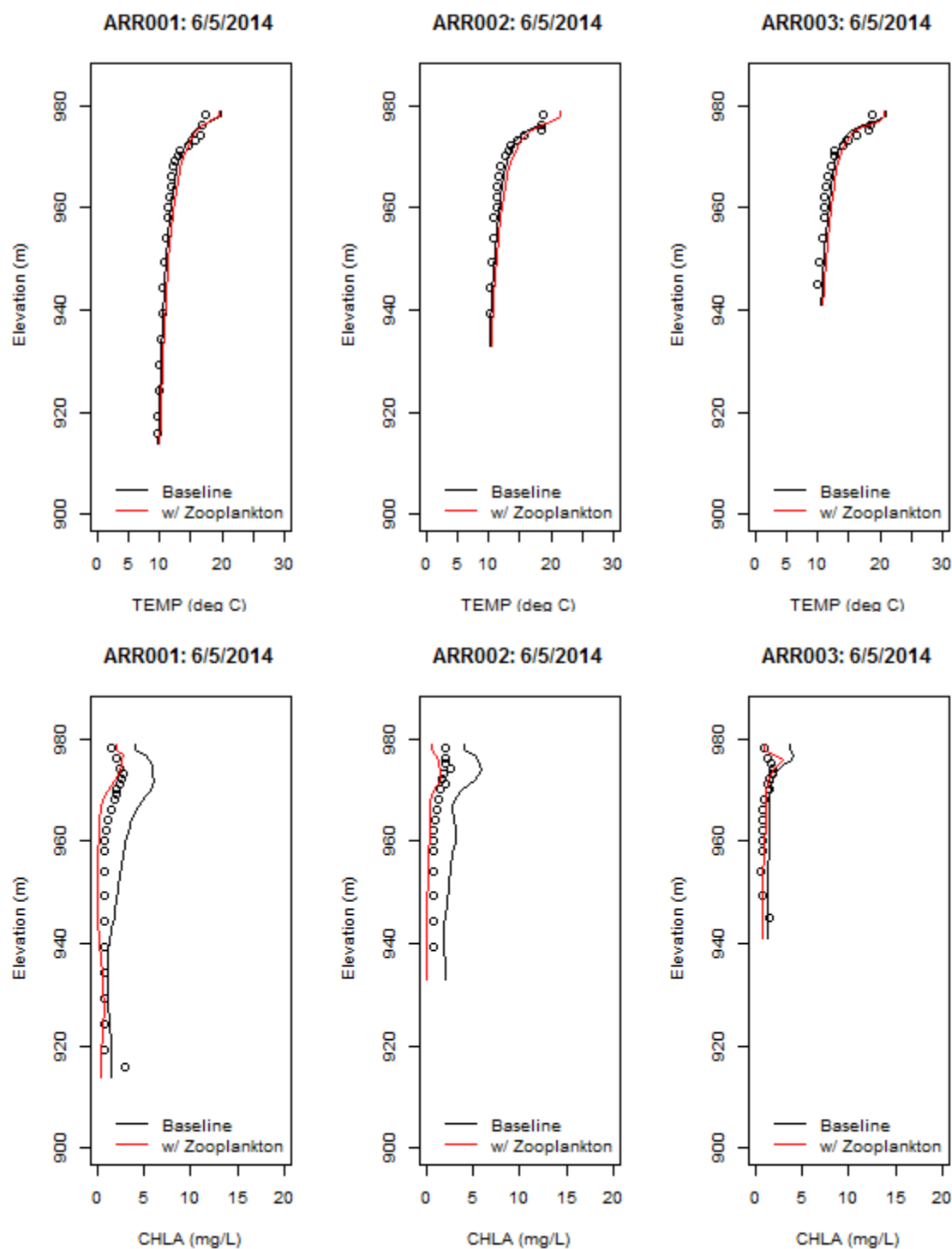


Figure 22: Observed (denoted by circles) and simulated (denoted by red and black lines) temperature and chlorophyll-a concentrations at ARR001, ARR002, and ARR003 on 6/5/2014.

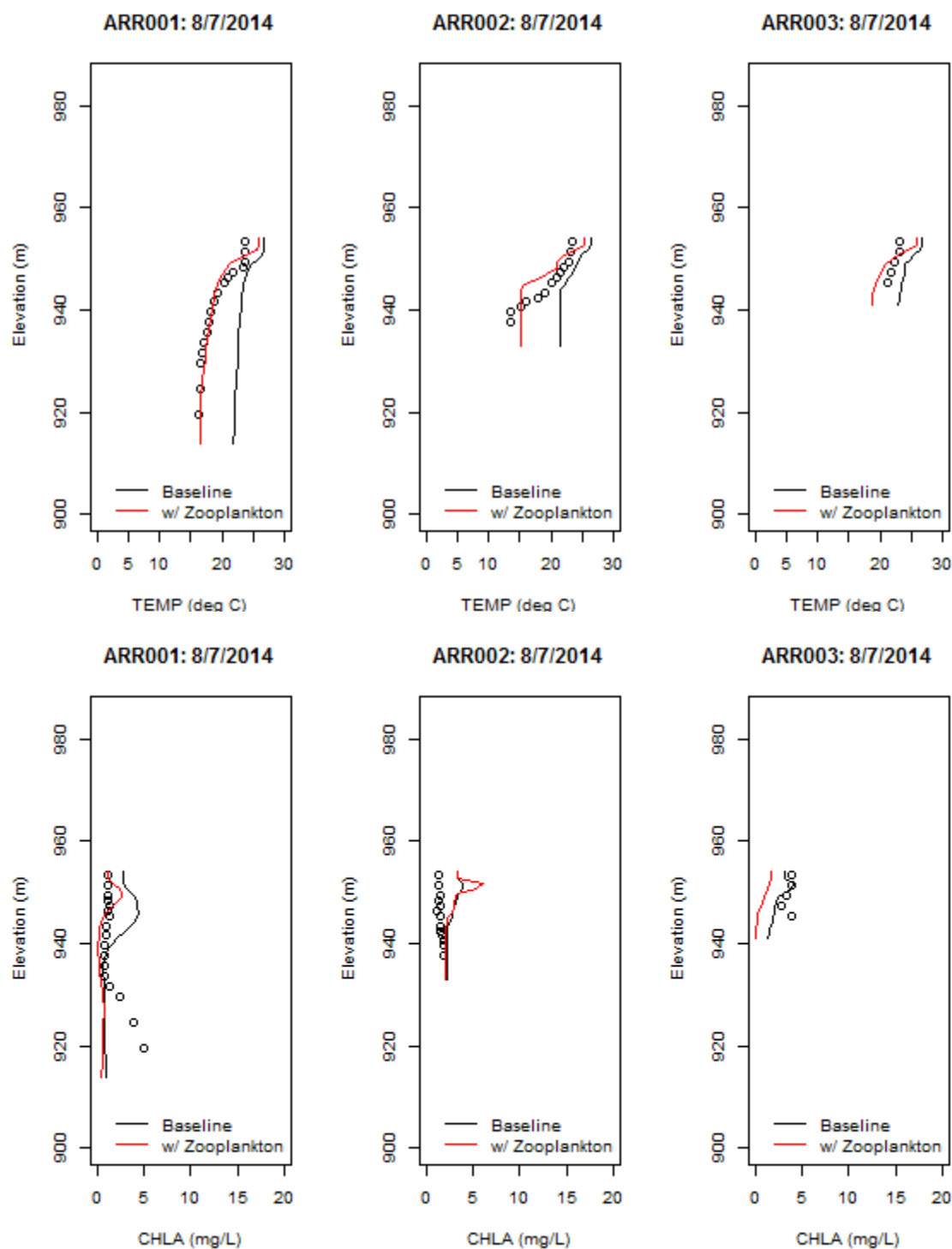


Figure 23: Observed (denoted by circles) and simulated (denoted by red and black lines) temperature and chlorophyll-a concentrations at ARR001, ARR002, and ARR003 on 8/7/2014.

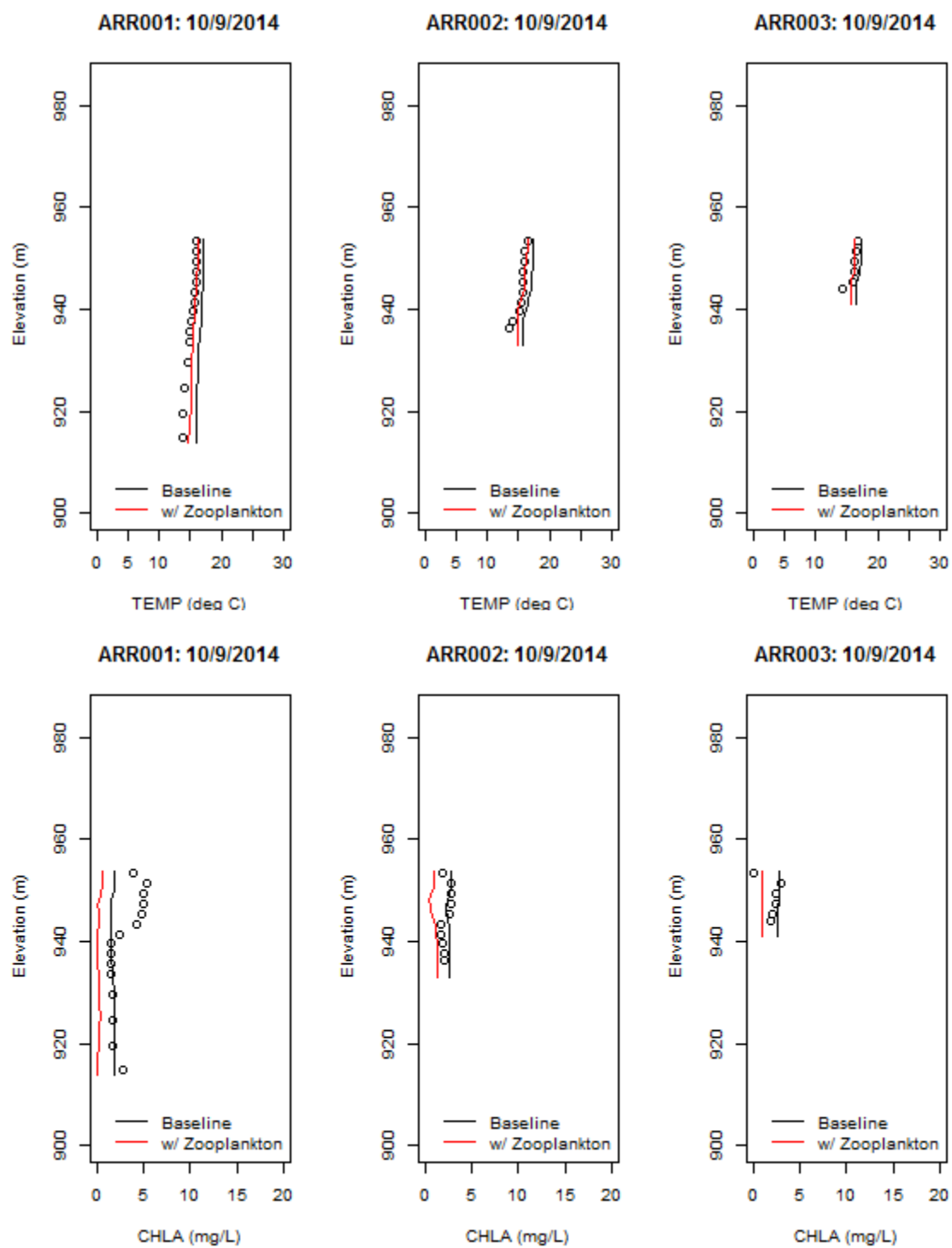


Figure 24: Observed (denoted by circles) and simulated (denoted by red and black lines) temperature and chlorophyll-a concentrations at ARR001, ARR002, and ARR003 on 10/9/2014.

3 MODEL RESULTS

3.1.1 Water Temperature

The updated baseline model (with zooplankton) performed well in simulating temperature profiles at all four locations, with root mean squared errors (RMSE) consistently less than 2 degrees Celsius¹. Figure 25 through Figure 30 show temperature profiles for the 2013 and 2014 summer and early-fall seasons, correlating with important bull trout migratory periods. The largest differences between simulated and observed temperatures generally occurred at the reservoir surface, where simulated values were frequently a few degrees warmer than observed. This might be attributed to the lack of shading in this model or the use of wind data that may not be indicative of conditions on the reservoir. Shading of the reservoir surface by the steep canyon walls is likely to have a cooling effect on the reservoir surface that is not accounted for in this version of the model. It is also suspected that wind speeds on the reservoir are actually greater than those measured at BOII. Greater wind speeds can increase mixing on the reservoir surface having a cooling effect on surface water temperatures.

Observations and model results both show that by mid-July temperatures throughout the reservoir are above 15 degrees Celsius (a temperature guideline for bull trout critical habitat; USFWS 2014) and typically stay elevated until mid to late-October when inflow temperatures cool and fall rains cause a bump in inflows from the Middle Fork of the Boise River (see Figure 8). Figure 31 through Figure 38 illustrate reservoir temperatures at the start and end of June and October.

¹ The highest RMSE was found to be 2.512 deg C and occurred on 12/18/2013. This was likely due to this model's inability to simulate ice formation. While there is functionality in CE-QUAL-W2 to model ice formation, turning this feature "on" adversely impacted the water mass balance. For this reason, the ice feature was turned "off" for this modelling application.

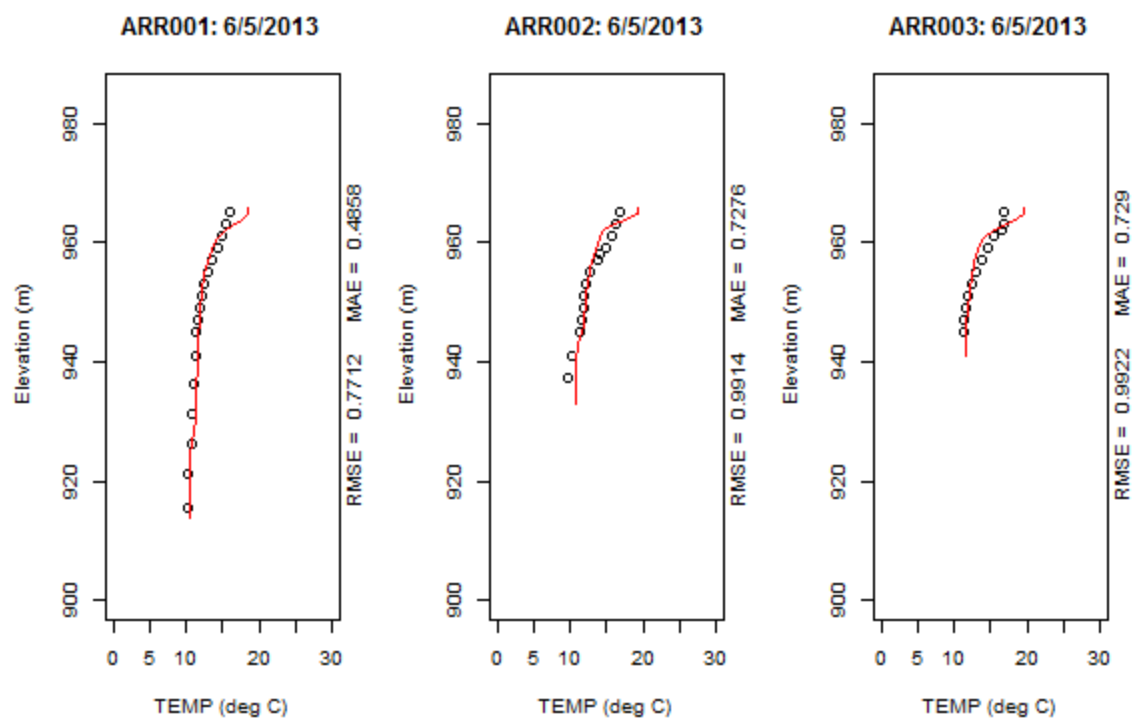


Figure 25: Observed (denoted by circles) and simulated (denoted by trend line) temperature profiles at ARR001, ARR002, and ARR003 on 6/5/2013.

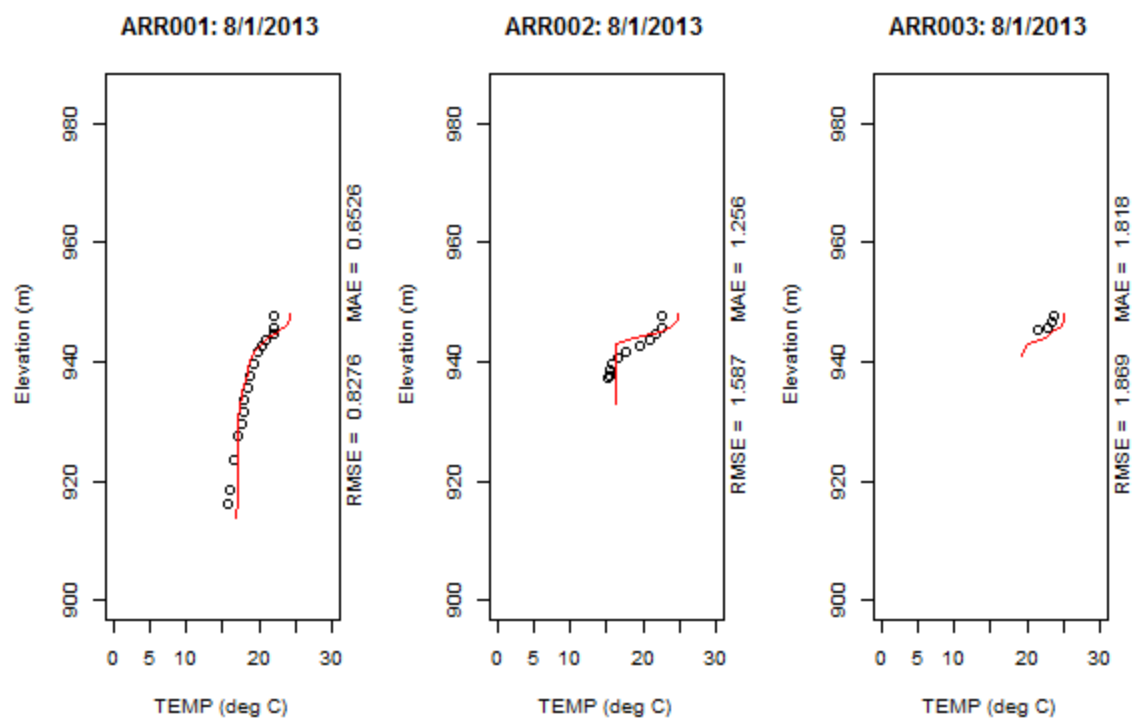


Figure 26: Observed (denoted by circles) and simulated (denoted by trend line) temperature profiles at ARR001, ARR002, and ARR003 on 8/1/2013.

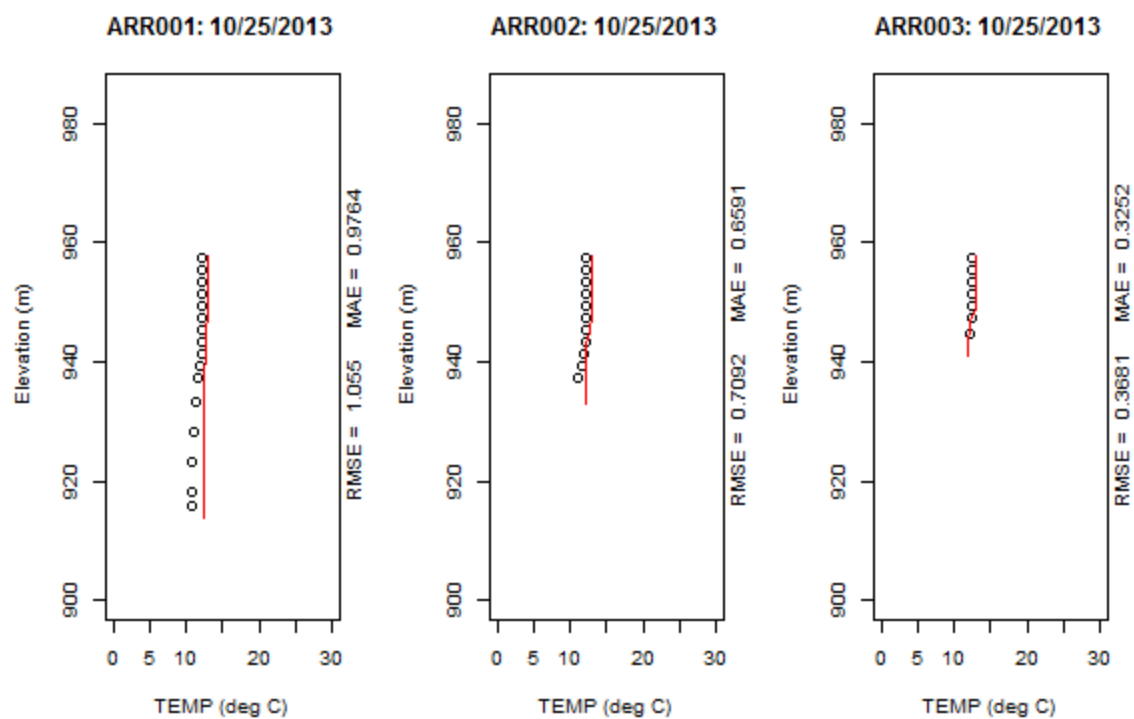


Figure 27: Observed (denoted by circles) and simulated (denoted by trend line) temperature profiles at ARR001, ARR002, and ARR003 on 10/25/2013.

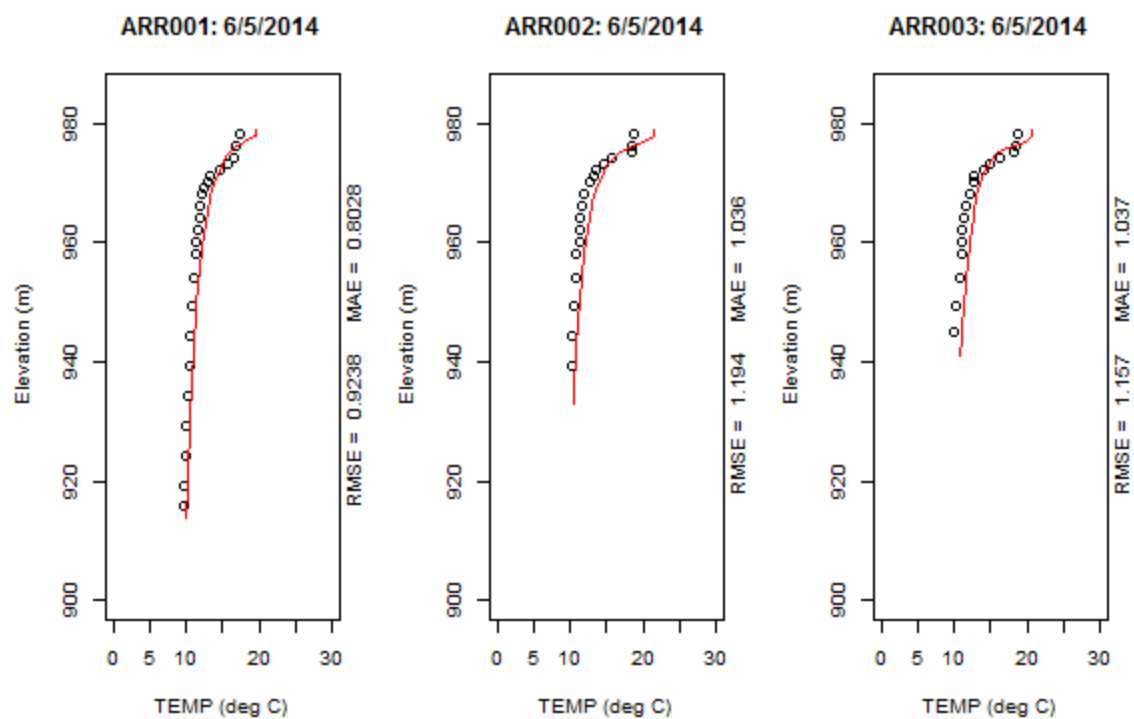


Figure 28: Observed (denoted by circles) and simulated (denoted by trend line) temperature profiles at ARR001, ARR002, and ARR003 on 6/5/2014.

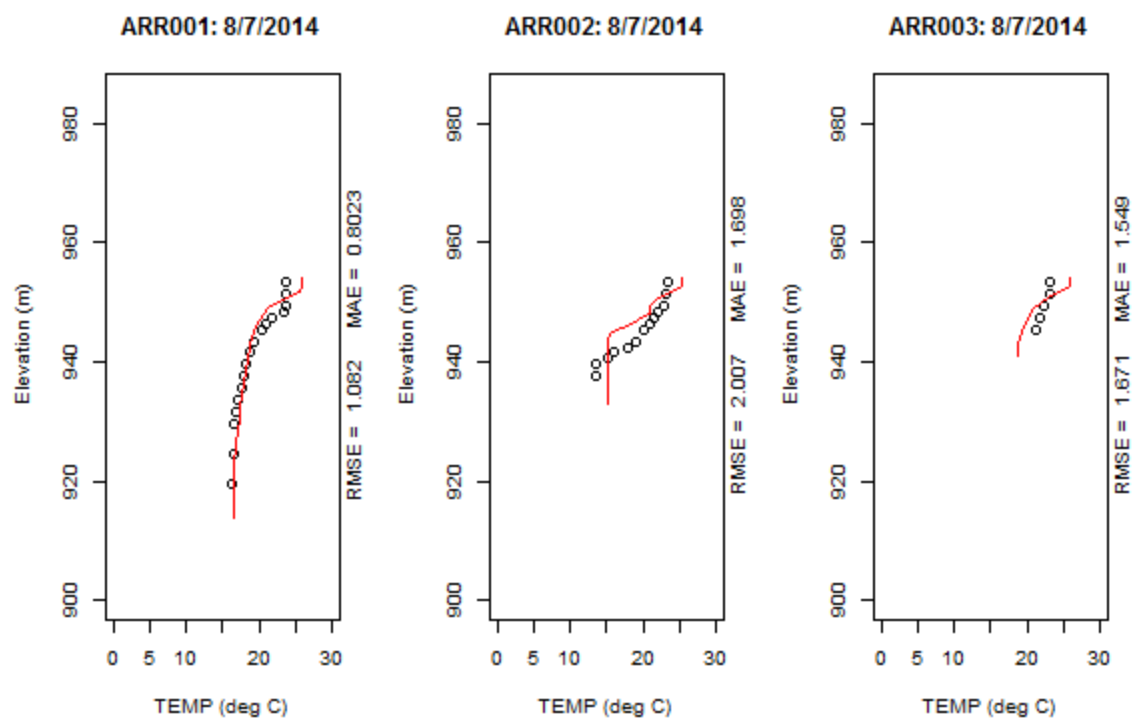


Figure 29: Observed (denoted by circles) and simulated (denoted by trend line) temperature profiles at ARR001, ARR002, and ARR003 on 8/7/2014.

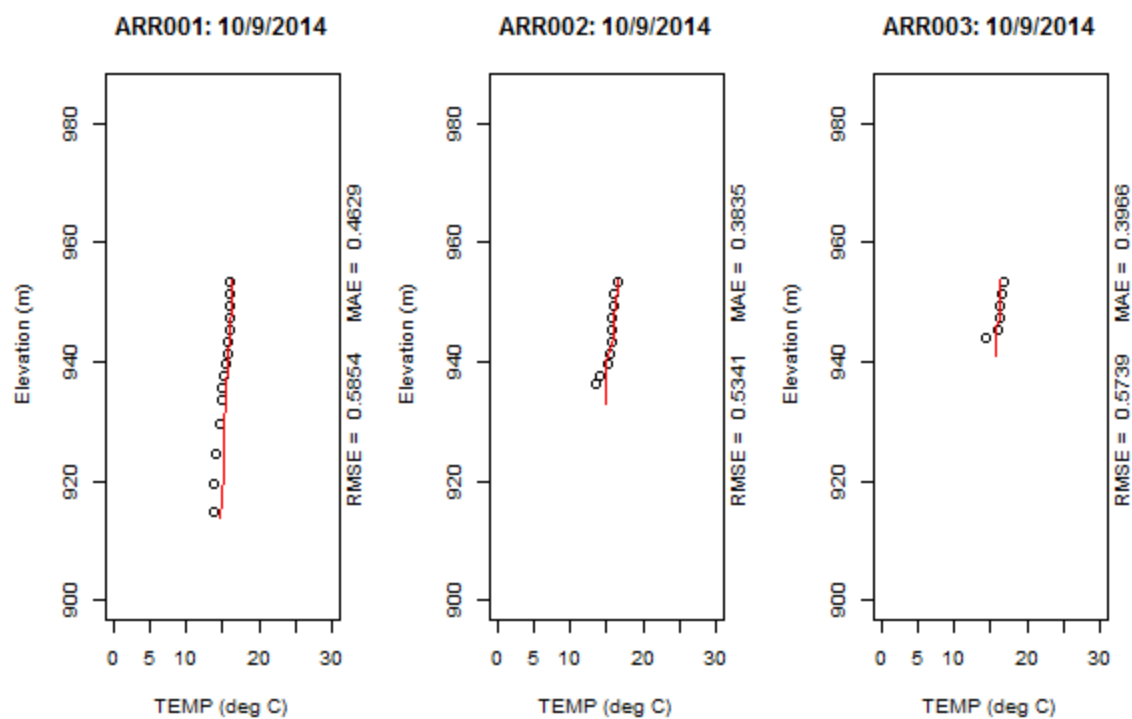


Figure 30: Observed (denoted by circles) and simulated (denoted by trend line) temperature profiles at ARR001, ARR002, and ARR003 on 10/9/2014.

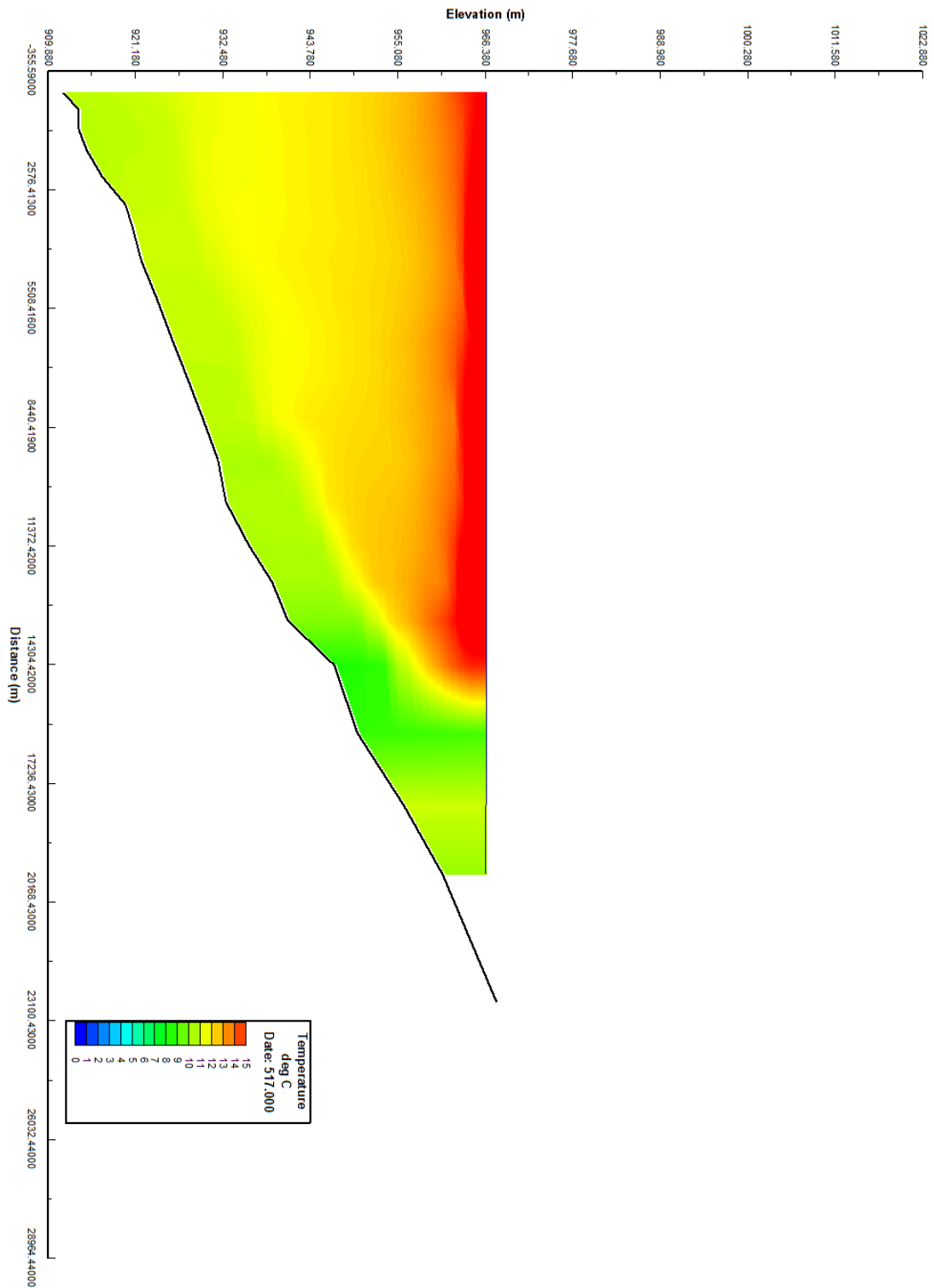


Figure 31: Simulated Arrowrock Reservoir temperature on 6/1/2013.

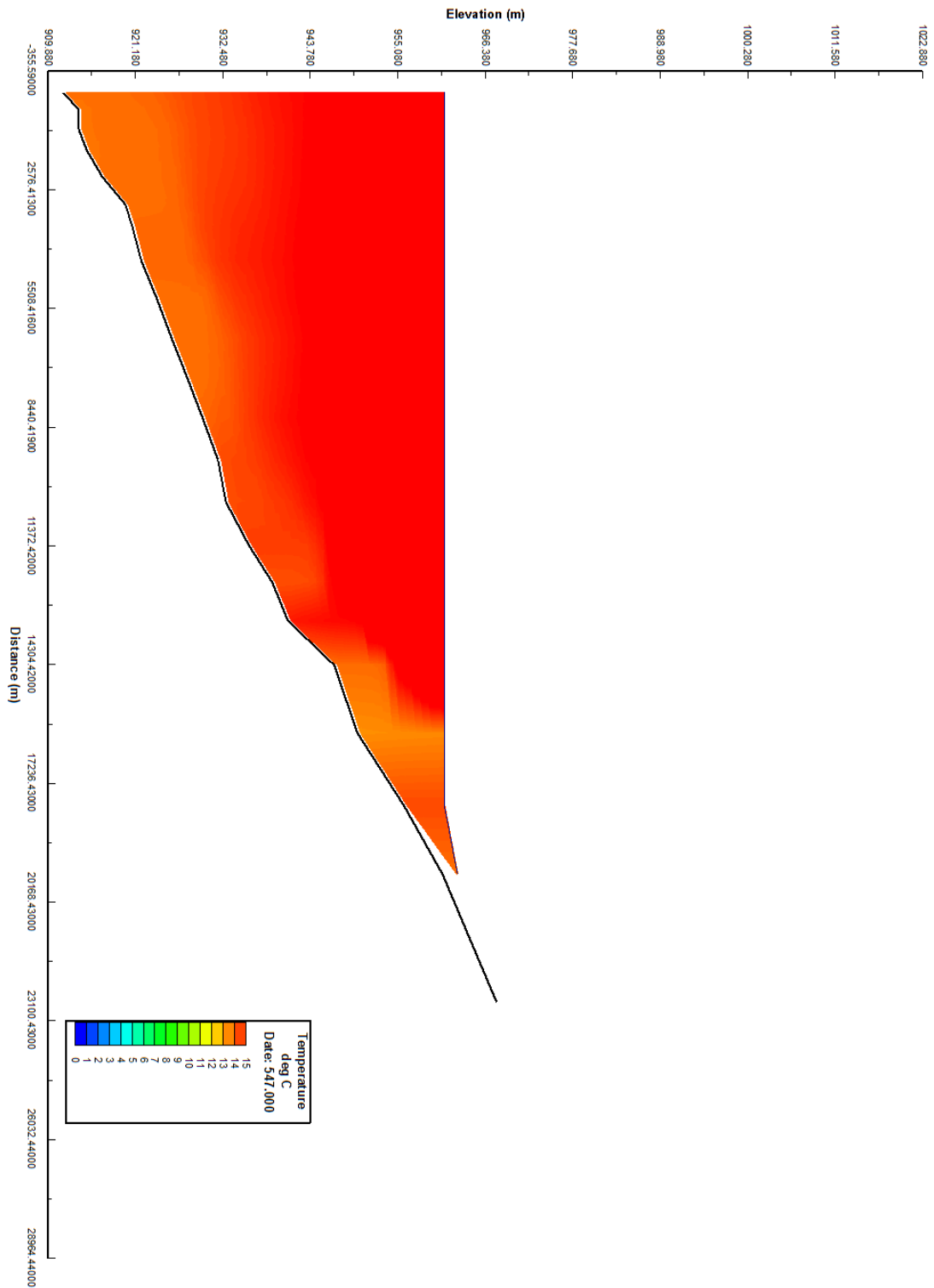


Figure 32: Simulated Arrowrock Reservoir temperature on 6/30/13.

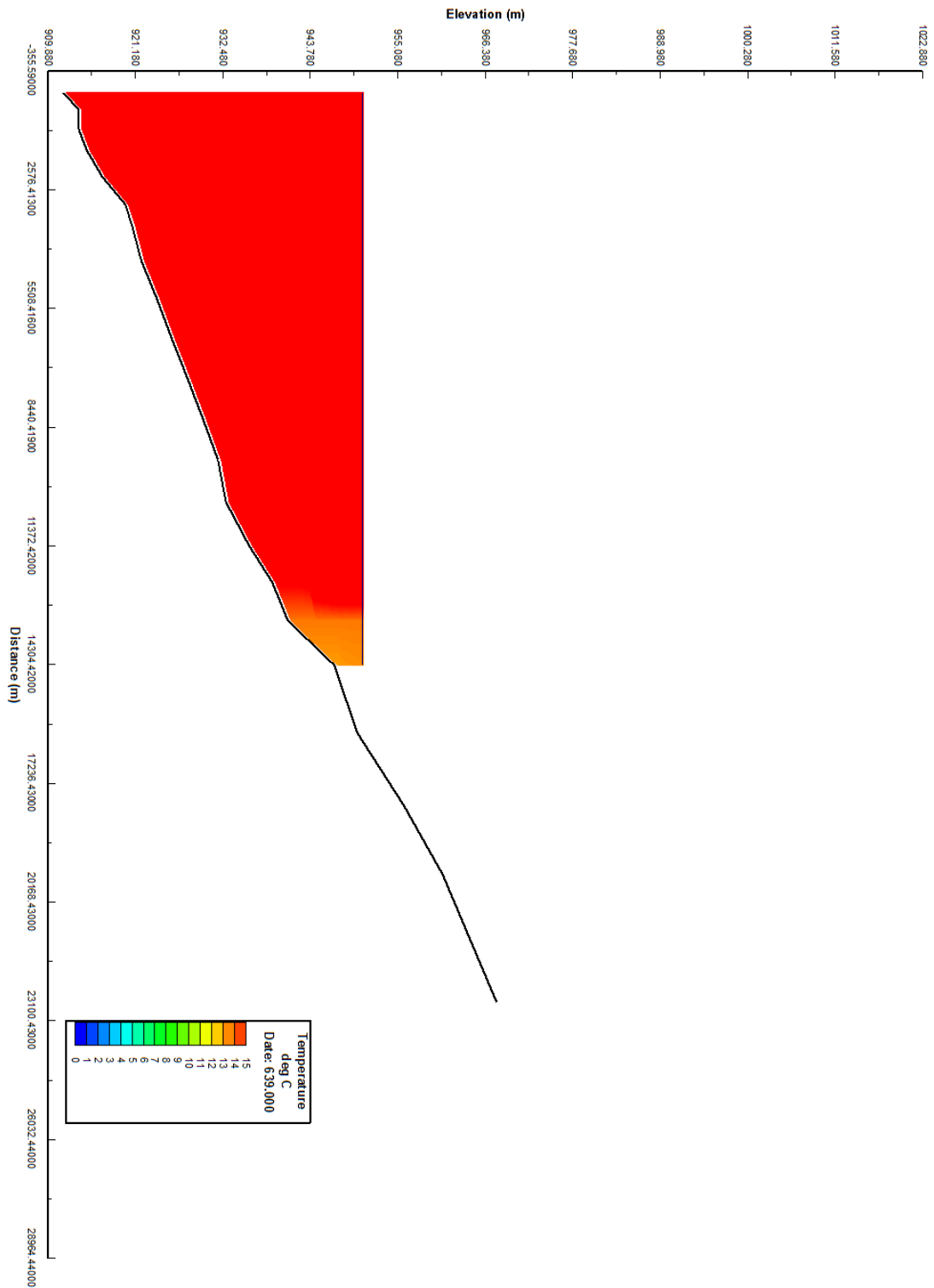


Figure 33: Simulated Arrowrock Reservoir temperature on 10/1/13.

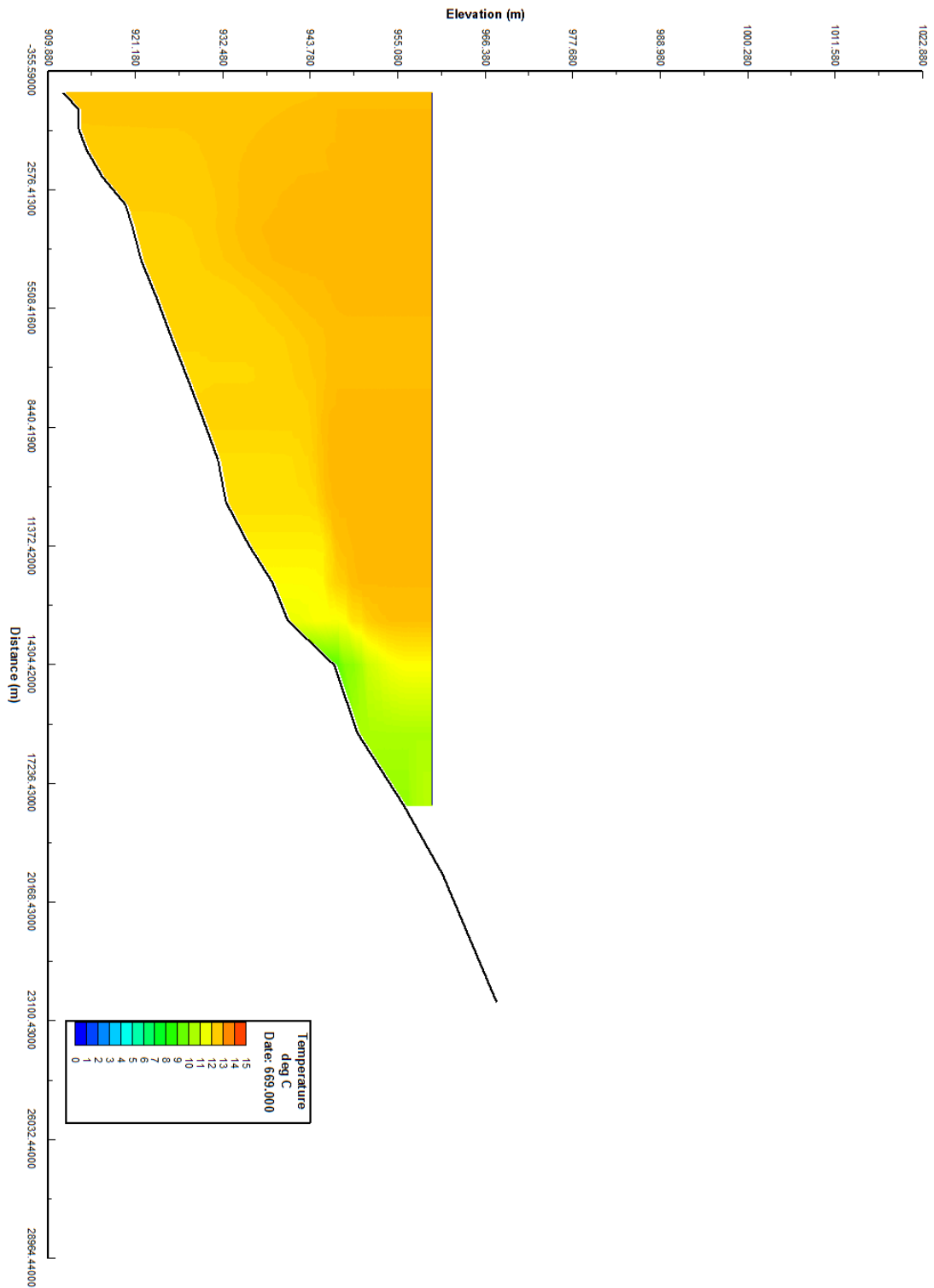


Figure 34: Simulated Arrowrock Reservoir temperature on 10/30/13.

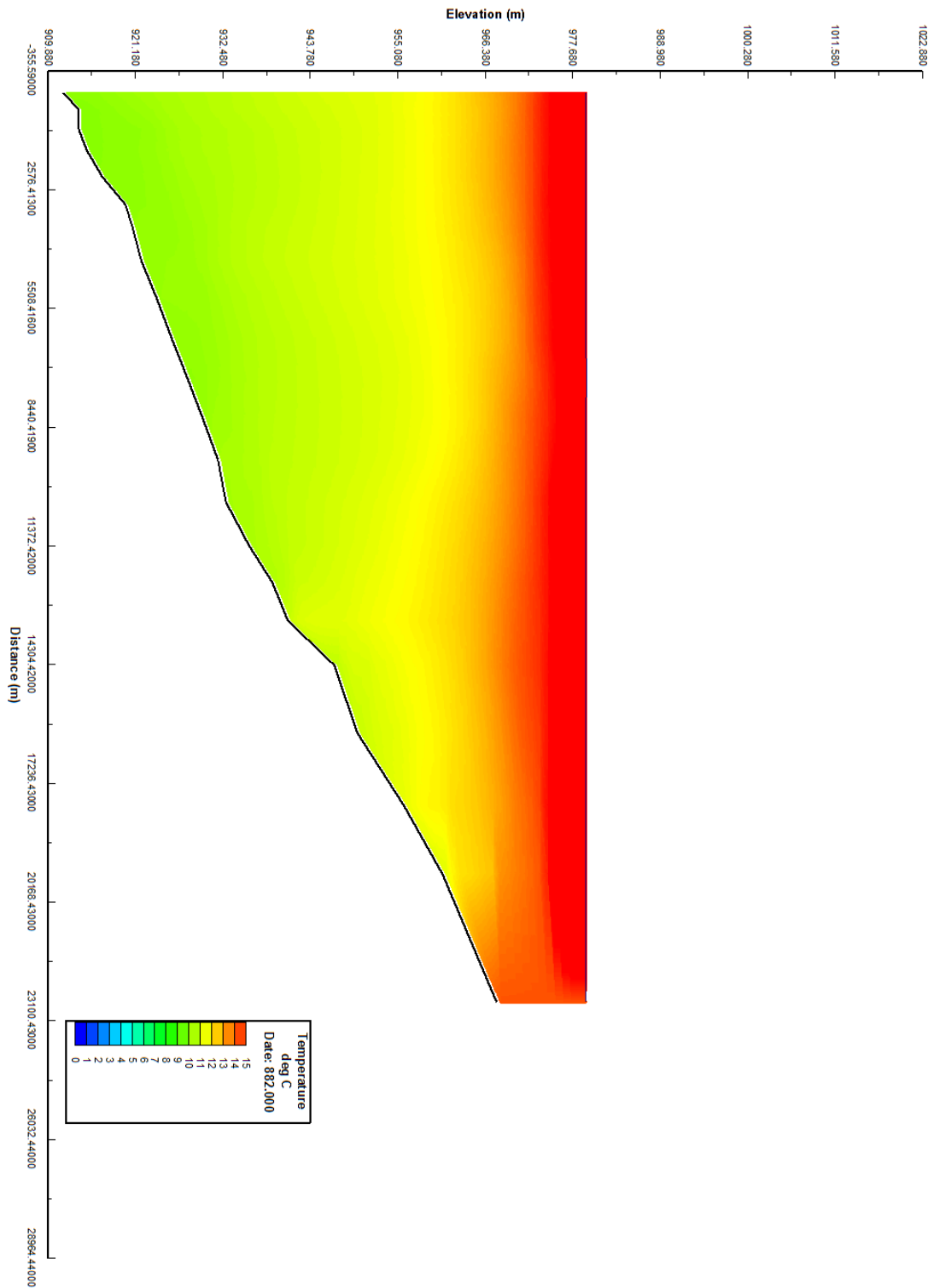


Figure 35: Simulated Arrowrock Reservoir temperature on 6/1/14.

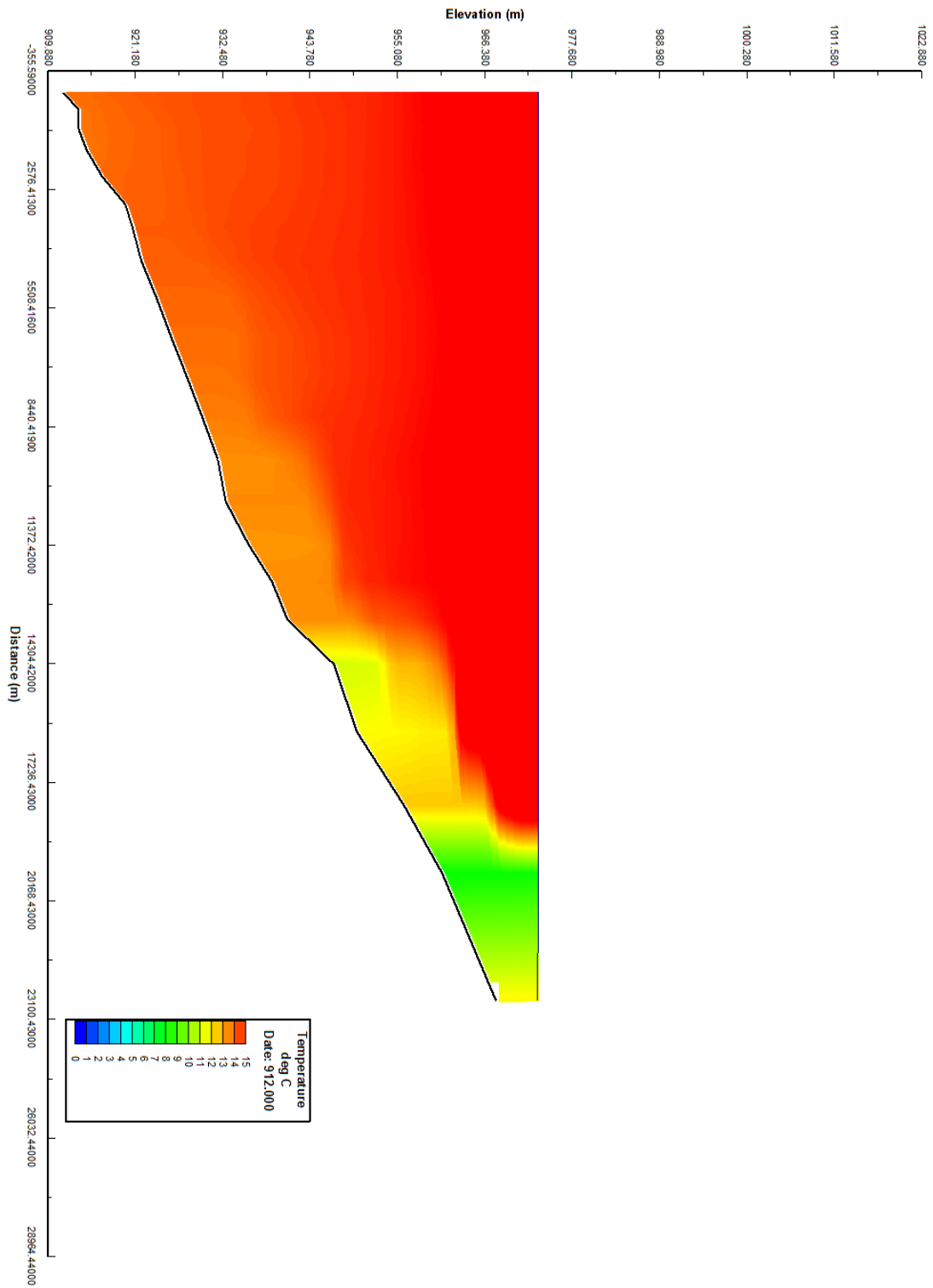


Figure 36: Simulated Arrowrock Reservoir temperature on 6/30/14.

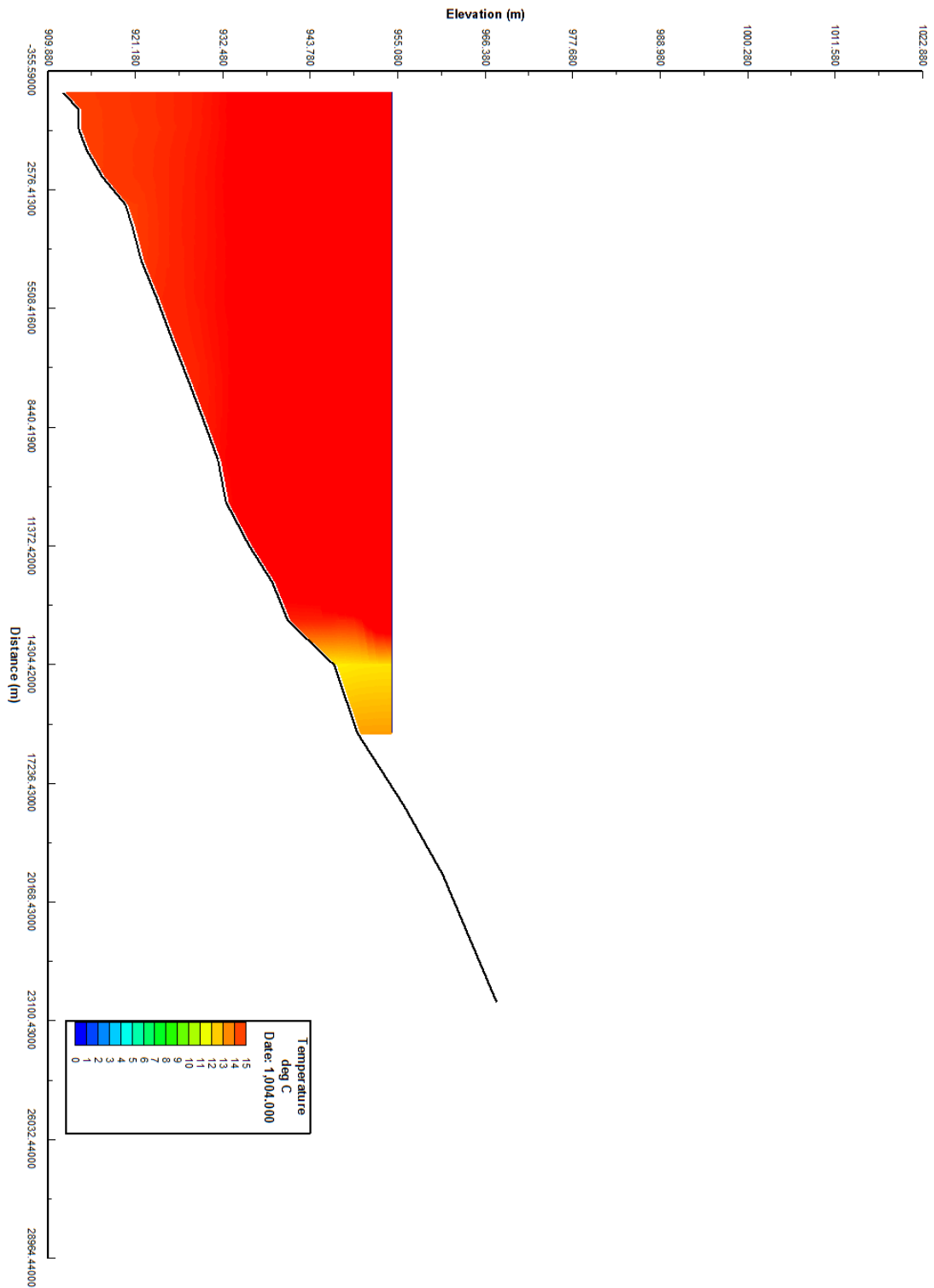


Figure 37: Simulated Arrowrock Reservoir temperature on 10/1/14.

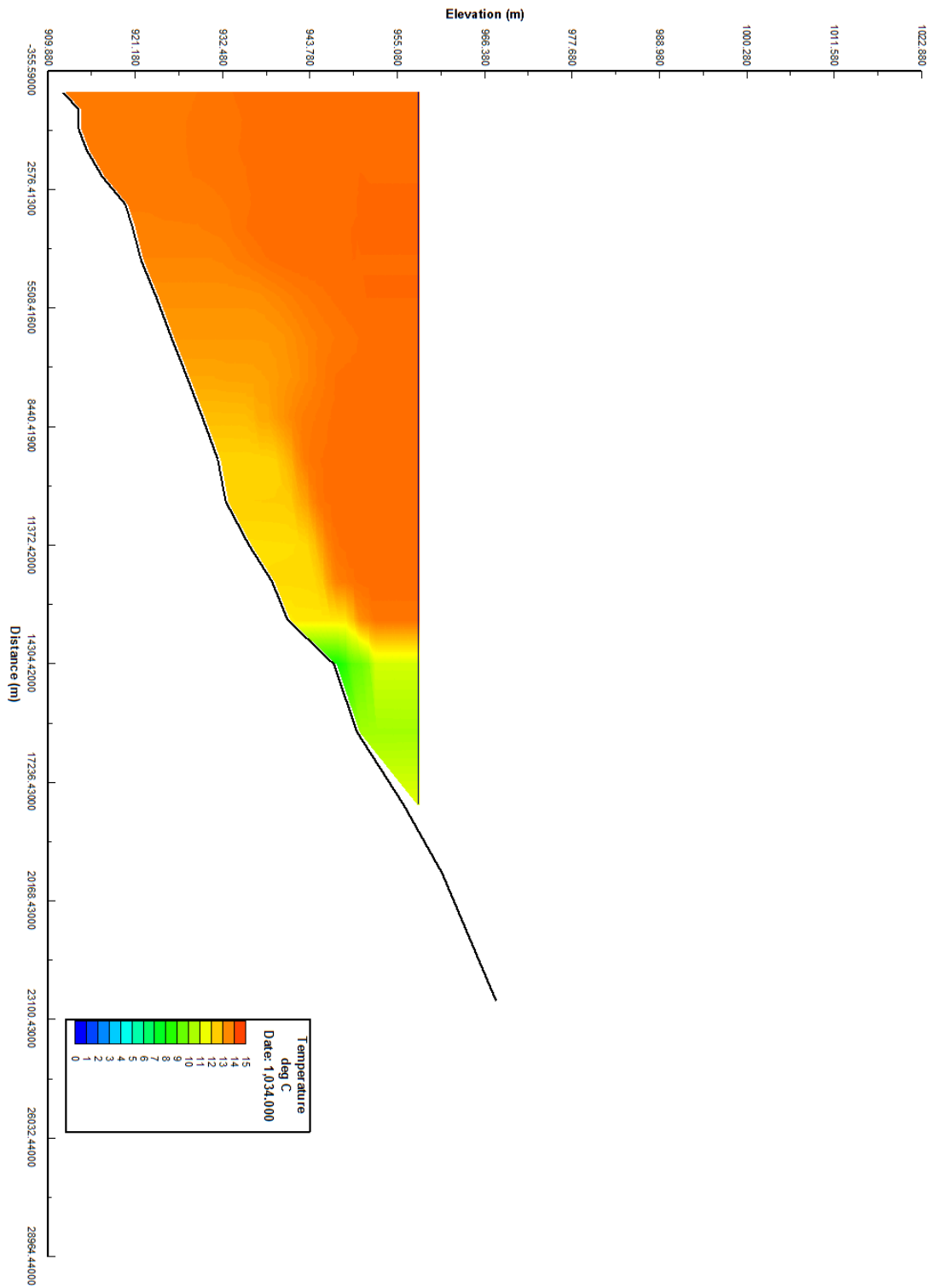


Figure 38: Simulated Arrowrock Reservoir temperature on 10/30/14.

3.1.2 Dissolved Oxygen and Chlorophyll-a

Compared to temperature simulation, the model did not perform quite as well in terms of its ability to simulate dissolved oxygen and chlorophyll-a profiles. Figure 39 through Figure 44 show a comparison of the simulated and observed profiles for dissolved oxygen and chlorophyll-a at ARR001, ARR002, and ARR003 along with the error statistics for that date shown in each panel margin. During the summer months, the model predicts chlorophyll-a concentrations sometimes two-times larger than what was observed. This also influences the model's ability to simulate dissolved oxygen and helps explain some of the error seen in the simulated dissolved oxygen profiles. Simulated dissolved oxygen profiles were calculated around 10 mg/L while summer observed values would fall towards 5 mg/L.

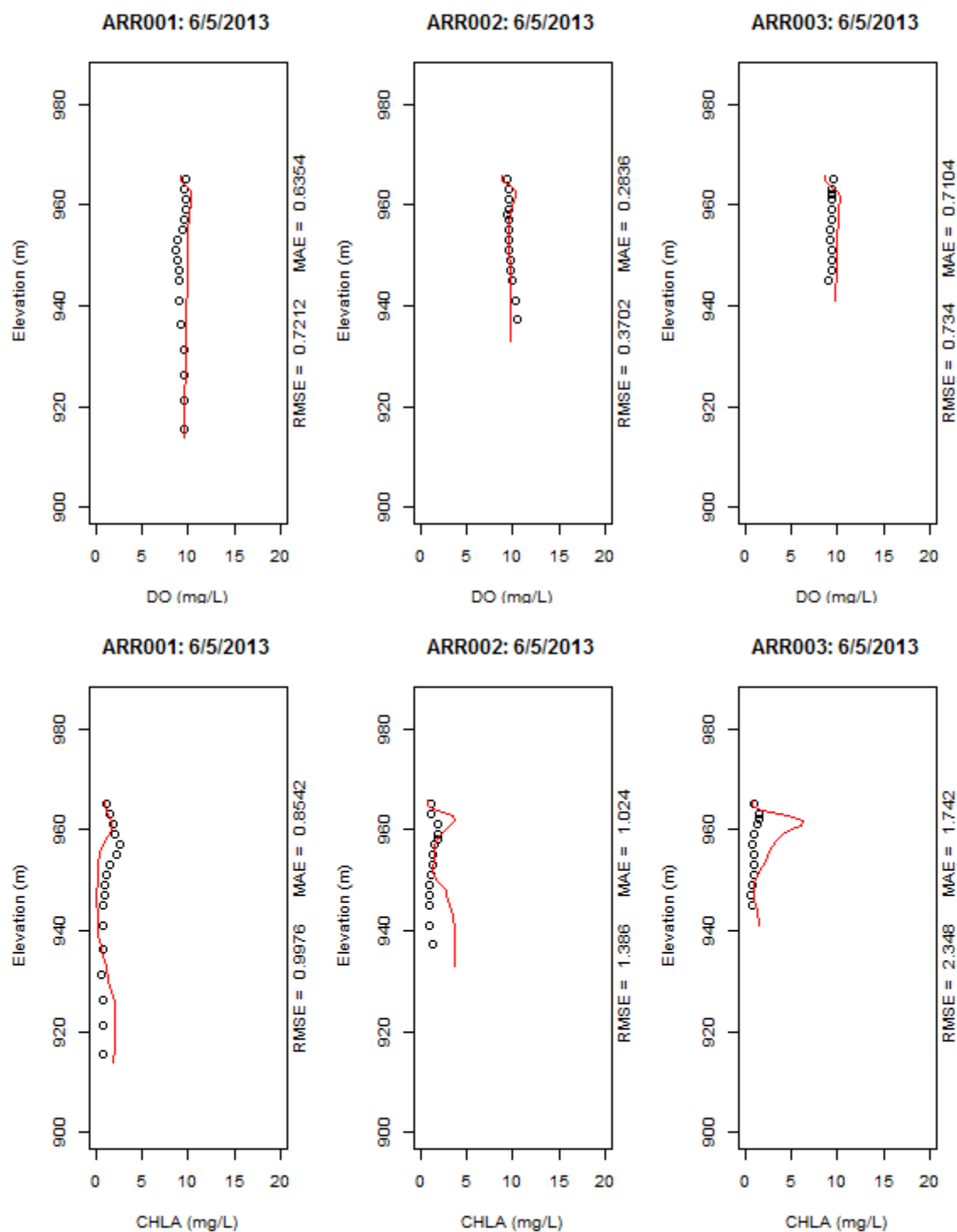


Figure 39: Observed (denoted by circles) and simulated (denoted by trend line) dissolved oxygen (top) and chlorophyll-a (bottom) concentrations at ARR001, ARR002, and ARR003 on 6/5/2013.

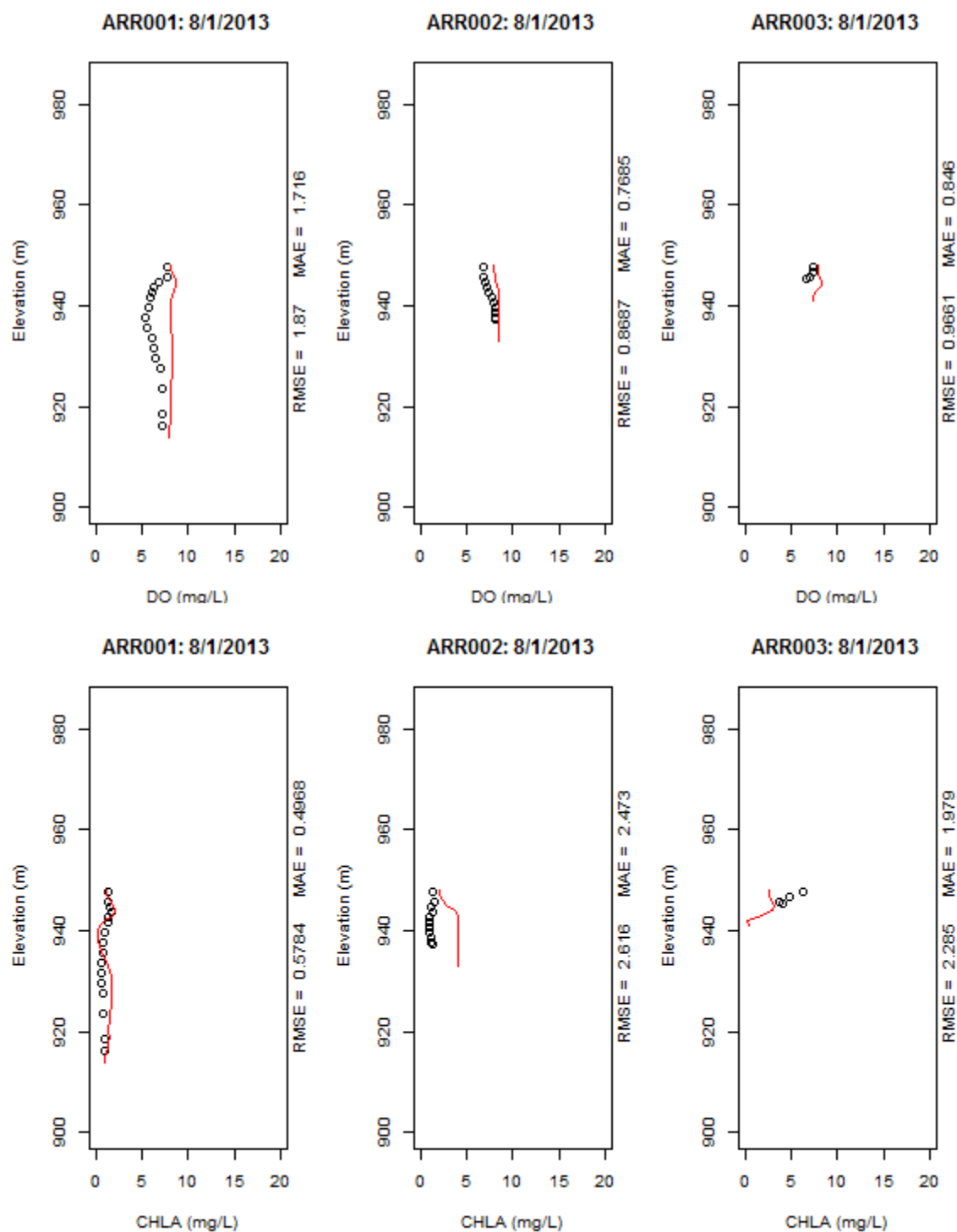


Figure 40: Observed (denoted by circles) and simulated (denoted by trend line) dissolved oxygen (top) and chlorophyll-a (bottom) concentrations at ARR001, ARR002, and ARR003 on 8/1/2013.

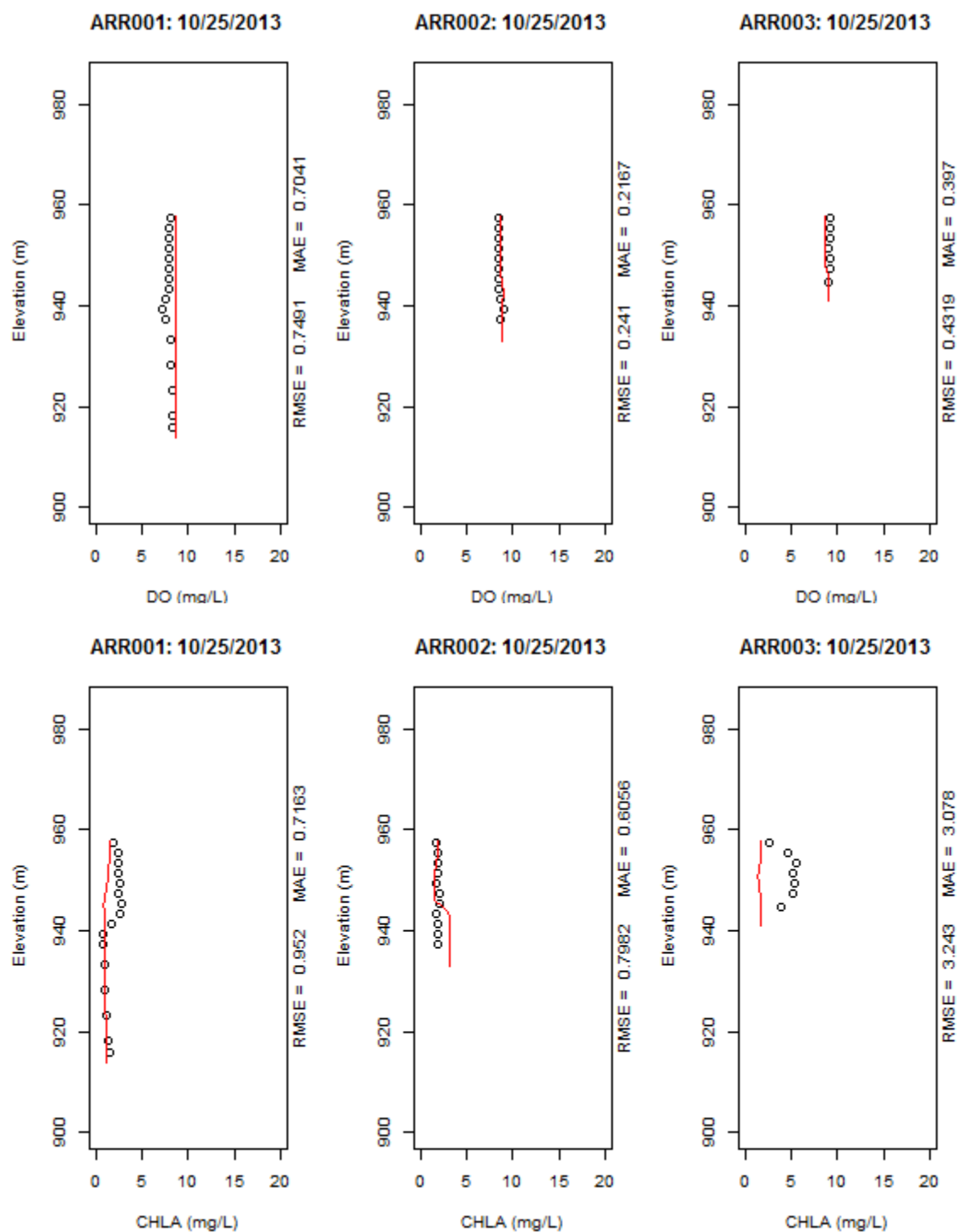


Figure 41: Observed (denoted by circles) and simulated (denoted by trend line) dissolved oxygen (top) and chlorophyll-a (bottom) concentrations at ARR001, ARR002, and ARR003 on 10/25/2013.

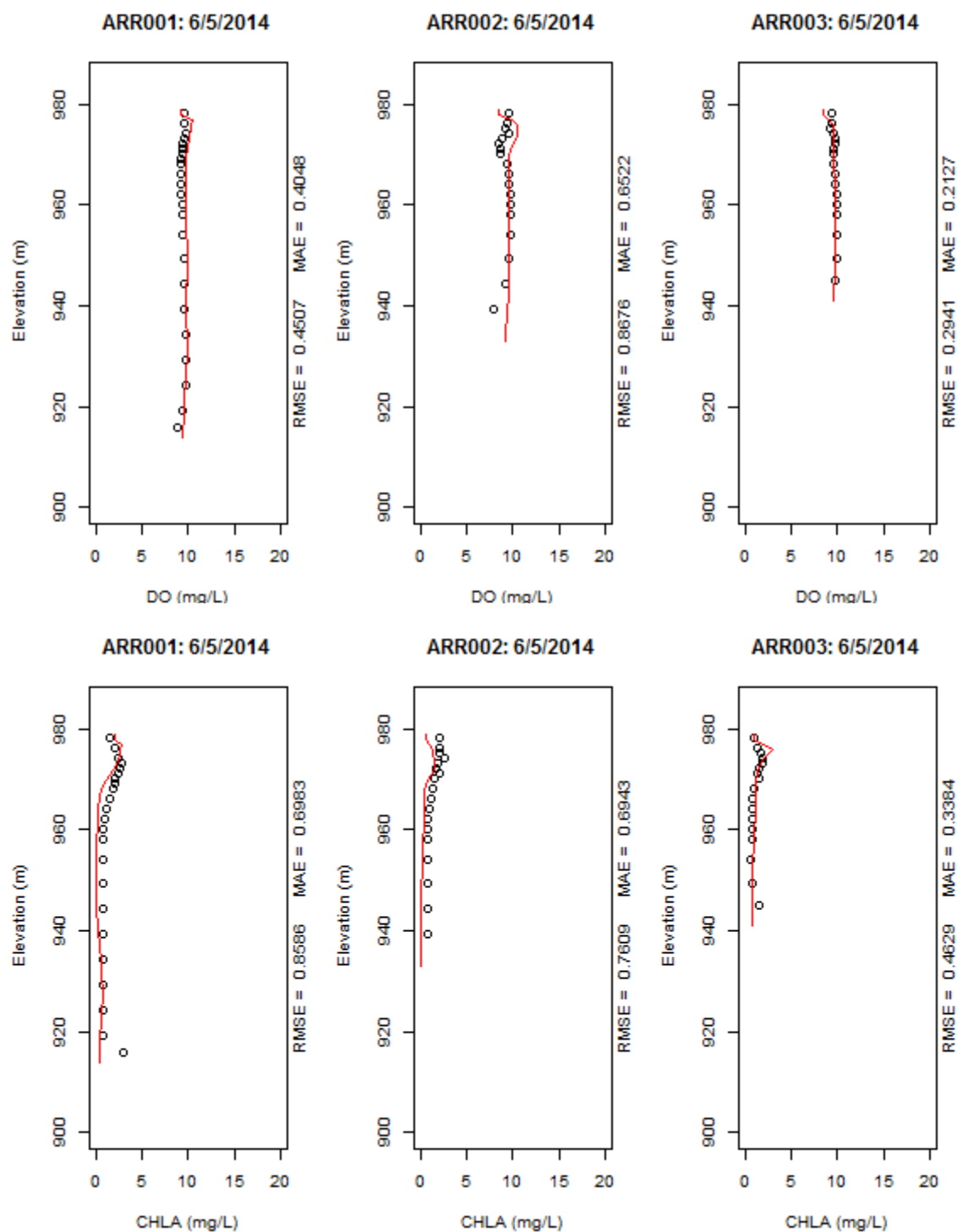


Figure 42: Observed (denoted by circles) and simulated (denoted by trend line) dissolved oxygen (top) and chlorophyll-a (bottom) concentrations at ARR001, ARR002, and ARR003 on 6/5/2014.

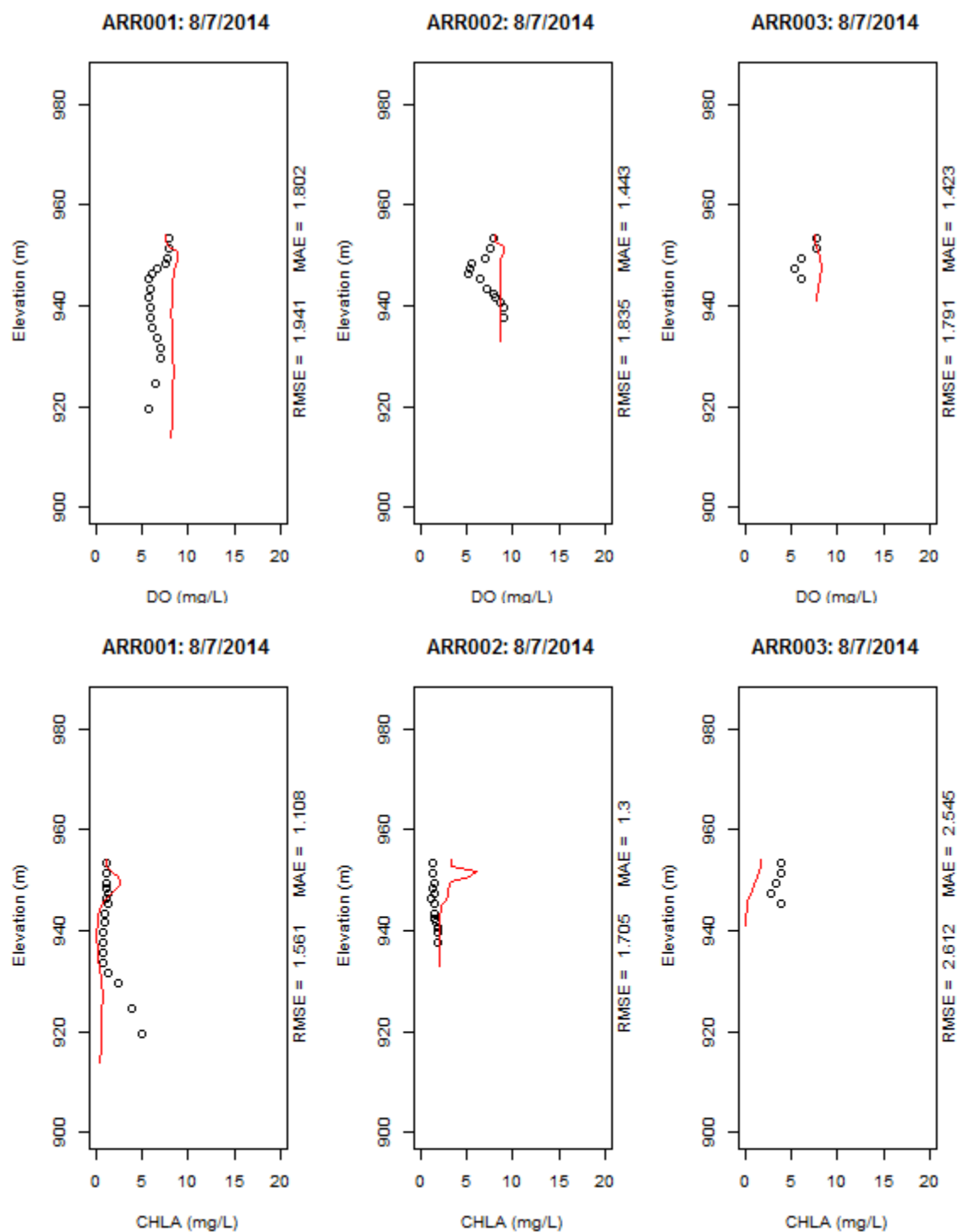


Figure 43: Observed (denoted by circles) and simulated (denoted by trend line) dissolved oxygen (top) and chlorophyll-a (bottom) concentrations at ARR001, ARR002, and ARR003 on 8/7/2014.

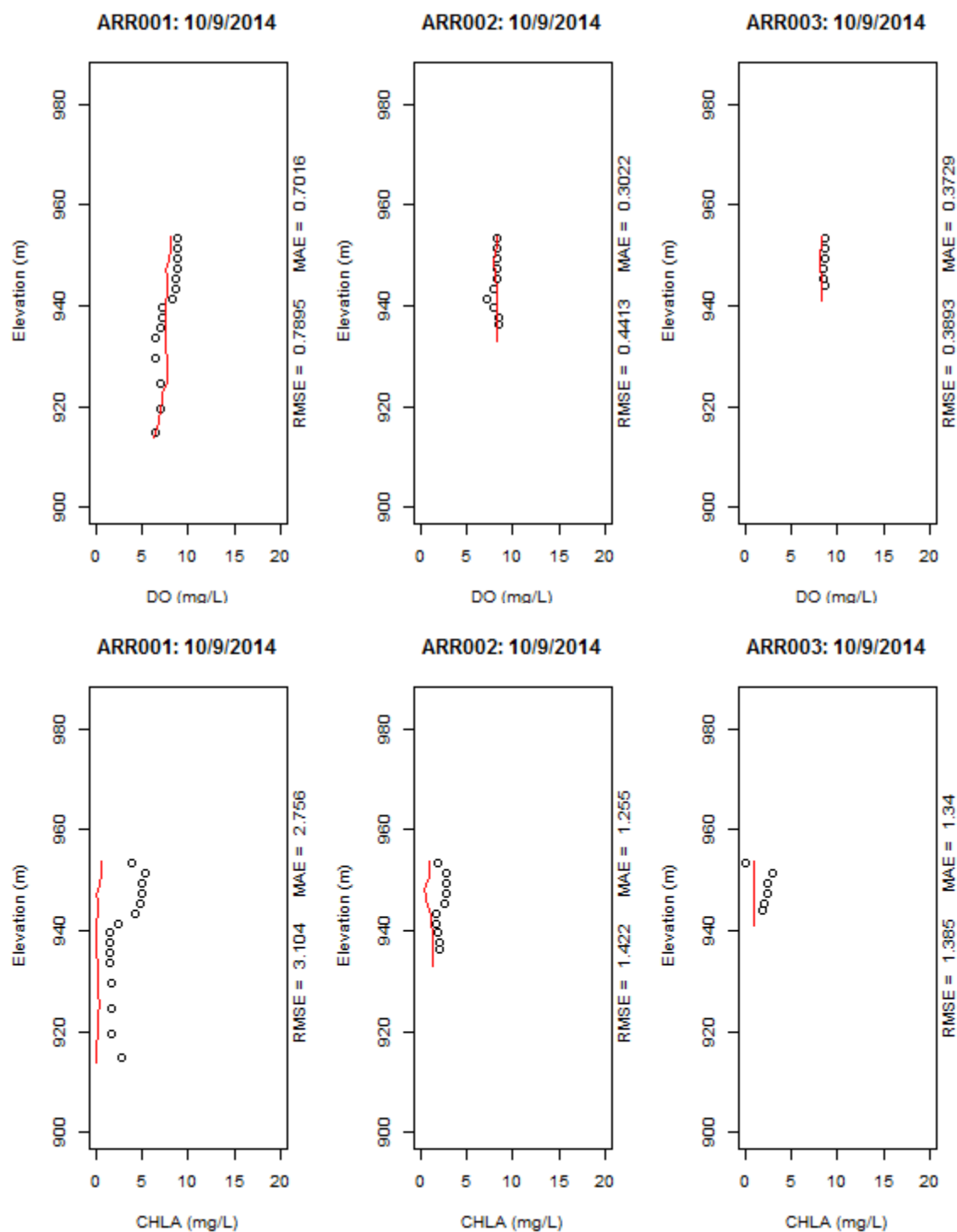


Figure 44: Observed (denoted by circles) and simulated (denoted by trend line) dissolved oxygen (top) and chlorophyll-a (bottom) concentrations at ARR001, ARR002, and ARR003 on 10/9/2014.

4 SCENARIO MODELING

Modeling the effects of operations on primary productivity and water temperatures within the reservoir will assist in addressing questions concerning the food base and thermal habitats for ESA listed aquatic species. Reservoir storage at the end of June was previously thought to determine productivity throughout the rest of the year (i.e. 200,000 AF at the end of June). Four scenarios were developed to help investigate this correlation. The first three scenarios leverage the fact that the two modeled years represent the opposing ends of the spectrum, with 2013 representing low-volume conditions (end of June storage observed at 114,735 AF) and 2014 representing high-volume conditions (end of June storage observed at 204,412 AF). These scenarios consisted of the following:

1. 2013 flow and volume conditions run with 2014 constituent inflow concentrations
2. 2014 flow and volume conditions run with 2013 constituent inflow concentrations
3. 2013 and 2014 with constituent concentrations held constant at their annual average value
4. 2013 outflow data modified to hold reservoir volume at 200,000 AF until the end of June

In many ways it does not make sense to decouple measured water quality concentrations from the corresponding hydrologic regime, because the concentration is largely dependent upon the amount of runoff and discharge in the river. However, when compared to one another, the results of these scenarios provide some insight into the relative importance of water quality boundary conditions and hydrologic regimes on summer/fall productivity.

4.1 Scenarios 1 and 2

These scenarios help illustrate the sensitivity of the model to small changes in nutrient concentration. In the first scenario, the 2013 season was run using 2014 water quality data at all inflow locations, while in the second scenario the 2014 season was run using 2013 water quality data. As shown in Figure 46, productivity was slightly reduced on all dates compared to the baseline condition however the differences fell within the range of model error. The second scenario showed similar results, but with slight increases in productivity compared to the baseline condition (Figure 47).

In the second scenario, 2014 water quality data was substituted for 2013 data at all inflow locations. On all dates, productivity was slightly increased compared to the baseline condition however the differences were insignificant compared to the model error in simulating Chlorophyll-a.

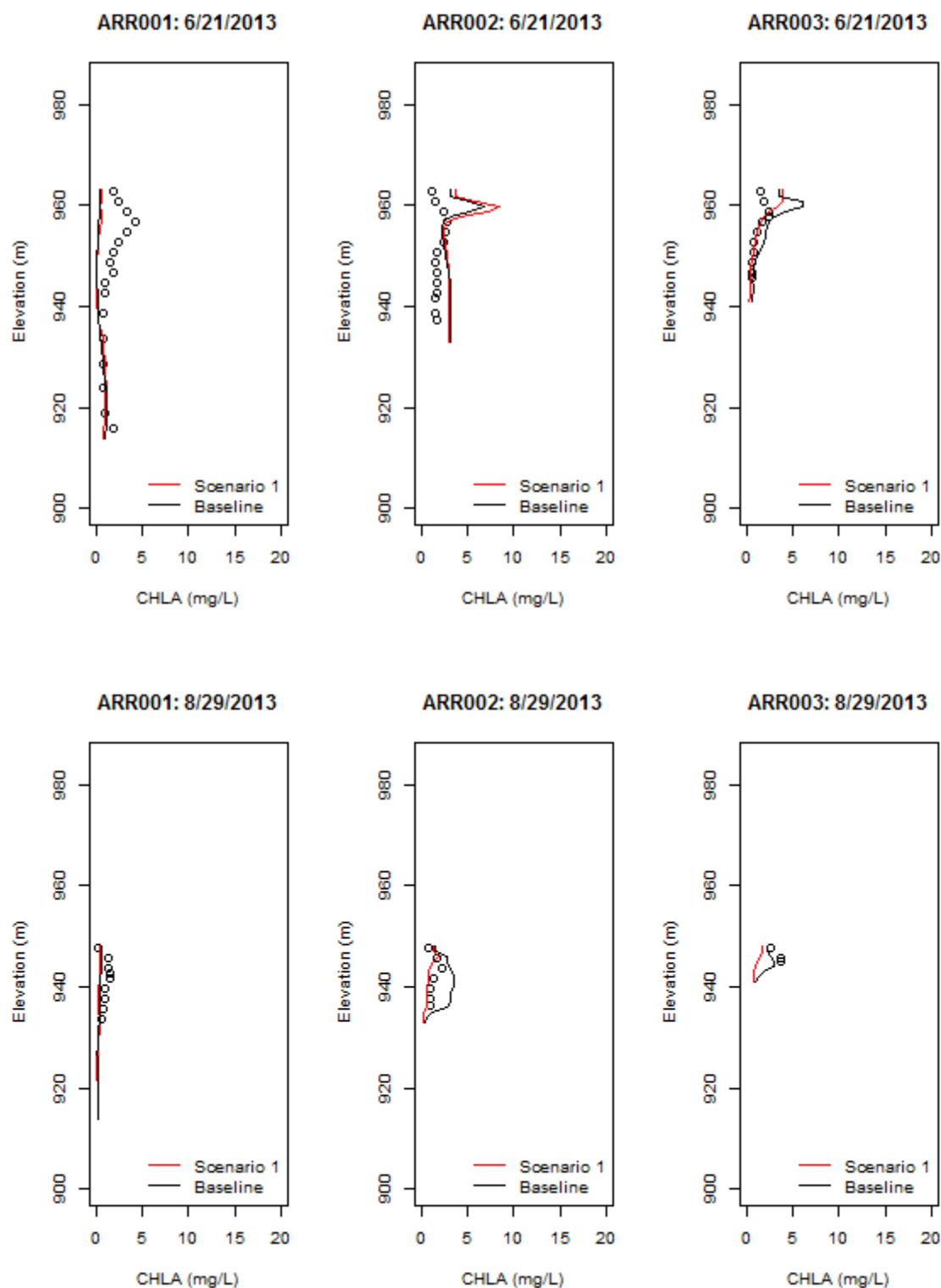


Figure 45: Observed (denoted by circles), simulated baseline (denoted by black line), and scenario 1 results (denoted by red line) chlorophyll-a concentrations at ARR001, ARR002, and ARR003 for 6/21/2013 and 8/29/2013.

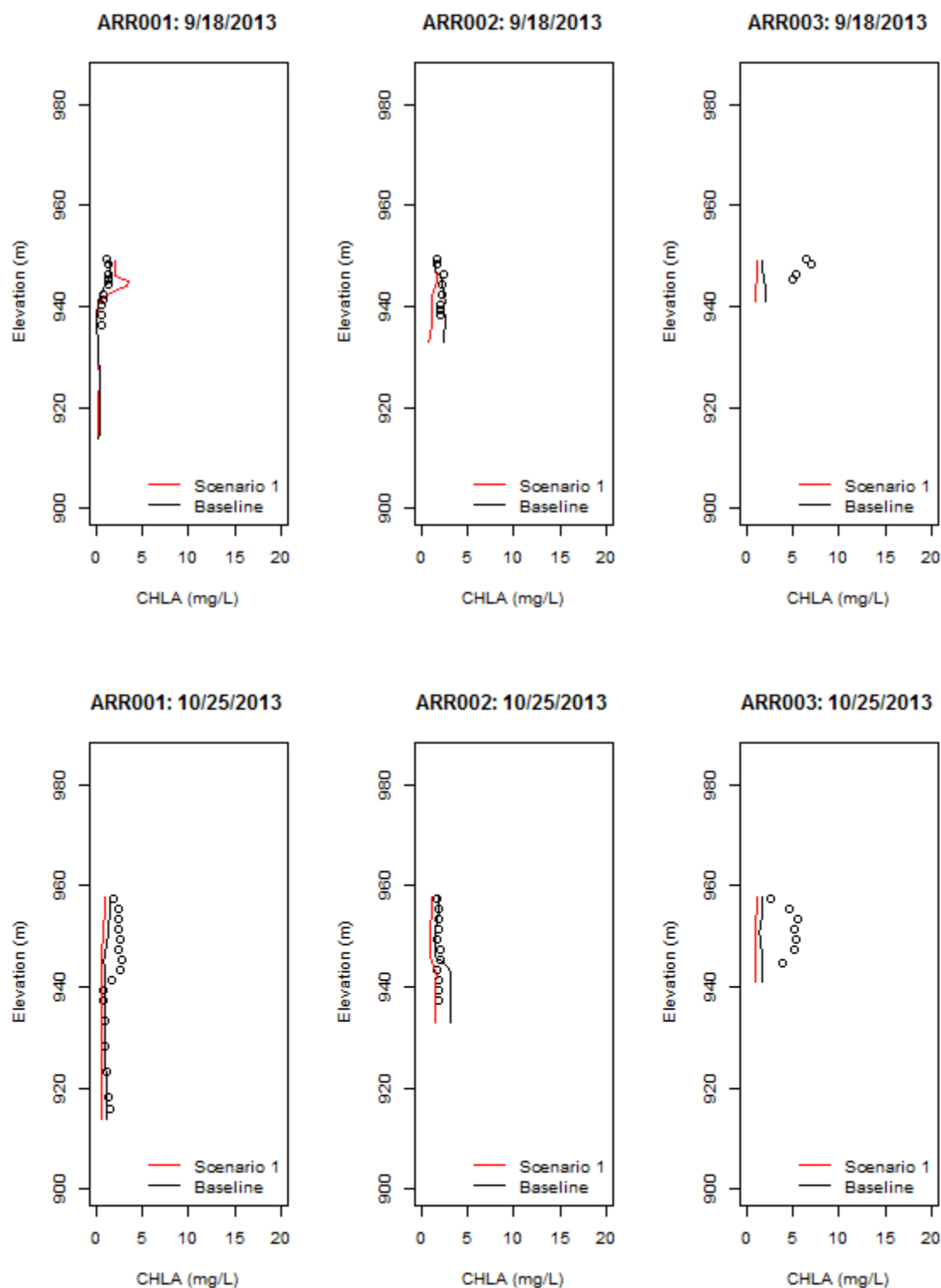


Figure 46: Observed (denoted by circles), simulated baseline (denoted by black line), and scenario 1 results (denoted by red line) chlorophyll-a concentrations at ARR001, ARR002, and ARR003 for 9/18/2013 and 10/25/2013.

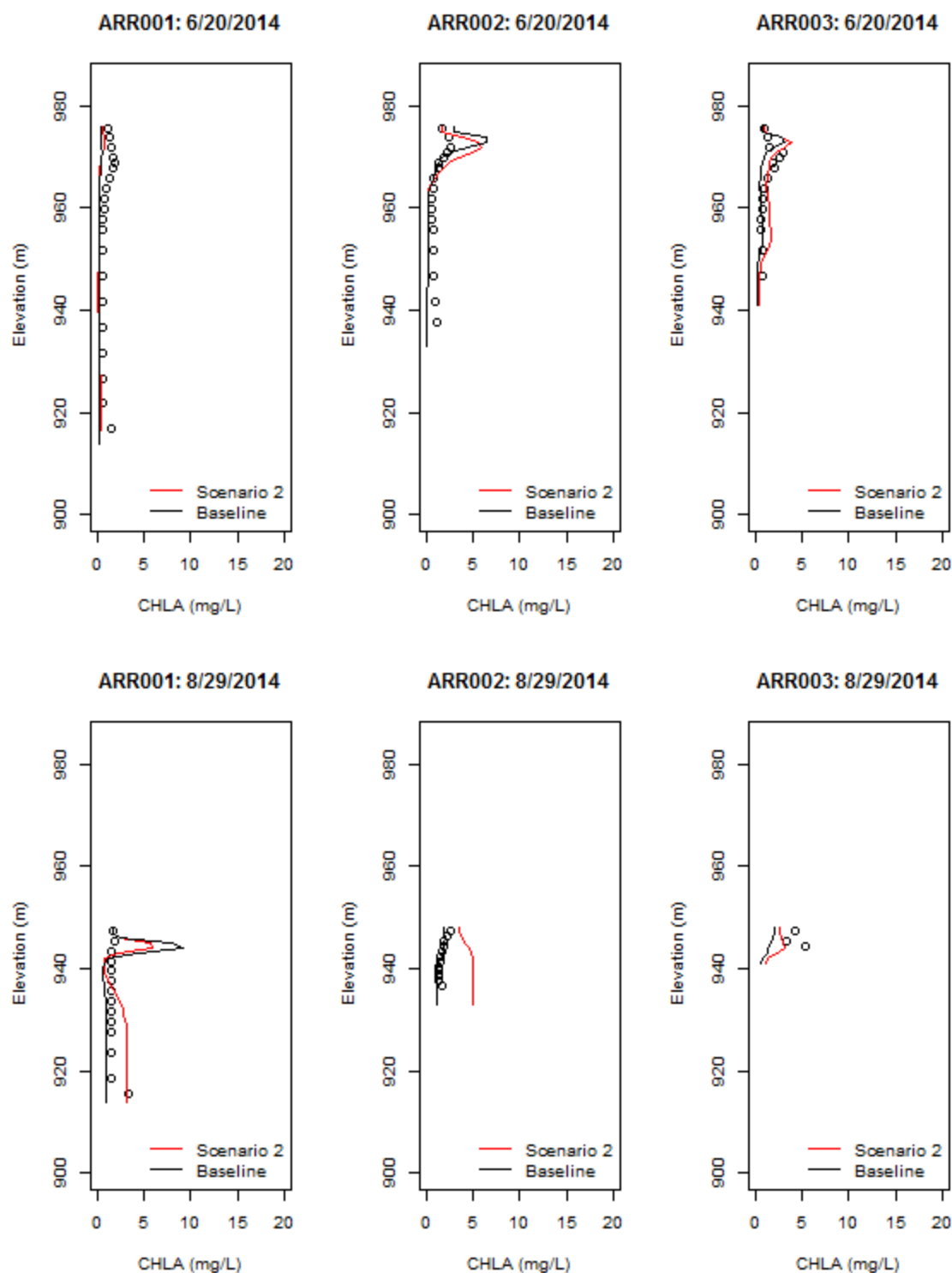


Figure 47: Observed (denoted by circles), simulated baseline (denoted by black line), and scenario 2 results (denoted by red line) chlorophyll-a concentrations at ARR001, ARR002, and ARR003 for 6/20/2014 and 8/29/2014.

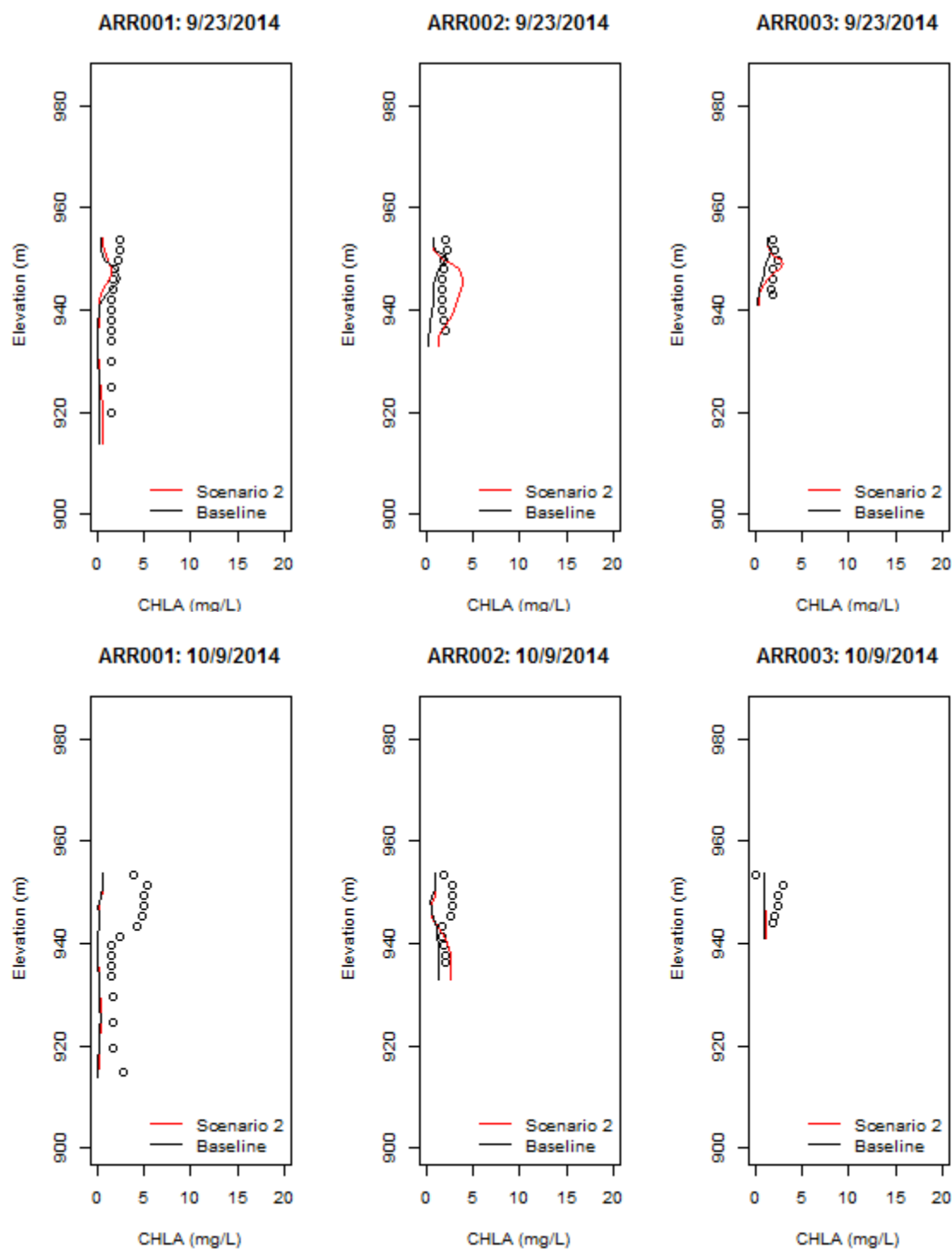


Figure 48: Observed (denoted by circles), simulated baseline (denoted by black line), and scenario 2 results (denoted by red line) chlorophyll-a concentrations at ARR001, ARR002, and ARR003 for 9/23/2014 and 10/9/2014.

4.2 Scenario 3

In this scenario water quality constituent concentrations were held constant throughout the simulation period. This scenario helps to isolate the influence of the differing 2013 and 2014 hydrologic/temperature regimes (including end of June reservoir storage volume) on productivity in Arrowrock Reservoir. Figure 49 and Figure 50 illustrate the results of this scenario.

Generally, 2013 and 2014 profiles were nearly identical suggesting that hydrologic regime may not be as influential on algae concentrations as was previously thought. When compared in terms of depth from the surface, rather than elevation, concentrations were almost identical between the two years. And while the higher volumes in 2014 would correspond to a greater total amount of algae, these greater numbers do not appear to influence the concentrations later in the season when the 2013 and 2014 volumes are roughly equal.

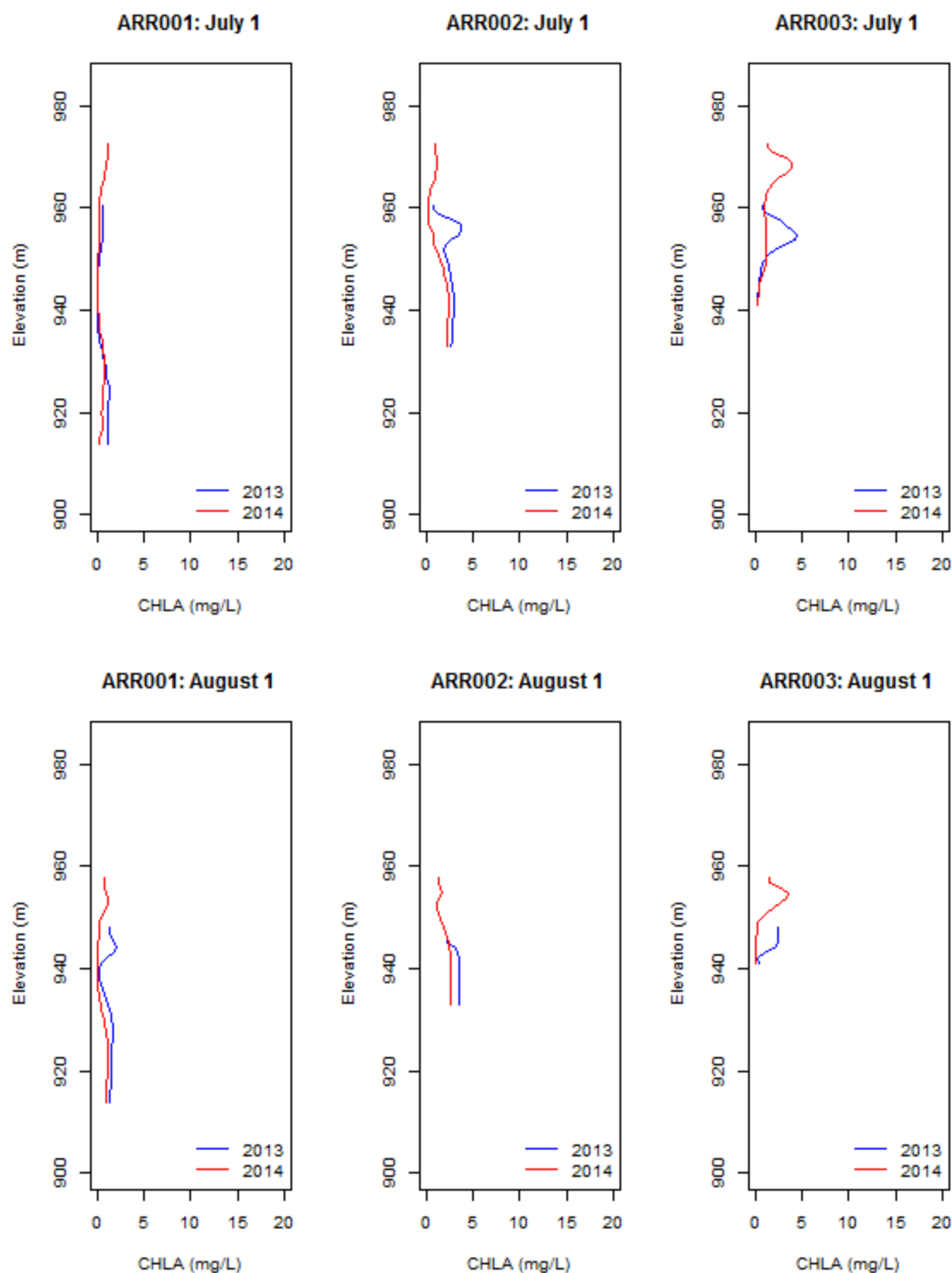


Figure 49: Scenario 3 Arrowrock Reservoir chlorophyll-a concentration profiles on July 1 and August 1 near Arrowrock Dam (ARR001), near the confluence of the South Fork Boise River (ARR002), and near the confluence of the Middle Fork Boise River (ARR003).

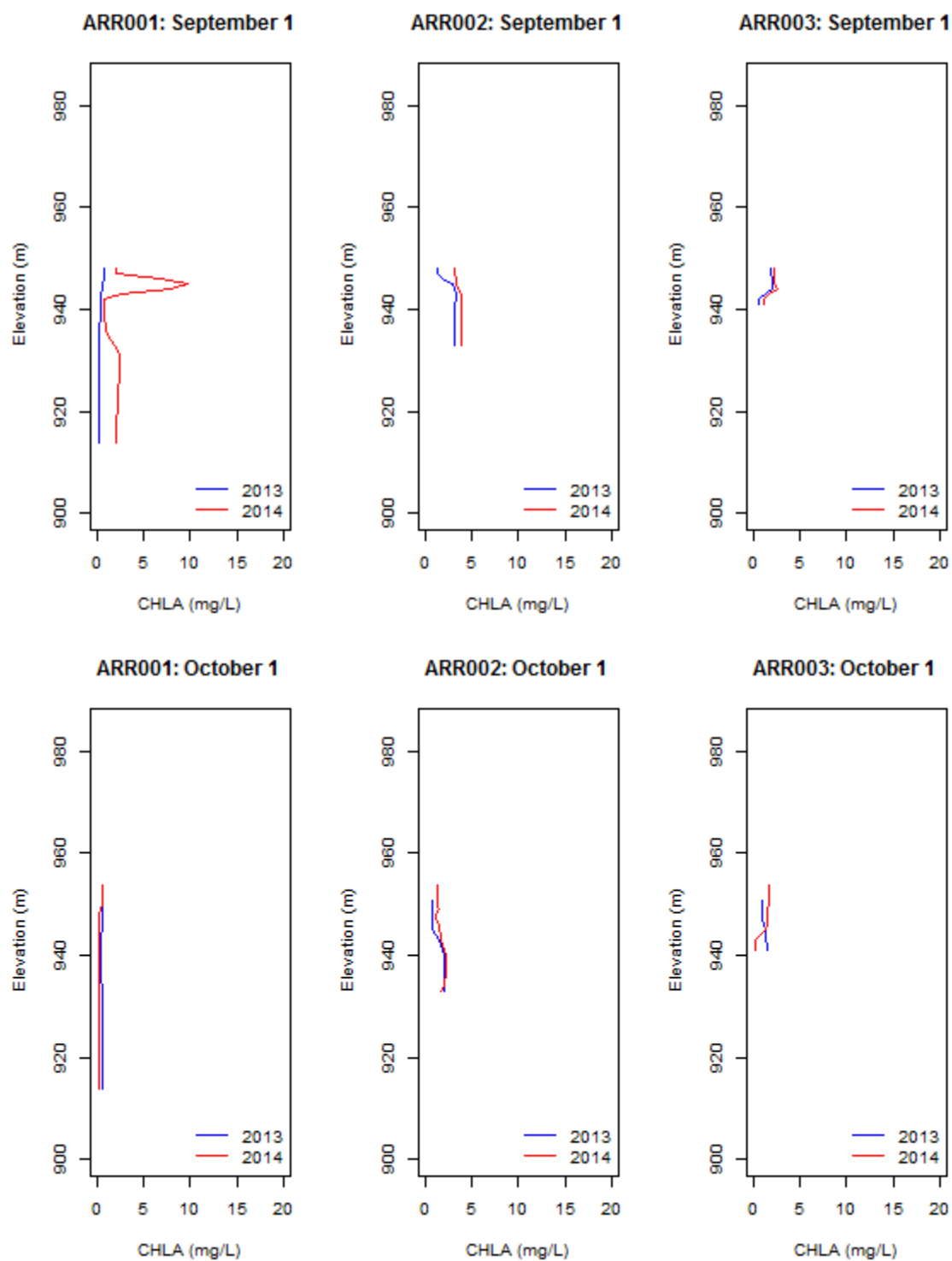


Figure 50: Scenario 3 Arrowrock Reservoir chlorophyll-a concentration profiles on September 1 and October 1 near Arrowrock Dam (ARR001), near the confluence of the South Fork Boise River (ARR002), and near the confluence of the Middle Fork Boise River (ARR003).

4.3 Scenario 4

In this scenario, outflow data for the 2013 simulation year was modified such that the volume of the reservoir would not drop below 200,000 AF before June 30. This was accomplished by simply setting the outflow values from April 25 (the date the reservoir reaches 200,000 AF) through June 30 to equal the sum of all inflows, thus holding the volume steady until the end of June. It is important to note that this scenario is an “unreal scenario” and did not take into account any real world operational objectives such as flood control or irrigation requirements. It is simply a look at the effect that a larger end of June storage volume might have on reservoir productivity through the summer and fall months. As depicted in Figure 51 and Figure 52, end of summer productivity does not appear to be influenced by the increased end of June storage volume. Figure 53 further supports this finding and illustrates the simulated algae and zooplankton biomass for 2013 in both the Baseline model and the Scenario 4 model. While the modified outflow regime does influence the timing of biomass fluctuations, biomass concentrations from each model are roughly equal by September.

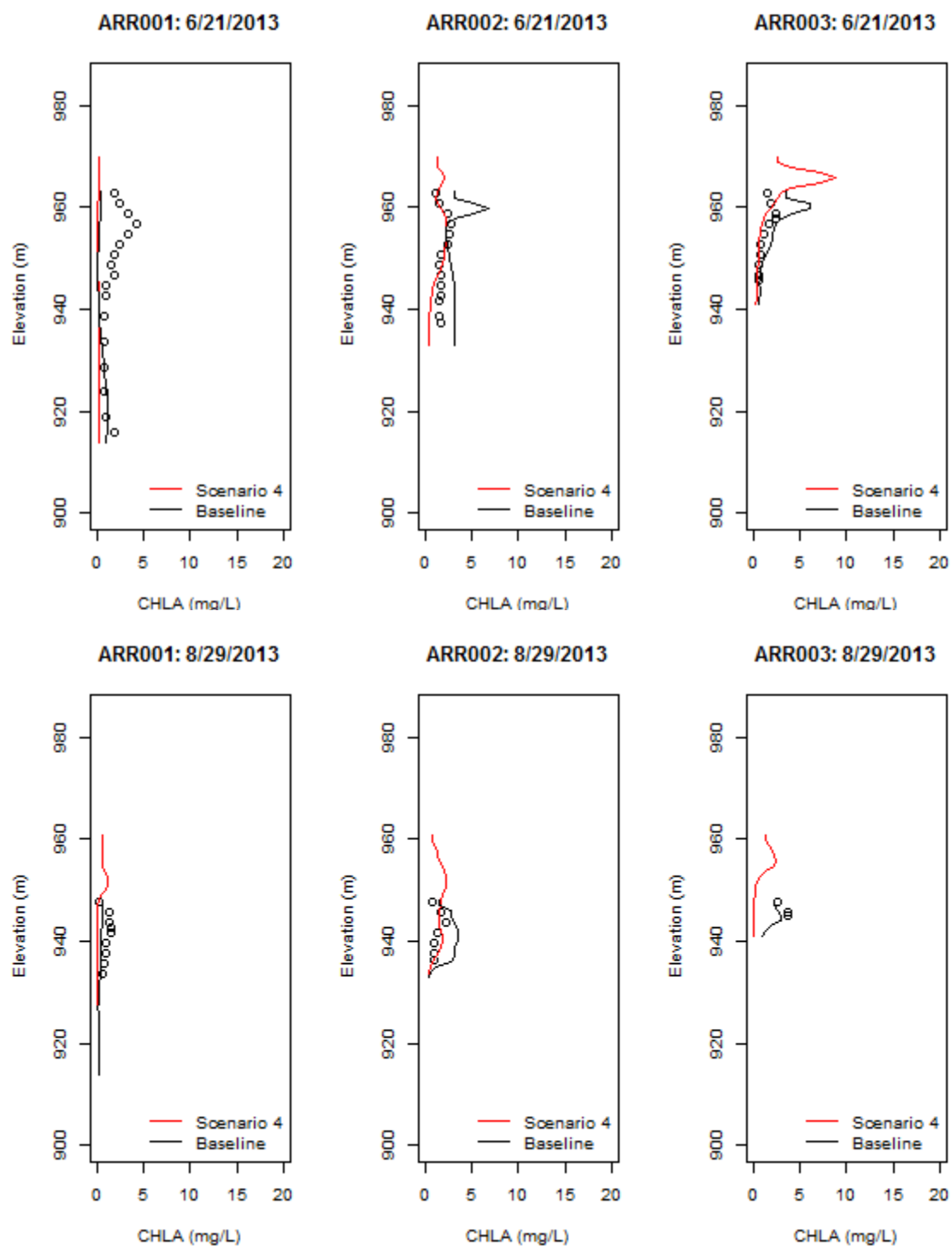


Figure 51: Observed (denoted by circles), simulated baseline (denoted by black line), and scenario 4 results (denoted by red line) chlorophyll-a concentrations at ARR001, ARR002, and ARR003 for 6/21/2013 and 8/29/2013.

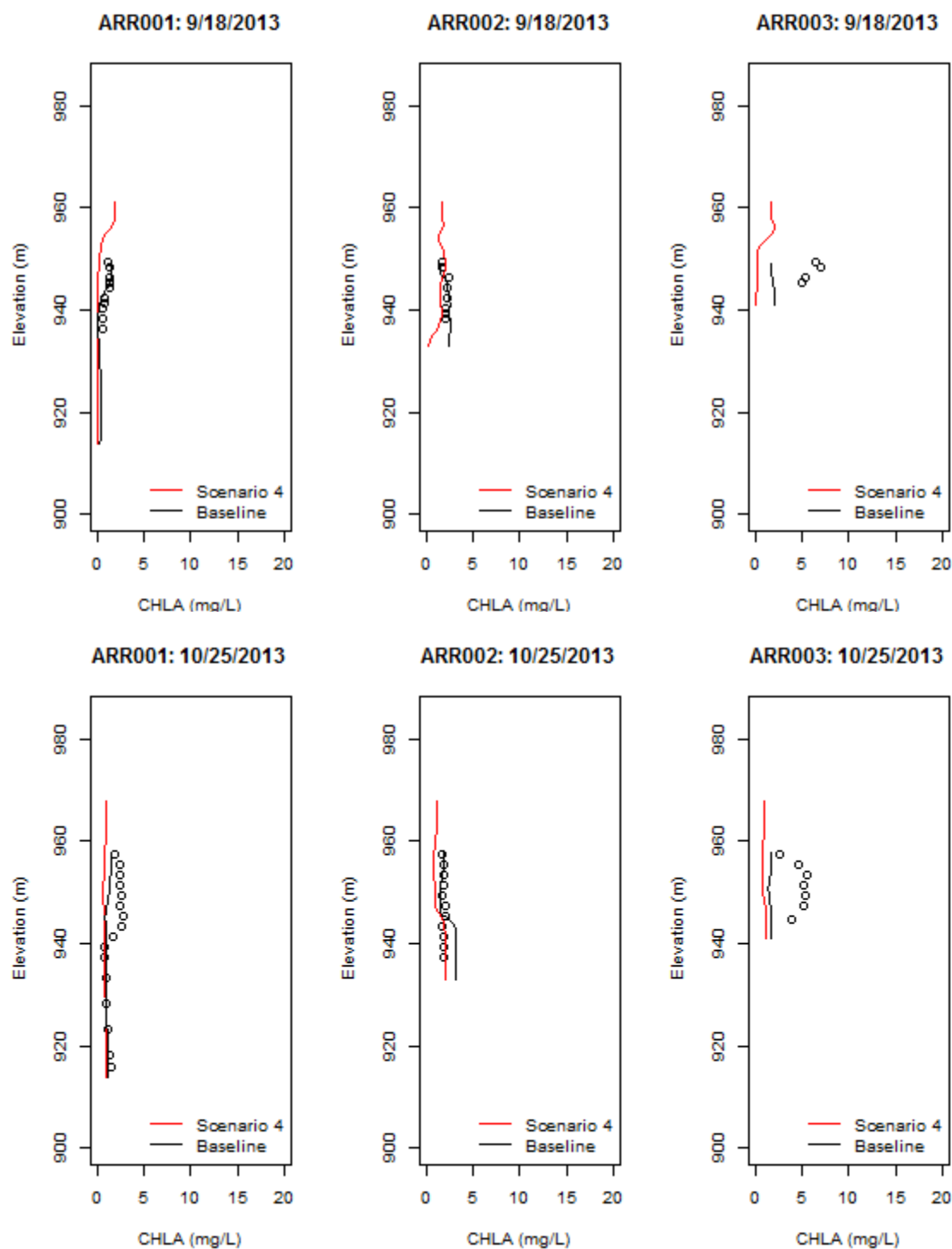


Figure 52: Observed (denoted by circles), simulated baseline (denoted by black line), and scenario 4 results (denoted by red line) chlorophyll-a concentrations at ARR001, ARR002, and ARR003 for 9/18/2013 and 10/25/2013.

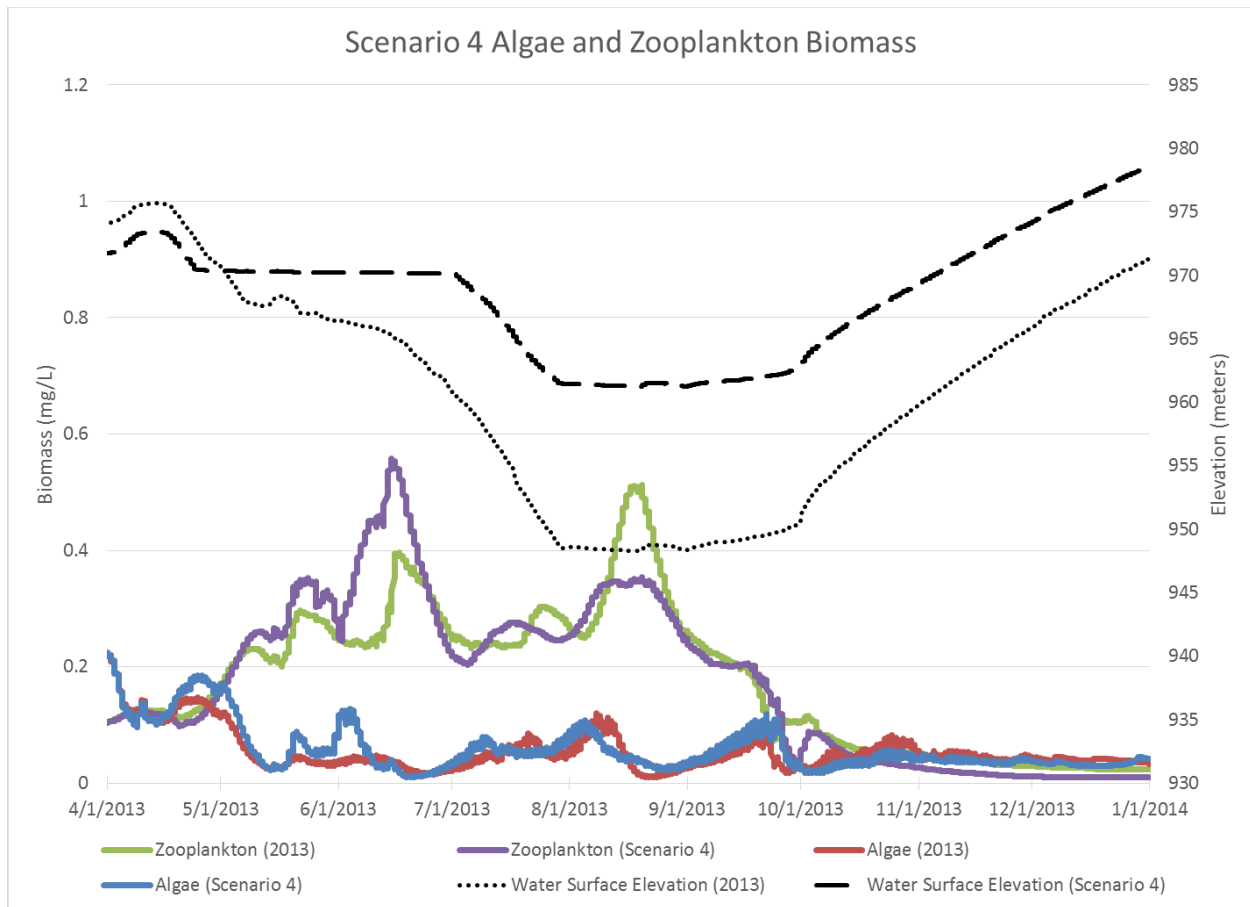


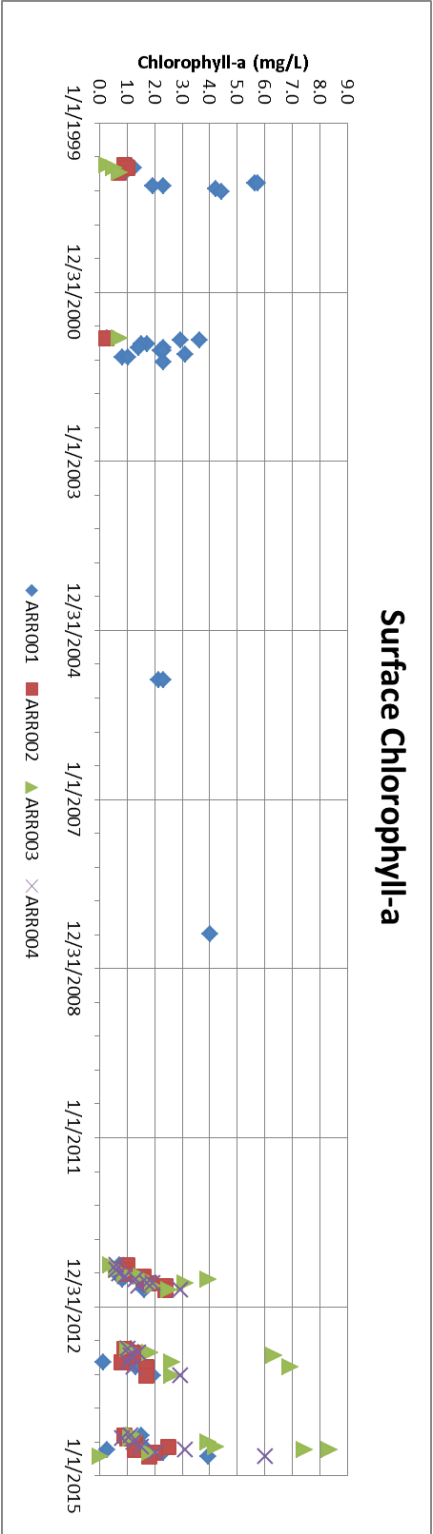
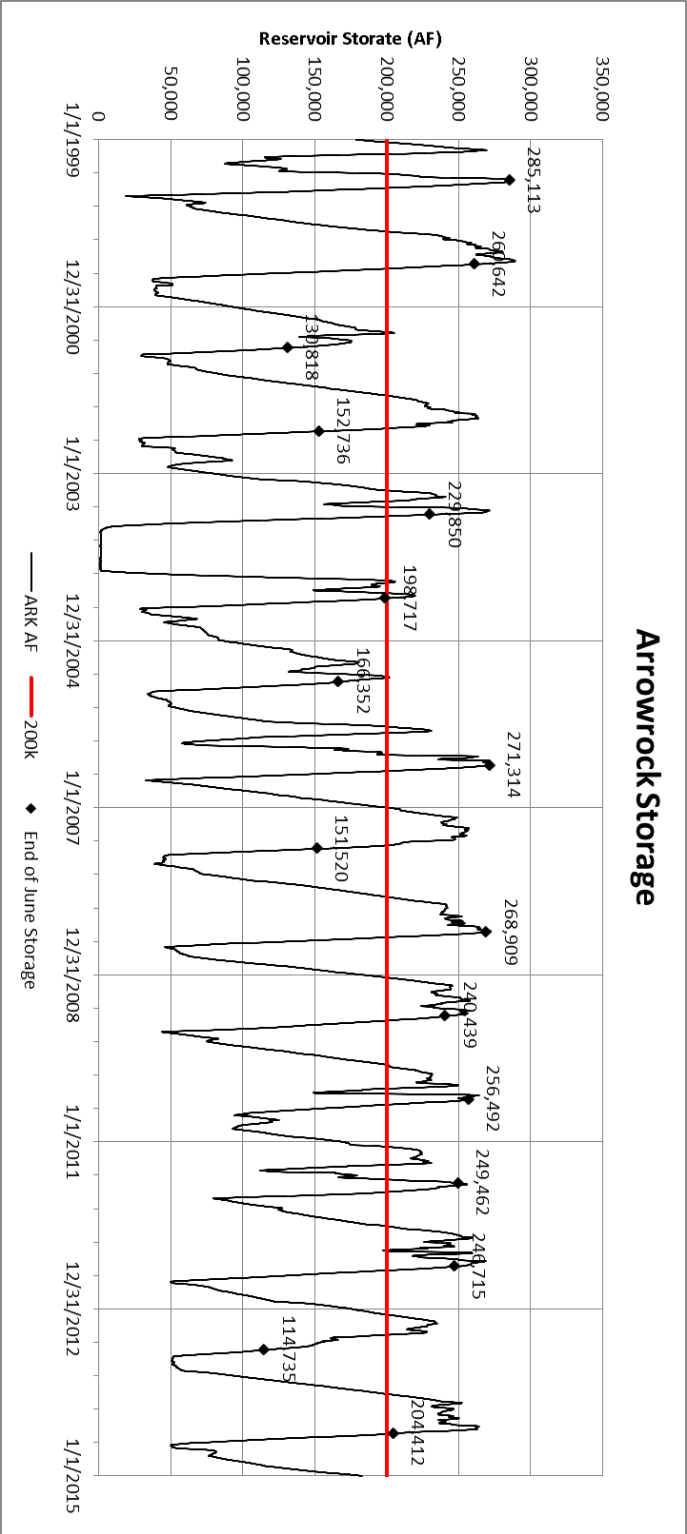
Figure 53: 2013 algae (red and blue lines) and zooplankton (green and purple lines) biomass concentrations as simulated by the Baseline and Scenario 4 model runs. Reservoir surface elevations for each model run are provided for reference.

5 CONCLUSIONS

The results of this study suggest that end of June reservoir storage does not significantly influence reservoir productivity throughout the remainder of the year. These results are further supported by an investigation of chlorophyll-a measurements collected from 1999 through 2014, which identify little or no correlation between end of June storage volume and chlorophyll-a concentrations. Plots for this analysis are included in the appendix.

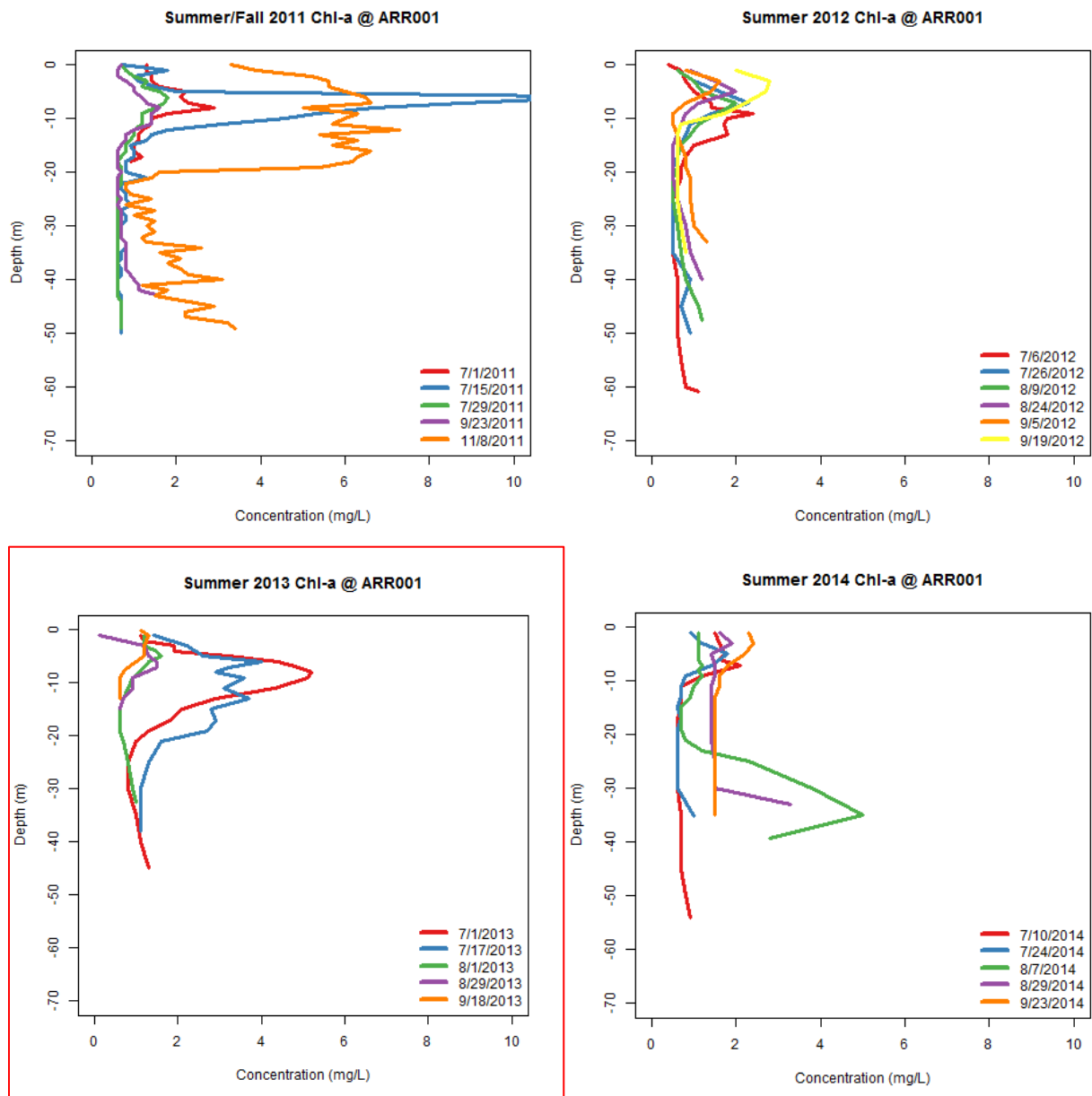
6 OTHER RESOURCES

| Parenthetical Reference | Bibliographic Citation |
|----------------------------|--|
| Reclamation 2003 | Bureau of Reclamation. 2003. Two-Dimensional Water Quality Modeling of Arrowrock Reservoir. Prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado. September 2003. |
| Essington 2004 | Essington, Michael E. 2004. <i>Soil and Water Chemistry: An Integrative Approach</i> . CRC Press LLC, 2000 N.W. Corporate Blvd., Boca Raton, Florida 33431. Pp. 504. |
| Gustafson and Behrman 1939 | Gustafson, H. and Behrman, A.S. 1939. Determination of Total Dissolved Solids in Water by Electrical Conductivity. <i>Ind. Eng. Chem. Anal. Ed.</i> 11 (7), pp 355-357. |
| Cole and Wells 2011 | Cole, T. and Wells, S. 2011. CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.7. Department of Civil and Environmental Engineering, Portland State University, Portland, Oregon. |
| USGS 2011 | Sullivan, A.B., Rounds, S.A., Deas, M.L., Asbill, J.R., Wellman, R.E., Stewart, M.A., Johnston, M.W., and Sogutlugil, I.E. 2011. Modeling Hydrodynamics, Water Temperature, and Water Quality in the Klamath River Upstream of Keno Dam, Oregon, 2006-09: U.S. Geological Survey Scientific Investigations Report 2011-5015, 70 p. |



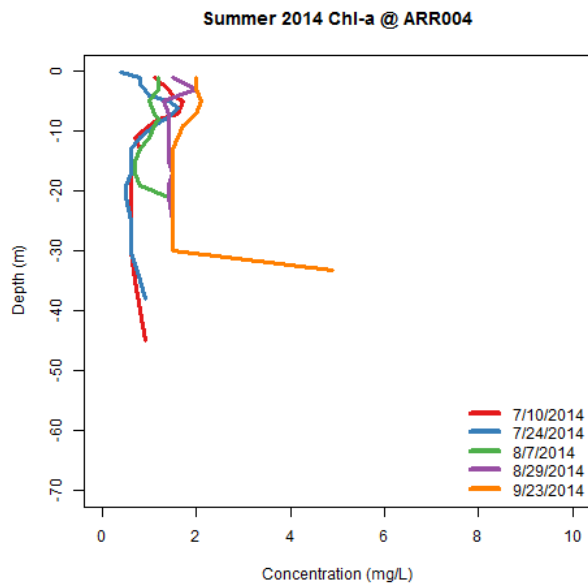
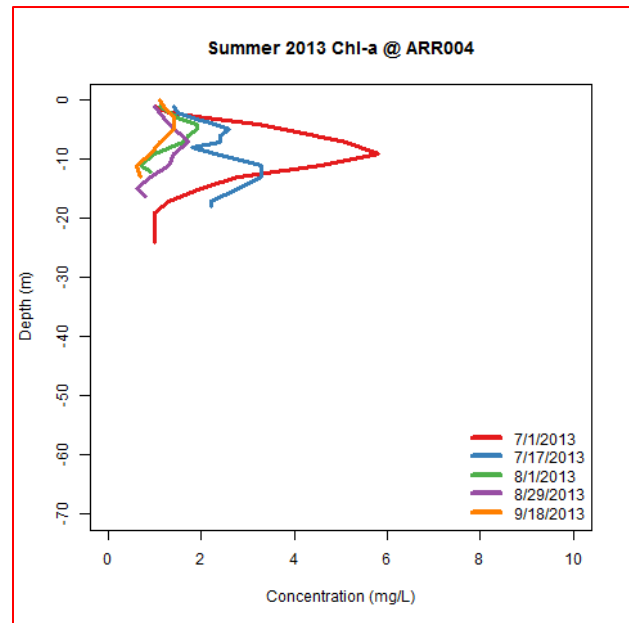
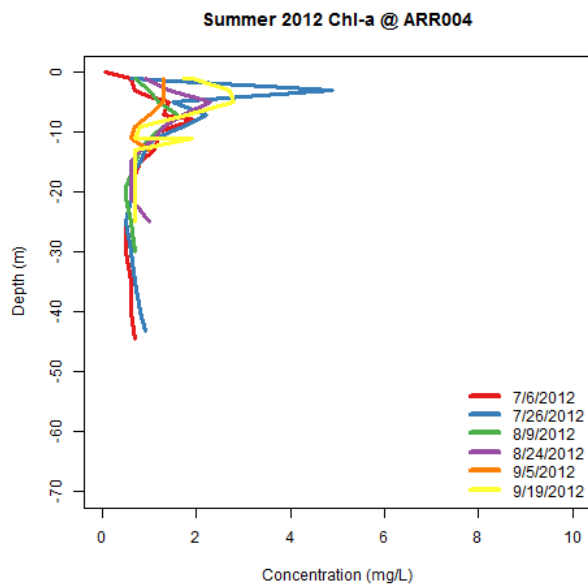
| | End of June Storage |
|-----------|------------------------|
| 6/30/1999 | 285,113 |
| 6/30/2000 | 260,642 |
| 6/30/2001 | 130,818 |
| 6/30/2002 | 152,736 |
| 6/30/2003 | 229,850 |
| 6/30/2004 | 198,717 |
| 6/30/2005 | 166,352 |
| 6/30/2006 | 271,314 |
| 6/30/2007 | 151,520 |
| 6/30/2008 | 268,909 |
| 6/30/2009 | 240,439 |
| 6/30/2010 | 256,492 |
| 6/30/2011 | 249,462 |
| 6/30/2012 | 246,715 |
| 6/30/2013 | 114,735 |
| 6/30/2014 | 204,412 |

ARR001 Observed Summer/Fall Chlorophyll-a Profiles²



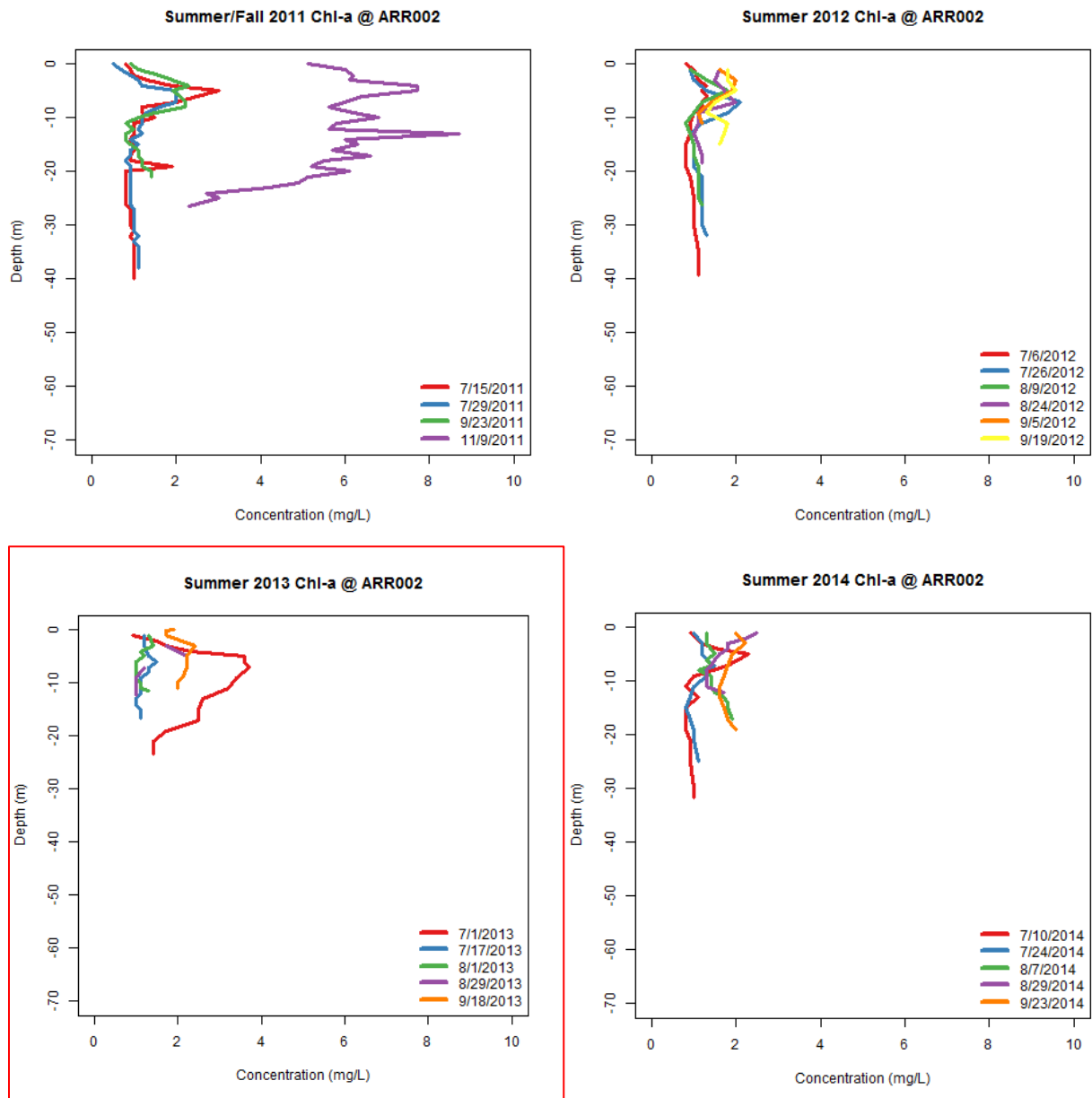
² Red box indicates year where end of June storage was less than 200,000 AF.

ARR004 Observed Summer/Fall Chlorophyll-a Profiles³



³ Data collection at ARR004 began in 2012. Red box indicates year where end of June storage was less than 200,000 AF.

ARR002 Observed Summer/Fall Chlorophyll-a Profiles⁴



⁴ Red box indicates year where end of June storage was less than 200,000 AF.

ARR003 Observed Summer/Fall Chlorophyll-a Profiles

