APPENDIX G

Water Quality Modeling of Miramar Reservoir in Support of Assessment of Nutrients and Productivity

FINAL

Task #: Kleinfelder Contract # H166753

Task Name: Water Quality Modeling of Miramar Reservoir in Support of Assessment of Nutrients and Productivity

Prepared For:

City of San Diego

Public Utilities Department

San Diego, California

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Project Title: Water Quality Modeling of Miramar Reservoir in Support of Assessment of Nutrients and Productivity

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1. Summary

1.1 Background

1.1.1 Reservoir Background

Miramar Reservoir (MR) (**Figure 1.1**), located in the Scripps Ranch community of San Diego, is owned, operated and maintained by the City of San Diego (City). The reservoir is adjacent to Miramar Water Treatment Plant (WTP), which serves the northern part of the City. MR has a maximum depth of 114 feet (ft) and a water storage capacity of 6,682 acre-feet (ac-ft).

In 2016, Water Quality Solutions Inc. (WQS) completed a limnological and detention study for MR, under an agreement with Kleinfelder, in support of the City's effort of augmenting 30 million gallons per day (MGD) of Purified Water (PW) to MR. The work included identifying overall strategies for adding PW to MR. The work also involved developing and applying a three-dimensional water quality model for MR, including the calibration of Estuary and Lake Coastal Ocean Model (ELCOM) and Computational Aquatic Ecosystem Dynamic Model (CAEDYM) for a two-year period (2013 – 2014). After that, the calibrated models were used to perform some limited future "what-if" scenarios to assess the mixing and dilution of PW in MR. The work also included performing future "what-if" CAEDYM model scenarios to assess long-term water quality changes in the reservoir after PW addition. The results of the work were reviewed by an Independent Advisory Panel (IAP), the California Department of Public Health (now known as Division of Drinking Water – DDW), and the Regional Water Quality Control Board (RWQCB). The consensus of the various reviews was that the addition of PW to MR does not produce any significant public health or water quality issues.

Since then, the City has retained WQS to provide additional water quality modeling for MR in support of ongoing design of the Pure Water Program facilities, which is the subject of this technical memorandum. This work is performed by WQS under sub-contracts with R.F. Yeager and Kleinfelder, on behalf of the City of San Diego.

All the previously completed modeling used various assumptions concerning nutrient loadings to MR. In particular, it considered nutrient loadings from inflows and internal nutrient loadings from anoxic sediments, but did not consider possible loadings from atmospheric deposition, birds, aquatic shoreline plants, etc. These sources were not included in the previous water quality modeling due to the lack of information about their magnitude at that time. Since the modeling was completed, the City has retained Dudek Environmental Consultants (Dudek) to re-assess the above potential nutrient loadings to MR. Dudek identified these unaccounted nutrient loadings with magnitudes comparable to the nutrient loadings of inflows. Since the algal growth in MR is controlled by phosphorus (WQS, 2016), it is important to add these newly-identified nutrient loadings, especially phosphorus, to the water quality modeling of MR.

1.1.2 Study Objectives

The overall objective of this study is to determine the potential effects of PW, at an average inflow rate of 30 MGD, on water quality in MR, especially algal production, when considering newly-identified nutrient loading sources such as atmospheric deposition and aquatic plants.

1.2 Alternatives Considered

1.2.1 General Approach

The nutrient loading calculations by Dudek included two scenarios for the newly-identified nutrient loadings: a moderate and a high scenario (Dukek, 2017). With the newly-identified loadings to the reservoir, some CAEDYM model parameters for algal growth needed to be updated so that the measured and computed water quality parameters remain in agreement. As a result, this study included performing two recalibrations, one for each of the newly-identified loading scenarios; i.e., moderate and high. The recalibrations were for the same two-year period (2013 – 2014) used in (WQS 2016).

An examination of in-reservoir chlorophyll *a* concentrations revealed that the values rarely dropped below 0.1 to 0.2 µg/L. Modeling results from (WQS 2016), however, showed significantly lower values when algal productivity was low. To address this, different from the previous water quality modeling, two algal groups are considered in this study. The first algal group used in the model generally grows with more favorable algal growth conditions including high solar radiation, favorable temperature, and relatively more abundant nutrients. A second algal group, which is a background algal group, was used to represent the algal species that are insensitive to seasonal variation of water temperature and can be sustained at low nutrient levels. This group of algae was capped at a chlorophyll *a* concentration of 0.2 µg/L.

After each model recalibration, the model was run for future scenarios whereby the present imported water inflow (labelled as "WTP return" in City documents, such as flow mass balance tables, and the previous documents produced by WQS) to MR, originating from Lake Skinner, was replaced with PW inflow. The methodologies for performing the new CAEDYM simulations presented herein closely followed those previously used in WQS's water quality modeling for MR (WQS, 2016). The same computational grid, inflow and outflow quantities, modeling period (four years), and meteorology data were used. The new CAEDYM simulations differ from previous simulations by using:

- additional nutrient loading calculations as developed by Dudek.
- a PW inflow diffuser (**Figure 1.1**), as being developed in the 60% design of the Pure Water facilities, versus a point source in the previous analyses.
- three values for total phosphorus (TP) concentrations in PW, ranging from 0.004 to 0.010 mg/L, versus a value of 0.004 mg/L used previously.

1.2.2 Newly-Identified Nutrient Loadings

Dudek's study (Dudek, 2017) identified five additional potential sources that may contribute nutrients to MR but were not considered in the previous water quality modeling. These newly-identified nutrient sources include atmospheric deposition, decomposition of aquatic vegetation, faunal contributions (waterfowl feces and stocking of rainbow trout), and internal nutrient cycling in the oxic zone. The nutrient loadings from these five sources were estimated for two scenarios: a moderate scenario and a high scenario. **Figures B.1 – B.4** presents the loadings of nitrogen (N) and phosphorus (P) for each scenario. Details about estimates of these newly-identified nutrient loadings can be found in (Dudek, 2017).

Besides the newly-identified nutrient loadings, the water quality model in this study also considered nutrient loadings from inflows (imported water, sludge return, etc.) and internal nutrient loadings from anoxic sediments, similar to the previous study (WQS, 2016). Similar to the previous water quality modeling, the nutrient concentrations in the sludge return were considered to be 10% of those in the imported water. The flow rate of the sludge return was relatively small, which made the nutrient loadings from the sludge return relatively insignificant. The total loadings from the newly-identified nutrient sources were compared to the nutrient loadings from the reservoir's inflows and the internal loadings from anoxic sediments in **Figure 1.2**. The nutrient loadings from the newly-identified sources are comparable to those from the imported water and the internal loadings from anoxic sediments; therefore, it is important to consider these sources in the water quality modeling for MR. The daily average TP loadings from various sources are compared in **Table 1.1** for both the calibration and the future scenario, in which the PW TP concentration is 0.004 mg/L.

Table 1.1: Average Total Phosphorus Loadings (kg/day): Calibration vs. Future Scenario

Sources	Moderate Nutrient Loadings		High Nutrient Loadings	
	Calibration	Future Scenario TP in PW = 0.004 mg/L	Calibration	Future Scenario TP in PW = 0.004 mg/L
Imported Water	0.81	N/A	0.81	N/A
Sludge Return	0.03	0.03	0.03	0.03
Newly-Identified Nutrient Sources	0.48	0.48	0.83	0.83
Internal Loading from Anoxic Sediments	0.20	0.16	0.20	0.16
Purified Water	N/A	0.45	N/A	0.45
Total	1.52	1.12	1.87	1.47

1.3 Findings

Based on the calibrations and future scenario simulations, the following conclusions have been drawn:

- The moderate and high nutrient loading scenarios did not seem to differ significantly, other than showing a slightly higher algal concentration in the simulation with the high nutrient loadings;
- Under the conditions of moderate nutrient loadings,
  - For various future scenarios with different TP concentrations in the PW inflow, the model predicted that most water quality variables' (DO, pH, and nutrients) trends are not greatly changed from (WQS 2016);
  - In the calibrations, the two-year average chlorophyll *a* level is 0.42 µg/L; while the average chlorophyll *a* levels for the first two years of the future scenarios were predicted to range from 0.24 µg/L to 0.30 µg/L with various TP concentrations in the PW inflow.

2. Model Calibration

With the newly-identified loadings to the reservoir, some CAEDYM model parameters for algal growth needed to be updated so that the measured and computed water quality parameters remain in agreement. As a result, this study included performing two recalibrations, one for each of the newly-identified loading scenarios (moderate and high).

2.1 CAEDYM Calibration Setup

The computer grid setup, initial conditions and inflow water quality inputs for CAEDYM calibration were the same as the calibration in the previous water quality modeling (WQS, 2016). The main difference from the previous study was that the calibration in this new study considered the additional nutrient loadings from the potential sources identified by Dudek. The calibration was carried out for each of the two nutrient loading scenarios: moderate and high.

2.2 CAEDYM Calibration Results

The calibration results were presented through comparisons between the CAEDYM simulation results and measured in-reservoir data focusing on dissolved oxygen (DO), nutrients, chlorophyll *a*, and pH.

2.2.1 Moderate Nutrient Loadings

Table 2.1 summarizes the statistical metrics for the calibration of parameters under the scenario of moderate nutrient loadings. **Figure 2.1** presents a comparison plot of the simulated and measured chlorophyll *a* concentrations at the water surface. **Figures B.5 – B.12** present the comparison plots of the simulated and measured values of the other water quality data, including water temperature, DO, nutrients, and pH.

Table 2.1: Calibration Metrics (Moderate Nutrient Loadings)

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Temperature	0.65 ºC	4.5%	0.22 ºC
Surface and Bottom Conductivity	22.6 µS/cm	8.1%	13.0 µS/cm
Surface and Bottom Dissolved Oxygen	0.82 mg/L	7.4%	0.23 mg/L
Surface and Bottom Total Nitrogen	0.18 mg/L	17.2%	0.03 mg/L
Surface and Bottom Total Phosphorus	0.05 mg/L	14.8%	0.01 mg/L
Surface Chlorophyll *a*	0.44 µg/L	18.4%	-0.06 µg/L
Surface and Bottom pH	0.20	14.2%	0.08

Note: 1. Relative RMSE = RMSE/|PAR_{max} – PAR_{min}|, where PAR_{max} and PAR_{min} are from measured data.
2. Mean error is the average of ($PAR_{measured}$ – $PAR_{simulated}$).

2.2.2 High Nutrient Loadings

Table 2.2 summarizes the statistical metrics for the calibration of parameters under the scenario of high nutrient loadings. **Figure 2.2** presents a comparison plot of the simulated and measured chlorophyll *a* concentrations at the water surface. **Figures B.13 – B.20** present the comparison plots of the simulated and measured values of the other water quality data, including water temperature, DO, nutrients, and pH.

Table 2.2: Calibration Metrics (High Nutrient Loadings)

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Temperature	0.65 ºC	4.5%	0.20 ºC
Surface and Bottom Conductivity	22.3 µS/cm	8.0%	12.2 µS/cm
Surface and Bottom Dissolved Oxygen	0.83 mg/L	7.4%	0.24 mg/L
Surface and Bottom Total Nitrogen	0.19 mg/L	18.6%	0.00 mg/L
Surface and Bottom Total Phosphorus	0.05 mg/L	14.7%	0.01 mg/L
Surface Chlorophyll *a*	0.44 µg/L	18.5%	-0.07 µg/L
Surface and Bottom pH	0.20	14.3%	0.08

Note: 1. Relative RMSE = RMSE/|PAR_{max} – PAR_{min}|, where PAR_{max} and PAR_{min} are from measured data.
2. Mean error is the average of ($PAR_{measured}$ – $PAR_{simulated}$).

2.2.3 Discussion of Calibration

For both the moderate and high nutrient loading scenarios, the calibrated model replicated the overall reservoir behaviors well, including surface and bottom temperatures, thermocline depth, surface and bottom conductivities, DO and nutrient levels in both epilimnion and hypolimnion, and surface algal levels. Overall the calibration metrics indicated a good calibration. Water temperature, conductivity, and DO were predicted with lower relative RMSEs, while nutrients (nitrogen and phosphorus, whose behavior depends on temperature and DO) and chlorophyll *a* and pH (depending on all other variables) were predicted with higher relative RMSEs.

The RMSEs of water temperature, conductivity, DO, nutrients, and pH in the re-calibrations were generally similar to the initial calibration performed in the previous study (WQS, 2016). The RMSE of chlorophyll *a* in the re-calibration was 0.4 µg/L, approximately a 40% improvement from the initial calibration (WQS, 2016). It is likely that the implementation of a second algal group sustained at low nutrient levels helped improve the chlorophyll *a* calibration.

3. Modeling Conditions

To evaluate how the PW may affect water quality of MR, four (4) future CAEDYM simulations were performed for a four-year modeling period under different scenarios of the newly-identified nutrient loadings. Note that the simulation period of the CAEDYM runs was four years, double that of the ELCOM runs. This was done in order to investigate the longer-term effects of the PW on water qualify of MR. The model inputs (meteorology, inflows, outflows, etc.) of the second two-year simulation period were simply a repetition of the first two-years.

Most of the modeling conditions in this study were identical to the previous water quality modeling study (WQS, 2016), including the PW inflow rates, outflow rates, open Port #2, and nominal operating water surface elevation (WSEL). Aside from updated nutrient loadings (Dudek 2017), the work presented herein incorporates a PW inflow diffuser (**Figure 1.1**), as being developed in the 60% design of the Pure Water facilities, instead of a point source in the previous analyses. It is noted that, while the diffuser increases initial dilution of the PW, the diffuser is not expected to greatly alter the overall water quality in the reservoir as algal growth and other water quality processes occur on time scales of weeks to months. Furthermore, the work presented herein considers three TP concentrations with TP = 0.004, 0.007, and 0.010 mg/L, versus a single value of 0.004 mg/L in (WQS 2016). The range of TP values in the PW was based on discussions between the City and Trussell Technologies. The four CAEDYM future scenario model runs are summarized in **Table 3.1**.

Table 3.1: Summary of CAEDYM Future Scenario Model Runs

Run #	TP Concentration in PW (mg/L)	Newly-Identified Nutrient Loadings
1	0.004	Moderate
2	0.004	High
3	0.007	Moderate
4	0.010	Moderate

4. CAEDYM Modeling Results

This section presents the results of the CAEDYM model runs. The WSEL of the CAEDYM runs is shown in **Figure B.21**. Similar to the two-year ELCOM model runs, the simulated WSEL remained relatively constant, within ±1 ft of the normal operating elevation (EL = 706 ft), corresponding to a water volume of approximately 5,500 acre-feet. The contour plots of water temperature and conductivity of the CAEDYM runs are shown in **Figure B.22** for the four-year modeling period. Similar to the two-year ELCOM model run results, the PW, with relatively warm temperature and low salinity, deepens the thermocline and decreases the reservoir conductivity. Note that WSEL, water temperature and conductivity do not change with nutrient loadings. The subsections below present the nutrient and algae modeling results, focusing on DO, nutrients, chlorophyll *a*, and pH.

4.1 TP = 0.004 mg/L in PW

4.1.1 Moderate Nutrient Loadings

4.1.1.1 Dissolved Oxygen

Figure 4.1 presents the simulated surface and bottom DO concentrations under the condition of a PW inflow rate of 30 MGD, TP = 0.004 mg/L in PW, and moderate nutrient loadings from the newly-identified nutrient sources. The surface DO concentrations remain nearly saturated. Bottom DO steadily decreases during the spring and summer months, a result of algal decay, sediment oxygen demand, and lack of replenishment from the atmosphere. The bottom of MR becomes anoxic during the summer and fall. DO is replenished as the reservoir begins turnover during the winter.

Table 4.1 lists the hypolimnetic anoxia (bottom DO values being less than 0.5 mg/L) period for each year, compared to the calibration. For Year 1, the hypolimnetic anoxia period is predicted to last 249 days (or 68% of the time). For the next three years, the hypolimnetic anoxia period is predicted to last 199 – 212 days (or 55% – 58% of the time), slightly shorter than the length of the hypolimnetic anoxia periods of the calibration. The longer hypolimnetic anoxia period for Year 1 in the CAEDYM run is a result of stratification starting earlier in Year 1, likely due to the introduction of warm PW inflow forming a thermocline earlier. The introduction of PW, however, does not show a significant effect on DO after Year 1.

Table 4.1: Summary of Simulated DO (TP = 0.004 mg/L in PW; Moderate Nutrient Loadings)

Year	Calibration		Moderate Nutrient Loadings	
	Bottom Anoxia Period[1]	Days under Anoxia: Total Days (Percentage)	Bottom Anoxia Period[1]	Days under Anoxia: Total Days (Percentage)
Year 1	5/11 – 12/11	215 (59%)	4/5 – 12/9	249 (68%)
Year 2	5/10 – 12/19	224 (61%)	5/4 – 12/1	212 (58%)
Year 3	N/A	N/A	5/21 – 12/5	199 (55%)
Year 4	N/A	N/A	5/6 – 11/25	204 (56%)

Note: 1. Anoxia is defined here as the bottom DO being less than 0.5 mg/L.

4.1.1.2 Nutrients

Figures 4.2, **4.3, and 4.4** illustrate the simulated ammonia (NH_4-N), nitrate (NO_3-N), and total nitrogen (TN), respectively. **Figures 4.5 and 4.6** show the simulated soluble reactive phosphorus (SRP) and total phosphorus (TP), respectively. For the reservoir's hypolimnion, TN and TP began to increase in the spring of every year as DO values decreased, a result of decaying organic matter and internal nutrient recycling from the sediments during anoxic or low DO conditions. The simulation shows similar trends during the last three years but a different trend during Year 1. In Year 1, the concentration of NO_3-N at the bottom is lower, and the sediment release periods of NH_4-N and SRP are longer, caused by the longer hypolimnetic anoxia period during Year 1. In general, the simulation shows high concentrations of nitrogen and low concentrations of phosphorus at the surface, a result of year-round high-rate inflow of PW with relatively high nitrogen and low phosphorus concentrations.

4.1.1.3 Chlorophyll *a*

Figure 4.7 presents the simulated surface chlorophyll *a* concentrations. In general, after reservoir turnover in winter, the reservoir surface is replenished by the phosphorus from the hypolimnion, resulting in an algal growth peak in the spring. Low phosphorus concentrations in the reservoir surface water limit algal growth during winter, summer, and fall. The peak value of surface chlorophyll *a* concentrations in Year 1 is higher than that of the other three years because of the existing phosphorus in the water column at the beginning of this simulation. In the next three years, the surface phosphorus concentrations are very low, a result of year-round high-rate inflow of PW with low phosphorus concentrations, thus limiting the algal growth.

Table 4.2 summarizes annual average surface chlorophyll *a* concentrations for the simulation under the moderate nutrient loading scenario, compared to the calibration. The average chlorophyll *a* concentration is predicted to be 0.26 µg/L for Year 1 and 0.21 or 0.22 µg/L for the next three years, which is lower than the algal levels in the calibration. This indicates that a PW inflow rate of 30 MGD is predicted to produce lower algal levels *(i.e.*, low surface chlorophyll *a* concentrations) and higher water clarity, due to the relatively low phosphorus concentrations in the year-round high-rate inflow of PW.

Note that chlorophyll *a* has been measured in MR, using an *in situ* fluorometric method, to an accuracy of 0.1 ug/l. That is to say, field measurements of chlorophyll a are accurate to one digit to the right of the decimal point. In this memorandum the numerical modeling results for chlorophyll *a* are presented with two digits to the right of the decimal point. This is done to show possible differences between various model scenarios. However, the model results for chlorophyll *a*, as presented herein, may imply a level of precision greater than can be measured in the field. The reader is cautioned to keep this in mind when assessing model outcomes for chlorophyll *a*.

Table 4.2: Annual Average Surface Chlorophyll *a* (μg/L) (TP = 0.004 mg/L; Moderate Nutrient Loadings)

Year	Calibration	Future Scenario: TP = 0.004 mg/L in PW; Moderate Nutrient Loadings
Year 1	0.47	0.26
Year 2	0.37	0.21
Year 3	N/A	0.22
Year 4	N/A	0.21

4.1.1.4 pH

Figure 4.8 illustrates the simulated pH for the reservoir surface and bottom. Surface pH values depend largely on algal productivity as elevated pH is generally an indicator of algal blooms. Algal levels are predicted to be relatively low in MR; therefore, the pH at the reservoir surface is predicted to be fairly constant for all four years, at ~8.2 during each simulated year. Bottom pH values depend largely on the development of the thermocline. The pH at the reservoir bottom is predicted to be around 7.2 when the reservoir is stratified and at a higher level, peaking at ~8.0, during turnover.

4.1.2 High Nutrient Loadings

The results of the model run under the high nutrient loadings scenario were generally similar to the results of the model run under the moderate nutrient loadings scenario, except for a slightly longer anoxic period for Year 4 (**Table 4.3**) and slightly higher average chlorophyll *a* level for Year 1 and Year 3 (**Figure 4.9 and Table 4.4**). The detailed results of this run are presented in **Figures B.23 – B.29**.

Table 4.3: Summary of Simulated DO (TP = 0.004 mg/L; High Nutrient Loadings)

Year	Calibration		High Nutrient Loadings	
	Bottom Anoxia Period[1]	Days under Anoxia: Total Days (Percentage)	Bottom Anoxia Period[1]	Days under Anoxia: Total Days (Percentage)
Year 1	5/11 – 12/10	214 (59%)	4/5 – 12/9	249 (68%)
Year 2	5/10 – 12/19	224 (61%)	5/4 – 12/1	212 (58%)
Year 3	N/A	N/A	5/21 – 12/5	199 (55%)
Year 4	N/A	N/A	5/6 – 11/29	208 (57%)

Note: 1. Anoxia is defined here as the bottom DO being less than 0.5 mg/L.

Table 4.4: Annual Average Surface Chlorophyll *a* (μg/L) (TP = 0.004 mg/L; High Nutrient Loadings)

Year	Calibration	Future Scenario: TP = 0.004 mg/L in PW; High Nutrient Loadings
Year 1	0.47	0.28
Year 2	0.37	0.21
Year 3	N/A	0.24
Year 4	N/A	0.21

4.1.3 Discussion

The annual average surface chlorophyll *a* levels predicted in this study are compared to the values predicted from the previous water quality modeling in (WQS, 2016) in **Table 4.5**. The implementation of a background algal group sustained at low nutrient levels resulted in more reasonable future scenario simulations.

Table 4.5: Comparison of Predicted Annual Average Surface Chlorophyll *a* (μg/L) (TP = 0.004 mg/L)

Year	Previous Study[1]: TP = 0.004 mg/L in PW; No Additional Nutrient Loadings	Future Scenario[2]: TP = 0.004 mg/L in PW; Moderate Nutrient Loadings	Future Scenario[2]: TP = 0.004 mg/L in PW; High Nutrient Loadings
Year 1	0.24	0.26	0.28
Year 2	0.04	0.21	0.21
Year 3	0.03	0.22	0.24
Year 4	0.03	0.21	0.21

Note: 1. The PW inflow enters MR as a surface inflow (WQS, 2016);
2. The PW inflow enters MR through a diffuser.

4.2 TP = 0.007 mg/L in PW

For the scenario with TP = 0.004 mg/L in PW, the modeling results did not show significant difference between the moderate and high nutrient loadings. As a result, for the future scenarios with TP = 0.007 mg/L and TP = 0.010 mg/L in PW, only the condition of moderate nutrient loadings was simulated.

The results of the model run with TP = 0.007 mg/L in PW showed a higher average chlorophyll *a* level for Year 1 and Year 3 (**Figure 4.10 and Table 4.6**) than the scenario with TP = 0.004 mg/L in PW. The detailed results of this run are presented in **Figures B.30 – B.36**. The results of other parameters, including DO, nutrients, and pH were similar to those of the scenario with TP = 0.004 mg/L in PW.

Table 4.6: Annual Average Surface Chlorophyll *a* (μg/L) (TP = 0.007 mg/L; Moderate Nutrient Loadings)

Year	Calibration	Future Scenario: TP = 0.007 mg/L in PW; Moderate Nutrient Loadings
Year 1	0.47	0.31
Year 2	0.37	0.22
Year 3	N/A	0.27
Year 4	N/A	0.21

4.3 TP = 0.010 mg/L in PW

The results of the model run with TP = 0.010 mg/L in PW showed a higher average chlorophyll *a* level for all four years (**Figure 4.11 and Table 4.7**) than the scenarios with lower PW TP concentrations. For Year 1, this model run predicted about 38% higher chlorophyll *a* concentrations than the model run with TP = 0.004 mg/L. For Year 3, it was about 55% more than the model run with TP = 0.004 mg/L. The detailed results of this model run are presented in **Figures B.37 – B.43**. The results of other parameters, including DO, nutrients, and pH were similar to those of the scenarios discussed above.

Table 4.7: Annual Average Surface Chlorophyll *a* (μg/L) (TP = 0.010 mg/L; Moderate Nutrient Loadings)

Year	Calibration	Future Scenario: TP = 0.010 mg/L in PW; Moderate Nutrient Loadings
Year 1	0.47	0.36
Year 2	0.37	0.23
Year 3	N/A	0.34
Year 4	N/A	0.23

4.4 Discussion of Model Run Results

The simulated chlorophyll *a* concentrations for different scenarios of TP concentration in PW, under the moderate nutrient loading condition, were compared to the calibration in **Figure 4.12 and Table 4.8**. For all three scenarios, the future scenario simulations showed a "base" algal productivity (+/- 0.2 µg/L) in Year 2 and Year 4, and less episodic increases in Year 1 and Year 3 than the calibration.

Even though the average daily TP loadings in the future scenarios were comparable to those of the calibration (**Table 4.9** and **Figure 4.13**), the surface TP concentrations in the future scenarios were somewhat lower than those in the calibration (**Figure 4.14**). The algal productivity in the future scenarios was generally limited by low phosphorus concentrations near the surface.

Table 4.8: Average Chlorophyll *a*: Future Scenarios vs. Calibration (Moderate Nutrient Loadings)

	Calibration	Future Scenario		
		TP in PW = 0.004 mg/L	TP in PW = 0.007 mg/L	TP in PW = 0.010 mg/L
Average Chlorophyll *a* in Year 1 (µg/L)	0.47	0.26	0.31	0.36
Average Chlorophyll *a* in Year 2 (µg/L)	0.37	0.21	0.22	0.23
Average Chlorophyll *a* in Year 3 (µg/L)	N/A	0.22	0.27	0.34
Average Chlorophyll *a* in Year 4 (µg/L)	N/A	0.21	0.21	0.23
First-Two-Year Average (µg/L)	0.42	0.24	0.27	0.30
Four-Year Average (µg/L)	N/A	0.23	0.25	0.29

Table 4.9: Summary of Average Total Phosphorus Loadings (kg/day)

Sources	Moderate Nutrient Loadings				High Nutrient Loadings	
	Calibration	Future Scenario			Calibration	Future Scenario
		TP in PW = 0.004 mg/L	TP in PW = 0.007 mg/L	TP in PW = 0.010 mg/L		TP in PW = 0.004 mg/L
Imported Water	0.81	N/A	N/A	N/A	0.81	N/A
Sludge Return	0.03	0.03	0.03	0.03	0.03	0.03
Newly-identified Nutrient Sources	0.48	0.48	0.48	0.48	0.83	0.83
Internal Loading from Anoxic Sediments	0.20	0.16	0.16	0.16	0.20	0.16
Purified Water	N/A	0.45	0.79	1.13	N/A	0.45
Total	1.52	1.12	1.46	1.80	1.87	1.47

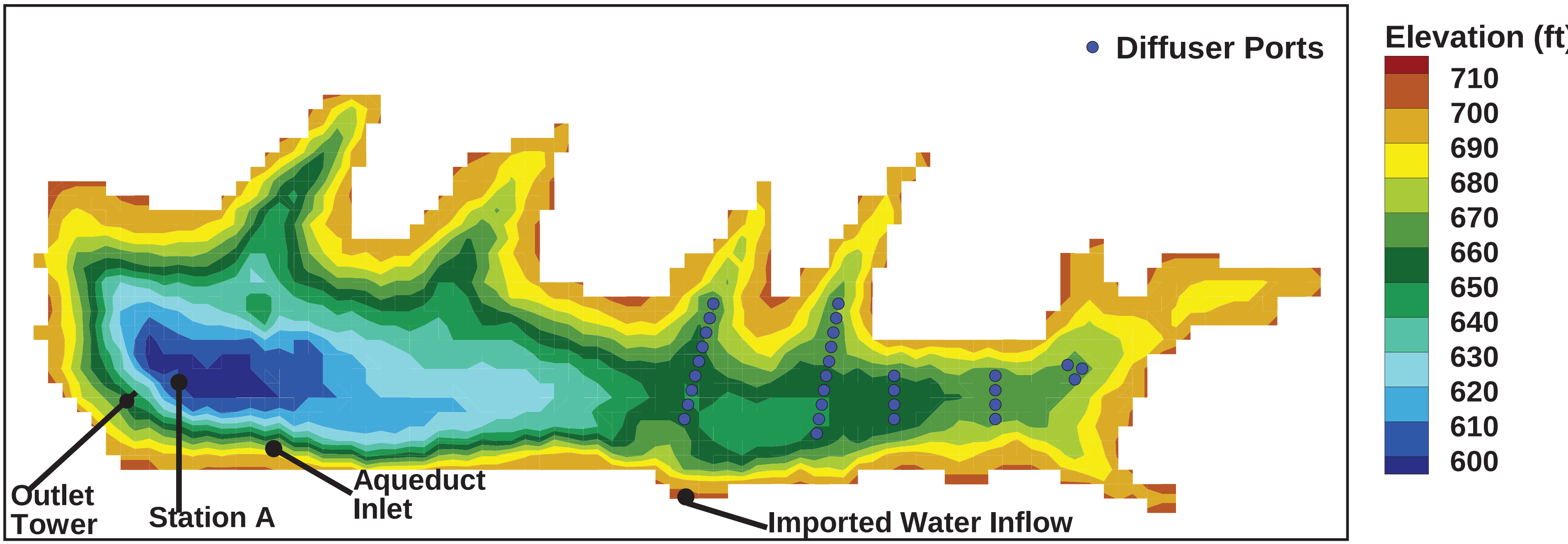
5. Conclusions

Based on the calibrations and future scenario simulations, the following conclusions have been drawn:

- The moderate and high nutrient loading scenarios did not seem to differ significantly, other than showing a slightly higher algal concentration in the simulation with the high nutrient loadings;
- Under the conditions of moderate nutrient loadings,

- For various future scenarios with different TP concentrations in the PW inflow, the model predicted that most water quality variables (DO, pH, and nutrients) trends are not greatly changed;
- In the calibrations, the two-year average chlorophyll *a* level is 0.42 µg/L; while the average chlorophyll *a* levels for the first two years were predicted to range from 0.24 µg/L to 0.30 µg/L for the future scenarios with various TP concentrations in the PW inflow.

Miramar Reservoir Bathymetry and Infrastructure



*Note that the number of blue dots in the figure does not represent the exact number of ports.

Figure 1.1

Nutrient Loadings in Calibration

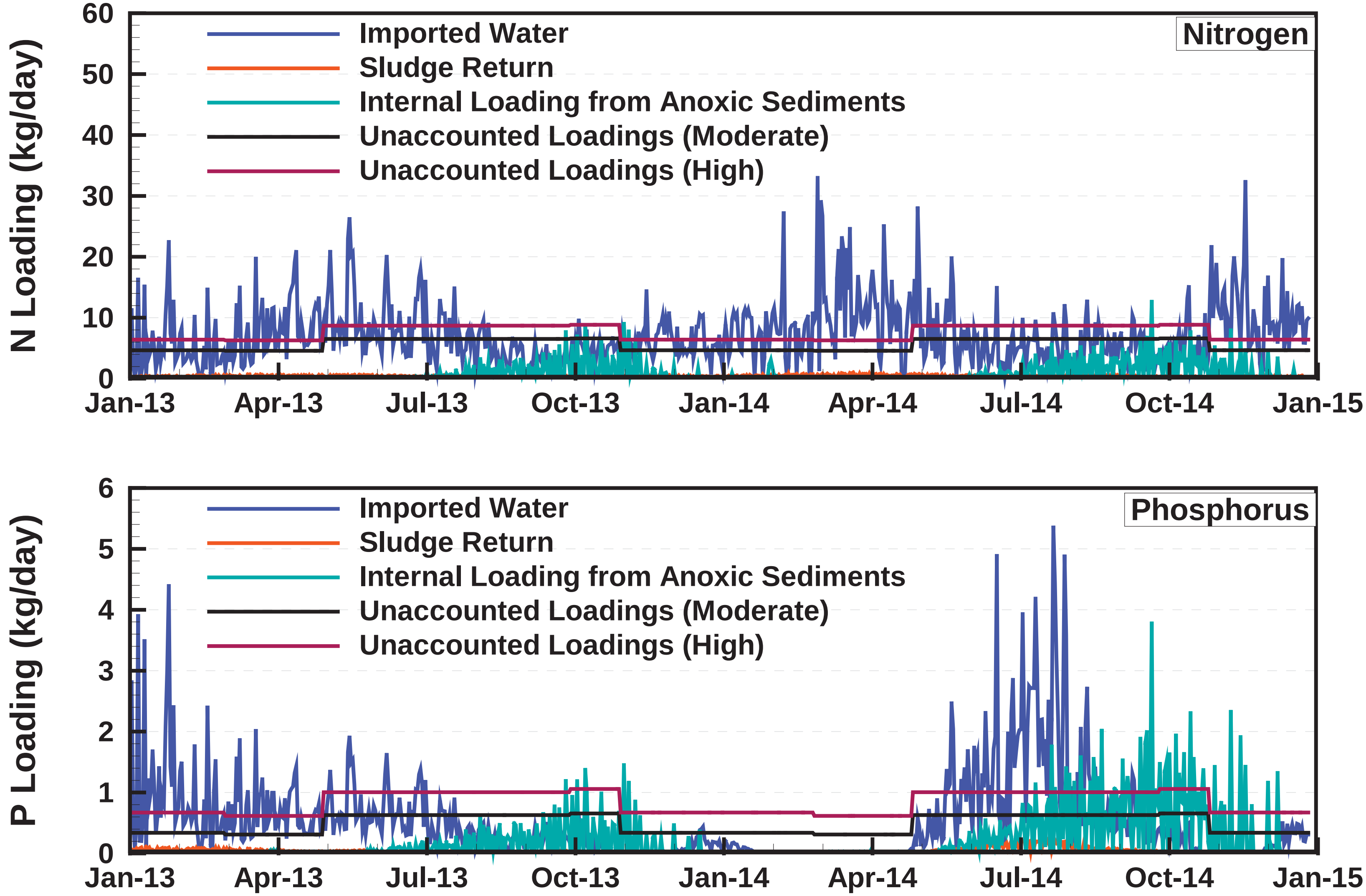


Figure 1.2

Calibration for Chlorophyll *a*

Moderate Nutrient Loadings

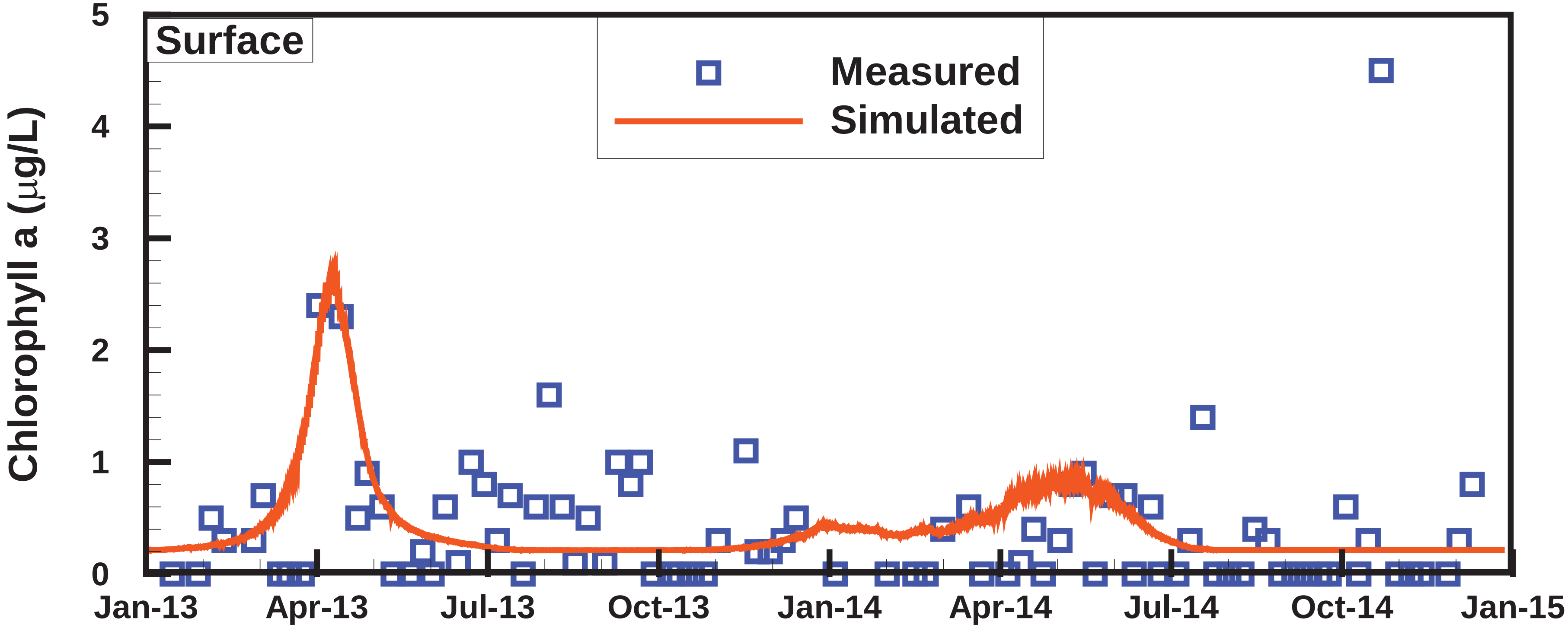


Figure 2.1

Calibration for Chlorophyll *a*

High Nutrient Loadings

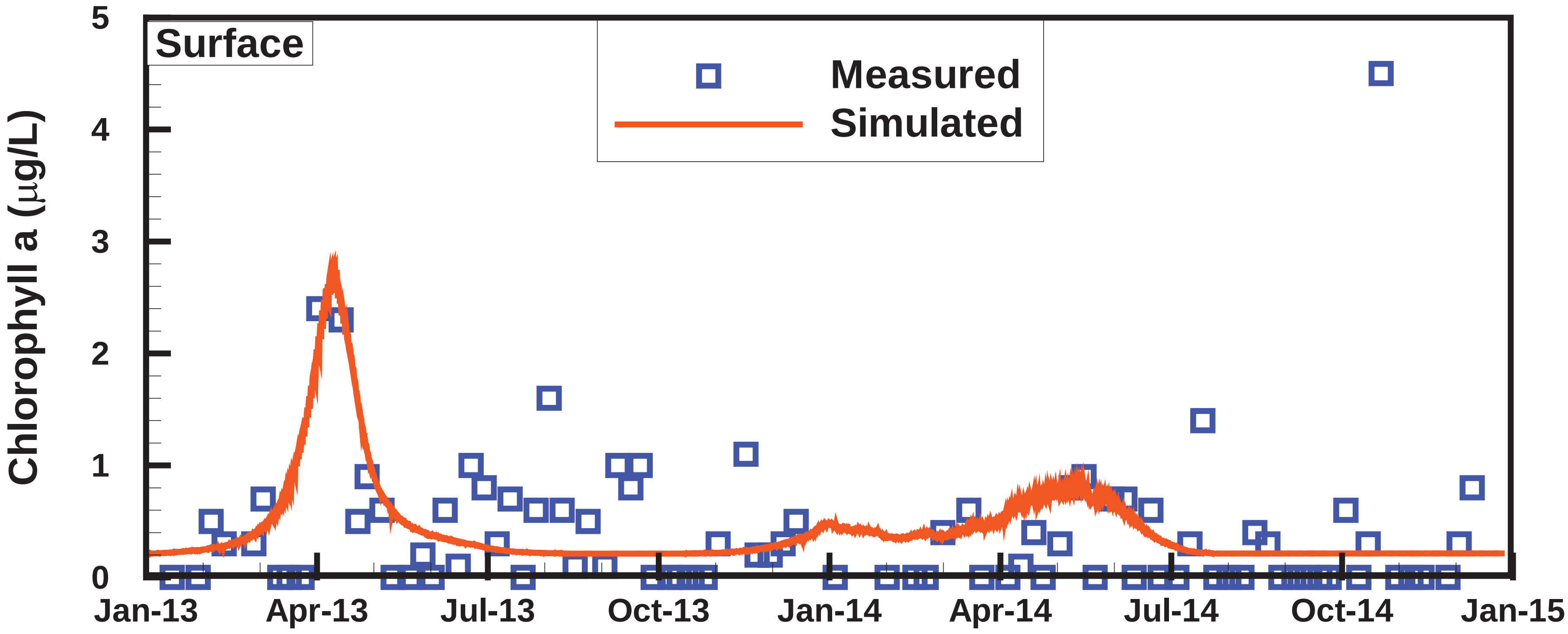


Figure 2.2

Future Scenario: Dissolved Oxygen

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

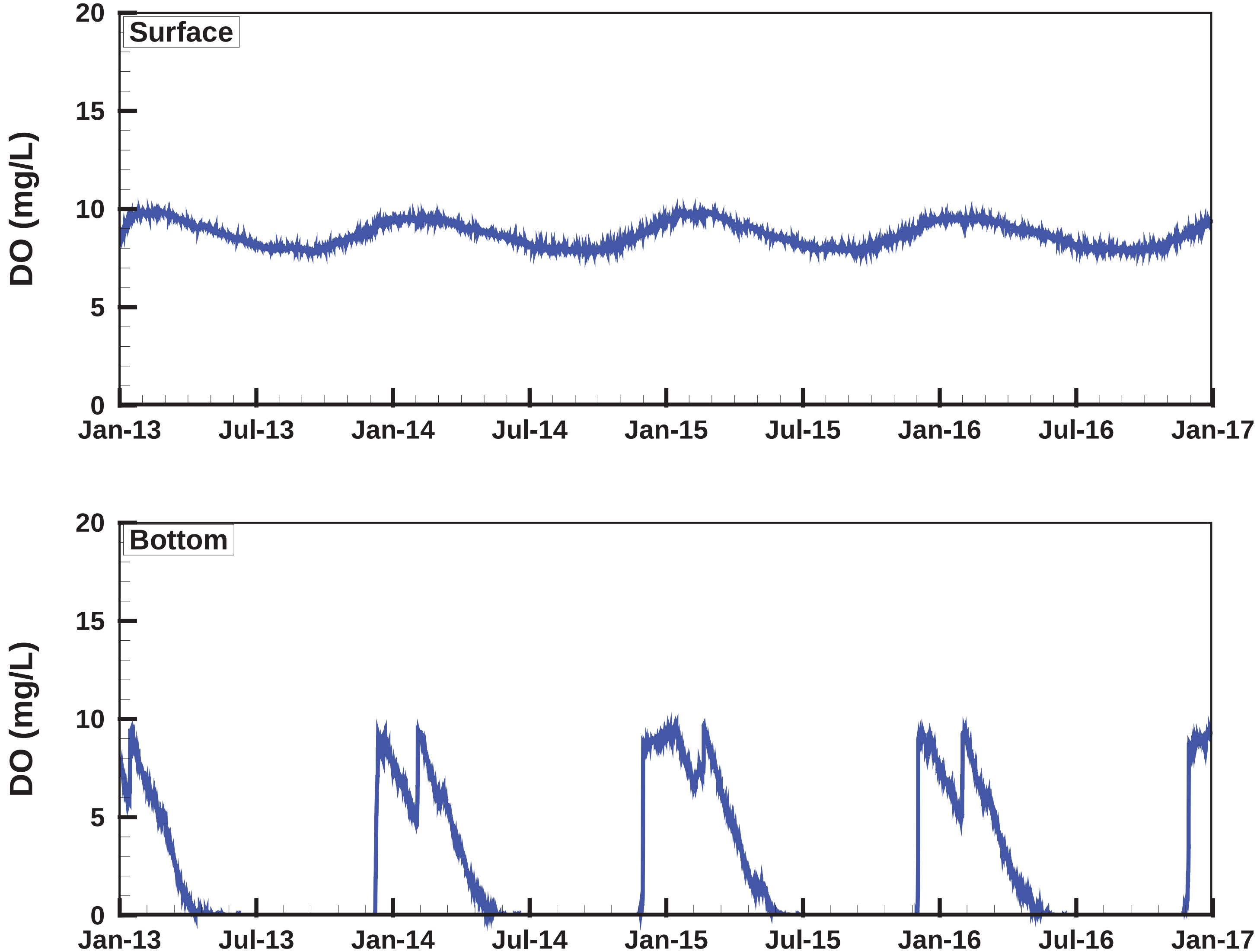


Figure 4.1

Future Scenario: Ammonia

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

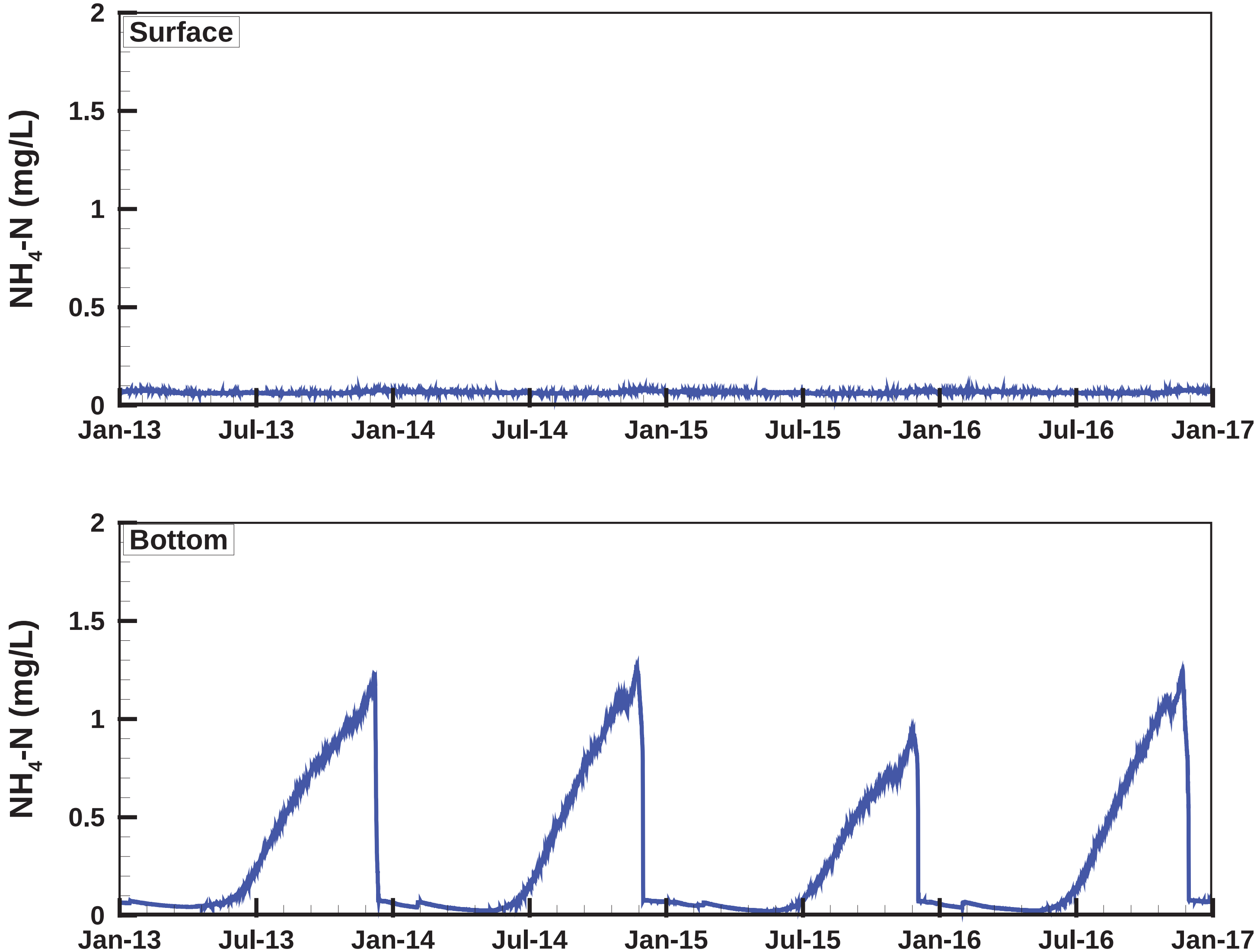


Figure 4.2

Future Scenario: Nitrate

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

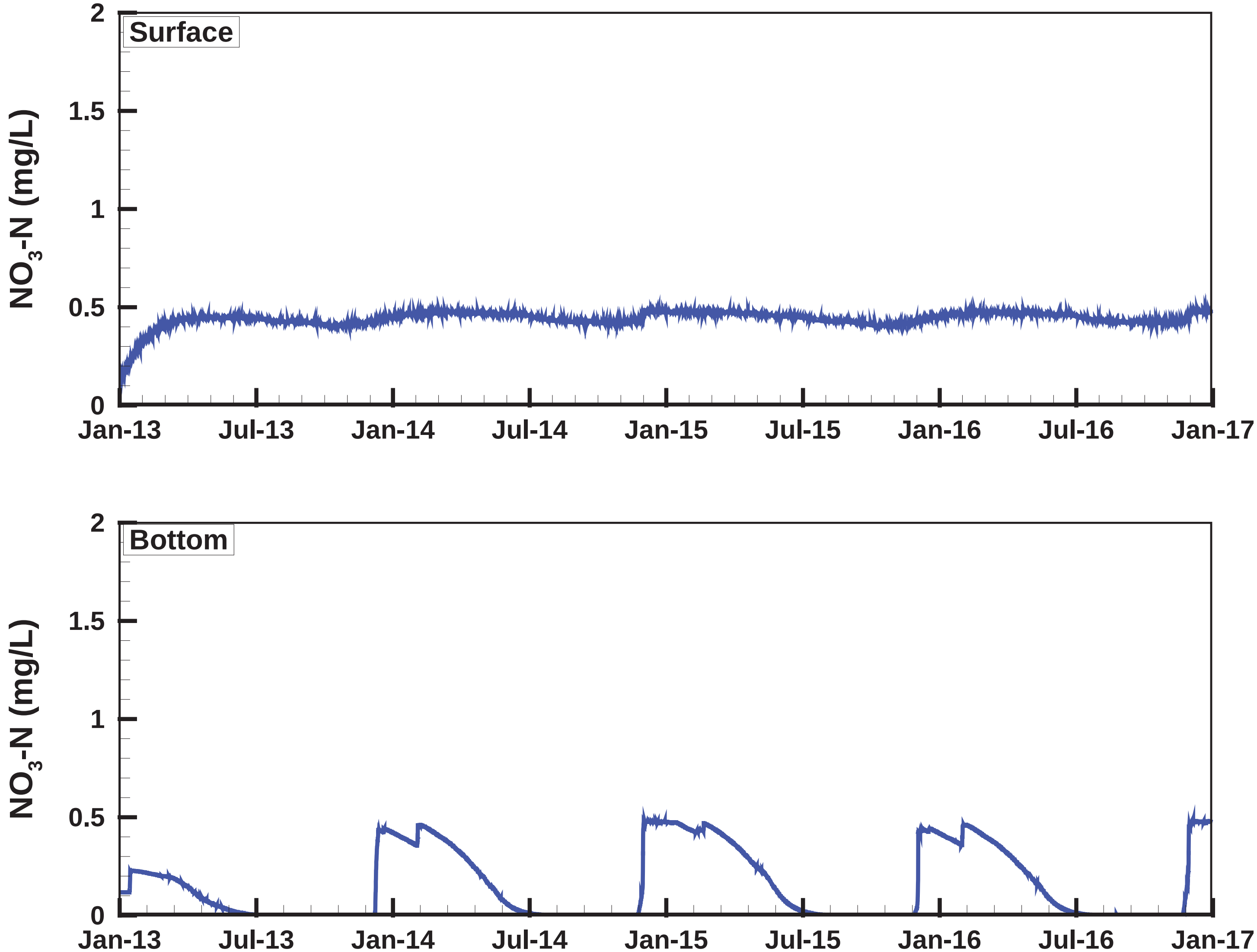


Figure 4.3

Future Scenario: Total Nitrogen

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

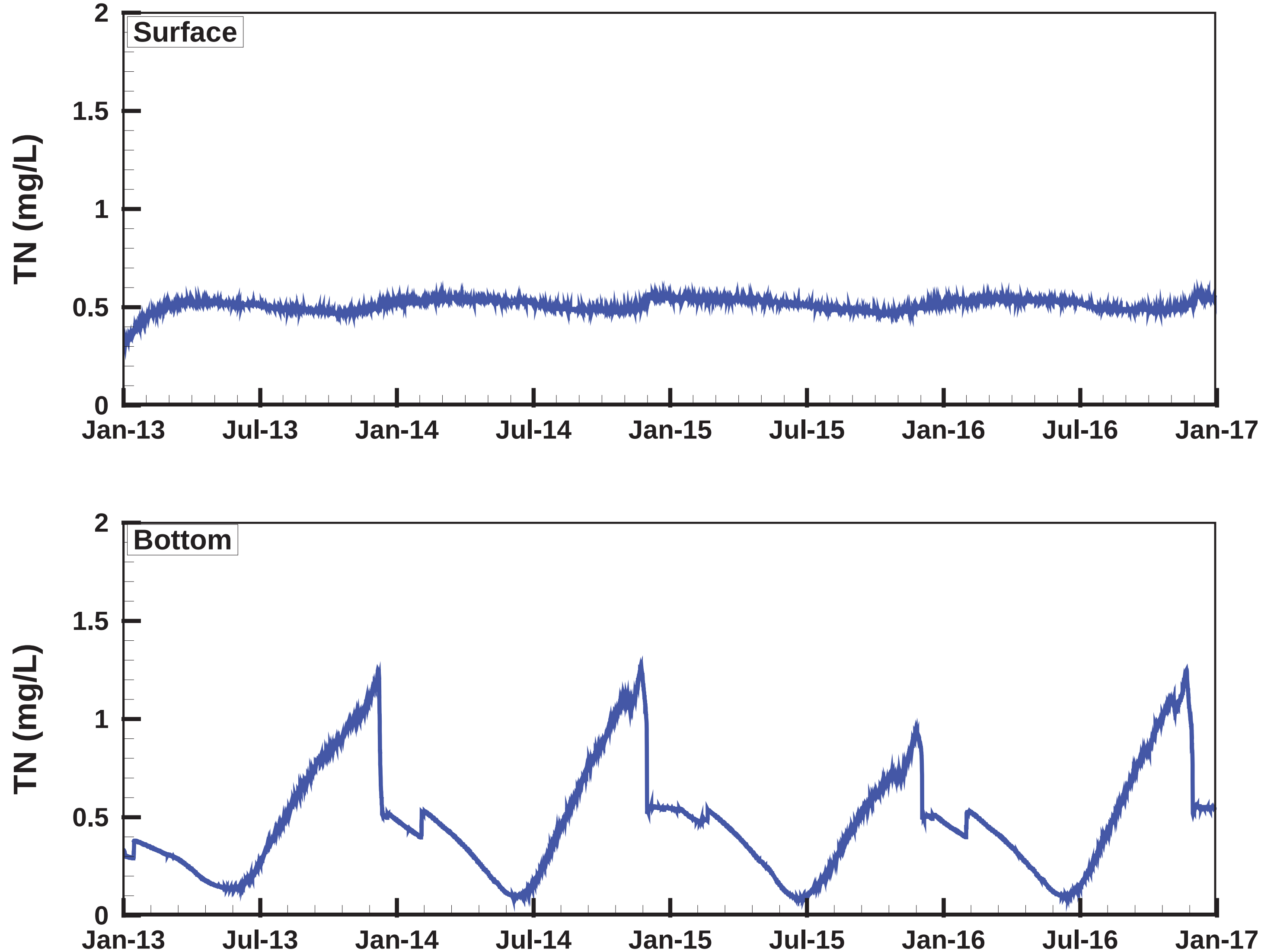


Figure 4.4

Future Scenario: Soluble Reactive Phosphorus

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

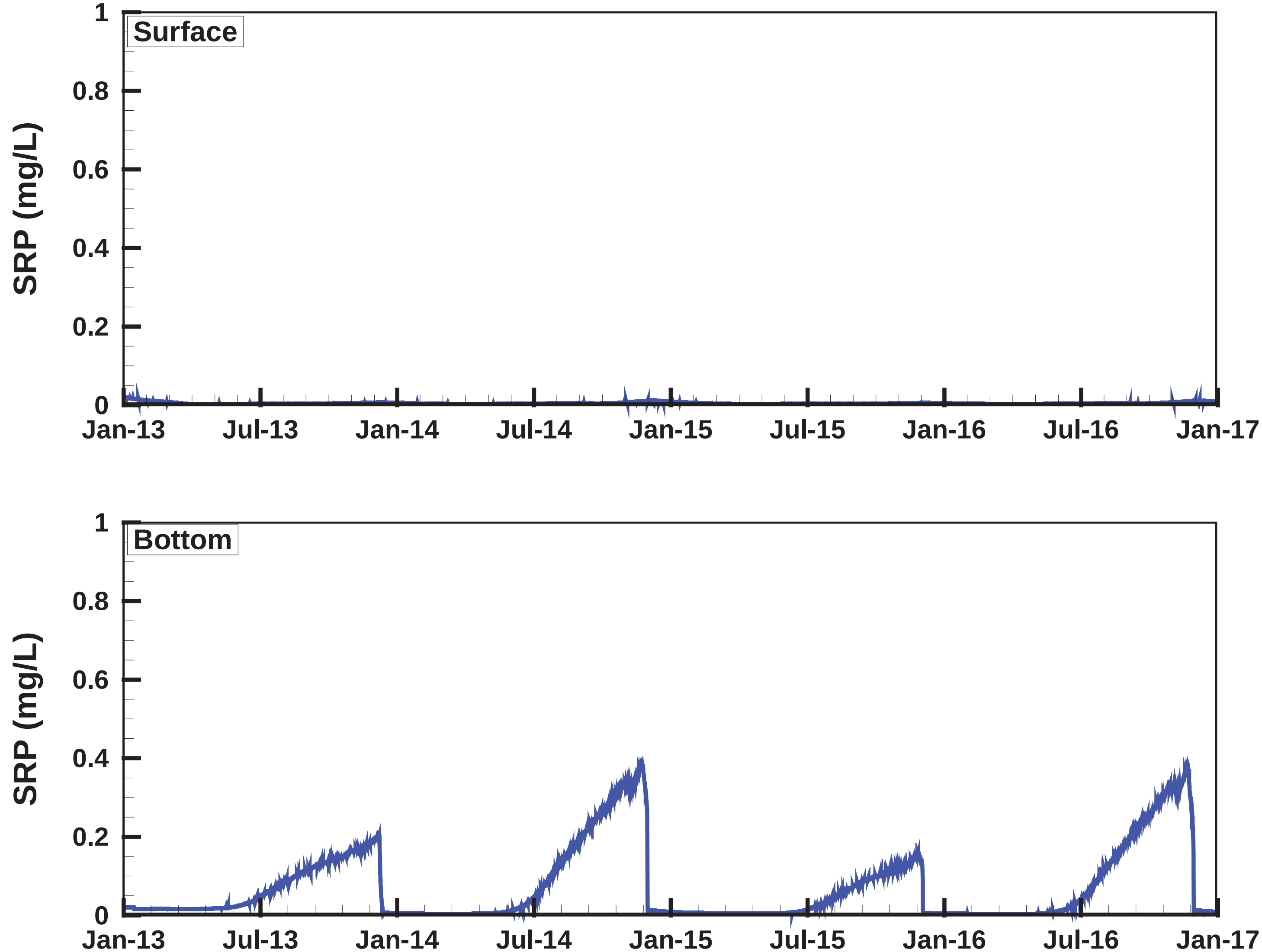


Figure 4.5

Future Scenario: Total Phosphorus

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

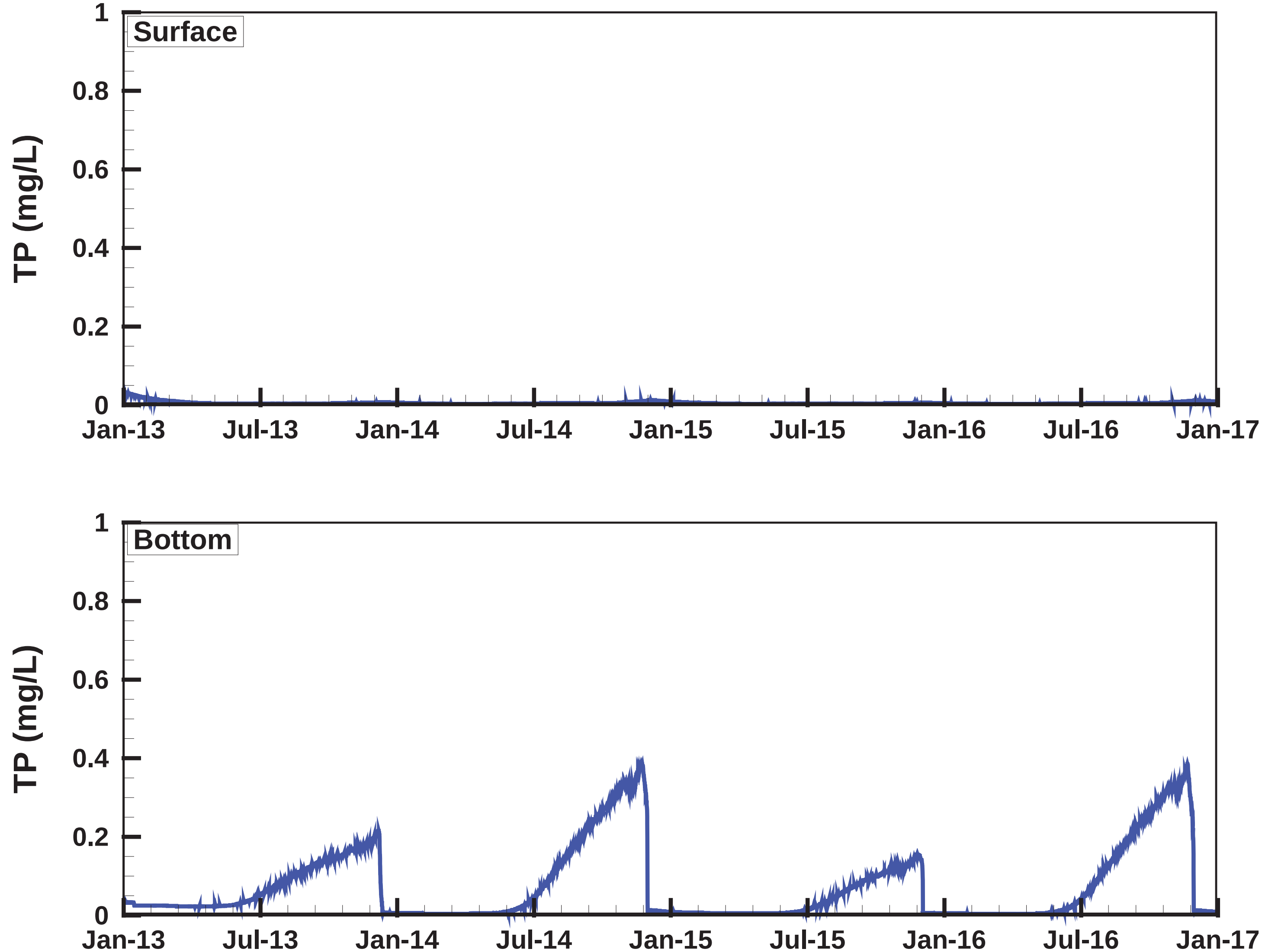


Figure 4.6

Future Scenario: Chlorophyll *a*

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

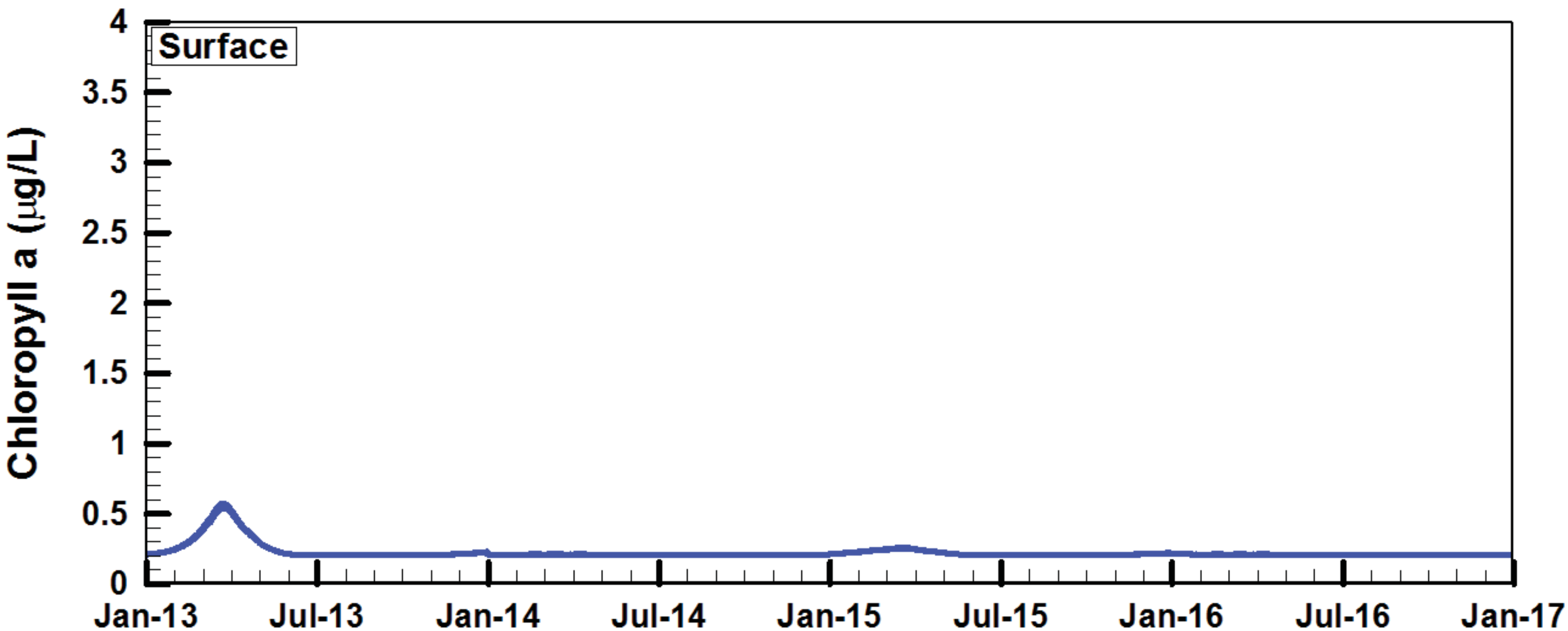


Figure 4.7

Future Scenario: pH

TP = 0.004 mg/L in PW; Moderate Nutrient Loadings

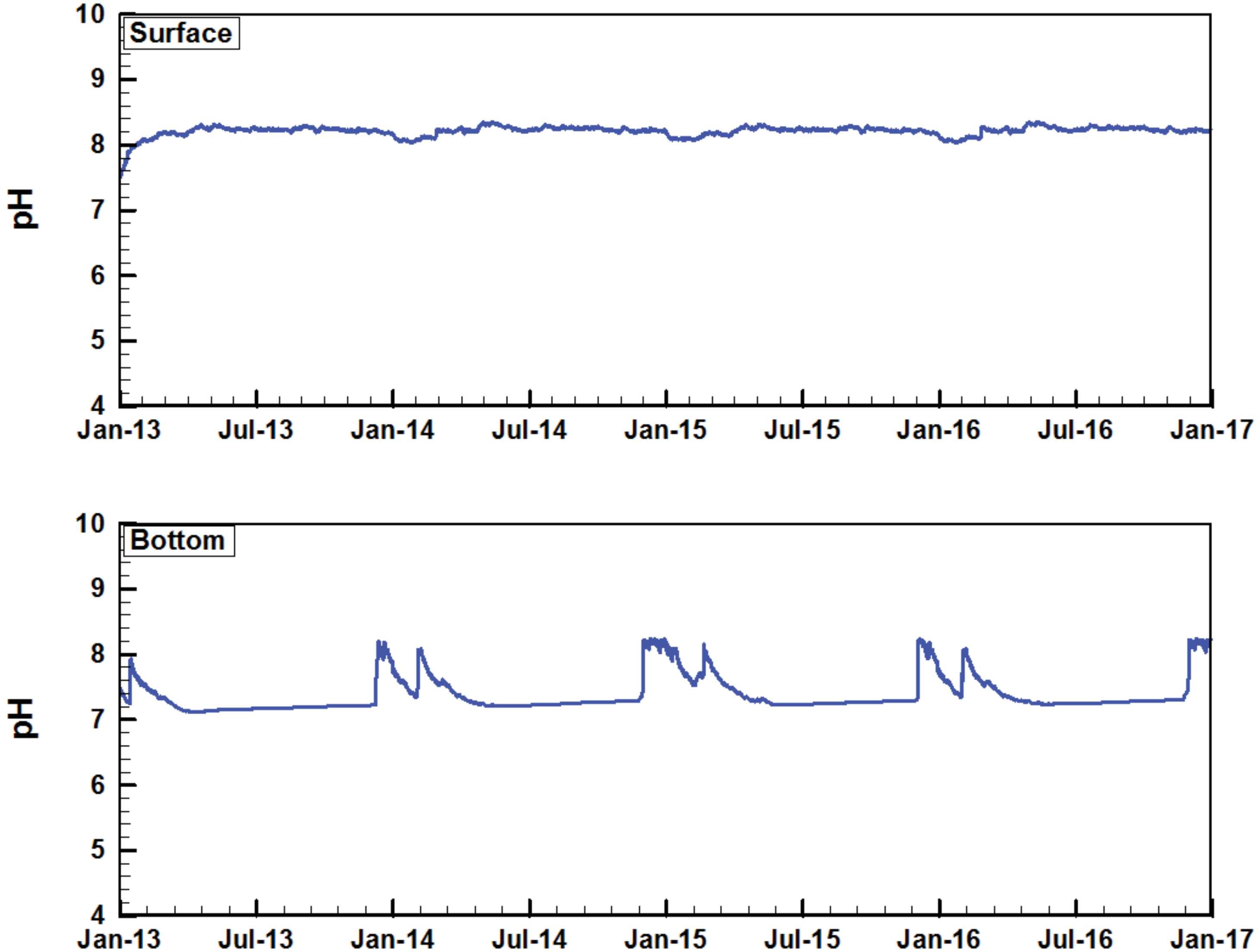


Figure 4.8

Future Scenario: Chlorophyll *a*

TP = 0.004 mg/L in PW; High Nutrient Loadings

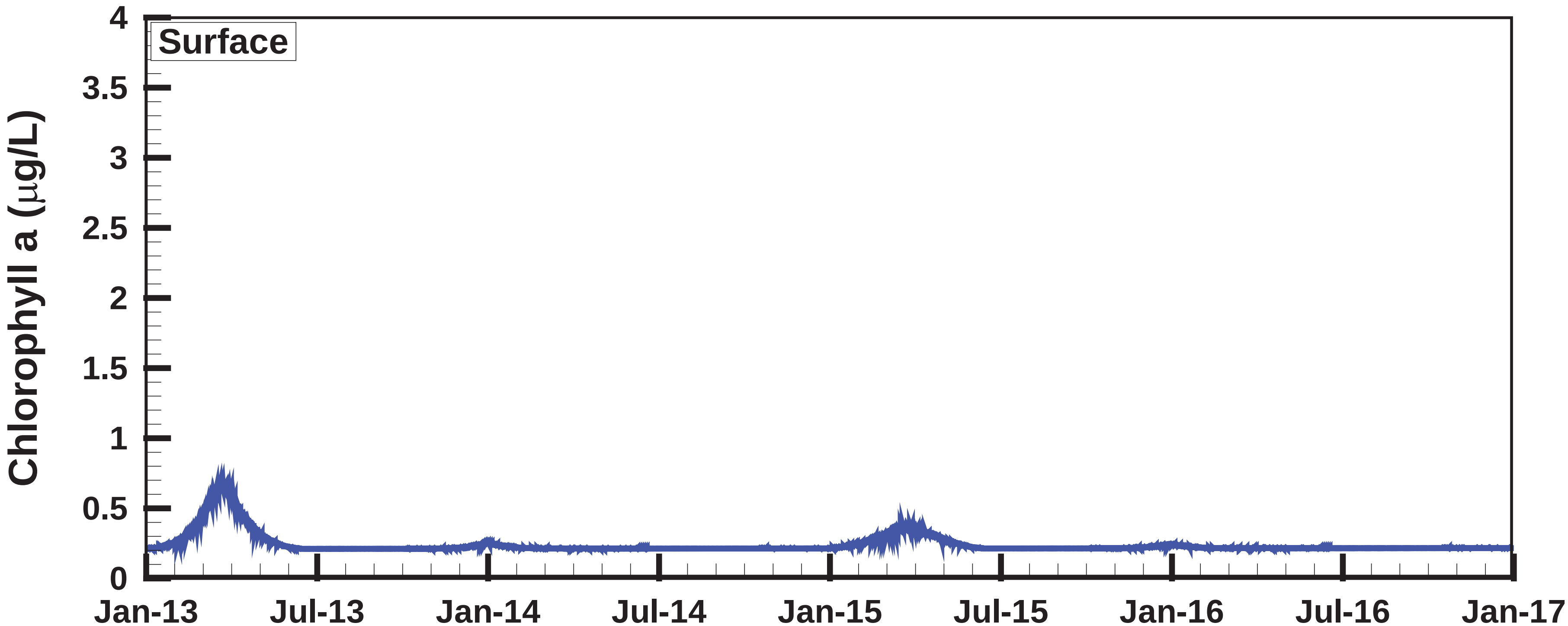


Figure 4.9

Future Scenario: Chlorophyll *a*

TP = 0.007 mg/L in PW; Moderate Nutrient Loadings

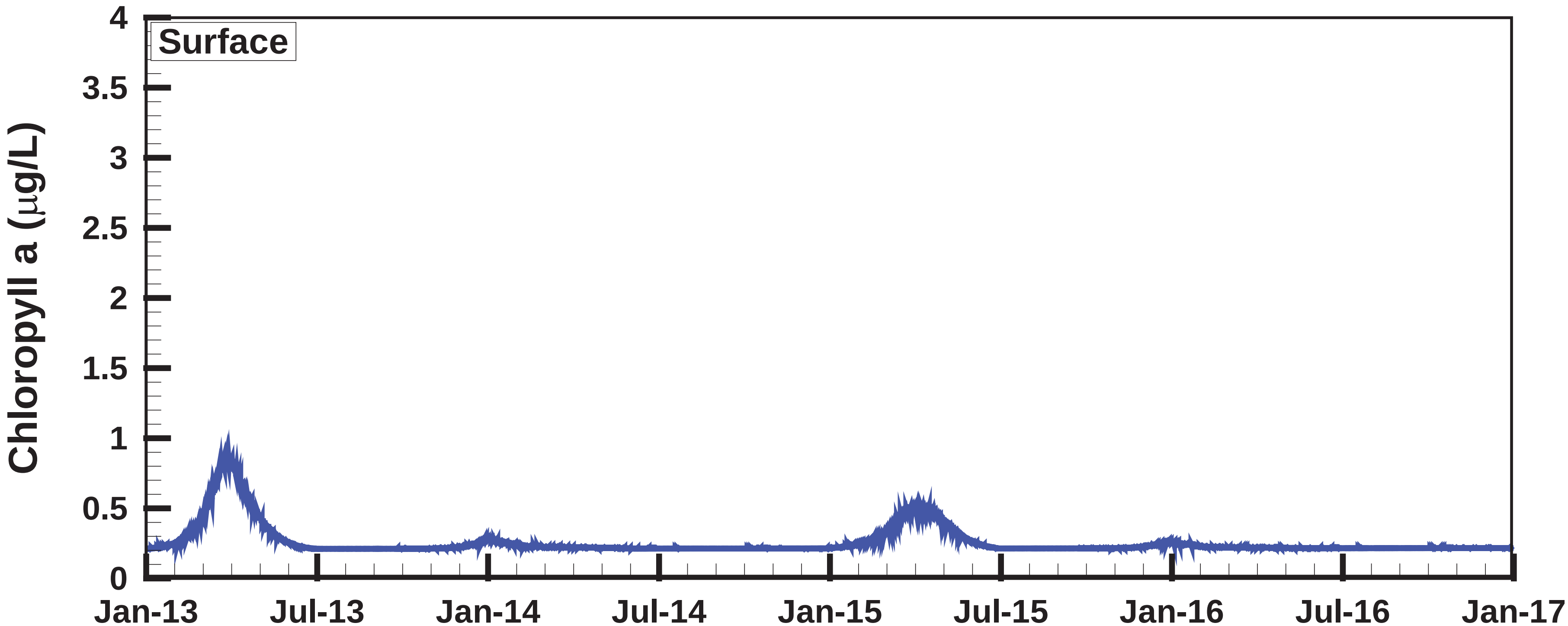


Figure 4.10

Future Scenario: Chlorophyll *a*

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings

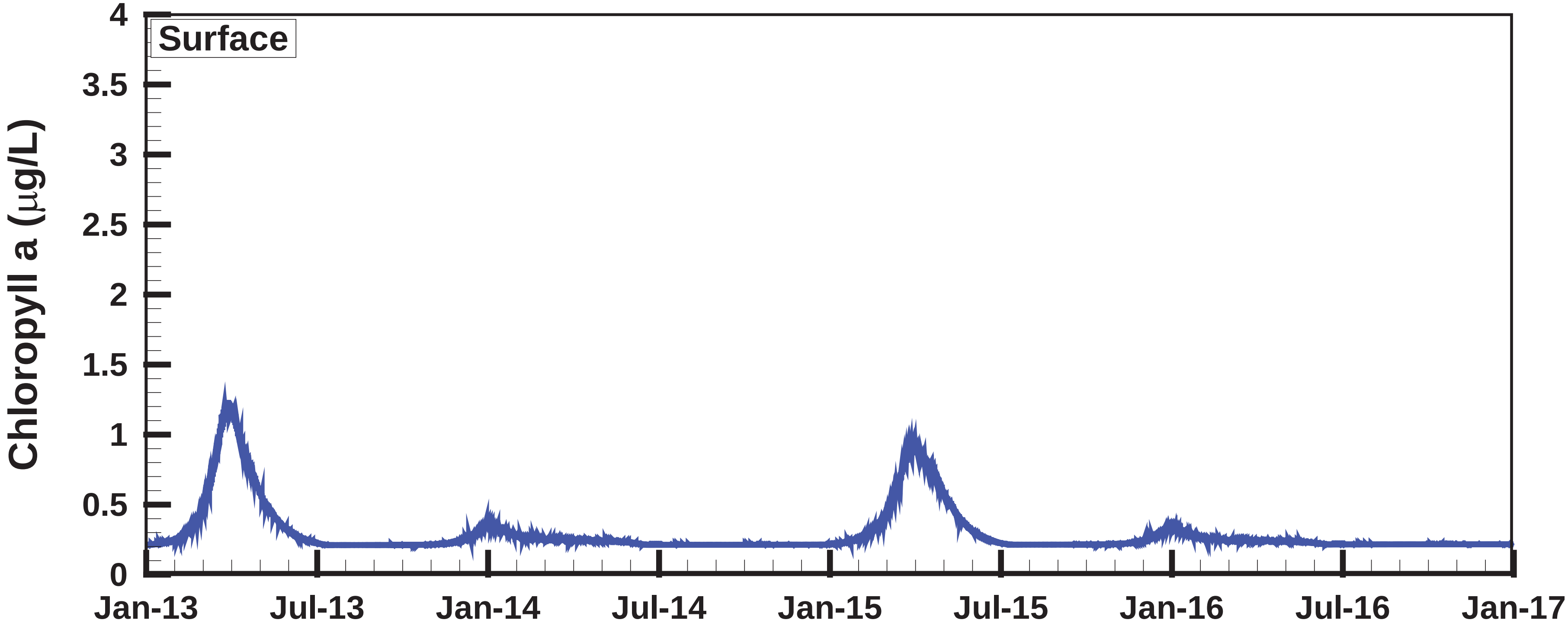


Figure 4.11

Chlorophyll *a*: Calibration vs. Future Scenarios

Moderate Nutrient Loadings

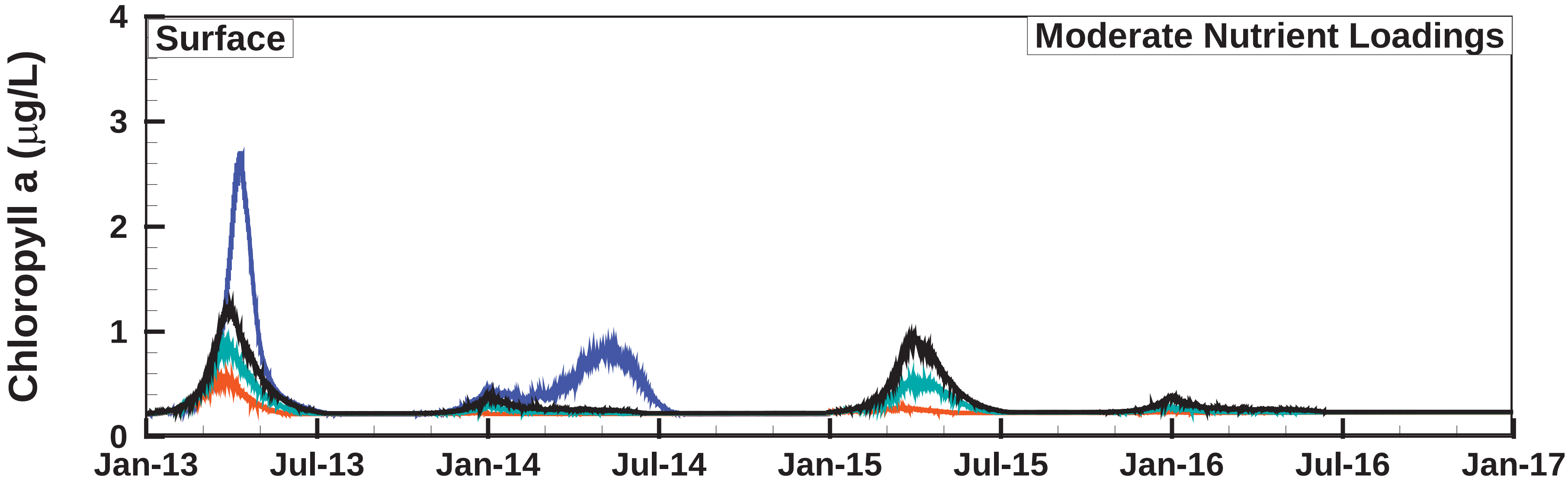
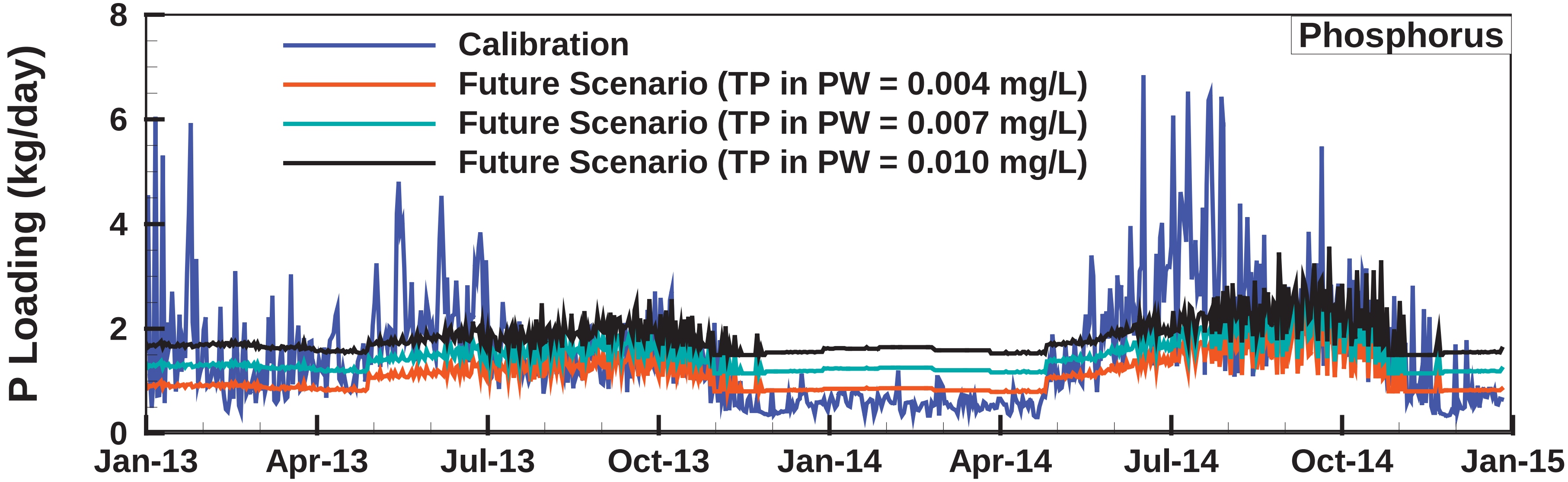


Figure 4.12

Total TP Loadings*: Calibration vs. Future Scenarios

Moderate Nutrient Loadings



*Including the nutrient loadings from inflows, unaccounted nutrient loadings, and the internal loading from anoxic sediments

Figure 4.13

Surface TP Concentrations: Calibration vs. Future Scenarios

Moderate Nutrient Loadings

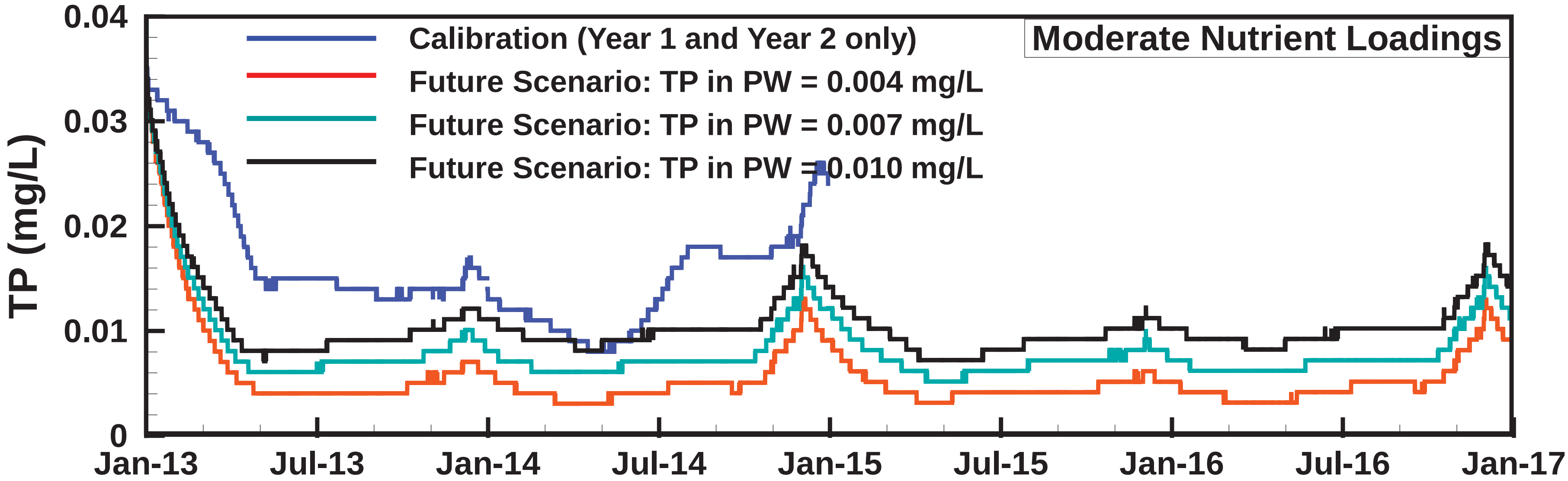


Figure 4.14

Appendix A: References

Dudek Environmental Consultants (2017). "Technical Memorandum on Identifying Potential Additional Sources of Nutrients to the Miramar Reservoir", Encinitas, CA, July, 2017.

Water Quality Solutions Inc. (2016). "Limnology and Detention Study of Miramar Reservoir", WQS Project 151005, McGaheysville, VA, August 2, 2016.

Appendix B: Additional Figures

Newly-Identified Nitrogen Loadings
Moderate Scenario

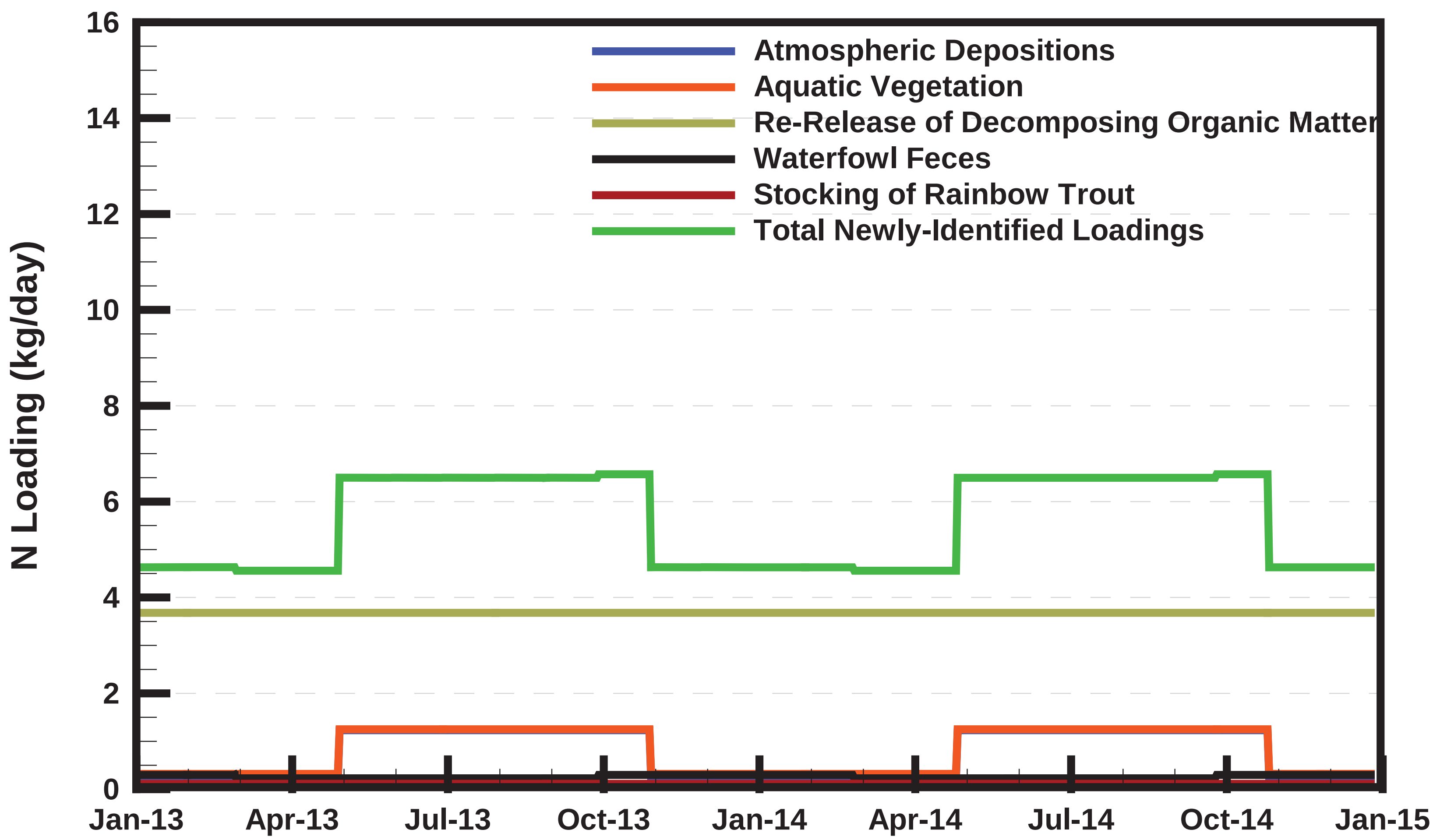


Figure B.1

Newly-Identified Nitrogen Loadings

High Scenario

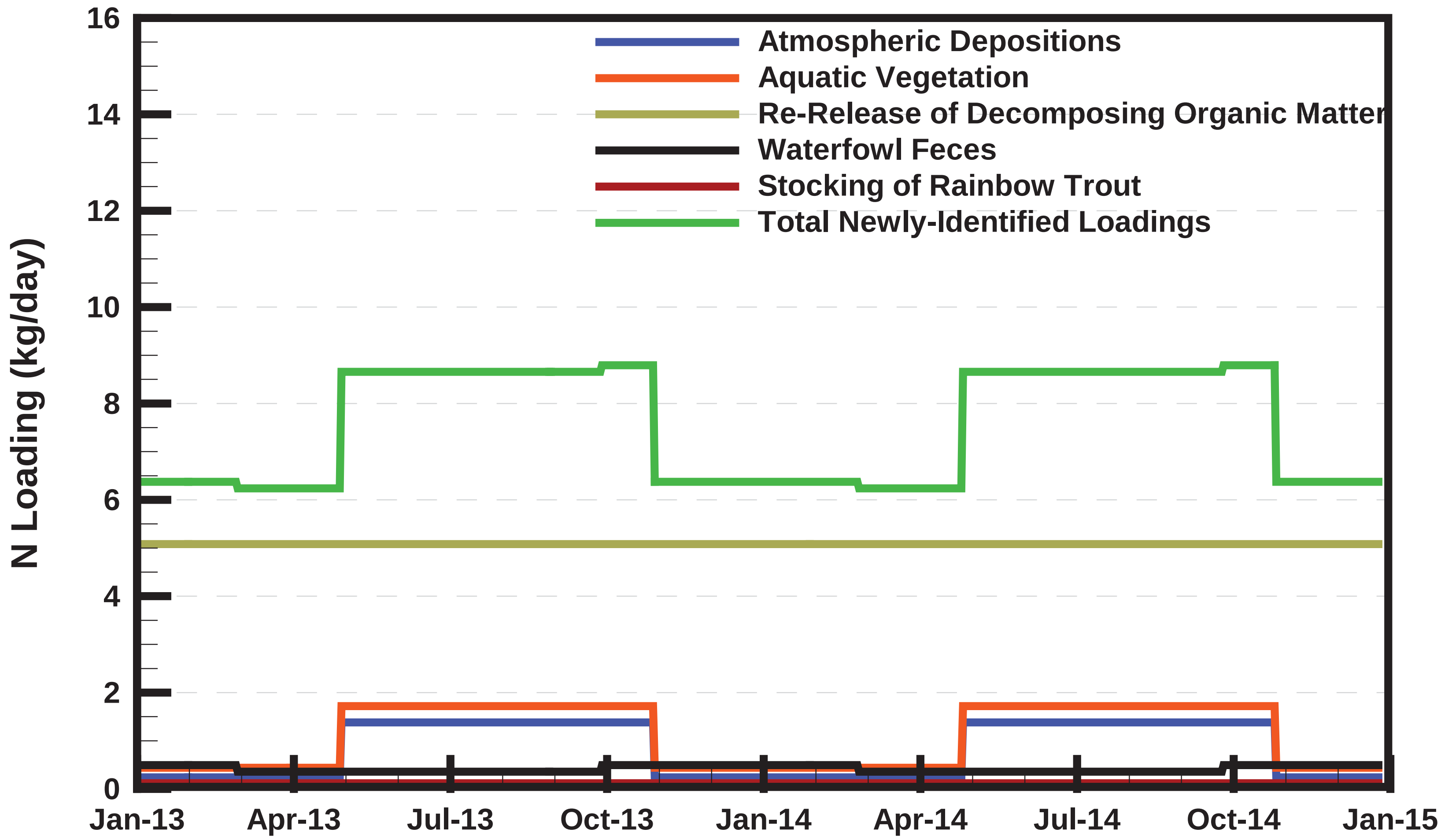
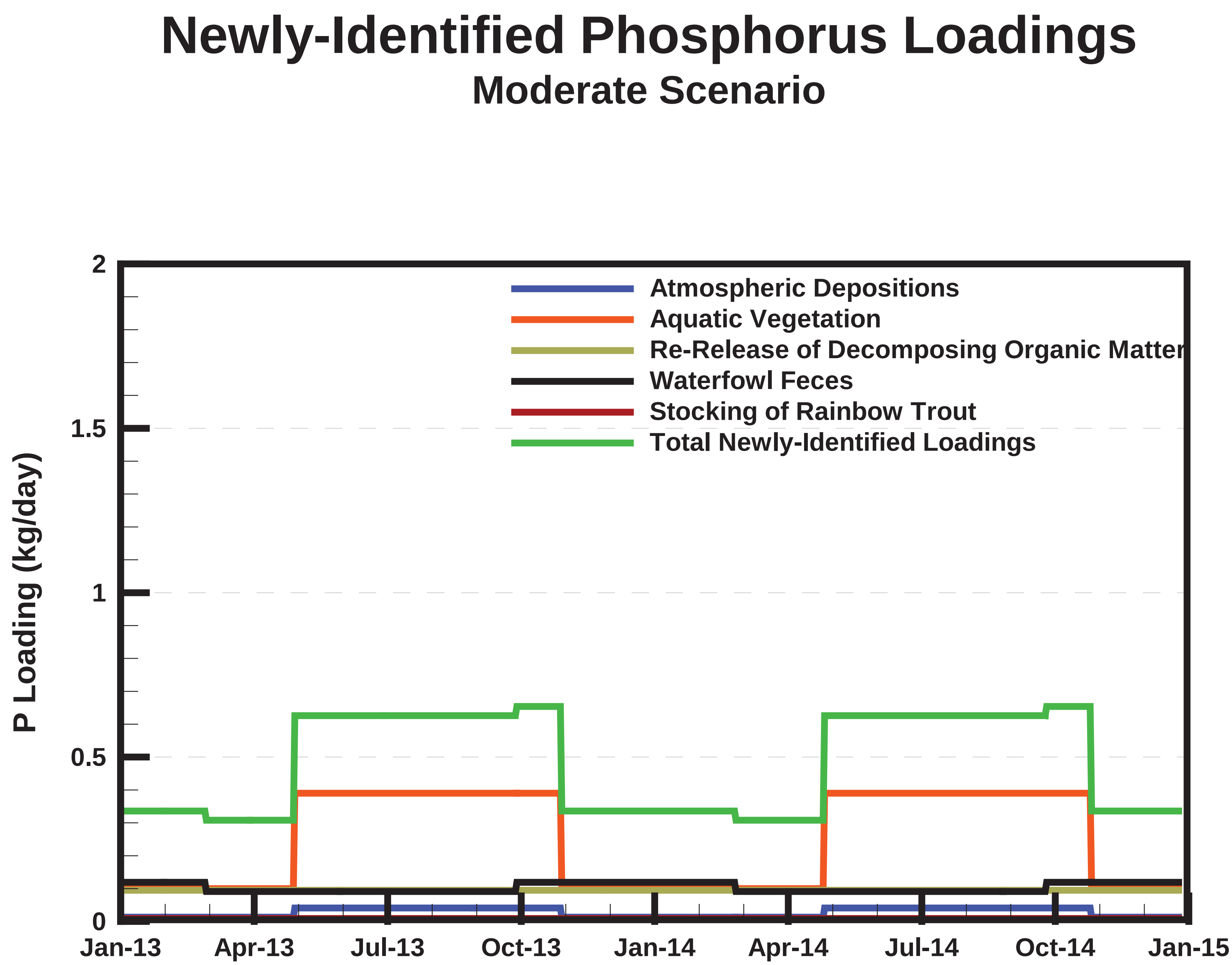
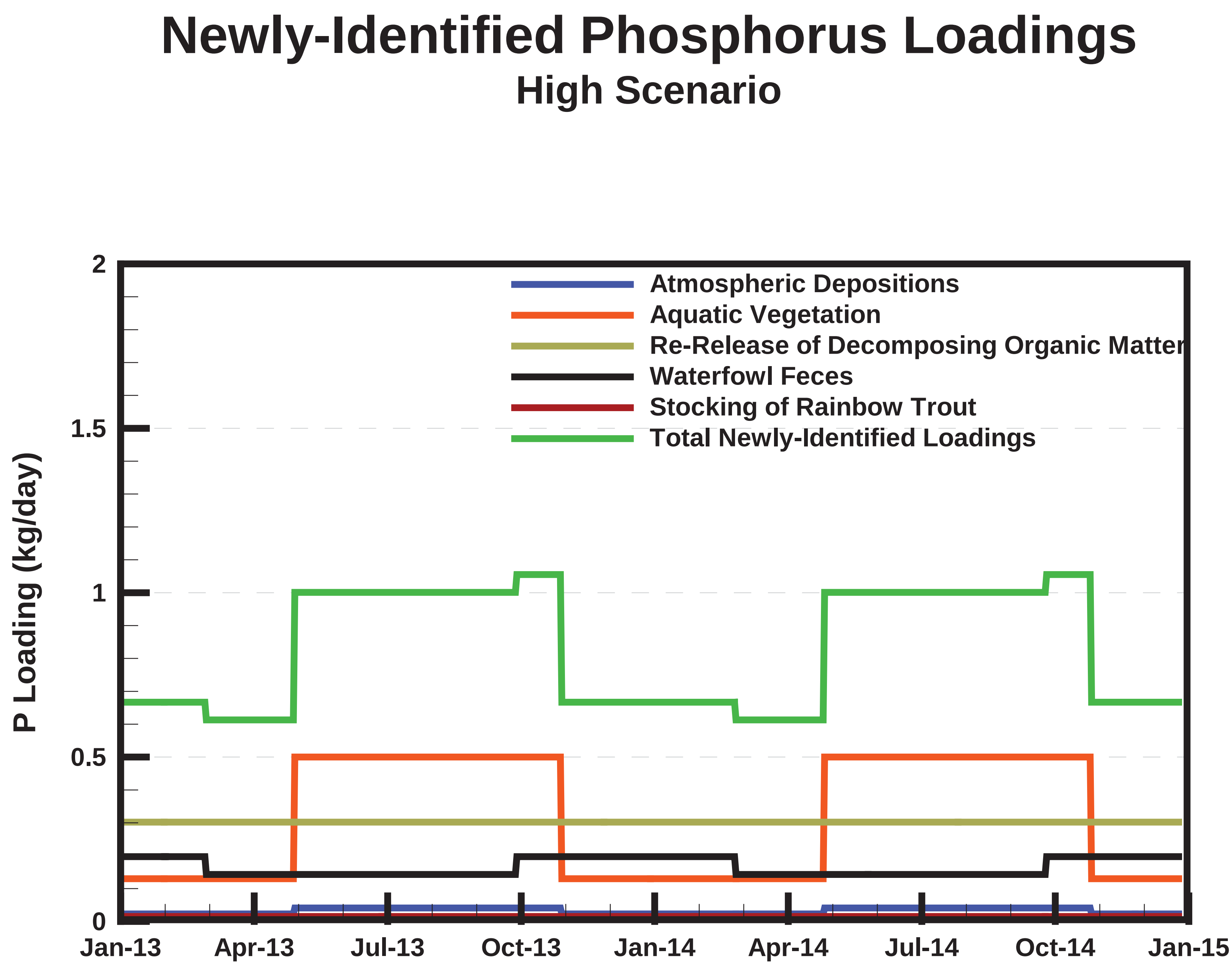


Figure B.2



Newly-Identified Phosphorus Loadings
Moderate Scenario
P Loading (kg/day)
2
1.5
1
0.5
0
Jan-13
Apr-13
Jul-13
Oct-13
Jan-14
Apr-14
Jul-14
Oct-14
Jan-15
Atmospheric Depositions
Aquatic Vegetation
Re-Release of Decomposing Organic Matter
Waterfowl Feces
Stocking of Rainbow Trout
Total Newly-Identified Loadings

Figure B.3



Newly-Identified Phosphorus Loadings
High Scenario
P Loading (kg/day)
2
1.5
1
0.5
0
Jan-13
Apr-13
Jul-13
Oct-13
Jan-14
Apr-14
Jul-14
Oct-14
Jan-15
Atmospheric Depositions
Aquatic Vegetation
Re-Release of Decomposing Organic Matter
Waterfowl Feces
Stocking of Rainbow Trout
Total Newly-Identified Loadings

Figure B.4

Calibration for Temperature

Moderate Nutrient Loadings

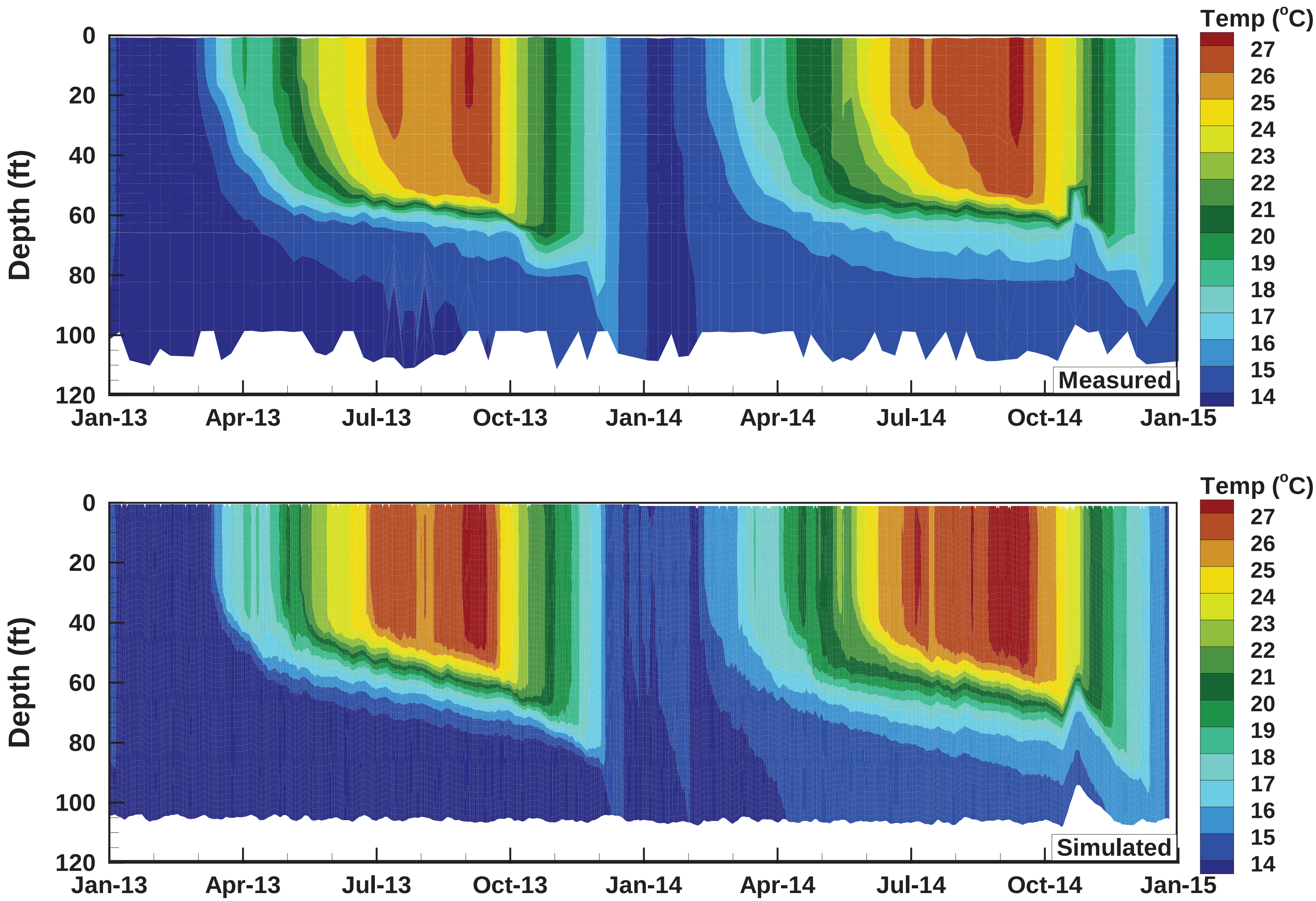


Figure B.5

Calibration for Dissolved Oxygen

Moderate Nutrient Loadings

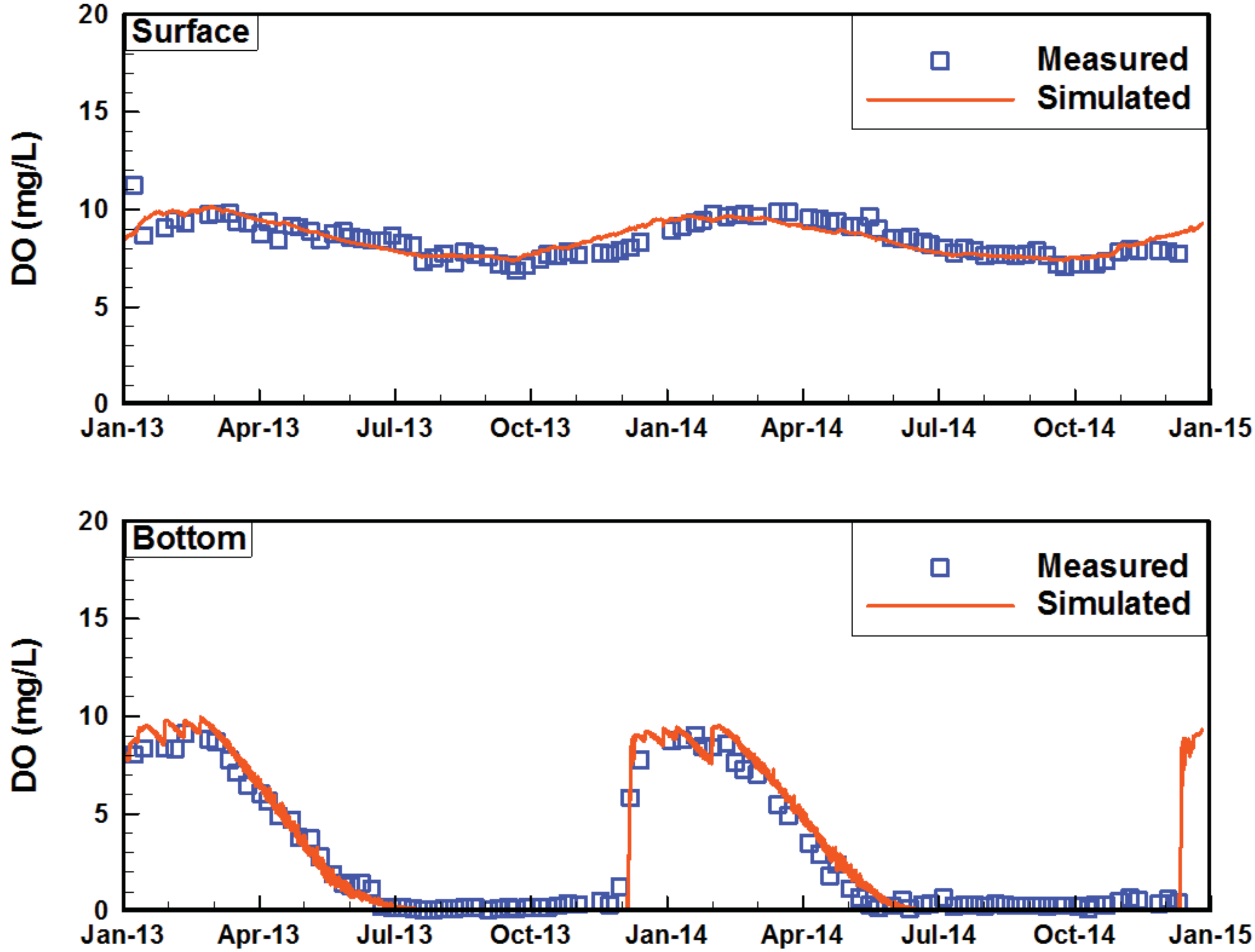


Figure B.6

Calibration for Ammonia

Moderate Nutrient Loadings

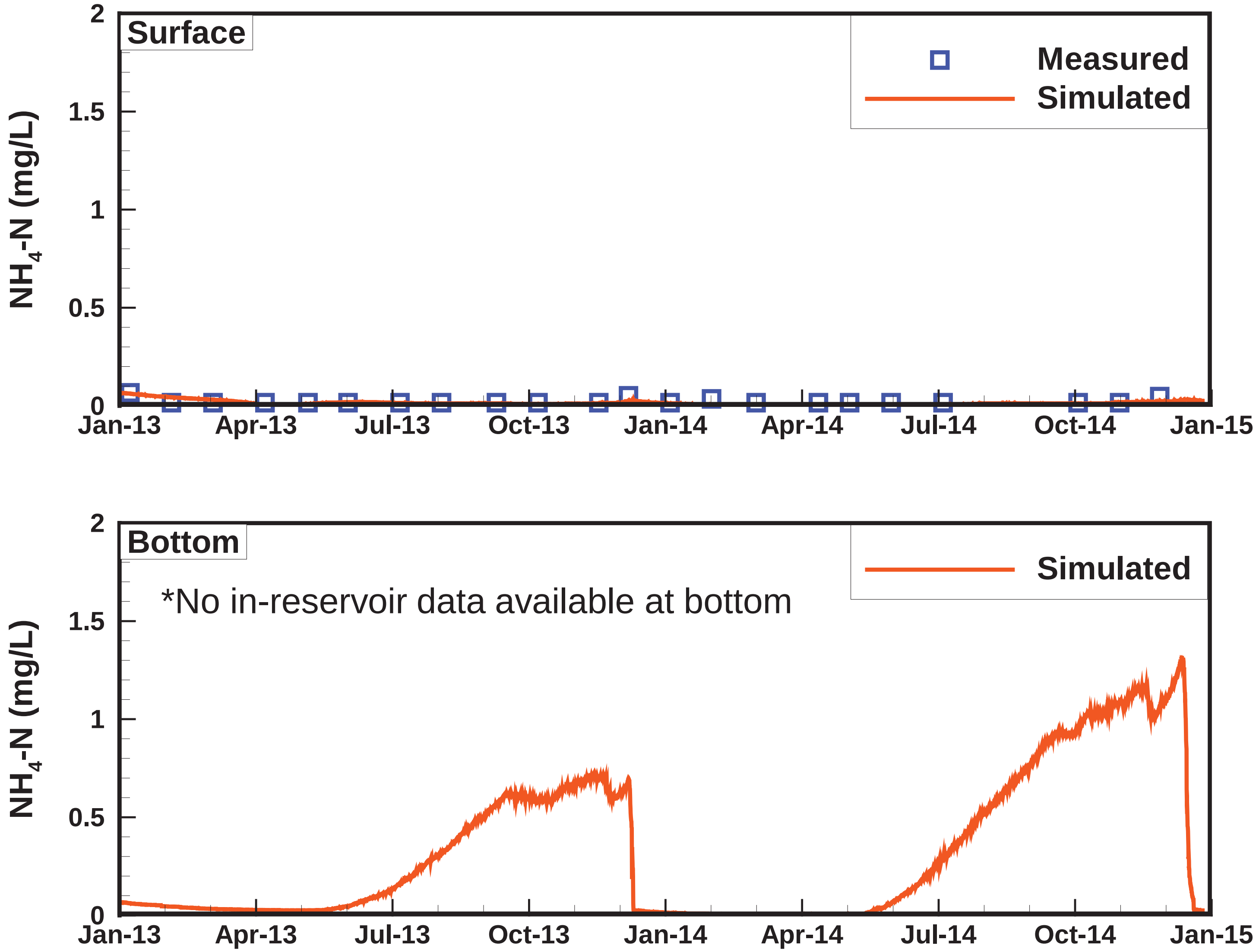
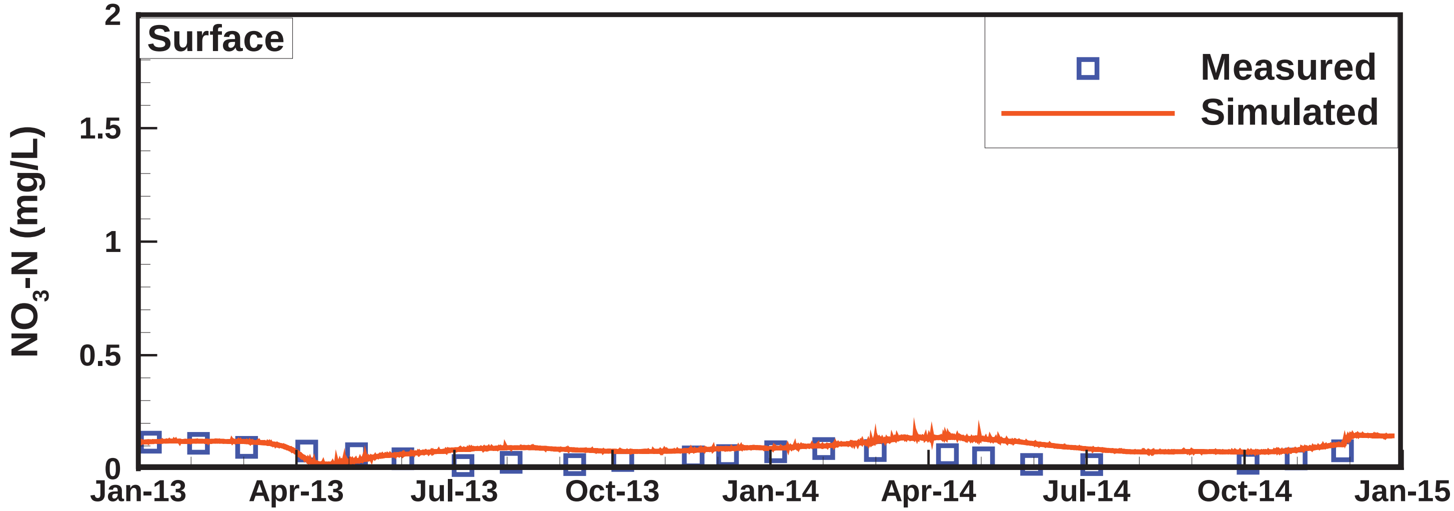


Figure B.7

Calibration for Nitrate

Moderate Nutrient Loadings



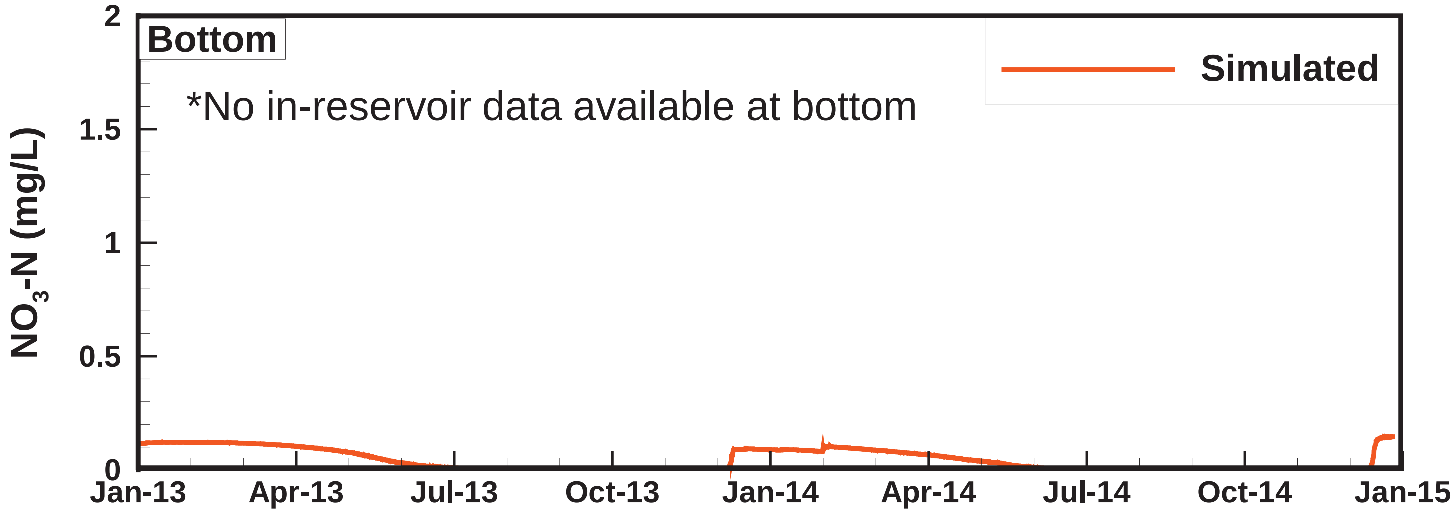
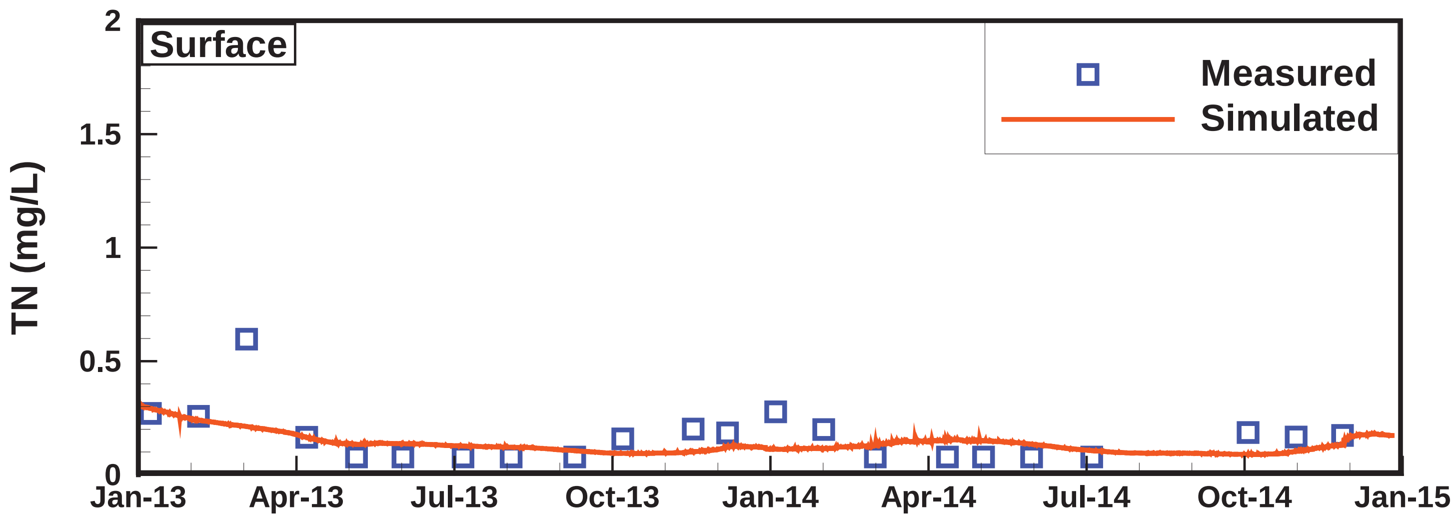


Figure B.8

Calibration for Total Nitrogen

Moderate Nutrient Loadings



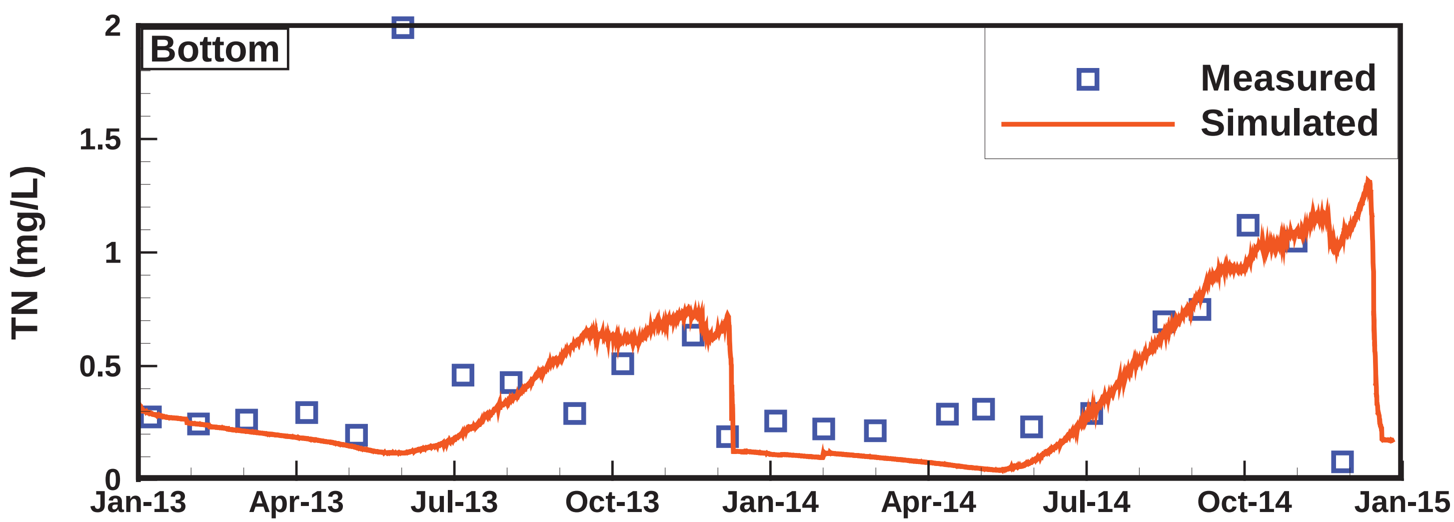
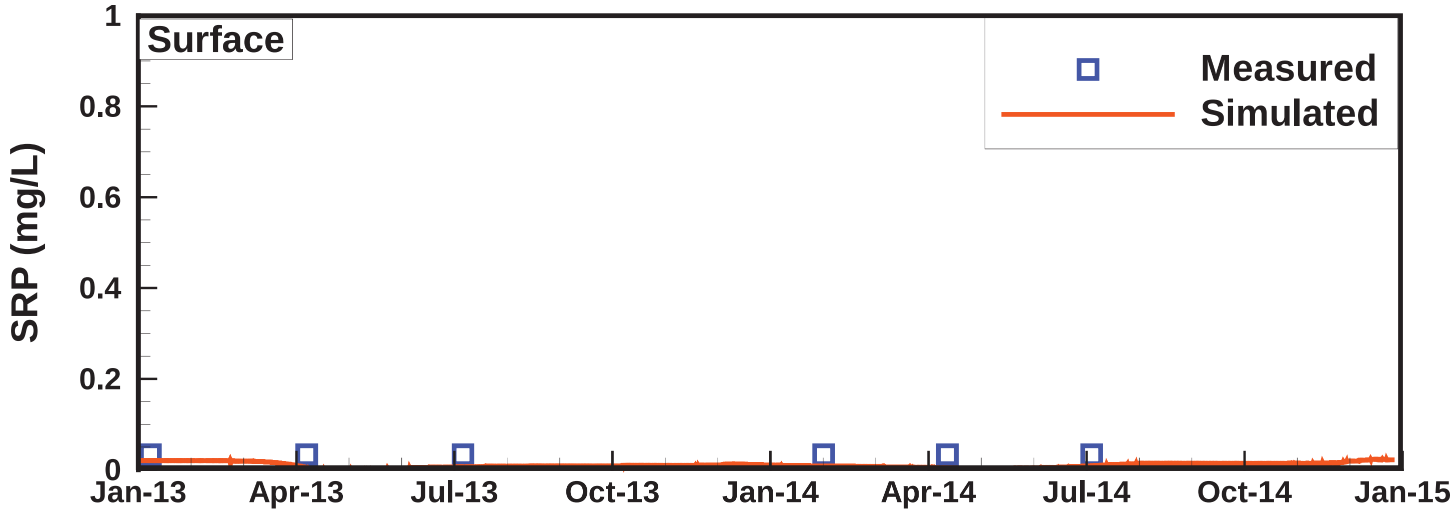


Figure B.9

Calibration for Soluble Reactive Phosphorus

Moderate Nutrient Loadings



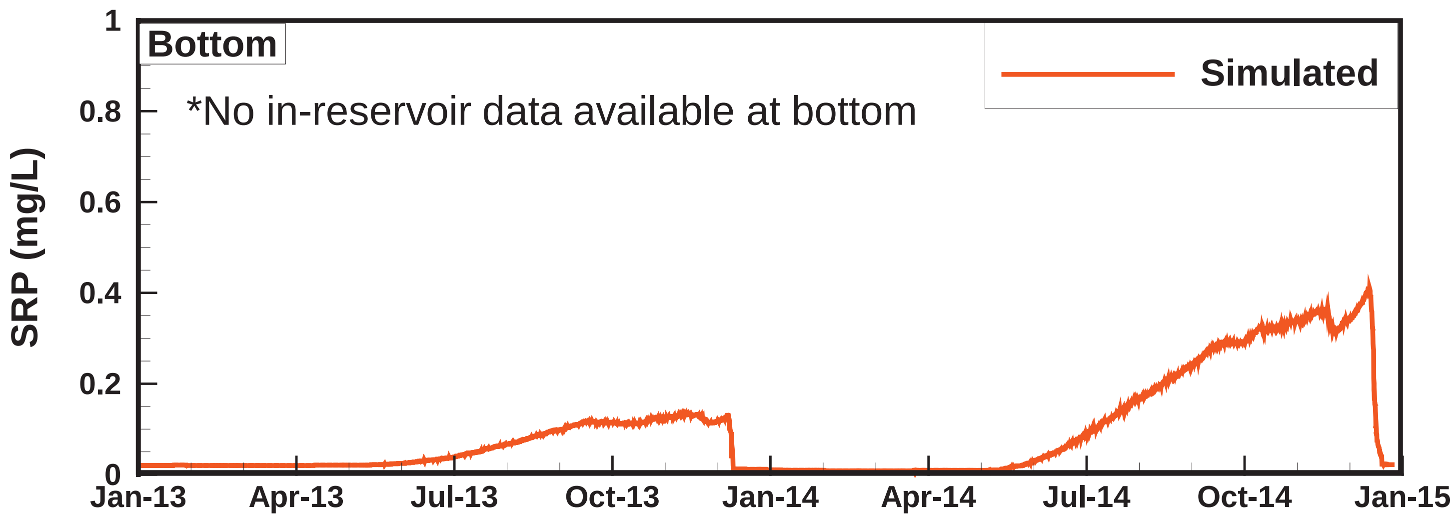


Figure B.10

Calibration for Total Phosphorus

Moderate Nutrient Loadings

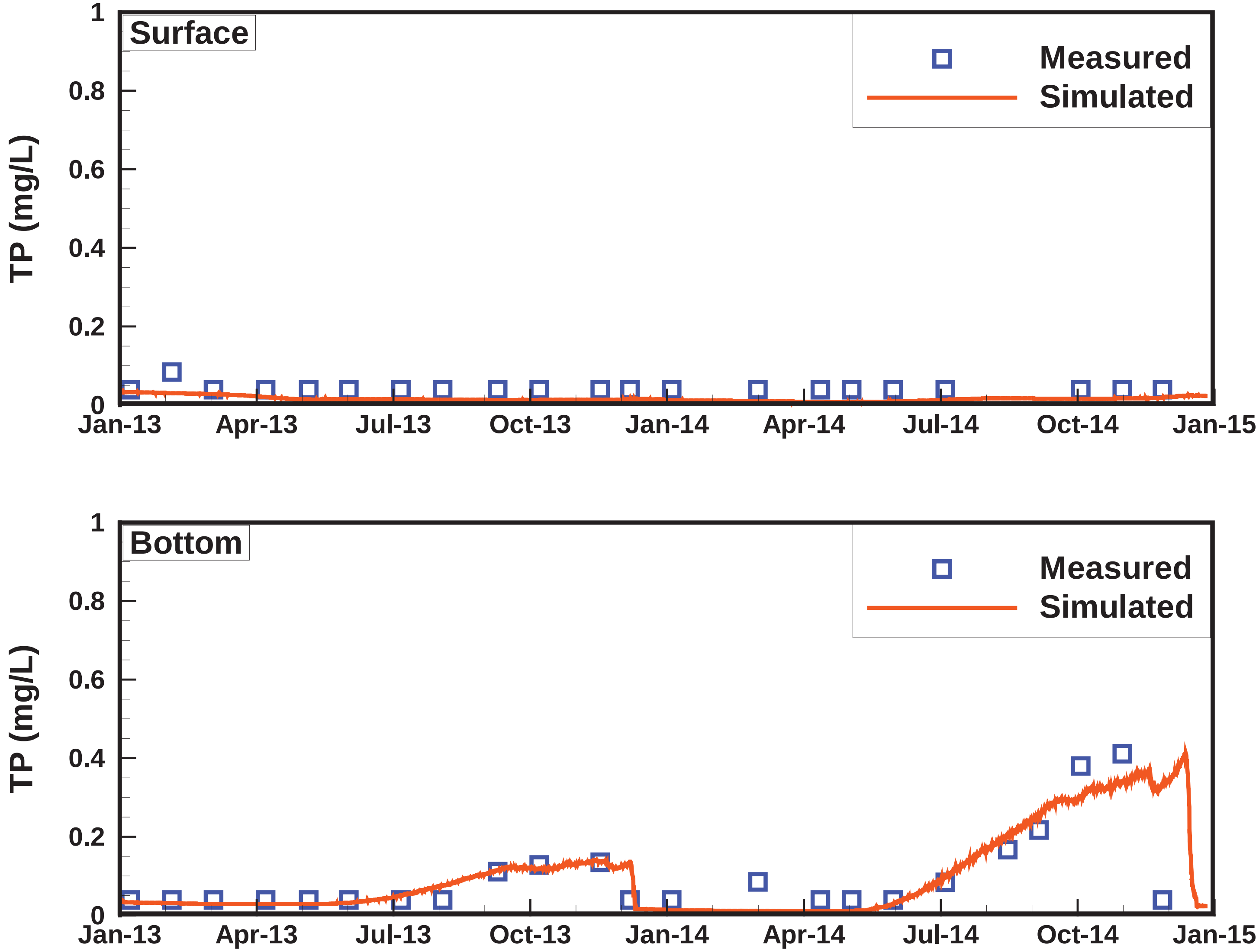
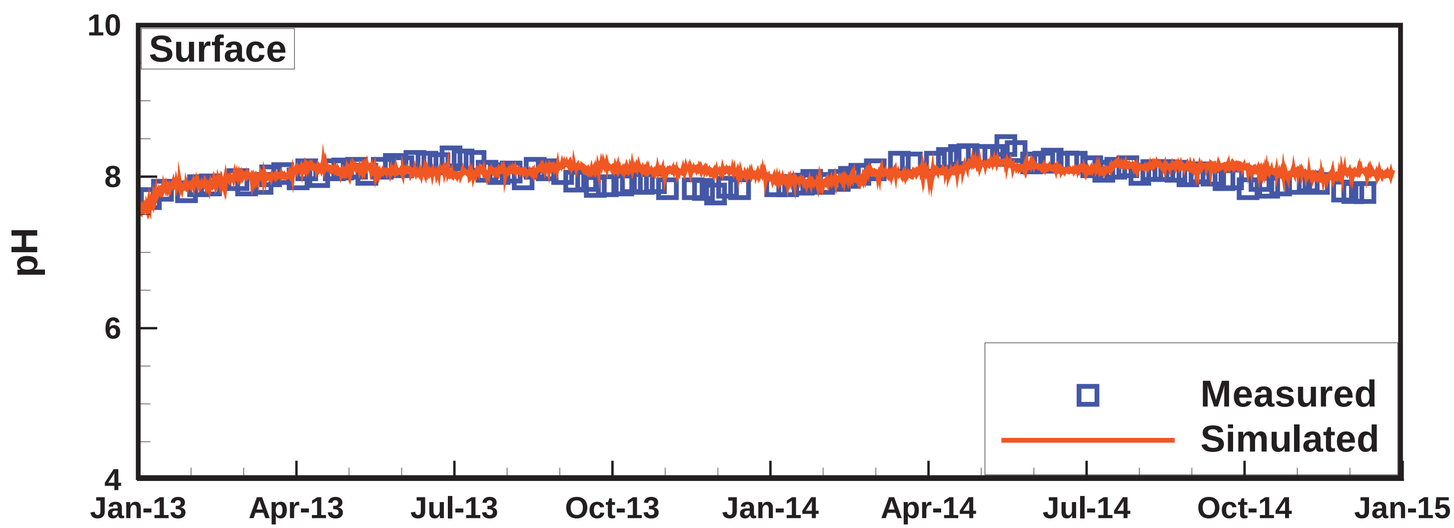


Figure B.11

Calibration for pH

Moderate Nutrient Loadings



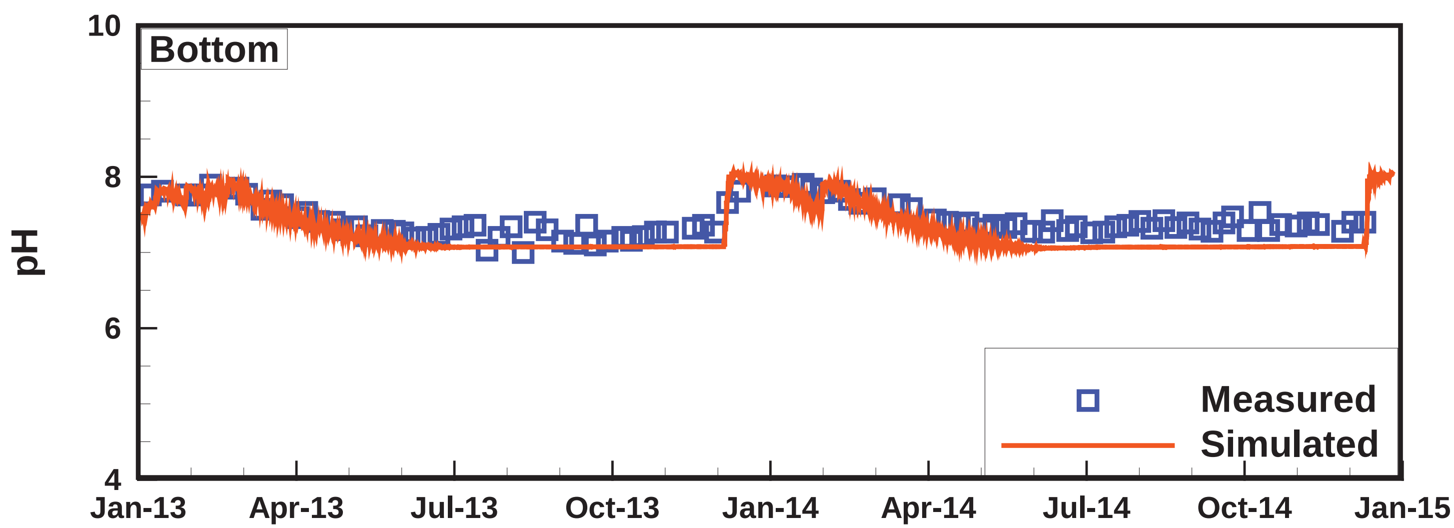


Figure B.12

Calibration for Temperature

High Nutrient Loadings

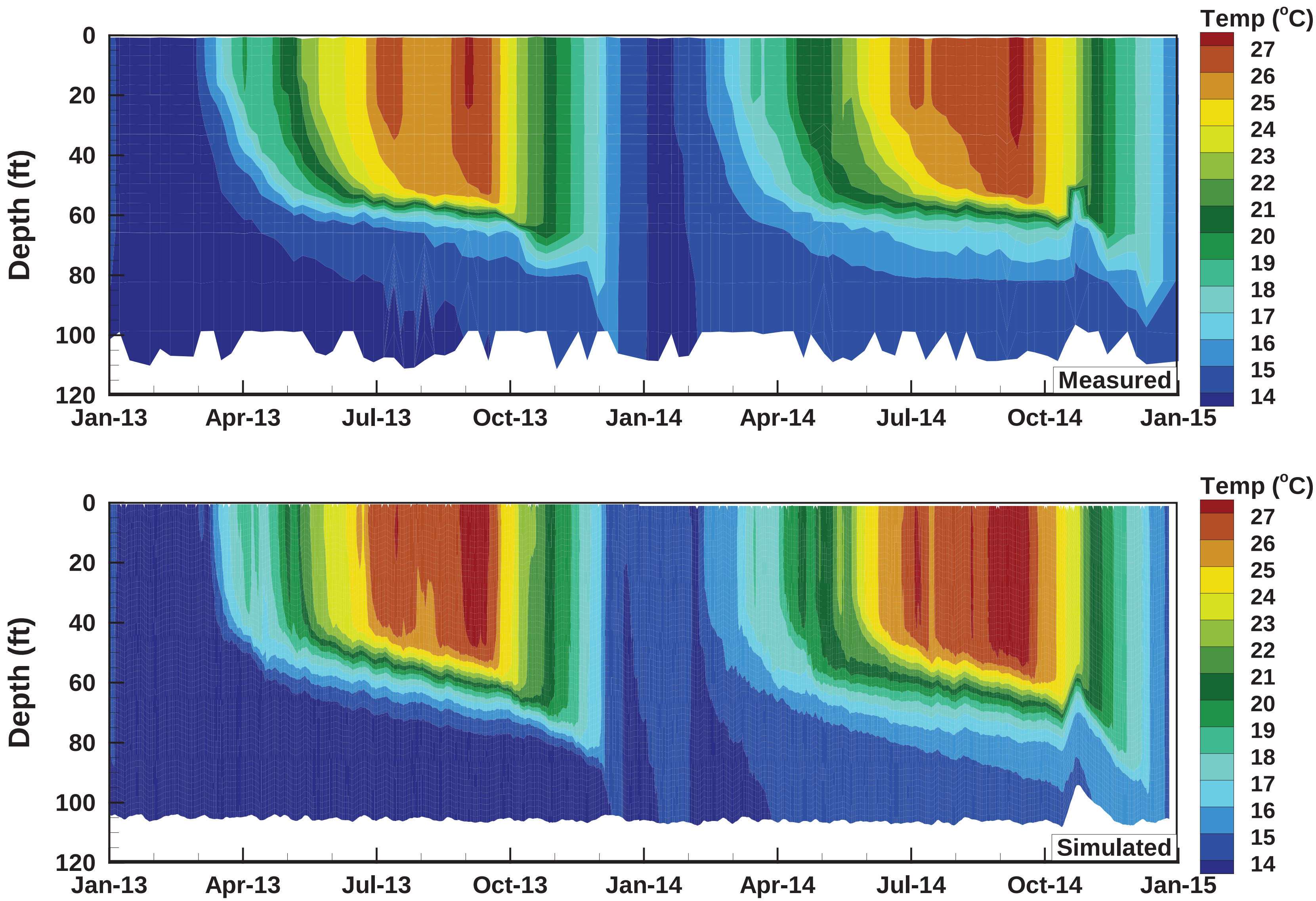


Figure B.13

Calibration for Dissolved Oxygen

High Nutrient Loadings

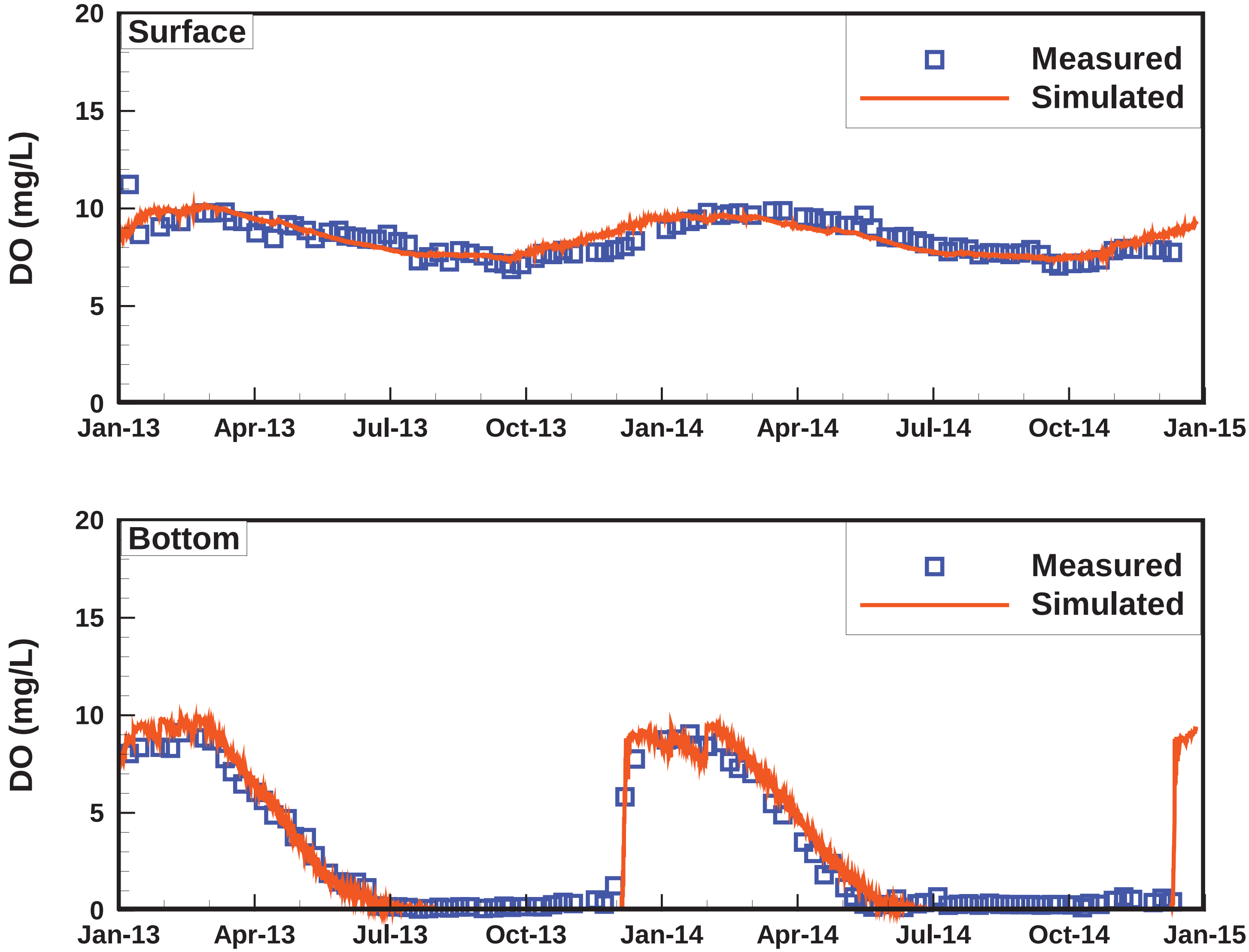
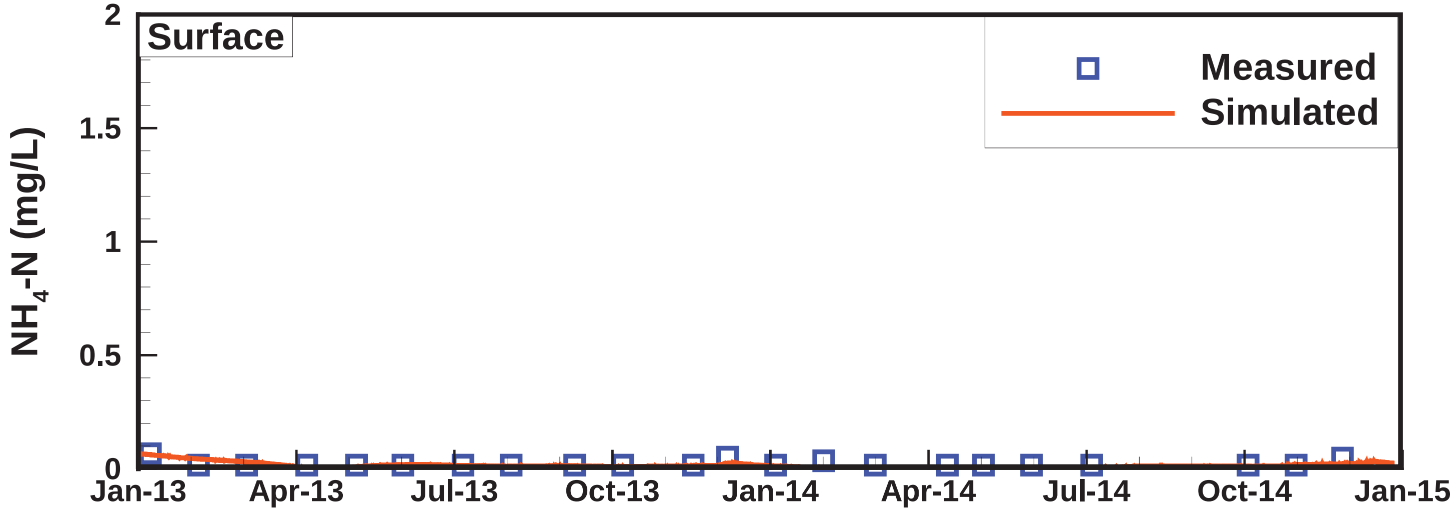


Figure B.14

Calibration for Ammonia

High Nutrient Loadings



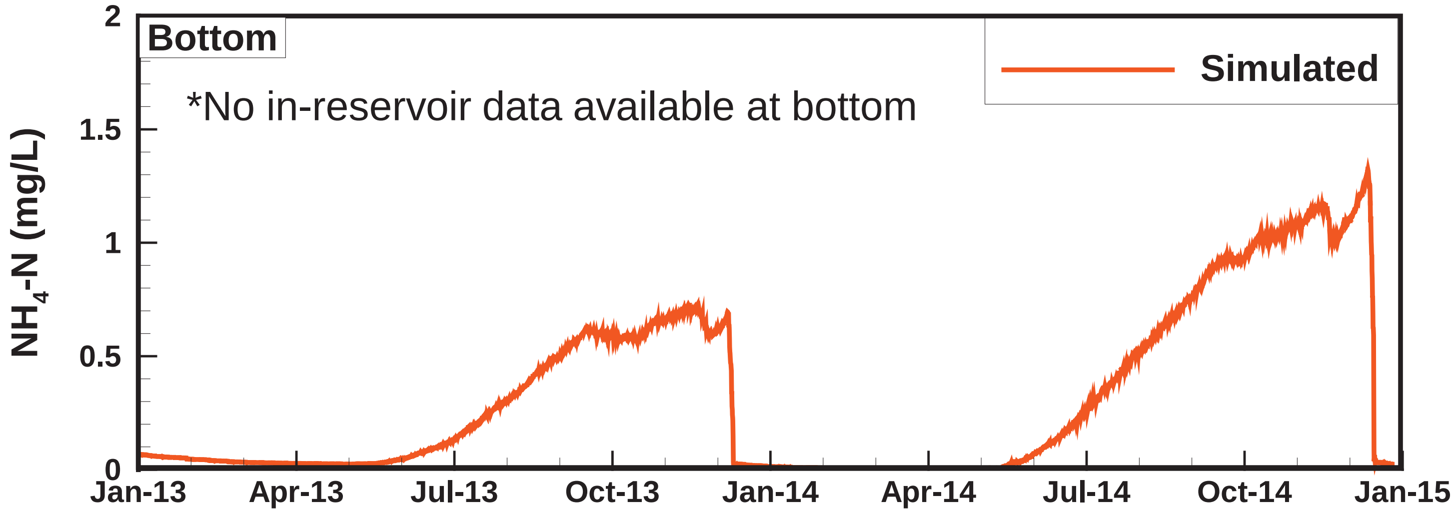
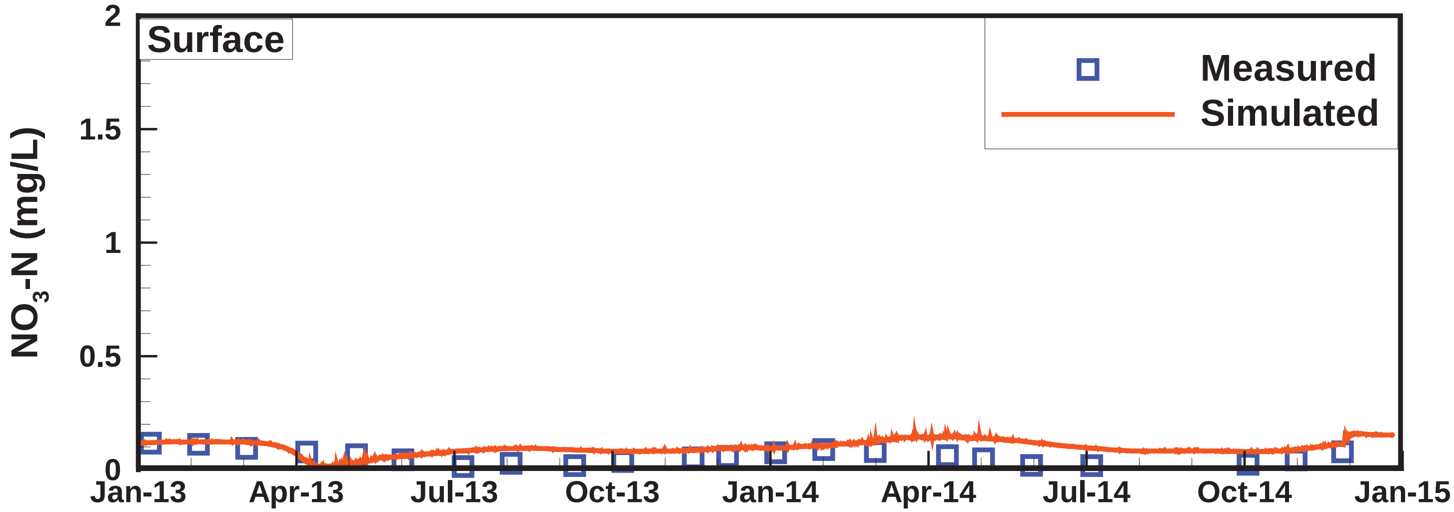


Figure B.15

Calibration for Nitrate

High Nutrient Loadings



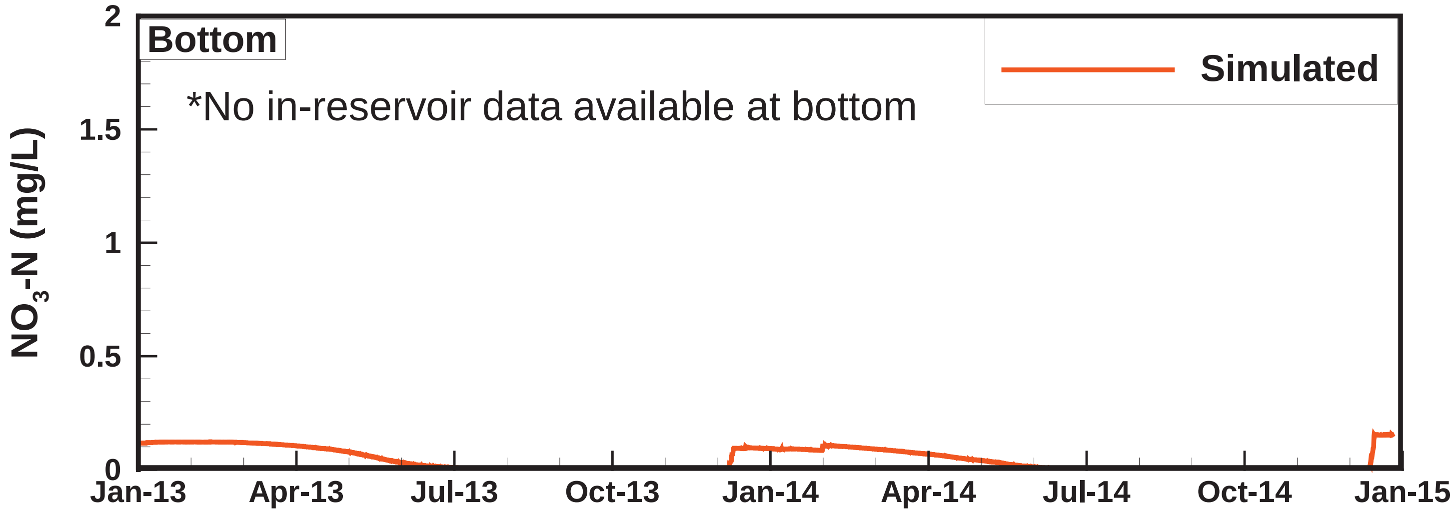
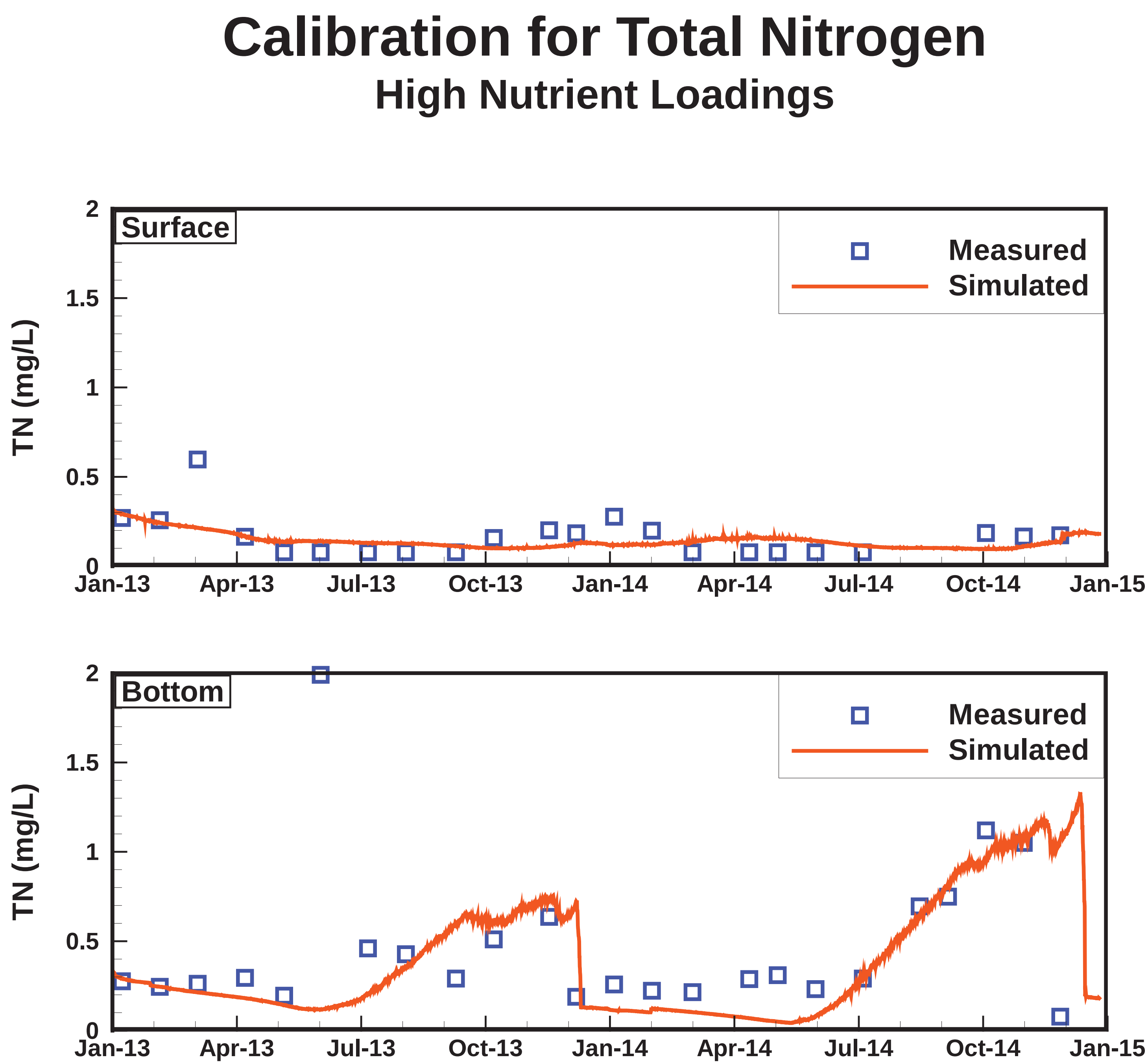


Figure B.16

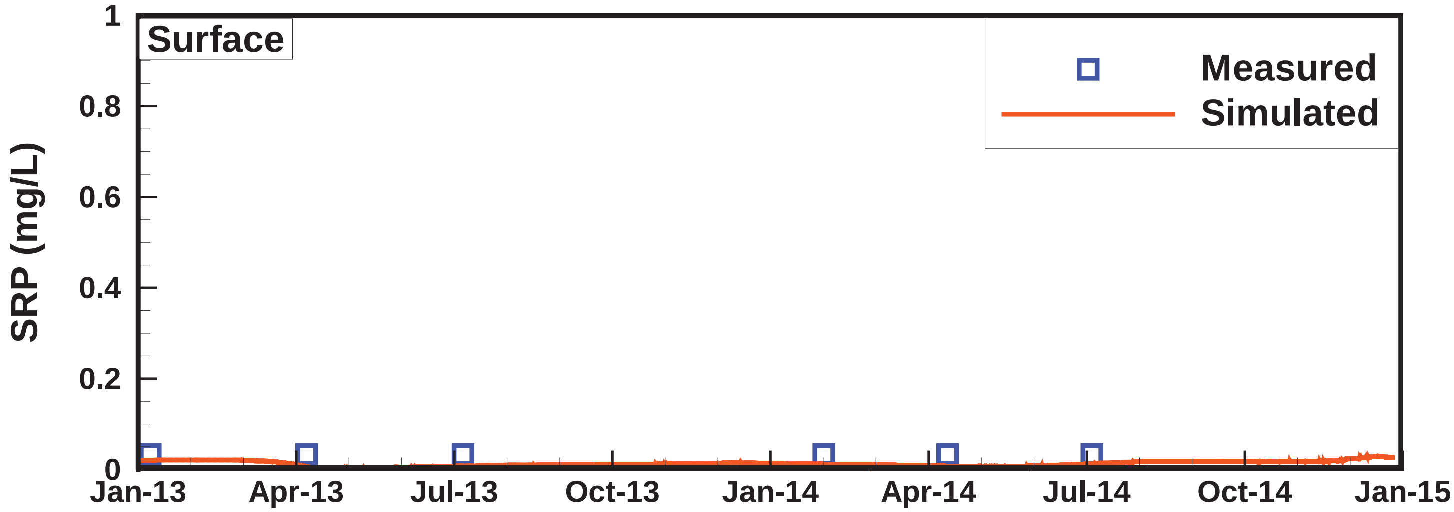


Calibration for Total Nitrogen
High Nutrient Loadings
Surface
Measured
Simulated
TN (mg/L)
2
1.5
1
0.5
0
Jan-13
Apr-13
Jul-13
Oct-13
Jan-14
Apr-14
Jul-14
Oct-14
Jan-15
Bottom
Measured
Simulated
TN (mg/L)
2
1.5
1
0.5
0
Jan-13
Apr-13
Jul-13
Oct-13
Jan-14
Apr-14
Jul-14
Oct-14
Jan-15

Figure B.17

Calibration for Soluble Reactive Phosphorus

High Nutrient Loadings



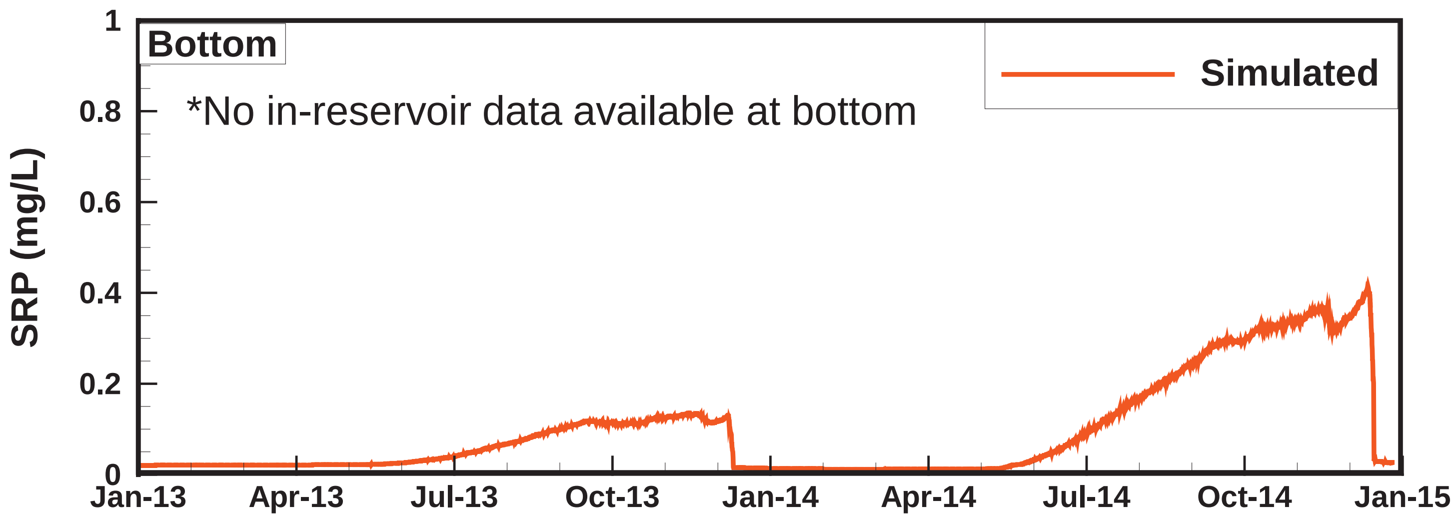


Figure B.18

Calibration for Total Phosphorus

High Nutrient Loadings

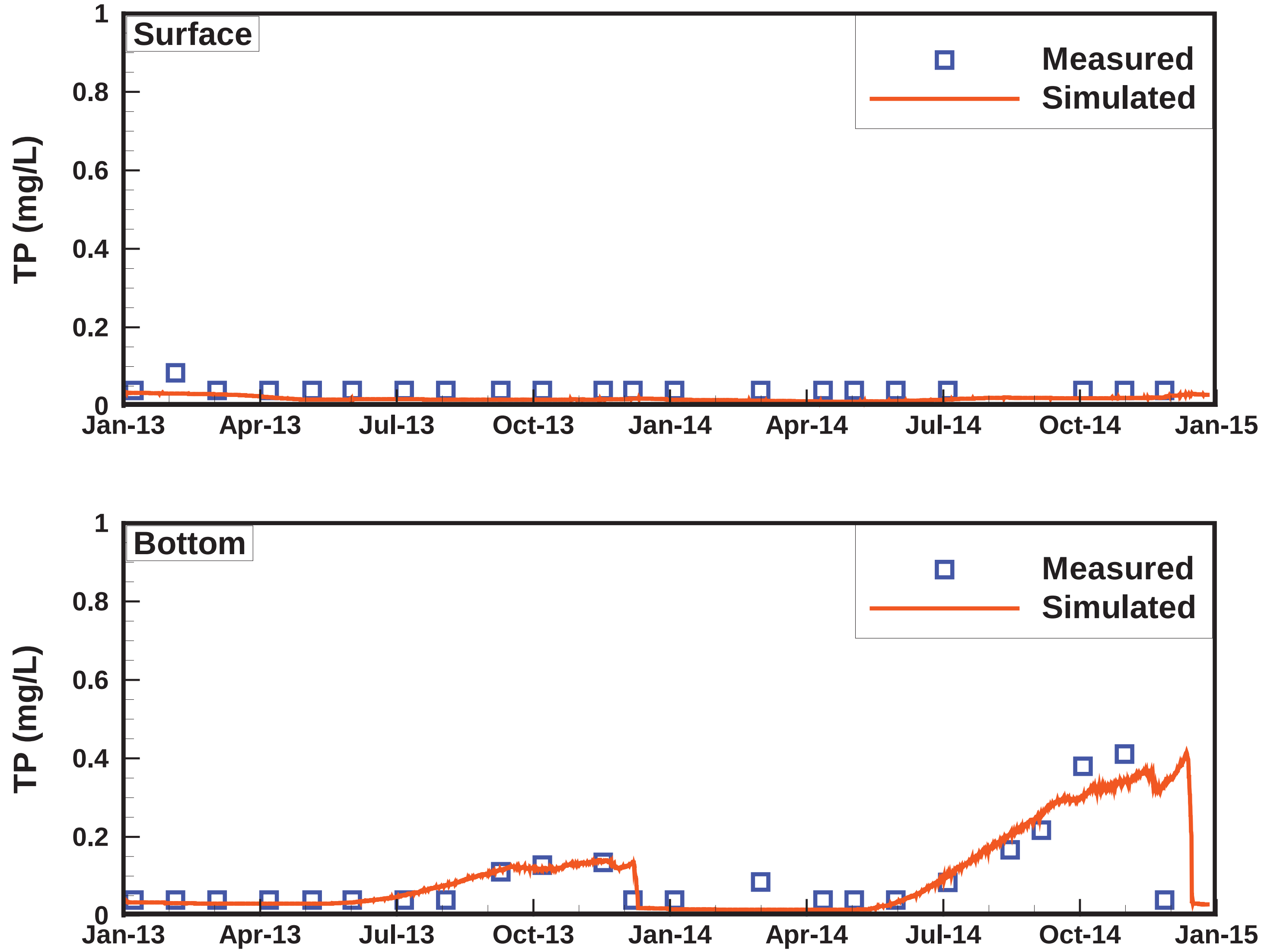
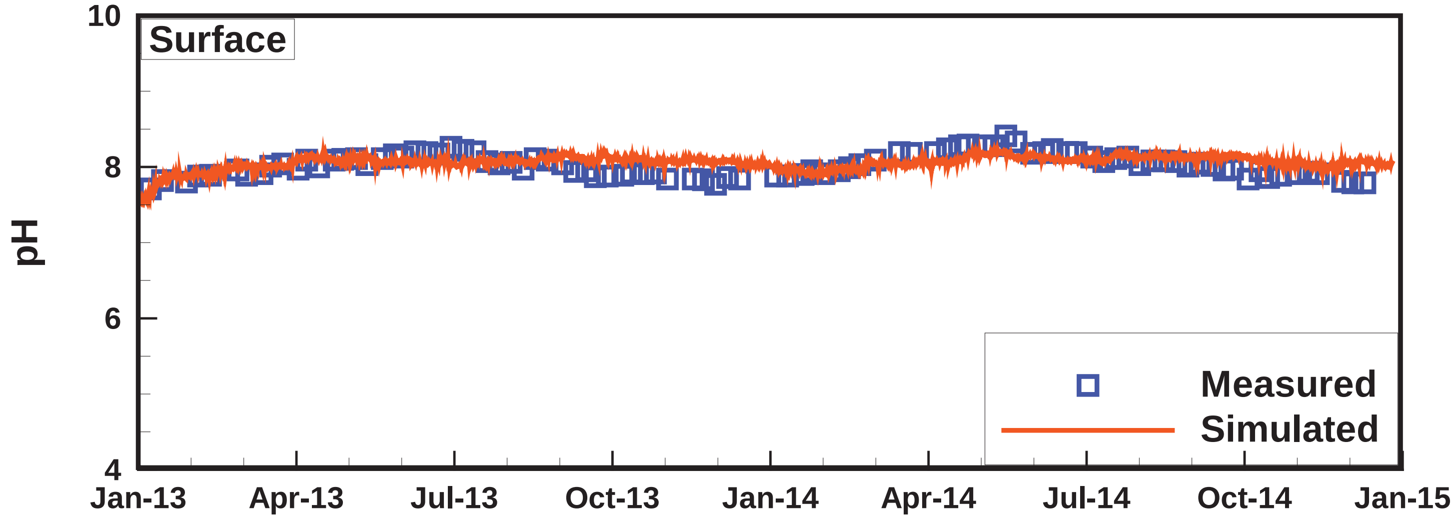


Figure B.19

Calibration for pH
High Nutrient Loadings



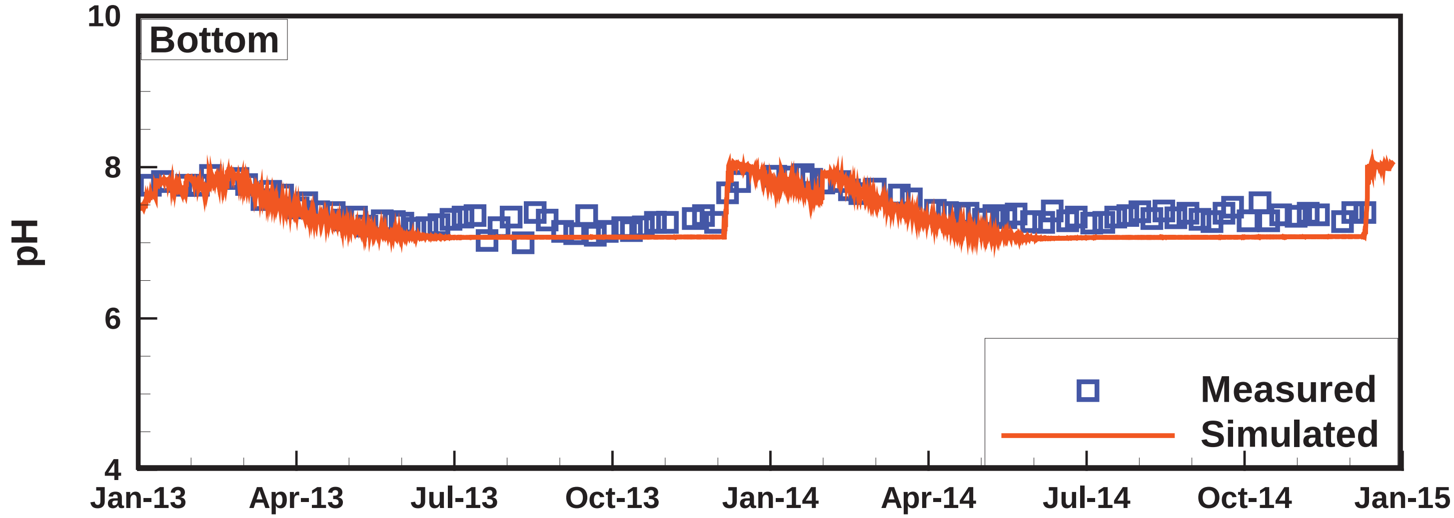
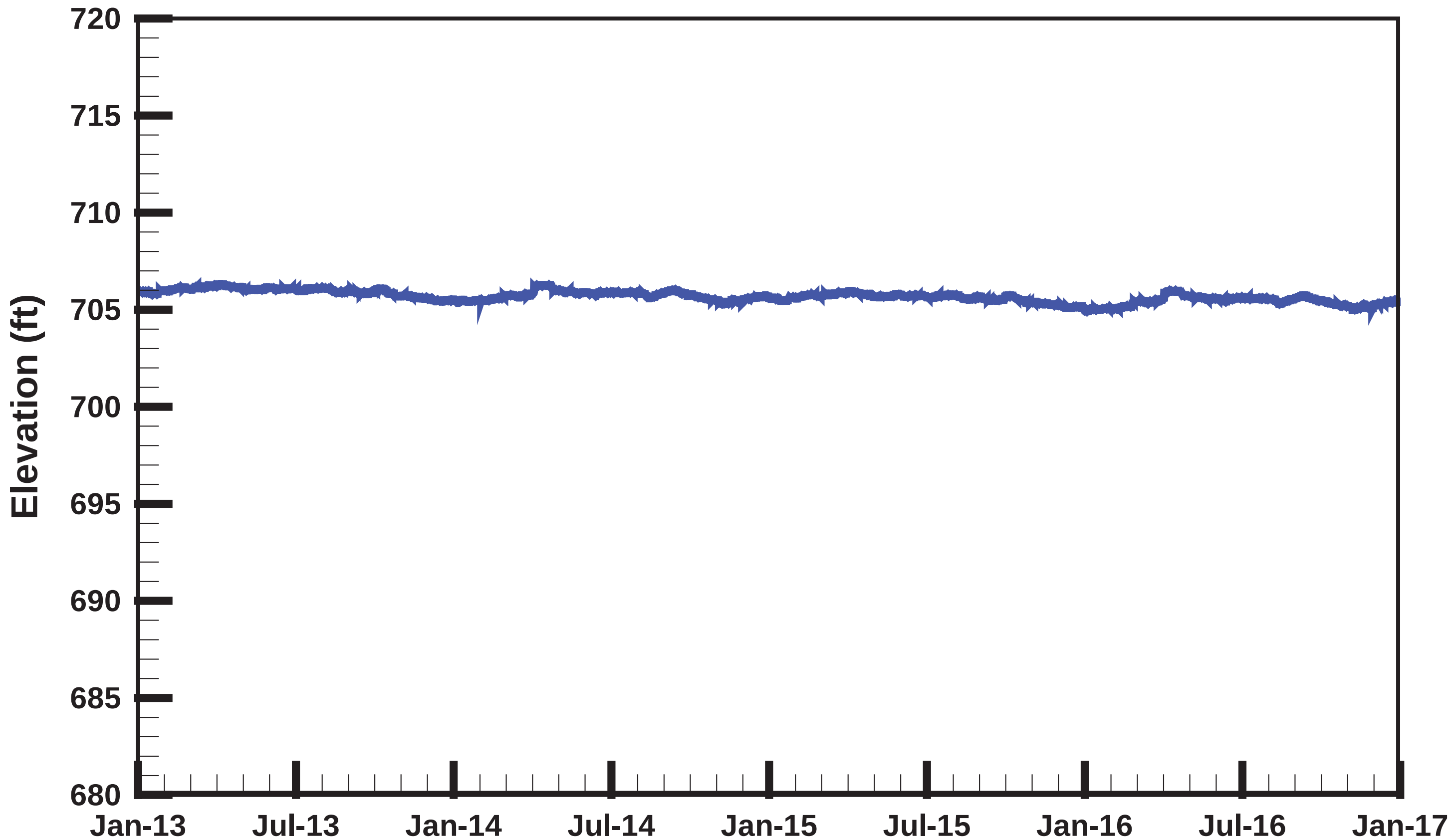


Figure B.20

Future Scenario: Water Surface Elevation*

Moderate and High Nutrient Loadings

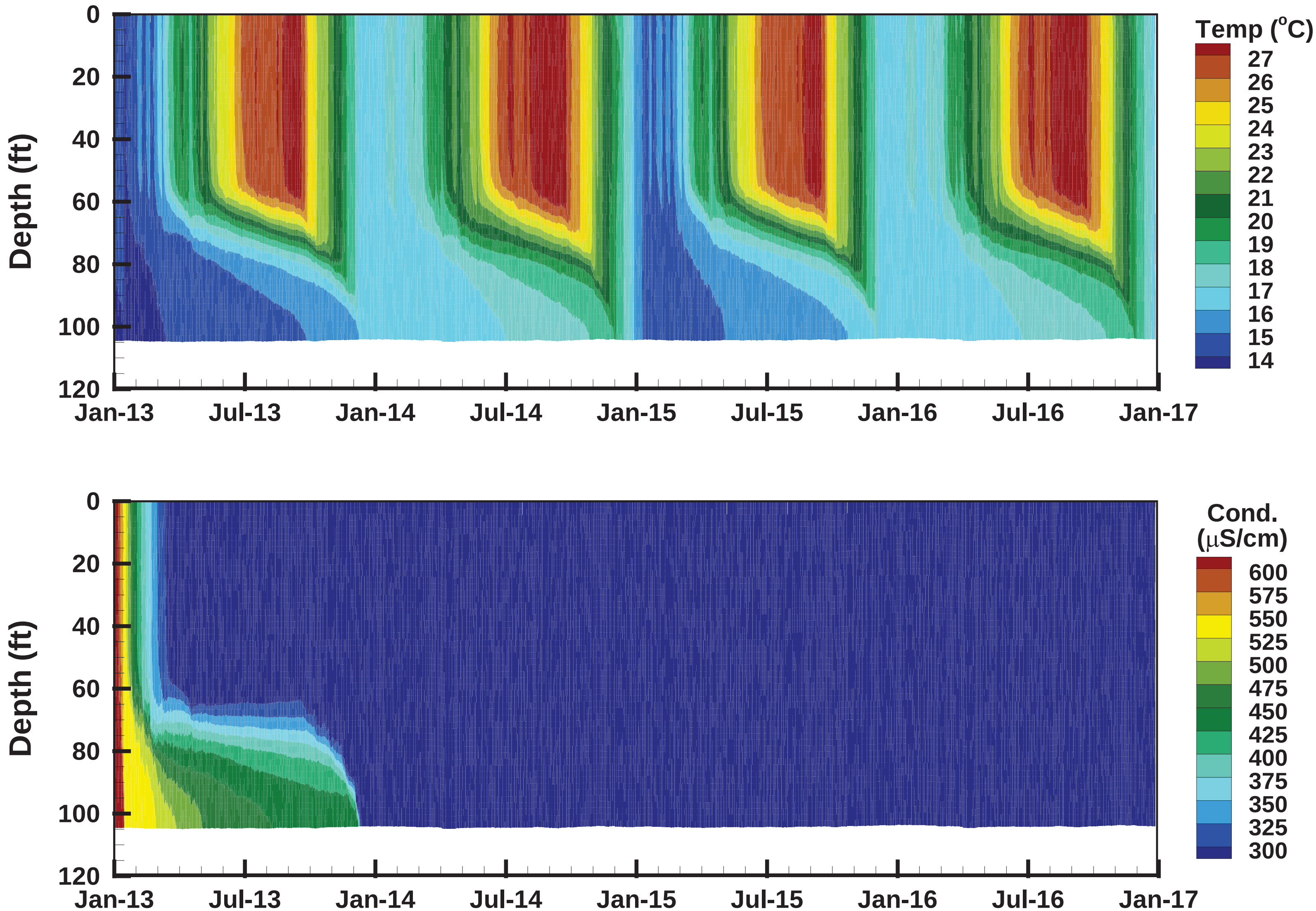


*Water surface elevation does not change with nutrient loadings.

Figure B.21

Future Scenario: Water Temperature and Conductivity*

Moderate and High Nutrient Loadings



*Water temperature and conductivity do not change with nutrient loadings.

Figure B.22

Future Scenario: Dissolved Oxygen

TP = 0.004 mg/L in PW; High Nutrient Loadings

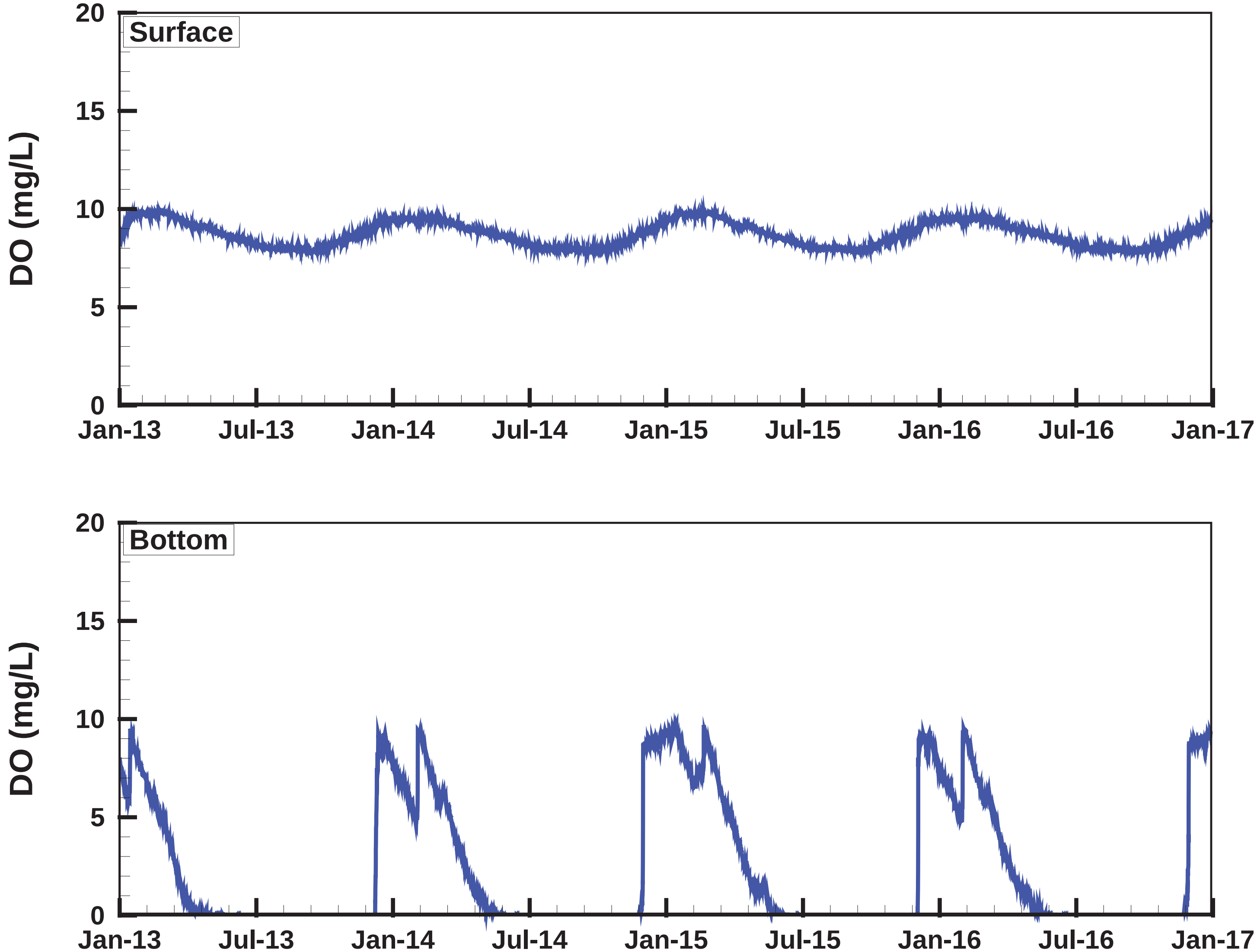


Figure B.23

Future Scenario: Ammonia

TP = 0.004 mg/L in PW; High Nutrient Loadings

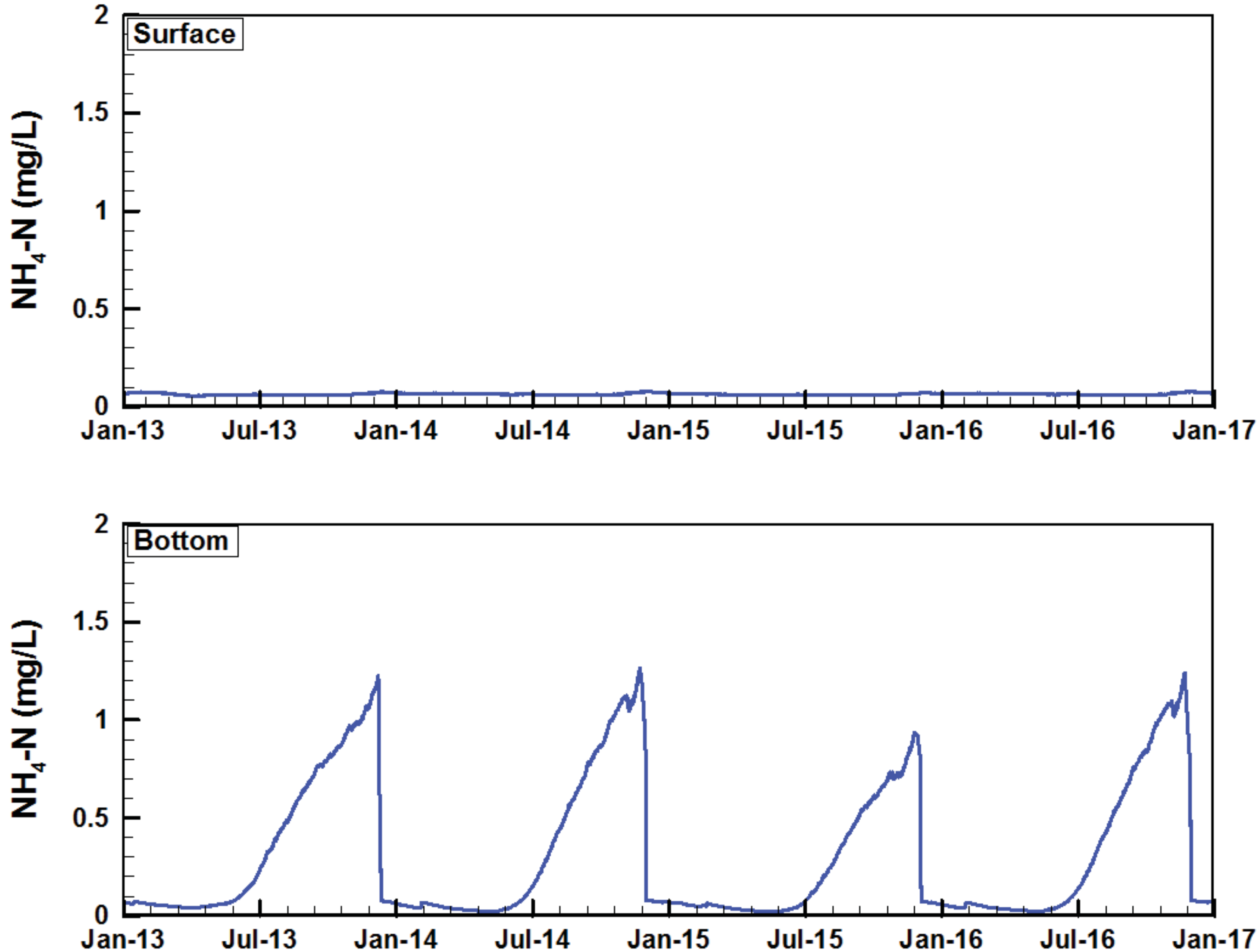
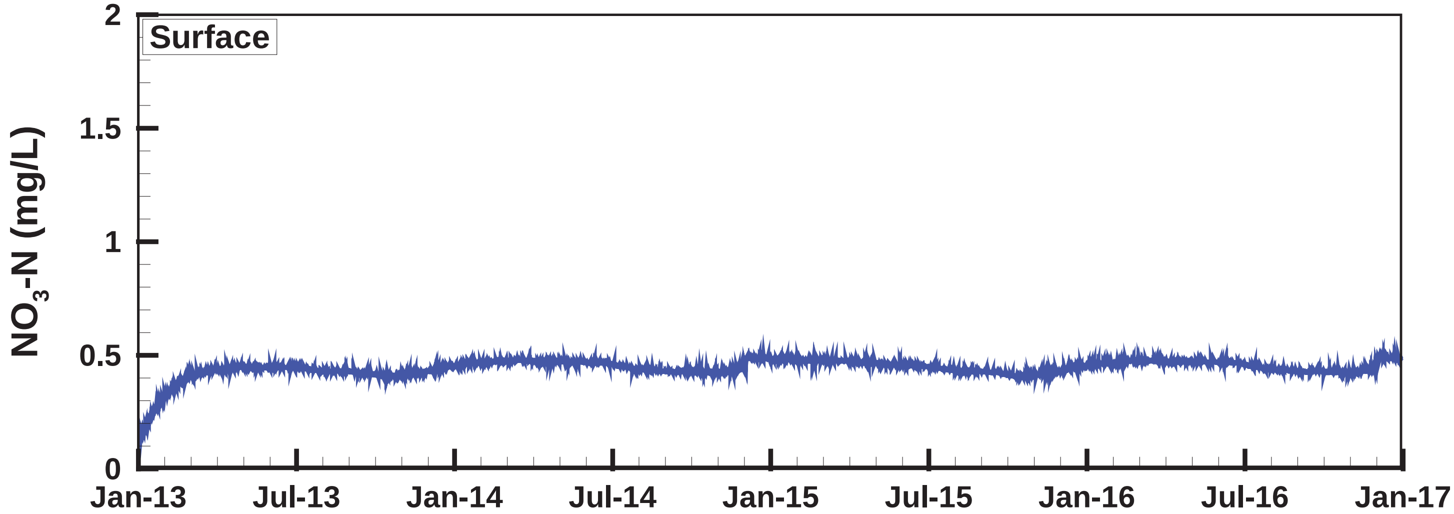


Figure B.24

Future Scenario: Nitrate

TP = 0.004 mg/L in PW; High Nutrient Loadings



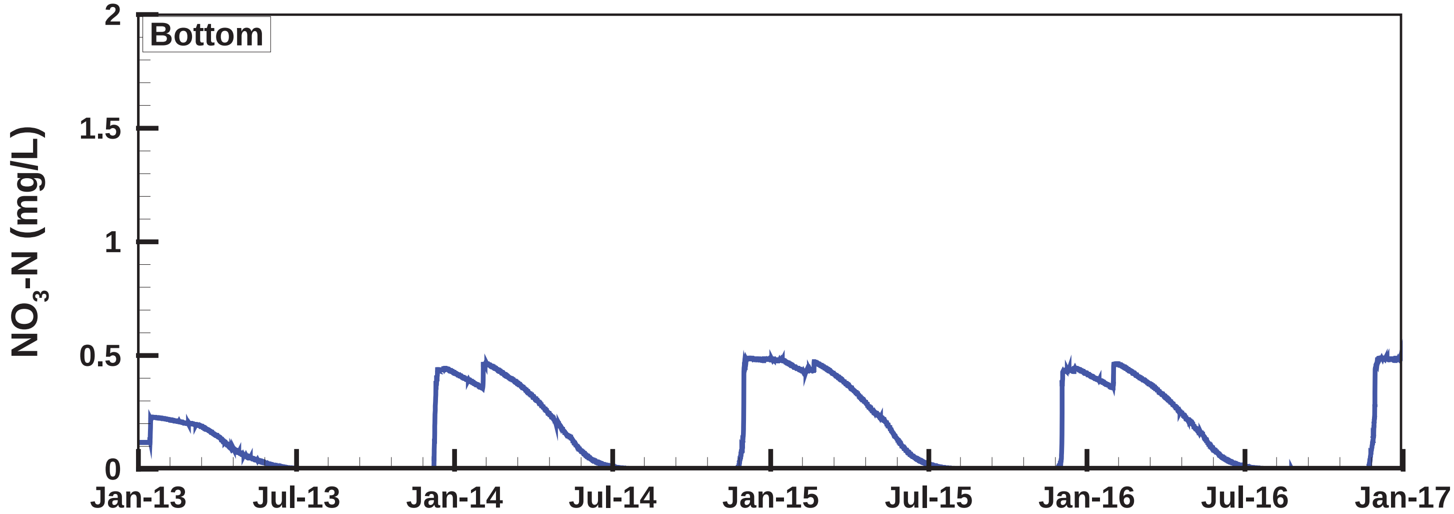
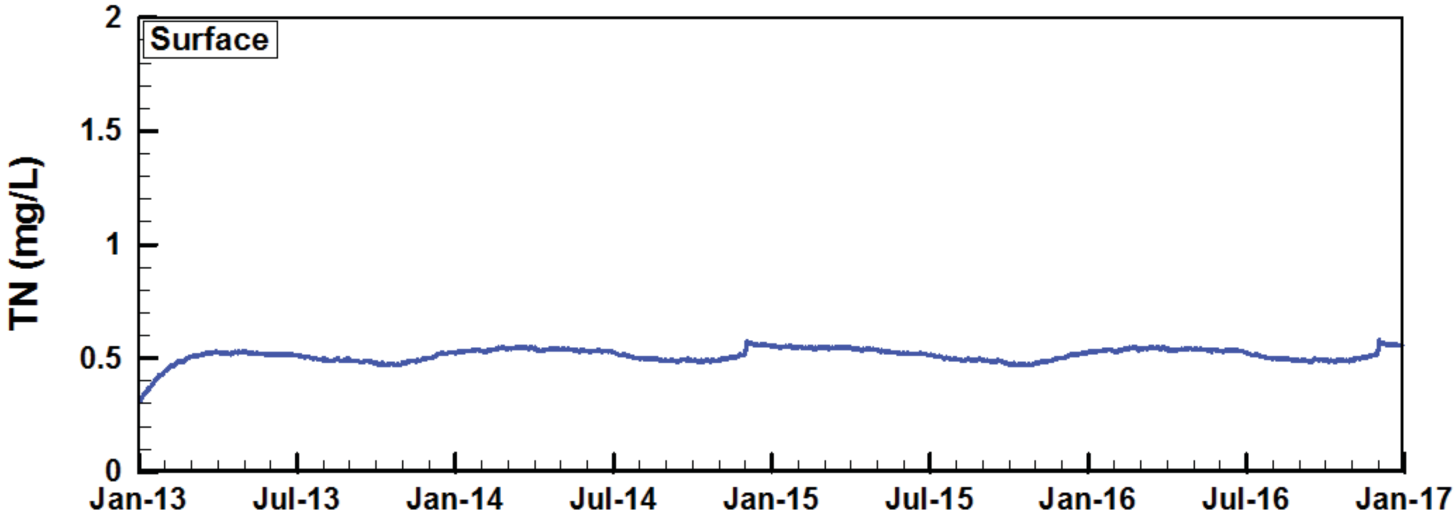


Figure B.25

Future Scenario: Total Nitrogen

TP = 0.004 mg/L in PW; High Nutrient Loadings



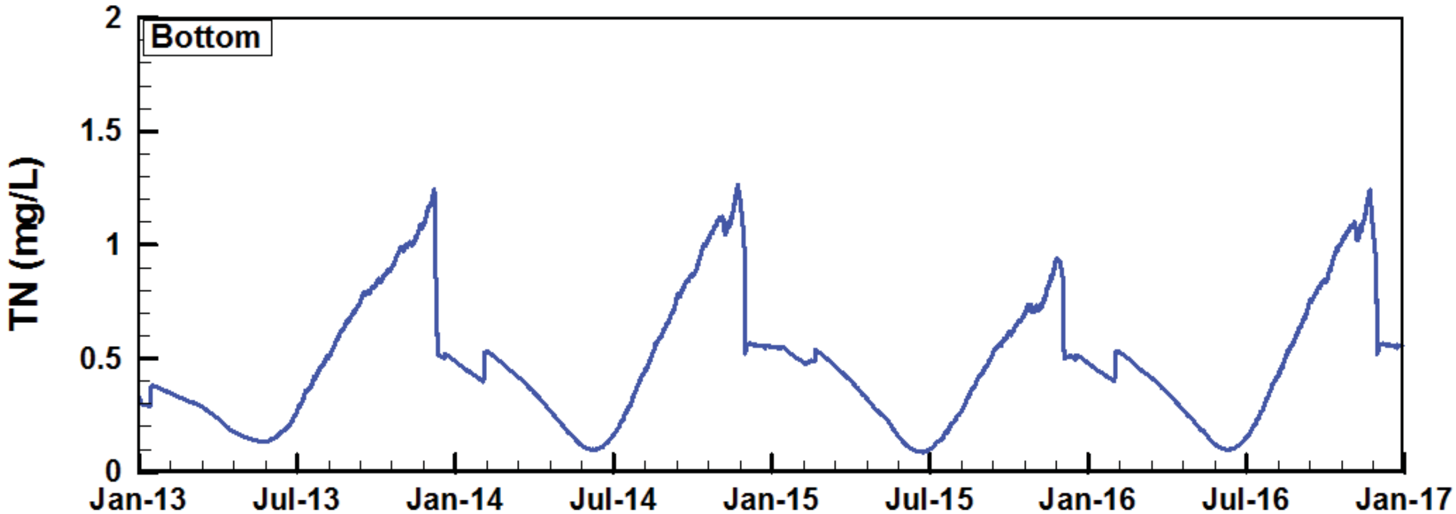


Figure B.26

Future Scenario: Soluble Reactive Phosphorus

TP = 0.004 mg/L in PW; High Nutrient Loadings

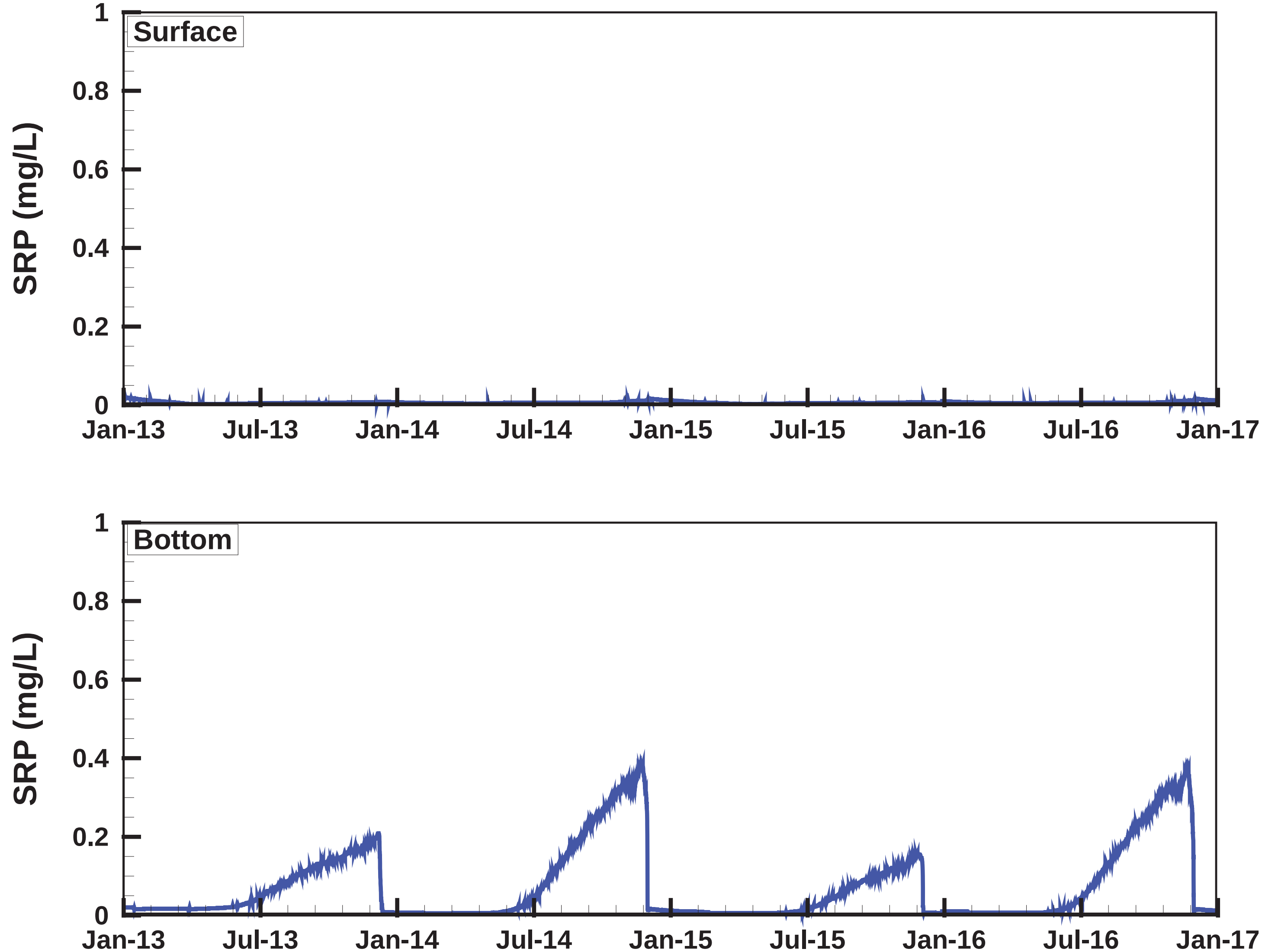


Figure B.27

Future Scenario: Total Phosphorus

TP = 0.004 mg/L in PW; High Nutrient Loadings

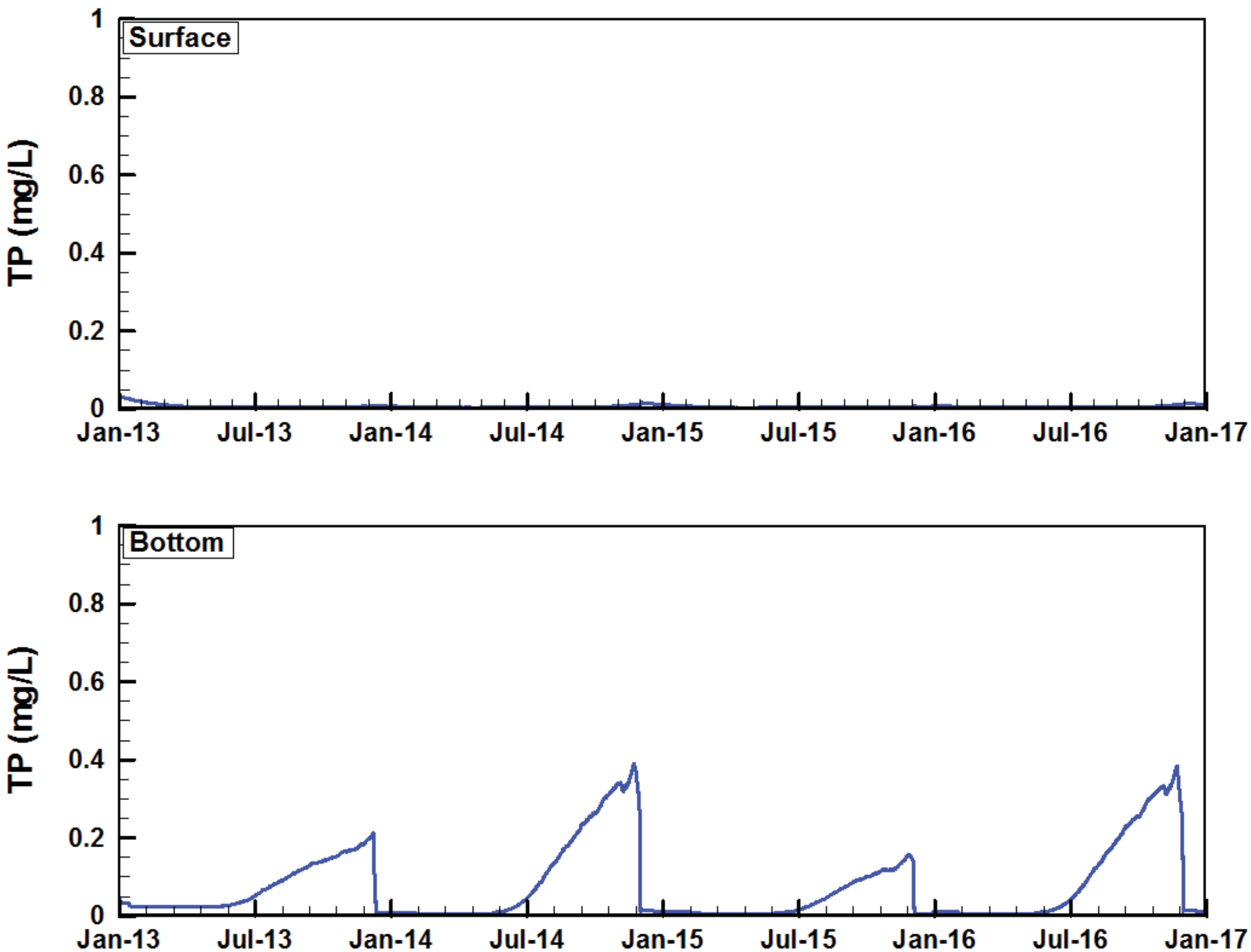


Figure B.28

Future Scenario: pH

TP = 0.004 mg/L in PW; High Nutrient Loadings

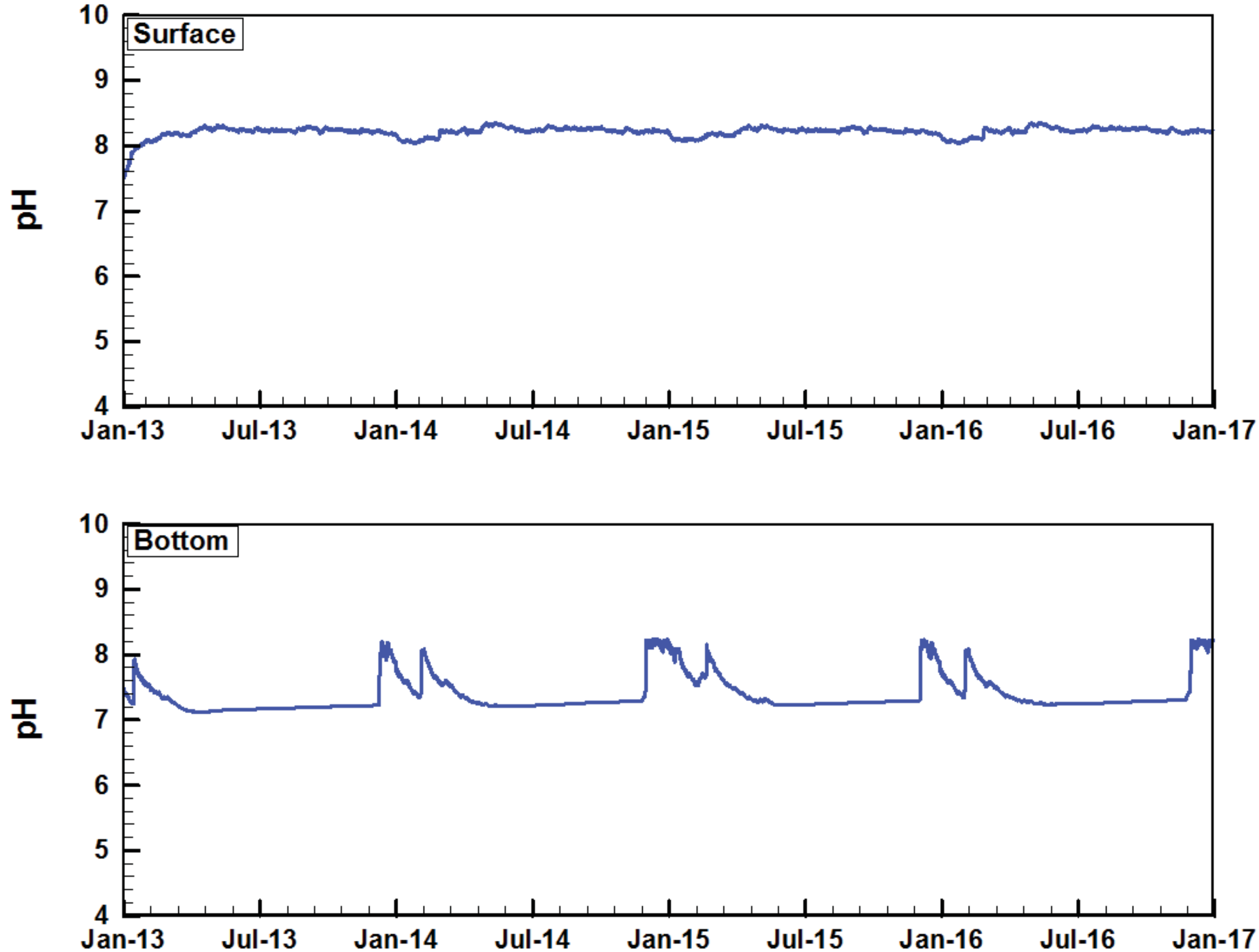


Figure B.29

Future Scenario: Dissolved Oxygen

TP = 0.007 mg/L in PW; Moderate Nutrient Loadings

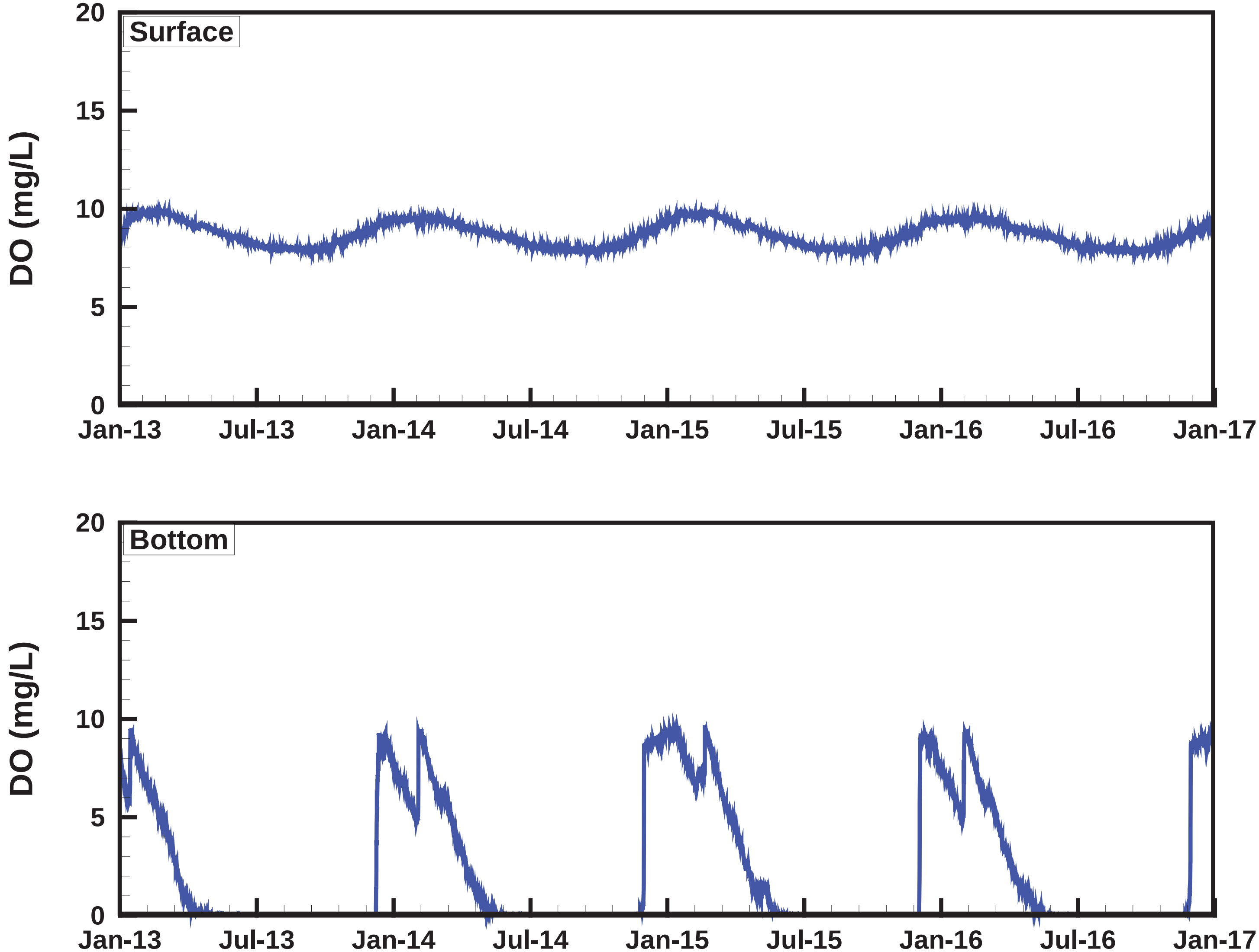


Figure B.30

Future Scenario: Ammonia

TP = 0.007 mg/L in PW; Moderate Nutrient Loadings

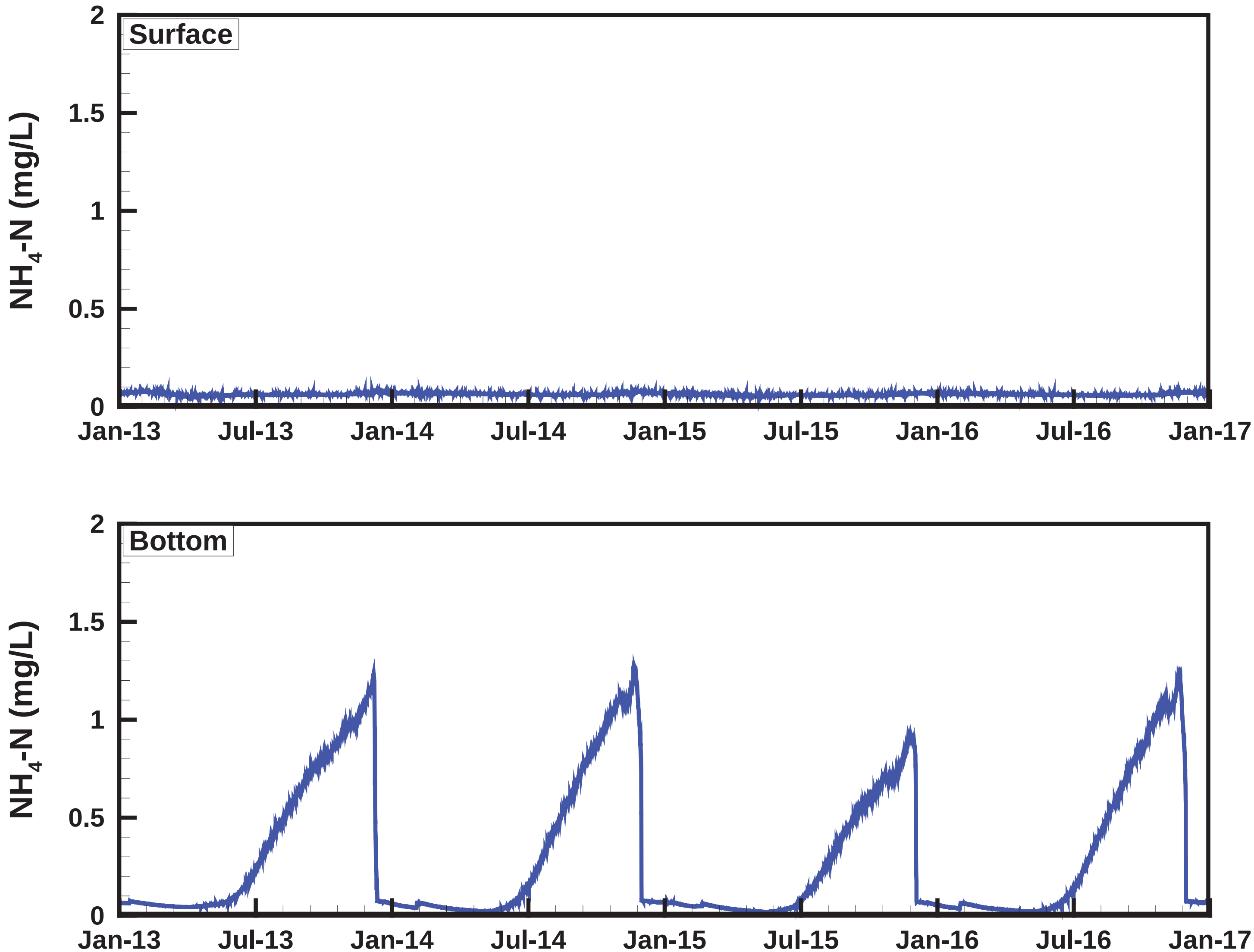


Figure B.31

Future Scenario: Nitrate
TP = 0.007 mg/L in PW; Moderate Nutrient Loadings

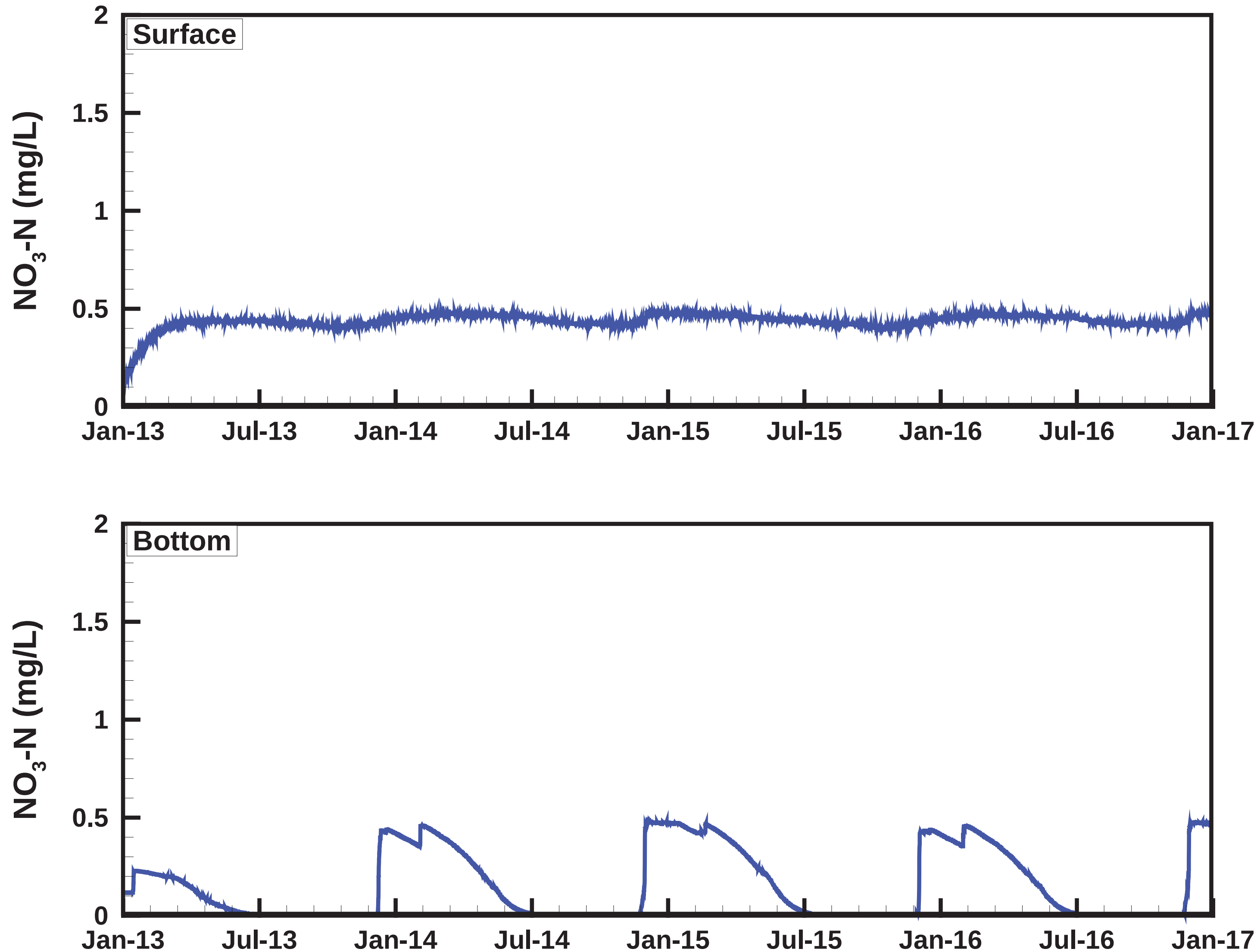


Figure B.32

Future Scenario: Total Nitrogen

TP = 0.007 mg/L in PW; Moderate Nutrient Loadings

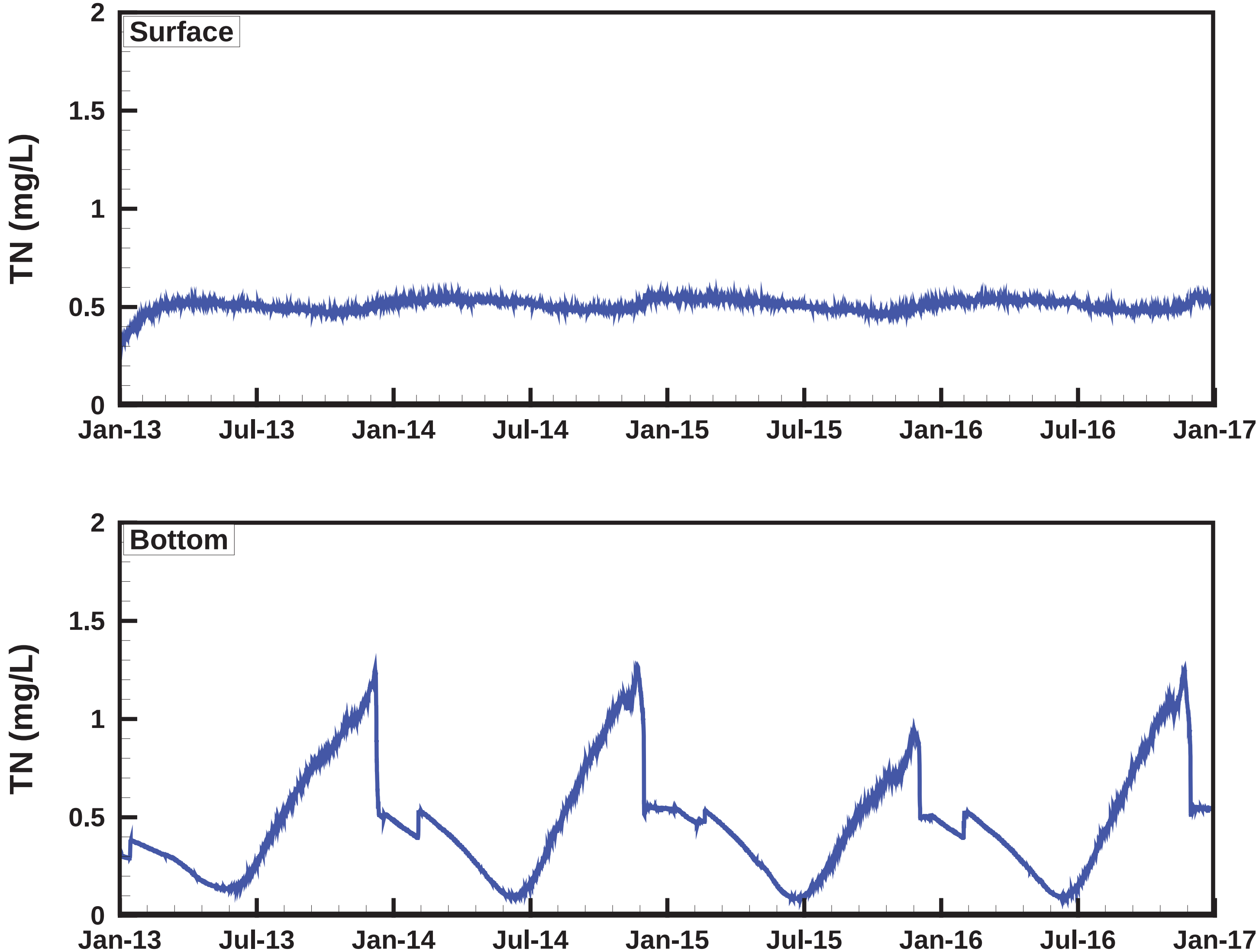


Figure B.33

Future Scenario: Soluble Reactive Phosphorus

TP = 0.007 mg/L in PW; Moderate Nutrient Loadings

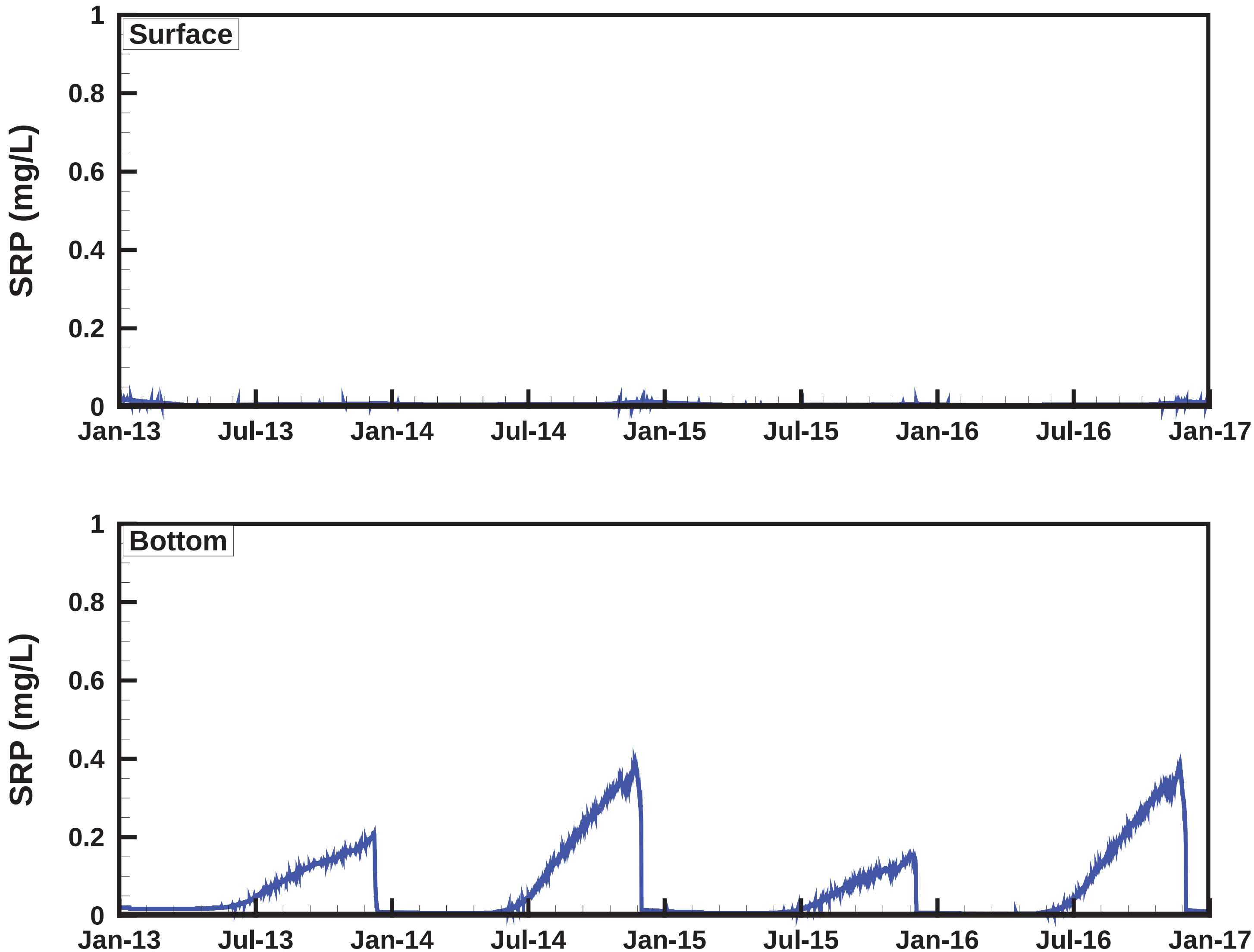
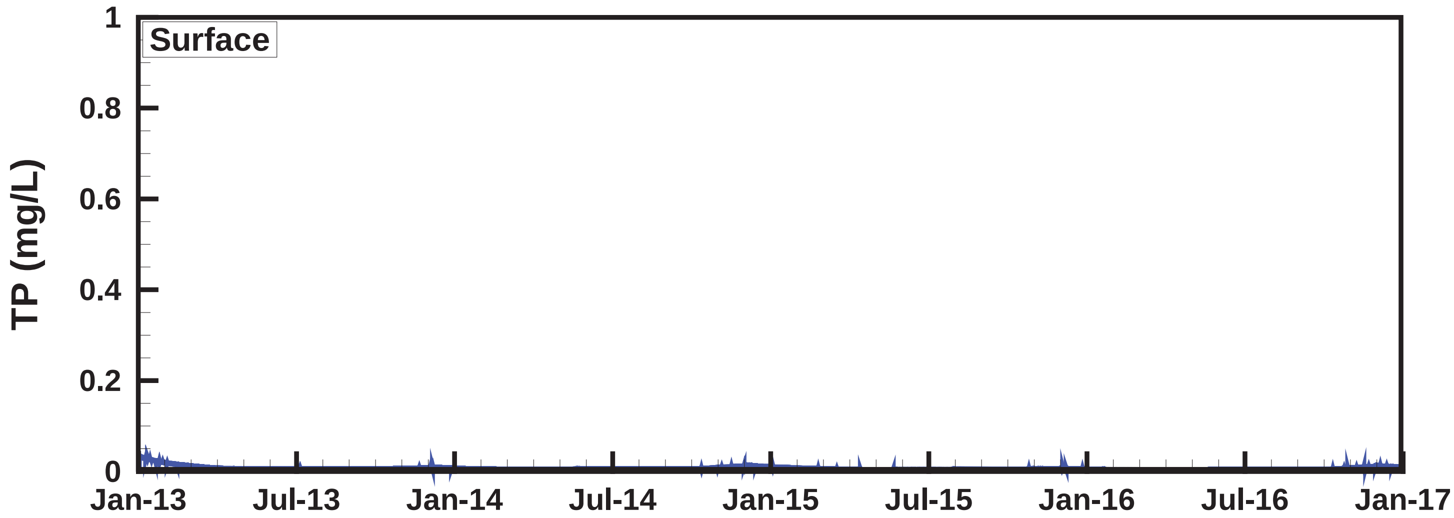


Figure B.34

Future Scenario: Total Phosphorus

TP = 0.007 mg/L in PW; Moderate Nutrient Loadings



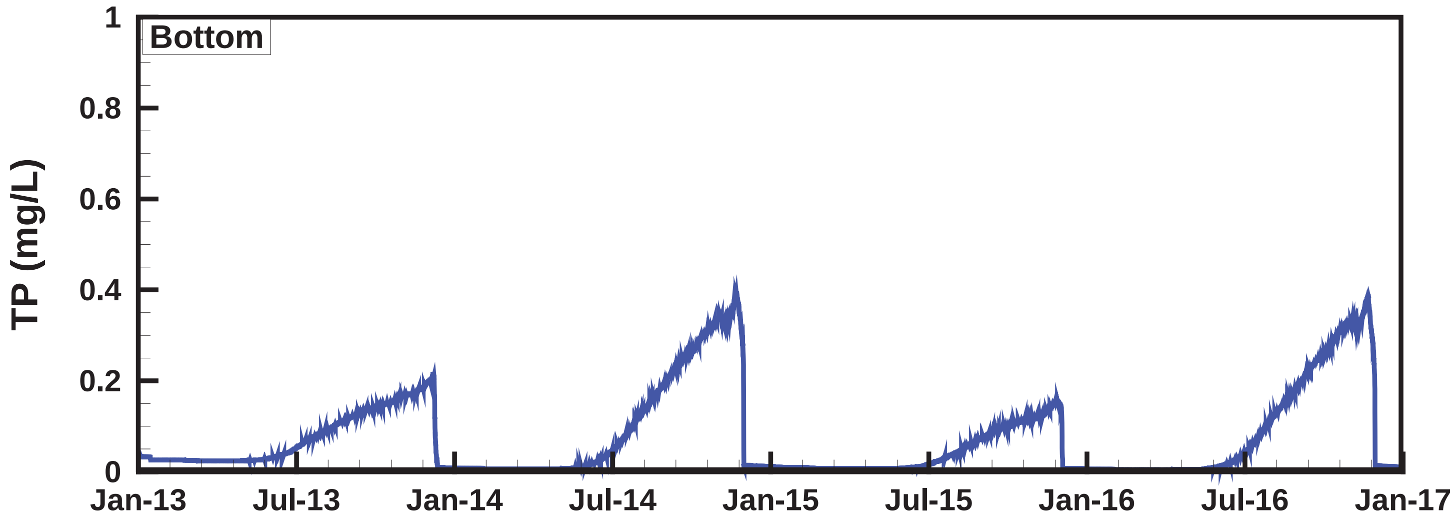


Figure B.35

Future Scenario: pH

TP = 0.007 mg/L in PW; Moderate Nutrient Loadings

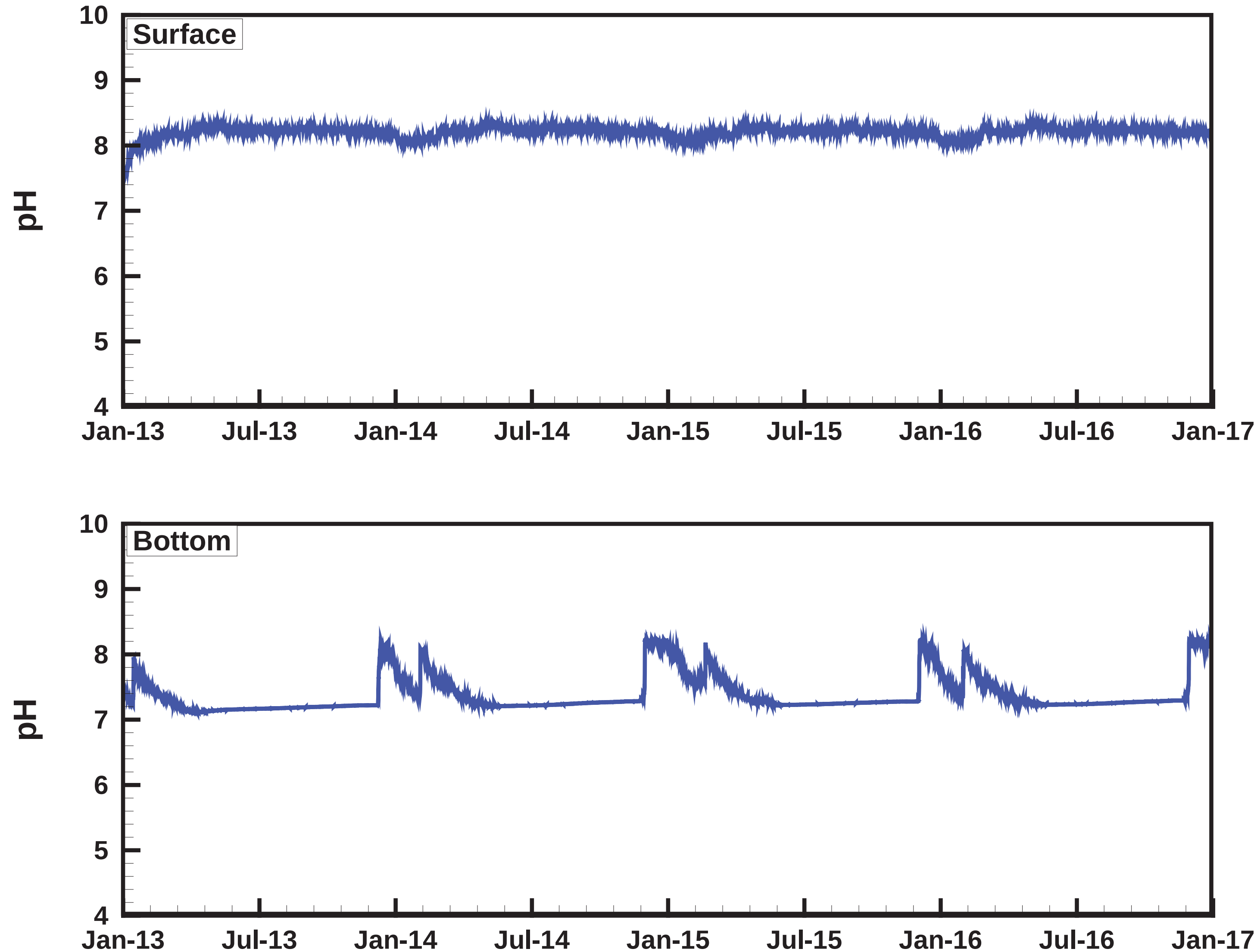


Figure B.36

Future Scenario: Dissolved Oxygen

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings

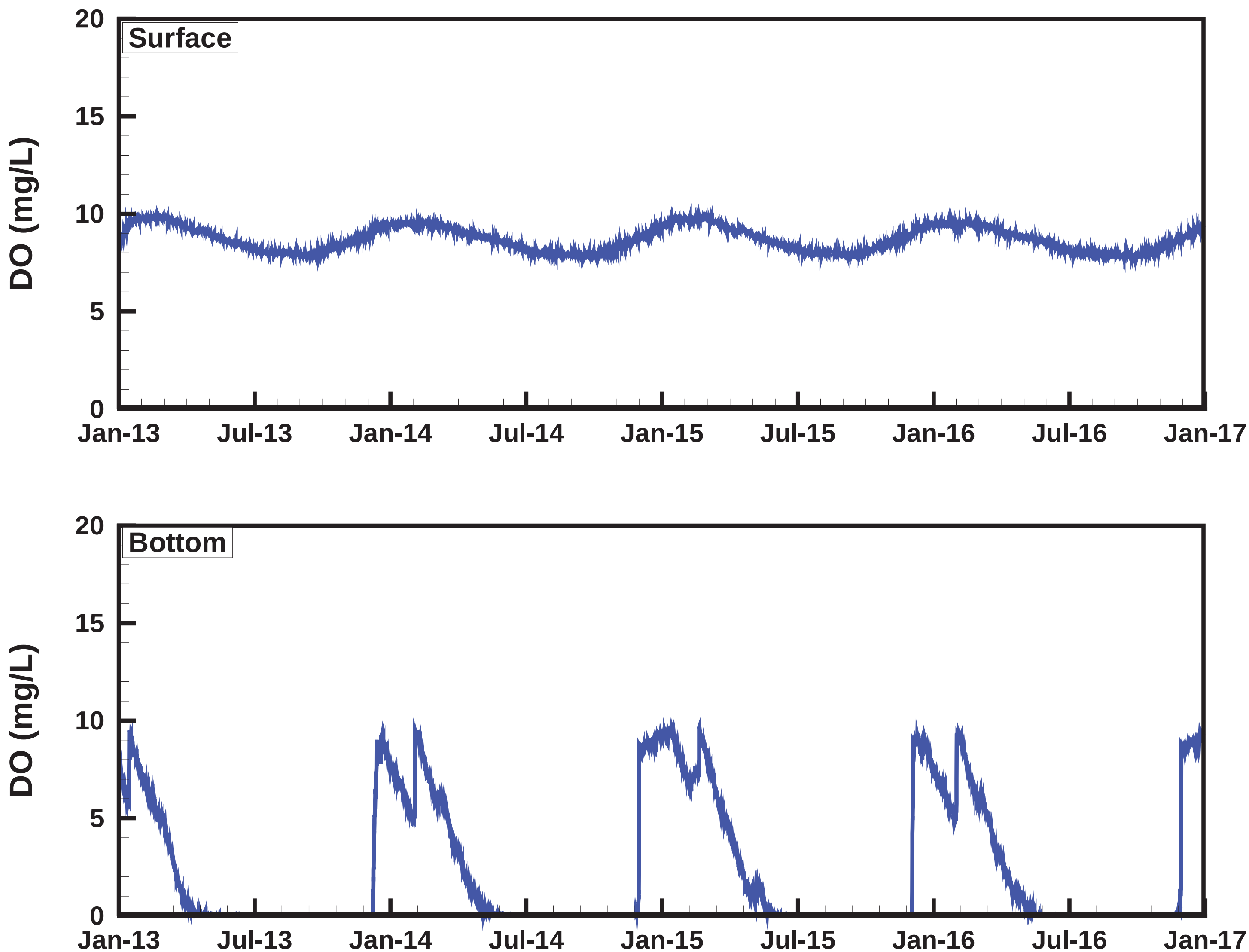


Figure B.37

Future Scenario: Ammonia

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings

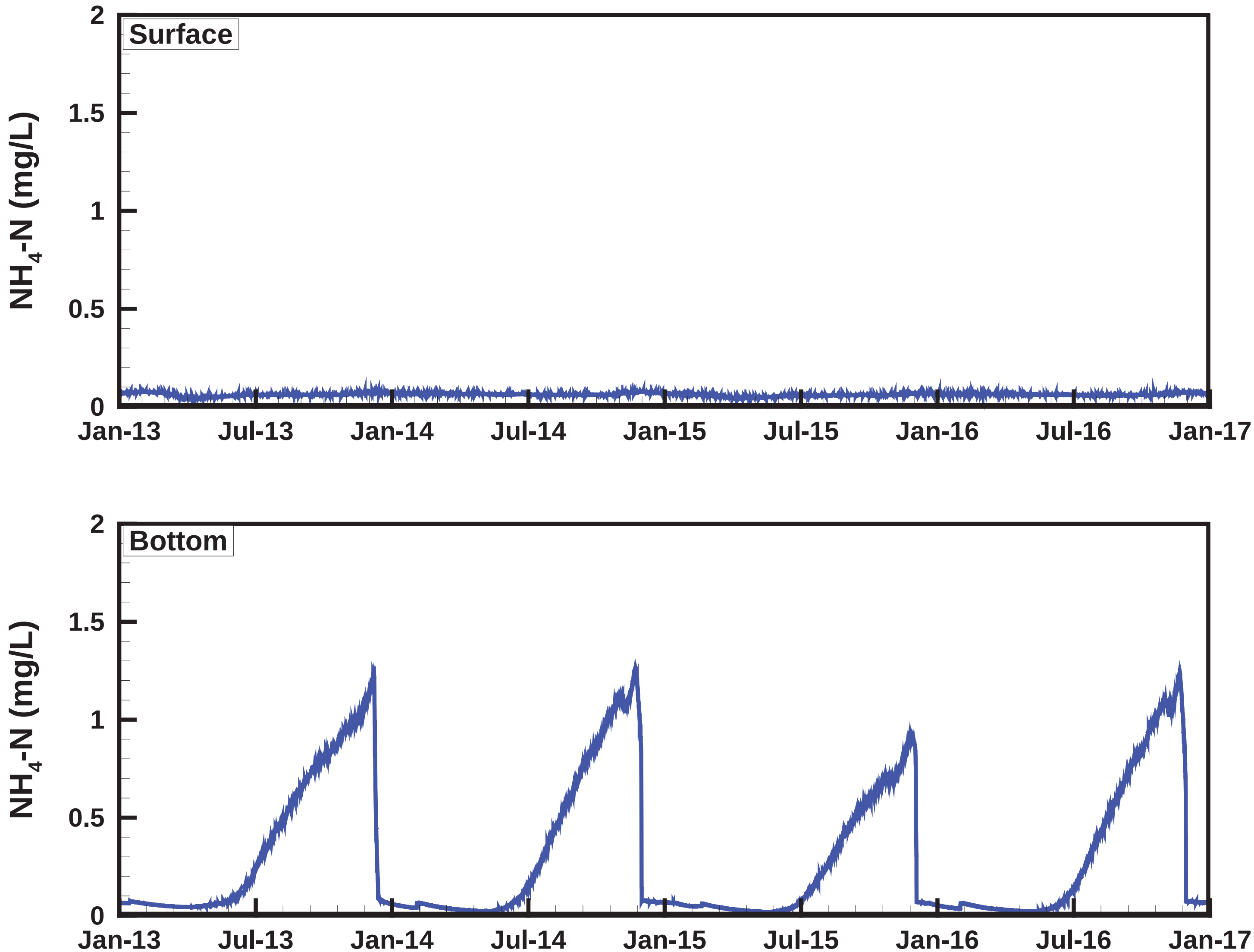
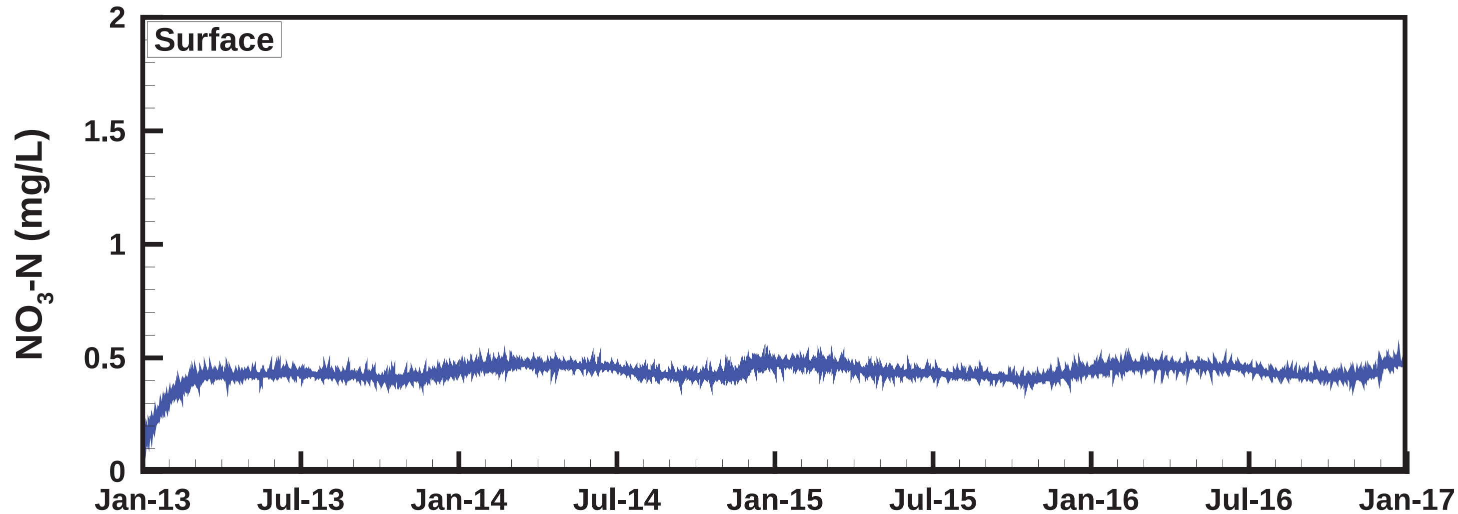


Figure B.38

Future Scenario: Nitrate

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings



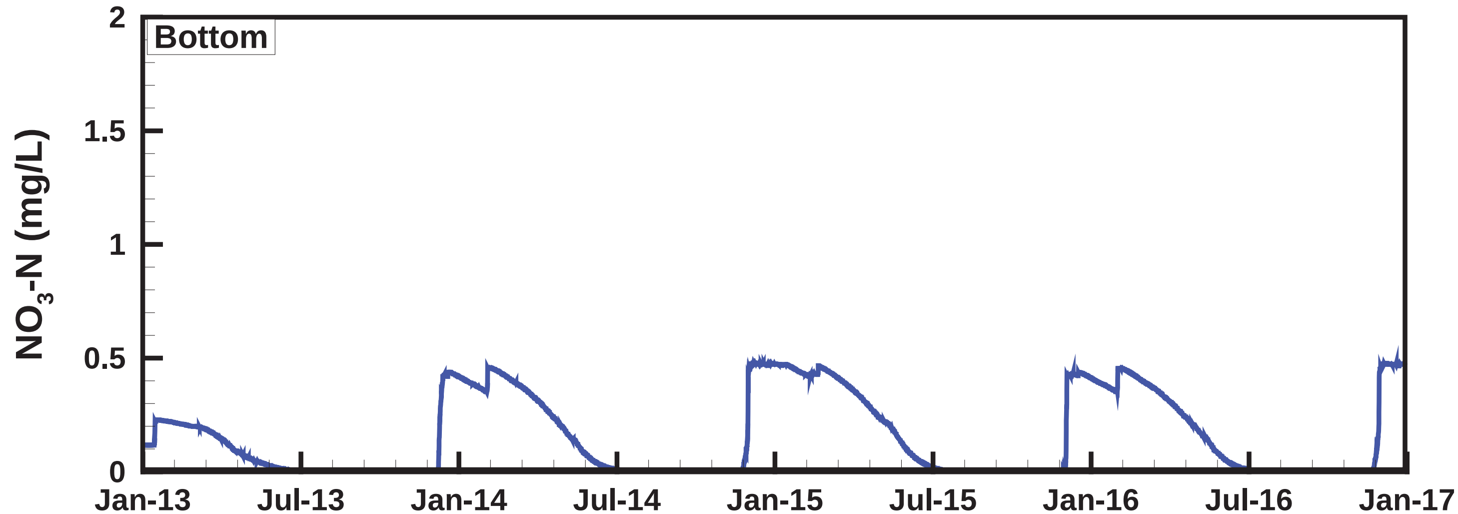


Figure B.39

Future Scenario: Total Nitrogen

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings

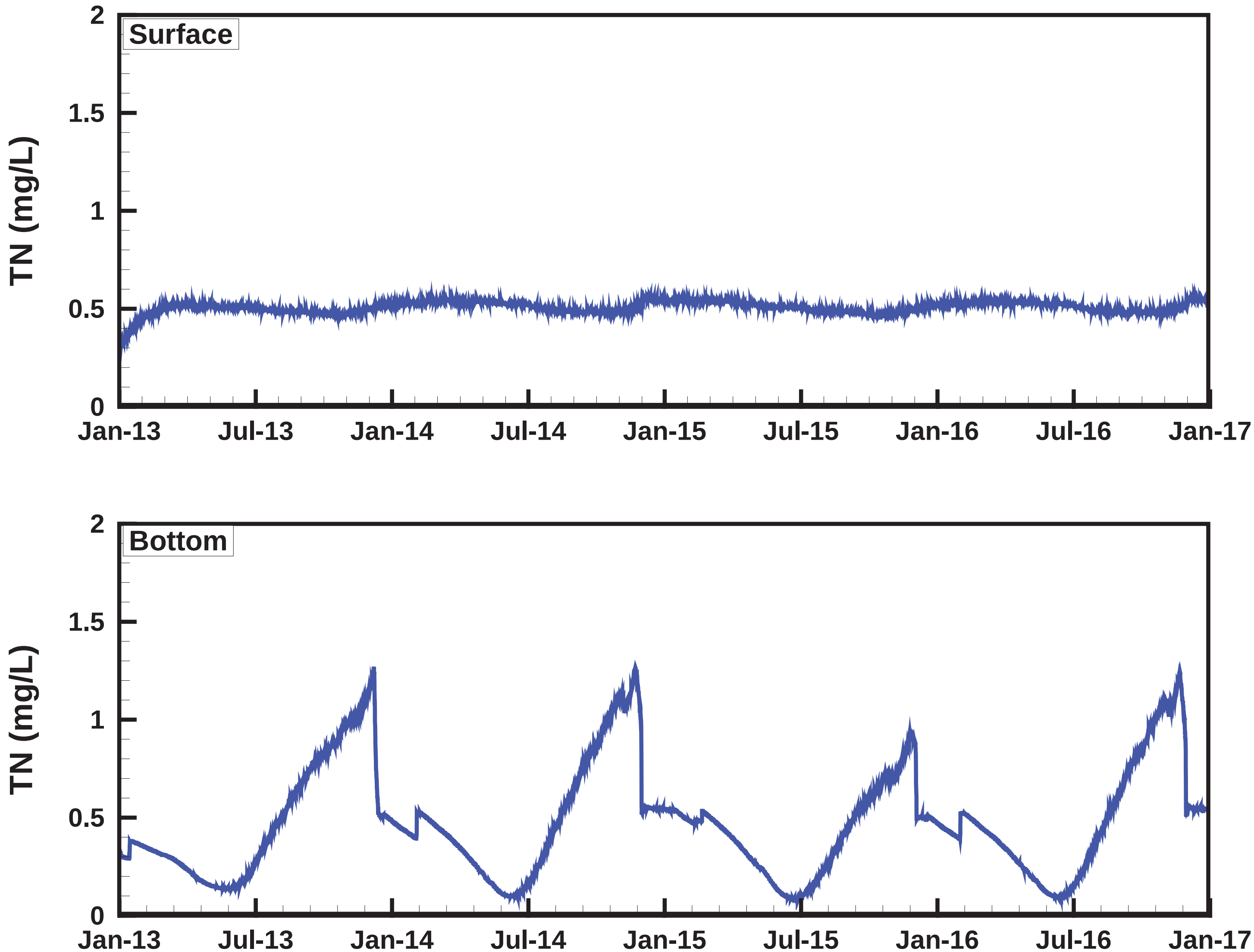


Figure B.40

Future Scenario: Soluble Reactive Phosphorus

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings

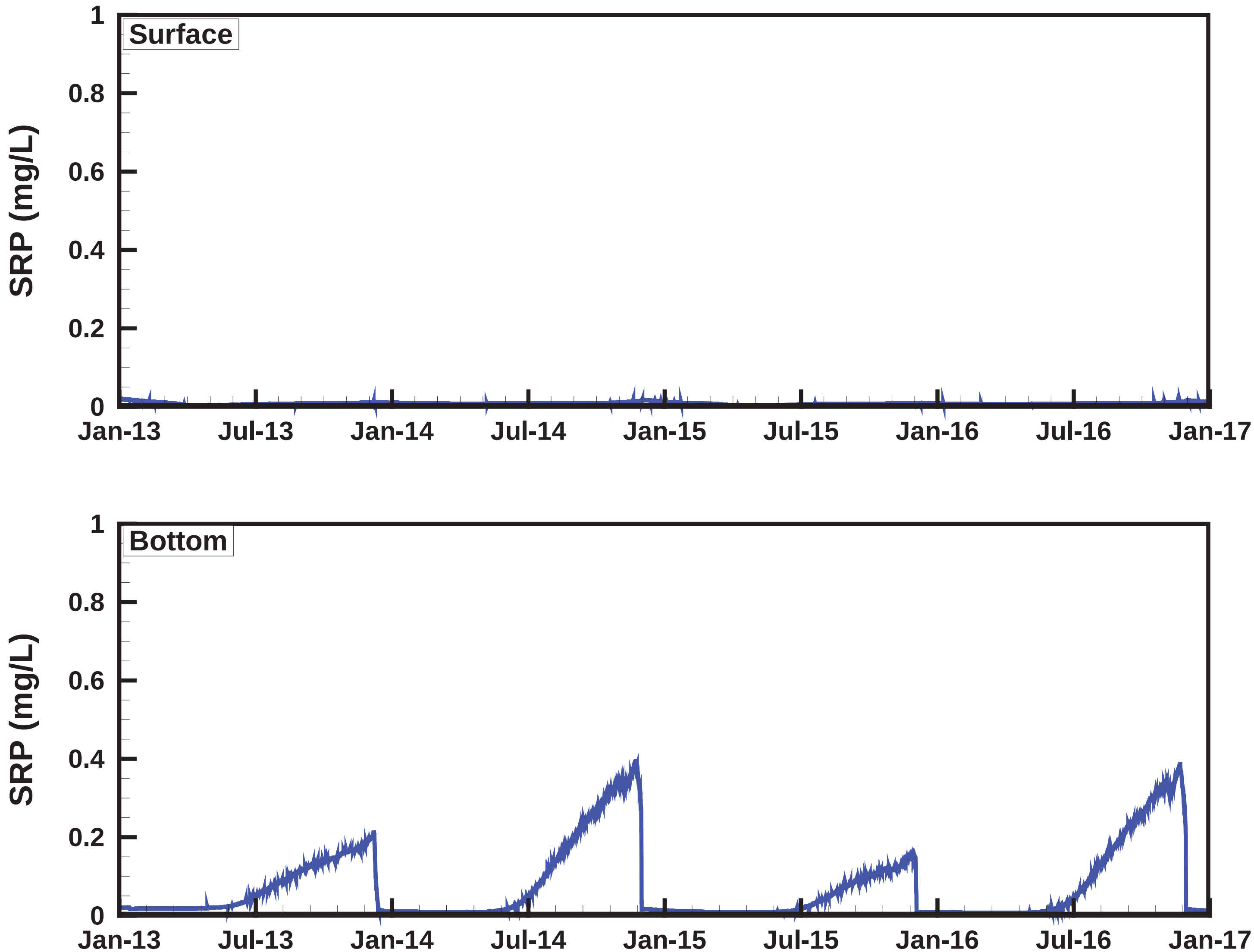
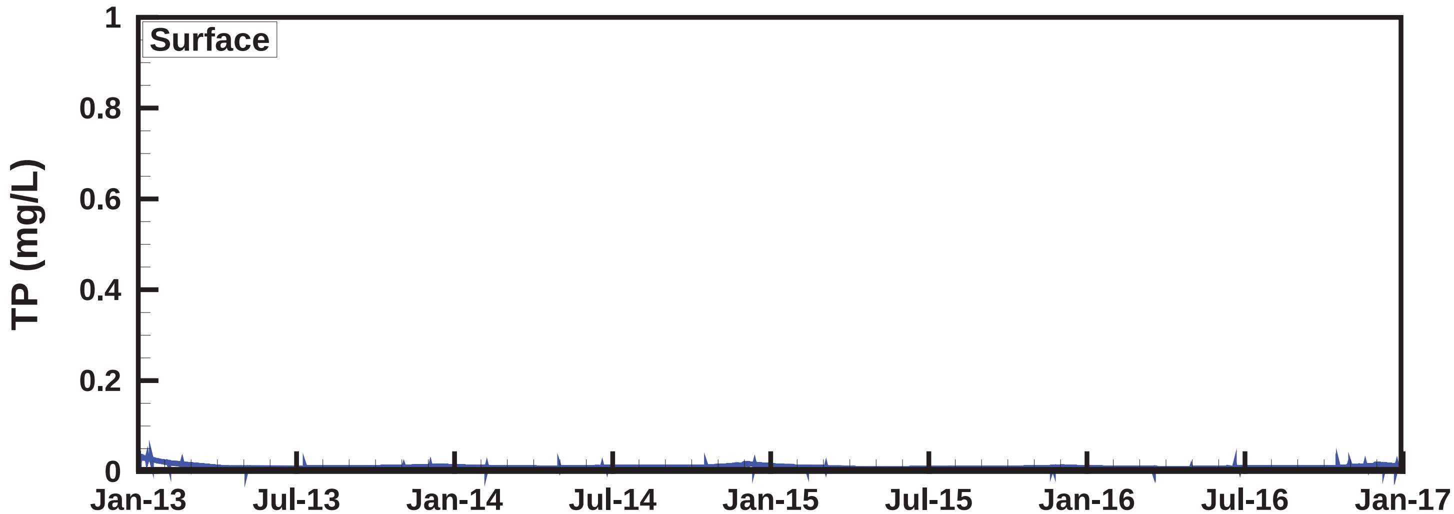


Figure B.41

Future Scenario: Total Phosphorus

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings



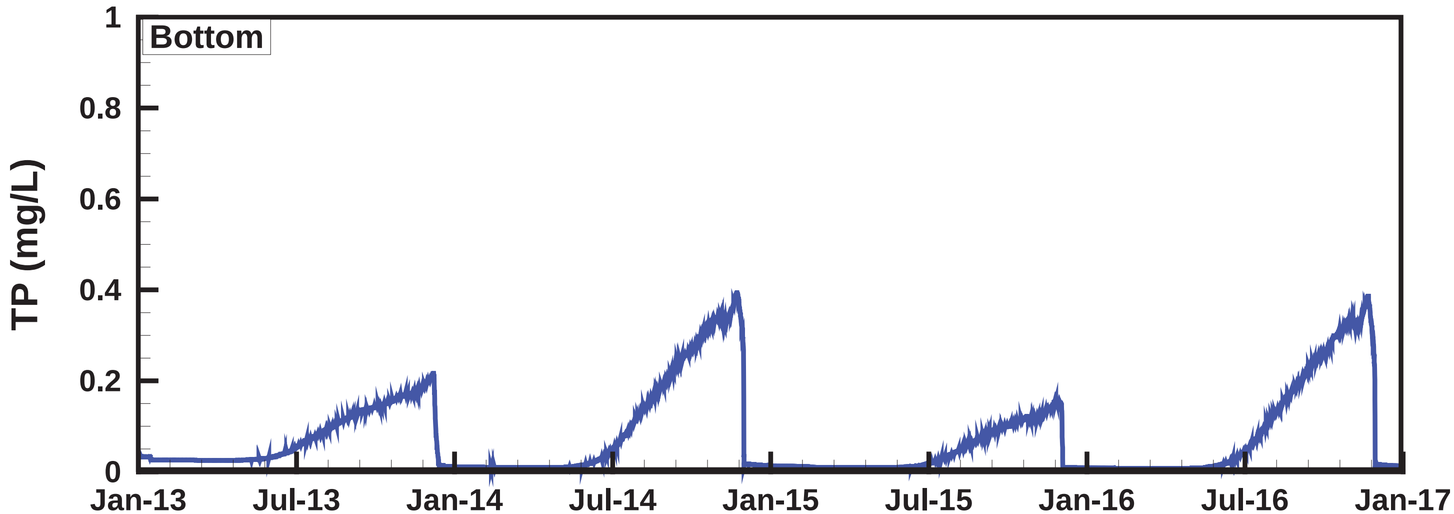


Figure B.42

Future Scenario: pH

TP = 0.010 mg/L in PW; Moderate Nutrient Loadings

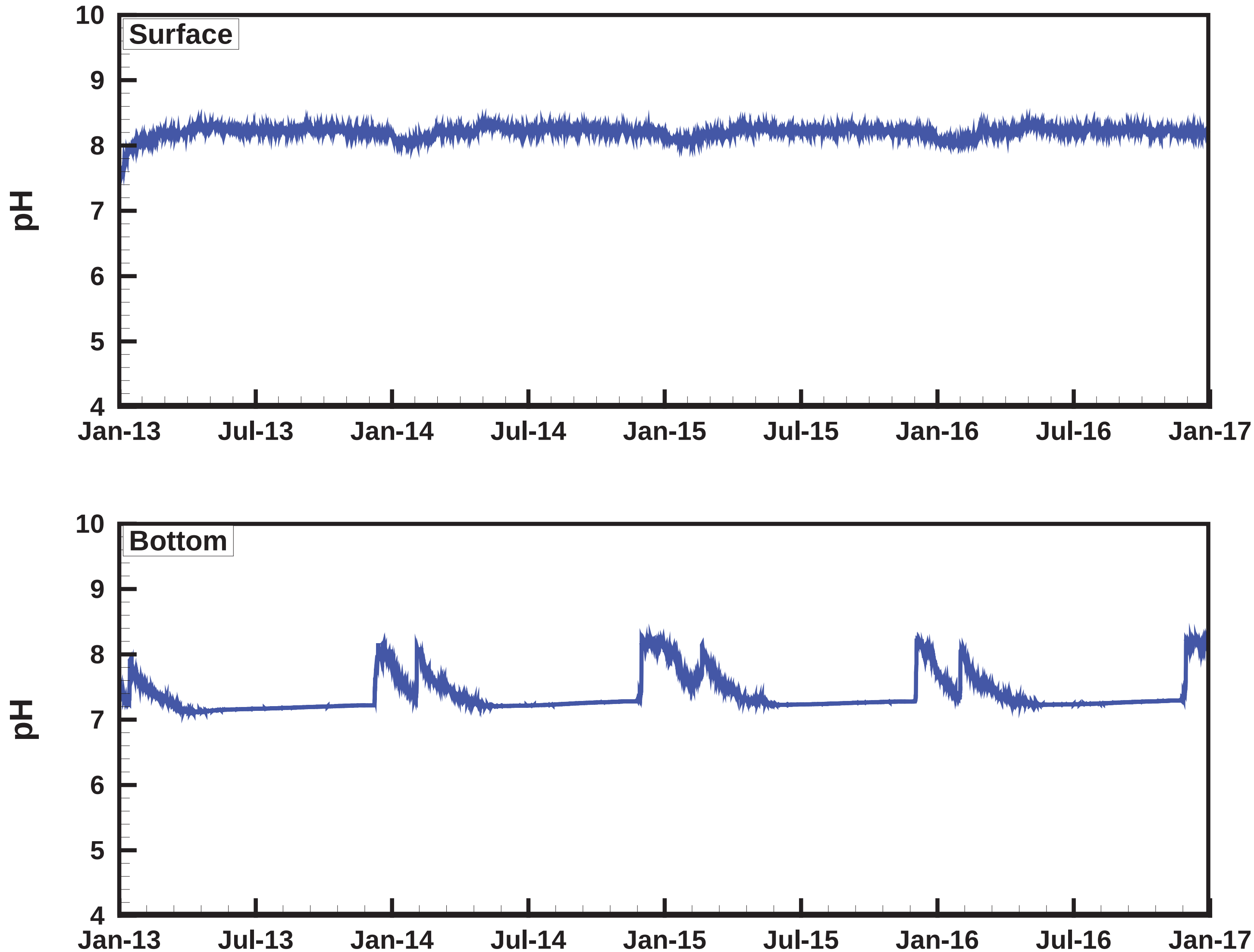


Figure B.43

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Limnology and Detention Study for Miramar Reservoir

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September 18th, 2016

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1.0 EXECUTIVE SUMMARY

A preliminary limnology study for Miramar Reservoir (MR) has been completed and was submitted to the City of San Diego on September 18th, 2016.

This report summarizes the results of a preliminary water quality and limnology study of Miramar Reservoir. It assesses the overall ability of the reservoir to accept purified water (PW) at an inflow rate of 30 million gallons per day (MGD) under five different operating scenarios (Nominal Case, Base Case, Low Lake Level Case, Nominal Case with Bubblers, and Nominal Case with Diffusers). The analysis is performed using a three-dimensional hydrodynamic and water quality model. The report is prepared by Water Quality Solutions Inc. (WQS), on behalf of Kleinfelder and the City of San Diego (the City). A more detailed study to further assess the reservoir's ability to accept PW, as well as make specific recommendations for reservoir operation, is underway.

1.1 Reservoir Background

Miramar Reservoir (**Figure ES-1**), located in the Scripps Ranch community of San Diego, is owned, operated and maintained by the City of San Diego. The reservoir is adjacent to Miramar Water Treatment Plant (WTP), which serves the northern part of the City. MR has a maximum depth of 114 feet (ft) and a water storage capacity of 6,682 acre-feet (ac-ft) (**Figure ES-2**).

In 2012, the City completed the Water Purification Demonstration Project, which investigated the feasibility of injecting 15 MGD of PW into San Vicente Reservoir (SVR). The PW would be blended with ambient reservoir water, stored in the reservoir, and eventually delivered to a water treatment plant for potable use. The Demonstration Project was reviewed by an Independent Advisory Panel (IAP), the California Department of Public Health (now known as Division of Drinking Water – DDW), and the Regional Water Quality Control Board (RWQCB). The consensus of the various reviews was that the addition of PW to SVR does not produce any significant public health or water quality issues.

In April 2013, the results of the Demonstration Project were presented to the San Diego City Council. The City Council accepted the results of the Demonstration Project and instructed the Public Utilities Department to investigate the feasibility of larger potable reuse projects at SVR and also a potable reuse project at Otay Reservoir

(OTR).

Since then, the City has retained WQS to provide limnological assessments and water quality modeling for OTR and SVR under various operating conditions, in support of the Pure Water San Diego Program. These modeling studies used state of the art three-dimensional hydrodynamic and water quality models to investigate the mixing and dilution of PW in SVR and OTR. In particular, the mixing and dilution of a non-decaying tracer injected with PW for 24 hours were evaluated. The results of the limnology studies indicate that both SVR and OTR may satisfy DDW's preliminary criteria for potable reuse.

In 2015, the City started considering an option in which 30 MGD of PW would be augmented to MR, in lieu of SVR. If approved by the DDW, the use of MR is expected to significantly reduce the cost of a pipeline that would transport PW from the North City Wastewater Treatment Plant to the target lake. The City then tasked WQS with performing a preliminary limnological investigation for MR, which is the subject of this report. While this report was being prepared, the City decided that MR would be the preferred site for the initial 30 MGD of PW.

Similar to the earlier limnology studies (FSI, 2010; FSI, 2011; FSI, 2012; WQS, 2015), WQS used a three-dimensional hydrodynamic and water quality model to evaluate the dilution, mixing, and transport of PW in MR under various projected future reservoir operating scenarios. This investigation considers an inlet location at the northeast corner of the reservoir (**Figure ES-1**). The detailed results include establishing dilution for PW in the reservoir and evaluating nutrients (phosphorus and nitrogen), dissolved oxygen (DO), and algal (chlorophyll *a*) concentrations.

1.2 Study Objectives

The overall objective of this preliminary study is to use modeling to assess MR's ability to accept PW at an inflow rate of 30 MGD. Specifically, this report answers the following five questions:

1. Does the PW, at an inflow rate of 30 MGD, cause any hydrodynamic changes in the reservoir?

2. Does the reservoir provide adequate mixing and blending of the PW at an inflow rate of 30 MGD under the Nominal scenario?

3. Does the reservoir still provide adequate dilution of the PW at an inflow rate of 30 MGD at low lake level?

4. Do mixing devices, such as bubblers or diffusers, provide more mixing and blending of the PW?

5. Does the PW, at an inflow rate of 30 MGD, affect the water quality of the reservoir, specifically algal dynamics?

One of the main draft criteria by the DDW for reservoir augmentation requires a 10:1 dilution of a 24-hour pulse of PW, if an additional treatment step is incorporated (NWRI, 2015). Therefore, the criterion of 10:1 dilution of a 1-day production of PW, simulated by a 24-hour conservative tracer, will be used to evaluate dilution in MR for a PW inflow rate of 30 MGD.

1.3 General Approach

The first step in hydrodynamic and water quality modeling is model calibration. The purpose of model calibration is to match the simulation results with the measured field data. During this process, input data is corrected if errors are identified, and consequently, some model parameters are adjusted.

The analysis approach for hydrodynamic modeling in this study includes using conservative tracers in Estuary Lake and Coastal Ocean Model (ELCOM) as surrogates for chemical constituents in the PW to examine the dilution of such constituents that flow into MR. Six conservative tracers, with an initial concentration of 100, were used to simulate non-decaying chemical constituents in the PW inflow. Such constituents can inadvertently enter the reservoir as a result of potential “excursion events” at the full-scale Advanced Water Purification Facility (AWPF). The tracers were injected into the reservoir’s inflow over a 24-hour period, representing a 1-day production of recycled water. The tracer concentration contours visually illustrate the movement of PW in the reservoir. The instantaneous dilution of the tracers at a specified location is obtained by dividing the source tracer concentration (i.e., 100) by the simulated tracer concentration at that location.

Specific approaches and methodologies will be used to provide the necessary information that will address the five questions stated in Section 1.2, including:

1. Matching the simulation results with the measured field data was used in model calibration to correct model input data and adjust model parameters;

2. Comparisons of the simulated reservoir water temperature and conductivity under various reservoir operating scenarios were used to examine hydrodynamic changes in the reservoir;

3. Selection of critical dates during both the stratified and turnover periods for the injection of the conservative tracers were used to examine the corresponding concentrations and peak times of these tracers in the reservoir outflow. Turnover is defined as the first day in late fall/early winter when the difference between the highest and lowest temperature is less than 1 degree Celsius (°C) along the water column**.** These conservative tracers provide estimates of the dilution of chemical constituents in the PW inflow;

4. Concentrations of the 24-hour conservative tracer in the outflow under the condition of a water surface level lower than a normal operation level were used to assess the mixing ability of MR at low lake levels.

5. Comparisons of the dilutions of 24-hour conservative tracers under the condition of bubblers or diffusers simulated in the model were used to assess the effect of mixing devices on the mixing ability of MR.

The goal of nutrient and chlorophyll *a* modeling using Computational Aquatic Ecosystem DYnamics Model (CAEDYM) is to determine the effects of the PW inflow on the reservoir's water quality, with a special emphasis on chlorophyll *a*. The analysis approach is to examine the water quality of the reservoir under the PW inflow rate of 30 MGD and compare the results with the reservoir's water quality before PW augmentation.

1.4 Discussion of Model Calibration

The purpose of model calibration is to match simulation results with measured field data. The comparison between the ELCOM simulation results and measured in-reservoir field data focuses on three parameters – Water Surface Elevation (WSEL), water temperature, and conductivity. The comparison between the CAEDYM simulation results and measured in-reservoir field data was performed for the following water quality parameters: DO, nutrients, chlorophyll *a*, and pH.

In general, the calibrated model replicated the overall behaviors of the lake well, including surface and bottom temperatures, thermocline depth, surface and bottom conductivities, DO and nutrient levels in both epilimnion and hypolimnion, and surface algal levels. **Table ES-1** summarizes the statistical metrics for the calibration of these parameters.

The relative root mean square errors (RMSEs) of a variable are affected by both the absolute values of the RMSEs and the range of the measured values of the variable, which is the difference between the maximum measured value and the minimum measured value. For variables with a small range in the measured values, an insignificant RMSE may result in a high value of relative RMSE. In the calibrations of the MR model, the relative RMSEs vary across different variables. Among the variables, water temperature, conductivity, and DO were predicted with lower relative RMSEs, while the nutrients (depending on temperature and DO) and chlorophyll *a* and pH (depending on all other variables) were predicted with higher relative RMSEs. However, for all variables, the predicted values match the measured values well. Furthermore, the temporal and spatial agreement between the model results and the data is deemed good. It is thus considered that the calibrations of ELCOM and CAEDYM were successful.

Table ES-1: Summary of ELCOM/CAEDYM Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Temperature	0.65 °C	4.5 %	0.11 °C
Surface and Bottom Conductivity	19.2 µS/cm	6.9 %	9.8 µS/cm
Surface and Bottom Dissolved Oxygen	0.82 mg/L	7.4 %	0.24 mg/L
Surface and Bottom Total Nitrogen	0.20 mg/L	20.8 %	0.04 mg/L
Surface and Bottom Total Phosphorus	0.06 mg/L	16.7 %	0.01 mg/L
Surface Chlorophyll *a*	0.74 µg/L	30.6 %	-0.10 µg/L
Surface and Bottom pH	0.17	12.3 %	0.05

Note: 1. Relative RMSE = RMSE/$|PAR_{max} – PAR_{min}|$, where PAR_{max} and PAR_{min} are from measured data.
2. Mean error is the average of ($PAR_{measured} – PAR_{simulated}$).

1.5 Modeling Conditions

After the calibration of the ELCOM and CAEDYM models at MR, various reservoir operating conditions were simulated using ELCOM and CAEDYM in order to achieve the study goals.

1.5.1 Hydrodynamic Modeling Conditions

The main variables of the hydrodynamic study include:

- Two-year model run using meteorological data from the years 2013-2014

- One PW inflow rate (30 MGD)

A PW inflow rate of 30 MGD was modeled to simulate the potential future PW inflow rate, which is the design value projection provided by the City. The PW inflow originates from the future full scale AWPF and is then transferred to MR.

- One potential inlet location (Inlet Location 1)

The potential PW inlet location, named Inlet Location 1, is shown in **Figure ES-1**. It is located at the northeast corner of the reservoir, about 1 mile from the outlet structure.

- Two operating lake levels (Normal lake level and Low Lake Level)

Consistent with the historical record, MR is expected to be operated with a relatively constant WSEL. In this study, the dilution and mixing of the PW was studied under two different WSELs: (1) the nominal expected operating lake level (706 ft), corresponding to a water volume of approximately 5,500 ac-ft, and (2) the expected low lake level (696.6 ft) in case of emergency withdrawal, corresponding to the water volume of approximately 4,275 ac-ft.

- Two mixing devices (Bubblers and diffusers)

Two types of mixing devices were considered in order to increase the dilution and mixing of the PW near the inlet. One simulation involved using bubblers to create water curtains near the inlet. In total, six bubblers were used, three in each row, with 50 horsepower per unit. The bubblers' elevations (ELs) range from EL 646 ft to EL 666 ft. Another simulation involved distributing 50% of the inflow through diffusers located in the eastern third of the reservoir, with the remainder of the inflow entering the reservoir through Inlet Location 1.

- One outflow port (Port #2) at EL 666.11 ft

Figure ES-2 illustrates the cumulative reservoir water volume capacity, the WSEL, and the elevations of all four outlet ports. The normal pool WSEL of MR is EL 706 ft, and with MR at full capacity (6,682 ac-ft), the WSEL is EL 714 ft. All simulations presented in this report used Port #2 (EL 666.11 ft) for withdrawals.

For each hydrodynamic model run, six conservative tracers were introduced through the PW inlet. For the Base Case scenario, the tracers were injected at relatively regular time intervals (once every other month during the second year), regardless of stratification conditions or wind events. For all other operating conditions, the tracers were introduced at times of weak thermal stratification conditions or high wind events. The injection dates for these tracers were determined using an analysis of meteorological data at MR to identify relatively strong winds that blow from the northeast throughout the year. Such high wind events may move the PW inflow from the inlet towards the outlet port rather quickly. Based on the analysis, the tracer injection dates were identified. **Table ES-2** summarizes the conservative tracer injection dates for each operating scenario.

Table ES-2: Conservative Tracer Injection Dates in Model Runs

Tracer #	**Injection Dates**	
	Nominal	Base Case
1	1/24, Year 1	1/1, Year 2
2	4/17, Year 1	3/1, Year 2
3	1/13, Year 2	5/1, Year 2
4	4/28, Year 2	7/1, Year 2
5	5/11, Year 2	9/1, Year 2
6	12/23, Year 2	11/1, Year 2

Table ES-3 summarizes the operating conditions for the five ELCOM model runs performed in this study. The model run number reflects the order in which the run is performed.

Table ES-3: Summary of ELCOM Model Runs

Model Run No.	Operating Scenario	Initial/Final Reservoir Water Volume (ac-ft/ac-ft)	Mixing Device	Tracer Injection Dates
1	Nominal	5,500/5,500	None	High Winds from NE
2	Base Case	5,500/5,500	None	Evenly Distributed
3	Low Lake Level	4,275/4,275	None	High Winds from NE
4	Nominal	5,500/5,500	Bubblers	High Winds from NE
5	Nominal	5,500/5,500	Diffusers	High Winds from NE

1.5.2 Nutrient and Algae Modeling Conditions

In this study, the nutrient and algae (chlorophyll *a*) modeling of MR was performed for the PW inflow rate of 30 MGD under the nominal operating scenario. Unlike the two-year hydrodynamic model runs, the nutrient and algae model run was performed for a four-year period in order to investigate the longer-term effects of the PW on water qualify of MR. The overall model inputs of the second two-year simulation period (inflows, outflows, meteorological data) are simply a repetition of the first two years.

The PW inflow water quality parameters used in the CAEDYM model run were obtained from initial testing at the North City pilot water treatment plant. The PW inflow has relatively high nitrogen and low phosphorus concentrations, exceeding typical algal usage of N:P of approximately 10:1 (Horne and Goldman, 1994).

1.6 Discussion of Model Run Results

Table ES-4 summarizes the 24-hour conservative tracer results including the overall minimum dilution (OMD) and the overall minimum lag time. The table also includes the injection date of the tracer with the lowest minimum dilution. Specific answers to the five main study questions stated above are addressed below.

1. Does the PW at an inflow rate of 30 MGD cause any hydrodynamic changes in the reservoir?

Yes, the PW inflow with a rate of 30 MGD will cause minor hydrodynamic changes in the reservoir. For the two-year simulation period, the addition of the warmer PW results in a deepening of the thermocline but does not show a significant effect on the turnover dates. If the simulations are continued past two years, the thermocline may deepen further.

2. Does the reservoir provide adequate mixing and blending of the PW at an inflow rate of 30 MGD under the Nominal scenario?

Yes, the preliminary limnology study shows that the reservoir provides adequate mixing and blending under the Nominal scenario. This reduces the effects of potential increases in concentration of chemical constituents in the PW inflow, resulting from potential “excursion events” at the full-scale AWPF. The OMD of the PW under the Nominal scenario is 20:1, greater than the required OMD of 10:1 for a 24-hour tracer, thus providing adequate mixing and blending of PW. However, due to uncertainties in model inputs and performance, additional evaluations are needed as discussed in the answer to Question #3 below.

Table ES-4: Summary of ELCOM Model Run Results

Model Run #	Operating Scenario	Initial/Final Reservoir Water Volume (ac-ft)	Tracer Injection Date[1]	Overall Max. Conc. (%)	Overall Min. Dilution	Overall Min. Lag Time[2] (days)
1	Nominal	5,500/5,500	4/28, Year 2	5.02	20	1.1
2	Base Case	5,500/5,500	1/1, Year 2	3.03	33	2.0
3	Low Lake Level	4,275/4,275	1/13, Year 2[3]	6.95[3]	14[3]	0.8
4	Bubblers	5,500/5,500	1/24, Year 1	3.74	27	0.8
5	Diffusers	5,500/5,500	1/24, Year 1	3.41	29	0.8

Note:

1. Injection date of the tracer with the lowest minimum dilution.
2. The minimum lag time does not necessarily correspond to the 24-hour conservative tracer injected that results in lowest minimum dilution.
3. The OMD of Run #3 was from a model run with a 4-minute output interval, while the OMDs of all other model runs were based on a 3-hour output interval. The effect of output intervals on model run results is discussed in the answer to Question #3.

3. Does the reservoir still provide adequate dilution of the PW at an inflow rate of 30 MGD at low lake level?

Overall, the preliminary results showed that at low lake levels, the reservoir can still provide adequate dilution of the PW at an inflow rate of 30 MGD (an OMD greater than 10:1 for a 24-hour tracer). For the simulation at low lake levels, the predicted OMD is 14:1 when a 4-minute output interval is invoked. However, due to uncertainties in model inputs and performance, additional evaluations are needed to ensure that the 10:1 dilution is adequately exceeded. These additional evaluations should address the following:

- Uncertainties in meteorological data

Currently meteorological data are available from two weather stations near MR. One is Station #150 of the California Irrigation Management Information System (CIMIS), located about 2.5 miles southwest of MR. The other is the Elliot Chaparral Reserve Station (ECR) of the Desert Research Institute (DRI), located about 1.5 miles south of MR. The difference between meteorological data from these two different weather stations can be significant, especially the difference in wind speed, which strongly affects reservoir mixing and tracer transport. On extreme event dates, the wind speed at ECR can be double or triple of that at the CIMIS station (**Figure ES-3**).

- Uncertainties in model inputs

Using more critical operating conditions (e.g. more extreme wind speeds, lower lake level, higher outflow rate, etc.) may result in lower dilutions than predicted.

- Uncertainties in model output

Different output intervals may affect the accuracy of the model run results. For example, in the Low Lake Level Case, model runs with 1-hour and 4-minute output intervals provided lower minimum dilution than those performed with a 3-hour output interval (**Figure ES-4**).

For the run at low lake level, the predicted OMD is 14:1 when a 4-minute output interval is invoked. Considering the uncertainties discussed above, the 14:1 dilution, however, may not provide a sufficient buffer to consistently insure that the dilution will be greater than 10:1. Based on the above discussion, further investigations are needed to evaluate confidence in model results, input data, and lake operating parameters. These investigations are being performed in a subsequent phase of the limnology study.

4. Do mixing devices, such as bubblers or diffusers, provide more mixing and blending of the PW?

Yes, the preliminary results have shown that the mixing devices (bubblers or diffusers) could potentially provide more mixing and blending of the PW. **Figure ES-5** shows the comparison between the minimum dilutions under the condition of mixing devices and the minimum dilutions with no mixing devices for all six tracers. Using a bubbler or a diffuser to disperse and vigorously mix some of the PW with ambient reservoir water could potentially increase the dilution for all simulated tracers. However, the current simulations of bubblers or diffusers are only preliminary, and further evaluation of the effect of mixing devices on dilution is needed to provide specific recommendations.

5. Does the PW, at an inflow rate of 30 MGD, affect the water quality of the reservoir, specifically algal dynamics?

Yes, the PW affects the water quality of MR. The preliminary water quality study shows that a PW inflow rate of 30 MGD is predicted to produce low algal levels (i.e., low surface chlorophyll *a* concentrations) and high water clarity. In fact, the PW inflow gradually reduces algal levels and increases water clarity. The simulated surface chlorophyll *a* concentration dropped from 0.24 µg/L in Year 1 to 0.03 µg/L in Year 4. This is related to the generally low phosphorus concentrations in the PW. The total phosphorus (TP) and total nitrogen (TN) concentrations in the PW are considered to be 0.004 and 0.78 mg/L, respectively; therefore, algal growth will be limited by phosphorus in MR.

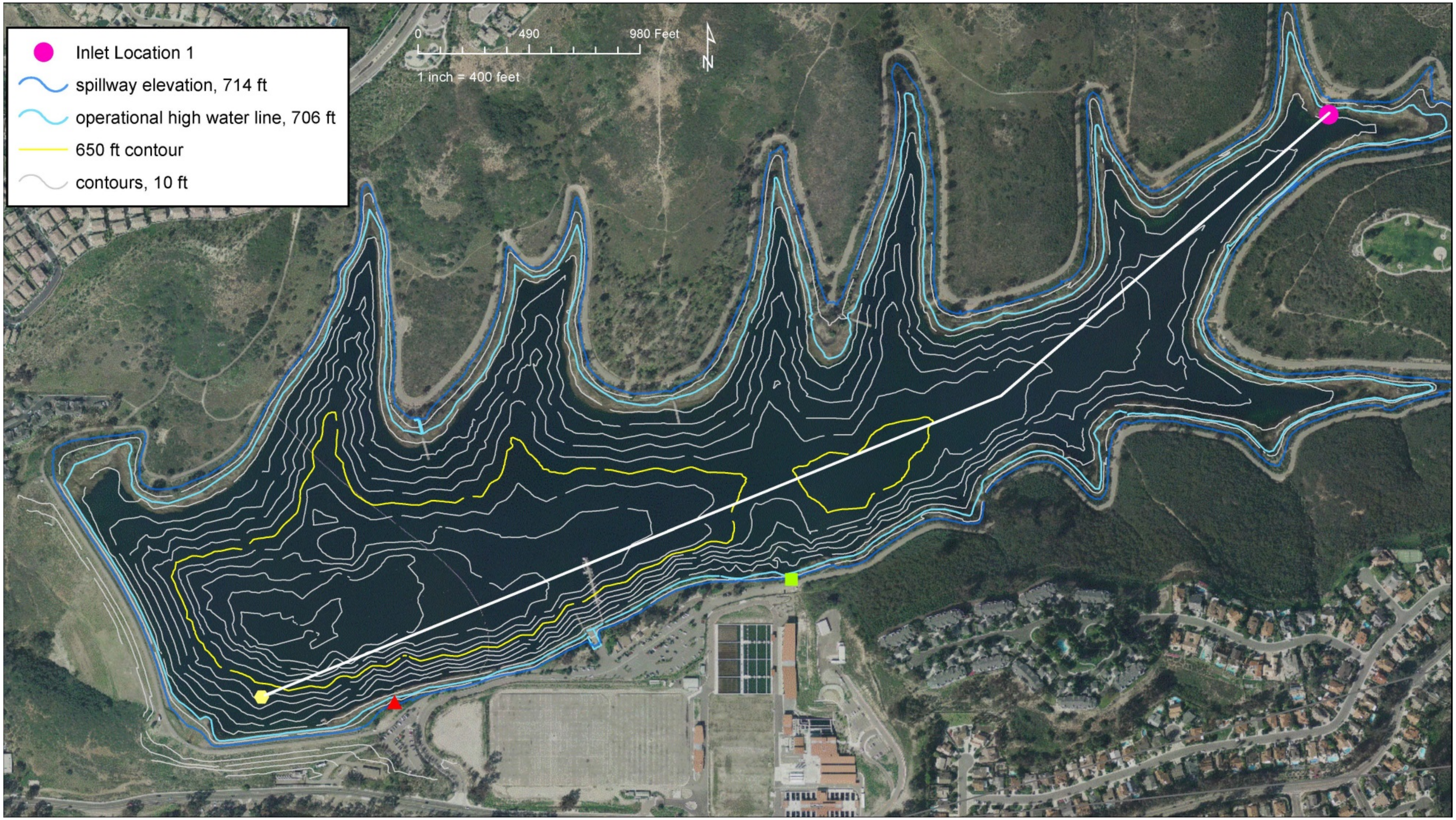
Note that the TP and TN values of the PW in the current study were based on the results from the Demonstration Plant during startup. These values from ongoing operation of the Demonstration plant may have changed and will be evaluated in the next phase of limnology study.

1.7 Recommendations

The current work shows promising results, but only partially answers the questions as the simulation results may have been affected by uncertainties (e.g. meteorological data, model input parameters, model output intervals, etc.), as mentioned in the discussions above. Therefore, additional analysis is needed to fully answer the questions, including

- Reviewing the model run results and discussing a new work plan with IAP;
- Developing a reservoir data collection plan to enhance model accuracy;
- Conducting a tracer study, analyzing the tracer study data, and performing a model run to reproduce the results of the future tracer study;
- Quantifying the uncertainty in the model prediction results caused by uncertainties in model input (e.g. meteorological data);
- Defining the required margin of safety for the predicted OMD for meeting the proposed DDW dilution requirement;
- Performing enhanced simulations of bubblers and diffusers;
- Selecting and designing systems that result in high PW mixing and dilution, with the purpose of reliably increasing the OMD;
- Defining extreme operational parameters under which PW addition may be curtailed or suspended or the reservoir outflow shut down.

Map of Miramar Reservoir



Note: Inlet Location 1 is the potential PW inlet location. Conservative tracers are injected at this location.

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Figure ES-1

Capacity of Miramar Reservoir and Outflow Ports

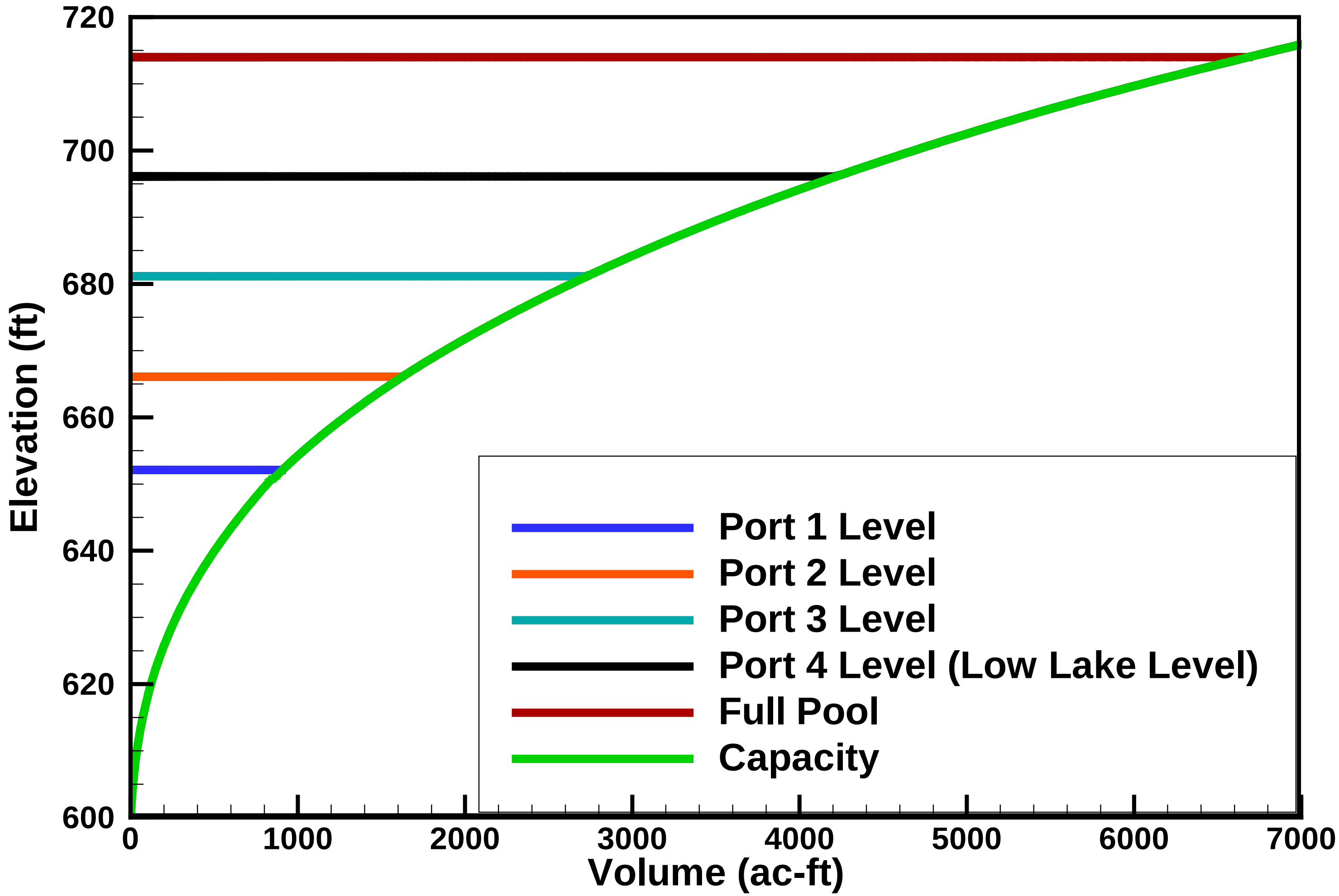

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Figure ES-2

Comparison of Wind Speed (Hourly Average)

CIMIS vs. ECR, on Tracer Injection Dates

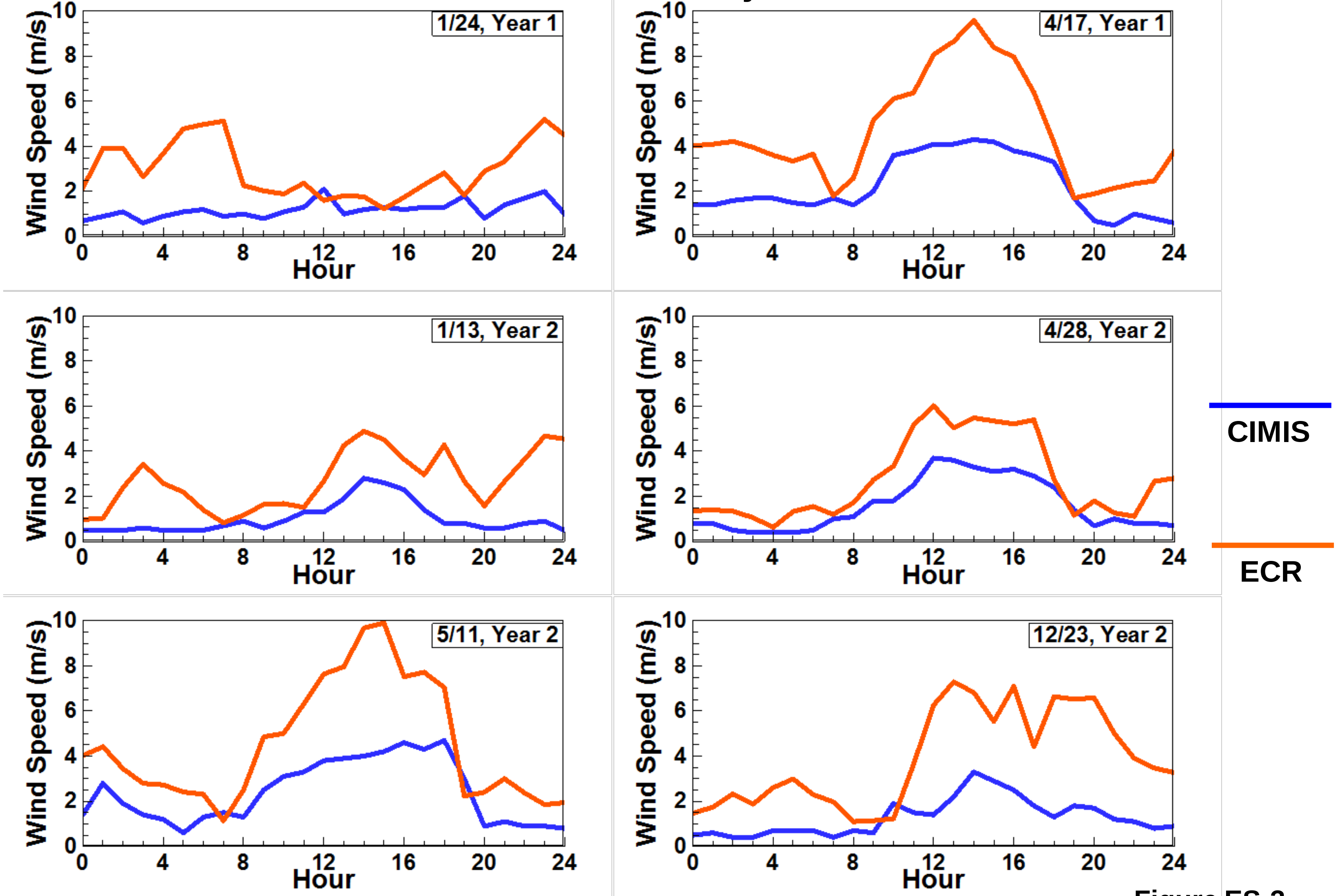
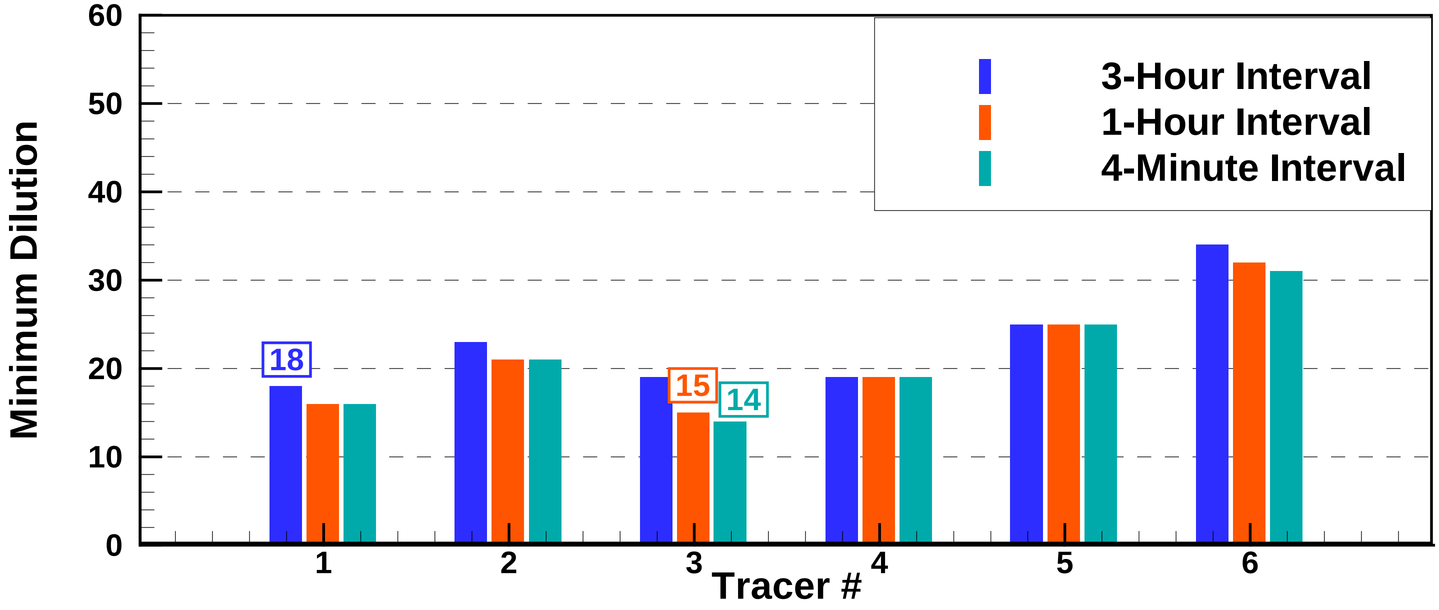


Figure ES-3

Run #3: Tracer Dilutions
Comparison of Model Output Intervals



*The boxed numbers are the overall minimum dilutions for different output intervals.

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Figure ES-4

Effect of Mixing Devices on Conservative Tracer Dilution

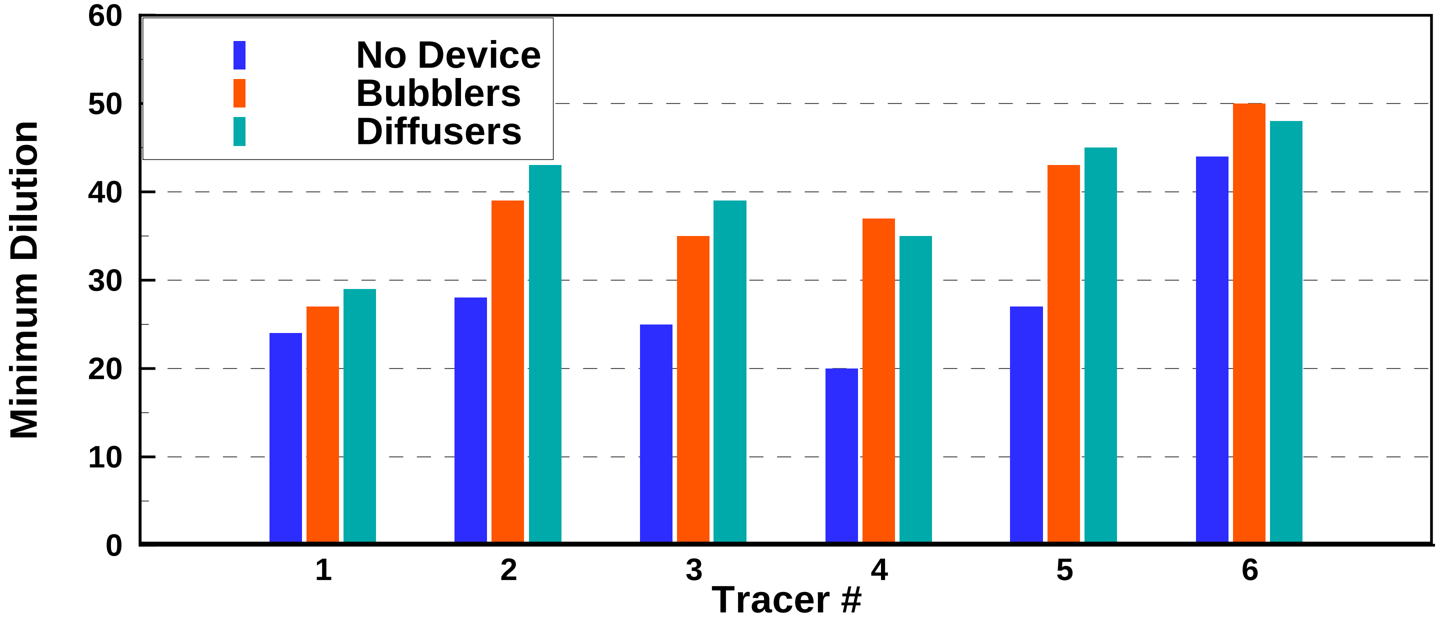

Figure ES-5

2.0 INTRODUCTION

This report summarizes the results of a preliminary water quality and limnology study of Miramar Reservoir (MR). It assesses the overall ability of the reservoir to accept purified water (PW) at an inflow rate of 30 million gallons per day (MGD) under five different operating scenarios (Nominal Case, Base Case, Low Lake Level Case, Nominal Case with Bubblers, and Nominal Case with Diffusers). The analysis is performed using a three-dimensional hydrodynamic and water quality model. The report is prepared by Water Quality Solutions Inc. (WQS), on behalf of Kleinfelder and the City of San Diego (the City). A more detailed study to further assess the reservoir's ability to accept PW, as well as make specific recommendations for reservoir operation, is underway.

2.1 Reservoir Background

Miramar Reservoir (**Figure 1**), located in the Scripps Ranch community of San Diego, is owned, operated and maintained by the City of San Diego. The reservoir is adjacent to Miramar Water Treatment Plant (WTP), which serves the northern part of the City. MR has a maximum depth of 114 feet (ft) and a water storage capacity of 6,682 acre-feet (ac-ft) (**Figure 2**).

In 2012, the City completed the Water Purification Demonstration Project, which investigated the feasibility of injecting 15 MGD of PW into San Vicente Reservoir (SVR). The PW would be blended with ambient reservoir water, stored in the reservoir, and eventually delivered to a water treatment plant for potable use. The Demonstration Project was reviewed by an Independent Advisory Panel (IAP), the California Department of Public Health (now known as Division of Drinking Water – DDW), and the Regional Water Quality Control Board (RWQCB). The consensus of the various reviews was that the addition of PW to SVR does not produce any significant public health or water quality issues.

In April 2013, the results of the Demonstration Project were presented to the San Diego City Council. The City Council accepted the results of the Demonstration Project and instructed the Public Utilities Department to investigate the feasibility of larger potable reuse projects at SVR and also a potable reuse project at Otay Reservoir (OTR).

Since then, the City has retained WQS to provide limnological assessments and water quality modeling for OTR and SVR under various operating conditions, in support of the Pure Water San Diego Program. These modeling studies used state of the art three-dimensional hydrodynamic and water quality models to investigate the mixing and dilution of PW in SVR and OTR. In particular, the mixing and dilution of a non-decaying tracer injected with PW for 24 hours were evaluated. The results of the limnology studies indicate that both SVR and OTR may satisfy DDW's preliminary criteria for potable reuse.

In 2015, the City started considering an option in which 30 MGD of PW would be augmented to MR, in lieu of SVR. If approved by the DDW, the use of MR is expected to significantly reduce the cost of a pipeline that would transport PW from the North City Wastewater Treatment Plant to the target lake. The City then tasked WQS with performing a preliminary limnological investigation for MR, which is the subject of this report. While this report was being prepared, the City decided that MR would be the preferred site for the initial 30 MGD of PW.

Similar to the earlier limnology studies (FSI, 2010; FSI, 2011; FSI, 2012; WQS, 2015), WQS used a three-dimensional hydrodynamic and water quality model to evaluate the dilution, mixing, and transport of PW in MR under various projected future reservoir operating scenarios. This investigation considers an inlet location at the northeast corner of the reservoir (**Figure 1**). The detailed results include establishing dilution for PW in the reservoir and evaluating nutrients (phosphorus and nitrogen), dissolved oxygen (DO), and algal (chlorophyll *a*) concentrations.

2.2 Description of Model

This limnology study has utilized a three-dimensional model of MR to address the mixing and detention of future PW inflow. The three-dimensional MR model consists of two coupled computer models – Estuary Lake and Coastal Ocean Model (ELCOM) for hydrodynamic simulation and the Computational Aquatic Ecosystem DYnamics Model (CAEDYM) for water quality simulation. The user inputs to ELCOM include boundary conditions, bathymetry, initial conditions, physical inputs, and meteorological inputs. The outputs from ELCOM include temperature, salinity (*i.e.*, conductivity), water velocities, and concentrations of conservative tracers. In this study, ELCOM was used to investigate the changes of these physical variables in space and time within the reservoir. The water quality module CAEDYM was coupled with ELCOM to simulate changes in DO, nutrients (phosphorus and nitrogen), pH, organic matter, and chlorophyll *a*. The coupled models were used to investigate the temporal and spatial relationships between physical, chemical, and biological variables in MR. Detailed descriptions of ELCOM and CAEDYM can be found in **Appendix A** of the following reports (FSI, 2010; FSI, 2011; FSI, 2012).

Bathymetry data for the reservoir was provided by the City, from which the model computational grid was created. The model grid was rotated 21 degrees clockwise from North in order to align the major channels of the reservoir with the model grid axes to reduce numerical approximations (**Figure 3**). For the ELCOM simulations, a grid with a resolution of 20 × 20 x 0.61 meters (m) was used **(Figures 4 and 5)**; in the CAEDYM simulations, a coarser grid with a resolution of 30 x 30 x 0.61 m was used to ensure a reasonable computational time **(Figure 6)**. The total number of grid cells was approximately 191,760 for the ELCOM simulations and 108,540 for the CAEDYM simulation.

2.3 Report Organization

- Section 3 describes the study objectives and approach.
- Section 4 presents the ELCOM/CAEDYM model calibration.
- Section 5 presents the modeling conditions.
- Section 6 presents the hydrodynamic simulation results.
- Section 7 presents the water quality simulation results.
- Section 8 provides conclusions and recommendations.
- Section 9 presents references cited in the report.
- Section 10 provides the glossary of this report.
- Section 11 presents the figures of this report.
- Section 12 presents the attachments.
- Attachment A* presents additional figures of ELCOM/CAEDYM calibration.
- Attachment B* presents additional result figures of hydrodynamic modeling.
- Attachment C contains tracer animations for various model runs.

*Note that the main body of the report only includes the highlights of the study. Additional figures can be found in the attachments.

3.0 STUDY OBJECTIVES AND APPROACH

In this section, the study objectives and modeling approach will be presented in detail. The first subsection discusses study objectives and draft retention criteria. The second subsection presents the general approach to hydrodynamic, nutrient, and algae modeling.

3.1 Study Objectives

The overall objective of this preliminary study is to use modeling to assess MR's ability to accept PW at an inflow rate of 30 MGD. Specifically, this report answers the following five questions:

1. Does the PW, at an inflow rate of 30 MGD, cause any hydrodynamic changes in the reservoir?

2. Does the reservoir provide adequate mixing and blending of the PW at an inflow rate of 30 MGD under the Nominal scenario?

3. Does the reservoir still provide adequate dilution of the PW at an inflow rate of 30 MGD at low lake level?

4. Do mixing devices, such as bubblers or diffusers, provide more mixing and blending of the PW?

5. Does the PW, at an inflow rate of 30 MGD, affect the water quality of the reservoir, specifically algal dynamics?

One of the main draft criteria by the DDW for reservoir augmentation requires a 10:1 dilution of a 24-hour pulse of PW, if an additional treatment step is incorporated (NWRI, 2015). Therefore, the criterion of 10:1 dilution of a 1-day production of PW, simulated by a 24-hour conservative tracer, will be used to evaluate dilution in MR for a PW inflow rate of 30 MGD.

3.2 General Approach

The first step in hydrodynamic and water quality modeling is model calibration.

The purpose of model calibration is to match the simulation results with the measured field data. During this process, input data is corrected if errors are identified, and consequently, some model parameters are adjusted.

After the model is calibrated, specific approaches and methodologies will be used in hydrodynamic, nutrient, and algae modeling to provide the necessary information that will address the five questions stated above.

3.2.1 Hydrodynamic Modeling

The analysis approach for hydrodynamic modeling in this study includes using ELCOM's conservative tracers as surrogates for chemical constituents in the PW to examine the dilution of such constituents that flow into MR. Six conservative tracers, with an initial concentration of 100, were used to simulate non-decaying chemical constituents in the PW inflow. Such constituents can inadvertently enter the reservoir as a result of potential "excursion events" at the full-scale Advanced Water Purification Facility (AWPF). The tracers were injected into the reservoir's inflow over a 24-hr period, representing a 1-day production of recycled water. The tracer concentration contours visually illustrate the movement of PW in the reservoir. The instantaneous dilution of the tracers at a specified location is obtained by dividing the source tracer concentration (i.e., 100) by the simulated tracer concentration at that location.

Specific approaches and methodologies will be used to provide the necessary information that will address the first four questions stated in Section 3.1, including

1. Comparisons of the simulated reservoir water temperature and conductivity under various reservoir operating scenarios were used to examine hydrodynamic changes in the reservoir;

2. Selection of critical dates during both the stratified and turnover periods for the injection of the conservative tracers were used to examine the corresponding concentrations and peak times of these tracers in the reservoir outflow. Turnover is defined as the first day in late fall/early winter when the difference between the highest and lowest temperature is less than 1 degree Celsius (°C) along the profile at Station A. Station A is located near the MR outlet (**Figure 3**). These conservative tracers provide estimates of the dilution of chemical constituents in the PW inflow;

3. Concentrations of the 24-hour conservative tracer in the outflow under the condition of a water surface level lower than a normal operation level were used to assess the mixing ability of MR at low lake level.

4. Comparisons of the dilutions of 24-hour conservative tracers under the condition of bubblers or diffusers simulated in the model were used to assess the effect of mixing devices on the mixing ability of MR.

3.2.2 Nutrient and Algae Modeling

The goal of nutrient and chlorophyll *a* modeling using CAEDYM is to determine the effects of the PW inflow on the reservoir's water quality, with a special emphasis on chlorophyll *a*. The analysis approach is to examine the water quality of the reservoir under the PW inflow rate of 30 MGD and compare the results with the reservoir's water quality before PW augmentation. This analysis approach will be used to provide the necessary information to address the last question stated in Section 3.1.

4.0 MODEL CALIBRATION

This section presents the calibrations of the MR model, with the first section focusing on the ELCOM calibration and the second section focusing on the CAEDYM calibration. The calibrations were conducted for the two-year period of 2013 – 2014.

4.1 ELCOM Calibration

The purpose of model calibration is to match the simulation results with measured field data. During this process, input data is corrected if errors are identified, and consequently, some model parameters are adjusted. In this study, the calibration of the hydrodynamic model (ELCOM) was carried out first.

The comparison between the ELCOM simulation results and measured in-reservoir field data focuses on three parameters – water surface elevation (WSEL), water temperature, and conductivity. The model calibration setup is presented first, and the calibration results for these three parameters will be presented in the next subsection.

4.1.1 ELCOM Calibration Setup

The required calibration setup of ELCOM includes a computational grid, initial conditions, inflow/outflow rates, inflow water temperature and conductivity, meteorological inputs, and withdrawal elevation.

4.1.1.1 Computational Grid Setup and Initial Conditions

The model grid with a constant grid size of 20 × 20 x 0.61 m was used for ELCOM calibration (**Figures 4 and 5**).

The calibration was performed as a continuous two-year simulation. The initial reservoir temperature profile at the beginning of Year 1 was based on a temporal interpolation of in-reservoir measured data from Station A (near the outlet tower, **Figure 3**).

ELCOM requires salinity as an input, but only conductivity is typically measured in the reservoir and in the inflows; therefore, salinity values were estimated from the conductivity data as

$$Salinity\ (psu) = 0.62 * conductivity\ (\mu S/cm)/1000\ .$$

Similar to the temperature data, the initial conductivity profile at the beginning of Year 1 was based on the temporal interpolation of in-reservoir measured data from Station A.

4.1.1.2 Flow Rates Inputs

Two surface inflows were included in the model calibration, including (1) the WTP return, which is the imported water from the aqueduct, and (2) the filter backwash and sludge return from the WTP. The locations where these two inflows enter the reservoir are shown in **Figure 3**.

The only modeled outflow in the calibration is the withdrawal from the outlet tower located near the southwest corner of the reservoir (see **Figure 3**). A detailed discussion of modeled withdrawal elevations is included in Section 5.1.5.

Daily flow volumes for the WTP return, the filter backwash, and the outflow were provided by the City. The flow volumes of the sludge return from the WTP, however, were not measured; instead, they were determined from the daily record of the WSEL. Based on the measured WSEL, daily reservoir storage data were calculated based on the capacity curve, and the daily volumes of the sludge return were calculated using a mass balance computation. A plot of the resulting inflow and outflow volumes used in the model calibration is included in **Figure 7**. As shown, the WTP return is the major inflow source to MR during this two-year period.

4.1.1.3 Inflow Temperature and Conductivity Inputs

The ELCOM calibration requires temperature and salinity of all inflows; however, these data were not available at all times for all inflows. Therefore, several assumptions and estimates were made when preparing these input files for the calibration. Daily temperature data for the aqueduct inflow to the WTP was provided by the WTP, and it is assumed that the temperature of the WTP return to MR does not change significantly from that of the aqueduct inflow.

Discharges from Lake Skinner generally supply the aqueduct. Therefore, since aqueduct inflow conductivity data is not measured at the WTP or the inlet to MR, data measured at the Lake Skinner outlet (located about 80 miles upstream) was used to characterize the WTP return for most of the two-year calibration period under the assumption that the conductivities in the aqueduct do not change significantly from the Lake Skinner discharge to the WTP then to the inlet of MR. Weekly or monthly records of the conductivity of the aqueduct inflow were provided by the Metropolitan Water District of Southern California (MWD).

Temperature and conductivity data for the filter backwash and sludge return were not available. They are assumed to be the same as those of the WTP return. **Figure A.1** in **Attachment A** includes plots of the input data used in the model calibration for the inflows.

4.1.1.4 Meteorological Inputs

The ELCOM model features a complete thermodynamic calculation and requires meteorological inputs that include measurements of solar radiation, air temperature, wind speed, wind direction, relative humidity, and rainfall. This meteorological data for the two-year period is available from two weather stations near MR (**Figure 8**). One is Station #150 of the California Irrigation Management Information System (CIMIS), located about 2.5 miles southwest of MR. The other is the Elliot Chaparral Reserve Station (ECR) of the Desert Research Institute (DRI), located about 1.5 miles south of MR.

The meteorological data from the two stations were compared for the two-year period. **Figure 9** includes the comparison of monthly averages between the two stations for the six variables mentioned above. For air temperature, wind direction, and rainfall, the data from the two stations are very similar. For solar radiation, the data from the two stations are similar for most of the two-year period, except the summer of Year 1. For wind speed, the data measured at ECR is consistently higher than the data measured at CIMIS #150. For relative humidity, the data measured at ECR is consistently lower than the data measured at CIMIS #150.

Wind speed has a significant effect on reservoir mixing; therefore, the wind speed data from the two stations were compared further on the tracer injection dates (**Figure 10**), which were identified with high wind events. On these dates, the difference between the data measured at the two stations is significant. The wind speeds measured at ECR can be double or triple of those measured at CIMIS #150.

Initially, the meteorological data measured at the two weather stations were used in different model calibration runs. The calibration run results based on the ECR data showed better agreement with the in-reservoir measurements of water temperature and conductivity; therefore, the meteorological data measured at ECR was used in the final calibration and in all model runs discussed in Sections 6 and 7.

4.1.1.5 Outflow Port Opening

Based on the operation record provided by the City, outflows were withdrawn from outlet Port #2 for the two-year period. In the model, water is considered to be withdrawn from Port #2 (EL 666.11 ft).

4.1.2 ELCOM Calibration Results

This section presents the calibration results by comparing the ELCOM simulation results and the measured in-reservoir field data for three parameters – WSEL, water temperature, and conductivity.

4.1.2.1 Water Surface Elevation

Figure 11 shows the measured versus simulated WSELs for the calibration based on the flow data provided by the City. As shown, the simulated WSELs are generally within ±1 ft of the measured WSELs.

4.1.2.2 Temperature

Figure 12 shows color contours of the simulated water temperatures compared to the measured data. **Figure 13** shows a time series plot of the simulated versus measured temperatures for the two-year modeling period at the surface and bottom of the reservoir. In addition, comparisons of simulated and measured temperature profiles at selected dates are included in **Attachment A** (**Figures A.2** – **A.5**). As presented, the simulated temperatures closely match the measured data and accurately predict the onset and duration of thermal stratification, as well as the depth of the thermocline.

A scatter plot of the measured and simulated temperature for the two-year calibration period is provided in **Figure 14**. The plot includes only surface and bottom temperatures. In the plot, the 45-degree theoretical line with zero intercept represents what would be a perfect correlation between the simulated and measured data. Therefore, the nearer the plotted points are to the 45-degree line, the better is the simulation. The graph indicates a good visual agreement.

A statistical analysis of the calibration results versus the measured temperature is presented in **Table 1**. The metrics quantitatively summarize the accuracy of the calibration results. For example, the computed root mean square errors (RMSEs) indicate that the calibrated temperatures during the two modeling years are on average within 0.65 ^{o}C of the measured data, corresponding to 4.5% of the range in measured temperatures (relative RMSE = RMSE / $|T_{max} – T_{min}|$). Mean error is the average of the difference between the measured and simulated values. Thus, the model on average overestimates temperatures by 0.11 ^{o}C during the two modeling years. These metrics indicate a good calibration.

Table 1: Temperature Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Temperature	0.65 ^{o}C	4.5 %	0.11 ^{o}C

Note: 1. Relative RMSE = RMSE / $|T_{max} – T_{min}|$, where T_{max} and T_{min} are from measured temperature data.
2. Mean error is the average of ($T_{measured} – T_{simulated}$).

4.1.2.3 Conductivity

Figures 15 and 16 are comparison plots (color contours and time series, respectively) for the simulated and measured conductivities (i.e., salinities). The simulated conductivity data plotted in both figures are computed based on the in-reservoir relationships between conductivity and salinity, discussed in Section 4.1.1.1. The resulting simulated conductivities capture the seasonal trends in both the surface and bottom conductivity values.

A scatter plot of the measured and simulated surface and bottom conductivity values for the two-year calibration period is provided in **Figure 17**. Statistical metrics are included in **Table 2**. The RMSEs indicate that the calibrated conductivity values are on average within 19.2 µS/cm of the measured values, corresponding to 6.9% of the range in measured conductivity. These values indicate a good conductivity calibration.

Table 2: Conductivity Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Conductivity	19.2 µS/cm	6.9 %	9.8 µS/cm

Note: 1. Relative RMSE = RMSE / $|Cond_{max} – Cond_{min}|$, where $Cond_{max}$ and $Cond_{min}$ are from measured conductivity data.

2. Mean error is the average of ($Cond_{measured}$ – $Cond_{simulated}$).

4.2 CAEDYM Calibration

The calibration of the nutrient and algae model CAEDYM was carried out after the ELCOM calibration was completed. The comparison between simulation results and measured in-reservoir field data was performed for the following water quality parameters: DO, nutrients, chlorophyll *a*, and pH.

4.2.1 CAEDYM Calibration Setup

The required calibration setup of CAEDYM includes a computational grid, initial conditions, and inflow water quality inputs in addition to the required model inputs of ELCOM.

4.2.1.1 Computational Grid Setup and Initial Conditions

A horizontally coarser grid with a resolution of 30 × 30 x 0.61 m, as shown in **Figure 6** (compared to the horizontally finer grid with a resolution of 20 × 20 x 0.61 m used in the ELCOM calibration), was used for the CAEDYM calibration in order to complete the CAEDYM run in a reasonable amount of computation time. The ELCOM calibration run was conducted on both grids to evaluate any difference in the predicted hydrodynamic conditions. **Figure A.6** in **Attachment A** shows a comparison of the predicted temperature profiles at Station A between the fine and coarse grids. **Figure A.7** in **Attachment A** shows a time series of predicted surface and bottom conductivity using both grids. The results indicate that using either the fine or coarse grids will result in almost the same predicted conductivity and very similar predicted temperature profiles. Therefore, it is appropriate to use the coarse grid in the CAEDYM calibration to provide both reasonable model run times as well as adequate model resolution.

The initial conditions of reservoir DO, nutrients, chlorophyll *a*, and pH at the beginning of Year 1 were based on in-reservoir measured data from Station A on the first available date (January 8, 2013).

4.2.1.2 Inflow Water Quality Inputs

Water quality parameters such as pH, DO, nutrients, and chlorophyll *a* of all inflows are required as inputs in the CAEDYM calibration; however, these data were not measured at all times for all inflows. Therefore, several assumptions and estimates were made when preparing these input files for the calibration.

WTP Return

Similar to the ELCOM calibration, water quality data measured at the Lake Skinner outlet was used to characterize the WTP return for most of the two-year calibration period. The data was obtained directly from MWD and included approximately monthly measurements of ammonia, nitrate, total phosphorus (TP), and Ortho-phosphate (OPO4, used interchangeably with soluble reactive phosphate, or SRP here). DO, chlorophyll *a*, and total nitrogen (TN) data were not available. Assumptions made in developing the WTP return water quality input files are noted below:

- DO concentrations were assumed to be 100% saturated based on water temperature.
- Chlorophyll *a* concentrations were assumed to be 0 µg/L since releases from Lake Skinner are generally at depths below photic zone and with limited algal growth.

Backwash and Sludge Return

Water quality data for the filter backwash and sludge return from the WTP were not available. Several assumptions were made in developing the water quality input files for backwash and sludge return, including:

- DO concentrations were assumed to be 100% saturated based on water temperature.
- Chlorophyll *a* concentrations were assumed to be 0 µg/L since the aqueduct inflow to the WTP was assumed to have 0 µg/L of chlorophyll *a* and there is very limited algal growth inside the WTP.
- Nutrient concentrations were assumed to be 10% of those in the WTP return.

It is believed that the nutrient loading of the backwash and sludge return has insignificant effect on the CAEDYM calibration. This is due to (1) its relatively small inflow volume, compared to inflow volume of the WTP return, and (2) the significant nutrient release from the sediment during the bottom anoxia period.

4.2.2 CAEDYM Calibration Results

This section presents the calibration results through comparisons between the CAEDYM simulation results and measured in-reservoir data focusing on DO, nutrients, Chlorophyll *a*, and pH.

4.2.2.1 Dissolved Oxygen

Figure 18 presents comparison plots for the simulated and measured DO concentrations at the reservoir surface and bottom. The simulated DO concentrations capture the major trends in the measured DO concentrations, including the onset, duration, and magnitude of periods of anoxia in the hypolimnion. The DO data shows that DO concentrations at the surface remained high throughout both years because of the supply of oxygen directly from the atmosphere by diffusion, as well as because of oxygen produced by photosynthetic activity of algae at the surface. The DO at the bottom was replenished through vertical mixing with the surface water featuring high DO concentrations during the reservoir turnover period in the winter of both years. However, during the summer, strong stratification in MR prevented such vertical mixing and DO at the bottom was quickly depleted by the decay of algae and other organic matter in the sediment (i.e., Sediment Oxygen Demand or SOD). The water conditions in the hypolimnion became anoxic (i.e., dissolved oxygen concentrations are near 0 mg/L) in the spring and anoxia lasted through the fall for both years, until the reservoir turnover in the winter.

Figure 19 presents a scatter plot of the measured and simulated DO concentrations for the two-year calibration period. A statistical analysis of the calibration results versus the measured data is shown in **Table 3**. The computed RMSEs indicate that the calibrated DO concentrations are on average within 0.82 mg/L of the measured data, corresponding 7.4% of the range in measured DO concentrations. These metrics indicate a good calibration for DO.

Table 3: Dissolved Oxygen Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Dissolved Oxygen	0.82 mg/L	7.4 %	0.24 mg/L

Note: 1. Relative RMSE = RMSE / $|DO_{max} – DO_{min}|$, where DO_{max} and DO_{min} are from measured data.
2. Mean error is the average of ($DO_{measured} – DO_{simulated}$).

4.2.2.2 Nutrients

The measured ammonia, nitrate, and SRP data were only available at the water surface, while the measured TN and TP data were available at both the surface and the bottom. The simulated ammonia, nitrate, and SRP are presented at both the surface and the bottom, but they are not compared to the measured data at the bottom.

Figures 20 – 22 present comparison plots of the simulated and measured ammonia, nitrate, and TN concentrations, respectively. In these figures, ammonia concentrations are below the detection limit (i.e., 0.031 mg/L N) at the surface throughout the simulation period. The nitrate concentrations are below the detection limit (i.e., 0.02 mg/L N) at the surface from early July through September of each year. At the bottom, ammonia concentrations were low at the beginning of both years when the reservoir was fully mixed. As the reservoir became stratified in the early spring, ammonia concentrations started to increase due to the release of ammonia from the sediment caused by anoxic conditions in the hypolimnion, until the reservoir was fully mixed again in winter. However, the trends of nitrate concentrations at the bottom are the reverse of those in ammonia concentrations; nitrate concentrations are high when the reservoir is in winter turnover and DO at bottom is high, and nitrate concentrations decrease when the reservoir is stratified and DO at bottom is low. This is because ammonia in the sediments can convert to nitrate through a nitrification process if oxygen is present and, consequently, the sediment releases nitrate instead of ammonia. Once the bottom of the reservoir becomes anoxic, nitrate is depleted slowly by denitrification. As shown, the simulated ammonia and nitrate closely match the trends and magnitude of the measured data at water surface, where measured data is available. The simulated TN concentrations match the measured concentrations fairly well and follow the general trends of the data.

Figure 23 presents a scatter plot of the measured and simulated TN concentrations for the two-year calibration period. A statistical analysis of the calibration results versus the measured data produced the metrics presented in **Table 4**. The computed RMSEs indicate that the calibrated TN concentrations are on average within 0.20 mg/L of the measured data, corresponding 20.8% of the range in measured TN concentrations. These indicate a fairly good calibration for TN.

Table 4: Total Nitrogen Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Total Nitrogen	0.20 mg/L	20.8 %	0.04 mg/L

Note: 1. Relative RMSE = RMSE / $|TN_{max} – TN_{min}|$, where TN_{max} and TN_{min} are from measured data.
2. Mean error is the average of ($TN_{measured} – TN_{simulated}$).

Figures 24 and 25 present comparison plots of the simulated and measured SRP and TP concentrations, respectively. The measured surface SRP and TP data are usually below the detection limits (i.e., 0.07 and 0.08 mg/L P, respectively), and the bottom TP data is also below the detection limits in the winter and spring. Despite this, general trends in the phosphorus data can still be observed. The observed trends in SRP data are similar to those in ammonia data. At the surface, phosphorus levels were usually low due to consumption by algae. At the bottom, phosphorus levels increased during the anoxic period due to sediment release. As shown, the model captures the trends of SRP at water surface, where measured data is available, and the trends of TP at both surface and bottom fairly well.

Figure 26 presents a scatter plot of the measured and simulated TP concentrations for the two-year calibration period. A statistical analysis of the calibration results versus the measured data produced the metrics presented in **Table 5**. The computed RMSEs indicate that the calibrated TP concentrations are on average within 0.06 mg/L of the measured data, corresponding 16.7% of the range in measured TP concentrations. These indicate a fairly good calibration for TP.

Table 5: Total Phosphorus Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom Total Phosphorus	0.06 mg/L	16.7 %	0.01 mg/L

Note: 1. Relative RMSE = RMSE / $|TP_{max} – TP_{min}|$, where TP_{max} and TP_{min} are from measured data.
2. Mean error is the average of ($TP_{measured} – TP_{simulated}$).

4.2.2.3 Chlorophyll a

Figure 27 presents a comparison plot of the simulated and measured chlorophyll *a* concentrations at the water surface. The measured chlorophyll *a* data provided by the City was estimated using an optical fluorometer. An optical fluorometer measures fluorescence and, if calibrated, can provide an estimate of relative chlorophyll *a* concentrations because algae fluoresce at characteristic wavelengths. Thus, a fluorometer provides more data (albeit of lower quality) more economically than could be obtained from grab samples and laboratory analysis. Furthermore, fluorometer readings can be corrupted by other particles present in the water column and indicate "false" algae blooms. In MR, there are a few chlorophyll *a* measurements that were significantly higher than the measurements before and after, such as the data point of 8.1 µg/L at the beginning of Year 1, the data point of 118.6 µg/L in April, Year 1 (out of the range of **Figure 27**), and the data point of 4.5 µg/L in October, Year 2. These data points were considered outliers. After eliminating these outliers, the simulated concentrations match the measured concentrations fairly well and follow the general trends of the data. In general, chlorophyll *a* concentrations are very low in MR. In the springs, after the reservoir surface is replenished with nutrients released from sediments during turnover and the temperature became warm enough for algal growth, the chlorophyll *a* concentration reached a peak. The yearly averages of simulated chlorophyll *a* concentrations match well with measured concentrations.

Figure 28 presents a scatter plot of the measured and simulated chlorophyll *a* concentrations for the calibration period. A statistical analysis of the calibration results versus the measured data produced the metrics presented in **Table 6**. The computed RMSEs indicate that the calibrated chlorophyll *a* concentrations are on average within 0.74 µg/L of the measured data, corresponding 30.6% of the range in measured chlorophyll *a* concentrations. These indicate a fairly good calibration for chlorophyll *a*.

Table 6: Chlorophyll *a* Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface Chlorophyll *a*	0.74 µg/L	30.6 %	-0.10 µg/L

Note: 1. Relative RMSE = RMSE / $|Chla_{max} - Chla_{min}|$, where $Chla_{max}$ and $Chla_{min}$ are from measured data.

2. Mean error is the average of ($Chla_{measured} - Chla_{simulated}$).

4.2.2.4 pH

Figure 29 presents comparison plots for the simulated and measured pH at the surface and the bottom of MR. The measured data shows that pH increased in the spring and summer of each year when inorganic carbon was consumed by the photosynthetic activity of algae; pH values were lower in the winter because of the release of CO_2 as a byproduct of algae respiration. The model accurately captures major trends in the measured pH and the simulated pH closely tracks measured data.

Figure 30 presents a scatter plot of the measured and simulated pH for the two-year calibration period. A statistical analysis of the calibration results versus the measured data is shown in **Table 7**. The computed RMSEs indicate that the calibrated pH data is on average within 0.17 of the measured data, corresponding to 12.3% of the range in measured pH values. These values indicate a good pH calibration, especially considering the small variation of pH during the two-year calibration period.

Table 7: pH Calibration Metrics

Parameters	Root Mean Square Error (RMSE)	Relative RMSE[1]	Mean Error[2]
Surface and Bottom pH	0.17	12.3 %	0.05

Note: 1. Relative RMSE = RMSE / $|pH_{max} – pH_{min}|$, where pH_{max} and pH_{min} are from measured data.
2. Mean error is the average of ($pH_{measured} – pH_{simulated}$).

4.3 Discussion of Calibration

In general, the calibrated model replicated the overall behaviors of the lake well, including surface and bottom temperatures, thermocline depth, surface and bottom conductivities, DO and nutrient levels in both epilimnion and hypolimnion, and surface algal levels. The calibration metrics, presented in **Tables 1 – 7**, indicate a good calibration.

The relative RMSEs of a variable are affected by both the absolute values of the RMSEs and the range of the measured values of the variable, which is the difference between the maximum measured value and the minimum measured value. For variables with a small range in the measured values, an insignificant RMSE may result in a high value of relative RMSE. In the calibrations of the MR model, the relative RMSEs vary across different variables. Among the variables, water temperature, conductivity, and DO were predicted with lower relative RMSEs, while the nutrients (depending on temperature and DO) and chlorophyll *a* and pH (depending on all other variables) were predicted with higher relative RMSEs. However, for all variables, the predicted values match the measured values well. Furthermore, the temporal and spatial agreement between the model results and the data is deemed good. It is thus considered that the calibrations of ELCOM and CAEDYM were successful.

5.0 MODELING CONDITIONS

After the calibration of the ELCOM and CAEDYM models at MR, various MR reservoir operating conditions were simulated using ELCOM and CAEDYM in order to achieve the study goals. Subsection 5.1 discusses the modeling conditions for the hydrodynamic modeling, and Subsection 5.2 discusses the modeling conditions for the nutrient and algae modeling.

5.1 Hydrodynamic Modeling Conditions

To achieve the study goals, various operating conditions were simulated using ELCOM in the MR hydrodynamic model. The main variables of this study include:

- Two-year model run using meteorological data from the years 2013-2014
- One PW inflow rate
    - 30 MGD
- One potential inlet location
    - Inlet Location 1
- Two operating lake levels
    - Normal lake level (water volume = 5,500 ac-ft)
    - Low lake level (water volume = 4,275 ac-ft)
- Two mixing devices
    - Bubblers
    - Diffusers
- One outflow port
    - Port #2 (the second lowest port at elevation (EL) 666.11 ft)

For every hydrodynamic model run, six conservative tracers were simulated. Details will be provided in the subsequent subsections.

- Subsections 5.1.1 – 5.1.6 provide details about the modeling conditions listed above.
- Subsection 5.1.7 summarizes all hydrodynamic modeling runs.

5.1.1 Purified Water Inflow Rates

A PW inflow rate of 30 MGD was modeled to simulate the potential future PW inflow rate, which is the design value projection provided by the City. The PW inflow originates from the future full scale AWPF and is then transferred to MR. The monthly inflow/outflow rates are summarized in **Table 8** and presented in **Figure 31**. The simulated operating scenarios consider zero WTP return and the same monthly filter backwash and sludge return from the WTP as in model calibration for both simulated years. Monthly inflow rates of the PW are the same as those simulated in the SVR limnology study. Monthly withdrawals for the simulated operating scenarios, ranging from 2,823 ac-ft/month to 3,536 ac-ft/month, are estimated under the assumption that the WSEL stays relatively constant.

5.1.2 PW Inlet Location

The potential PW inlet location, Inlet Location 1, is shown in **Figure 1**. It is located at the northeast corner of the reservoir, about 1 mile from the outlet structure. This potential PW inlet location was evaluated to investigate the dilution and mixing of the PW under various reservoir operating conditions.

5.1.3 Modeled Operating Lake Levels

Consistent with the historical record, MR is expected to be operated with a relatively constant WSEL. In this study, the dilution and mixing of the PW was studied under two different WSELs. The first is 706 ft, corresponding to a water volume of approximately 5,500 ac-ft. This is the nominal expected operating lake level. The second WSEL is 696.6 ft, corresponding to the water volume of about 4,275 ac-ft. This is the expected low lake level in case of emergency withdrawal, assuming 90 MGD of water withdrawn from the reservoir for a week prior to the beginning of the simulation.

Table 8: Monthly Inflow and Outflow Volumes for All Model Runs (PW Inflow = 30 MGD)

Month	WTP Return[1] (ac-ft)	Backwash + Sludge[2] (ac-ft)	PW Inflow (ac-ft)	Withdrawal (ac-ft)
Jan-Year 1	0	392	3,098	3,491
Feb-Year 1	0	369	3,172	3,536
Mar-Year 1	0	395	3,098	3,483
Apr-Year 1	0	424	2,948	3,351
May-Year 1	0	495	2,648	3,111
Jun-Year 1	0	458	2,723	3,146
Jul-Year 1	0	506	2,349	2,823
Aug-Year 1	0	539	2,573	3,081
Sep-Year 1	0	638	2,648	3,257
Oct-Year 1	0	553	2,498	3,038
Nov-Year 1	0	414	2,798	3,205
Dec-Year 1	0	388	3,023	3,405
Jan-Year 2	0	380	3,098	3,470
Feb-Year 2	0	356	3,172	3,521
Mar-Year 2	0	392	3,098	3,474
Apr-Year 2	0	346	2,948	3,269
May-Year 2	0	381	2,648	2,987
Jun-Year 2	0	458	2,723	3,142
Jul-Year 2	0	546	2,349	2,854
Aug-Year 2	0	552	2,573	3,090
Sep-Year 2	0	515	2,648	3,132
Oct-Year 2	0	408	2,498	2,890
Nov-Year 2	0	352	2,798	3,140
Dec-Year 2	0	298	3,023	3,311

Notes:

1. No WTP return in the simulated period.
2. Filter backwash and sludge return from the water treatment plant.

5.1.4 Modeled Mixing Devices

In this study, two types of devices were considered in order to increase the dilution and mixing of the PW near the inlet. One simulation involved using bubblers to create water curtains near the inlet, with a layout shown in **Figure 32**. In total, six bubblers were used, three in each row, with 50 horsepower per unit. The bubblers' elevations range from EL 646 ft to EL 666 ft. Another simulation was to distribute 50% of the inflow through diffusers located in the eastern third of the reservoir, with the remainder of the inflow entering the reservoir through Inlet Location 1 (**Figure 33)**. These two mixing devices were simulated in the model runs #4 and #5, respectively, to investigate their effect on the dilution and mixing of the PW water.

5.1.5 Reservoir Outflow Port Elevations

Table 9 presents available withdrawal levels for the outlet structure of the reservoir. The lowest level has a single port. The three levels above outflow Port #1 have two ports at each level, which are paired on opposite sides of the tower. Each outlet port has a diameter of 36 inches. All simulations presented in this report used Port #2 for withdrawals. **Figure 2** illustrates the cumulative reservoir water volume capacity, the WSEL, and the elevations of all four outlet ports. The normal pool WSEL of MR is EL 706 ft, and with MR at full capacity (6,682 ac-ft), the WSEL is EL 714 ft.

Table 9: Available Withdrawal Elevations on Reservoir Outflow Tower

Outflow Port	Centerline Elevation
# 4	696.12 ft
# 3	681.15 ft
# 2	666.11 ft
# 1	652.09 ft

5.1.6 Conservative Tracer Injection Dates

For each model run, conservative tracers were introduced through the PW inlet. For the Base Case scenario, six tracers were injected at relatively regular time intervals (once every other month during the second year), regardless of stratification conditions or wind events.

For all other operating conditions, six conservative tracers were introduced at times of weak thermal stratification conditions or high wind events. The injection dates for these conservative tracers were determined using an analysis of meteorological data at MR to identify relatively strong winds that blow from the northeast throughout the year. Such high wind events may move the PW inflow from the inlet towards the outlet port rather quickly. Based on the analysis, the tracer injection dates were identified. **Table 10** summarizes the conservative tracer injection dates for each operating scenario.

Table 10: Conservative Tracer Injection Dates in Model Runs

Tracer #	Injection Dates	
	Nominal	Base Case
1	1/24, Year 1	1/1, Year 2
2	4/17, Year 1	3/1, Year 2
3	1/13, Year 2	5/1, Year 2
4	4/28, Year 2	7/1, Year 2
5	5/11, Year 2	9/1, Year 2
6	12/23, Year 2	11/1, Year 2

5.1.7 Summary of ELCOM Model Runs

Table 11 summarizes the operating conditions for the five ELCOM model runs performed in this study. In the discussion of model run results, a model run will sometimes be referred to by its model run number for the sake of simplicity. The model run number reflects the order in which the run is performed.

Table 11: Summary of ELCOM Model Runs

Model Run No.	Operating Scenario	Initial/Final Reservoir Water Volume (ac-ft/ac-ft)	Mixing Device	Tracer Injection Dates
1	Nominal	5,500/5,500	None	High Winds from NE
2	Base Case	5,500/5,500	None	Evenly Distributed
3	Low Lake Level	4,275/4,275	None	High Winds from NE
4	Nominal	5,500/5,500	Bubblers	High Winds from NE
5	Nominal	5,500/5,500	Diffusers	High Winds from NE

5.2 Nutrient and Algae Modeling Conditions

In this study, the nutrient and algae (chlorophyll *a*) modeling of MR was performed for the PW inflow rate of 30 MGD under the nominal operating scenario. Unlike from the two-year hydrodynamic model runs, the nutrient and algae model run was performed for a four-year period in order to investigate the longer-term effects of the PW on water qualify of MR. The overall model inputs of the second two-year simulation period (inflows, outflows, meteorological data) are simply a repetition of the first two years.

Table 12 lists PW inflow water quality parameters used in the CAEDYM model run that were obtained from initial testing at the North City pilot water treatment plant.

Note that particulate and organic nutrients are considered to be negligible in the PW inflow. Thus, the concentration of TN is the sum of the ammonia (NH_4+NH_3), nitrate (NO_3), and nitrite (NO_2); the concentration of TP in the PW inflow is equal to the concentration of Soluble Reactive Phosphorus (SRP). The PW inflow has relatively high nitrogen and low phosphorus concentration, exceeding typical algal usage of N:P of approximately 10:1 (Horne and Goldman, 1994).

There was no measured data available for the required nutrient input (nitrate, nitrite, SRP, TN, and TP) of other inflows (backwash and sludge return); therefore, assumptions and estimates were made based on the measured nutrient data of the imported water to the water treatment plant. **Table 12** lists the estimated nutrient concentrations in the backwash and sludge return as used in the simulations. These estimated concentrations produced best calibration results; therefore, they were used in the simulation model runs.

Table 12: Inflow Water Quality Parameters

Water Quality Parameter	PW Inflow	Backwash + Sludge
(NO_3 + NO_2)–N (mg/L)	0.64	0.01 – 0.03
(NH_4+NH_3)–N (mg/L)	0.14	0 – 0.01
TN (mg/L)	0.78	0.01 – 0.04
SRP (mg/L)	0.004	0 – 0.008
TP (mg/L)	0.004	0 – 0.02

6.0 HYDRODYNAMIC MODELING RESULTS

This section presents the hydrodynamic results of the ELCOM model runs. First, the overall hydrodynamic results are discussed. Following that, the highlights of the results are presented in the order of run numbers in subsections 6.2 – 6.6, respectively. **Attachment B** presents additional results consisting of illustrations of water temperature/conductivity and conservative tracer concentrations in outflow for each run. Subsection 6.7 summarizes the hydrodynamic results of all five runs.

6.1 Overall Hydrodynamic Results

Figure 34 presents the comparison contour plots of temperature at Station A for (1) the scenario before PW augmentation (Before PW) and (2) the Nominal scenario with a PW inflow rate of 30 MGD. The temperature along the water column increased with the warm PW inflow and the thermocline deepened consequently. For example, the depth of the 15 °C contour on August 15, Year 1 under the scenario Before PW is 66 ft. Under the Nominal scenario, the depth of the 15 °C contour on the same day is 82 ft. Introducing the PW at an inflow rate of 30 MGD under the Nominal scenario increases the depth of the 15 °C contour by 16 ft. If the simulations are continued past two years, the thermocline may deepen further.

Figure 35 presents the comparison contour plots of conductivity at Station A for (1) Before PW and (2) the Nominal scenario with a PW inflow rate of 30 MGD. The PW, which is low in salinity, decreases the reservoir conductivity. If the simulations are continued past two years, the conductivity is expected to continue to decrease until it reaches a near steady state condition.

Table 13 presents the simulated turnover dates for Before PW and the Nominal scenario with a PW inflow rate of 30 MGD. Turnover is defined as the first day in late fall/early winter when the difference between the highest and lowest temperature is less than 1 °C along the vertical profile at Station A. For the scenario Before PW, the turnover occurs on 12/10 for Year 1 and 12/17 for Year 2. For the Nominal scenario with a PW inflow rate of 30 MGD, turnover occurs on 12/13 for Year 1 and 12/12 for Year 2. The PW at an inflow rate of 30 MGD warms the water column and deepens the thermocline, but does not show a significant effect on the turnover dates.

Table 13: Simulated Turnover Dates

Operating Condition	Beginning of Turnover[1]	
	Year 1	Year 2
Before PW	12/10	12/17
PW=30MGD	12/13	12/12

Note:

1. Turnover date is defined as the first day in winter when the difference between the highest temperature and the lowest temperature is less than 1 °C along the profile at Station A.

6.2 Nominal Case

Model Run #1 presents the Nominal scenario, which is the median expected operating condition. **Figure 36** shows the WSEL during the two-year simulation period. The WSEL is relatively constant during the simulation period, within ±1 ft of the initial WSEL. **Figure 37** presents the simulated 24-hour conservative tracer concentrations in the reservoir outflow at Port #2 for the 20 day interval after each tracer injection date. **Table 14** summarizes the 24-hour conservative tracer results from the model run. The maximum observed concentration is 5.02, reflecting a minimum dilution of 20, and it occurs for the tracer injected on 4/28, Year 2. The shortest lag time between the injection of a 24-hour tracer and the occurrence of peak concentration in reservoir outflow is 1.1 days, and it occurs for the tracers injected on 5/11, Year 2 and 12/23, Year 2.

Table 14: Summary of Model Run #1

Tracer Injection Date	Max. Conc.	Dilution	Lag Time (days)
1/24, Year 1	4.14	24	1.5
4/17, Year 1	3.59	28	1.3
1/13, Year 2	4.04	25	1.4
4/28, Year 2	5.02	20	1.3
5/11, Year 2	3.64	27	1.1
12/23, Year 2	2.26	44	1.1
Overall Max. Conc.	5.02		
Overall Min. Dilution	20		
Overall Min. Lag Time (days)	1.1		

6.3 Base Case

Model Run #2 presents a Base Case scenario. It is similar to the Nominal scenario, but with conservative tracers injected at relatively regular time intervals during Year 2. The simulated WSEL of Run #2 is identical to that of Run #1, as shown in **Figure 36**. **Figure 38** presents the simulated 24-hour conservative tracer concentrations in the reservoir outflow at Port #2 for the 20 day interval after each tracer injection date. **Table 15** summarizes the 24-hour conservative tracer results from the model run. The maximum observed concentration is 3.03, reflecting a minimum dilution of 33, and it occurs for the tracer injected on 1/1, Year 2. The shortest lag time between the injection of a 24-hour tracer and the occurrence of peak concentration in reservoir outflow is 2.0 days, and it occurs for the tracer injected on 3/1, Year 2.

Table 15: Summary of Model Run #2

Tracer Injection Date	Max. Conc.	Dilution	Lag Time (days)
1/1, Year 2	3.03	33	3.1
3/1, Year 2	2.75	36	2.0
5/1, Year 2	1.79	56	6.0
7/1, Year 2	1.63	61	10.0
9/1, Year 2	2.09	48	4.0
11/1, Year 2	1.80	56	3.5
Overall Max. Conc.	3.03		
Overall Min. Dilution	33		
Overall Min. Lag Time (days)	2.0		

6.4 Low Lake Level Case

Model Run #3 presents a Low Lake Level scenario, which is the expected operating lake level in case of emergency withdrawal, assuming 90 MGD of water withdrawn from the reservoir for a week prior to the beginning of the simulation. **Figure 39** shows the WSEL during the two-year simulation period. The WSEL is relatively constant during the simulation period, within ±1 ft of the initial WSEL (696.6 ft). **Figure 40** presents the simulated 24-hour conservative tracer concentrations in the reservoir outflow at Port #2 for the 20 day interval after each tracer injection date. **Table 16** summarizes the 24-hour conservative tracer results from this model run. The maximum observed concentration is 5.67, reflecting a minimum dilution of 18, and it occurs for the tracer injected on 1/24, Year 1. The shortest lag time between the injection of a 24-hour tracer and the occurrence of peak concentration in reservoir outflow is 0.8 days, and it occurs for the tracer injected on 12/23, Year 2.

There is, however, uncertainty in the results. The current model run results were based on a 3-hour output interval, meaning the model run wrote the results in the output file every 3-hr model run time; however, different output intervals may affect the accuracy of the model run results. Model Run #3 has been performed using three different output intervals (3-hour, 1-hour, and 4-minute). The comparison of tracer dilutions between these three output intervals is shown in **Figure 41**. Model runs with 1-hour and 4-minute output intervals may provide lower minimum dilutions of the conservative tracers than a model run with 3-hour output intervals. For Model Run #3 with 4-minute output intervals, the results show an overall minimum dilution (OMD) of 14:1, lower than the 18:1 value from the model run with 3-hour output interval, as shown in **Table 16.** The 14:1 OMD value occurs for the tracer injected on 1/13, Year 2.

Table 16: Summary of Model Run #3

Tracer Injection Date	Max. Conc.	Dilution	Lag Time (days)
1/24, Year 1	5.67	18	1.4
4/17, Year 1	4.31	23	1.1
1/13, Year 2	5.38	19	1.3
4/28, Year 2	5.38	19	1.3
5/11, Year 2	3.93	25	1.3
12/23, Year 2	2.95	34	0.8
Overall Max. Conc.	5.67[1]		
Overall Min. Dilution	18[2]		
Overall Min. Lag Time (days)	0.8		

Notes: 1. The overall maximum concentration is 6.95 for the run with a 4-minute output interval;
2. The overall minimum dilution is 14 for the run with a 4-minute output interval.

6.5 Nominal Case with Bubblers

Model Run #4 presents a Nominal scenario with bubblers installed near the PW inlet location (**Figure 32**). The simulated WSEL of Run #4 is similar to that of Run #1, as shown in **Figure 36**. **Figure 42** presents the simulated 24-hour conservative tracer concentrations in the reservoir outflow at Port #2 for the 20 day interval after each tracer injection date. **Table 17** summarizes the 24-hour conservative tracer results from this model run. The maximum observed concentration is 3.74, reflecting a minimum dilution of 27, and it occurs for the tracer injected on 1/24, Year 1. The shortest lag time between the injection of a 24-hour tracer and the occurrence of peak concentration in reservoir outflow is 0.8 days, and it occurs for the tracer injected on 12/23, Year 2.

Table 17: Summary of Model Run #4

Tracer Injection Date	Max. Conc.	Dilution	Lag Time (days)
1/24, Year 1	3.74	27	1.4
4/17, Year 1	2.59	39	1.4
1/13, Year 2	2.87	35	1.3
4/28, Year 2	2.70	37	1.3
5/11, Year 2	2.31	43	1.3
12/23, Year 2	1.99	50	0.8
Overall Max. Conc.	3.74		
Overall Min. Dilution	27		
Overall Min. Lag Time (days)	0.8		

6.6 Nominal Case with Diffusers

Model Run #5 presents a Nominal scenario where 50% of the PW inflow enters MR through diffusers located in the eastern third of the reservoir, with the remaining 50% entering MR through the Inlet Location 1 (**Figure 33**). The simulated WSEL of Run #5 is similar to that of Run #1, as shown in **Figure 36**. **Figure 43** presents the simulated 24-hour conservative tracer concentrations in the reservoir outflow at Port #2 for the 20 day interval after each tracer injection date. **Table 18** summarizes the 24-hour conservative tracer results from this model run. The maximum observed concentration is 3.41, reflecting a minimum dilution of 29, and it occurs for the tracer injected on 1/24, Year 1. The shortest lag time between the injection of a 24-hour tracer and the occurrence of peak concentration in reservoir outflow is 0.8 days, and it occurs for the tracer injected on 12/23, Year 2.

Table 18: Summary of Model Run #5

Tracer Injection Date	Max. Conc.	Dilution	Lag Time (days)
1/24, Year 1	3.41	29	1.4
4/17, Year 1	2.33	43	1.4
1/13, Year 2	2.59	39	1.3
4/28, Year 2	2.83	35	1.4
5/11, Year 2	2.24	45	1.4
12/23, Year 2	2.08	48	0.8
Overall Max. Conc.	3.41		
Overall Min. Dilution	29		
Overall Min. Lag Time (days)	0.8		

6.7 Discussion of Results

Table 19 summarizes the 24-hour conservative tracer results including the OMD and the overall minimum lag time. The table also includes the injection date of the tracer with the lowest minimum dilution. Specific answers to four of the five main study questions are addressed below. The answer to the fifth study question related to nutrients and algal dynamics is answered in Section 7.5.

Table 19: Summary of ELCOM Model Run Results

Model Run #	Operating Scenario	Initial/Final Reservoir Water Volume (ac-ft)	Tracer Injection Date[1]	Overall Max. Conc. (%)	Overall Min. Dilution	Overall Min. Lag Time[2] (days)
1	Nominal	5,500/5,500	4/28, Year 2	5.02	20	1.1
2	Base Case	5,500/5,500	1/1, Year 2	3.03	33	2.0
3	Low Lake Level	4,275/4,275	1/13, Year 2[3]	6.95[3]	14[3]	0.8
4	Bubblers	5,500/5,500	1/24, Year 1	3.74	27	0.8
5	Diffusers	5,500/5,500	1/24, Year 1	3.41	29	0.8

Note:

1. Injection date of the tracer with the lowest minimum dilution.
2. The minimum lag time does not necessarily correspond to the 24-hour conservative tracer injected that results in lowest minimum dilution.
3. The OMD of Run #3 was from a model run with a 4-minute output interval, while the OMDs of all other model runs were based on a 3-hour output interval.

1. Does the PW at an inflow rate of 30 MGD cause any hydrodynamic changes in the reservoir?

   Yes, the PW inflow at a rate of 30 MGD will cause minor hydrodynamic changes in the reservoir. For the two-year simulation period, the addition of the warmer PW results in a deepening of the thermocline but does not show significant effect on the turnover dates. If the simulations are continued past two years, the thermocline may deepen further.

2. Does the reservoir provide adequate mixing and blending of the PW at an inflow rate of 30 MGD under the Nominal scenario?

Yes, the preliminary limnology study shows that the reservoir provides adequate mixing and blending under the Nominal scenario. This reduces the effects of potential increases in concentration of chemical constituents in the PW inflow, resulting from potential “excursion events” at the full-scale AWPF. The OMD of the PW under the Nominal scenario is 20:1, greater than the required OMD of 10:1 for a 24-hour tracer, thus providing adequate mixing and blending of PW. However, due to uncertainties in model inputs and performance, additional evaluations are needed as discussed in the answer to Question #3 below.

3. Does the reservoir still provide adequate dilution of the PW at an inflow rate of 30 MGD at low lake level?

Overall, the preliminary results showed that at low lake levels, the reservoir can still provide adequate dilution of the PW at an inflow rate of 30 MGD (an OMD greater than 10:1 for a 24-hour tracer). For the simulation at low lake levels, the predicted OMD is 14:1 when a 4-minute output interval is invoked. However, due to uncertainties in model inputs and performance, additional evaluations are needed to ensure that the 10:1 dilution is adequately exceeded. These additional evaluations should address the following:

- Uncertainties in meteorological data

Currently meteorological data are available from two weather stations near MR, CIMIS #150 and ECR (**Figure 8**). The difference between meteorological data from these two different weather stations can be significant, especially the difference of wind speed, which strongly affects reservoir mixing and tracer transport. On extreme event dates, the wind speed at ECR can be double or triple of that at the CIMIS station (**Figure 10**).

- Uncertainties in model inputs

Using more critical operating conditions (e.g. more extreme wind speeds, lower lake level, higher outflow rate, etc.) may result in lower dilutions than predicted.

- Uncertainties in model output

Different output intervals may affect the accuracy of the model run results. For example, in the Low Lake Level Case, model runs with 1-hour and 4-minute output intervals provided lower minimum dilution than those performed with a 3-hour output interval (**Figure 41**).

For the run at low lake level, the predicted OMD is 14:1 when a 4-minute output interval is invoked. Considering the uncertainties discussed above, the 14:1 dilution, however, may not provide a sufficient buffer to consistently insure that the dilution will be greater than 10:1. Based on the above discussion, further investigations are needed to evaluate confidence in model results, input data, and lake operating parameters. These investigations are being performed in a subsequent phase of the limnology study**.**

4. Do mixing devices, such as bubblers or diffusers, provide more mixing and blending of the PW?

Yes, the preliminary results have shown that the mixing devices (bubblers or diffusers) could potentially provide more mixing and blending of the PW. **Figure 44** shows the comparison between the minimum dilutions under the condition of mixing devices and the minimum dilutions with no mixing devices for all six tracers. Using a bubbler, or using a diffuser to disperse and vigorously mix some of the PW with ambient reservoir water, could potentially increase the dilution for all simulated tracers. However, the current simulations of bubblers or diffusers are only preliminary, and further evaluation of the effect of mixing devices on dilution is needed to provide specific recommendations.

7.0 NUTRIENT AND ALGAE MODELING RESULTS

To evaluate how the PW at an inflow rate of 30 MGD may affect water quality of MR, an CAEDYM simulation was performed for a four-year modeling period. Note that the simulation period of the CAEDYM run is double that of the ELCOM runs. This was done in order to investigate the longer-term effects of the PW on water qualify of MR. The model inputs of the second two-year simulation period are simply a repetition of the first two-year.

The CAEDYM model run utilizes the Nominal operating scenario and Port #2 is assumed open for the whole simulation period. The WSEL of the CAEDYM run is shown in **Attachment B.11**. Similar to the two-year ELCOM model runs, the simulated WSEL remains relatively constant, within ±1 ft of the normal operating level (EL = 706 ft), over the four-year modeling period. The contour plots of water temperature and conductivity of the CAEDYM run are shown in **Attachment B.12** for the four-year modeling period. Similar to the two-year ELCOM model run results, the PW, with warm temperature and low salinity, deepens the thermocline and decreases the reservoir conductivity. The subsections below present the nutrient and algae modeling results, focusing on DO, nutrients, chlorophyll *a*, and pH.

7.1 Dissolved Oxygen

Figure 45 presents the simulated surface and bottom DO concentrations under the condition of a PW inflow rate of 30 MGD. The surface DO concentrations remain nearly saturated. Bottom DO steadily decreases during the spring and summer months, a result of algal decay, sediment oxygen demand, and lack of replenishment from the atmosphere. The bottom of MR becomes anoxic during the summer and fall. DO is replenished as the reservoir begins turnover during the winter.

Table 20 lists the hypolimnetic anoxia (bottom DO values being less than 0.5 mg/L) period of each year for this model run, compared to the scenario of Before PW. For Year 1, the hypolimnetic anoxia period is predicted to last 254 days (or 70% of the time), longer than that of the next three years. For the next three years, the hypolimnetic anoxia period is predicted to last 210 – 214 days (or 57% – 59% of the time), nearly equal to the length of the hypolimnetic anoxia period of Year 1 of the scenario Before PW. The significantly longer hypolimnetic anoxia period for Year 1 in the CAEDYM run is a result of stratification starting earlier in Year 1, likely due to the introduction of warm PW inflow at the reservoir surface forming a thermocline earlier. The PW, however, does not show a significant effect on DO after Year 1.

Table 20: Summary of Simulated DO

Year	PW = 30 MGD		Before PW	
	Bottom Anoxia Period[1]	Days Under Anoxia: Total Days (Percentage)	Bottom Anoxia Period[1]	Days Under Anoxia: Total Days (Percentage)
Year 1	4/5 –12/14	254 (70%)	5/14 –12/11	212 (58%)
Year 2	5/8 – 12/6	213 (58%)	5/10 – 12/19	223 (61%)
Year 3	5/7 – 12/6	214 (59%)	N/A	N/A
Year 4	5/9 – 12/4	210 (57%)	N/A	N/A

Notes: 1. Anoxia is defined here as the bottom DO being less than 0.5 mg/L;

7.2 Nutrients

Figures 46, **47, and 48** illustrate the simulated NH_4-N, NO_3-N, and TN, respectively. **Figures 49 and 50** show the simulated SRP and TP, respectively. For the reservoir's hypolimnion, TN and TP begin to increase in the spring of every year as DO values decreased, a result of decaying organic matter and internal nutrient recycling from the sediments during anoxic or low DO conditions. The simulation shows similar trends during the last three years but a different trend during Year 1. In Year 1, the concentration of NO_3-N at the bottom is lower, and the sediment release periods of NH_4-N and SRP are longer, caused by the longer hypolimnetic anoxia period during Year 1. In general, the simulation shows high concentrations of nitrogen and low concentrations of phosphorus at the surface, a result of year-round high-rate inflow of PW with relatively high nitrogen and low phosphorus concentrations.

7.3 Chlorophyll *a*

Figure 51 presents the simulated surface chlorophyll *a* concentrations. In general, after reservoir turnover in winter, the reservoir surface is replenished by the phosphorus from the hypolimnion, resulting in an algal growth peak in the spring. Low phosphorus concentrations in the reservoir surface water limit algal growth during winter, summer, and fall. The peak value of surface chlorophyll *a* concentrations in Year 1 is higher than that of the other three years because of the existing phosphorus in the water column at the beginning of this simulation. In the next three years, the surface phosphorus concentrations are very low, a result of year-round high-rate inflow of PW with low phosphorus concentrations, thus limiting the algal growth.

Table 21 summarizes annual average surface chlorophyll *a* concentrations for the simulation, compared to the scenario of Before PW. The average chlorophyll *a* concentration is predicted to be 0.24 µg/L for Year 1 and 0.03 or 0.04 µg/L for the next three years, which is significantly lower than the algal levels Before PW. This indicates that a PW inflow rate of 30 MGD is predicted to produce lower algal levels *(i.e.*, low surface chlorophyll *a* concentrations) and higher water clarity, due to the very low phosphorus concentrations in the year-round high-rate inflow of PW.

Table 21: Summary of Chlorophyll *a*

Year	Average Surface Chlorophyll *a* (µg/L)	
	PW = 30 MGD	Before PW
Year 1	0.24	0.47
Year 2	0.04	0.33
Year 3	0.03	N/A
Year 4	0.03	N/A

7.4 pH

Figure 52 illustrates the simulated pH for the reservoir surface and bottom. Surface pH values depend largely on algal productivity as elevated pH is generally an indicator of algal blooms. Algal levels are predicted to be relatively low in MR; therefore, the pH at the reservoir surface is predicted to be fairly constant for all four years, at ~8.2 during each simulated year. Bottom pH values depend largely on the development of the thermocline. The pH at the reservoir bottom is predicted to be around 7.2 when the reservoir is stratified and at a higher level, peaking at ~8.0, during turnover.

7.5 Discussion of Results

This section summarizes the results of the water quality modeling, and in particular, answers the fifth question in the study.

5. Does the PW, at an inflow rate of 30 MGD, affect the water quality of the reservoir, specifically algal dynamics?

Yes, the PW affects the water quality of MR. The preliminary water quality study shows that a PW inflow rate of 30 MGD is predicted to produce low algal levels (i.e., low surface chlorophyll *a* concentrations) and high water clarity. In fact, the PW inflow gradually reduces algal levels and increases water clarity. The simulated surface chlorophyll *a* concentration dropped from 0.24 µg/L in Year 1 to 0.03 µg/L in Year 4. This is related to the generally low phosphorus concentrations in the PW. The TP and TN concentrations in the PW are considered to be 0.004 and 0.78 mg/L, respectively; therefore, the algal growth will be very limited by phosphorus in MR.

Note that the TP and TN values of the PW in the current study were based on the results from the Demonstration Plant during startup. These values from ongoing operation of the Demonstration plant may have changed and will be evaluated in the next phase of the limnology study.

8.0 CONCLUSIONS AND RECOMMENDATIONS

This report summarizes the results of a water quality and limnology study of Miramar Reservoir (MR). It assesses the ability of the reservoir to accept the purified water (PW) at an inflow rate of 30 MGD under various operating conditions. The analysis is performed using a three-dimensional hydrodynamic and water quality model. The report is prepared by Water Quality Solutions Inc., on behalf of Kleinfelder and the City of San Diego.

8.1 Conclusions

1. Does the PW at an inflow rate of 30 MGD cause any hydrodynamic changes in the reservoir?

   Yes, the PW inflow at a rate of 30 MGD will cause minor hydrodynamic changes in the reservoir. For the two-year simulation period, the addition of the warmer PW results in a deepening of the thermocline but does not show significant effect on the turnover dates. If the simulations are continued past two years, the thermocline may deepen further.

2. Does the reservoir provide adequate mixing and blending of the PW at an inflow rate of 30 MGD under the Nominal scenario?

   Yes, the preliminary limnology study shows that the reservoir provides adequate mixing and blending under the Nominal scenario. This reduces the effects of potential increases in concentration of chemical constituents in the PW inflow, resulting from potential "excursion events" at the full-scale AWPF. The OMD of the PW under the Nominal scenario is 20:1, greater than the required OMD of 10:1 for a 24-hour tracer, thus providing adequate mixing and blending of PW. However, due to uncertainties in model inputs and performance, additional evaluations are needed as discussed in the answer to Question #3 below.

3. Does the reservoir still provide adequate dilution of the PW at an inflow rate of 30 MGD at low lake level?

   Overall, the preliminary results showed that at low lake levels, the reservoir can still provide adequate dilution of the PW at an inflow rate of 30 MGD (an OMD greater than 10:1 for a 24-hour tracer). For the simulation at low lake levels, the predicted OMD is 14:1 when a 4-minute output interval is invoked. However, due to uncertainties in model inputs and performance, additional evaluations are needed to ensure that the 10:1 dilution is adequately exceeded. These additional evaluations should address the following:

- Uncertainties in meteorological data

Currently meteorological data are available from two weather stations near MR, CIMIS #150 and ECR (**Figure 8**). The difference between meteorological data from these two different weather stations can be significant, especially the difference of wind speed, which strongly affects reservoir mixing and tracer transport. On extreme event dates, the wind speed at ECR can be double or triple of that at the CIMIS station (**Figure 10**).

- Uncertainties in model inputs

Using more critical operating conditions (e.g. more extreme wind speeds, lower lake level, higher outflow rate, etc.) may result in lower dilutions than predicted.

- Uncertainties in model output

Different output intervals may affect the accuracy of the model run results. For example, in the Low Lake Level Case, model runs with 1-hour and 4-minute output intervals provided lower minimum dilution than those performed with a 3-hour output interval (**Figure 41**).

For the run at low lake level, the predicted OMD is 14:1 when a 4-minute output interval is invoked. Considering the uncertainties discussed above, the 14:1 dilution, however, may not provide a sufficient buffer to consistently insure that the dilution will be greater than 10:1. Based on the above discussion, further investigations are needed to evaluate confidence in model results, input data, and lake operating parameters. These investigations are being performed in a subsequent phase of the limnology study.

4. Do mixing devices, such as bubblers or diffusers, provide more mixing and blending of the PW?

Yes, the preliminary results have shown that the mixing devices (bubblers or diffusers) could potentially provide more mixing and blending of the PW. **Figure 44** shows the comparison between the minimum dilutions under the condition of mixing devices and the minimum dilutions with no mixing devices for all six tracers. Using a bubbler, or using a diffuser to disperse and vigorously mix some of the PW with ambient reservoir water, could potentially increase the dilution for all simulated tracers. However, the current simulations of bubblers or diffusers are only preliminary, and further evaluation of the effect of mixing devices on dilution is needed to provide specific recommendations.

5. Does the PW, at an inflow rate of 30 MGD, affect the water quality of the reservoir, specifically algal dynamics?

Yes, the PW affects the water quality of MR. The preliminary water quality study shows that a PW inflow rate of 30 MGD is predicted to produce low algal levels (i.e., low surface chlorophyll *a* concentrations) and high water clarity. In fact, the PW inflow gradually reduces algal levels and increases water clarity. The simulated surface chlorophyll *a* concentration dropped from 0.24 µg/L in Year 1 to 0.03 µg/L in Year 4. This is related to the generally low phosphorus concentrations in the PW. The TP and TN concentrations in the PW are considered to be 0.004 and 0.78 mg/L, respectively; therefore, algal growth will be limited by phosphorus in MR.

Note that the TP and TN values of the PW in the current study were based on the results from the Demonstration Plant during startup. These values from ongoing operation of the Demonstration plant may have changed and will be evaluated in the next phase of limnology study.

8.2 Recommendations

The current work shows promising results, but only partially answers the questions as the simulation results may have been affected by uncertainties (e.g. meteorological data, model input parameters, model output intervals, etc.), as mentioned in the discussions above. Therefore, additional analysis is needed to fully answer the questions, including

- Reviewing the model run results and discussing a new work plan with IAP;
- Developing a reservoir data collection plan to enhance model accuracy;
- Conducting a tracer study, analyzing the tracer study data, and performing a model run to reproduce the results of the future tracer study;
- Quantifying the uncertainty in the model prediction results caused by uncertainties in model input (e.g. meteorological data);
- Defining the required margin of safety for the predicted OMD for meeting the proposed DDW dilution requirement;
- Performing enhanced simulations of bubblers and diffusers;
- Selecting and designing systems that result in high PW mixing and dilution, with the purpose of reliably increasing the OMD;
- Defining extreme operational parameters under which PW addition may be curtailed or suspended or the reservoir outflow shut down.

9.0 REFERENCES CITED

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10.0 GLOSSARY

Advanced Water Purification Facility: The demonstration facility located at the North City Water Reclamation Plant. The facility is considered “advanced” because of the high level of treatment utilizing reverse osmosis and advanced oxidation.

Blending: Mixing one water source with another such as purified water with raw water resources.

Conductivity: *See Salinity*.

Constituent: A dissolved chemical, compound, or suspended material transported in a body of water.

Drought: A defined period of time when rainfall and runoff in a geographic area are much less than average.

Excursion events at the advanced purification facility: Events in which the water quality of the recycled water into the advanced purification facility deviates from normal or expected conditions. As a result, the final outflow from the advanced purification facility may contain chemical constituents at higher levels than during normal operating conditions.

Purified water: Recycled water treated to an advanced level beyond tertiary treatment. Ultimately the water is used for drinking water. Treatment includes membrane filtration with microfiltration or ultrafiltration, reverse osmosis, and advanced oxidation consisting of disinfection with ultraviolet light (UV) and hydrogen peroxide (H_2O_2).

Purified water inflow: Flow of purified water released from the advanced treatment facility into MR.

Purified water inlet: Inlet used to control the release of purified water in to MR. *Note that purified water is assumed to be released at the surface of MR.*

Reservoir: A manmade lake used to store water for future use.

Reservoir augmentation: A process of adding purified water to the surface water of a reservoir. After advanced treatment, the purified water is blended with the untreated water in a reservoir. The blended water is then treated and distributed into the drinking water delivery system.

Reservoir Mixing: A period when water temperatures become vertically uniform, eliminating the thermocline. In temperate reservoirs this period occurs during the winter.

Reservoir outflow: The withdrawal flow through an opening at the outflow structure of a reservoir.

Reservoir outflow ports: A number of openings located at the outflow structure of a reservoir used to control flow from a reservoir.

Salinity: The concentration of dissolved mineral salts in a body of water. It can be measured by weight (total dissolved solids) or by electrical conductivity.

Storage: A volume of water contained in a reservoir for later use.

Water Measurement Terms

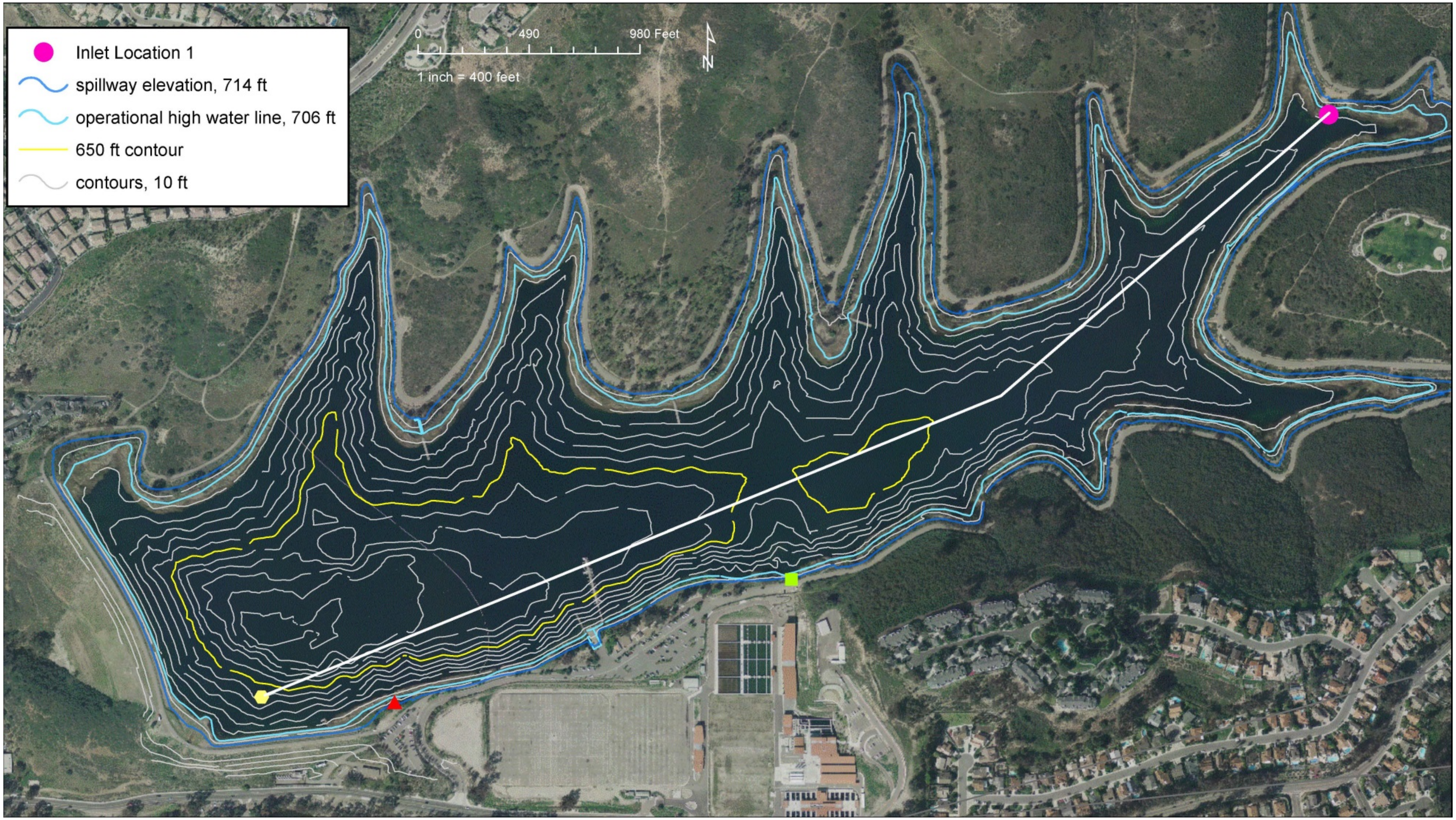
Milligrams per liter (mg/L): A measurement describing the amount of substance (ie. mineral, chemical or contaminant) in a liter of water.

Acre-ft: A unit of water volume used in the water industry to measure large-scale water resources. An ac-ft equals 325,851 gallons (43,560 cubic feet) and is considered enough to meet the water needs of two families of four with a house for one year.

microSiemens per centimeter (µS/cm): A measurement of water conductivity.

11.0 FIGURES

Map of Miramar Reservoir



Note: Inlet Location 1 is the potential PW inlet location. Conservative tracers are injected at this location.

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Figure 1

Capacity of Miramar Reservoir and Outflow Ports

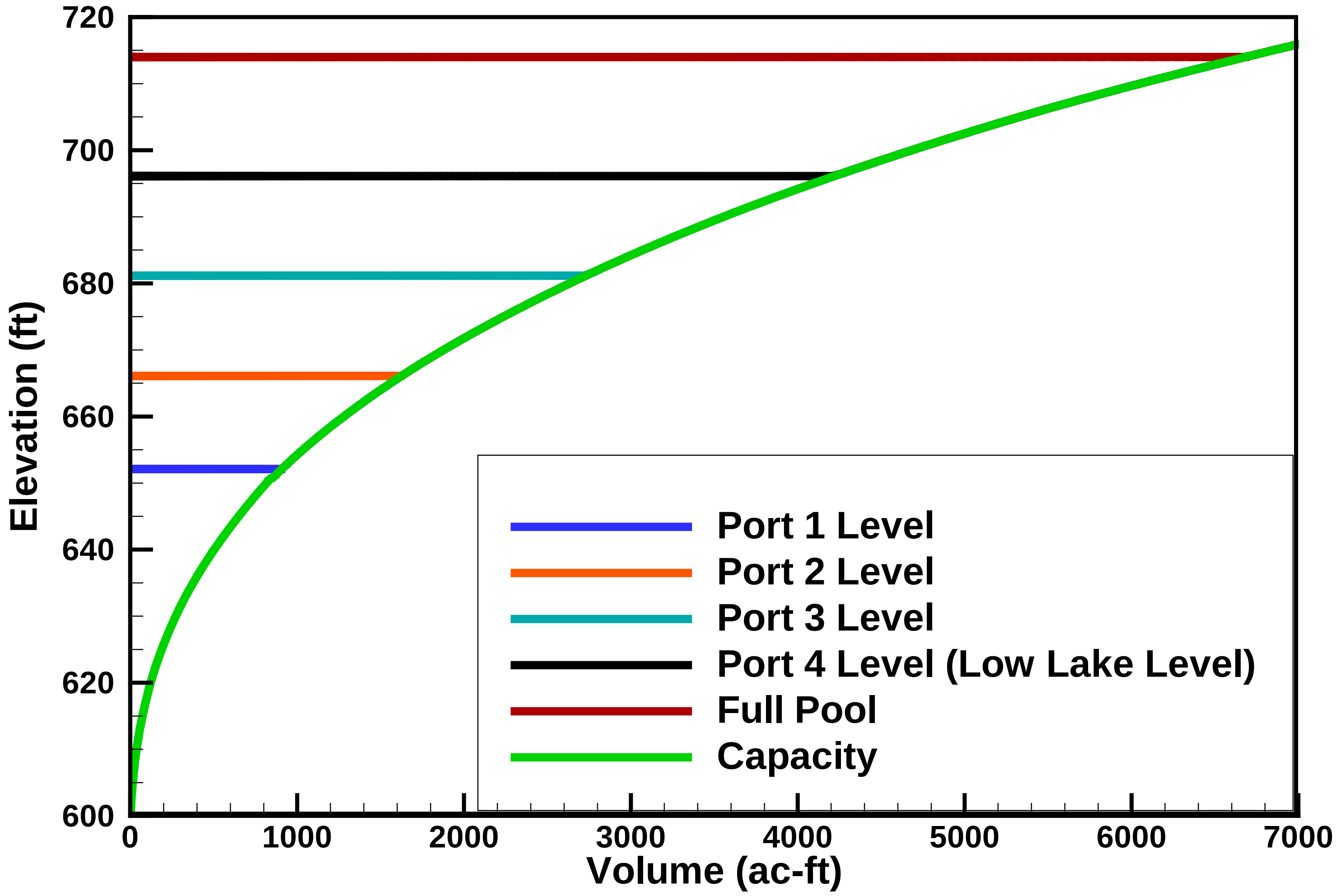
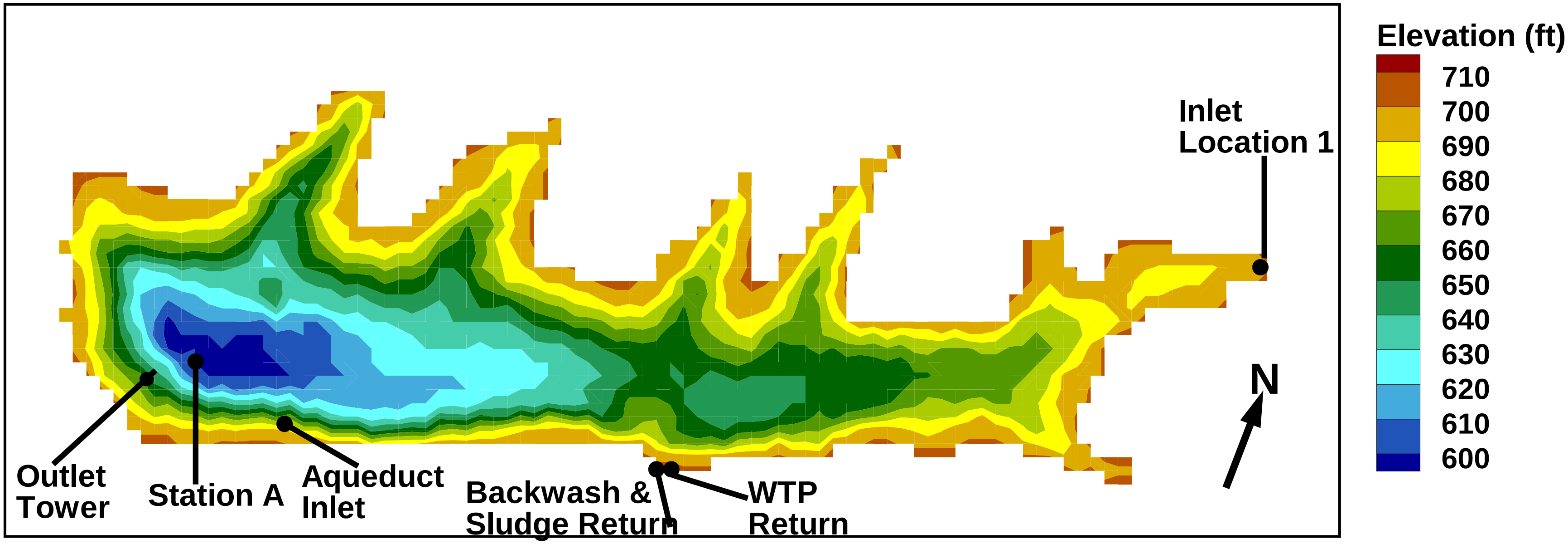


Figure 2

Bathymetry of Miramar Reservoir



Note: there is no water entering the reservoir through the aqueduct inlet.

Figure 3

ELCOM Model Grid: 3-D View

Cell Size: 20m x 20m x 0.61m

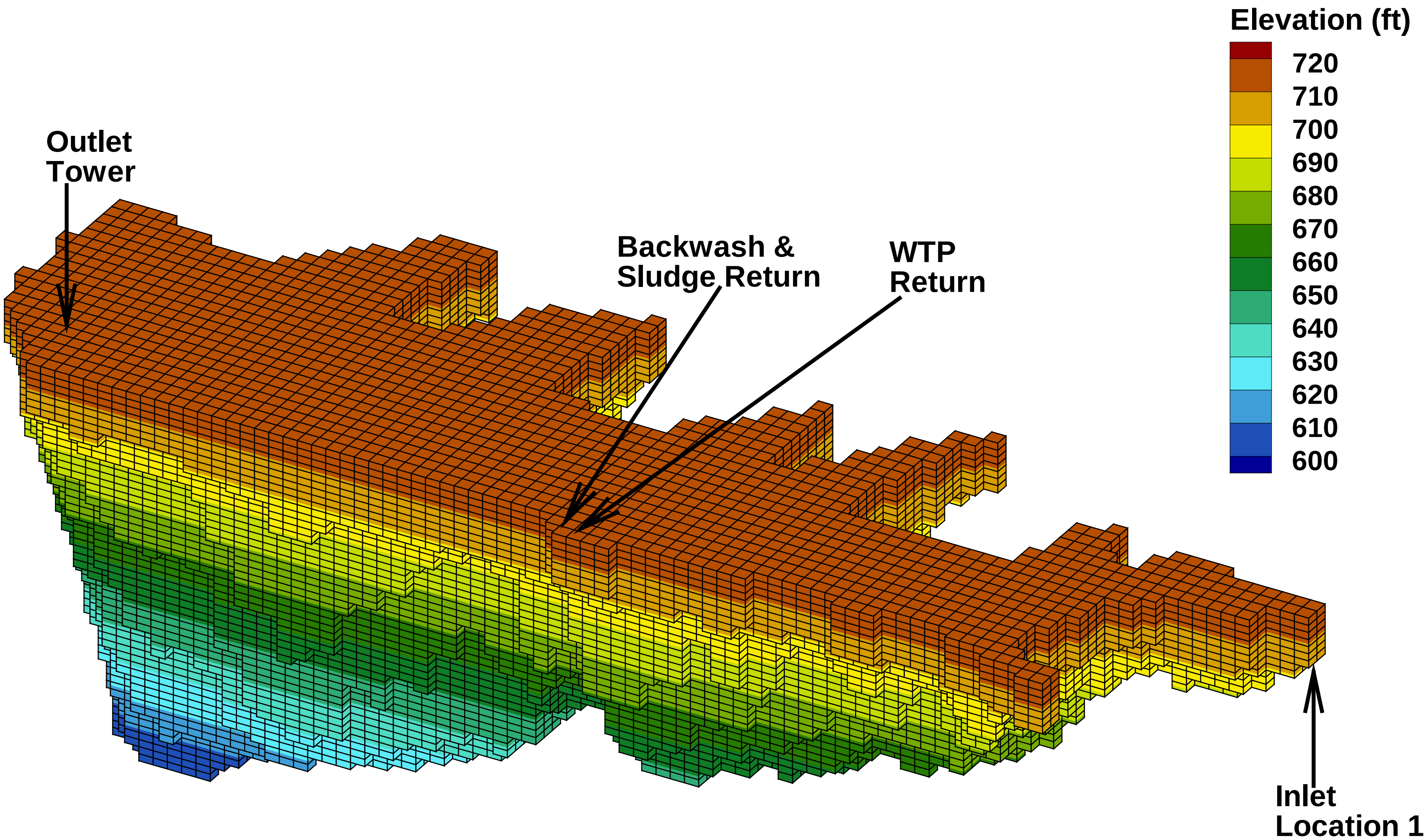


Figure 4

ELCOM Model Grid: Cross-Section View

Cell Size: 20m x 20m x 0.61m

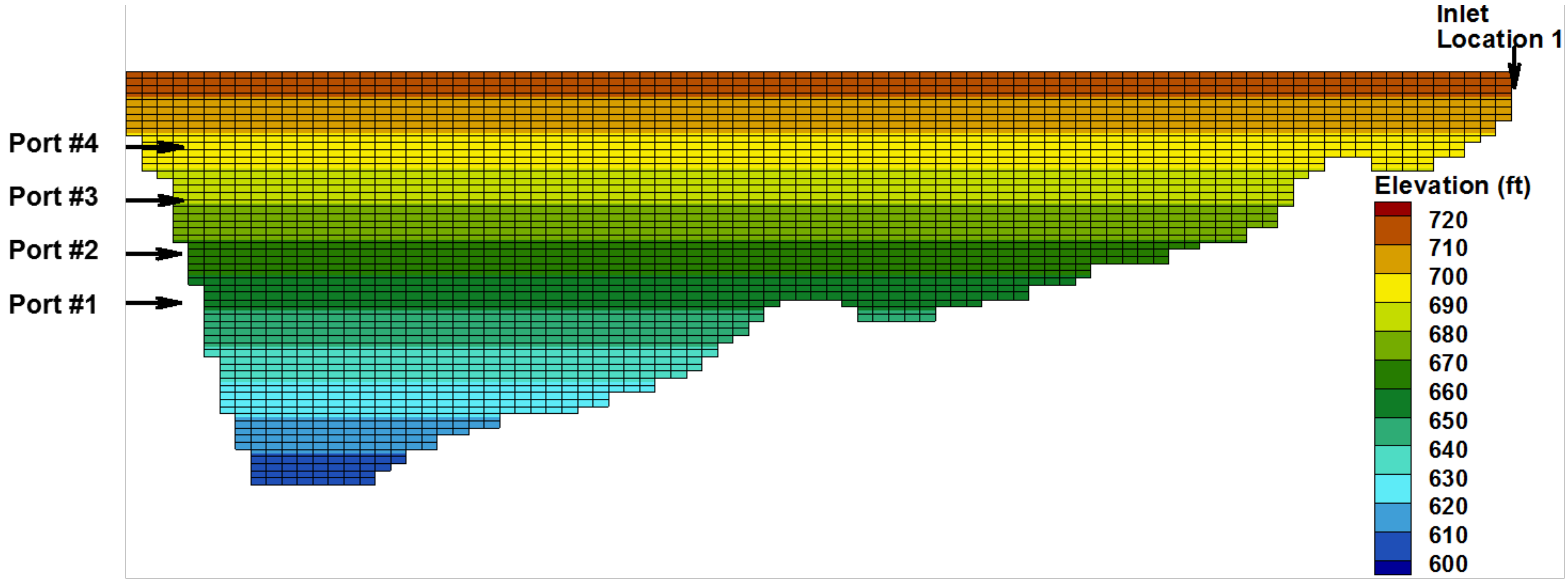


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Figure 5

CAEDYM Model Grid: 3-D View

Cell Size: 30m x 30m x 0.61m

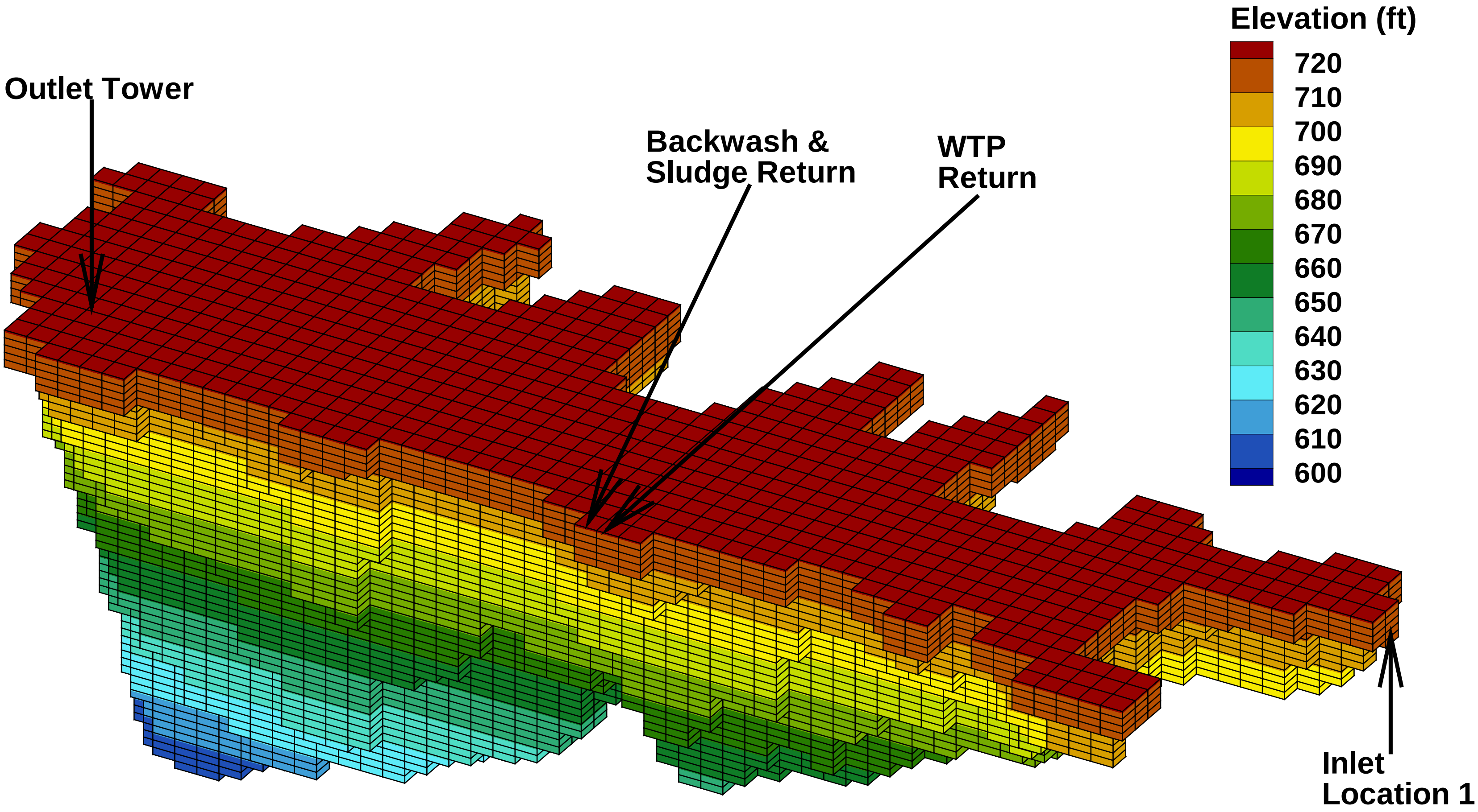

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Figure 6

Modeled Inflow/Outflow Volumes in Calibration

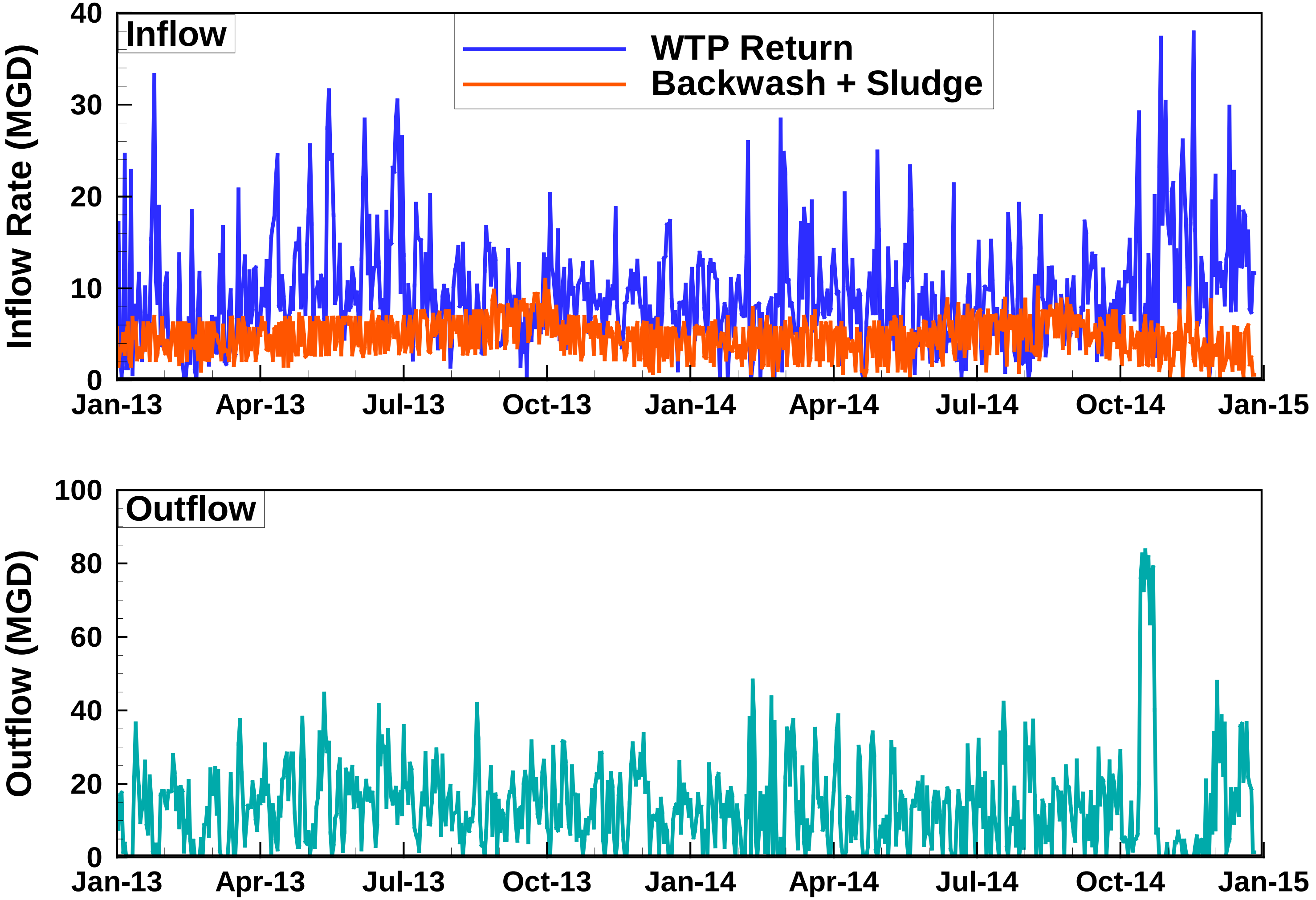

Figure 7

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Weather Stations near Miramar Reservoir

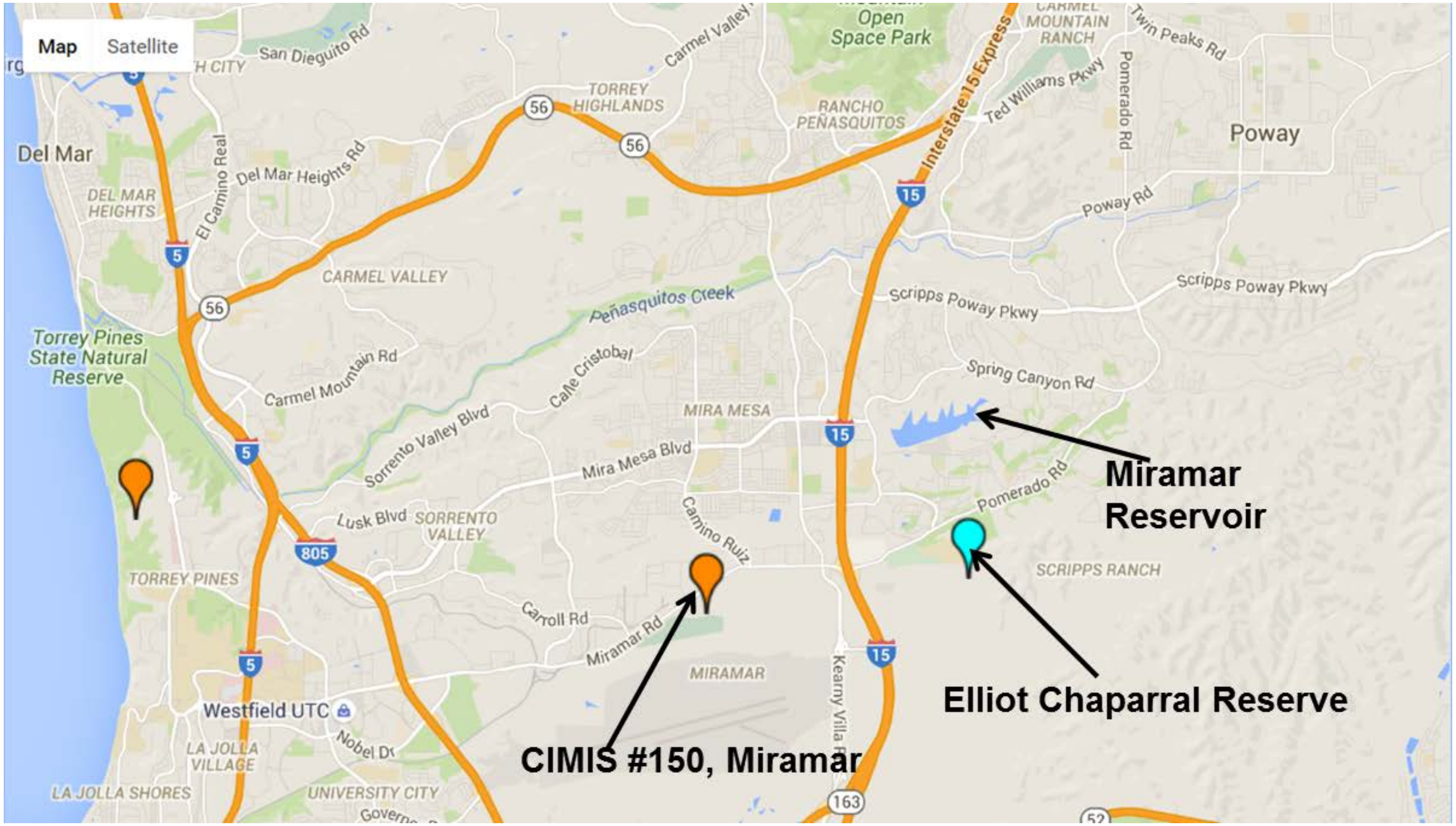

Figure 8

Comparison of Meteorological Data (Monthly Average)

CIMIS #150, Miramar (CIMIS) vs. Elliot Chaparral Reserve (ECR), 1/2013 – 12/2014

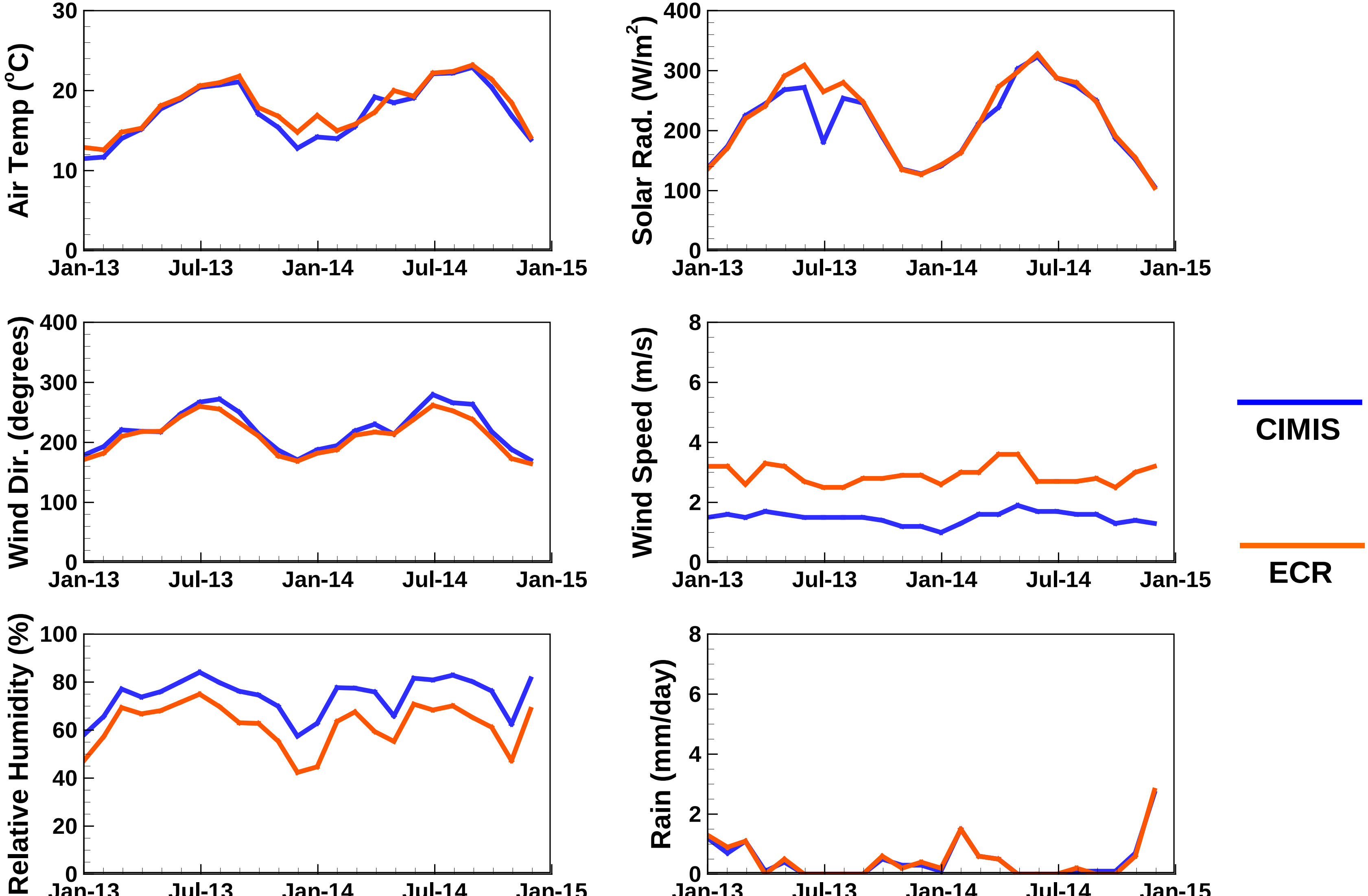

Figure 9

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Comparison of Wind Speed (Hourly Average)

CIMIS vs. ECR, on Tracer Injection Dates

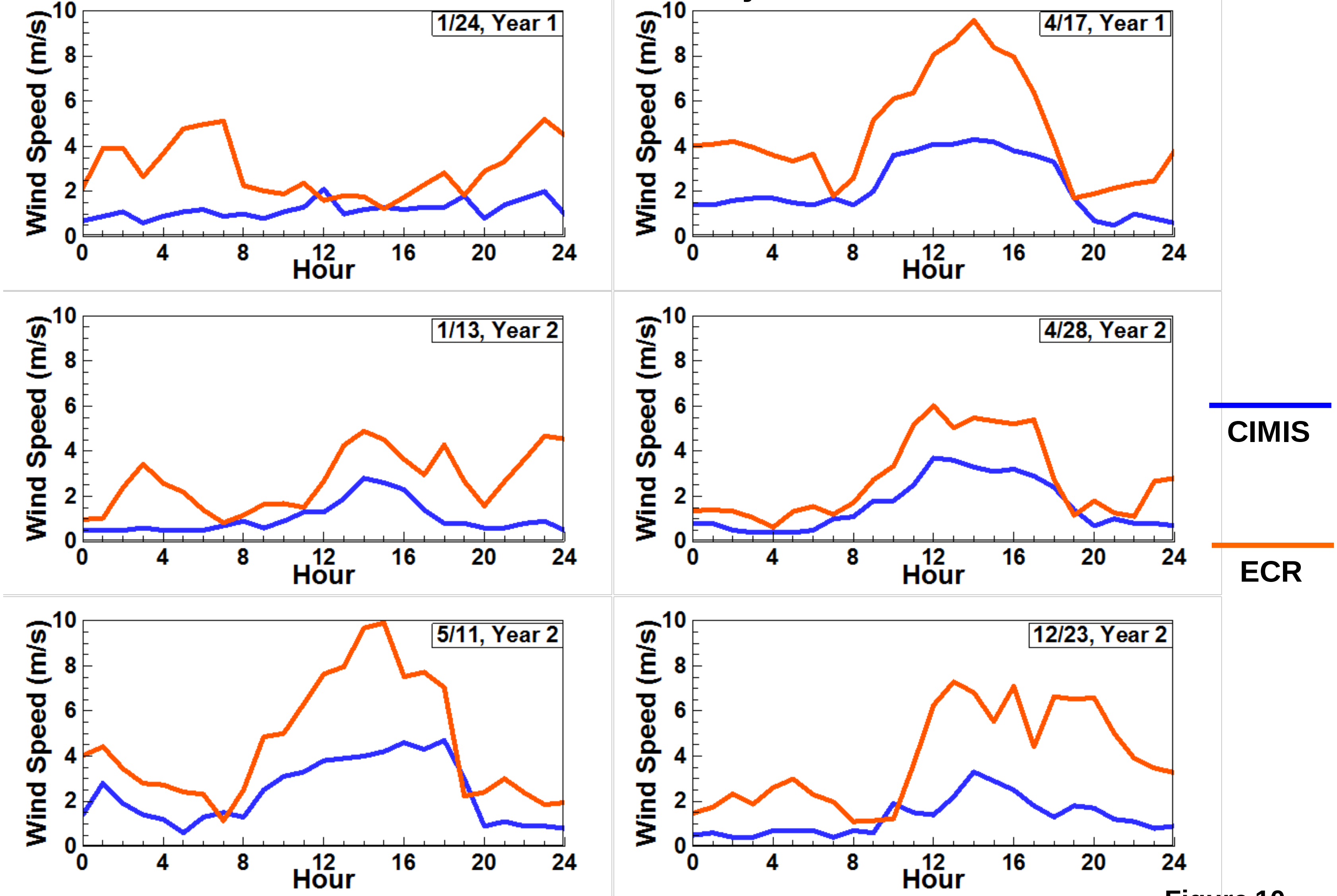

Figure 10

ELCOM Calibration: Water Surface Elevation

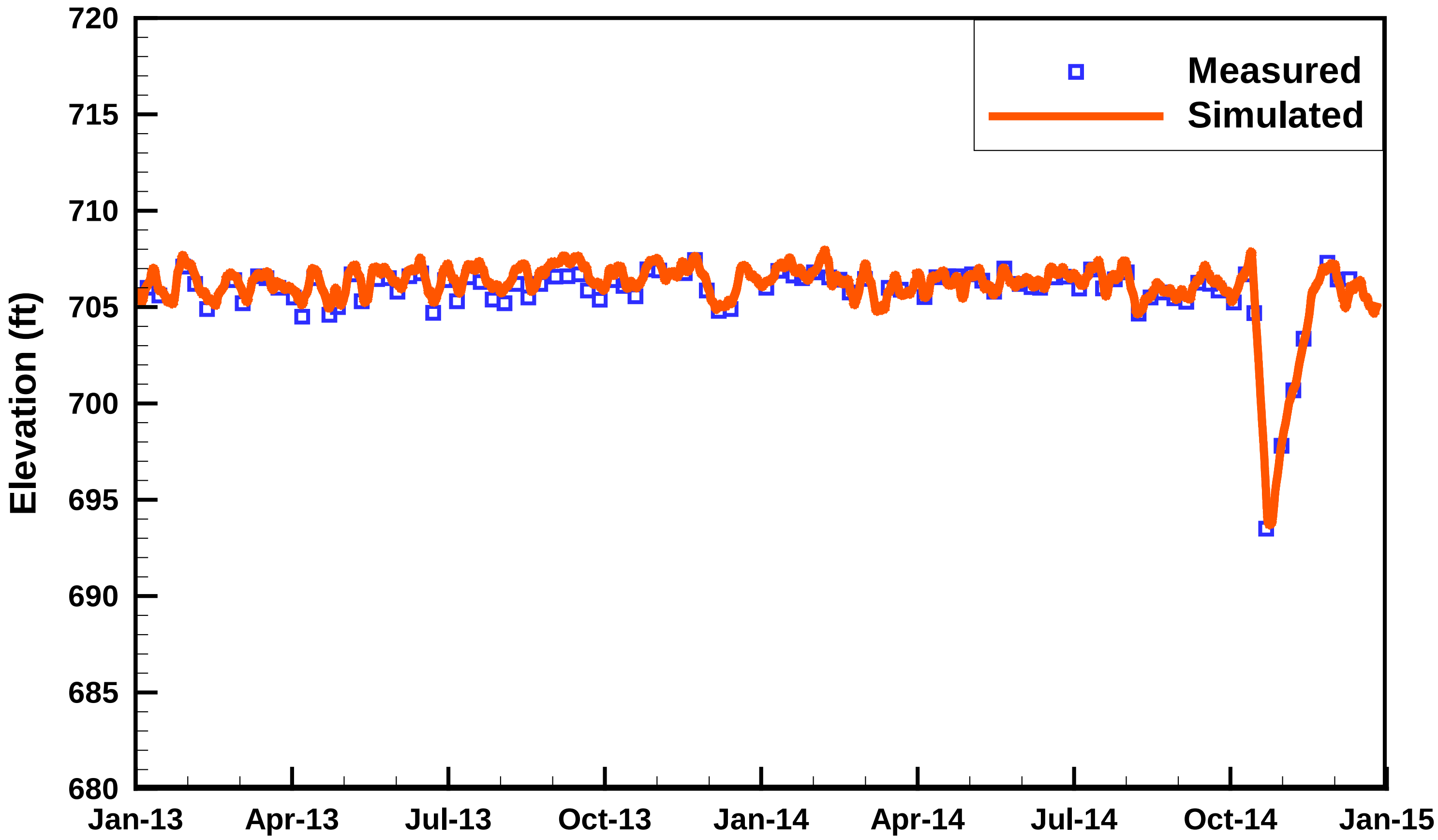

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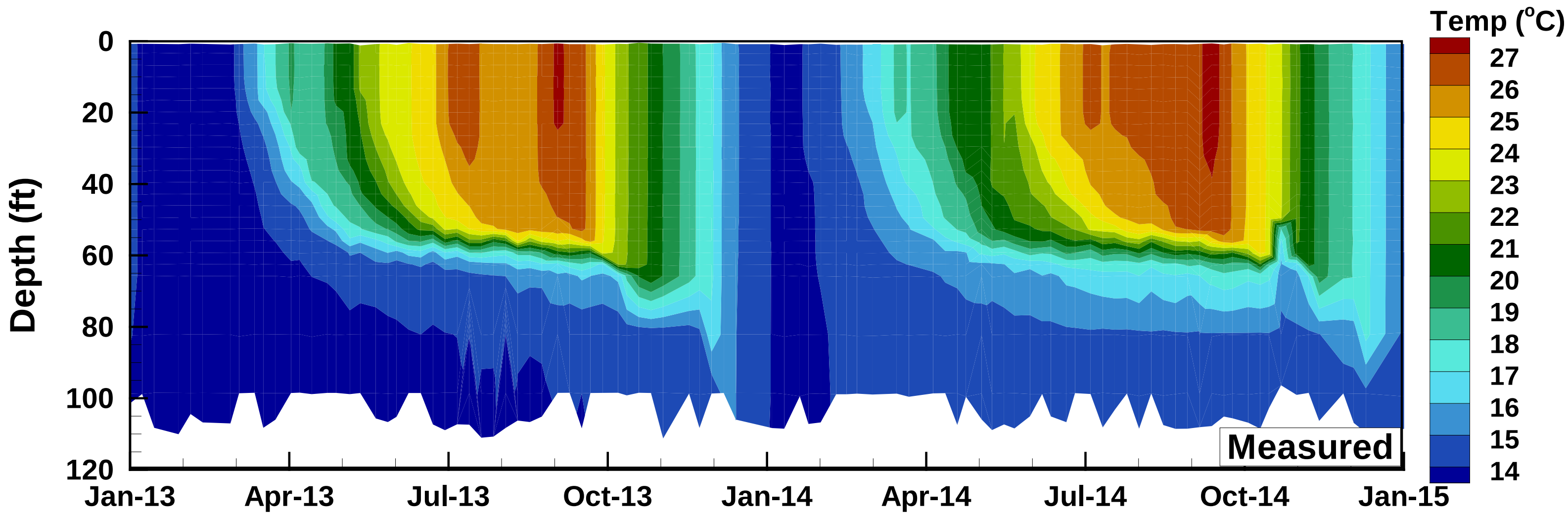
Figure 11

ELCOM Calibration: Water Temperature Contour



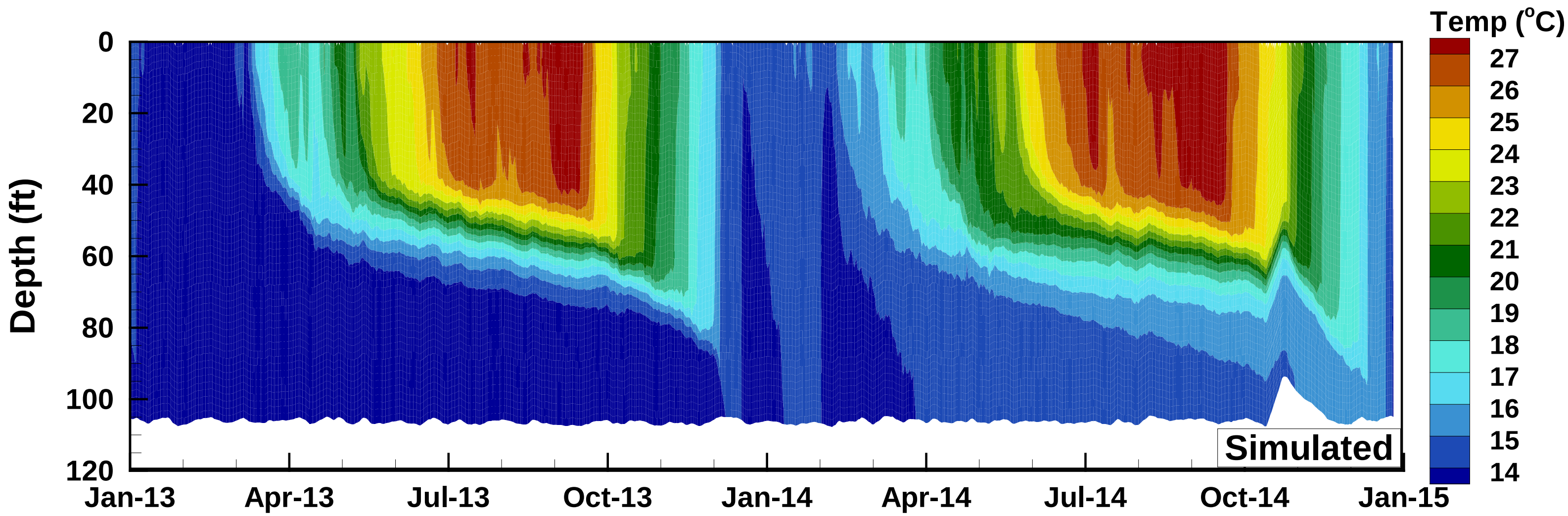


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Figure 12

ELCOM Calibration: Surface and Bottom Temperature

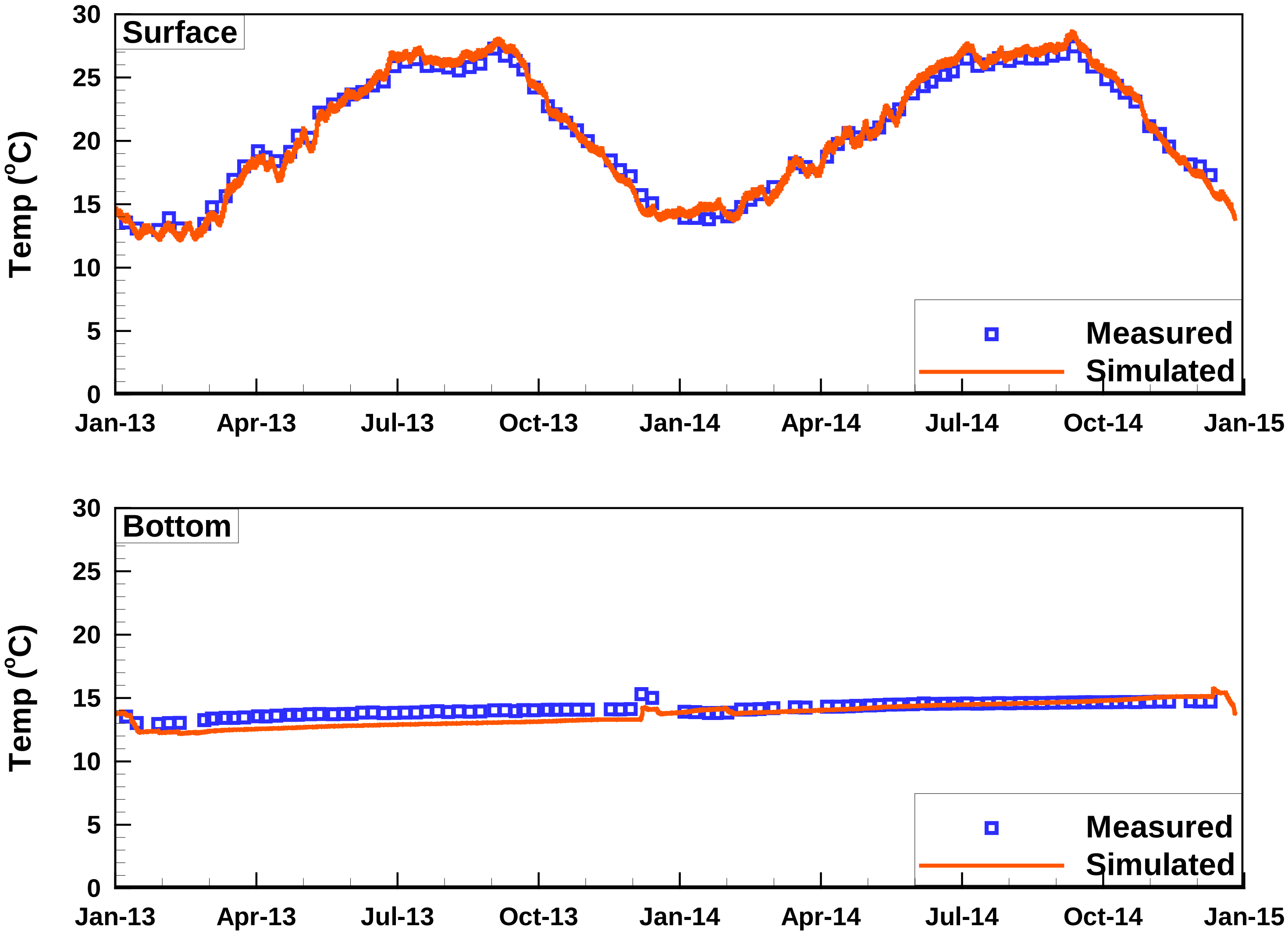

Figure 13

Scatter Plot of Measured vs. Simulated Temperature

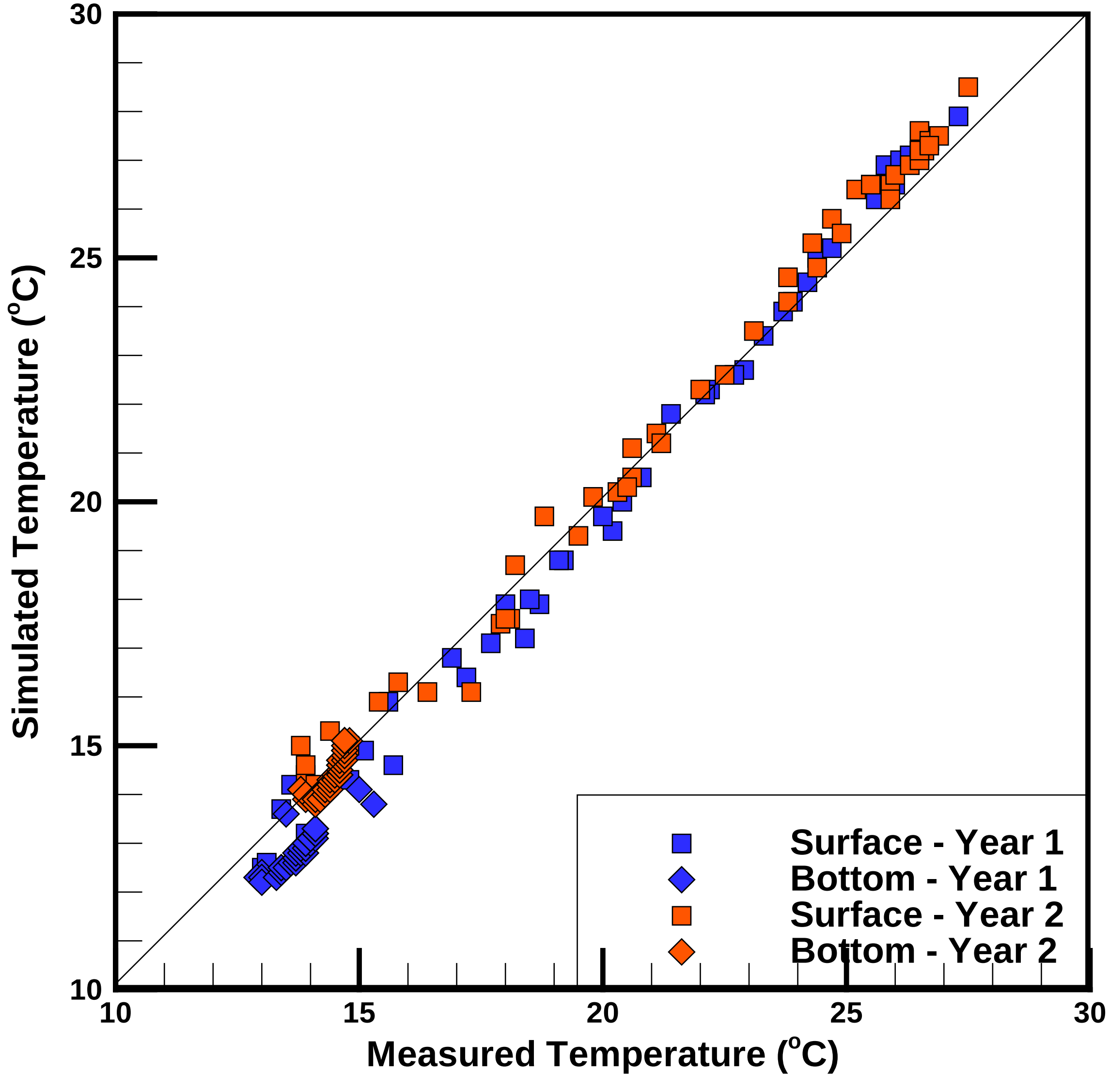

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Figure 14

ELCOM Calibration: Water Conductivity Contour

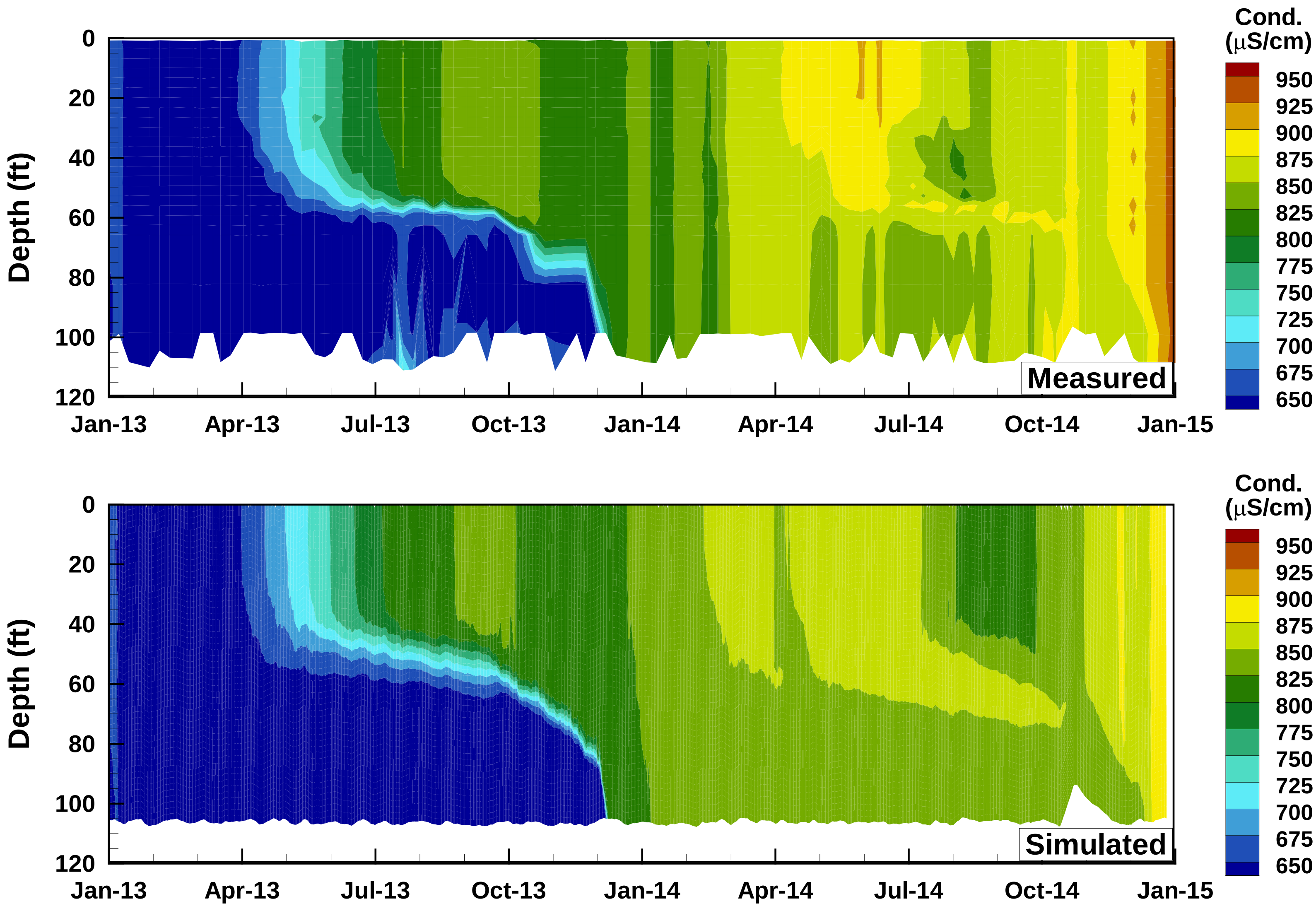
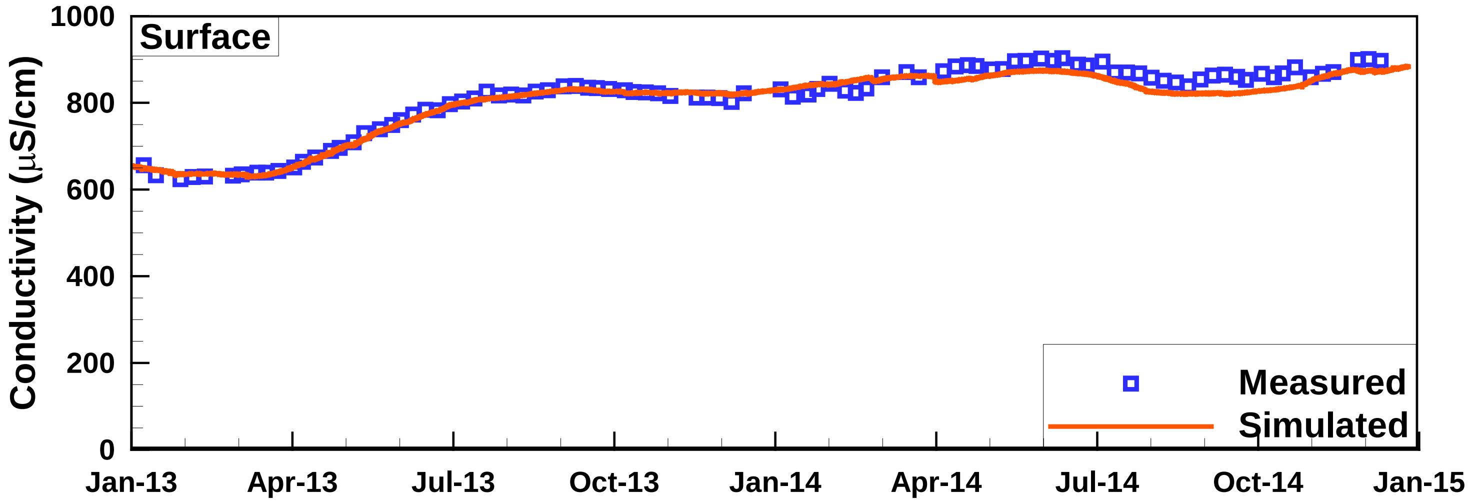


Figure 15

ELCOM Calibration: Surface and Bottom Conductivity



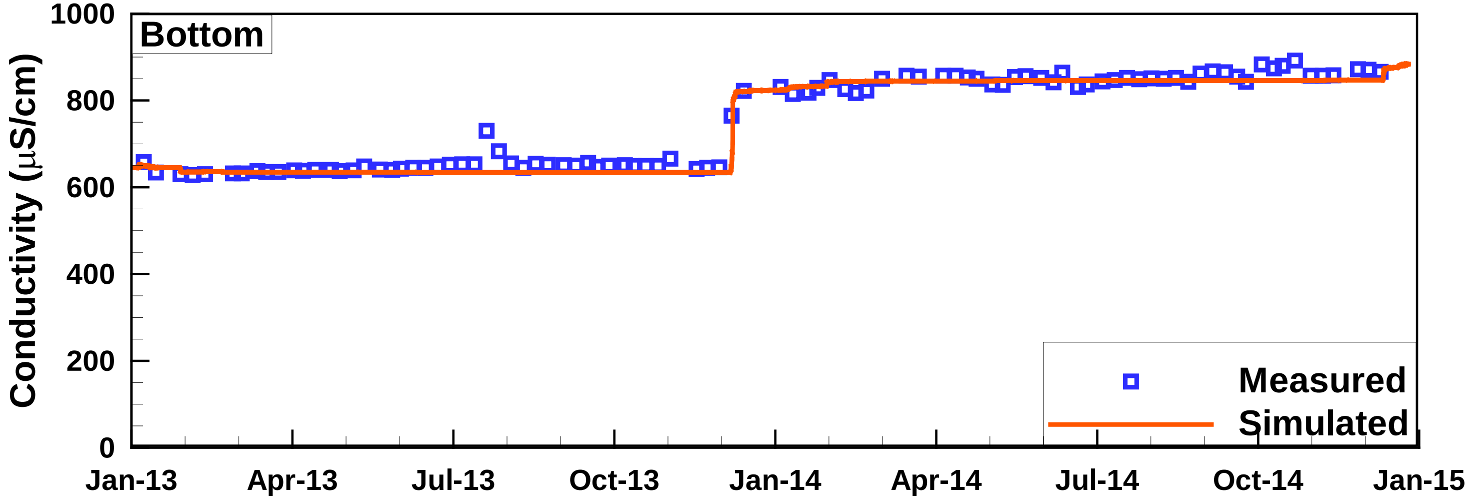


Figure 16

Scatter Plot of Measured vs. Simulated Conductivity

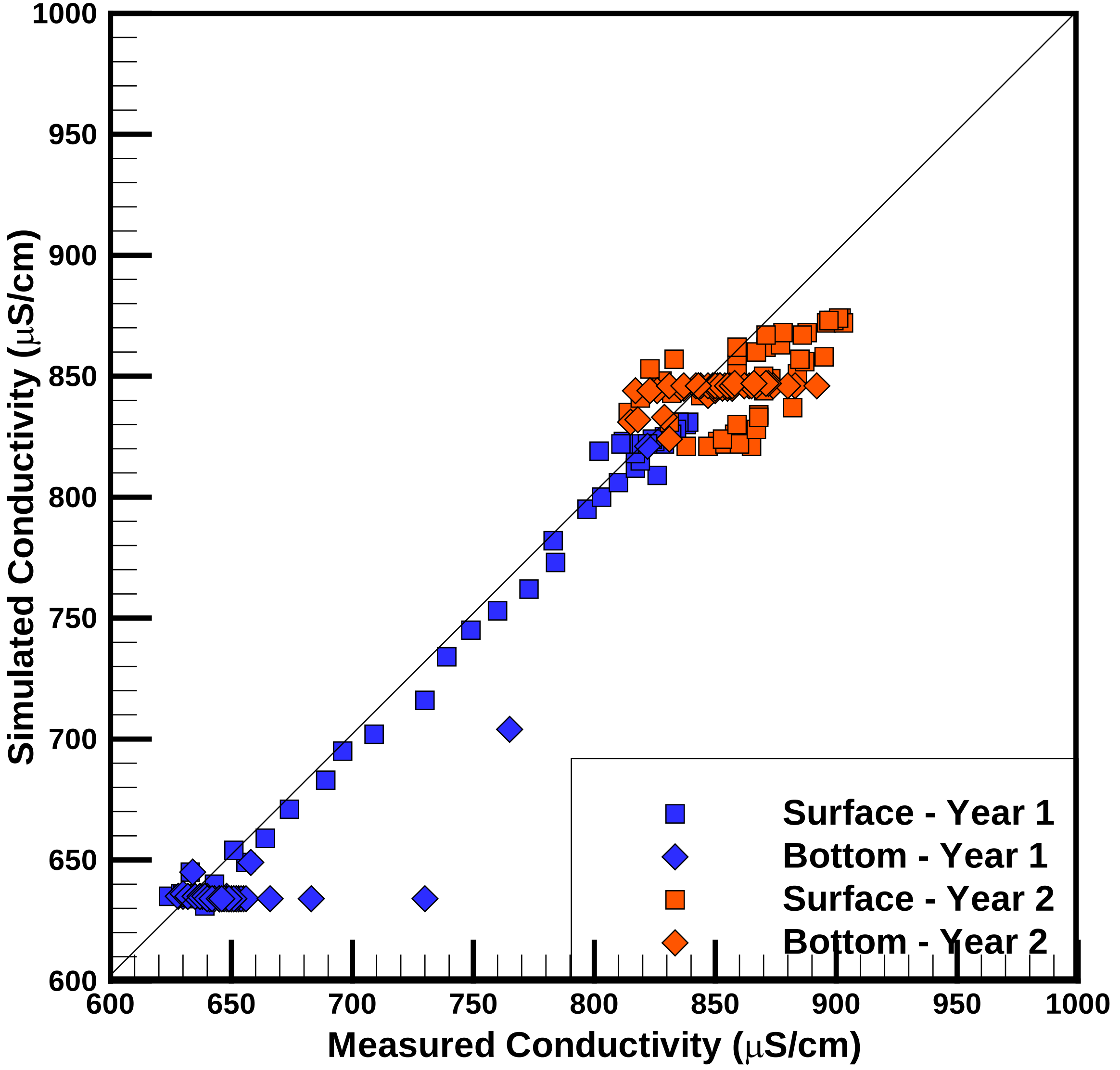


Figure 17

CAEDYM Calibration: Dissolved Oxygen

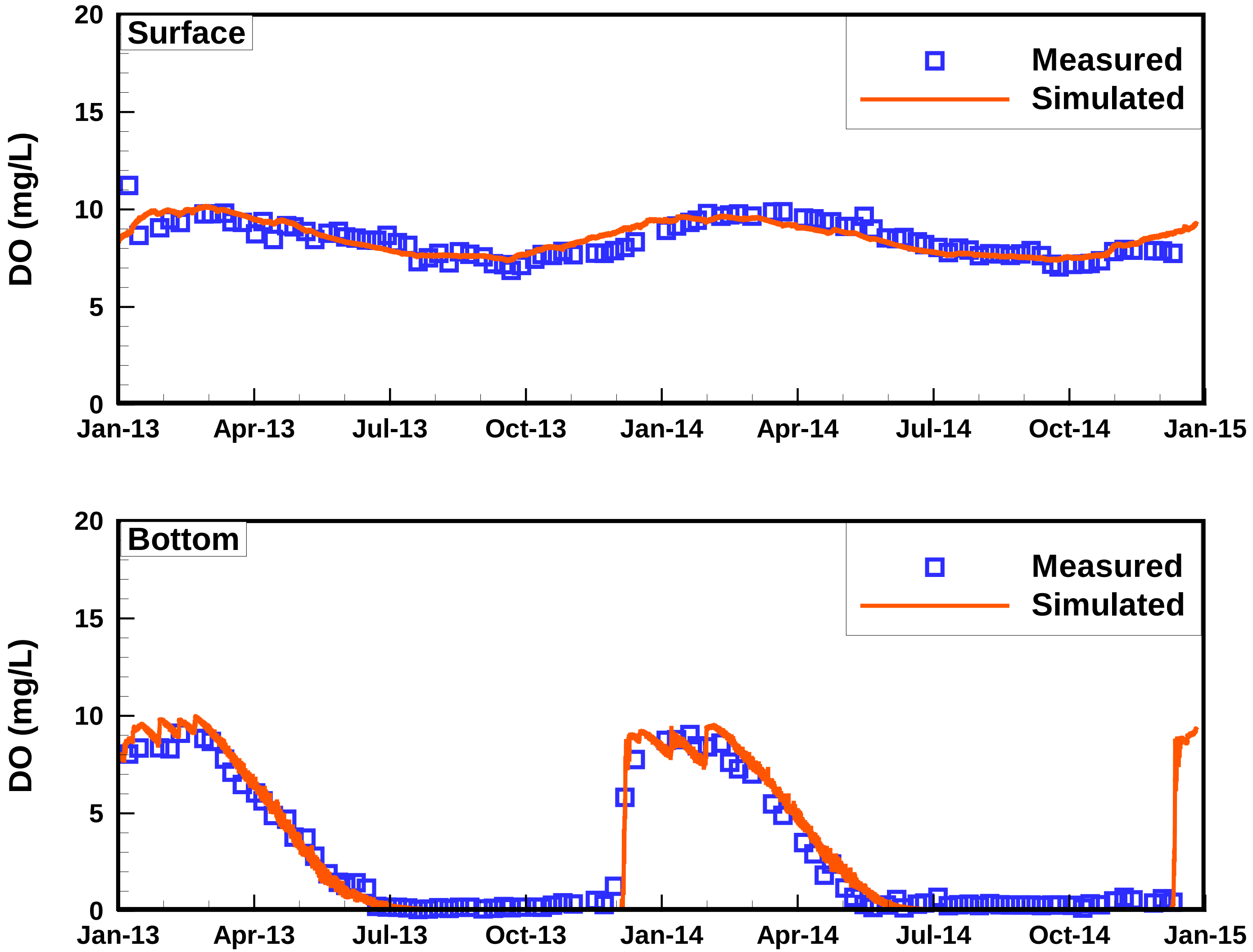


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Figure 18

Scatter Plot of Measured vs. Simulated Dissolved Oxygen

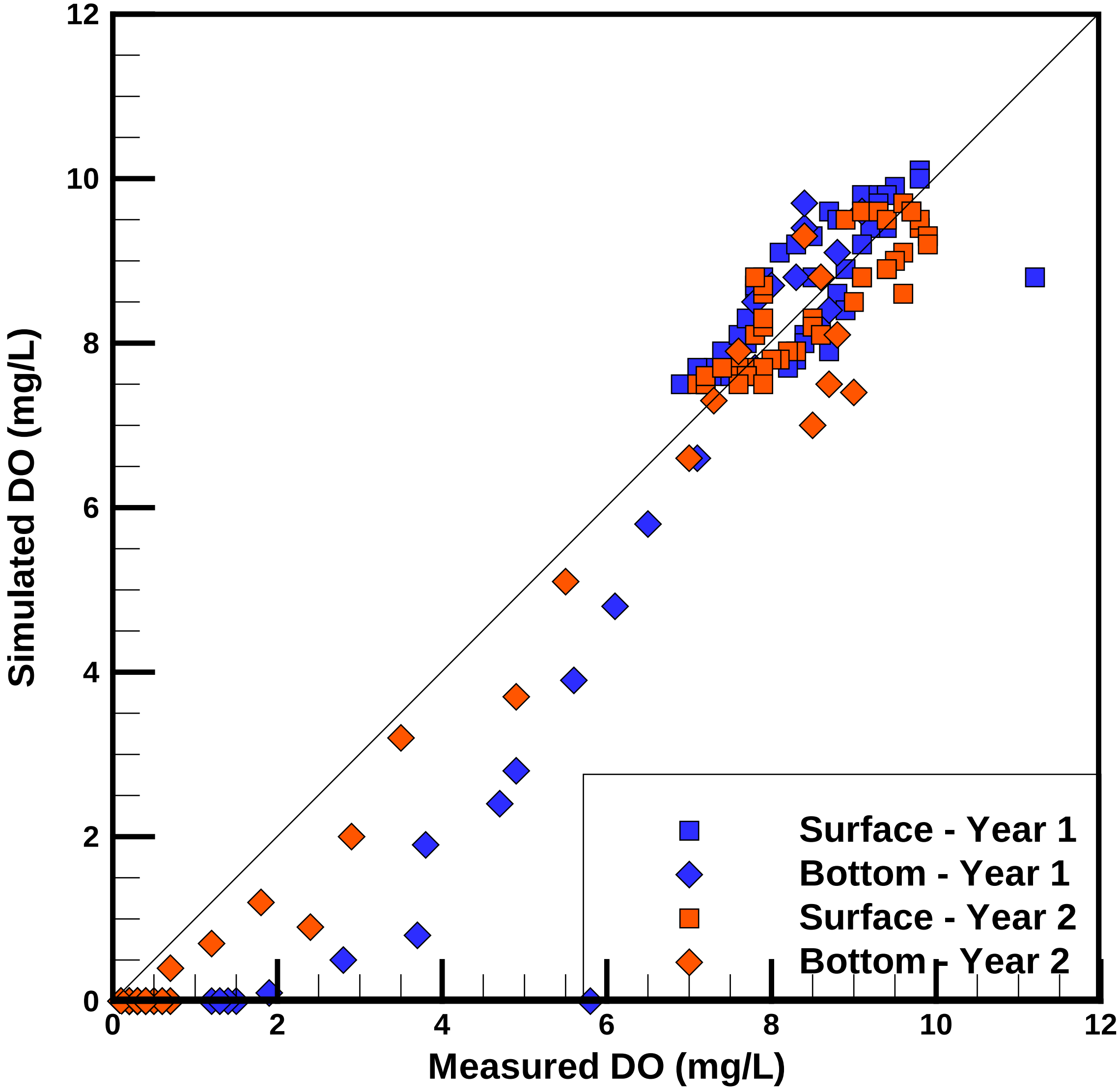

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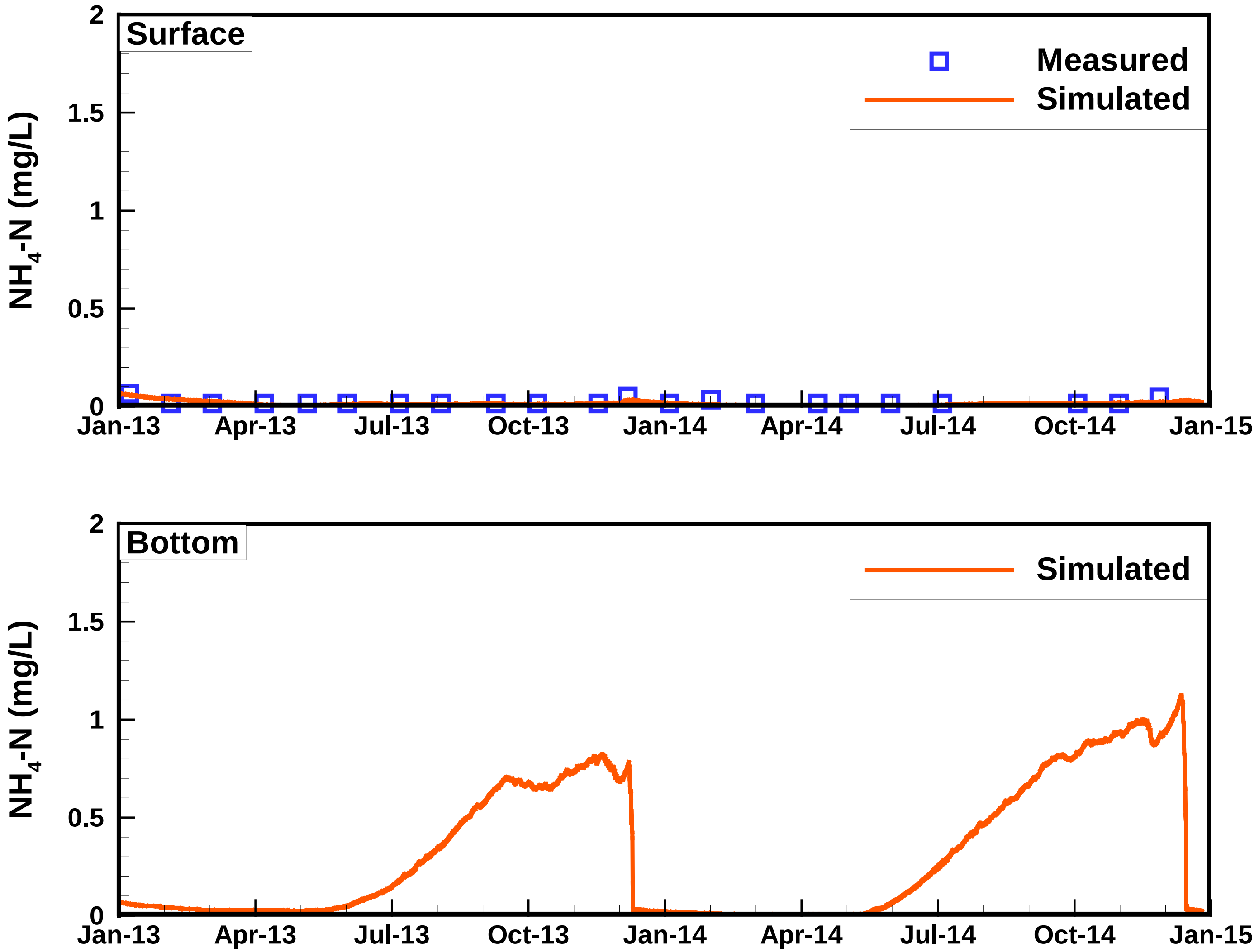
Figure 19

CAEDYM Calibration: Ammonia*



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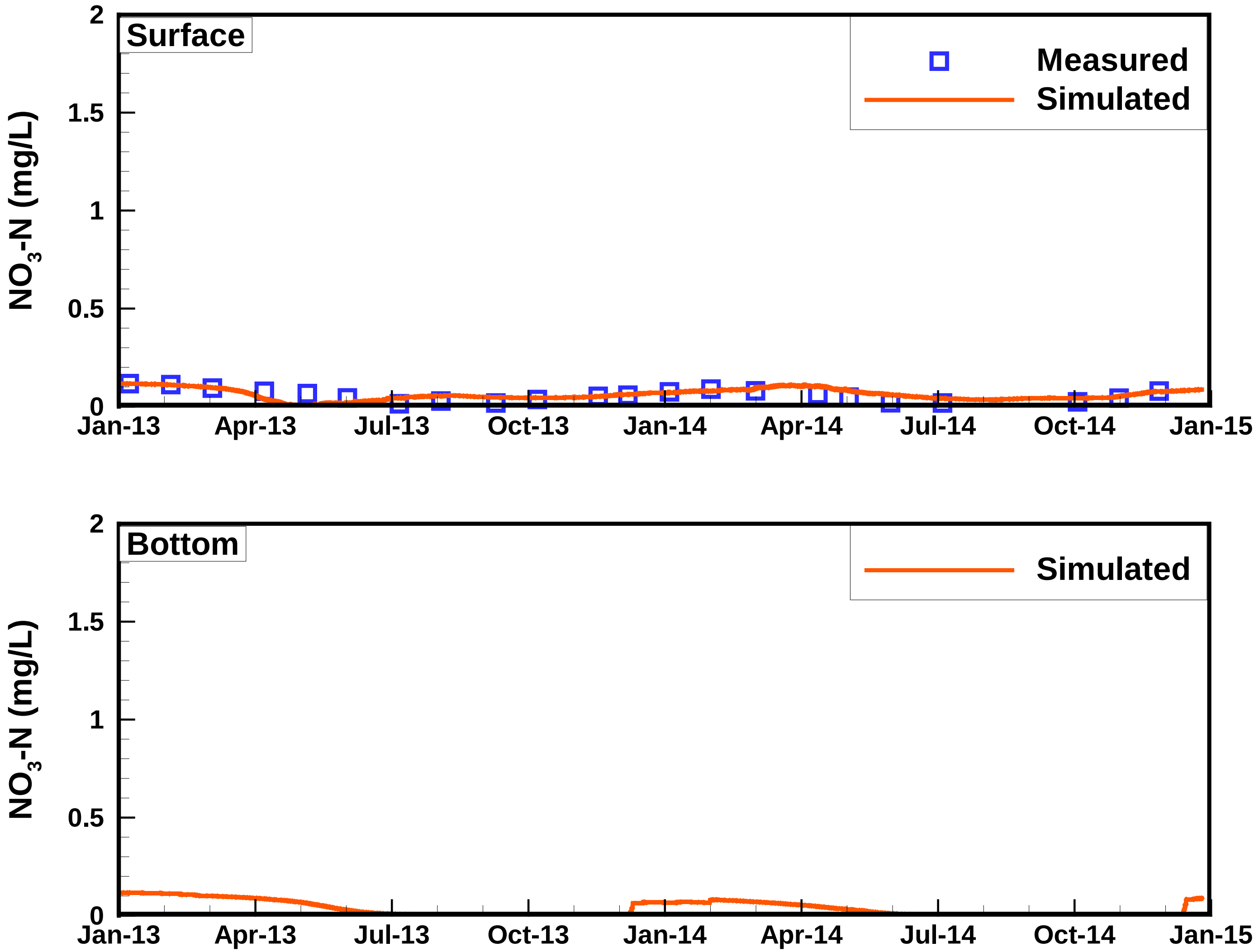
*Note: Measured data is only available at water surface.

Figure 20

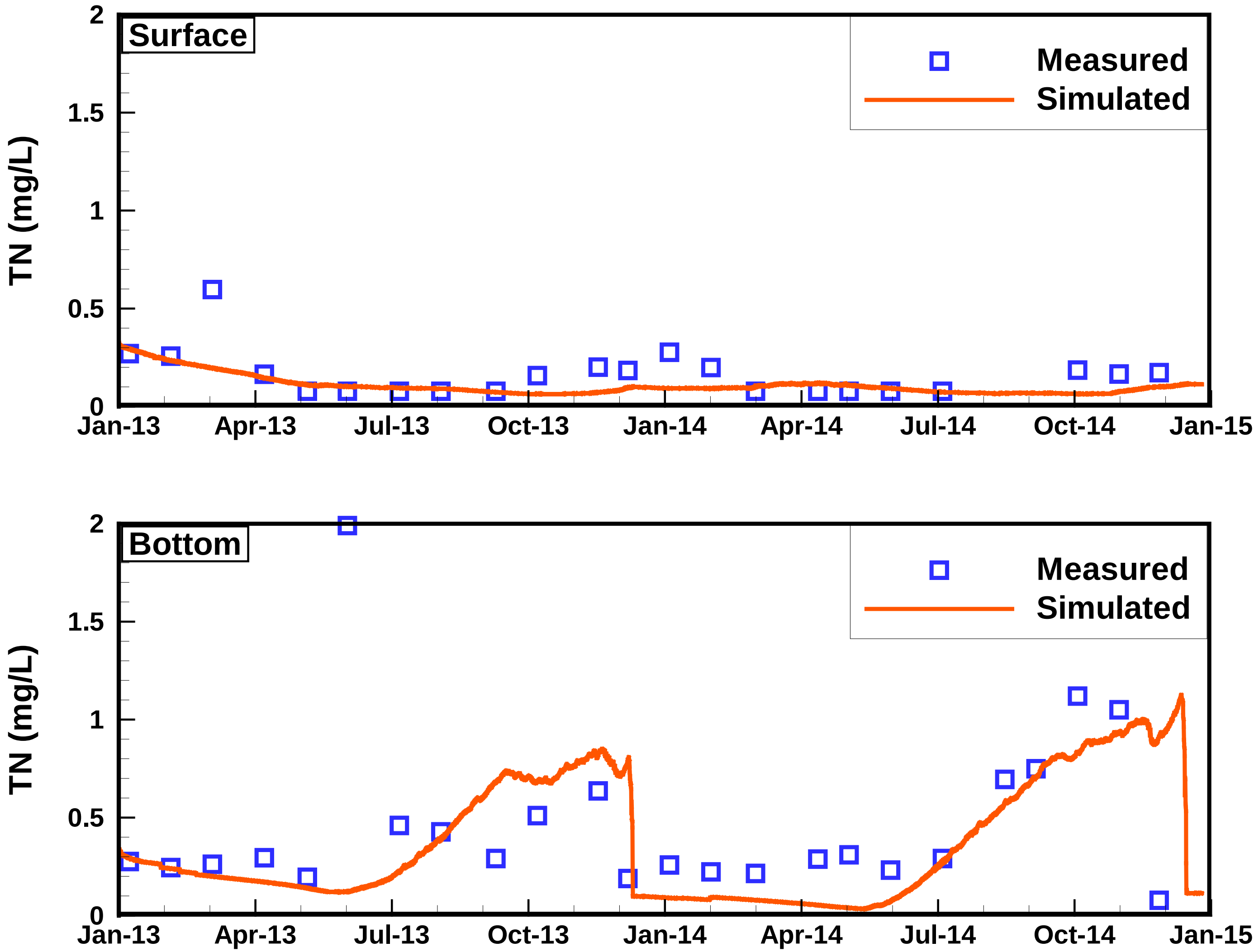
CAEDYM Calibration: Nitrate*



*Note: Measured data is only available at water surface.

Figure 21

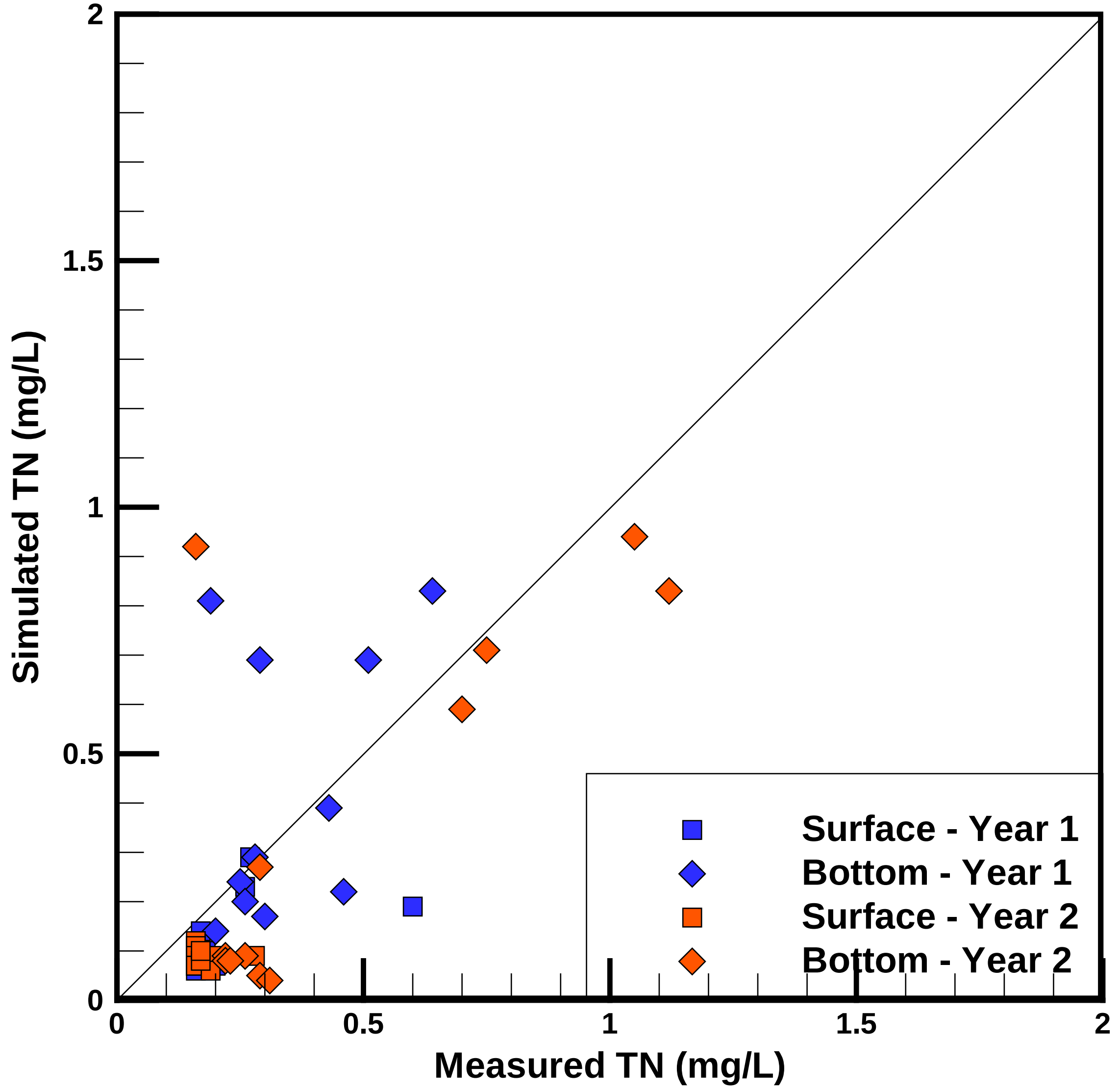
CAEDYM Calibration: Total Nitrogen



Water Quality Solutions

Figure 22

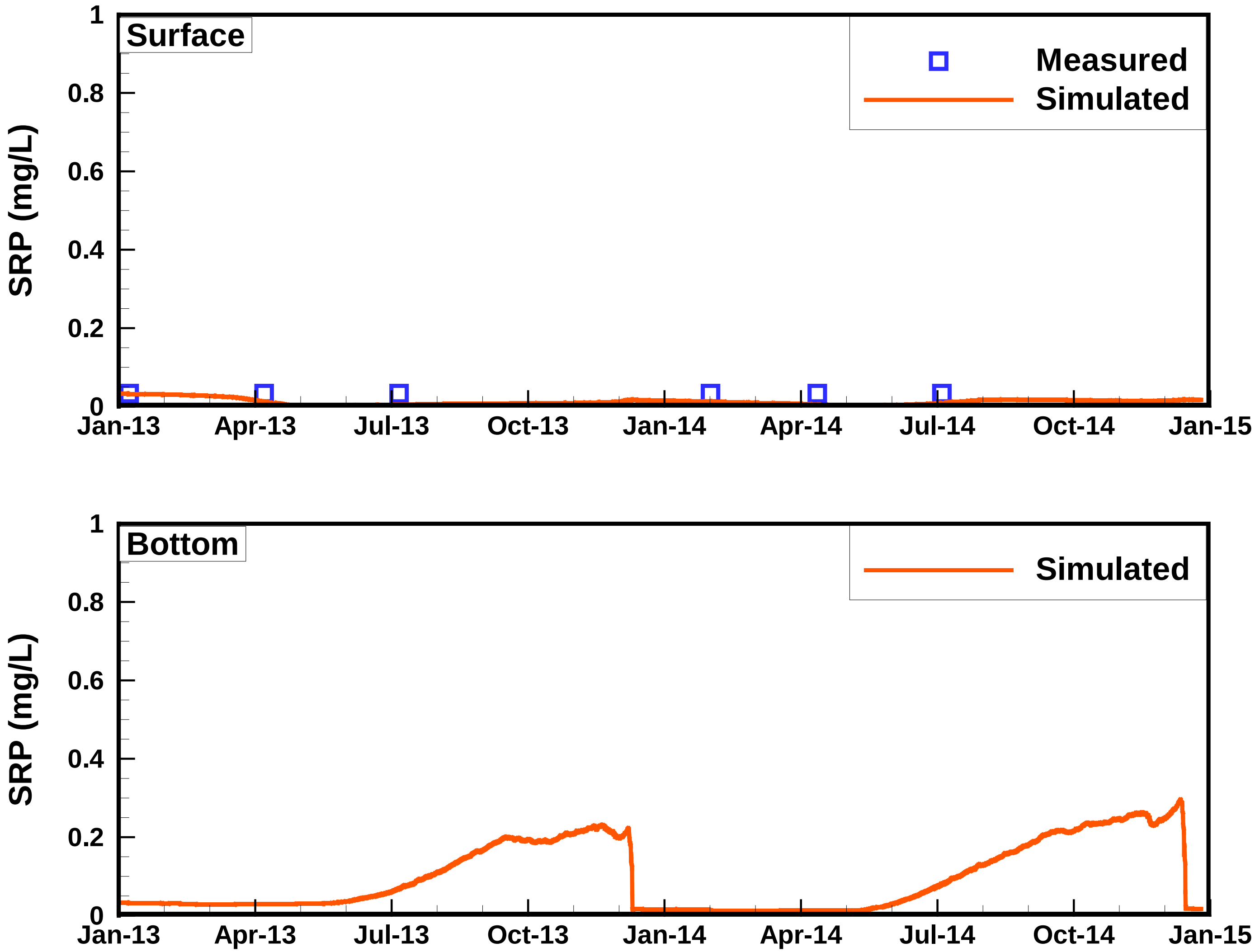
Scatter Plot of Measured vs. Simulated Total Nitrogen



Water Quality Solutions

Figure 23

CAEDYM Calibration: Soluble Reactive Phosphorus*

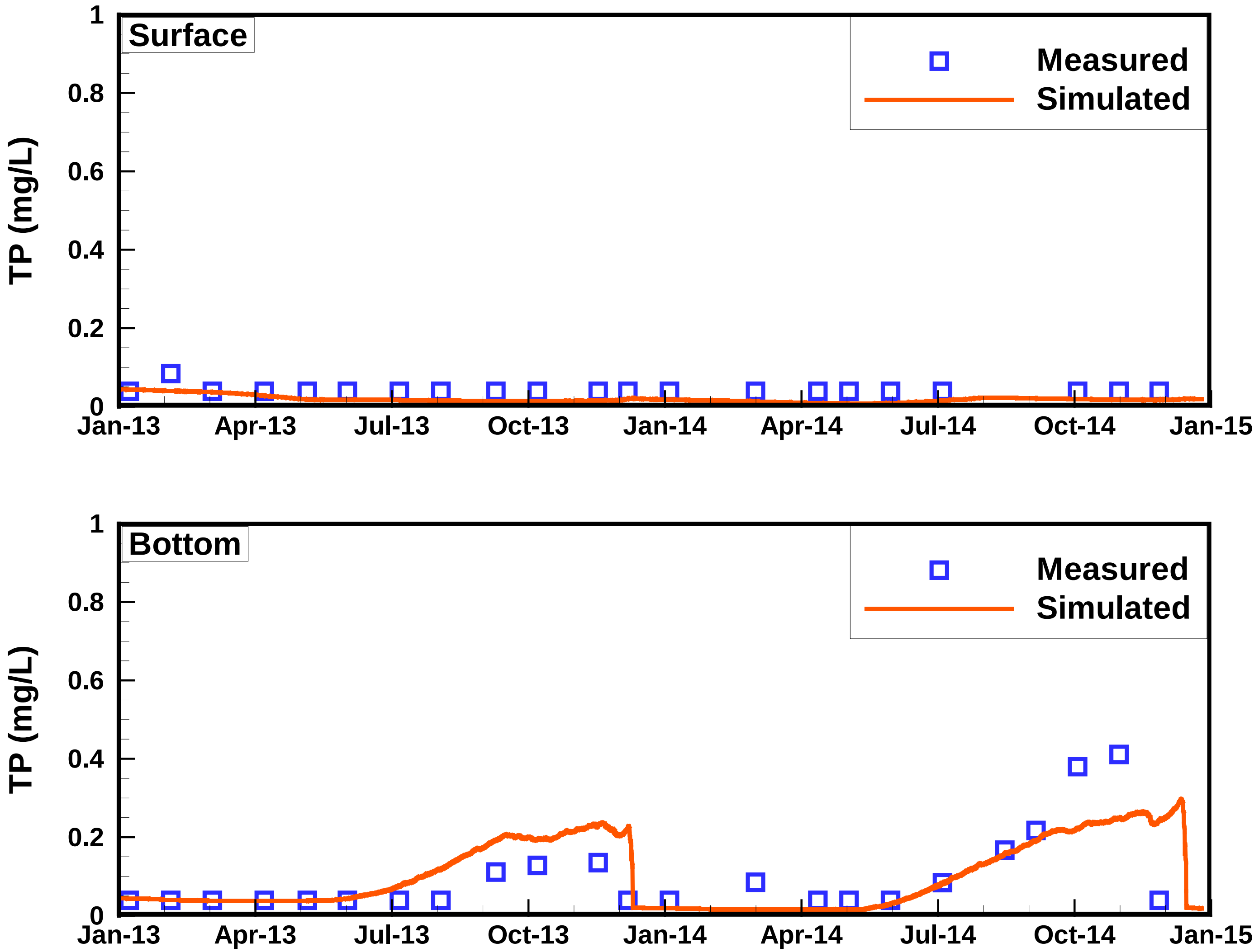


Water Quality Solutions

*Note: Measured data is only available at water surface.

Figure 24

CAEDYM Calibration: Total Phosphorus



Water Quality Solutions

Figure 25

Scatter Plot of Measured vs. Simulated Total Phosphorus

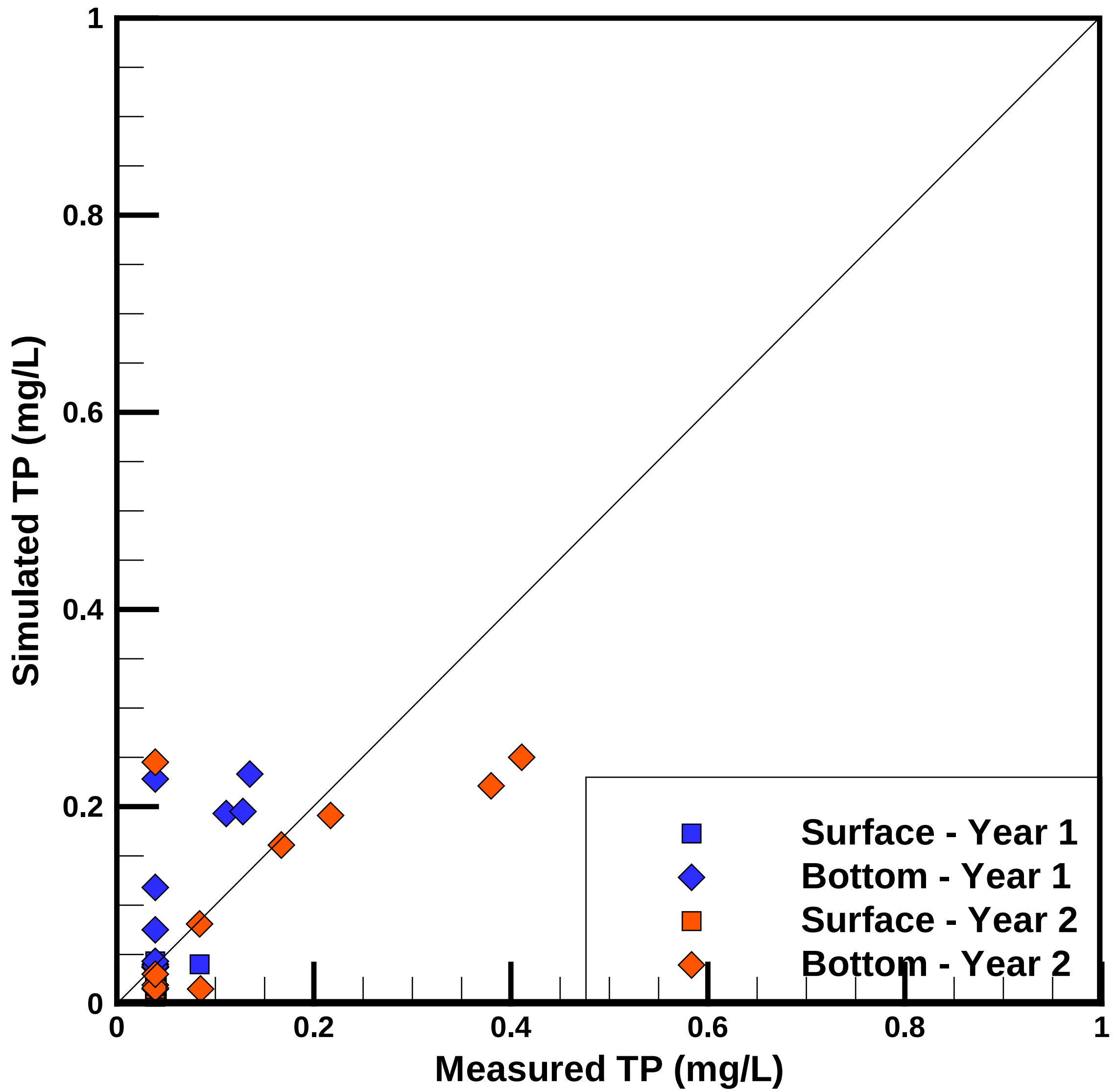
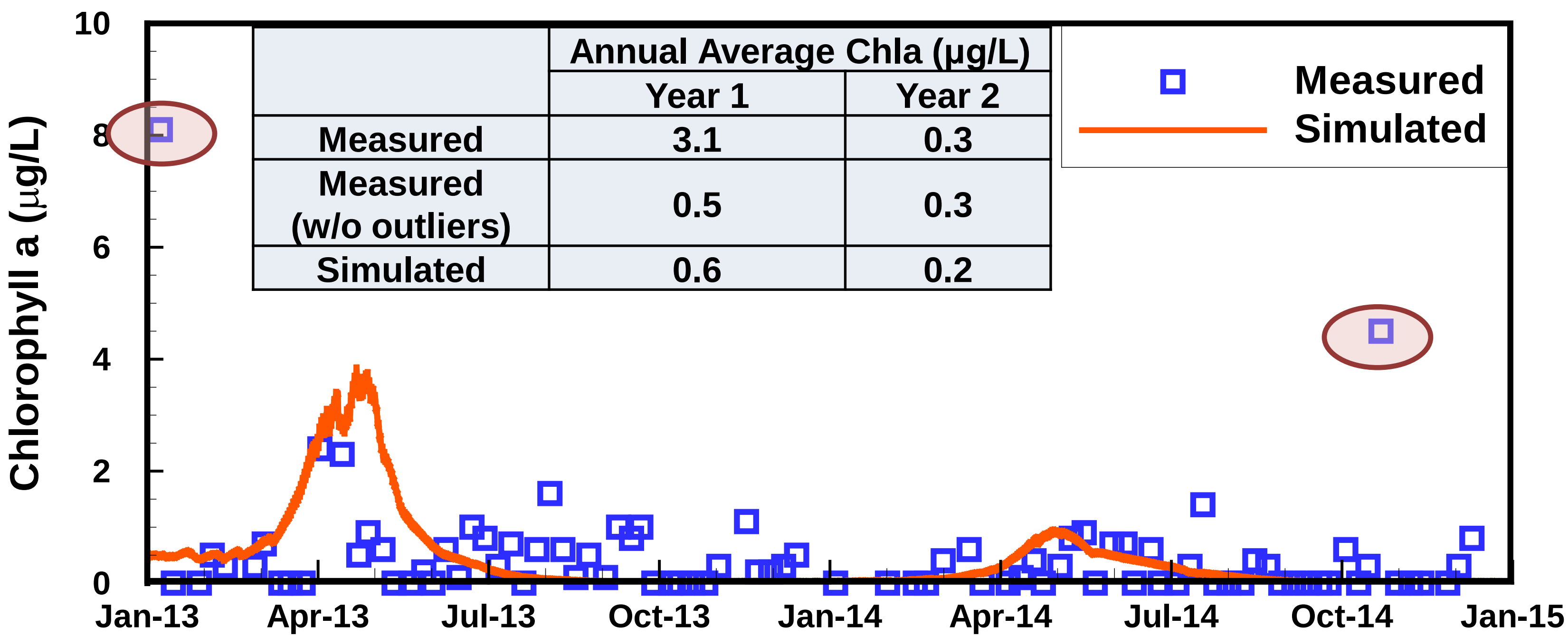


Figure 26

CAEDYM Calibration: Chlorophyll *a*



	Annual Average Chla (µg/L)	
	Year 1	Year 2
Measured	3.1	0.3
Measured (w/o outliers)	0.5	0.3
Simulated	0.6	0.2

*Note: The two circled data points and another data point (118.6 µg/L), which is out of this chart, are considered outliers.

Figure 27

Scatter Plot of Measured vs. Simulated Chlorophyll *a*

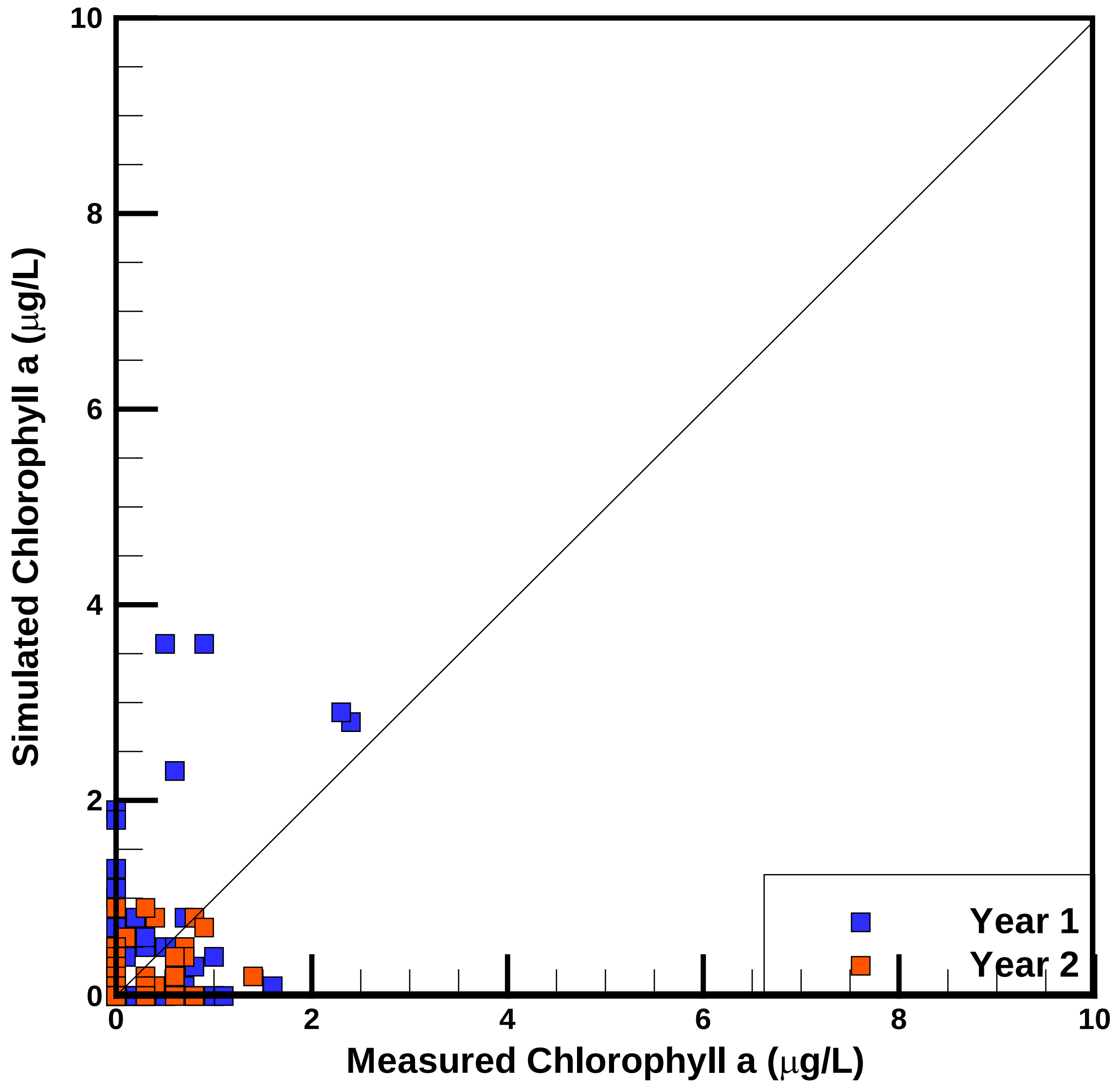
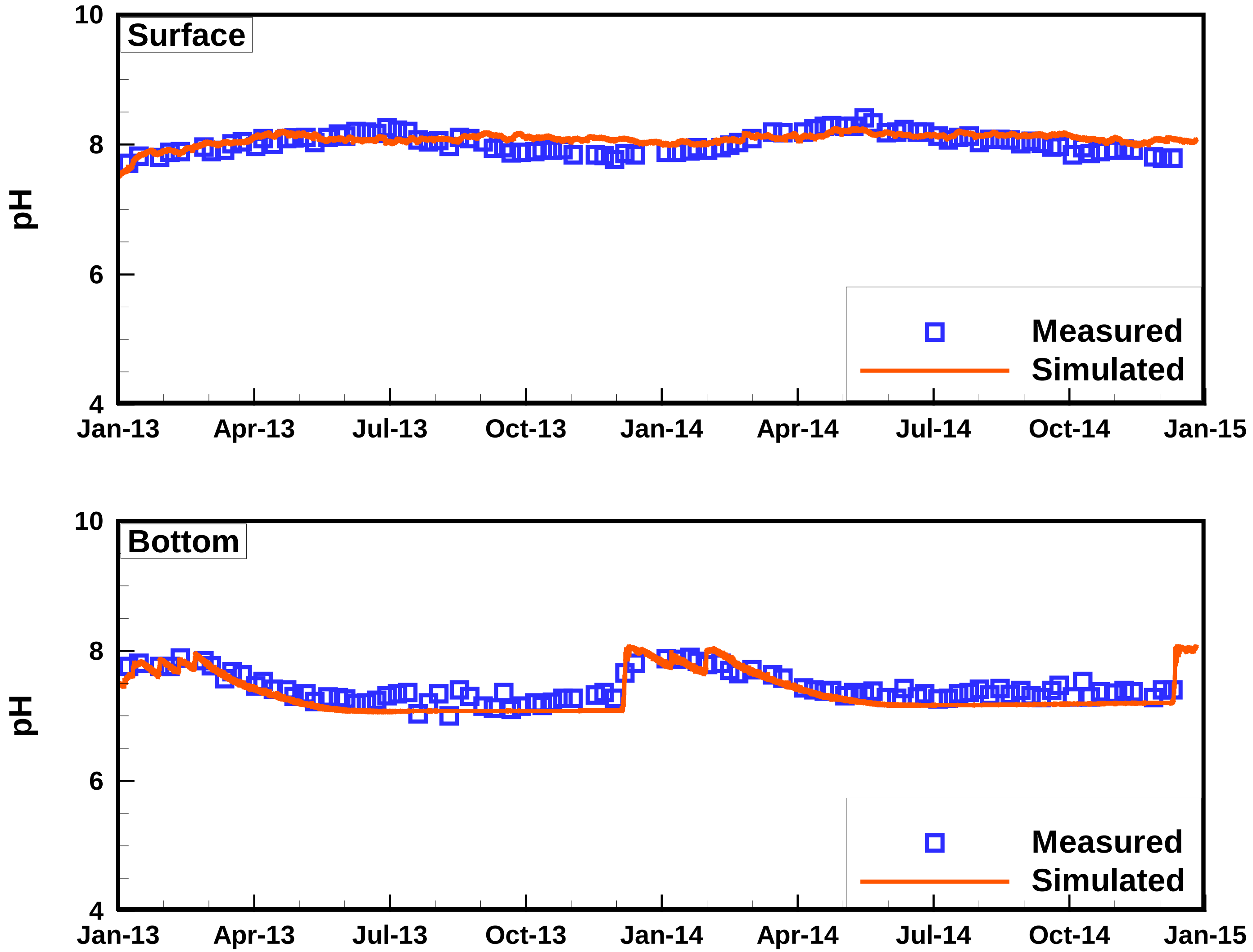


Figure 28

CAEDYM Calibration: pH



Water Quality Solutions

Figure 29

Scatter Plot of Measured vs. Simulated pH

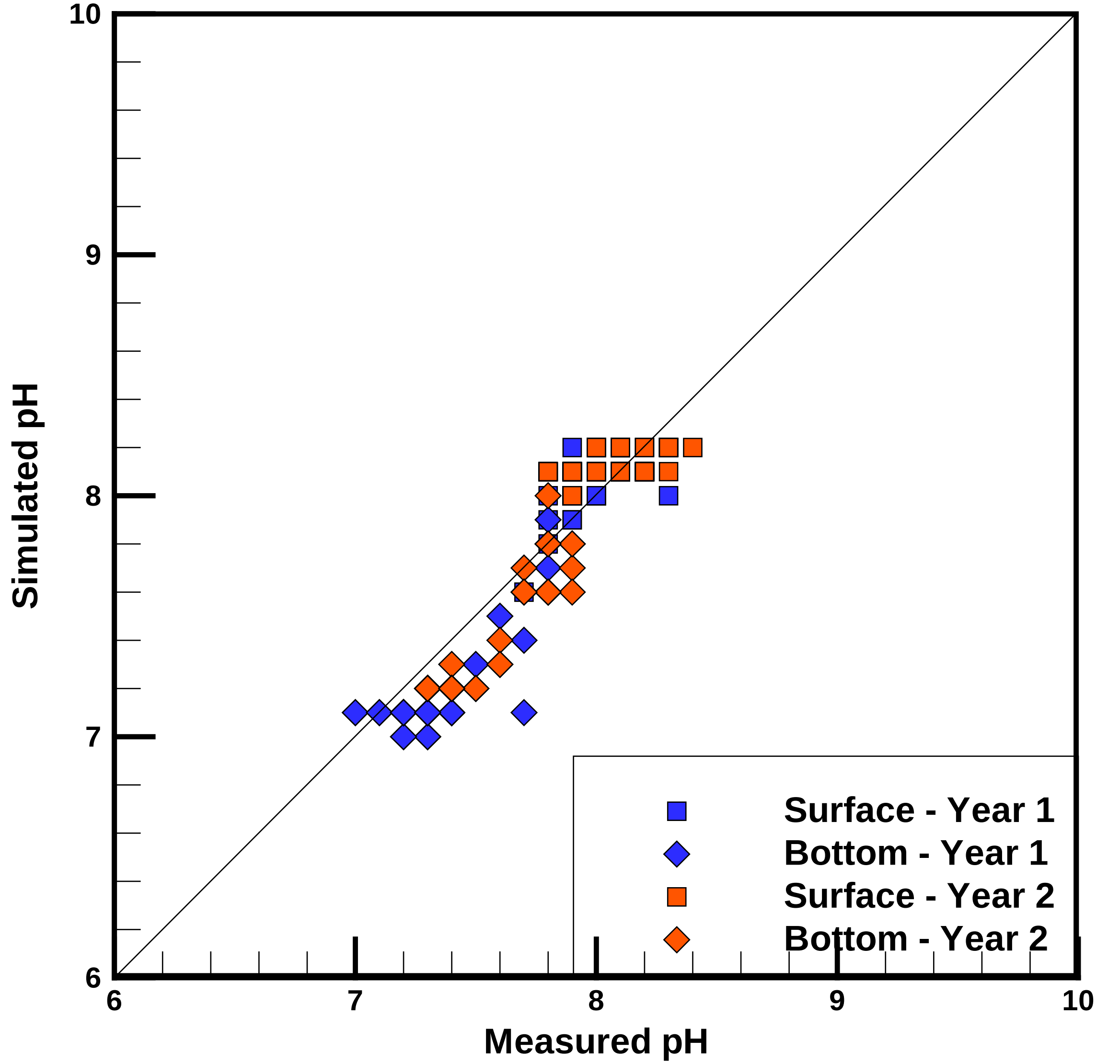
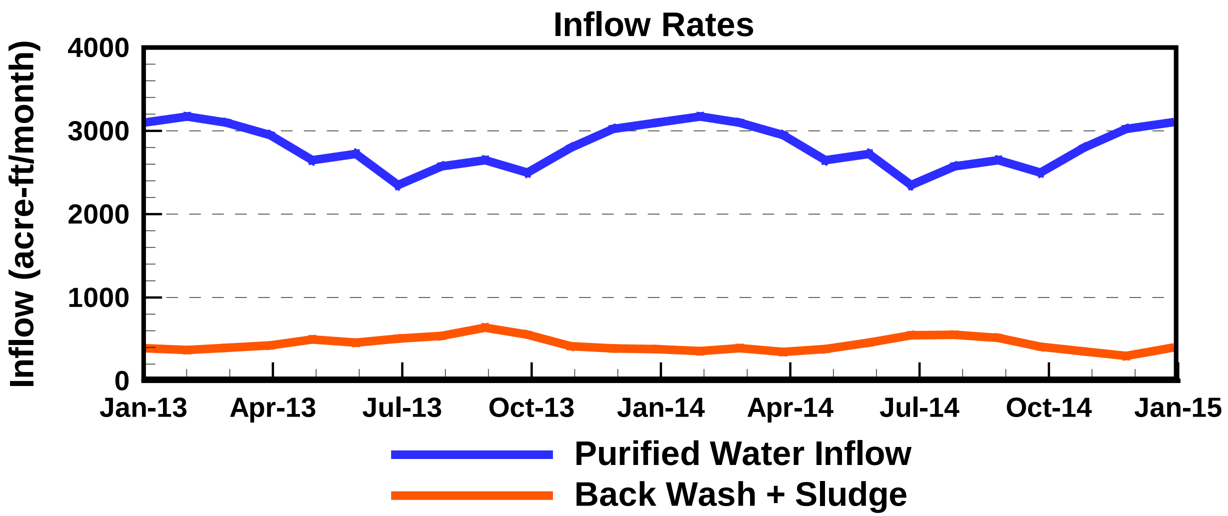


Figure 30

Inflows and Outflows



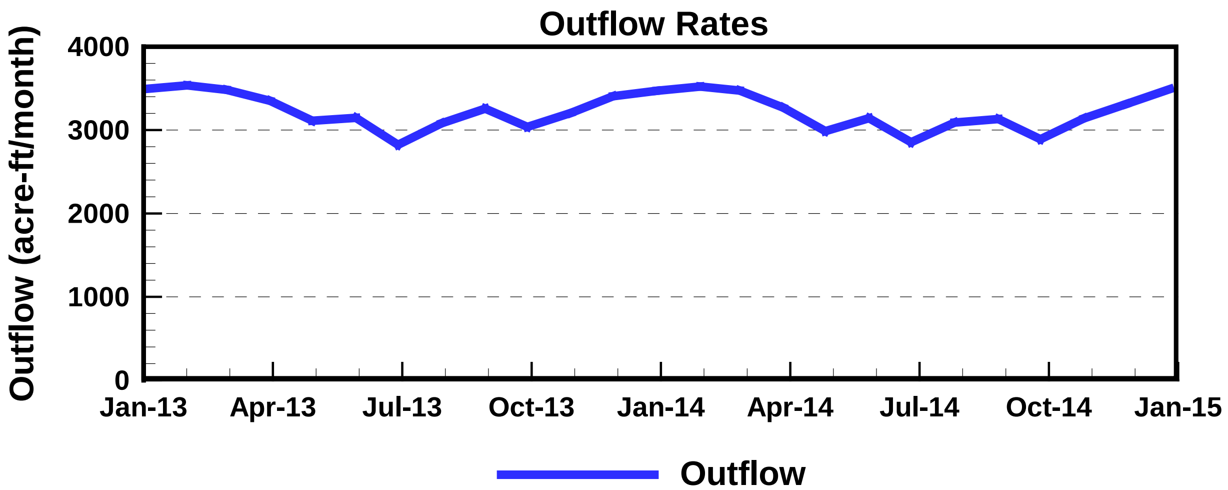


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Figure 31

Bubbler Layout

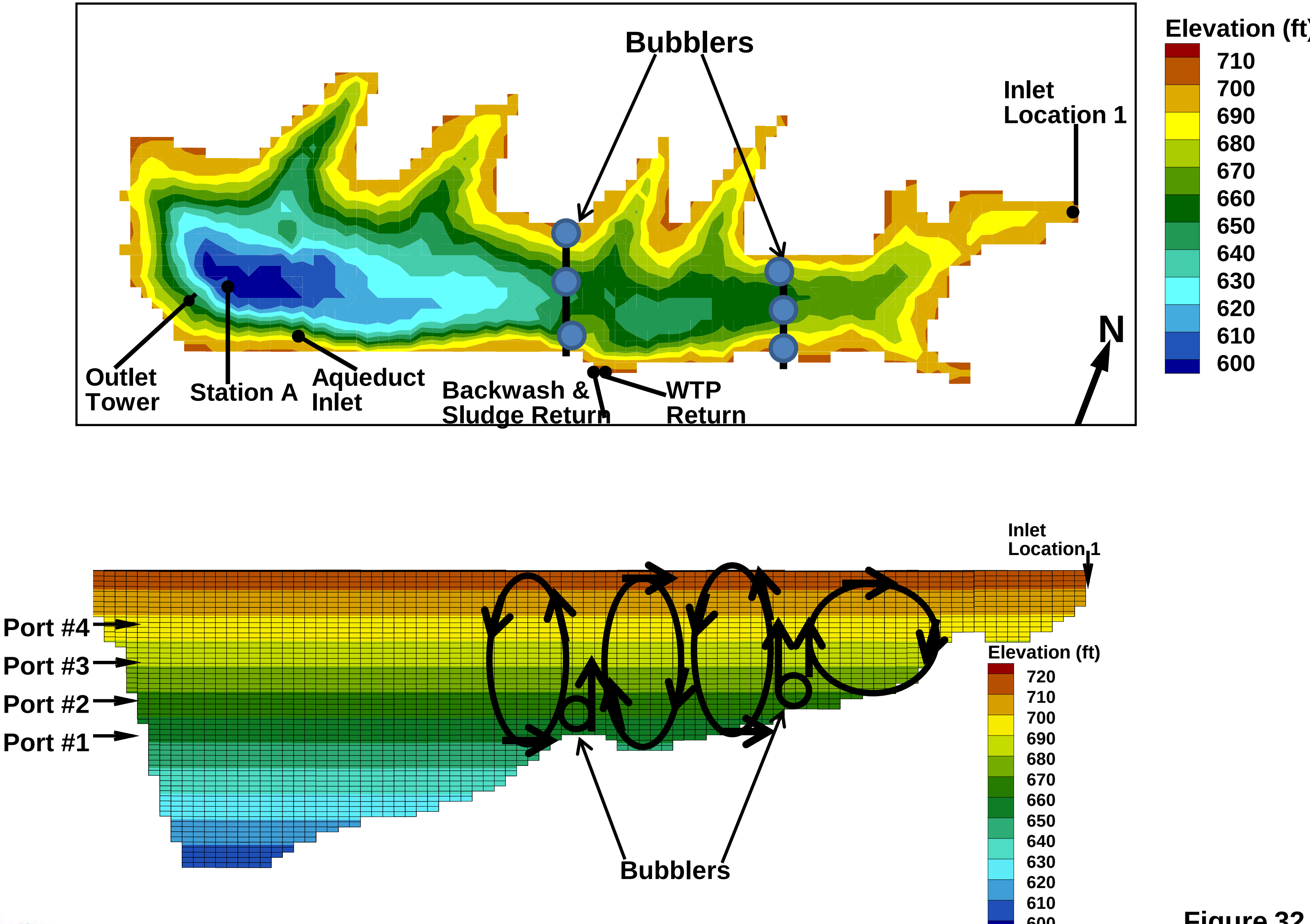

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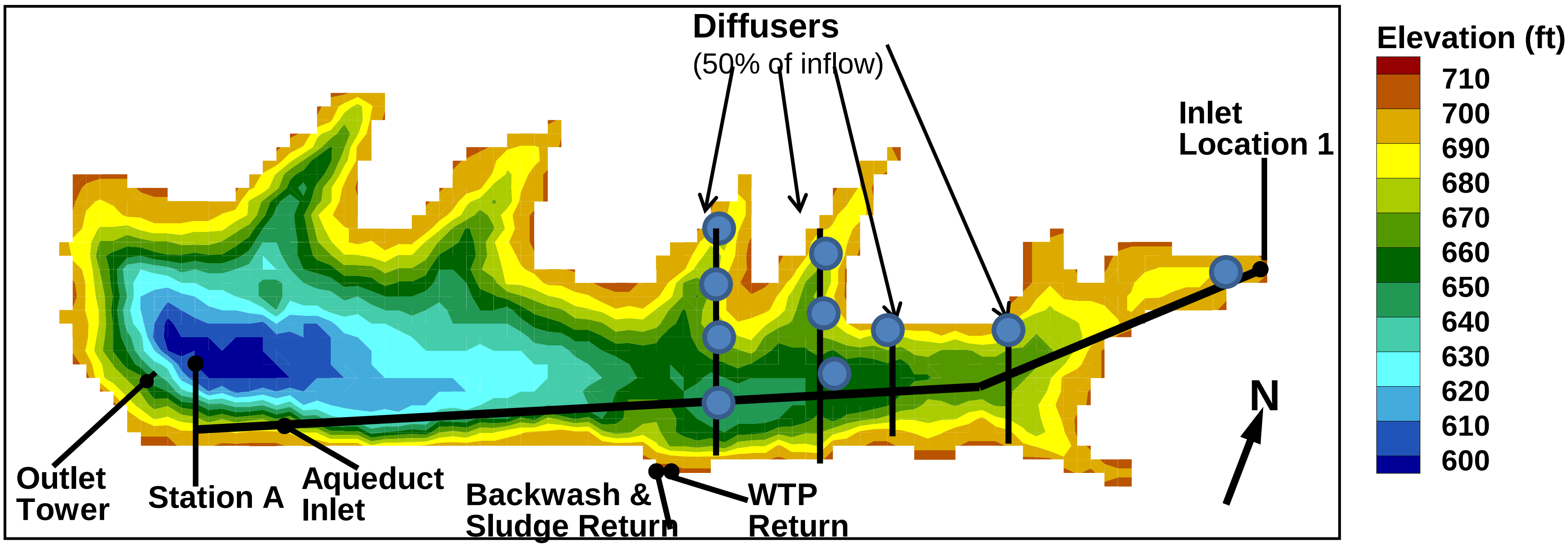
Figure 32

Diffuser Layout



Note: Diffusers are approximately simulated in the current model run, as self-rising inflows from the reservoir bottom.

Figure 33

Water Temperature at Station A

Effect of PW Inflow

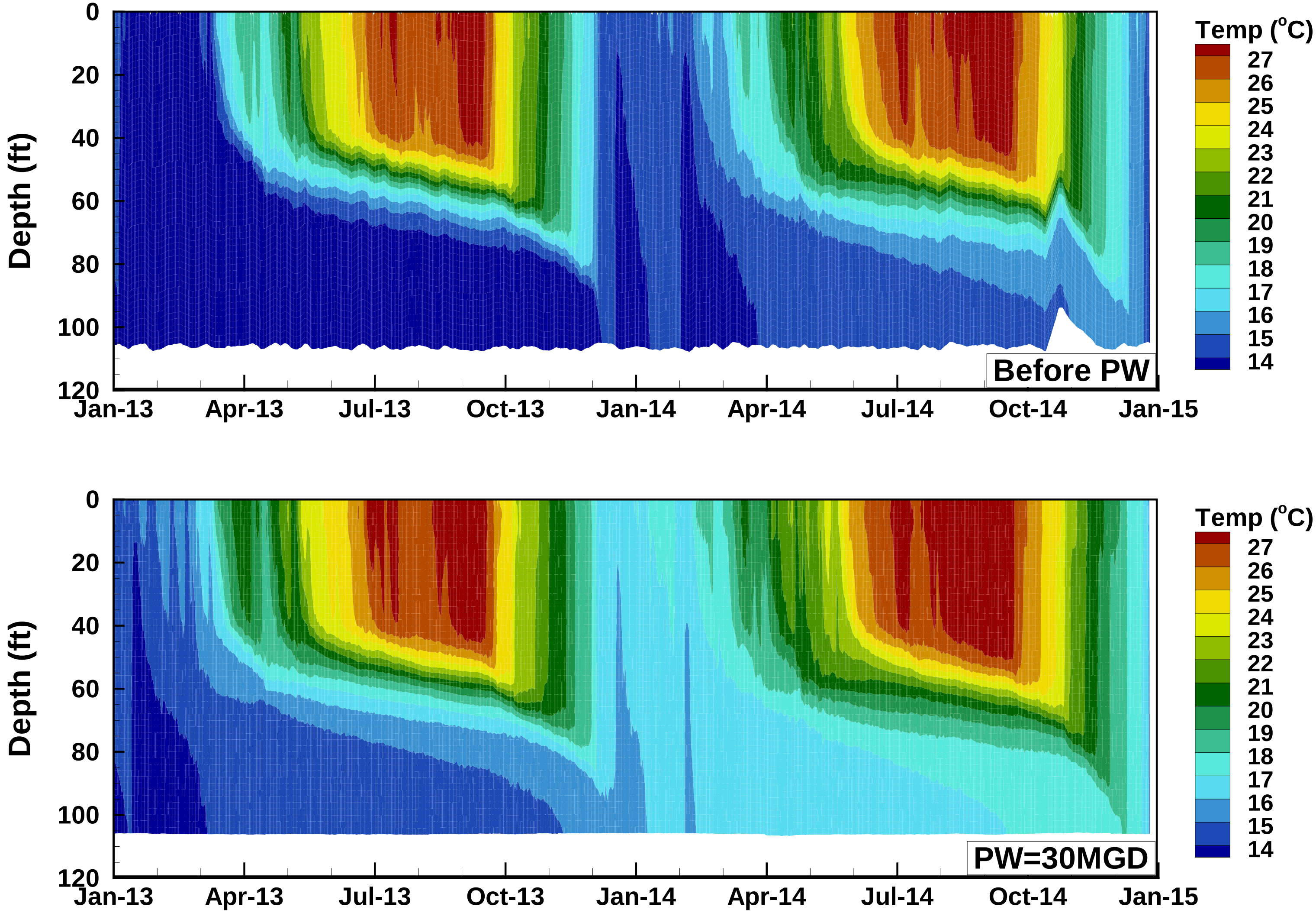
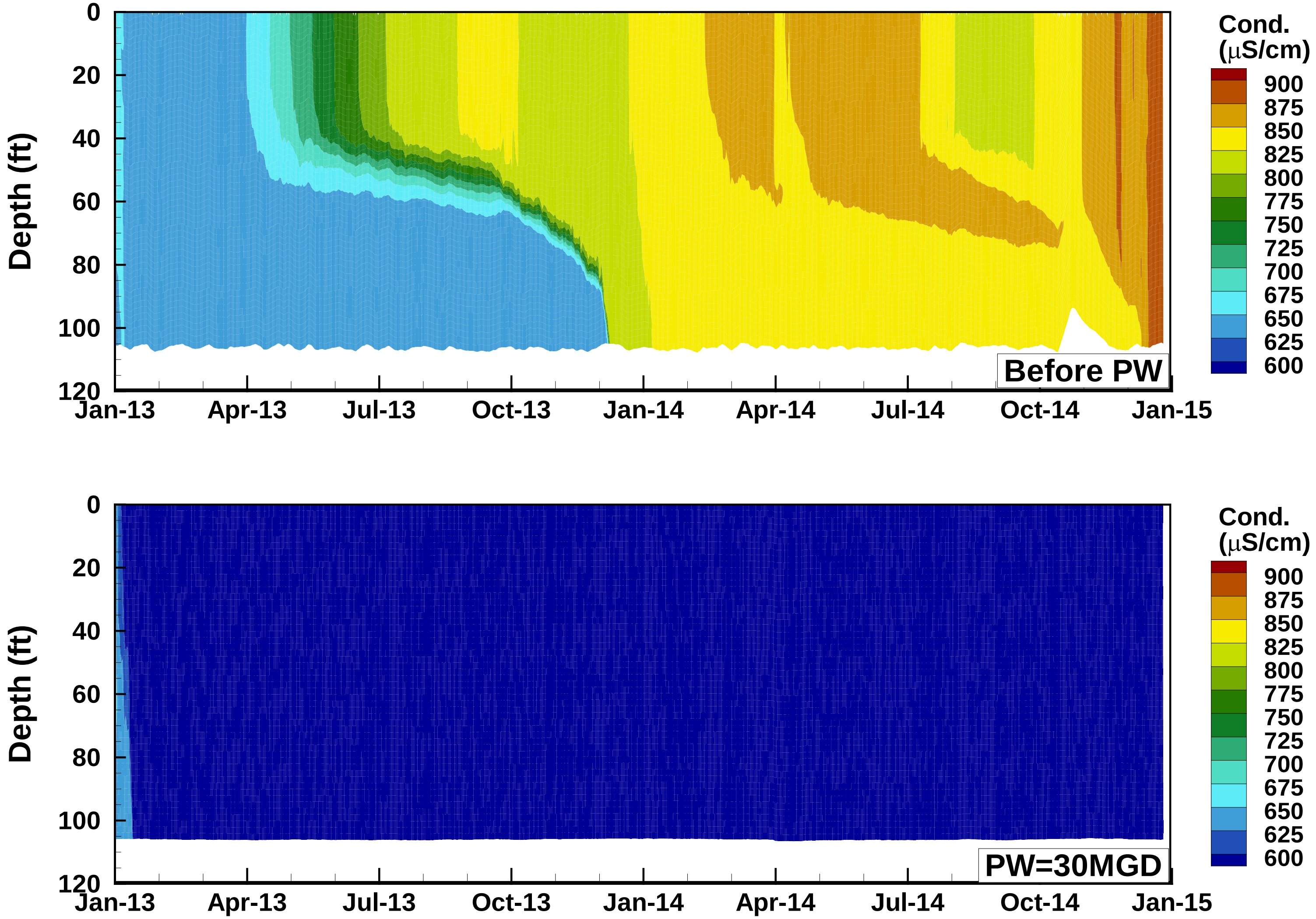


Figure 34

Water Conductivity at Station A

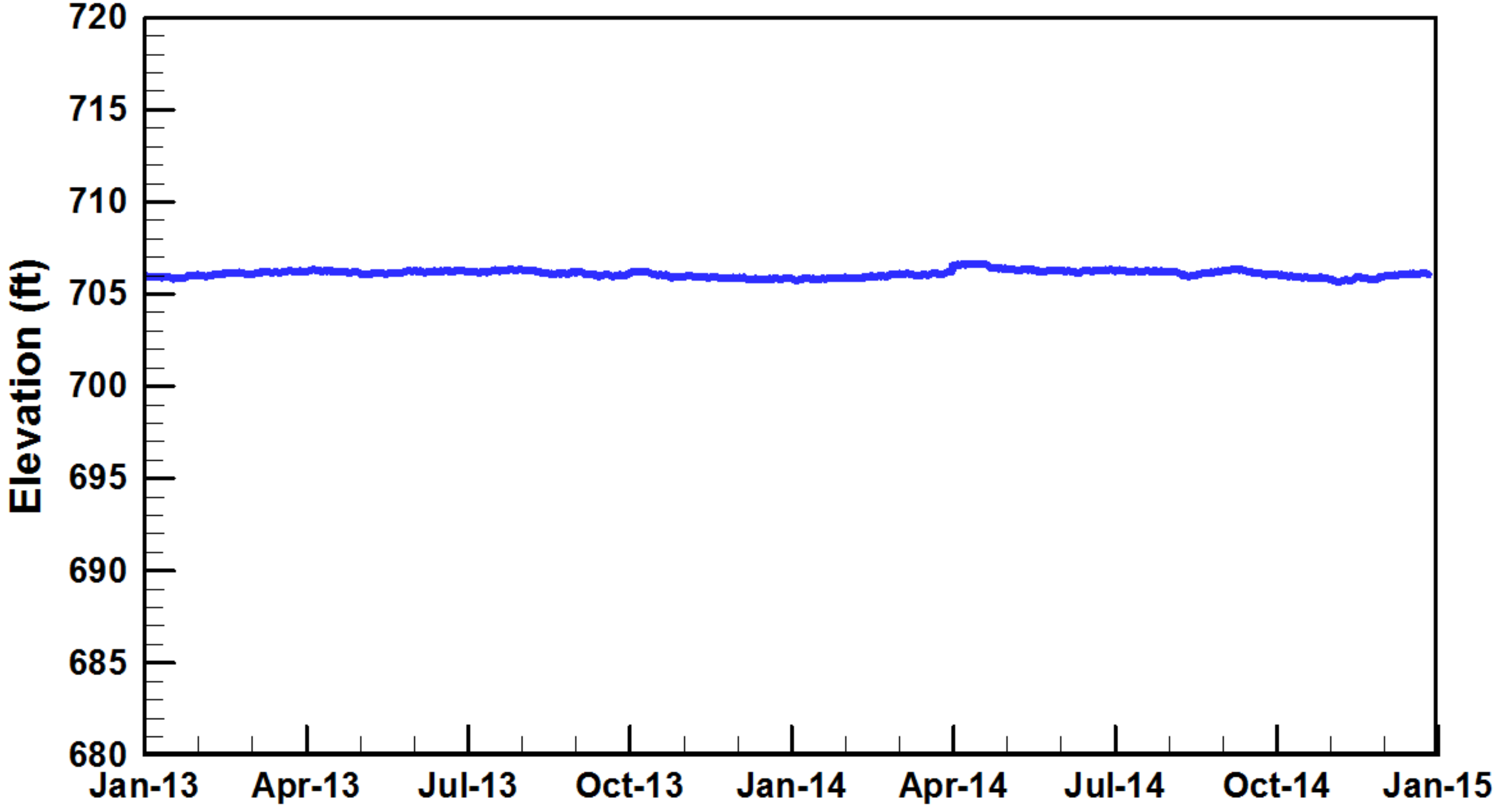
Effect of PW Inflow



Water Quality Solutions

Figure 35

Water Surface Elevation
Runs #1, #2, #4 & #5
Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2



Water Quality Solutions

Figure 36

24-hour Conservative Tracer Concentrations in Outflow Run #1

Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

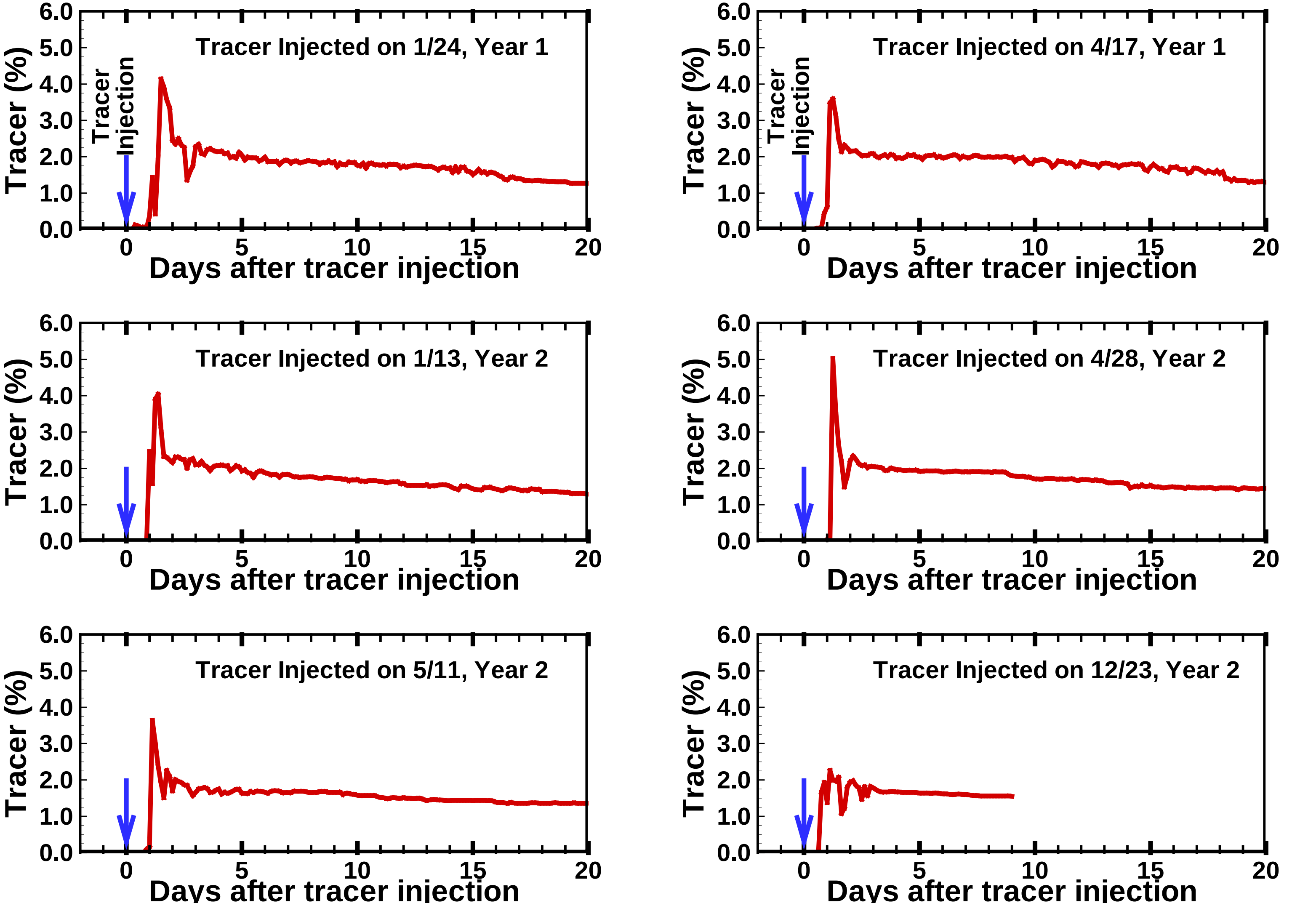


Figure 37

24-hour Conservative Tracer Concentrations in Outflow Run #2

Base Case; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

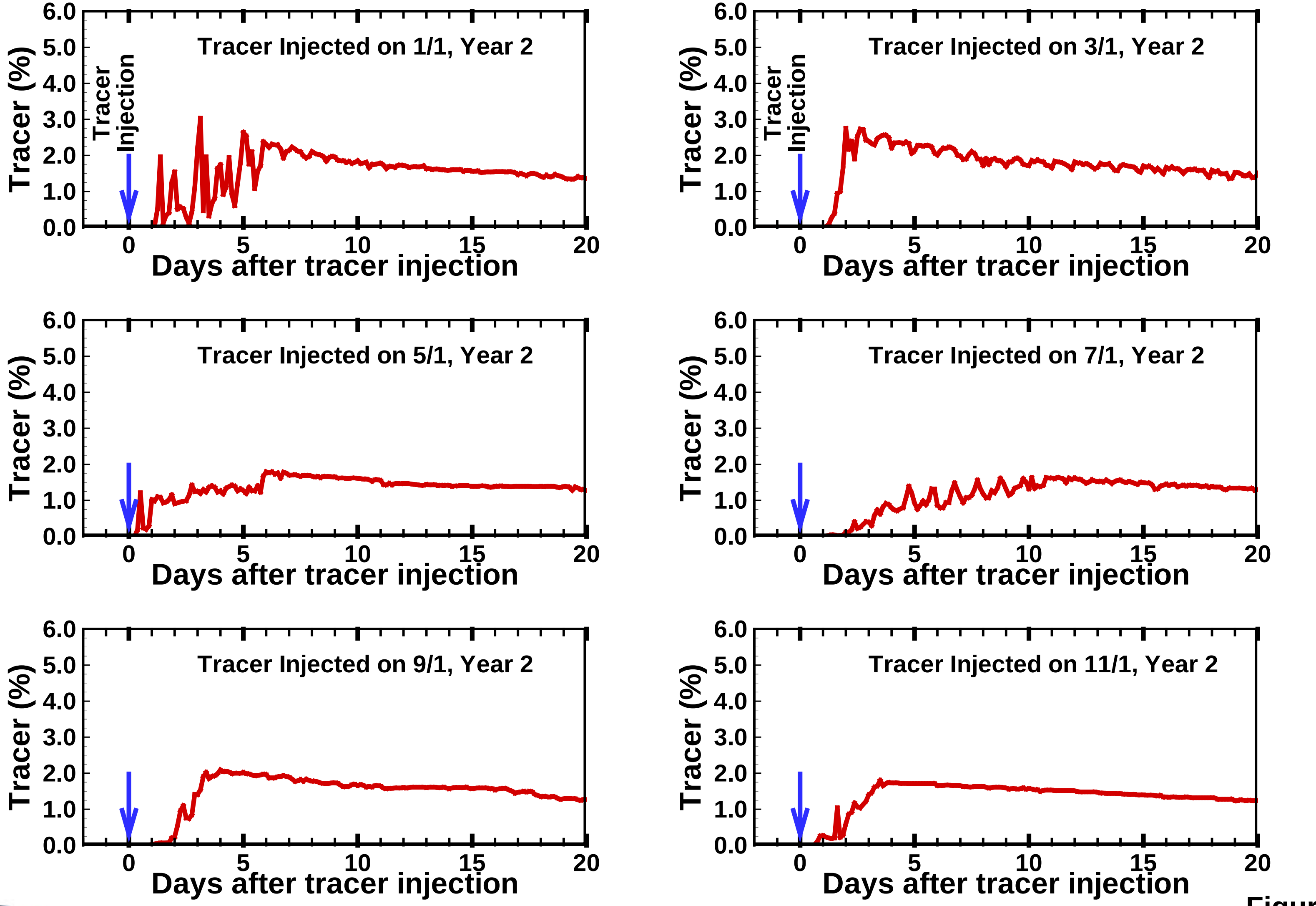
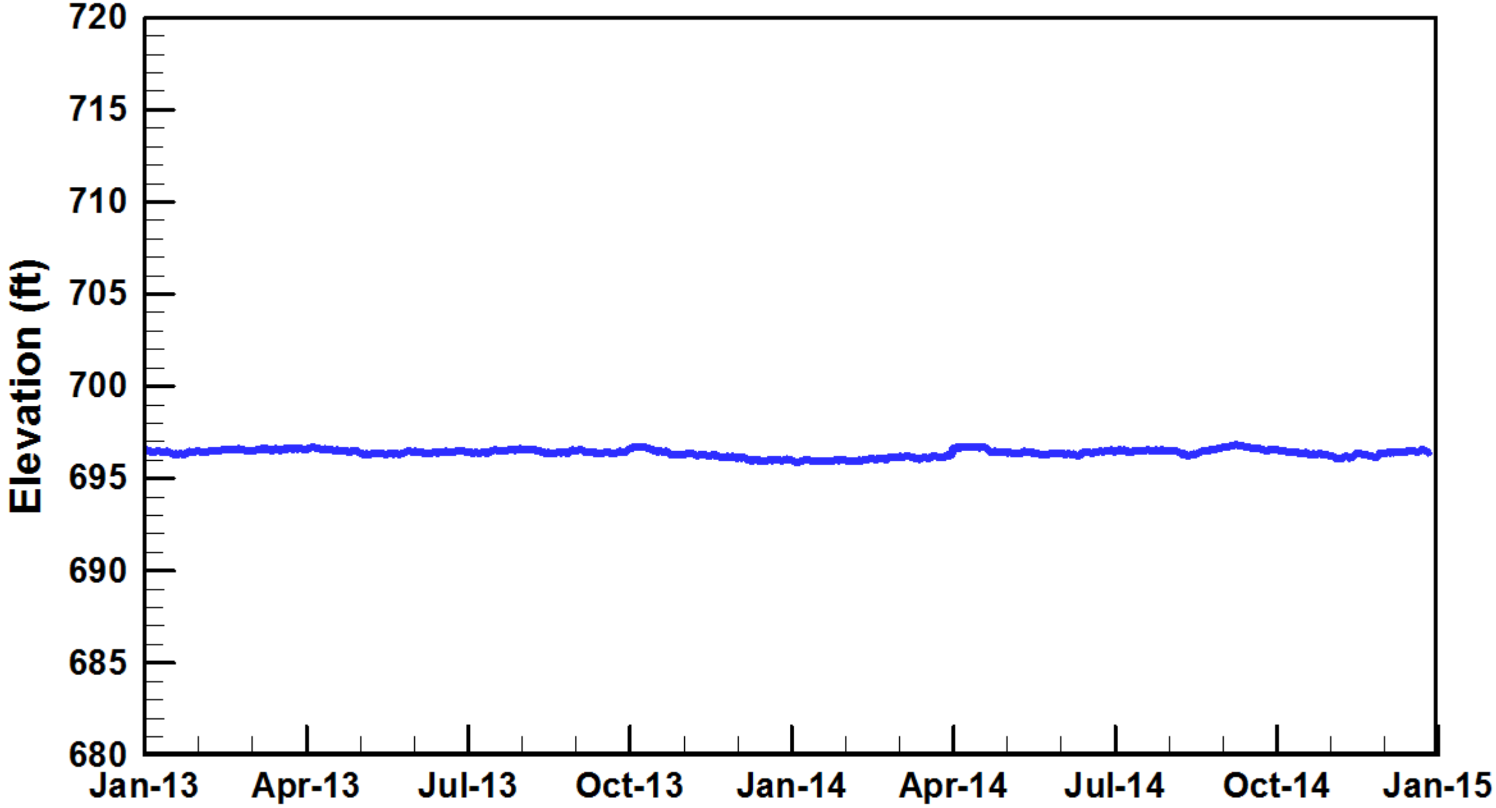


Figure 38

Water Surface Elevation
Run #3
Lower Lake Level; Inlet Location 1; PW Inflow=30 MGD; Open Port #2



Water Quality Solutions

Figure 39

24-hour Conservative Tracer Concentrations in Outflow Run #3

Lower Lake Level; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

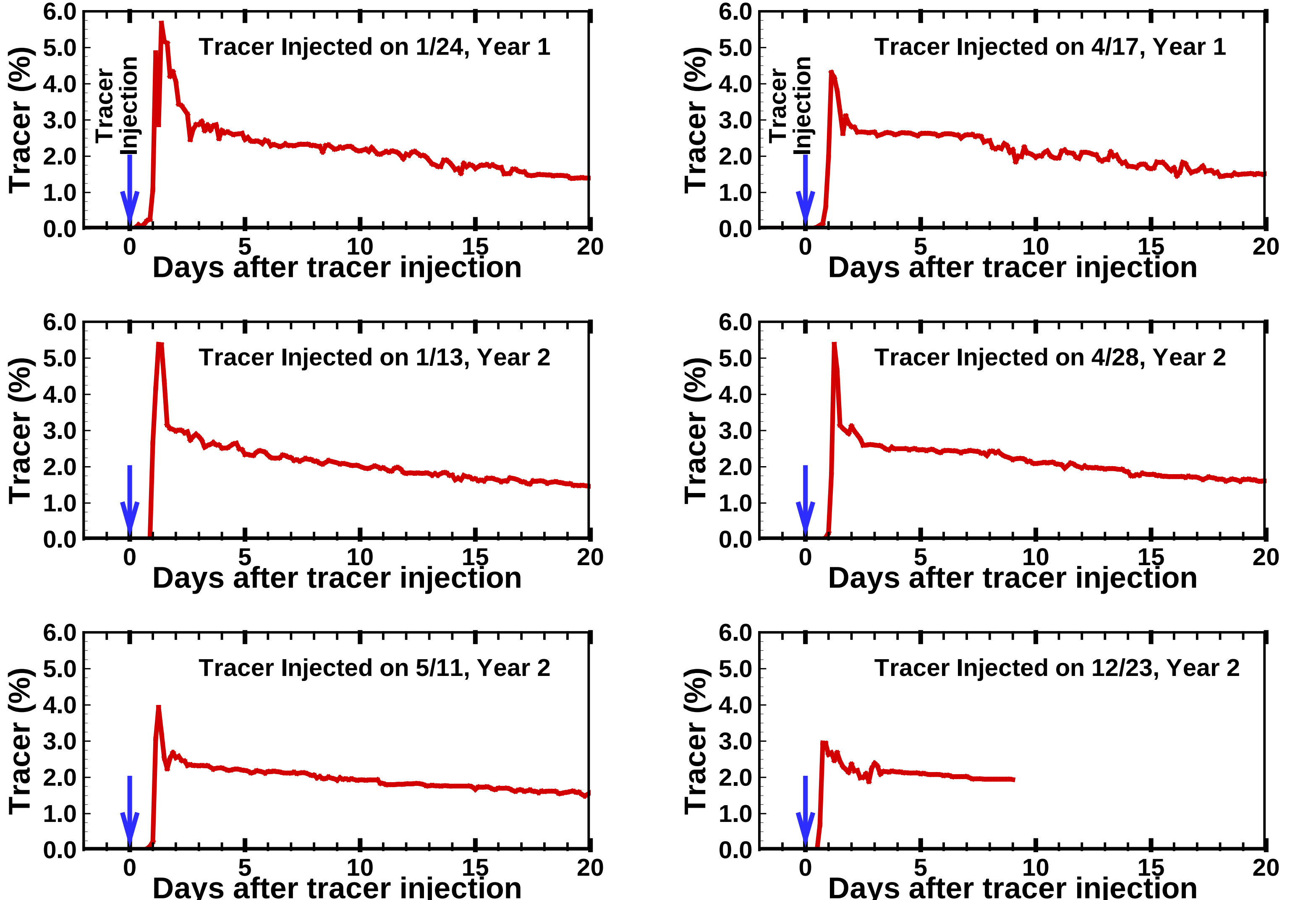
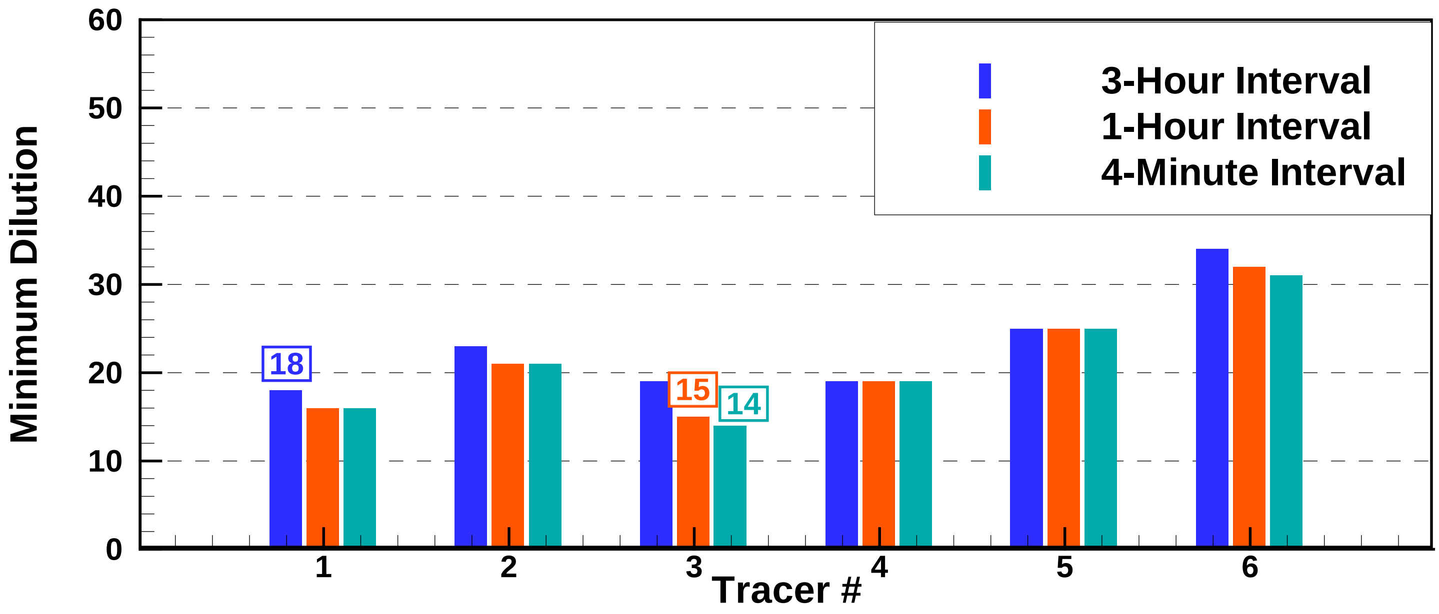


Figure 40

Run #3: Tracer Dilutions
Comparison of Model Sampling Intervals

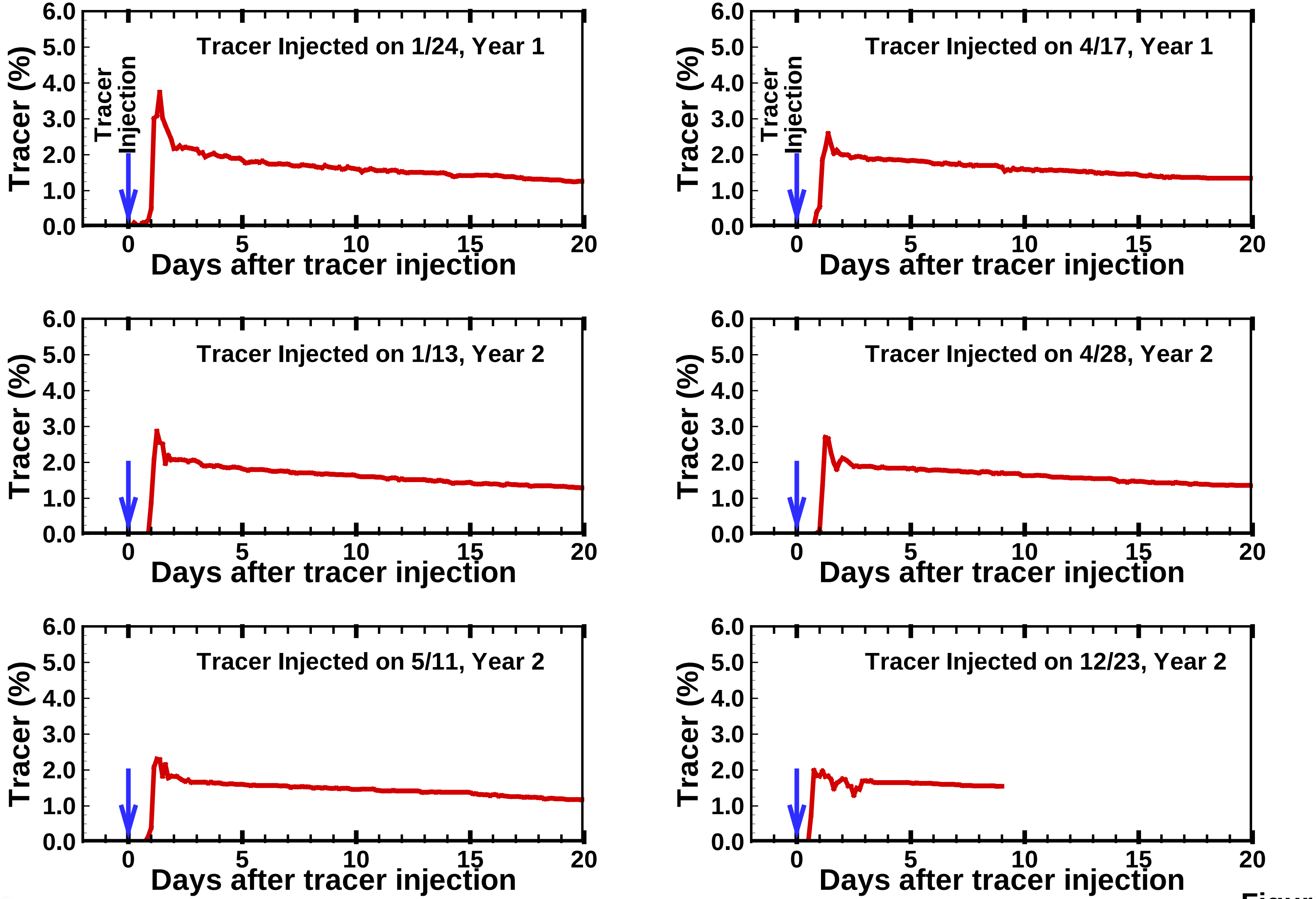


*The boxed numbers are the overall minimum dilutions for different sampling intervals.

Figure 41

24-hour Conservative Tracer Concentrations in Outflow Run #4

Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2; Bubblers



Water Quality Solutions

Figure 42

24-hour Conservative Tracer Concentrations in Outflow Run #5

Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2; Diffusers

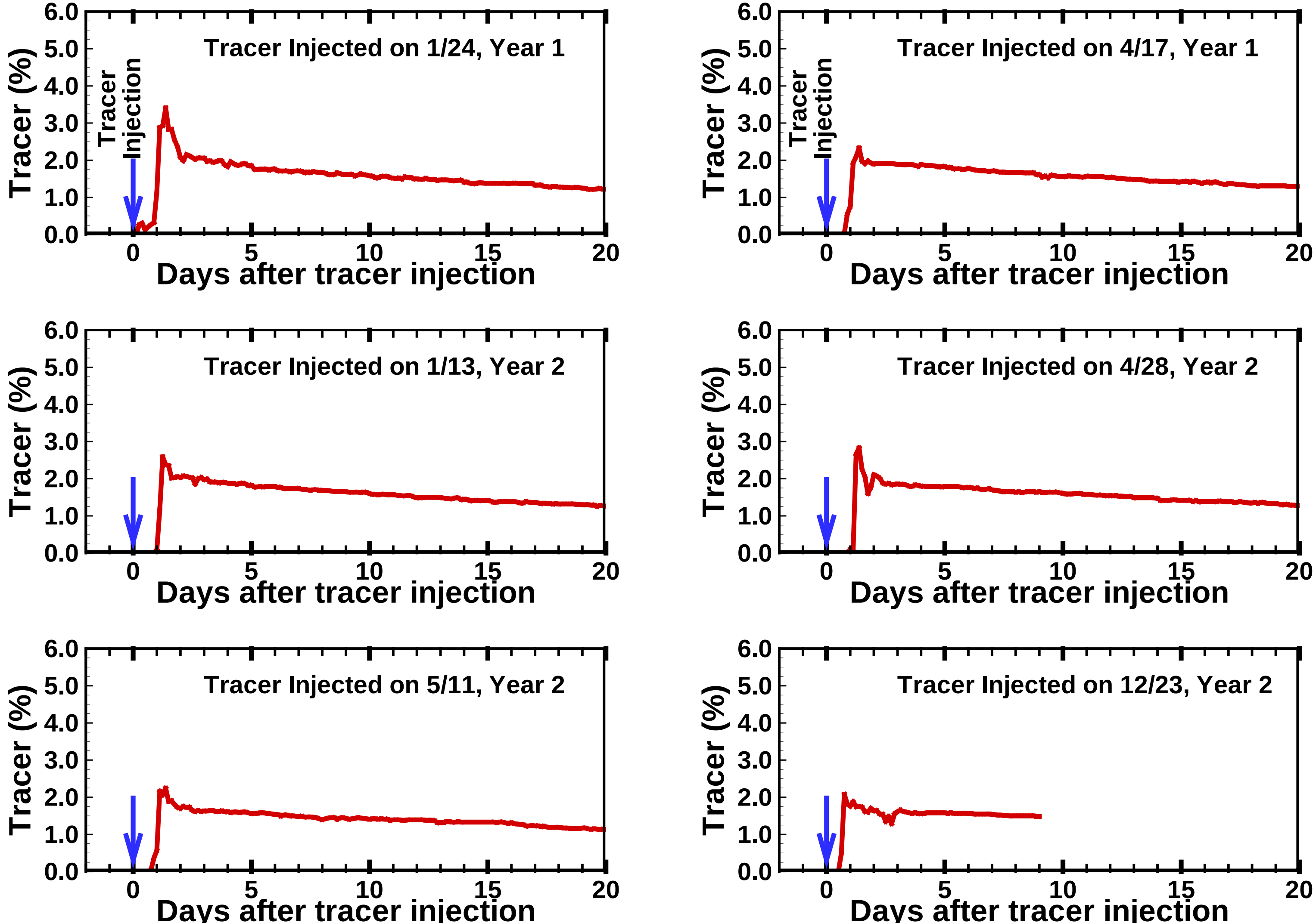


Figure 43

Effect of Mixing Devices on Conservative Tracer Dilution

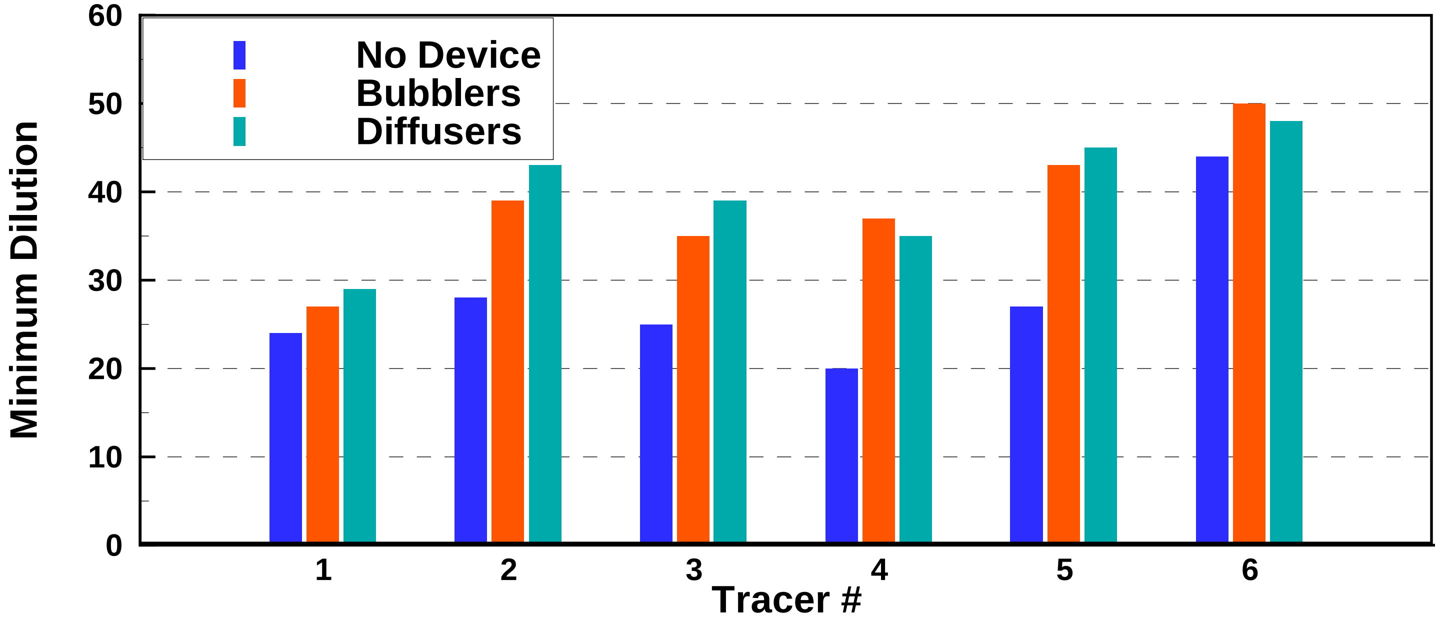
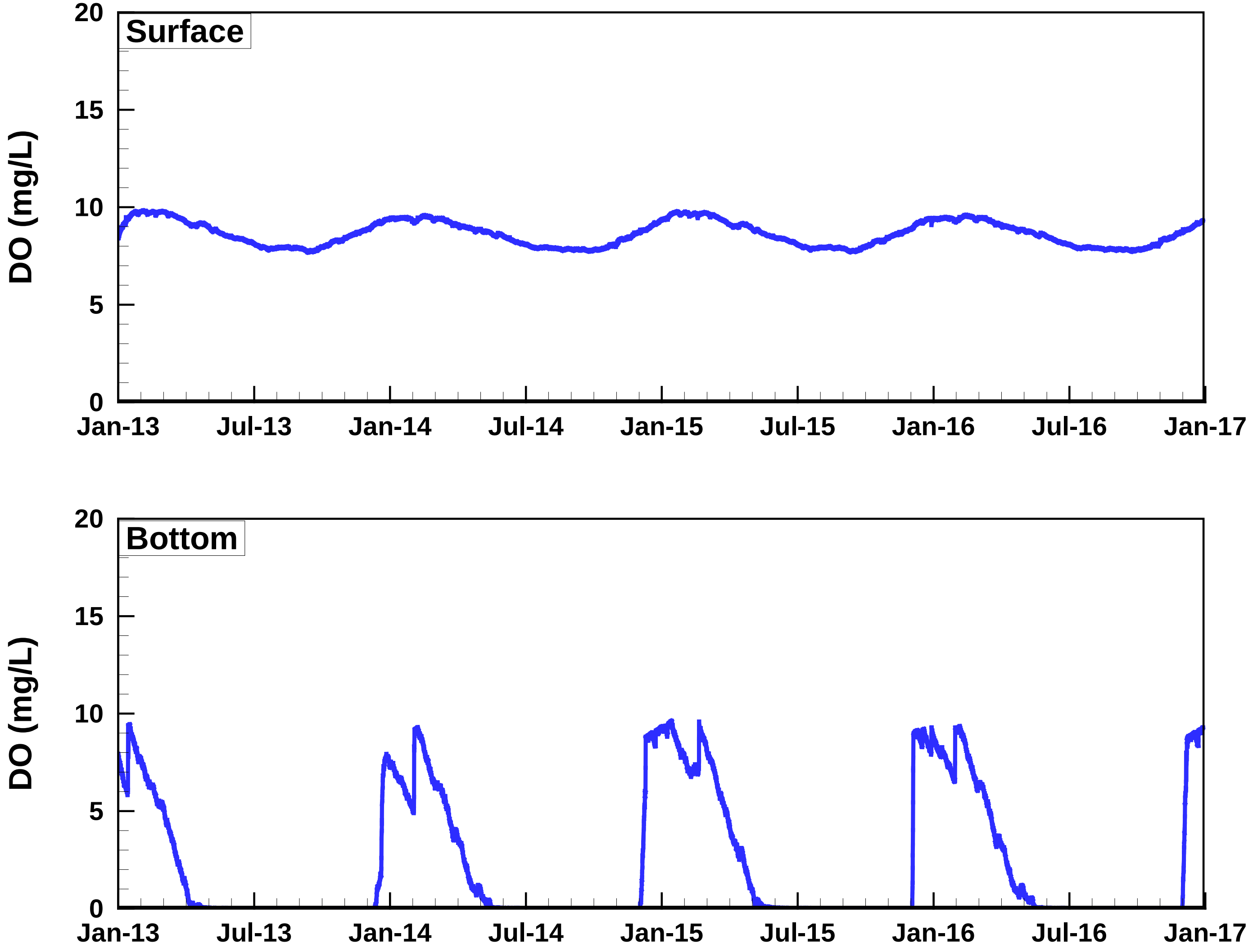


Figure 44

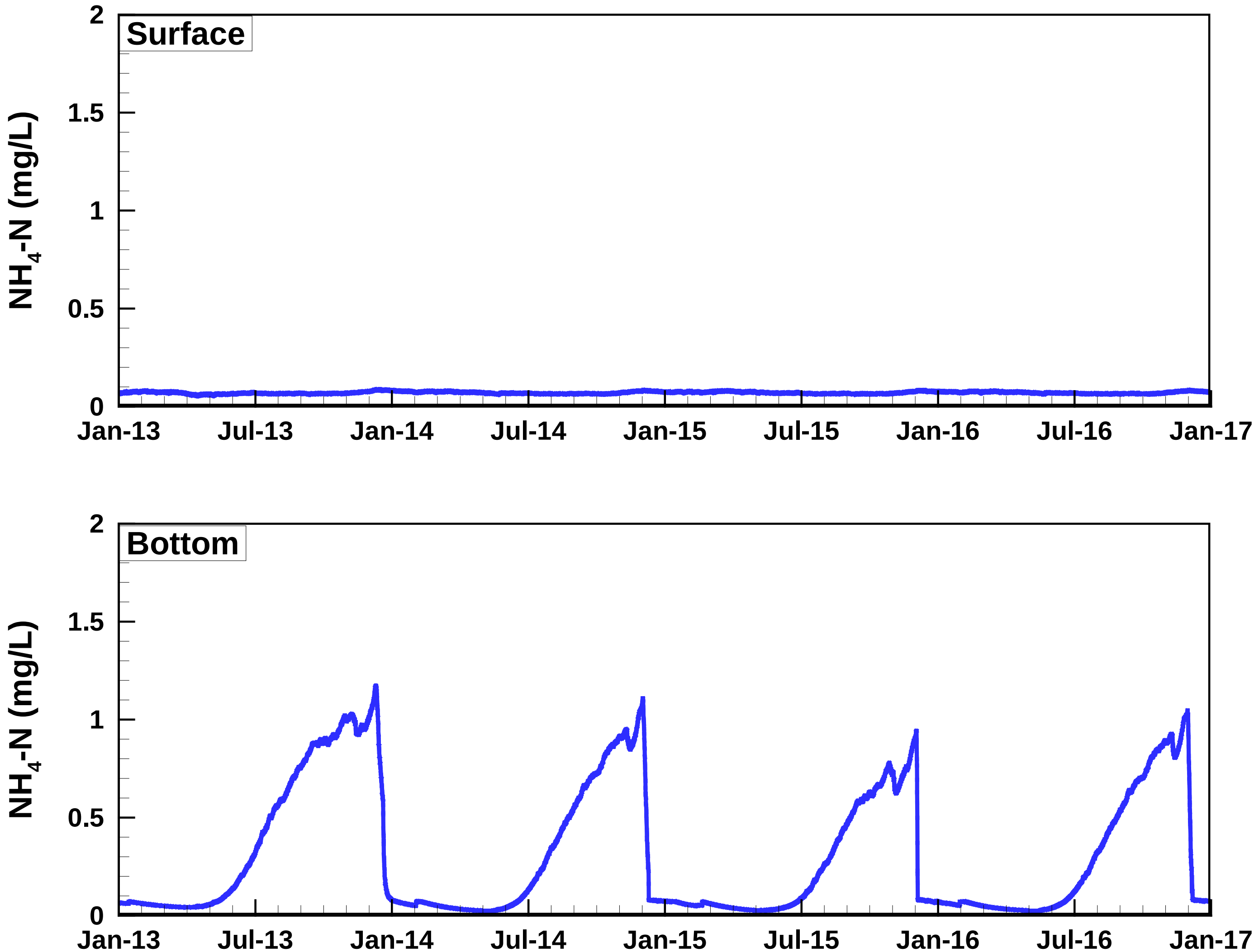
CAEDYM Run: Simulated Dissolved Oxygen



Water Quality Solutions

Figure 45

CAEDYM Run: Simulated Ammonia



Water Quality Solutions

Figure 46

CAEDYM Run: Simulated Nitrate

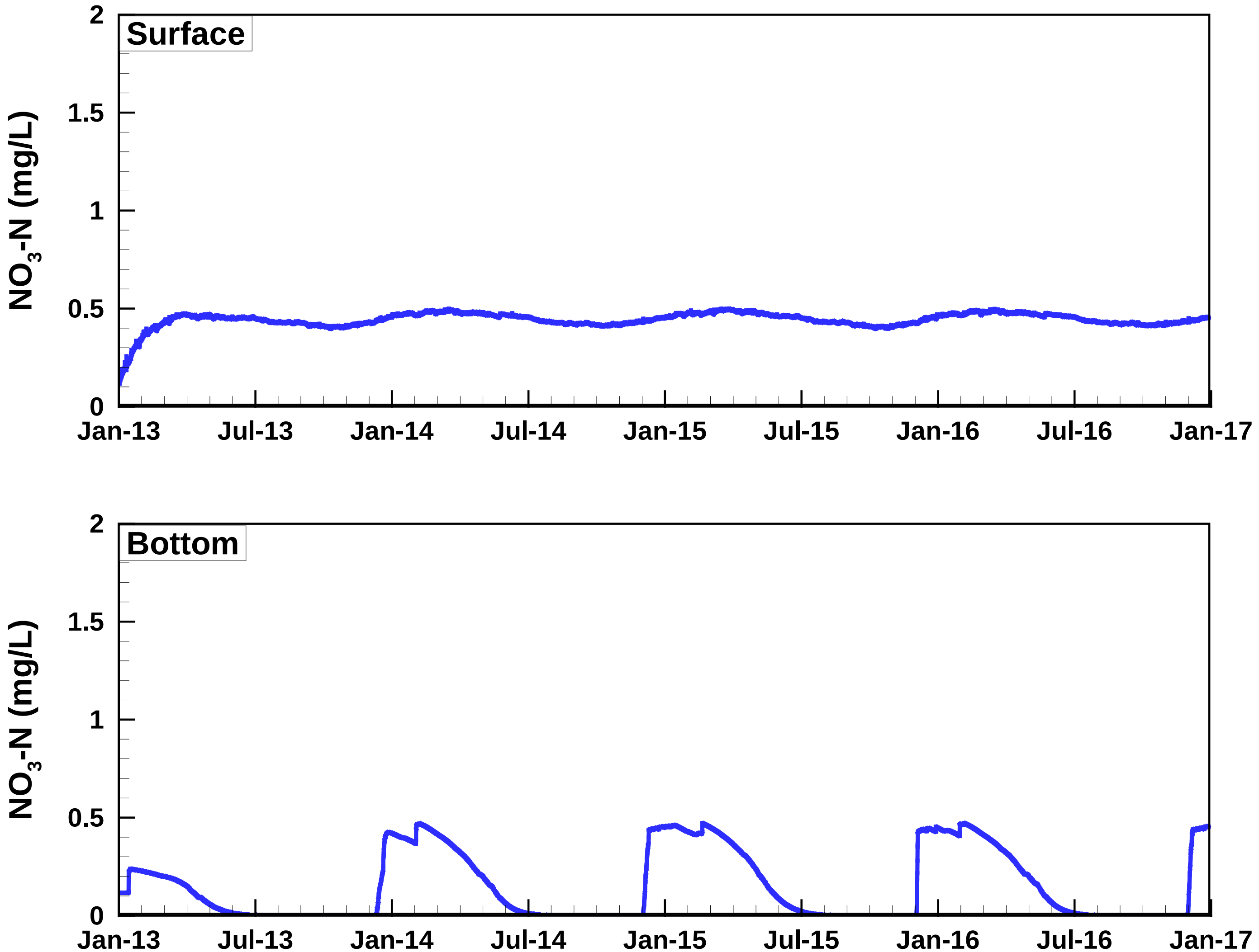


Figure 47

CAEDYM Run: Simulated Total Nitrogen

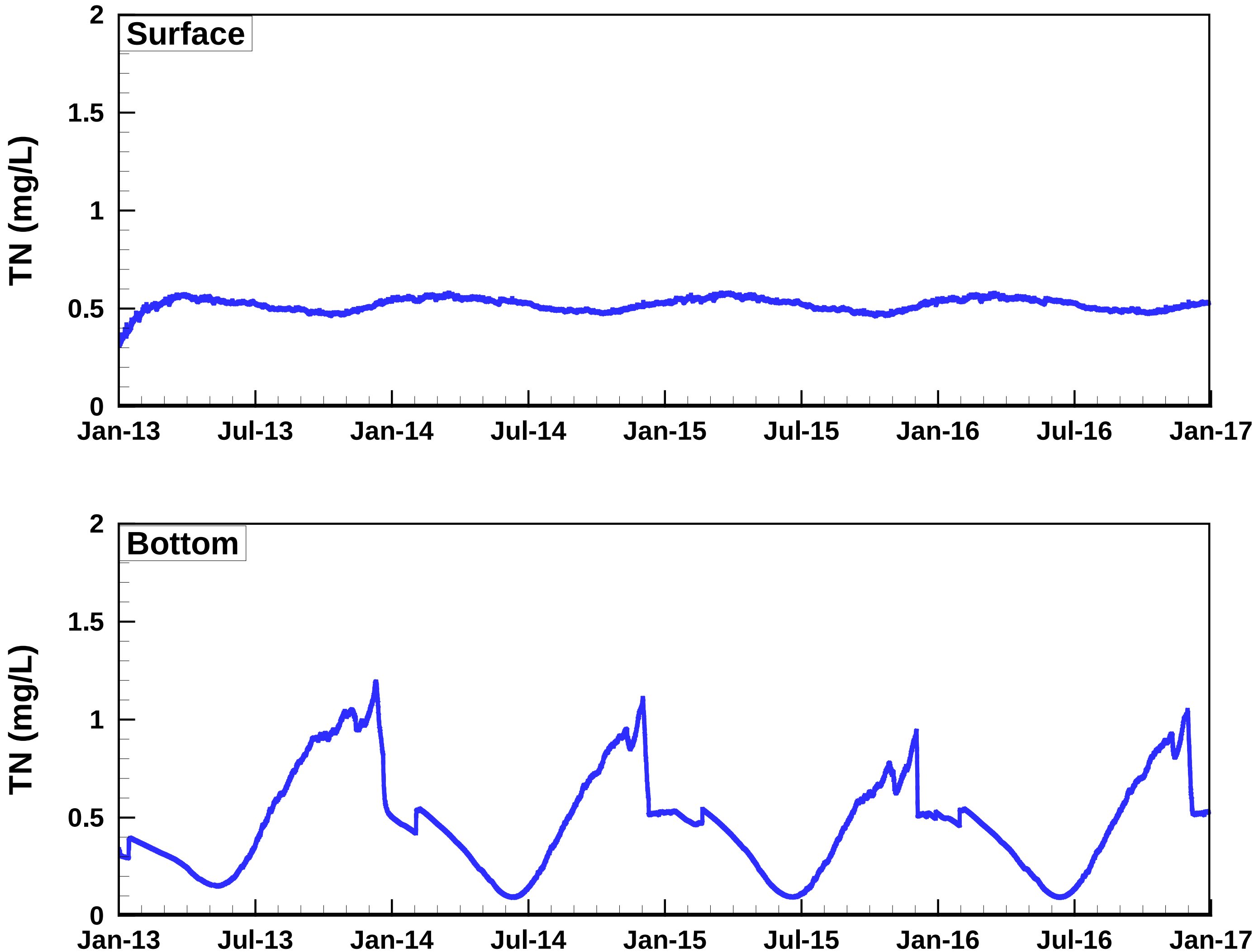
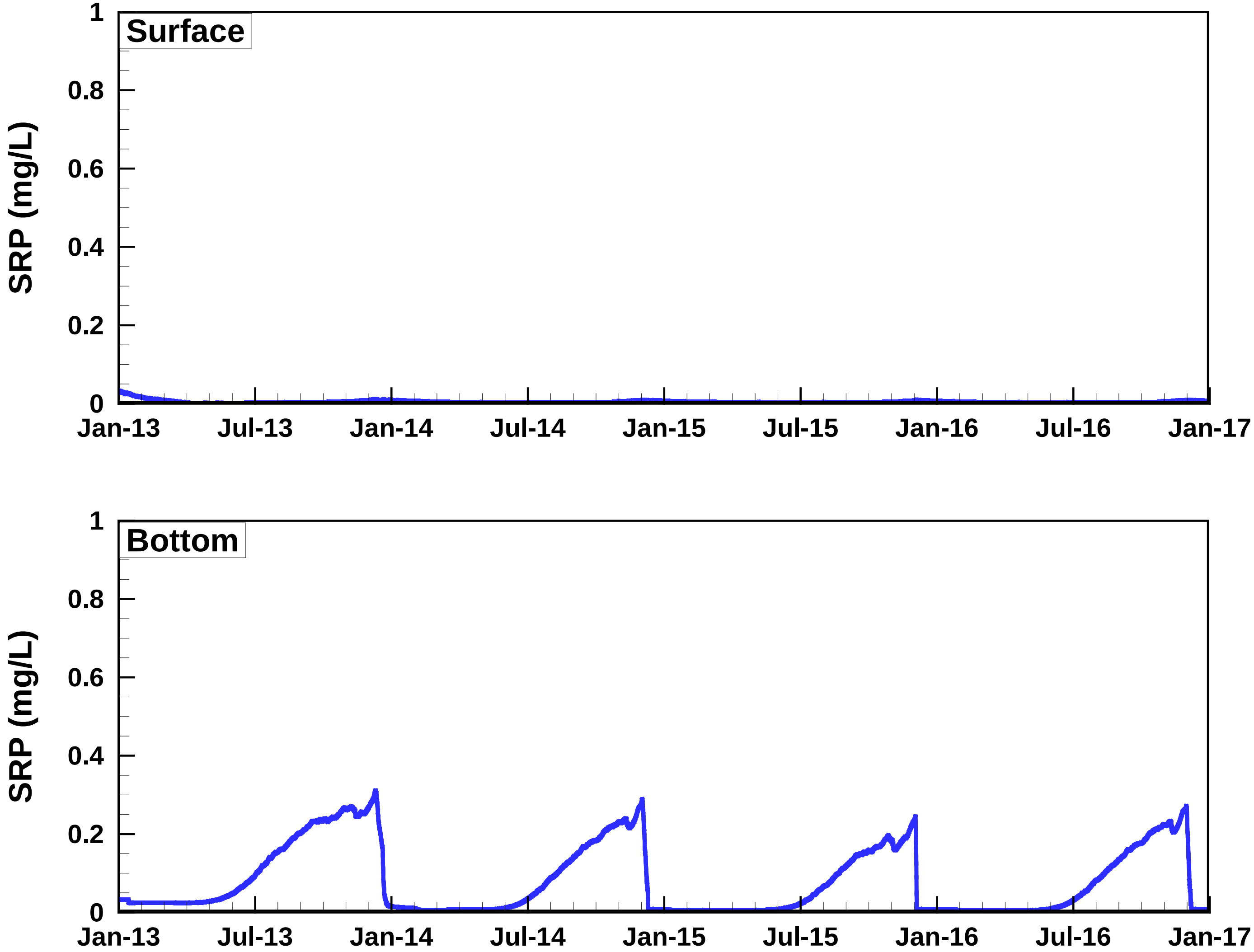


Figure 48

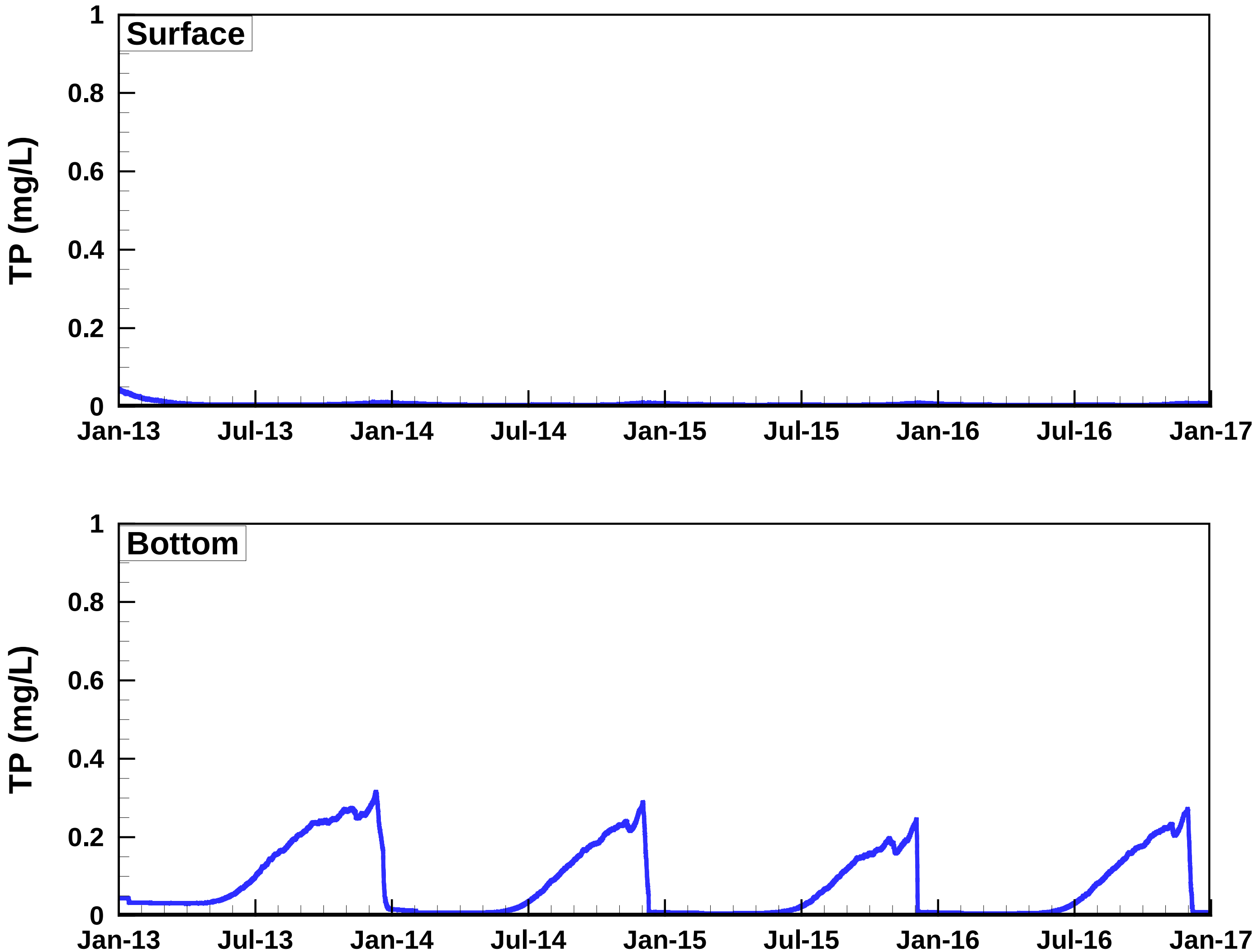
CAEDYM Run: Simulated Soluble Reactive Phosphorus



Water Quality Solutions

Figure 49

CAEDYM Run: Simulated Total Phosphorus



Water Quality Solutions

Figure 50

CAEDYM Run: Simulated Chlorophyll *a*

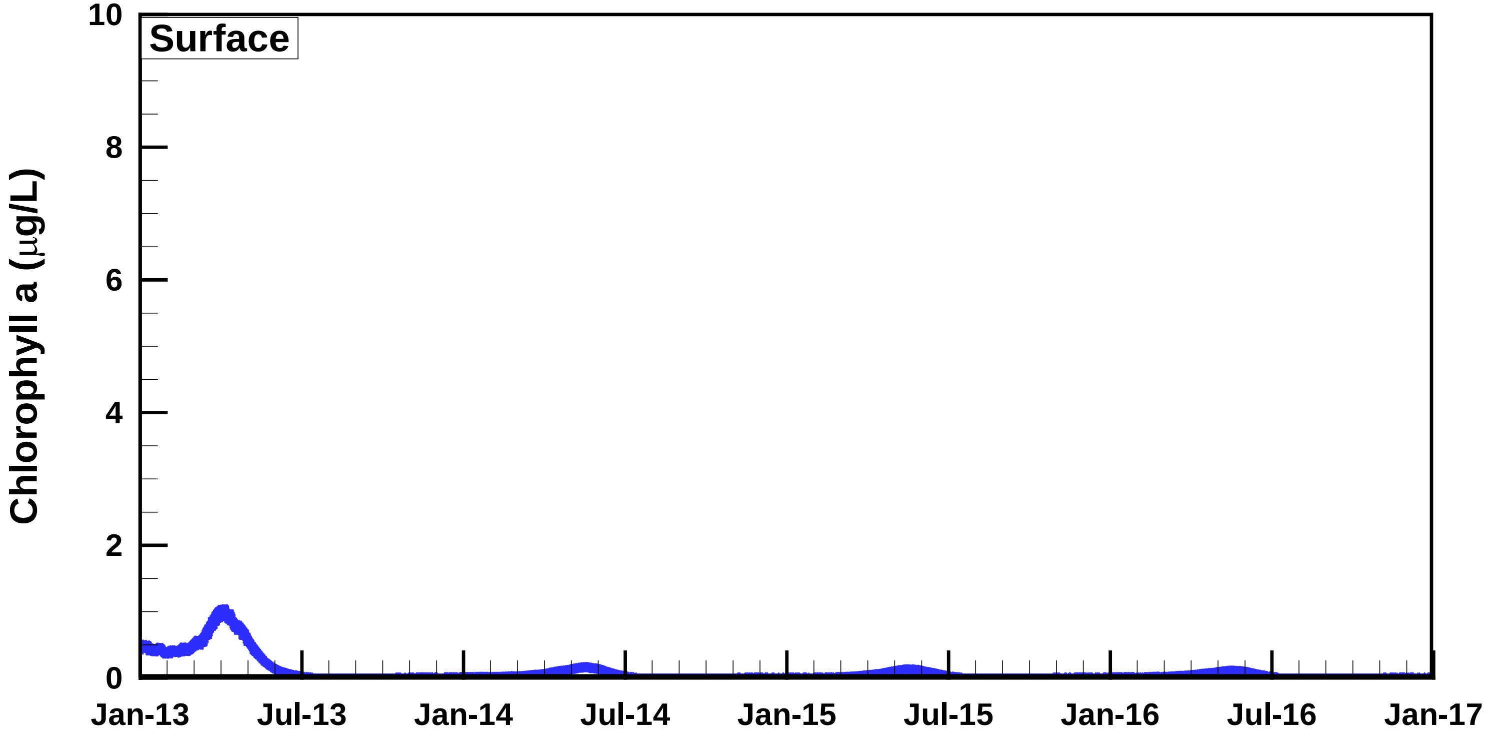


Figure 51

CAEDYM Run: Simulated pH

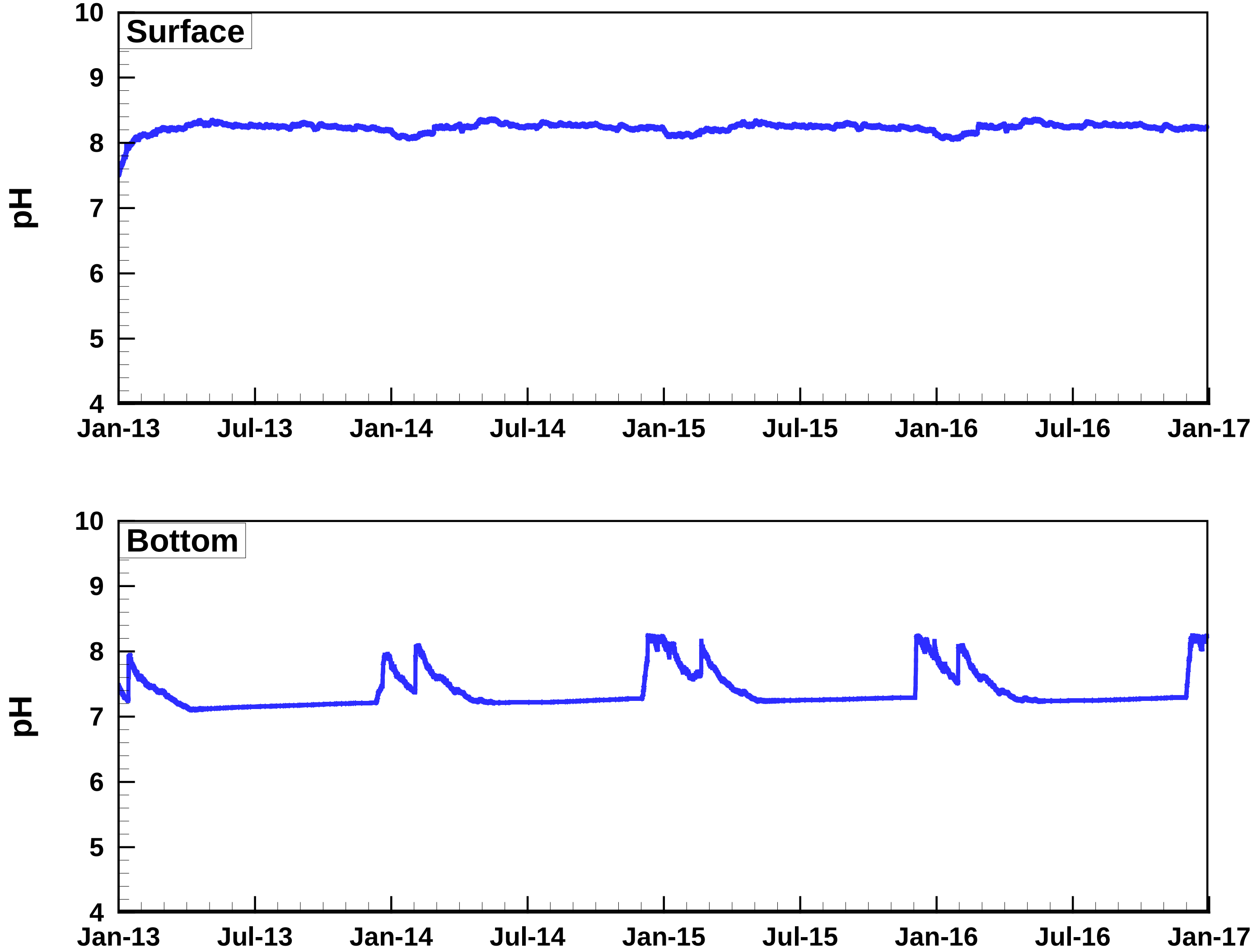
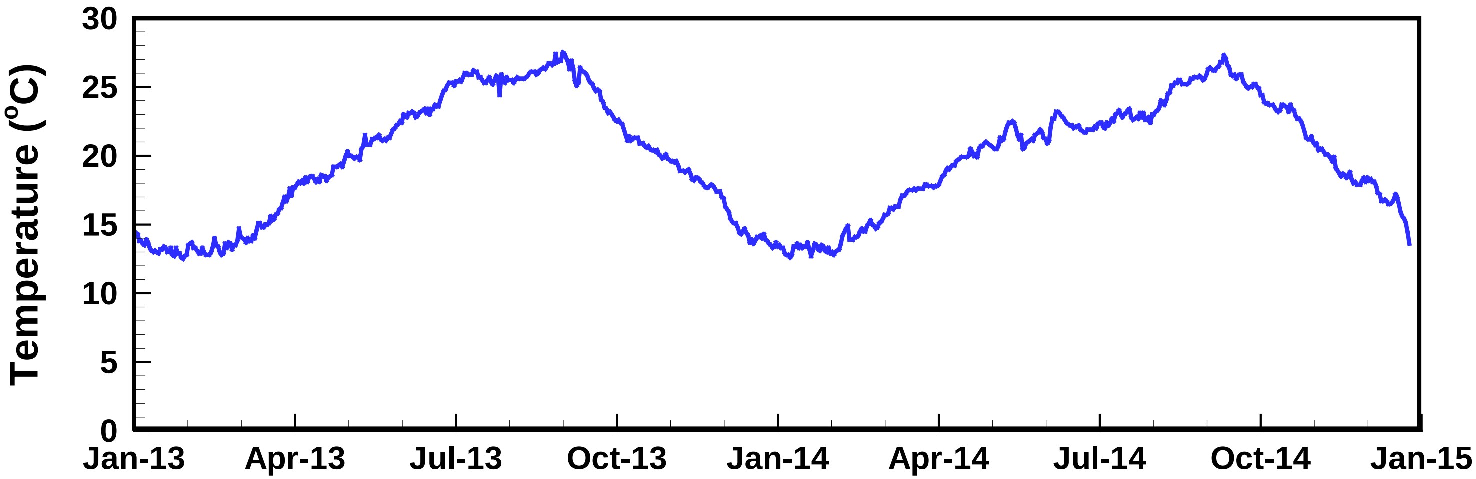


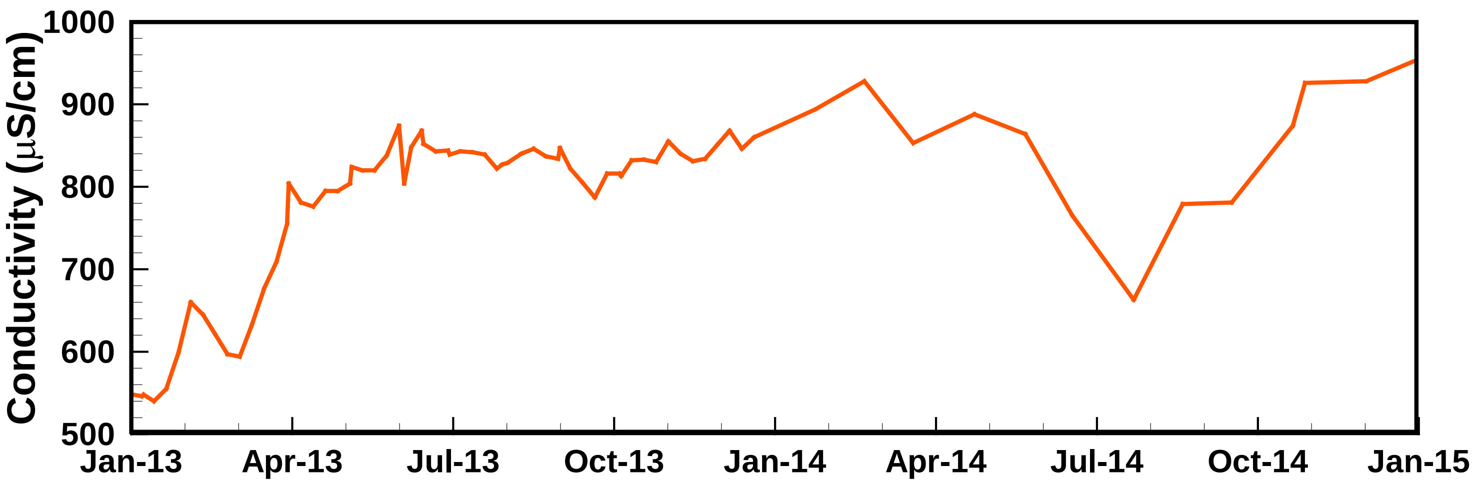
Figure 52

12.0 ATTACHMENTS

Attachment A. Additional Figures of ELCOM/CAEDYM Calibration

Modeled Inflow Temperature and Conductivity in Calibration

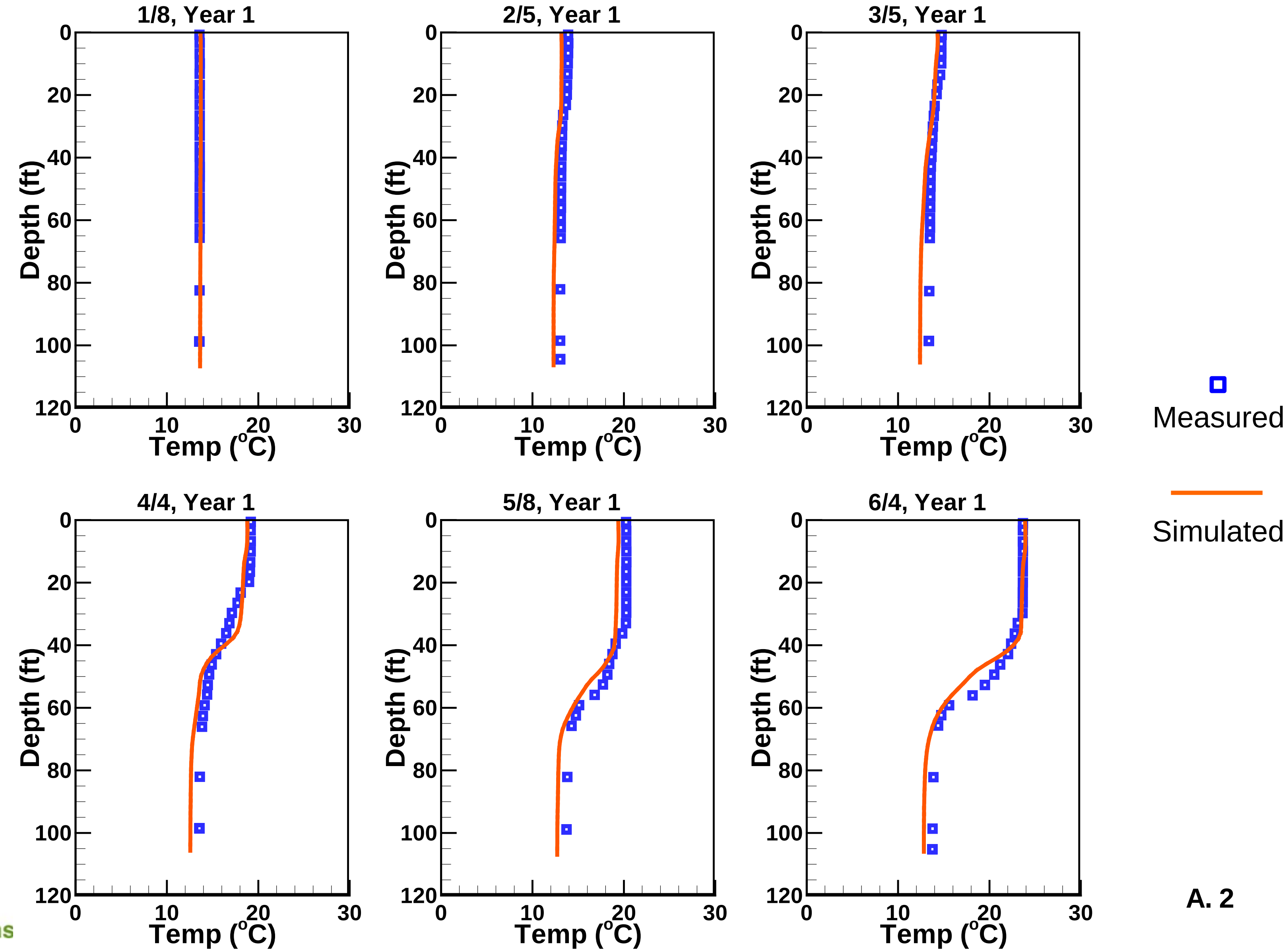




*Note that the WTP return, filter backwash, and sludge return are assumed to have the same temperature and conductivity.

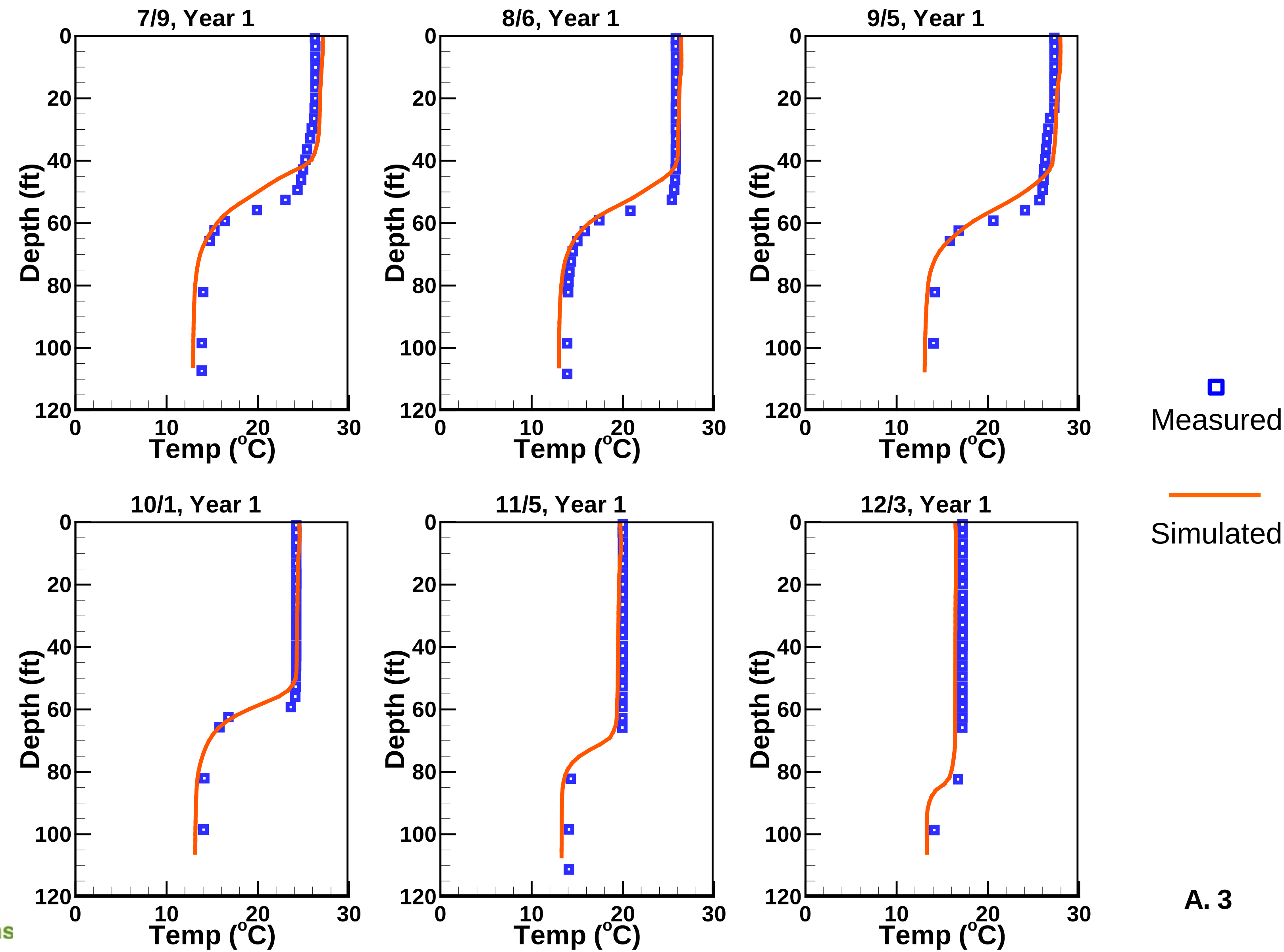
Water Quality Solutions

ELCOM Calibration: Water Temperature Profiles (1)



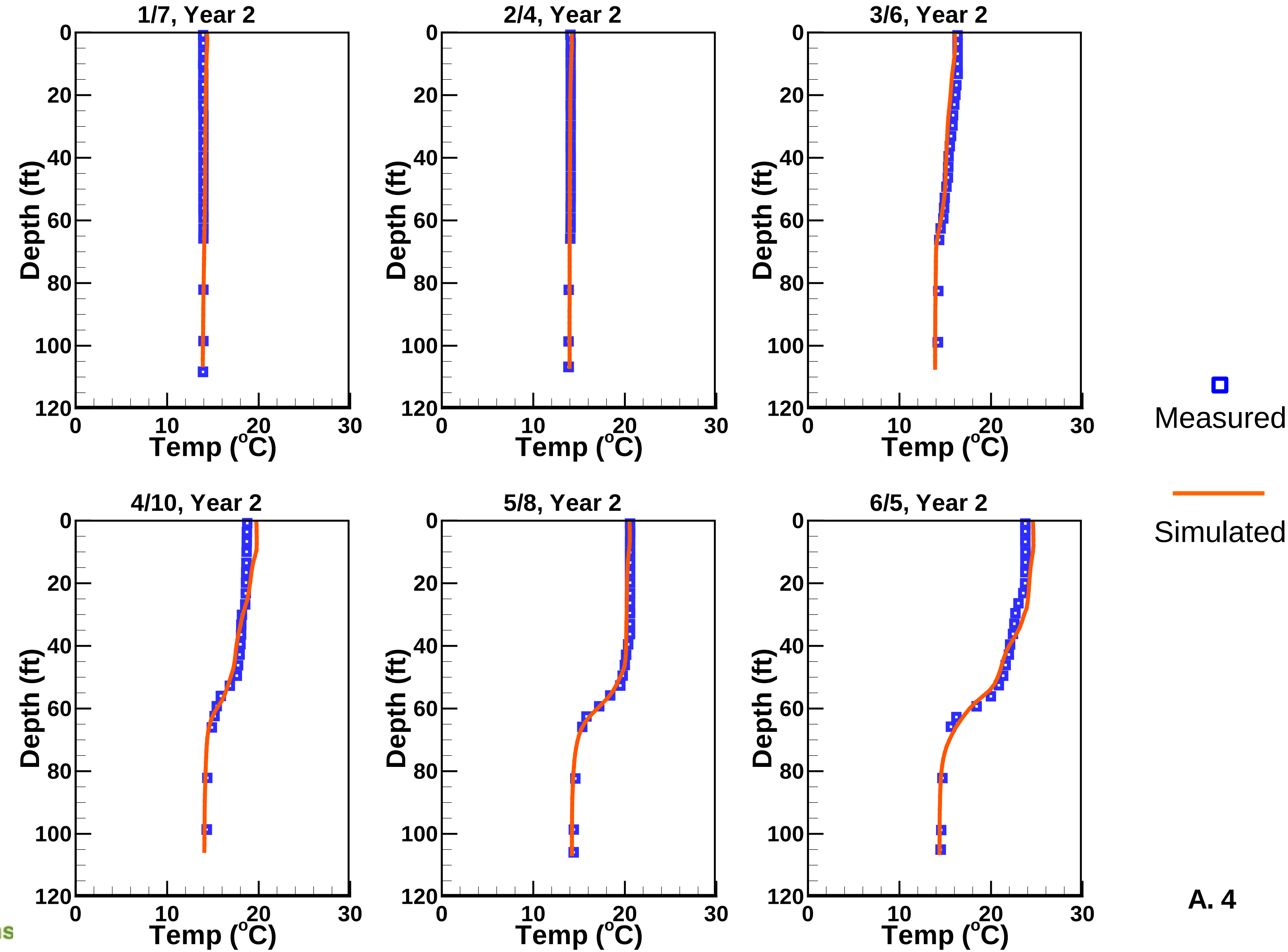
A. 2

ELCOM Calibration: Water Temperature Profiles (2)

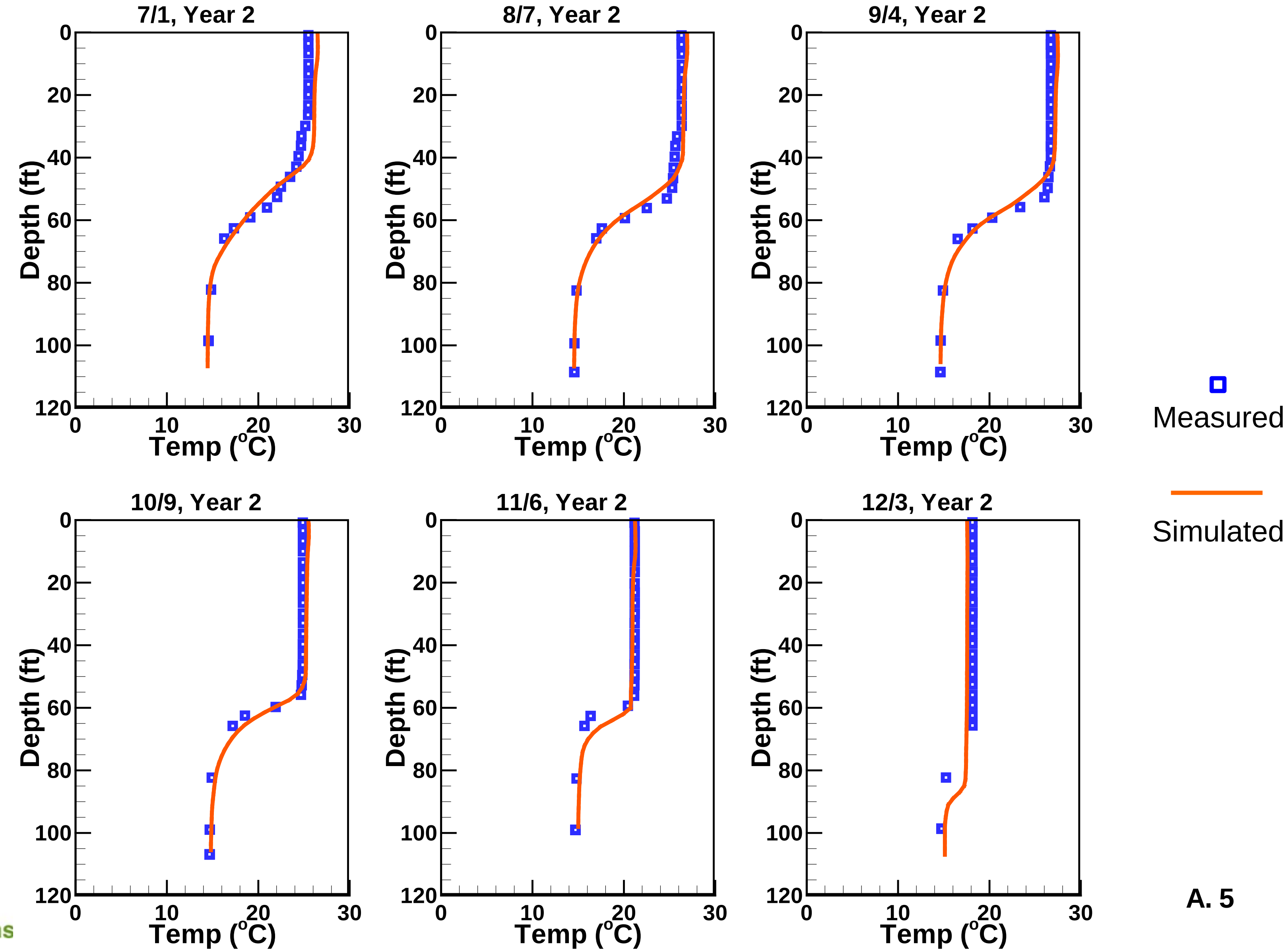


A. 3

ELCOM Calibration: Water Temperature Profiles (3)

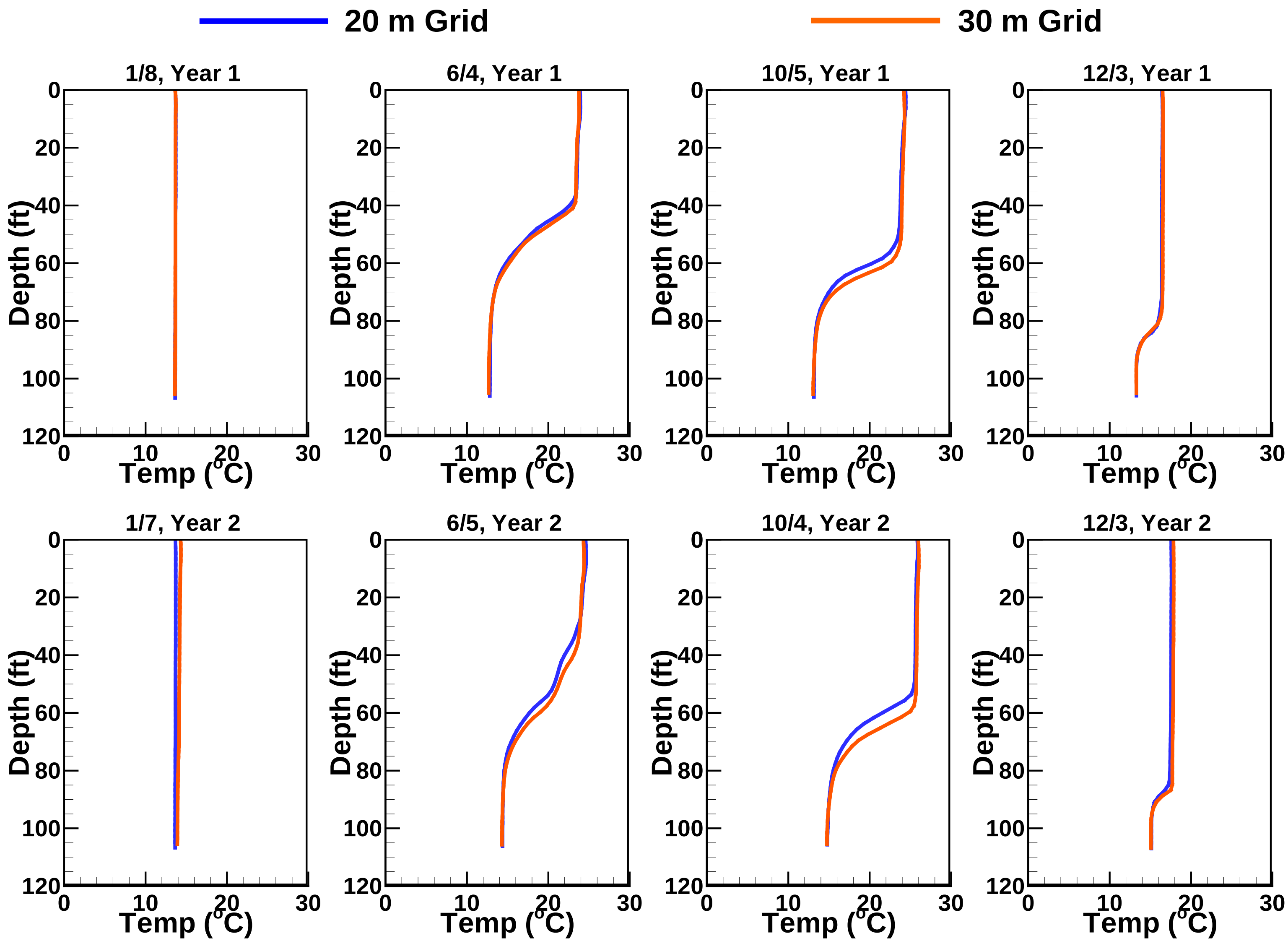


ELCOM Calibration: Water Temperature Profiles (4)

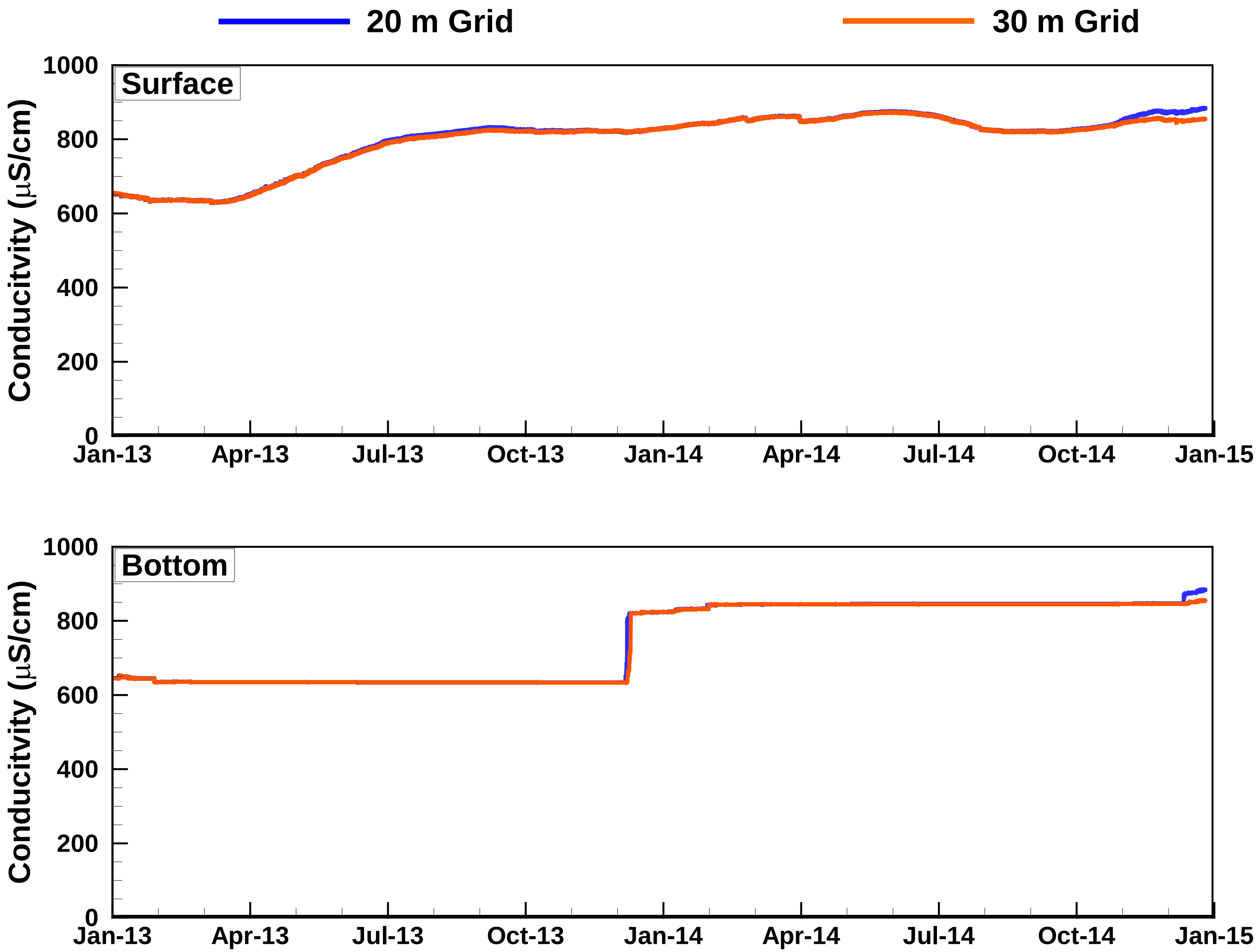


A. 5

ELCOM/CAEDYM Calibration: Water Temperature

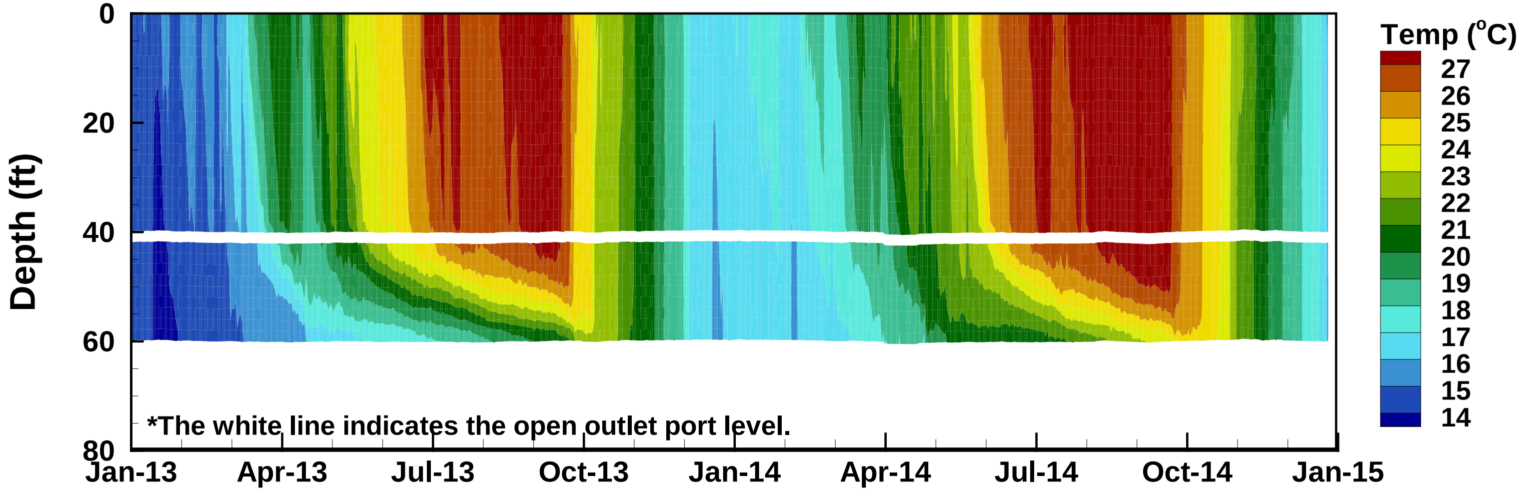


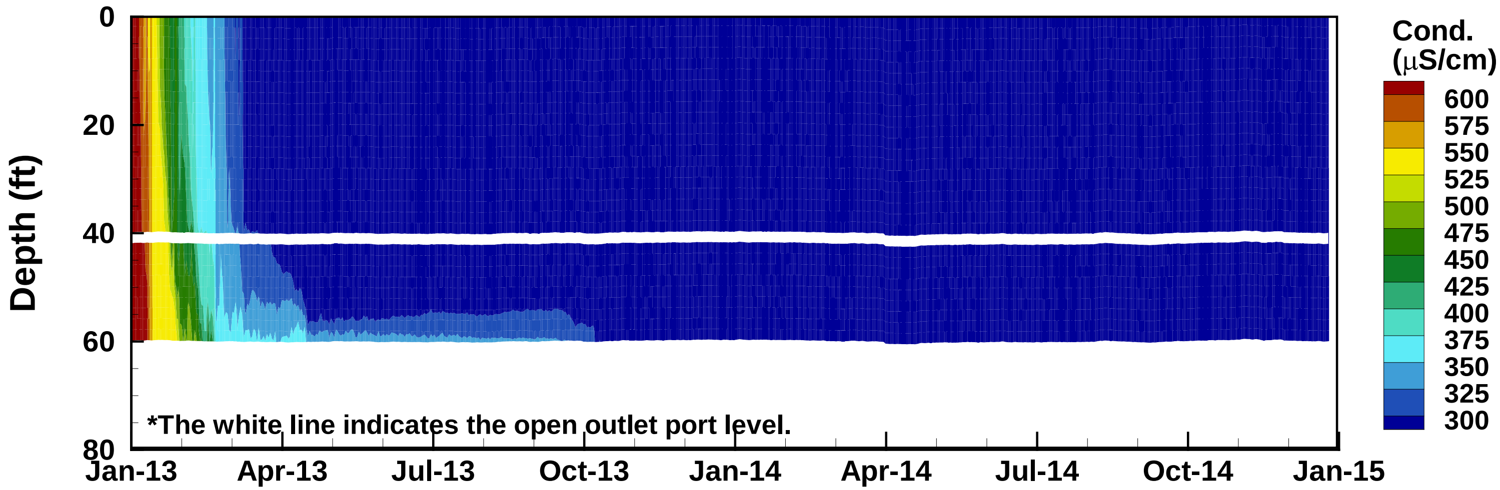
ELCOM/CAEDYM Calibration: Water Conductivity



Attachment B. Additional Result Figures of Hydrodynamic Modeling

Water Temperature and Conductivity at Outlet
Run #1
Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

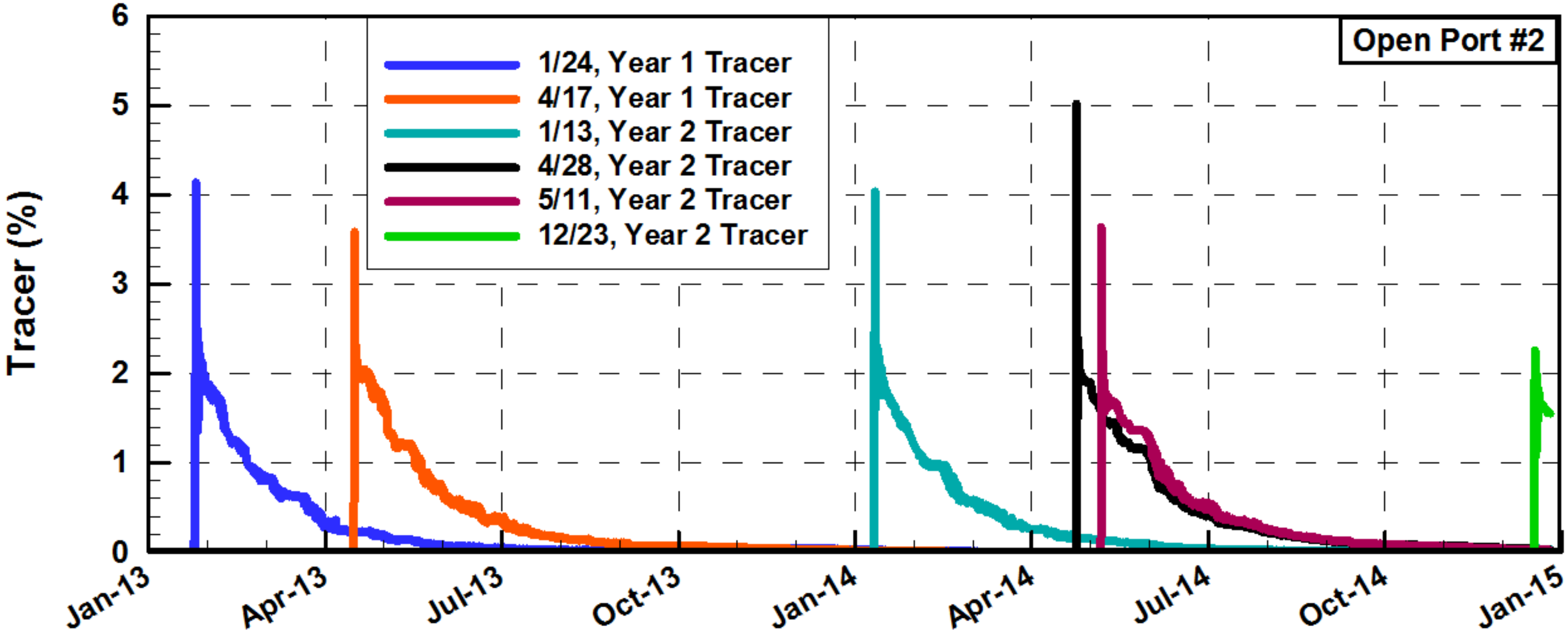




Water Quality Solutions

24-hour Conservative Tracer Concentrations in Outflow Run #1

Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

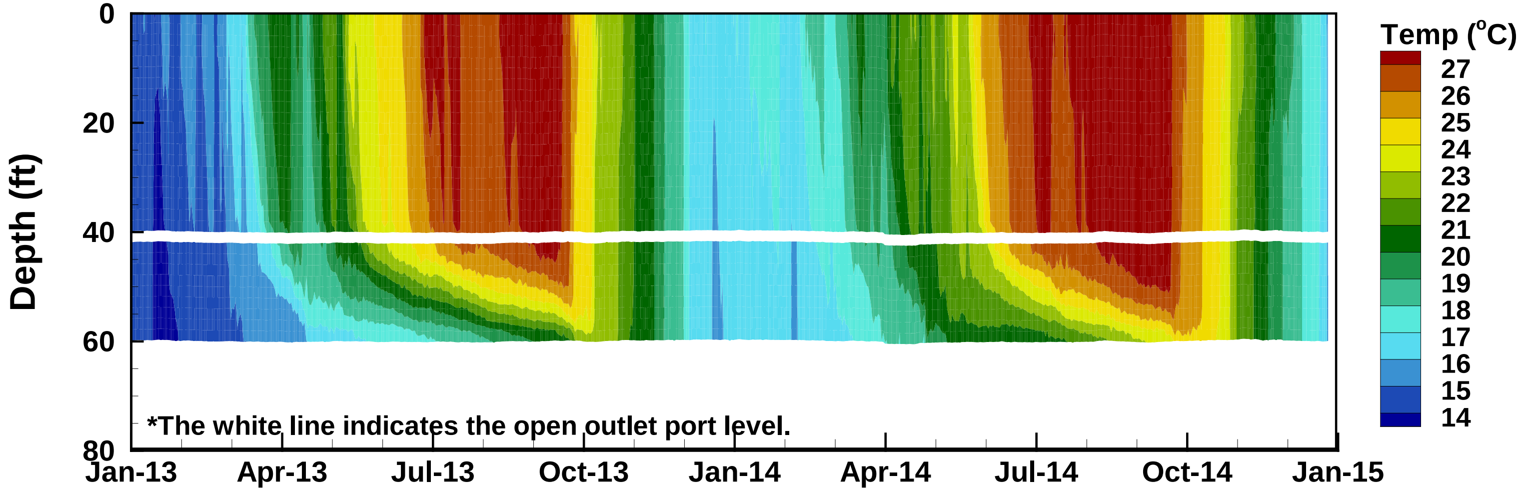


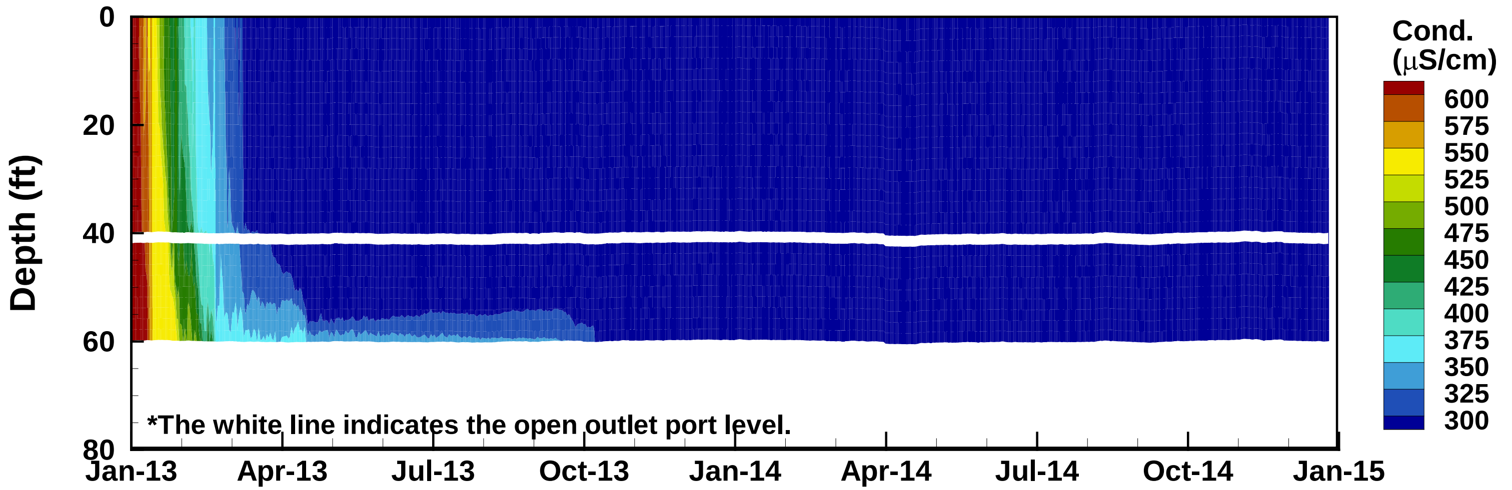
*Initial Inflow Concentration = 100%

Water Quality Solutions

Water Temperature and Conductivity at Outlet
Run #2

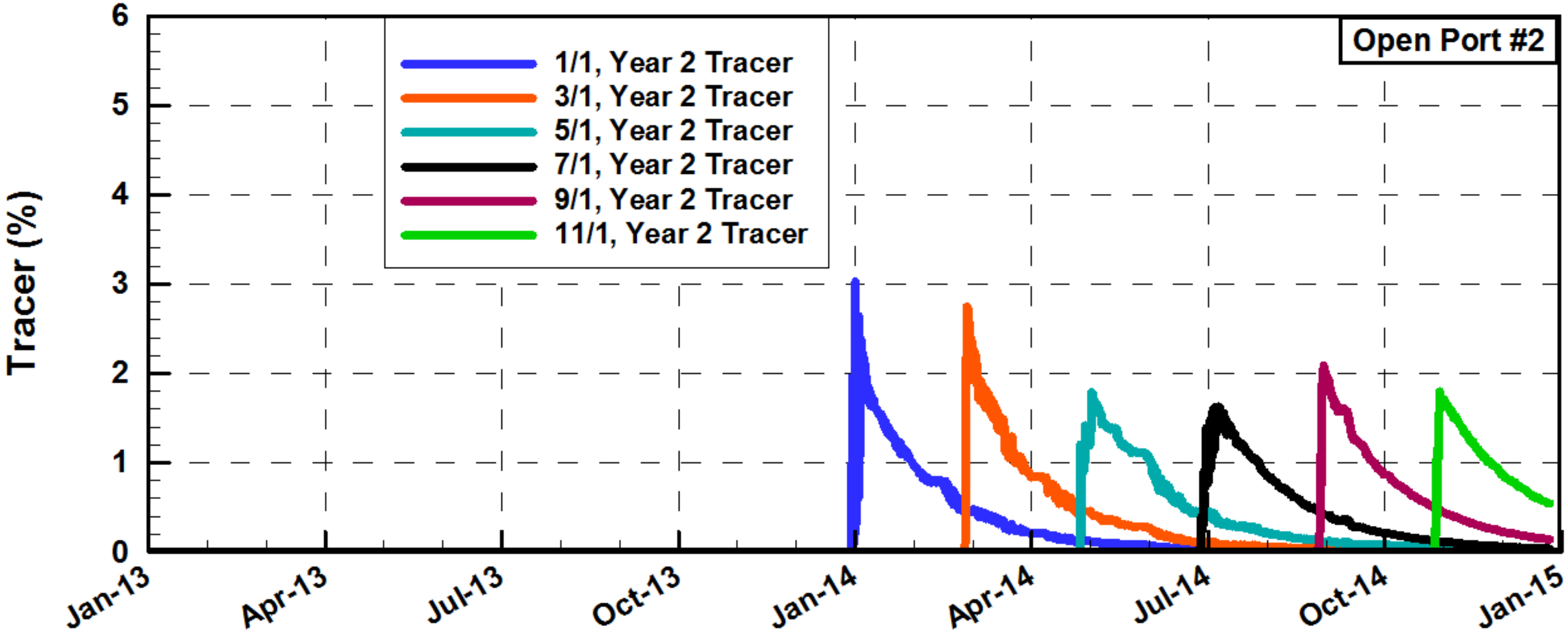
Base Case; Inlet Location 1; PW Inflow=30 MGD; Open Port #2





24-hour Conservative Tracer Concentrations in Outflow Run #2

Base Case; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

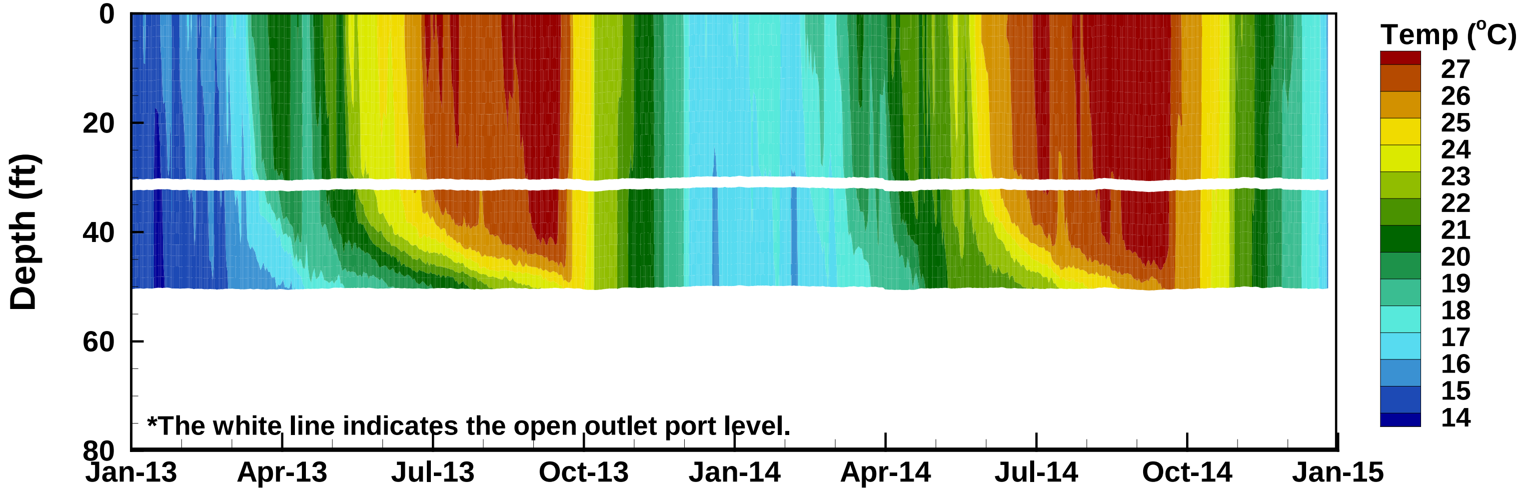


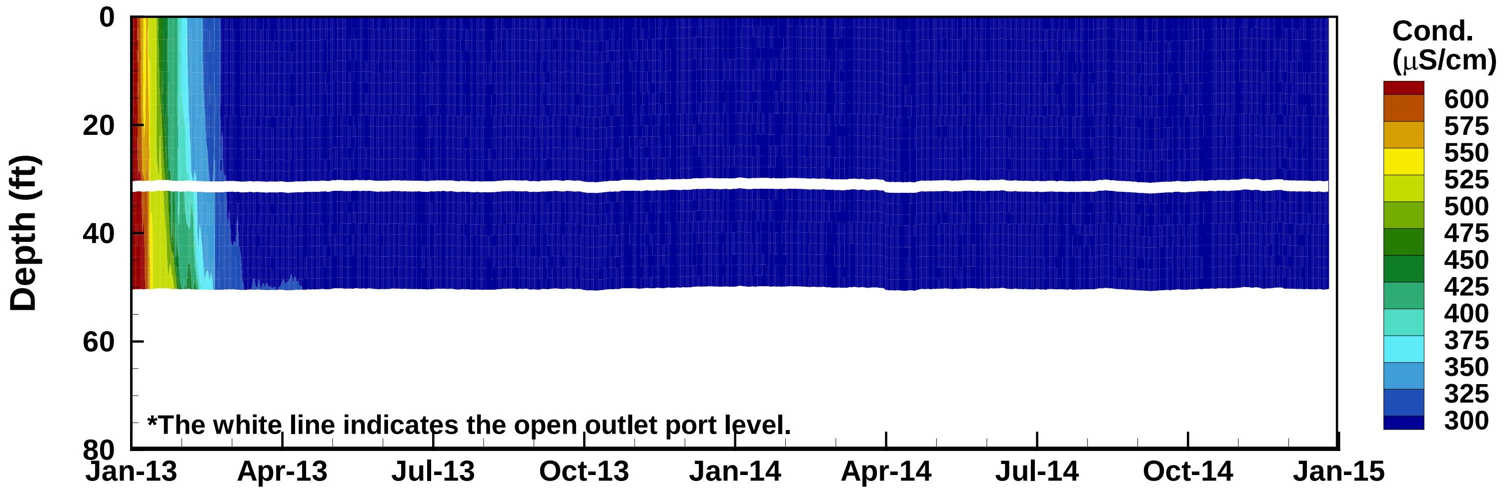
*Initial Inflow Concentration = 100%

Water Quality Solutions

Water Temperature and Conductivity at Outlet
Run #3

Lower Lake Level; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

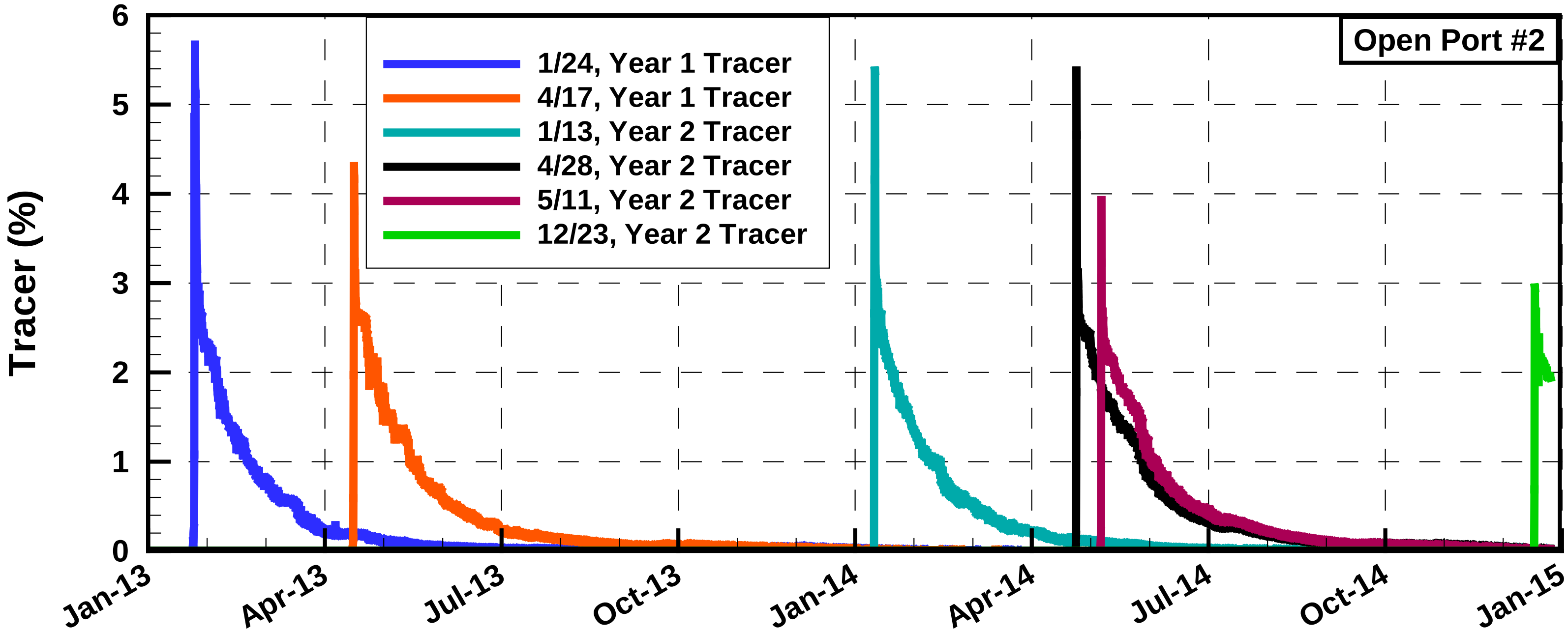




Water Quality Solutions

24-hour Conservative Tracer Concentrations in Outflow Run #3

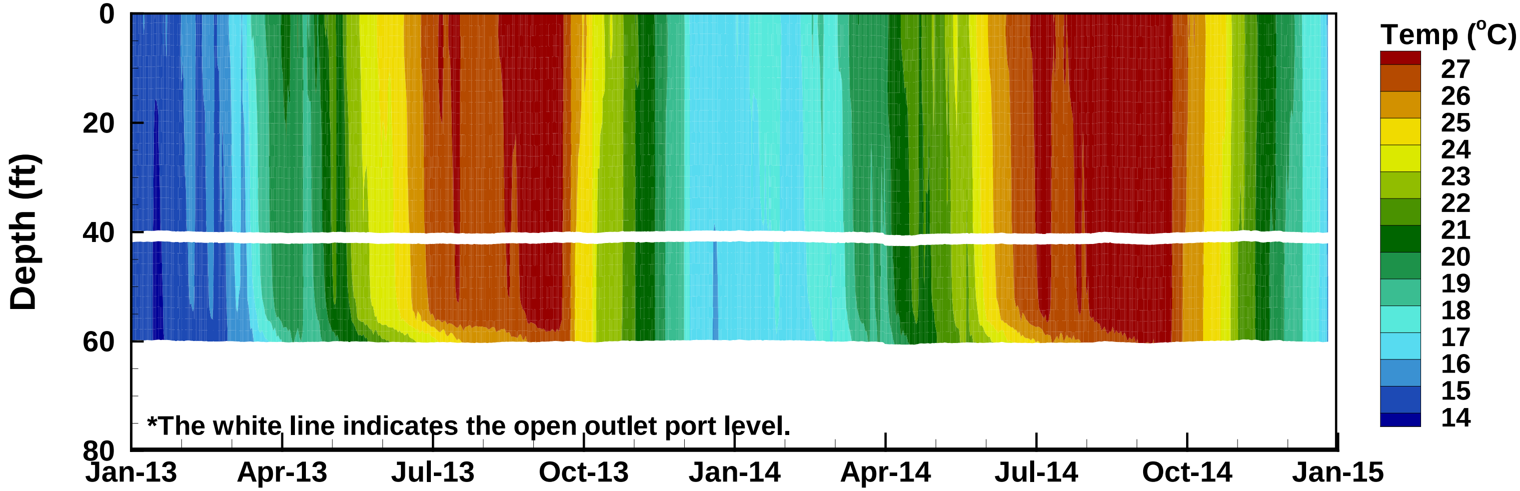
Lower Lake Level; Inlet Location 1; PW Inflow=30 MGD; Open Port #2

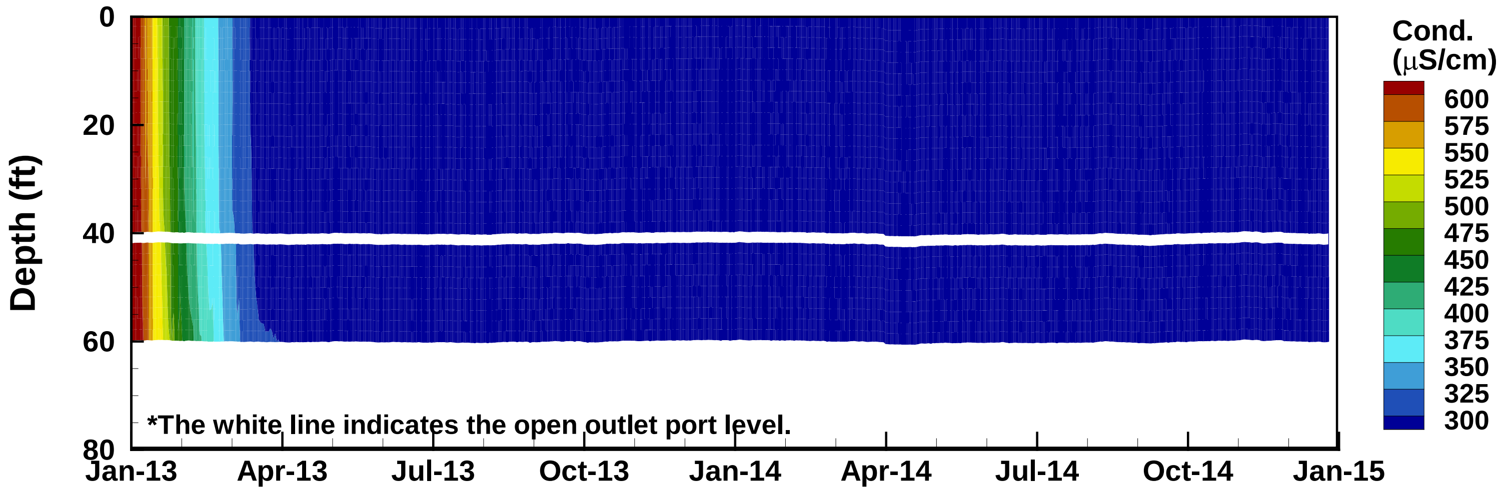


***Initial Inflow Concentration = 100%**

Water Quality Solutions

Water Temperature and Conductivity at Outlet
Run #4
Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2; Bubblers

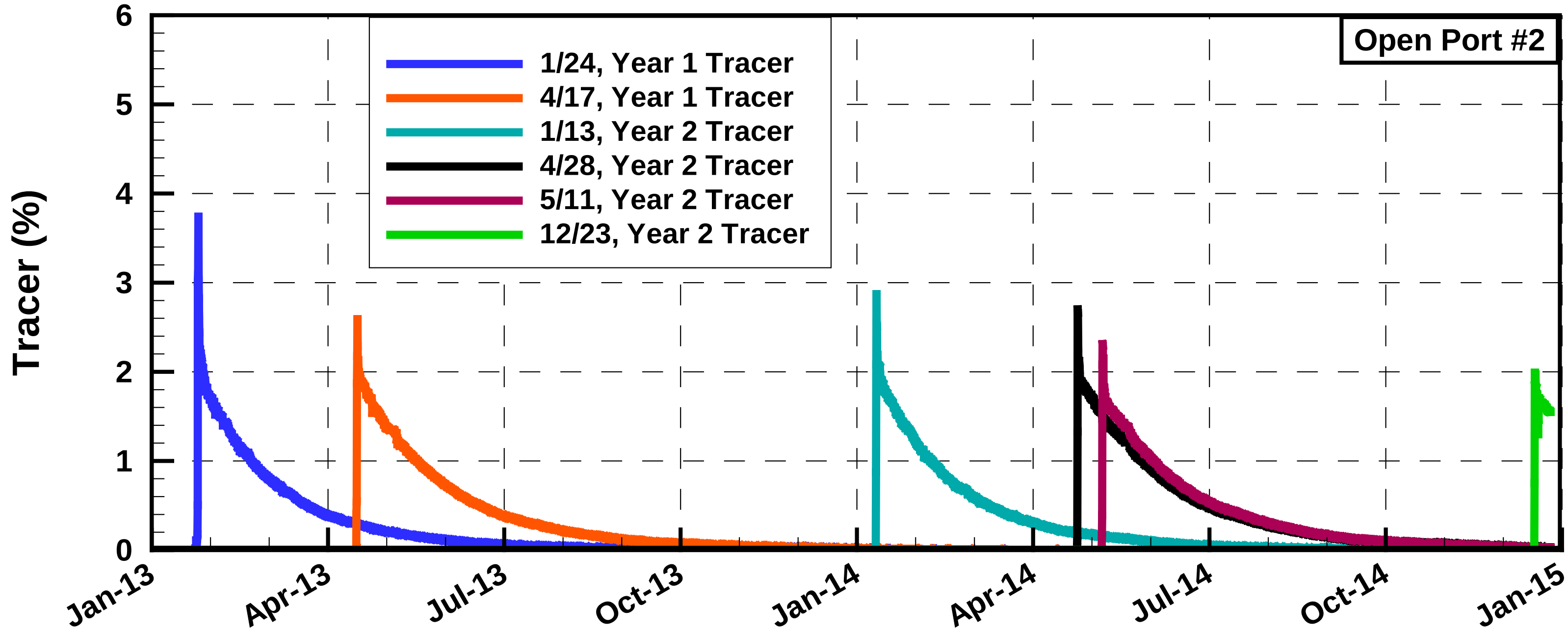




Water Quality Solutions

24-hour Conservative Tracer Concentrations in Outflow Run #4

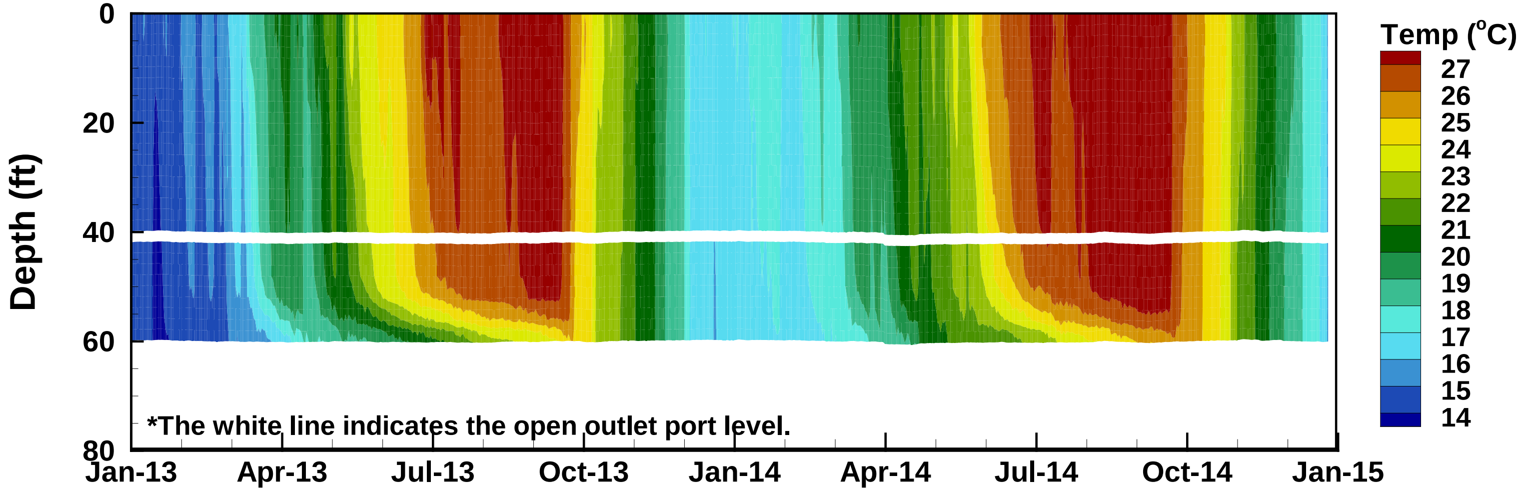
Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2; Bubblers

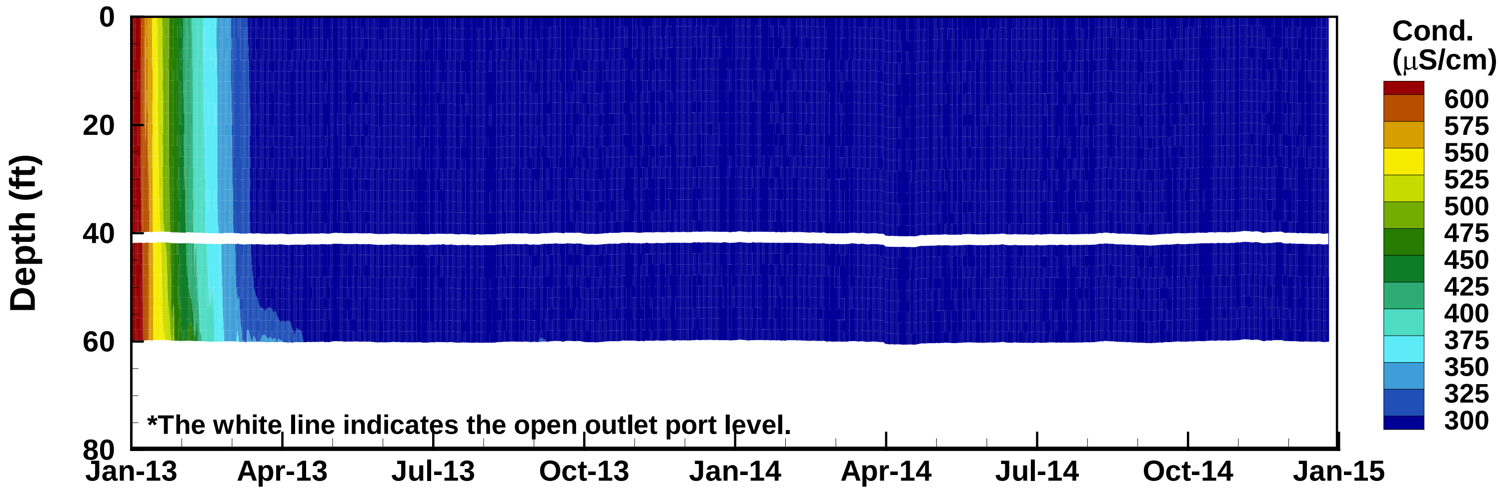


*Initial Inflow Concentration = 100%

Water Temperature and Conductivity at Outlet
Run #5

Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2; Diffusers

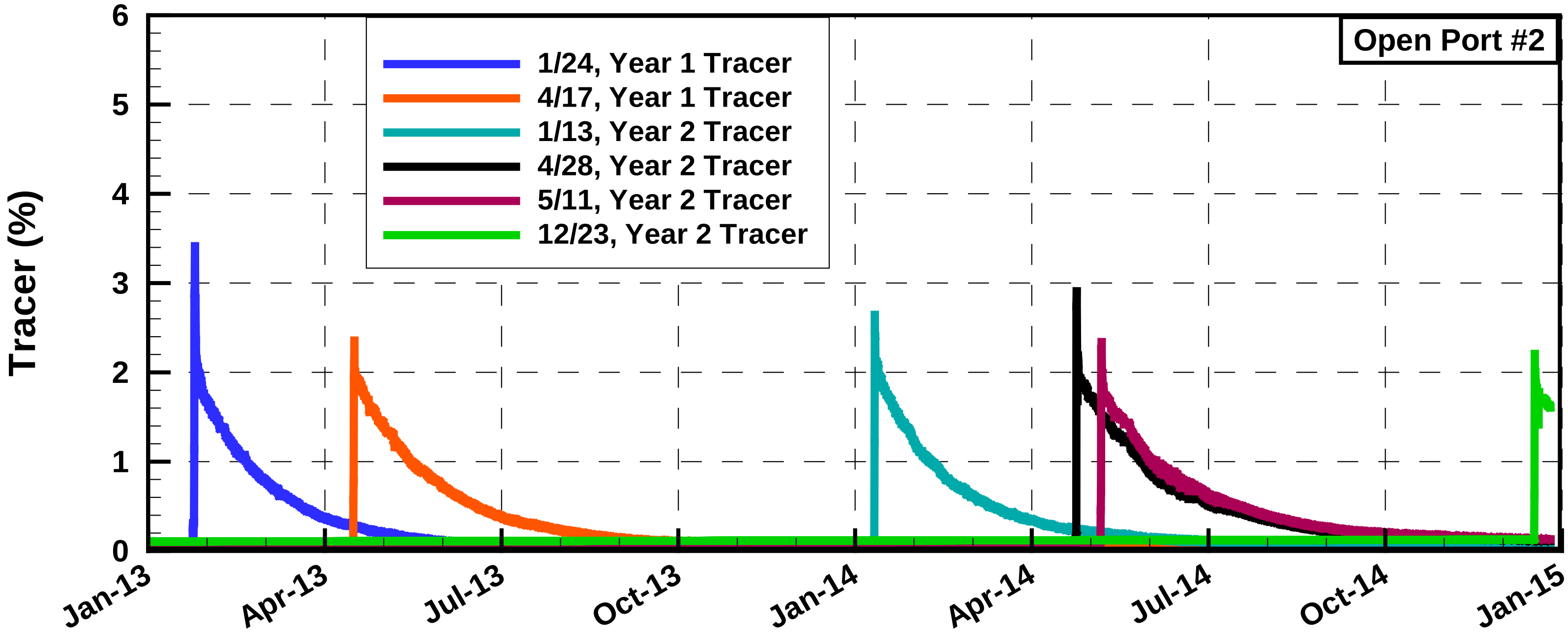




Water Quality Solutions

24-hour Conservative Tracer Concentrations in Outflow
Run #5

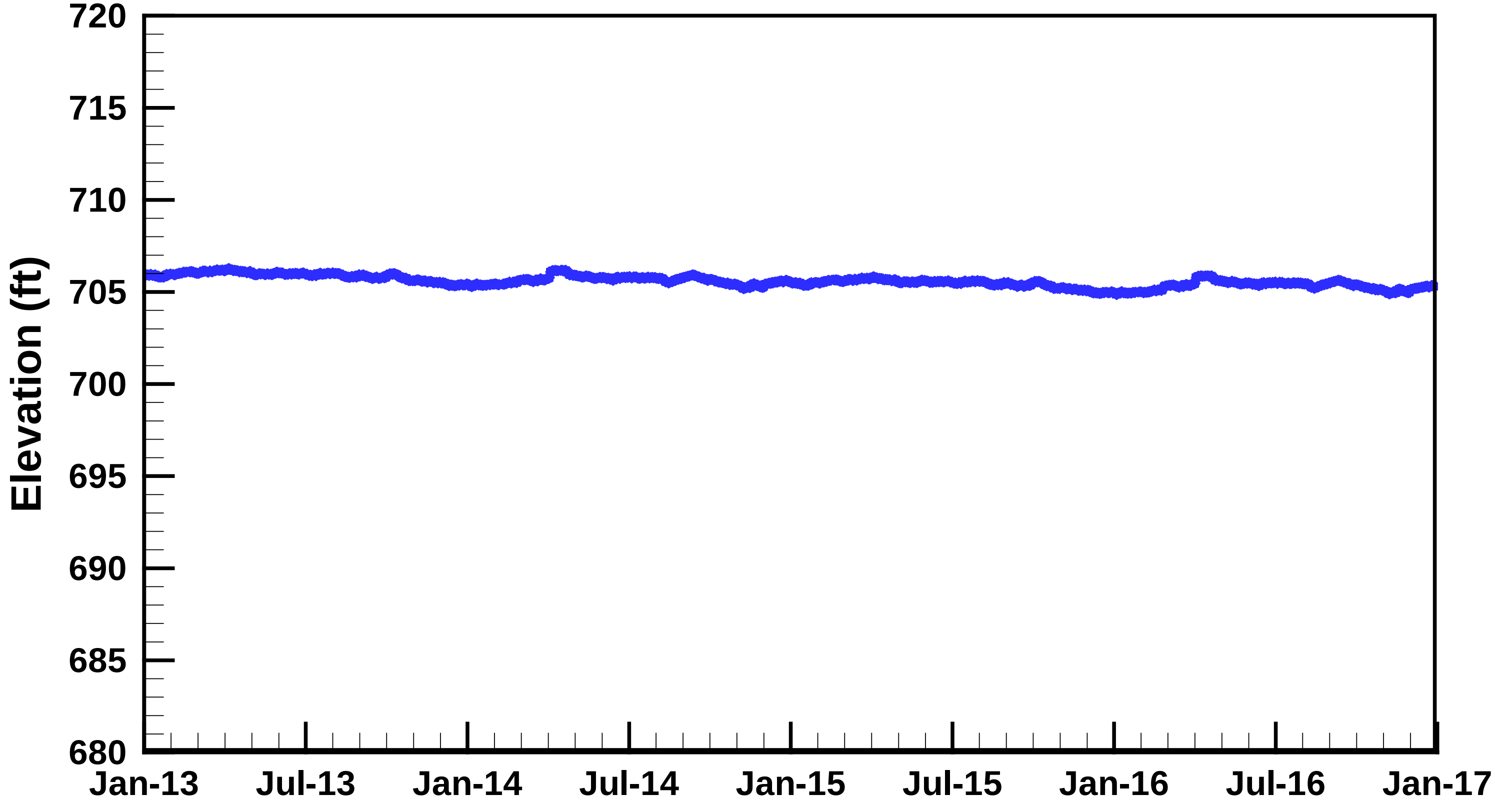
Nominal; Inlet Location 1; PW Inflow=30 MGD; Open Port #2; Diffusers



*Initial Inflow Concentration = 100%

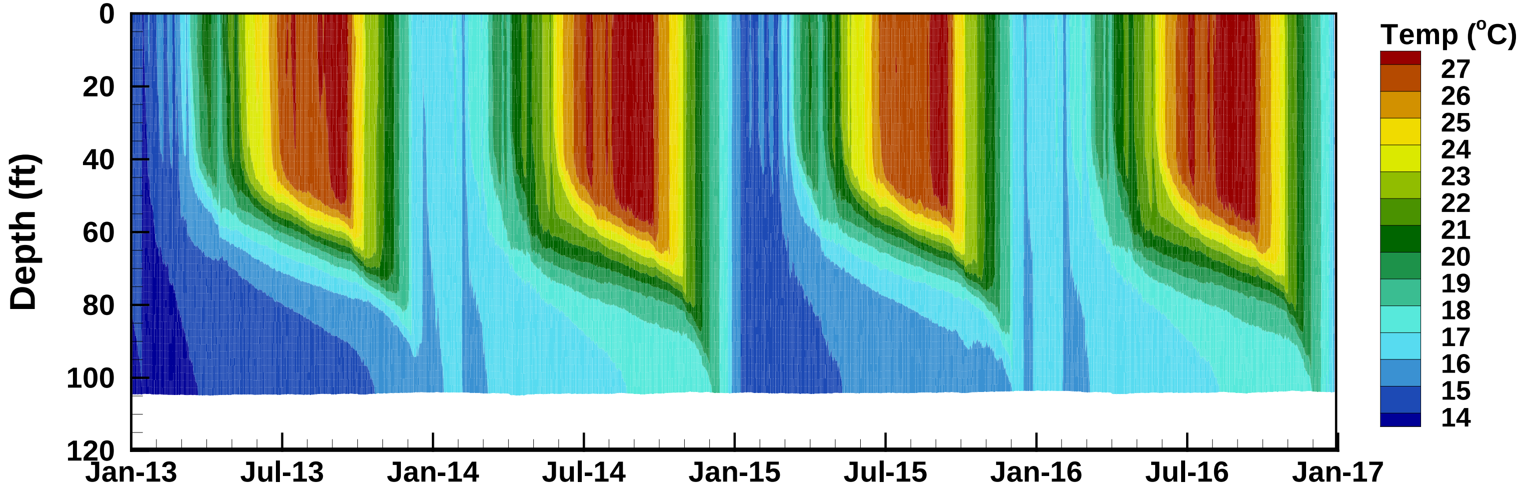
Water Quality Solutions

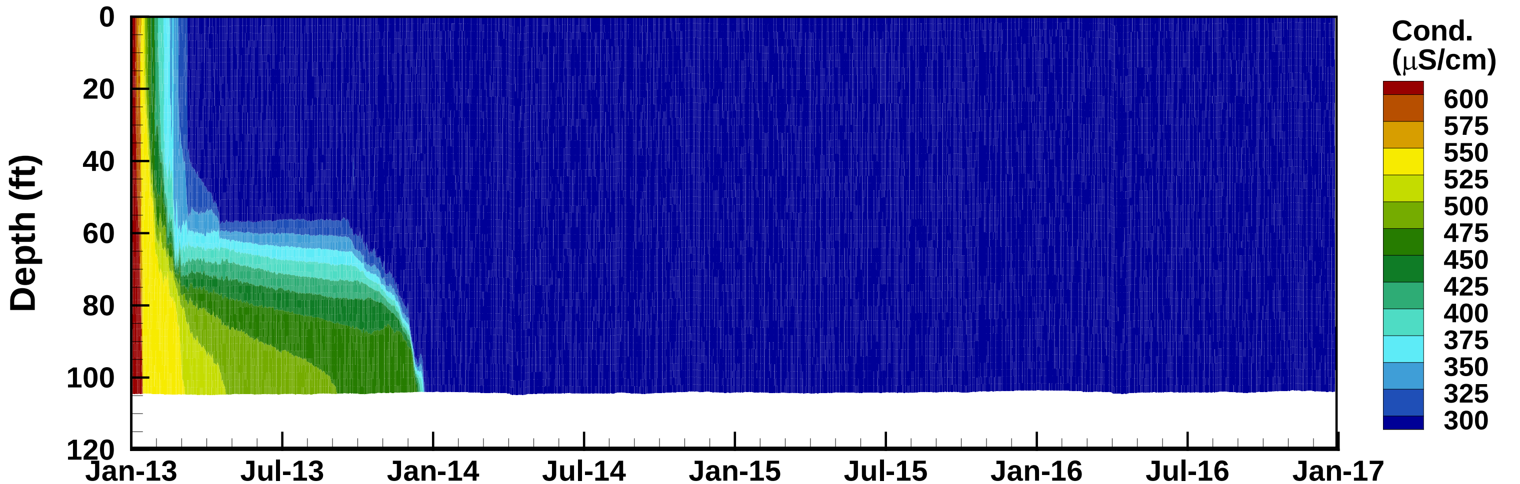
CAEDYM Run: Water Surface Elevation



Water Quality Solutions

CAEDYM Run: Water Temperature and Conductivity





Water Quality Solutions

Attachment C. Animations

Animation #	Model Run #	Operating Scenario	Initial/Final Reservoir Water Volume (ac-ft)	Tracer Injection Date
1	1	Nominal	5,500/5,500	1/24, Year 1
2	1	Nominal	5,500/5,500	4/28, Year 2
3	2	Base Case	5,500/5,500	1/1, Year 2
4	3	Low Lake Level	4,275/4,275	1/24, Year 1
5	3	Low Lake Level	4,275/4,275	1/13, Year 2
6	3	Low Lake Level	4,275/4,275	4/28, Year 2
7	4	Bubblers	5,500/5,500	1/24, Year 1
8	4	Bubblers	5,500/5,500	4/28, Year 2
9	5	Diffusers	5,500/5,500	1/24, Year 1
10	5	Diffusers	5,500/5,500	4/28, Year 2

Technical Memorandum on Identifying Potential Additional Sources of Nutrients to the Miramar Reservoir

Prepared for:

The City of
SAN DIEGO
Contact: Keli Balo

Prepared by:

DUDEK
605 Third Street
Encinitas, California 92024
Contact: Jonathan Martin

JUNE 2017

Printed on 30% post-consumer recycled material.

Technical Memorandum on Identifying Potential External Sources of Nutrients to the Miramar Reservoir

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1 INTRODUCTION AND PURPOSE

The City of San Diego's (City) Pure Water Program (Program) proposes to produce 83 million gallons per day (MGD) of locally controlled treated wastewater (potable), and will be implemented in phases over a 20-year period. The first phase is the North City Project that will produce 30 MGD of purified water. The 30 MGD of purified water will be piped to the existing Miramar Reservoir, which will replace its current source of water derived from the State Water Project and the Colorado River Aqueduct. Prior to Program implementation, the City is evaluating the potential impacts to the reservoir's ambient water quality resulting from the discharge of purified water from the Program instead of State Water Project and Colorado River Aqueduct water.

The City contracted Water Quality Solutions, Inc. (WQS) of McGaheysville, Virginia, to develop a numerical model to simulate the potential effects on water quality in the reservoir after the implementation of the Program. An initial simulation was completed in 2016. One of the findings from the initial simulation was that production of chlorophyll-a (algae) in the reservoir would decrease due to decreased concentrations of total phosphorus (TP). While reducing algal production within a drinking water reservoir is a benefit to its primary use, it could have negative effects on the aquatic ecosystem and its provision of the reservoir's secondary beneficial uses (e.g. warm freshwater habitat and wildlife habitat). The initial simulation did not include external sources (e.g. avian excrement, aerial deposition, organic matter decay) of nutrients (total nitrogen [TN] and TP) to the reservoir, nor internal recycling of nutrients in the oxic regions. Since such additional sources are potentially important factors in the reservoir's nutrient cycle, the City has requested that an additional simulation be conducted that included additional nutrient contributions.

Dudek was contracted by the City to develop a list of potential additional sources of TN and TP to the reservoir for incorporation into an updated water quality simulation. This investigation was conducted to identify primary nutrient contributions to the reservoir outside of the municipal water inflows and recycling of nutrients in the anoxic regions of the reservoir, which were included in the initial water quality simulation. Through discussions with City and WQS staff, five additional sources were identified as having the greatest potential effect on future water quality conditions within the reservoir. Dudek reached out to wetland specialists and conducted literature reviews to develop potential moderate and high daily loading rates for each of the five sources. The resources and methods used for developing these potential loading rates are presented in this technical memorandum.

2 MIRAMAR RESERVOIR EXISTING CONDITIONS

2.1 Hydrology/Water Quality

The Miramar Reservoir holds 6,680 acre-feet of water at full capacity, has a surface area of 183 acres, and has a maximum depth of 114 feet. However, the normal operating condition corresponds to a water surface elevation of 706 feet above mean sea level (an approximate depth of 105 feet) and water volume of approximately 5,500 acre-feet (WQS 2016). In the case of emergency withdrawals by the City, the reservoir could be drawn down to 697 feet above mean sea level (i.e., by about 10 feet), leaving a volume of approximately 4,275 acre feet (WQS 2016). The natural watershed draining into Miramar Reservoir is limited to the adjacent area (approximately 1 square mile) that surrounds it, and the reservoir is largely a constructed feature that does not intersect a major drainage. The reservoir itself occupies 21% of this watershed area, and all of the surface runoff from the urban portions of the watershed (primarily consisting of single-family residential subdivisions) is collected in storm drain facilities serving those areas and diverted to adjoining watersheds (i.e., diverted away from the reservoir). As a result, the existing watershed draining to the reservoir is limited to the upland open space area that immediately surrounds it. Due to the small size of the reservoir and its contributing area, reservoir water quality is characterized primarily by its source water.

Miramar Reservoir is a municipal water reservoir accepting a blend of water from the local watershed and deliveries from both the Colorado River and State Water Project. The reservoir's primary water quality monitoring station (Station A) is located within the deepest part of the reservoir roughly 300 feet northwest of the outlet tower. The reservoir is normally kept at approximately 80% full, but has 4 outlet ports at depths of 52 feet (Port #1), 66 feet (Port #2), 81 feet (Port #3), and 96 feet (Port #2) below the normal operating surface, in addition to an emergency outlet. General physical and biochemical parameters within the reservoir, including temperature, conductivity, total dissolved solids, pH, dissolved oxygen, chlorophyll and blue-green algae, are monitored weekly at Station A at 24 vertical intervals throughout the water column. General mineral parameters, including nitrogen and phosphorus, are monitored monthly at the reservoir's water surface, bottom, at depths corresponding to the reservoir's outlet ports, and at the middle of the hypolimnion.

Based on this monitoring data, dissolved oxygen within the reservoir ranges seasonally from approximately 7 to 10 milligrams per liter (mg/L) at the surface to 0 to 10mg/L at the bottom. Total nitrogen and total phosphorus, two key biological nutrients in aquatic systems, had recorded medians from surface samples collected monthly between 2005 and 2014 of 0.24 mg/L and <0.078 mg/L, respectively (> 90% of the TP samples had concentrations below the method detection limit of 0.078 mg/L). Chlorophyll-*a* measurements from the surface (City of San Diego, 2012-2015 data), which are a proxy measurement of primary productivity-(i.e., presence of algae), range from 4.9 micrograms per liter (µg/L) to < 0.1 µg/L. Water column clarity is generally good, with visibility ranging from 3.9 to 14.3 meters (12.8 to 46.9 feet) with a mean value of 9.5 meters (31 feet) (City of San Diego, 2012-2014 data).

Miramar Reservoir is listed as impaired for nitrogen under CWA Section 303(d), based on data collected by the City of San Diego from January 2005 to December 2006 showing that 26 of the 28 samples collected exceeded the Basin Plan objective (SWRCB 2016) of achieving a 10:1 ratio of TN to TP. With a desired TP concentration of 0.025 mg/L (as defined in the Basin Plan in order to prevent plant nuisance), any TN concentrations over 0.25 mg/L were considered in exceedance.

2.2 Geology

The soil beneath the reservoir is characterized as colluvium consisting of silty to gravelly loams (NRCS, 2017). This layer is approximately 2 feet thick and is underlain by Pleistocene/Eocene siltstones, sandstones, and conglomerates. The Eocene Scripps Formation consists of silty sandstone and sandy siltstone with occasional cobble conglomerate beds with strong cementation. The Pleistocene Lindavista Formation occurs within the central and southwestern sections of the reservoir and consists of interfingered strandline, beach, estuarine and colluvial deposits (siltston, sandstone, conglomerate), and can have strong cementation (Kennedy and Tan, 2008).

One geotechnical study for the Program installed monitoring wells approximately 50 feet from the reservoir into the Stadium Conglomerate to depths greater than 120 feet below ground surface (TerraCosta, 2017). The monitoring wells were completed in December 2016. Water levels were measured at 640 feet above mean sea level (ft amsl) in early February 2017. Assuming the reservoir was operating at typical operational levels (~706 ft amsl) when the groundwater levels were measured in February 2017, then there was an apparent hydraulic gradient from the reservoir to the monitoring wells. Based on a higher hydraulic head in the reservoir compared to the adjacent aquifer, it appears that there is little potential for groundwater to flow to the reservoir.

3 ADDITIONAL INPUTS TO RESERVOIR

Dudek identified five potential additional sources that may contribute nutrients to Miramar Reservoir in addition to the Pure Water Program. These additional nutrient sources include atmospheric deposition, decomposition of aquatic vegetation, faunal contributions, sludge returns from the Miramar Water Treatment Plant (MWTP), and internal nutrient cycling. Other potential nutrient sources were identified but were not evaluated since they were minor contributors.

3.1.1 Atmospheric Deposition

A potential input of nutrients to Miramar Reservoir is atmospheric deposition of particulate matter and rainfall. The California Energy Commission implemented a study to investigate the potential risks to California ecosystems from nitrogen deposition (Weiss, S. B., 2006). The study characterized nitrogen loading on a regional scale (36 km x 36 km) and examined potential impacts to aquatic and terrestrial ecosystems in California. Nitrogen deposition was quantified at this regional scale using the Community Multiscale Air Quality Model (CMAQ), which is an active open-source development project of the U.S. EPA Atmospheric Science Modeling Division. Atmospheric deposition of nitrogen is defined in units of kilograms of nitrogen per hectare per year (kg-N ha^{-1} yr^{-1}). Weiss (2006) noted that "in the San Diego Air Basin (SDAB), maximum values are 8–9 kg-N ha^{-1} yr^{-1}, just east of San Diego. The coastal areas receive 1–2 kg-N ha^{-1} yr^{-1}. Deserts in eastern San Diego County receive 6 kg-N ha^{-1} yr^{-1}." Therefore, the atmospheric deposition of nitrogen to Miramar Reservoir was estimated to range from 8 kg-N ha^{-1} yr^{-1} (low end estimate) to 9 kg-N ha^{-1} yr^{-1} (high end estimate), which resulted in approximately 528 kg-N to 594 kg-N entering Miramar Reservoir on a yearly basis, respectively. Dry season deposition is approximately 85% of the annual contribution (Padgett, P. et al., 2007). Therefore, the dry season input was estimated at 1.23 to 1.38 kg-N per day; whereas, the wet season input was estimated at 0.22 to 0.24 k-N per day (Table 1).

Jassby (1994) conducted a study evaluating the effect of nutrient atmospheric deposition on Lake Tahoe, which hypothesized that the lake receives significant concentrations of macronutrients from atmospheric deposition. Jassby (1994) noted that "indirect evidence suggests that atmospheric deposition has played a role in the ongoing eutrophication of the lake." Studies of Lake Tahoe over the last 25 years have resulted in a comprehensive database that could define a nitrogen to phosphorus ratio (N:P). Water samples were collected from a typical rain gauge collector. Rainfall samples were collected during the wet seasons. Deionized water introduced in the rain gauge collector during the dry seasons was collected in a procedure that mimicked wet season sample collection. The estimated average wet season contribution of total phosphorus from atmospheric deposition was 0.88 ± 0.23 micromhos per meter squared per day (μmhos m^{-2} d^{-1}). Therefore, the moderate estimate of total phosphorus contribution in the wet season was estimated at 0.65 μmhos m^{-2} d^{-1}, which is equivalent to 0.013 kg-P per day. The high-end estimate of total phosphorus contribution in the wet season was estimated at 1.11 μmhos m^{-2} d^{-1}, which is equivalent to 0.023 kg-P per day. The estimated average dry season contribution of total phosphorus from atmospheric deposition was 2 ± 0.0 μmhos m^{-2} d^{-1}, which is equivalent to 0.041 kg-P per day (Table 1).

3.1.2 Aquatic Vegetation

Decaying organic matter from the reservoir's macrophyte (i.e., aquatic plant) community is considered a potential major source of nutrients. Dudek biologists identified approximately 24.15 acres of *Schoenoplectus Californicus* (California bulrush) along the reservoir's shoreline. Due to the young age of the reservoir (57 years), it is assumed that the organic layer in the littoral zone is shallow, and that *S. californicus* is rooted in the silty/gravelly loams where all nutrients within the plant biomass are derived from. This assumption was confirmed through personal communication with staff at the UC Davis Wetland's Lab (2017) and a review of one of their former staff's dissertation regarding *S. californicus* (Carpenter, 2009). In estimating annual nutrient loading from decomposing *S. californicus*, it was assumed that the annual nutrient loading rate from decaying organic matter was equivalent to the biomass production rate. Estimates of the annual biomass production rate and the biomass concentrations of nitrogen and phosphorus were derived from data collected from the studies presented below.

Pratolongo et al. (2008) conducted a study monitoring the biomass production of *S. californicus* in different tidally influenced sections of the Parańa River delta in Argentina. The biomass production rate measured from the community least impacted by tidal flooding was 1.3 kg m^{-2} yr^{-1}. This estimate was assigned to the reservoir's macrophyte community.

An additional study within the same floodplain marsh of the Parańa River (Villar et al., 1996), measured the nitrogen and phosphorus content of *S. californicus* between the river and the floodplain marsh. The high and low concentrations reported in this study were used to represent the moderate and high-end estimates for nutrient production for the *S. californicus* in the reservoir (0.45% - 0.62% nitrogen; 0.14% - 0.18% phosphorus). Using the estimated range of bioavailable nutrients released from soils from a study conducted on lakes in China and Ireland (21% to 67% - Zhou et al., 2001), we assumed that 50% of the annually produced nitrogen and phosphorus to return to the reservoir as bioavailable.

Biomass production was also split seasonally between the dry season (May – October) and the wet season (November - April), with 80% of *S. californicus* production occurring in the dry season, and 20% in the wet season. The moderate estimates of daily TN and TP contributions to the reservoir from decaying organic matter from the reservoir's macrophyte community during the dry/wet seasons are 1.25/0.32 kg d^{-1} and 0.39/0.10 kg d^{-1}, respectively. The high-end estimates of daily TN and TP contributions to the reservoir from decaying organic matter from the reservoir's macrophyte community during the dry/wet seasons are 1.72/0.44 kg d^{-1} and 0.50/0.13 kg d^{-1}, respectively (see Table 1).

3.1.3 Fauna Contributions

Contributions of nutrients to the reservoir from local fauna were considered in estimating external sources for the model. The two populations assessed were the avifauna (birds) and the piscifauna (fish) populations. In order to decouple the internal cycling of nutrients identified in Section 3.1.5 with external contributions from these fauna, two assumptions were made: 1) all nutrients in avian feces come from external sources, and 2) the only external nutrient contributions from piscifauna come from the addition of fish biomass to the reservoir via fish stocking.

3.1.3.1 Avian Contributions

Dudek biologists provided a seasonal distribution of 14 avian species observed at the reservoir, and an average body weight in kilograms (Table 2). A study of avian nutrient contributions to a wetland in California's San Jacinto Valley (Anderson et al., 2003), provided general metrics for avian feces production (as a percent of body mass) and percent content phosphorus which were applied to this exercise. It was assumed that each bird produces 3% of its body mass in feces daily, and approximately 1.4% of the feces produced is phosphorus (Anderson et al., 2003). Total nitrogen in avian feces was estimated to be approximately 2.5 times greater than total phosphorus. All nutrients within the avian feces were considered bioavailable.

Avian contributions were split around their migratory seasons which were lumped into a dry (March – September) and wet (October – February) season. Using the per-bird fecal production and percent nutrient concentrations estimated above, seasonal moderate and high-end estimates for daily avian contributions to the reservoir nutrients were derived (Table 1). The moderate estimates of daily external TN and TP contributions to the reservoir during the dry/wet seasons are 0.23/0.30 kg d^{-1} and 0.09/0.12 kg d^{-1}, respectively. The high-end estimates of daily external TN and TP contributions to the reservoir during the dry/wet seasons are 0.36/0.49 kg d^{-1} and 0.14/0.20 kg d^{-1}, respectively.

3.1.3.2 Fish Stocking

The City of San Diego provided an annual fish report for the reservoir that dates back to 2007. Data provided in this report include number of permits checked, number/species fish removed, and weight of fish stocked. Dudek biologists provided an average weight for each fish species identified in the city's report in order to convert counts to weight. The total annual weight of fish removed from the reservoir was subtracted from the total annual weight of fish stocked in the reservoir, providing a total annual flux (in weight) of fish to the reservoir (Table 3). Any positive flux of fish mass to the reservoir was assumed to end up as decaying organic matter at the bottom of the reservoir.

Based on a study on *Oncorhynchus nerka* (sockeye salmon) carcass decomposition (Johnston et al, 2004), the average dry weight of the *O. nerka* carcass was 15.6% of the wet weight. Of that, 13.3% was nitrogen, and 1.7% was phosphorus. These metrics were applied to the entire average daily net influx of fish biomass, which was calculated at 0.12 kg day^{-1}. The high-end nutrient loading estimates assumed all nutrients return to the reservoir as bioavailable, and were 0.12 kg d^{-1} for TN and 0.01 kg d^{-1} for TP. The moderate estimates were based on a report by Parmenter and Lamarra (1991), where 95% of the nitrogen and 60% of the phosphorus were reported to return as bioavailable from the decomposing fish carcasses: 0.11 kg d^{-1} for TN, and 0.01 kg d^{-1} for TP. No seasonal distribution was applied to the nutrient loading from fish carcasses.

3.1.4 Water Treatment Plant Sludge Returns

For the latest water quality simulation, return of nutrients to the reservoir from the Miramar Water Treatment Plant (MWTP) sludge returns are assumed to have nutrient concentrations equal to 10% of the nutrient concentrations of the incoming municipal water (i.e. State Water Project and Colorado River Aqueduct water). For this exercise, additional information regarding filter types and uses of flocculants were not identified, therefor no adjustments to this estimation are recommended in this report.

3.1.5 Internal Nutrient Recycling

The release of nutrients from decaying organic matter was only included in the first water quality simulation for the regions of the lake that undergo anoxic conditions (approximately 20% of the reservoir for approximately 50% of the year). This means that the majority of nutrients removed in the model for algae production are not returned back into the system. City staff identified the recycling of nutrients within the oxic regions of the reservoir as a potential nutrient source for inclusion in the water quality simulation. Dudek’s literature review identified a study that characterized the bioavailability of nutrients in a lake’s organic rich sediment. Zhou et al. (2001) quantified the amount of bioavailable phosphorus in the sediment of three lakes in China (West Lake and Lake Tai) and Northern Ireland (Lough Erne). Phosphorus dynamics identified in this study are assumed comparable to those in Miramar Reservoir, and were used in establishing ratios for nutrient recycling within the reservoir.

Zhou measured the bioavailable phosphorus in sediment in three forms in their study: 1) water soluble phosphorus (WSP), 2) readily desorbable phosphorus (RDP), and 3) algal available phosphorus (AVP). Results from their analyses were provided as a percentage of total phosphorus (TP) in the soil. These three values were combined to establish the total percentage of bioavailable phosphorus in the reservoir’s oxic region that is recycled from the daily Aqueduct inflow and WTP back flushing. The recycling of nitrogen was assigned a higher percentage relative to the bioavailable phosphorus (Equation 1):

$$Eq\ 1: \%Bioavailable\ Nitrogen = \%Bioavailable\ Phosphorus + \frac{(100 - \%Bioavailable\ Phosphorus)}{2}$$

The lowest and highest percent concentrations of bioavailable phosphorus in Zhou's study (21% and 67%, respectively) were used to bracket the moderate and high-end loading estimates for the reservoir (Table 1). Using Equation 1, the estimated moderate and high percent concentrations of bioavailable nitrogen were 61% and 84%, respectively. While an unknown portion of the algae produced is consumed by aquatic fauna and does not immediately settle as decaying organic matter, it was assumed in this exercise that this is a closed system and that 100% of the incoming nutrients are available for recycling.

Table 1 – Miramar Reservoir: Additional Nutrient Inputs and Internal Nutrient Recycling

Source			Daily Loading Values			
			Moderate		High	
			Dry Season[1]	*Wet Season*[2]	*Dry Season*[1]	*Wet Season*[2]
Atmospheric Depositions		Nitrogen (kg/day)	1.23	0.22	1.38	0.24
		Phosphorus (kg/day)	0.041	0.013	0.041	0.023
Aquatic Vegetation		Nitrogen (kg/day)	1.25	0.32	1.72	0.44
		Phosphorus (kg/day)	0.389	0.099	0.500	0.127
Reservoir Fauna	Avian Contributions[3]	Nitrogen (kg/day)	0.23	0.30	0.36	0.49
		Phosphorus (kg/day)	0.091	0.119	0.143	0.197
	Fish Stocking	Nitrogen (kg/day)	0.11		0.12	
		Phosphorus (kg/day)	0.009		0.015	
Water Treatment Plant Filter and Sludge Backwash (as % of reservoir inflow)		Nitrogen (%)	10%			
		Phosphorus (%)	10%			
Recycling of Nutrients in the Oxic Region (as % of reservoir inflow)		Nitrogen (%)	60.6%		83.7%	
		Phosphorus (%)	21.2%		67.4%	

1. Dry Season - May 1 – October 31
2. Wet Season - November 1 - April 30
3. Water Fowl Seasons split between October through February (wet season) and March through September (dry season)

Table 2 – Miramar Reservoir: Estimated Avian Population

Species	Estimated Number	Seasonality	Average Mass (kg)
Belted kingfisher	1 or 2	Nov - Feb	0.15
Gadwall	10 to 20	Oct - Feb	1
Canada Geese	10 to 20	Oct - Feb	3.63
Bufflehead	10 to 20	Oct - Feb	0.5
Mallard	50 to 100	Year-round	1.14
American coot	100	Year-round	0.6
Merganser	5 to 10	Year-round	1.5
Cormorants	10 to 20	Year-round	2
Heron	5	Year-round	2.2
Egret	5	Year-round	0.2
Bittern	2	Year-round	0.45
Osprey	1	Year-round	1.6
Other domestic waterfowl	50	Year-round	1
Grebes	5-10/10-20	Year-round/Oct - Feb	1.3

Table 3 – Miramar Reservoir: Estimated Annual Flux of Fish Biomass

Year	Net Flux - Wet (kg)	Net Flux - Dry (kg)
2007	7073.45	1103.46
2008	5315.79	829.26
2009	3196.62	498.67
2010	1752.76	273.43
2011	883.51	137.83
2012	-138.53	-21.61
2013	755.90	117.92
2014	961.23	149.95
2015	463.33	72.28
2016	402.83	62.84
	Average Daily (kg)	**0.88**

3.1.6 Other Potential Sources

Other potential nutrient sources to the reservoir may include the following:

- Runoff generated from rainfall events and/or any local irrigation practices that carry surface waters with urban pollutants (e.g. animal feces, fertilizers) to the reservoir;
- Recreation impacts including the use of fishing bait, duck feeding, and any other human waste;
- Terrestrial leaf litter transported by wind and/or water.

Based on the small contributing watershed area and limited human use (no physical contact), these sources were not considered significant contributors of nutrients to the reservoir compared to the other sources identified above.

4 SUMMARY

The resulting total contributions of external nutrients to the reservoir and recycling of nutrients in the reservoir's inflow are provided in Table 4.

Table 4 – Miramar Reservoir: Summary of Additional Nutrient Inputs

External Nutrients ($kg\ d^{-1}$)	Moderate Loading		High Loading	
	Dry Season	*Wet Season*	*Dry Season*	*Wet Season*
Total Nitrogen	2.82	0.95	3.58	1.29
Total Phoshporus	0.53	0.24	0.70	0.36
Internal Recycling (%)[a]	**Moderate Loading**		**High Loading**	
Total Nitrogen	60.6%		83.7%	
Total Phoshporus	21.2%		67.4%	
MWTP Sludge Returns (%)[b]	**All Scenarios**			
TN and TP	10%			

a. As % of municipal water inflow to reservoir, and only to be applied over oxic regions of reservoir (80%).
b. As % of concentrations in municipal water inflow.

The estimated contributions from the community of *S. californicus* are the greatest additional sources of nitrogen and phosphorus to the reservoir, with the exception of avian feces during the wet season, where TN and TP contributions are only reported as 10s of grams higher per day for the high loading estimate. With the projected concentrations of TN and TP in the purified water from the Program being 0.78 mg/L and 0.004 mg/L, respectively, and with an estimated daily inflow of 30 million gallons, the total daily nutrient loading from the Program will be 89 kg d^{-1} TN and 0.5 kg d^{-1} TP, respectively. While external sources of nitrogen are an order of magnitude smaller than what is coming in with Program inflows, external phosphorus sources are nearly identical during the dry season, and approximately half in the wet season.

The recycling of nutrients from the inflow to the reservoir (not including back flushing and sludge returns from the MWTP), while only identified as a percentage of inflow in this study, has the potential to be a substantial contribution of nutrients to the reservoir. Assuming the Program's inflow will be providing 0.5 kg d^{-1} of TP, the internal recycling of TP from these inflows could lead to daily loading between 0.09 kg d^{-1} to 0.27 kg d^{-1} of TP. The daily recycling of TN is much greater, with potential loadings between 42.7 kg d^{-1} and 57.6 kg d^{-1} estimated.

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