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Memorandum

From: Derek Schlea, Hans Holmberg **Date:** March 12, 2020

To: Justin Watkins, Kristen Dieterman,
Dennis Wasley, Marco Graziani (MPCA)

Project: Zumbro River Watershed HSPF Model Extension 2018

Subject: Technical memorandum to document model extension, recalibration, and application

Statement of Purpose

This memorandum has been prepared for the Minnesota Pollution Control Agency (MPCA) to document Objectives 1, 2, and 3 of the "Zumbro River Watershed HSPF Model Extension 2018" project and serves as an Objective 4 deliverable, as outlined in the Work Plan, Contract No. 156410. The objectives for this phase of work include the following:

- Objective 1: Refine the ZRWHSPF model;
- Objective 2: Update the ZRWHSPF model calibration; and
- Objective 3: Apply the ZRWHSPF model to assess various management scenarios.

Project Background

The Minnesota Pollution Control Agency (MPCA) is undertaking a watershed restoration and protection (WRAPS) approach at the 8-digit HUC scale. The Zumbro River watershed (ZRW) 8-digit HUC includes waters impaired by excessive bacteria (fecal coliform and *Escherichia coliform* (*E. coli*)), total suspended solids (TSS), and phosphorus. The Zumbro River Watershed WRAPS was approved in November 2018, and the watershed TMDLs were approved by EPA in February of 2018. A site specific eutrophication standard for Lake Zumbro has been approved by EPA. Rice Lake is impaired by excessive nutrients and addressed in the approved TMDLs document. The MPCA has selected the Hydrologic Simulation Program FORTRAN (HSPF) model to simulate watershed hydrology and water quality. The HSPF is an important tool in developing an understanding of existing conditions, simulating conditions under various management scenarios and informing the development of implementation strategies and plans to restore and protect streams and lakes.

In previous phases of work, an HSPF model of the ZRW (hereafter ZRWHSPF) was developed to simulate hydrology and water quality for the 1995-2009 period (Phase I; LimnoTech, 2014), applied to evaluate various management scenarios for reducing sediment and nutrient loading (Phase II; LimnoTech, 2015), and used to construct TMDLs for impaired stream segments and inform development of a nutrient TMDL for Rice Lake (Phase III; LimnoTech, 2017a; LimnoTech 2017b).

In the current project (Phase IV), the ZRWHSPF model was refined by extending the simulation period through 2018 and updating the hydrology and water quality calibration based on new data and information. The ZRWHSPF model was also applied to evaluate management scenarios, building from scenarios constructed during previous phases of work.

Model Refinement

The primary purpose of the first objective was to compile and process the time series data required to extend the model simulation period through 2018. This objective also included a refinement of the model landside segmentation, improved representation of Silver Lake, and updated representation of point sources.

Model Segmentation

The previous ZRWHSPF model's grouping of land segments into weather regions was based on a Theissen polygon analysis conducted for meteorological stations with observed precipitation data. This approach was somewhat limiting in that land segments of a common land cover and soil type might cover a vast geographic area spanning multiple ten digit hydrologic unit code (HUC-10) subwatersheds, varying slope characteristics, and multiple ecoregions. The revised approach used during this model refinement phase involved updating the landside segmentation to better align with HUC-10 subwatershed boundaries and the three major ecoregions spanning the ZRW (Western Corn Belt Plains, Rochester Plateau, and Blufflands). Switching from the local observed precipitation datasets to a national-scale, gridded precipitation dataset facilitated this refinement. This model segmentation refinement was advantageous for two major reasons: (1) it led to an improved calibration by allowing for more spatially refined parameterization when supported by observed streamflow and/or water quality data, and (2) during the model application phase it allowed for better alignment with the nonpoint source management scenarios defined in the Zumbro River WRAPS, which were defined based on major lobe boundaries (HUC-10 subwatersheds). Land segments were grouped into the 15 precipitation zones shown in Figure 1.

Meteorological Time Series

Two gridded precipitation datasets were obtained for constructing ZRWHSPF model input time series for the entire 1995-2018 simulation period: daily time series from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; PRISM Climate Group, 2019) and hourly time series from the North American Land Data Assimilation System (NLDAS; Xia et al., 2012). An initial processing step involved aggregating the raw time series obtained for individual PRISM and NLDAS grid cells into a unique time series for each of the 15 precipitation zones using an area-weighted approach. The PRISM dataset was found to have annual precipitation patterns more consistent with observations, evaluated for the Rochester International Airport station, than the NLDAS dataset. This finding was consistent with those described in other Minnesota HSPF model development reports (TetraTech, 2016a; TetraTech, 2016b). Therefore, we followed a similar approach of using the NLDAS hourly precipitation time series as the reference time series for disaggregating the PRISM daily precipitation time series into the final, hourly input time series to be used in the model simulations. The disaggregation function in WDMUtil was used for this step.

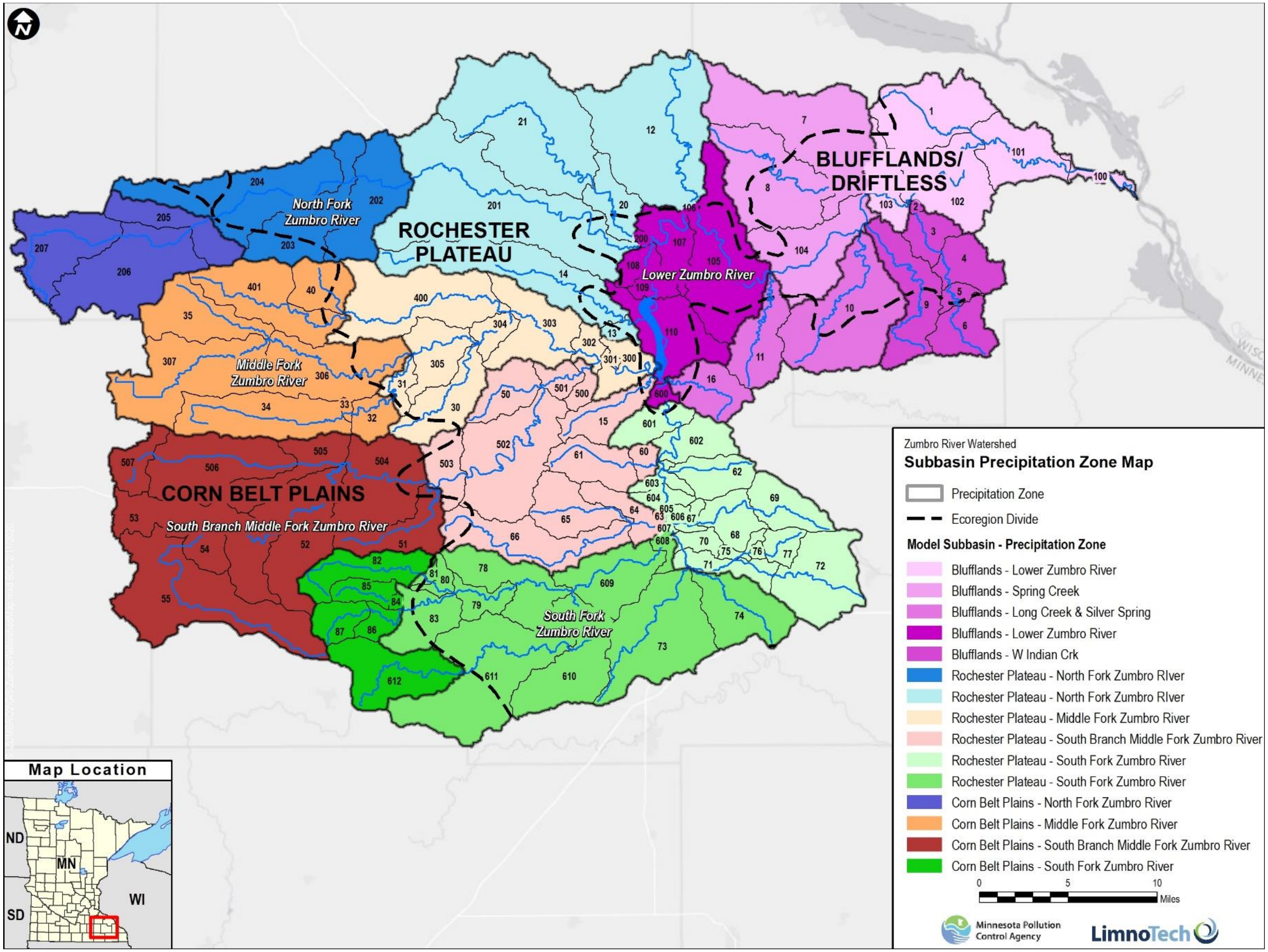

Figure 1: ZRWHSPF model subbasin map with revised precipitation regions and major ecoregion divides

Time series for the other meteorological inputs were developed using data obtained from the National Climatic Data Center (NCDC) Climate Data Online (CDO) database for the 2010-2018 extension period (NOAA, 2019). Hourly meteorological datasets were obtained for the same four stations used in the original model: Rochester International Airport, Faribault, Owatonna, and Winona. Datasets for air temperature, dew point temperature, and wind speed were sufficient for all four stations to append the 1995-2009 input time series with hourly time series for the full 2010-2018 extension period. The cloud cover dataset was complete for the Rochester station, but beginning in 2013 there was an absence of “overcast” observations for the other three stations, resulting in much lower cloudiness. Because of this, the cloud cover and subsequent solar radiation calculation for the Rochester station were used to fill the gap beginning in 2013 for the other three stations. Likewise, because the Penman pan evaporation calculation relies on solar radiation as an input, all four stations used the same potential evaporation time series beginning in 2013. The compute solar radiation function in WDMUtil was used to estimate solar radiation based on the input cloud cover time series. The compute Penman pan evaporation function in WDMUtil was used to estimate potential evaporation based on daily minimum and maximum air temperature, dew point, wind, and solar radiation inputs.

Silver Lake

The hydraulic functional table (FTABLE) for the RCHRES representing Silver Lake, an impounded portion of the South Fork Zumbro River in the City of Rochester, was modified to better represent the hydrologic and sedimentation characteristics of this riverine segment. This model segment was previously represented as a run-of-the-river RCHRES, and the FTABLE was developed using the standard BASINS method of applying a power function to estimate stream depth and width as a function of upstream drainage area. The revised depth, surface area, and volume relationship for Silver Lake was based on bathymetry estimates assuming dredged conditions. The revised outflow as a function of depth was determined using the sharp-crested weir equation based on an estimated weir coefficient of 3.2 and effective weir length of 140 feet.

Representation of Point Sources

Point source effluent datasets were provided by MPCA for all ZRW facilities to append input time series to cover the 2010-2018 extension period. During this process, LimnoTech worked with MPCA to reevaluate the list of point sources represented in the ZRWHSPF model to ensure all permitted facilities that continuously or intermittently discharge to surface waters were represented. In addition to extending the input time series for the 2010-2018 period, the following modifications were made to represent the appropriate facilities, to reflect changes that occurred during the 2010-2018 period, or to develop placeholders for potential future changes:

- Kerry, Inc. (MNG250047), which was previously mischaracterized as having no discharge to surface water, was added to the model;
- Stussy Mantorville Quarry (MNG490134), which previously was inactive and did not start discharging until 2012, was added to the model;
- The routing of Mantorville’s municipal wastewater to the Kasson WWTP (MN0050725) was represented by increasing Kasson WWTP discharge according to observed data and setting Mantorville WWTP (MN0021059) discharge to zero beginning in November 2017;
- The Kasson WWTP discharge location was updated to the South Branch Middle Fork Zumbro River instead of the previous assignment to the adjacent Masten Creek;

- Heat loads from the once-through cooling water discharge from Rochester Public Utilities (RPU) Silver Lake Power Plant (MN0001139) were represented based on historical data until the plant's decommissioning in 2015; and
- Though not represented in calibration simulations for the 1995-2018 historic period, placeholders for potential future discharges from a municipal facility in Oronoco and an industrial facility in Zumbrota (Dairy Farmers of America) were built into the model for use during the hypothetical scenarios in the model application phase.

Other Input Time Series

The remaining temporally-variable inputs extended for the 2010-2018 period included atmospheric deposition and Lake Zumbro water level controls. Atmospheric deposition of nitrogen was extended using data obtained from the National Atmospheric Deposition Program (NADP) National Trends Network (NTN) (NADP, 2019) and the Clean Air Status and Trends Network (CASTNET) (USEPA, 2019). Dates of raising and lowering of Lake Zumbro water levels to reach summer pool and winter pool target elevations were obtained from the RPU website (RPU, 2019). These dates were used to extend the SPECIAL ACTIONS block, which was developed in the original model to specify the dates when Lake Zumbro is operated at summer pool elevation, winter pool elevation, or the transition period by using different discharge columns of the FTABLE.

Observed Streamflow and Water Quality Data

The 2010-2018 model extension period had a relatively greater abundance of observed streamflow data, discrete water quality sampling data, and water quality load estimates than the former 1995-2009 simulation period. As discussed in model calibration section, these additional data facilitated significant expansion of model-data comparisons and led to better constrained ZRWHSPF model hydrology and water quality calibrations. The following resources were used to obtain the observed streamflow and water quality datasets for the 2010-2018 extension period:

- United States Geological Survey (USGS) National Water Information System (USGS, 2019);
- Minnesota Department of Natural Resources Cooperative Stream Gaging (MNDNR, 2019);
- MPCA Environmental Quality Information System (EQuIS) (MPCA, 2019a); and
- MPCA Watershed Pollutant Load Monitoring Network (WPLMN) (MPCA, 2019b).

The primary model calibration locations were those with the most abundant datasets and near the outlets of major subwatersheds: Zumbro River at Kellogg; North Fork Zumbro River near Mazeppa; Middle Fork Zumbro River near Oronoco; South Branch Middle Fork Zumbro River near Oronoco; and South Fork Zumbro River at 37th St. (streamflow) and 90th St. (water quality). Secondary model calibration locations included those further upstream on the major forks with smaller drainage areas. These locations were used to confirm or further support evaluation of model performance for major subwatersheds, but were not intended to be evaluated as critically as the primary calibration locations. Auxiliary calibration locations included tributaries with relatively smaller drainage areas, but a relatively large number of observed streamflow and water quality measurements. These locations were used to confirm model behavior for the sub-drainage areas or evaluate unique hydrologic behavior (e.g., West Indian Creek), but were not intended to be evaluated as critically as the primary calibration locations.

Model Calibration

Following the model extension and refinement activities, the next objective was to reevaluate the model calibration and recalibrate if necessary. Due to the relatively greater abundance of observed data in the 2010-2018 extension period, reevaluation of the model calibration involved much more than just evaluating model performance using datasets previously compared against, which covered the 1996-2009 period. The model performance evaluations were extended to cover more locations spatially and more water quality concentration measurements and load estimates. The original ZRWHSPF model development project used 2004-2009 as the calibration period and 1996-2003 as the validation period. The first year (1995) served as a "warm-up period" to allow the model to equilibrate and not be strongly influenced by the initial conditions. For this Phase IV work, 2010-2018 was used as the calibration period and 1996-2009 was used as a validation period.

As stated in the work plan, updates to the calibration prioritized the accuracy of the phosphorus simulation, especially at key water quality monitoring stations upstream of Lake Zumbro. As such, during the course of calibration, if deemed necessary, the quality of the sediment simulation and other water quality constituent simulations were intended to be secondary to that of the phosphorus simulation. Nonetheless, model performance evaluations were conducted for both sediment and other water quality constituents, as described below.

The calibration approach followed the procedures described in the MPCA modeling guidance document (AQUA TERRA Consultants, 2012) and the original ZRWHSPF model development report (LimnoTech, 2014). Assessments of model performance followed a "weight of evidence" approach, consisting of using multiple model comparisons, both graphical and statistical. Statistical metrics for hydrology included the average relative percent difference (RPD), the coefficient of determination (R-squared), percent bias (PBIAS) (applied to the monthly interval only) and the Nash-Sutcliffe efficiency (NSE). The statistical metric used to evaluate the water quality calibration was the average RPD between simulated and observed values (Duda et al., 2012). Tolerance ranges described in the MPCA modeling guidance document were used. Appendix A contains the equations used to calculate these performance metrics and the qualitative ratings associated with each.

Hydrology Calibration

The model calibration for hydrology was reevaluated using the additional observational datasets available for the 2010-2018 model extension period. These datasets included stream gaging locations that were not established during the first phase of ZRWHSPF modeling work, including the North Fork Zumbro River near Mazeppa (Site ID 41006001), the Middle Fork Zumbro River near Oronoco (Site ID 41071003), and the South Branch Middle Fork Zumbro River near Oronoco (Site ID 41071002). The stream gaging station near the watershed outlet (Zumbro River at Kellogg, Site ID 41043001) had nearly five times more daily streamflow observations for the 2010-2018 extension period, relative to the previous 1995-2009 simulation period. Based on the new data and information available to support the revision of the hydrology calibration, the following revisions were made to the ZRWHSPF model:

- The snow simulation parameters modified included TSNOW, CCFACT, and MGMELT;
- SNOWCF was previously higher for two precipitation zones where local rain gages appeared to under-report precipitation falling as snow relative to the rest of the watershed. This was reset due to the switch to the common, gridded precipitation inputs across the entire watershed;
- LSUR and SLSUR were modified to better represent the difference in ecoregions spanning the ZRW, from the relatively flat, longer runoff lengths in the Western Corn Belt Plains transitioning to the relatively steep, shorter runoff lengths in eastern Blufflands areas; and

- AGWRC, UZSN, INTERFLOW, IRC, and LZETPARM were modified to reflect gradients in ecoregions and differences in observed streamflow responses.

Summary performance statistics for the hydrology calibration period are shown in Table 1 for the five primary locations. Visual comparisons of observed and simulated streamflow are shown in Figures 2 to 5 for the Zumbro River at Kellogg and in Appendix C for the other primary calibration locations. Summary performance statistics for the secondary calibration locations are provided in Table B-1 for the calibration period, and validation period statistics are provided in Table B-2. The overall model performance for hydrology in the current model can be summarized as follows:

- The majority of statistical evaluations for the five primary calibration locations and five secondary calibration locations indicate satisfactory model performance, including several "very good" to "excellent" ratings for monthly and annual intervals for the 2010-2018 model extension period;
- Visual inspection of the annual and monthly flow volume plots, the daily streamflow plot, and the cumulative frequency distribution plots suggest the model is able to reproduce flow volumes, the magnitude and timing of peak flows, and the distribution of flows at all five primary calibration locations very well; and
- Statistical evaluations for the two primary locations and three secondary locations with observed data during the 1996-2009 validation period confirm satisfactory model performance.

Table 1: Model performance evaluation statistics for primary hydrology calibration locations for the 2010-2018 model extension period

Time Interval	Statistic	Zumbro at Kellogg	South Fork at 37th St.	S. Branch Middle Fork near Oronoco	Middle Fork near Oronoco	North Fork near Mazeppa
		2010-2018	2010-2018	2013-2017	2013-2018	2013-2018
Annual	*Count*	9	9	5	6	6
	R-Squared	0.97	0.98	0.97	0.98	0.91
	NSE	0.93	0.96	0.91	0.96	0.78
	RPD	-5.8%	5.6%	0.3%	-2.0%	-12.7%
Monthly	*Count*	105	108	42	61	61
	R-Squared	0.89	0.91	0.85	0.81	0.87
	NSE	0.87	0.90	0.84	0.81	0.85
	P-Bias	5.52	-3.82	5.53	0.75	10.82
	RPD	-11.5%	6.0%	5.3%	7.6%	-15.7%
Daily	*Count*	2970	3287	1085	1693	1746
	R-Squared	0.71	0.75	0.69	0.56	0.59
	RPD	-13.8%	3.7%	6.8%	5.4%	-13.4%

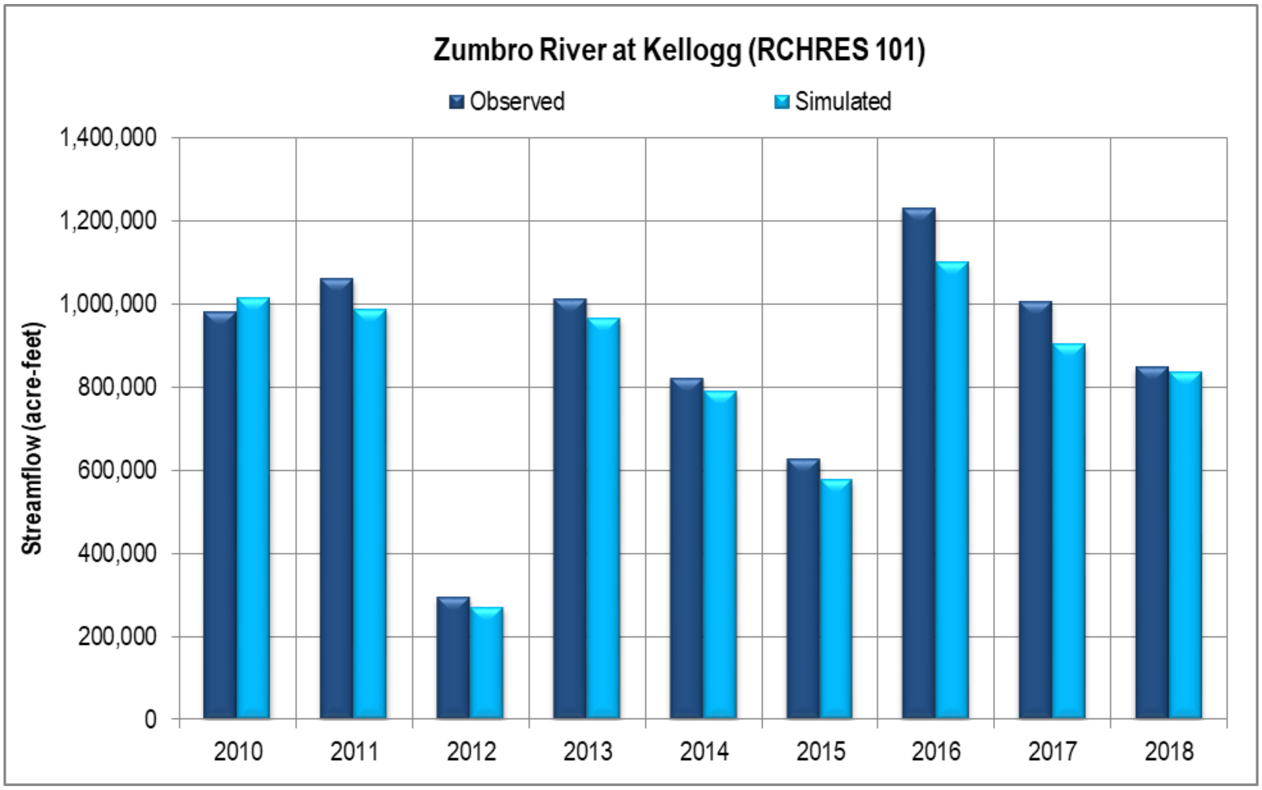

Figure 2: Observed and simulated annual streamflow volumes for Zumbro River at Kellogg

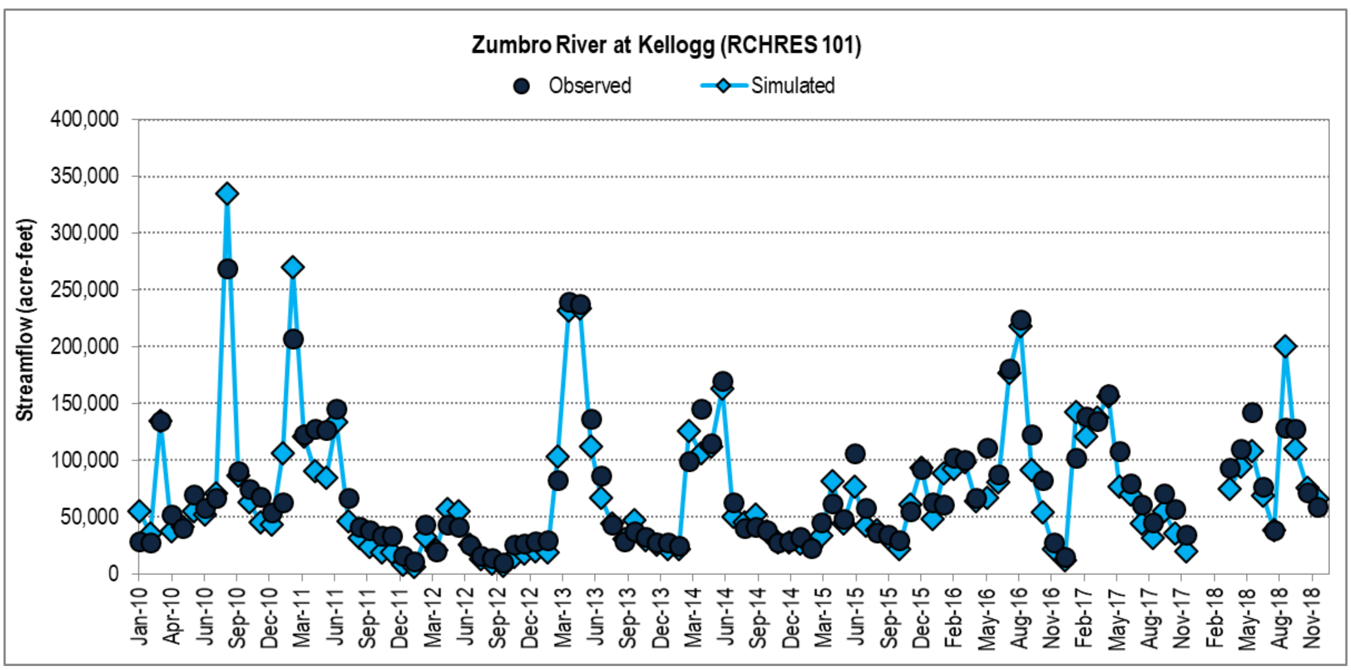

Figure 3: Observed and simulated monthly streamflow volumes for Zumbro River at Kellogg

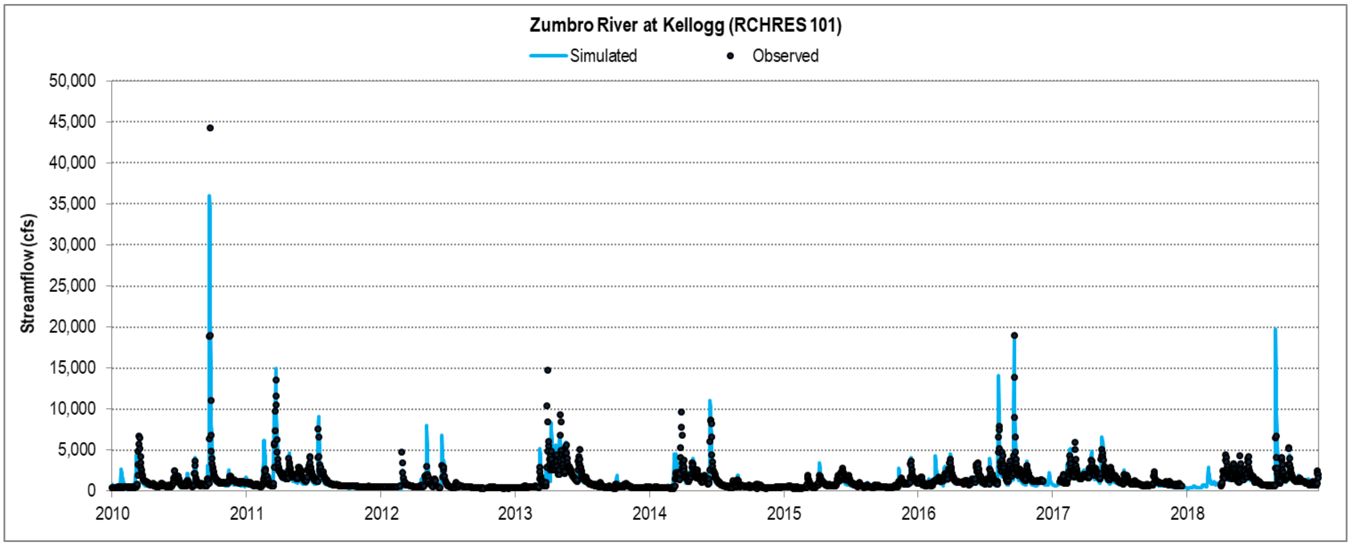

Figure 4: Observed and simulated daily average streamflow for Zumbro River at Kellogg

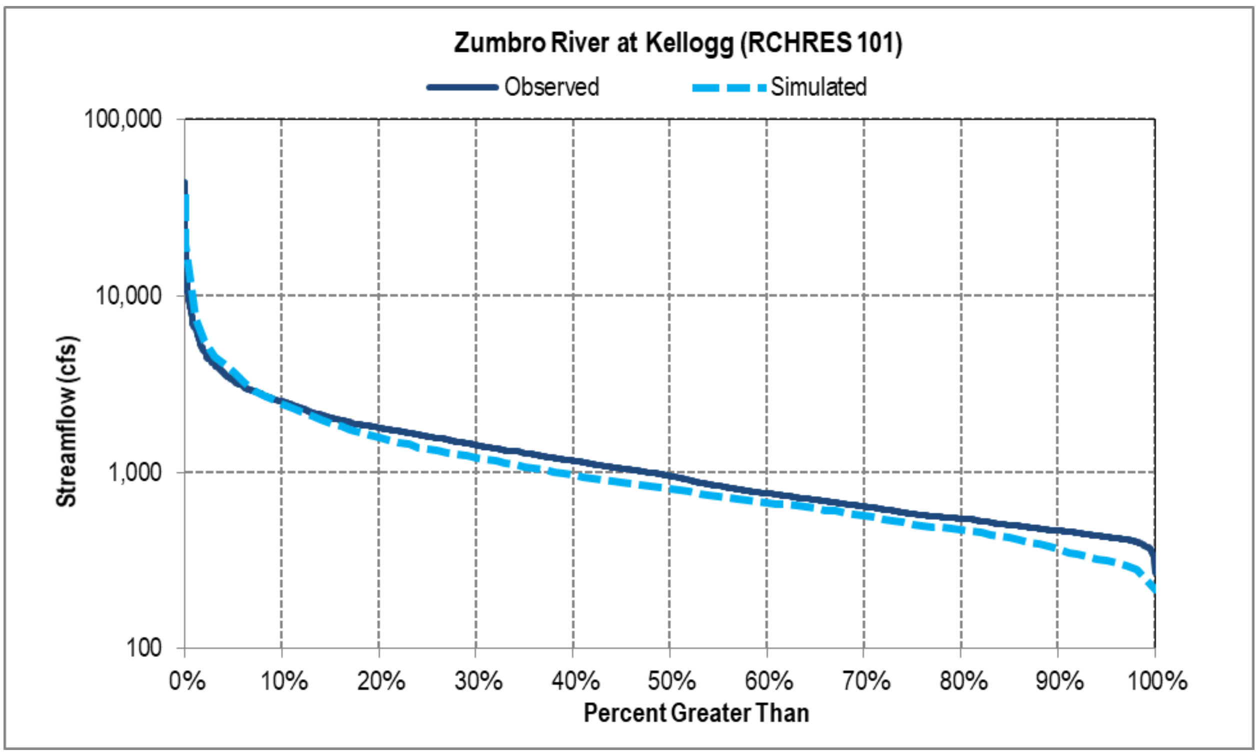

Figure 5: Observed and simulated daily streamflow cumulative frequency distribution for Zumbro River at Kellogg

Sediment Calibration

The model calibration for sediment was reevaluated primarily using the additional observational datasets available for the 2010-2018 model extension period. This included monthly sediment loads from the WPLMN for the watershed outlet and four upstream locations, which were not available during previous phases of ZRWHSPF modeling work. Model performance for the extension period was also evaluated using grab sample TSS concentrations at the five WPLMN locations and other, secondary locations throughout the watershed. Based on the new data and information available to support the revision of the sediment calibration, the following revisions were made to the ZRWHSPF model:

- The primary landside sediment parameters modified were KRER (coefficient in soil detachment equation), KSER (coefficient in soil washoff equation), and KGER (coefficient in soil matrix scour equation); and
- Critical shear stresses for silt and clay scour (TAUCS) and deposition (TAUCD) were modified, including targeting depositional behavior in Silver Lake and flood control reaches of the South Fork Zumbro River, Bear Creek, and Cascade Creek.

Summary performance statistics for the sediment calibration are shown in Table 2 for the five primary locations. Visual comparisons of observed and simulated daily TSS concentrations and monthly TSS loads are shown in Figures 6 to 8, for the Zumbro River at Kellogg and in Appendix C for the other primary calibration locations. Summary performance statistics for the validation period are provided in Table B-3. The overall model performance for sediment in the current model can be summarized as:

- The relative percent difference between observed and simulated monthly TSS loads are "good" to "very good" at all five WPLMN locations;
- The relative percent difference between observed and simulated TSS concentrations are "fair" to "very good" at all five WPLMN locations; and
- Visual inspection of the time series plots and cumulative frequency plots suggests that overall, the model was able to reproduce the range, timing, and magnitude of TSS concentration measurements.

Table 2: Model performance evaluation statistics for TSS loads and TSS concentrations for the 2010-2018 model extension period

Station Name	Monthly TSS loads		TSS concentrations	
	Count	RPD	Count	RPD
Zumbro River at Kellogg	84	-21%	384	-28%
S. Fork Zumbro River at 90th St.	16	21%	189	-28%
S. Branch M. Fork Zumbro River near Oronoco	32	-4%	137	-36%
M. Fork Zumbro River near Oronoco	33	20%	159	-19%
N. Fork Zumbro River near Mazeppa	33	-3%	151	-14%

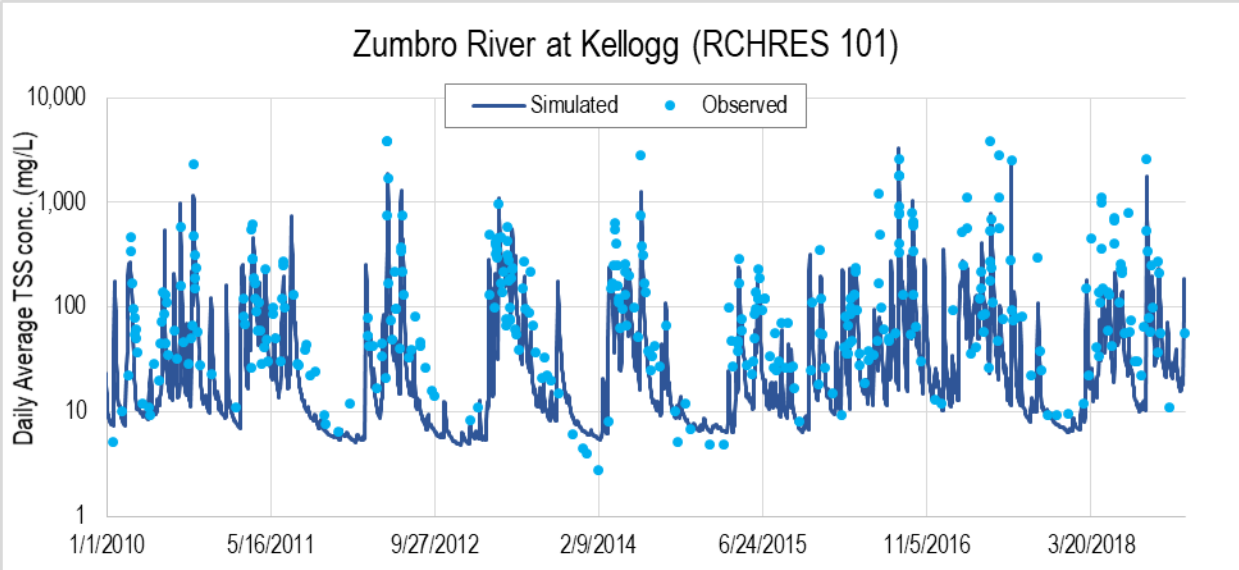

Figure 6: Observed and simulated daily average TSS concentrations for Zumbro River at Kellogg

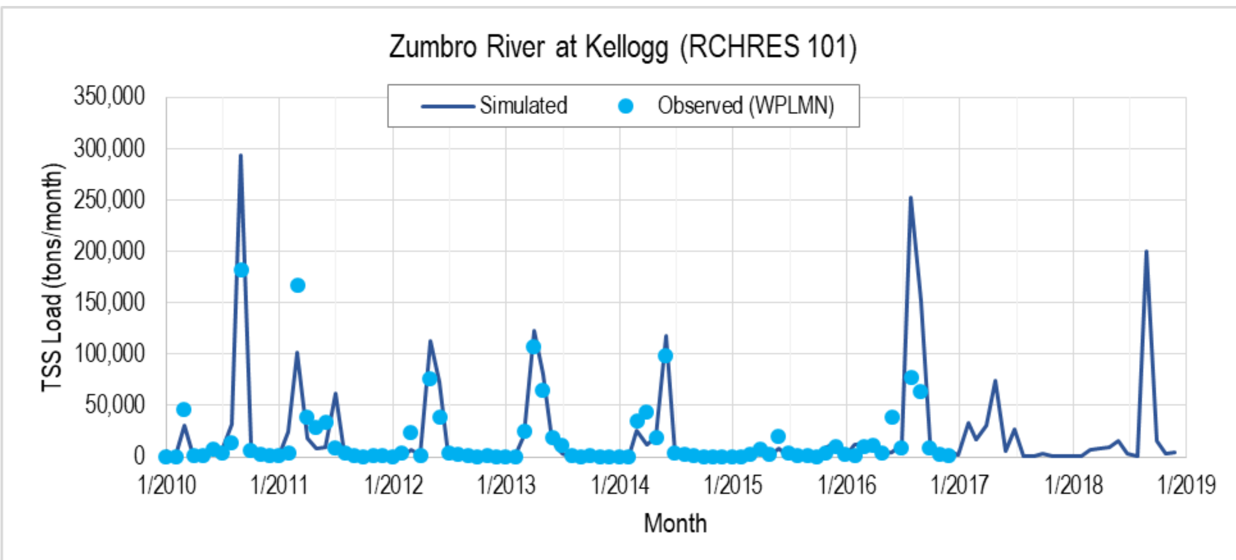

Figure 7: Observed and simulated monthly TSS loads for Zumbro River at Kellogg

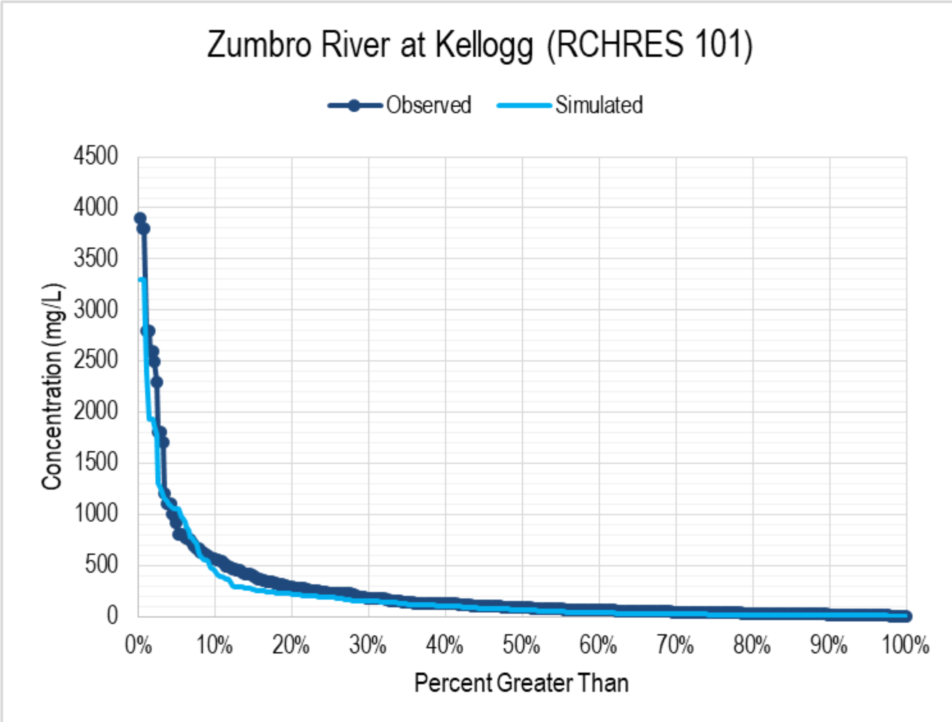

Figure 8: Observed and simulated TSS concentration cumulative frequency distributions for Zumbro River at Kellogg for the 2010-2018 model extension period

Phosphorus Calibration

The model calibration for total phosphorus (TP) and dissolved orthophosphate (PO_4) was reevaluated and recalibrated using the additional observational datasets available for the 2010-2018 model extension period. This included monthly TP and PO_4 loads from the WPLMN for the watershed outlet and four upstream locations, which were not available during previous phases of ZRWHSPF modeling work. Model performance for the extension period was also evaluated using grab sample TP and PO_4 concentrations at the five WPLMN locations and other, secondary locations throughout the watershed. Emphasis was placed on the phosphorus calibration at key water quality monitoring locations upstream of Lake Zumbro. The recalibration work also relied on previous work completed regarding the ZRWHSPF model's sensitivity to specified phosphorus concentrations in interflow, groundwater, and bed sediments (LimnoTech, 2017a). Based on the new data and information available to support the revision of the phosphorus calibration, the following ZRWHSPF model inputs were modified:

- Landside potency factors for PO_4 and organic phosphorus;
- Landside interflow and groundwater phosphorus concentrations; and
- Riverine adsorption coefficients and bed sediment phosphorus concentrations, benthal release rate of BOD, and settling rate for dead refractory organics.

Summary performance statistics for the phosphorus calibration are shown in Table 3 for the five primary locations and three secondary locations on the South Fork Zumbro River (37^{th}, 55^{th}, and 75^{th} streets). Visual comparisons of observed and simulated TP and PO_4 concentrations and monthly loads are shown in Figures 9 to 18 for the Zumbro River at Kellogg and the South Fork Zumbro River at 90^{th} St. Visual comparisons for the other primary calibration locations and secondary locations on the South Fork Zumbro River are provided in Appendix C. Summary performance statistics for the validation period are provided in Table B-3. The overall model performance for phosphorus in the current model can be summarized as:

- The relative percent difference between observed and simulated monthly TP and PO_4 loads are "good" to "very good" at all five WPLMN locations;
- The relative percent difference between observed and simulated TP and PO_4 concentrations are "good" to "very good" at all primary and secondary locations evaluated; and
- Visual inspection of time series plots and cumulative frequency plots suggests that overall, the model was able to reproduce the range, timing, and magnitude of phosphorus concentration measurements.

Table 3: Model performance evaluation statistics for TP loads, TP concentrations, PO_4 loads, and PO_4 concentrations for the 2010-2018 model extension period

Station Name	Monthly TP loads		TP concentrations		Monthly PO_4 loads		PO_4 concentrations	
	Count	RPD	Count	RPD	Count	RPD	Count	RPD
Zumbro at Kellogg	60	8%	257	14%	72	-1%	317	13%
S. Fork at 90th St.	24	3%	252	4%	24	1%	192	7%
S. Fork at 75th St.	-	-	66	-3%	-	-	51	-11%
S. Fork at 55th St.	-	-	51	-10%	-	-	35	-46%
S. Fork at 37th St.	-	-	87	-22%	-	-	71	-27%
S. Br. M. Fork near Oronoco	32	-15%	137	-6%	32	1%	119	10%
M. Fork near Oronoco	33	7%	159	10%	25	17%	141	14%
N. Fork near Mazeppa	33	-19%	151	-2%	33	-17%	134	-1%

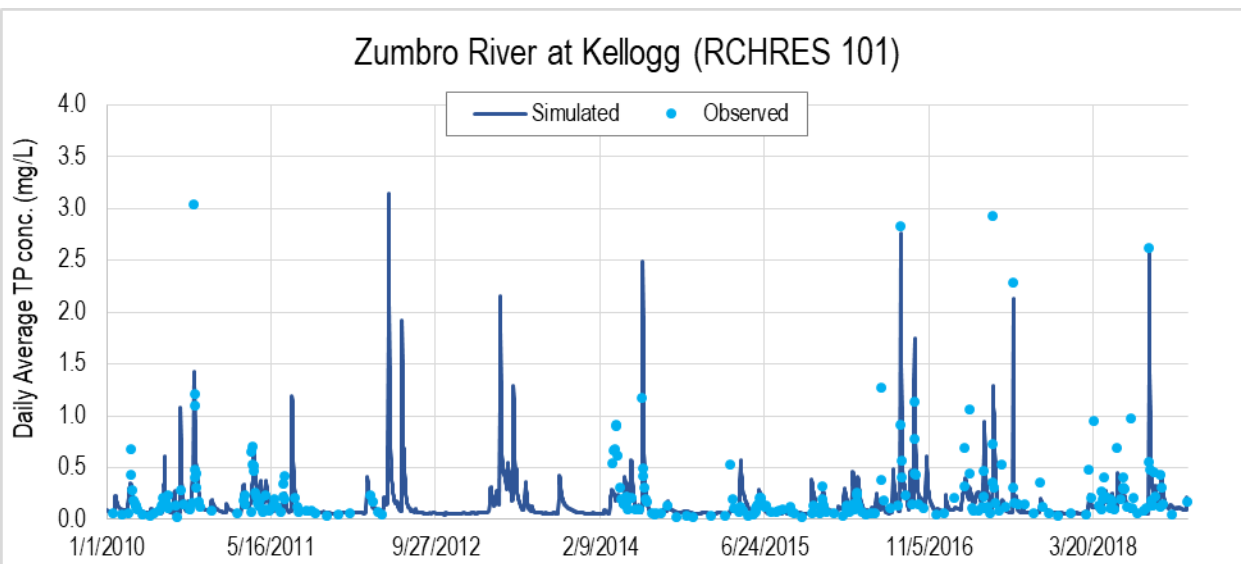

Figure 9: Observed and simulated daily average TP concentrations for Zumbro River at Kellogg

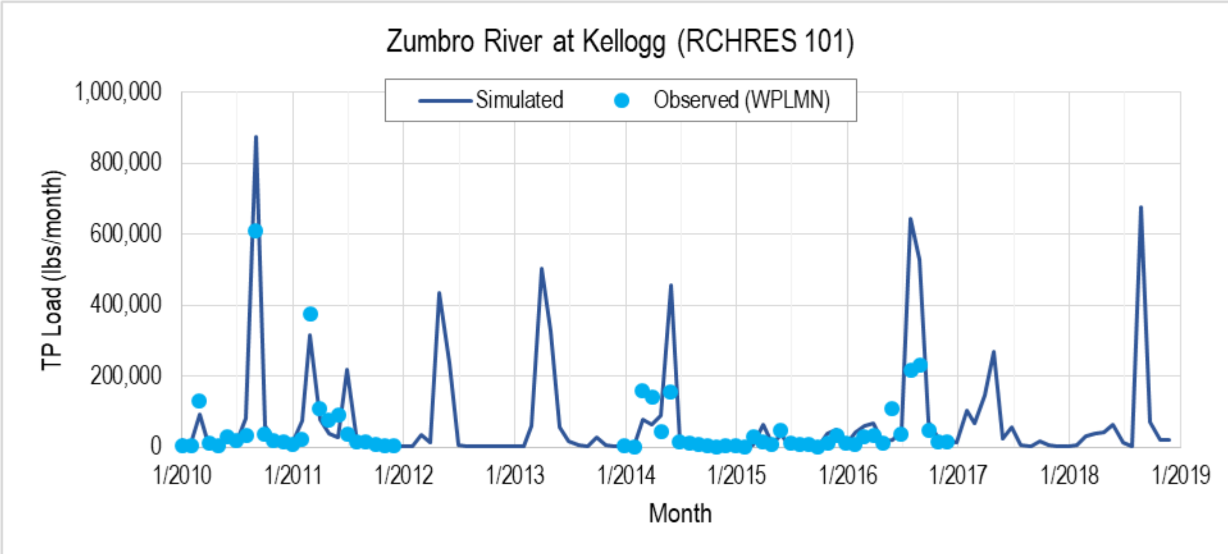

Figure 10: Observed and simulated monthly TP loads for Zumbro River at Kellogg

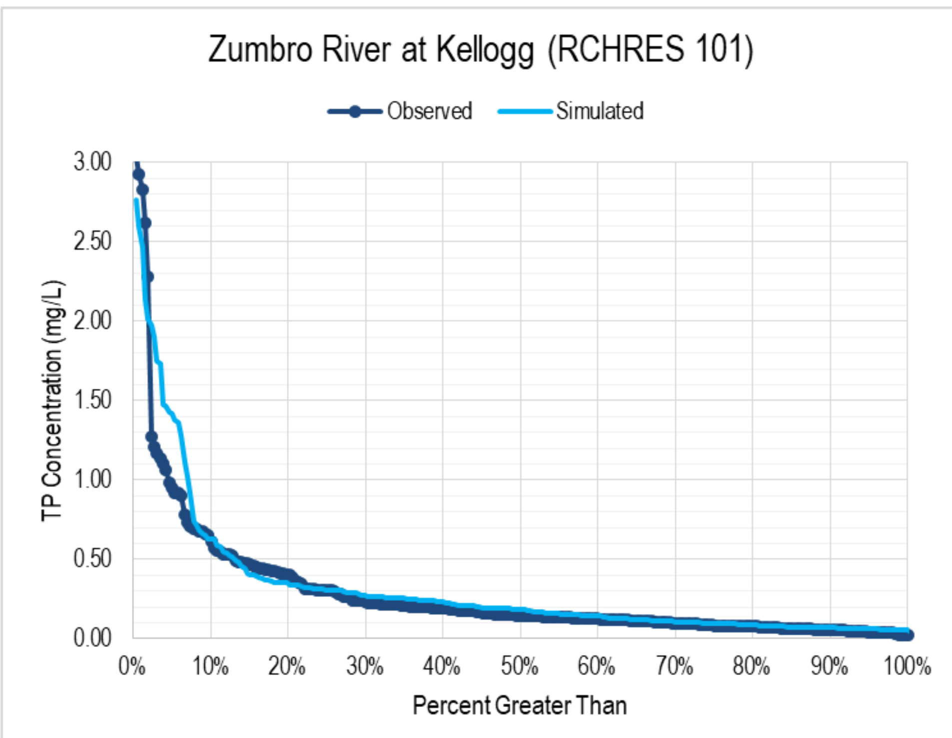

Figure 11: Observed and simulated TP concentration cumulative frequency distributions for Zumbro River at Kellogg for the 2010-2018 model extension period

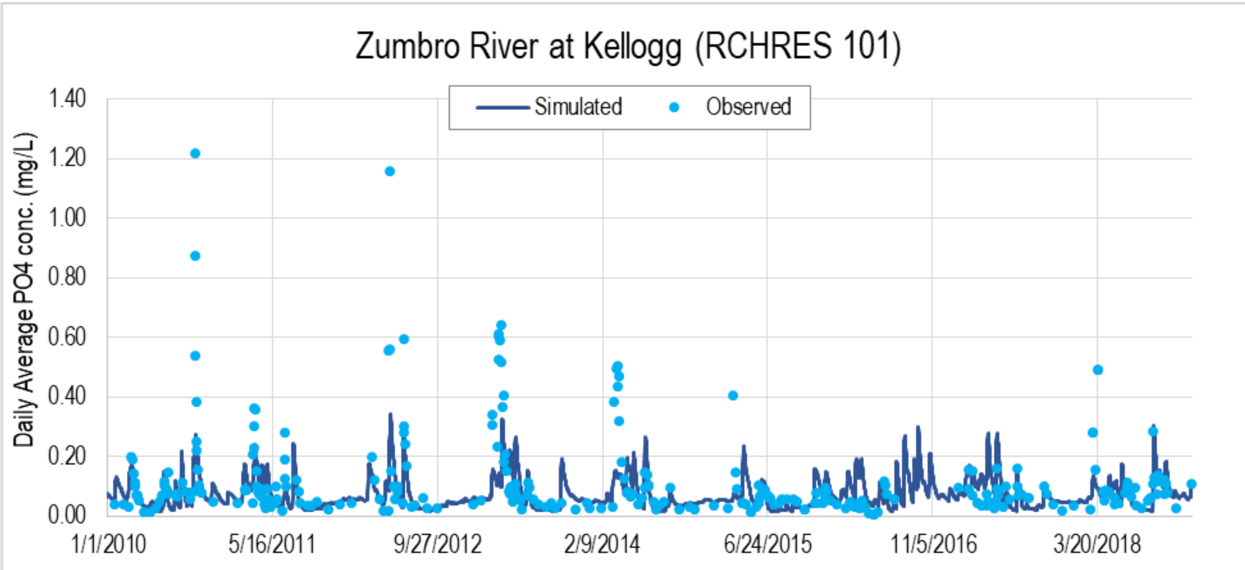

Figure 12: Observed and simulated daily average PO_4 concentrations for Zumbro River at Kellogg

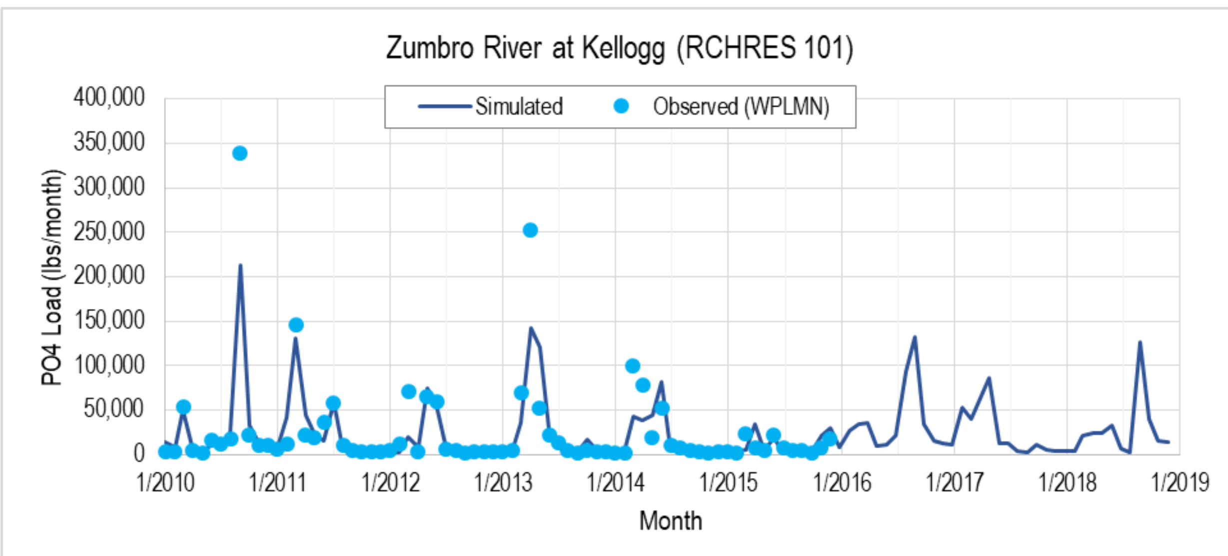

Figure 13: Observed and simulated monthly PO_4 loads for Zumbro River at Kellogg

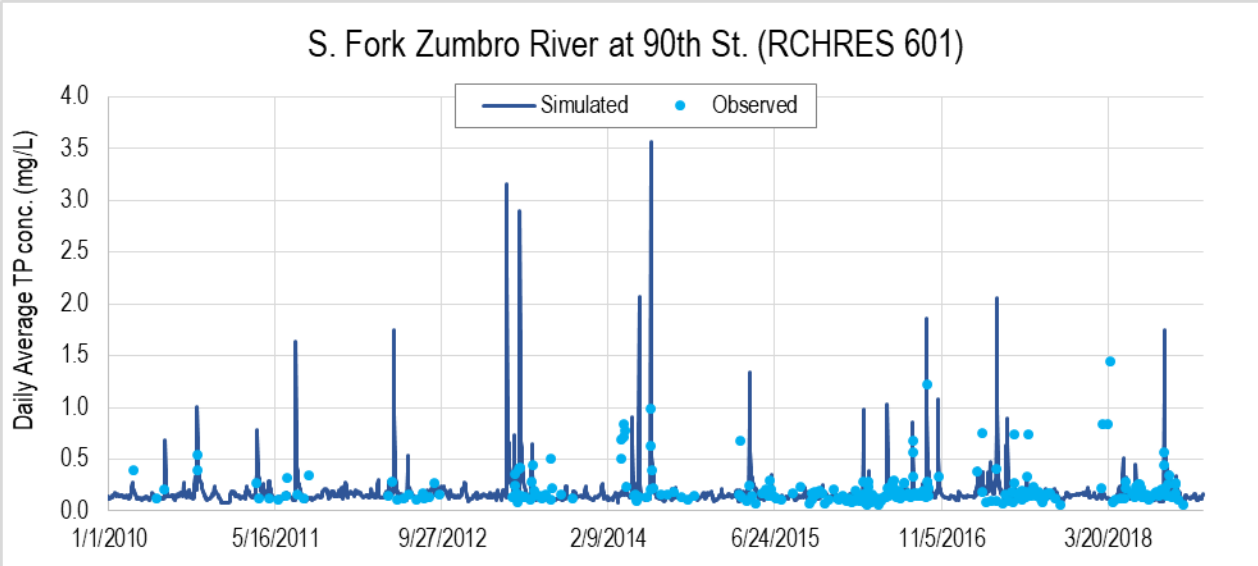

Figure 14: Observed and simulated daily average TP concentrations for South Fork Zumbro River at 90th Street

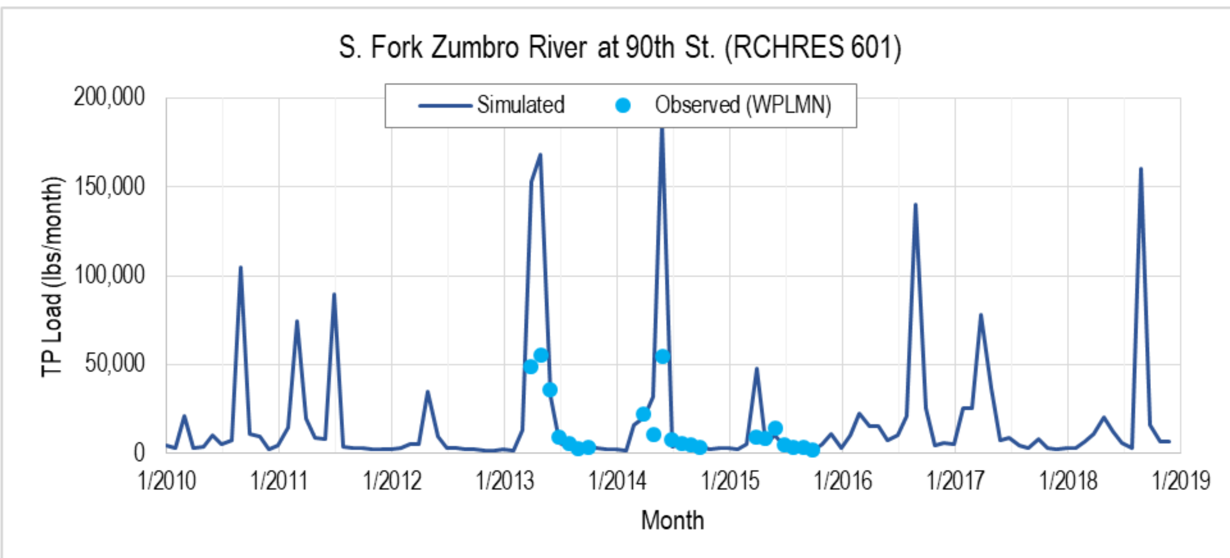

Figure 15: Observed and simulated monthly TP loads for South Fork Zumbro River at 90th Street

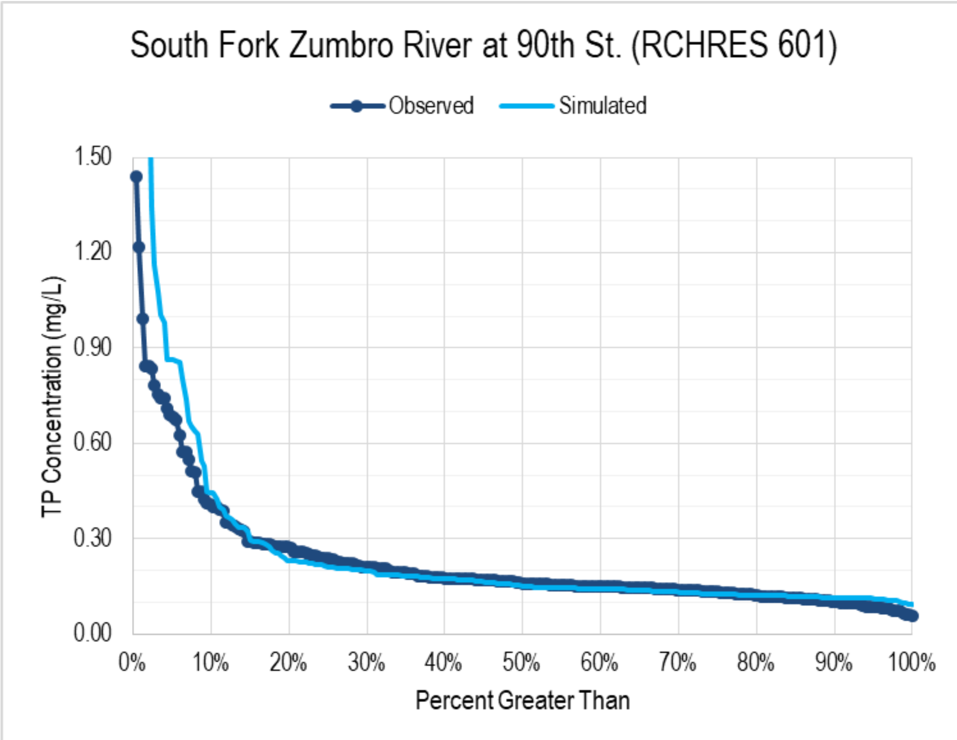

Figure 16: Observed and simulated TP concentration cumulative frequency distributions for South Fork Zumbro River at 90th Street for the 2010-2018 model extension period

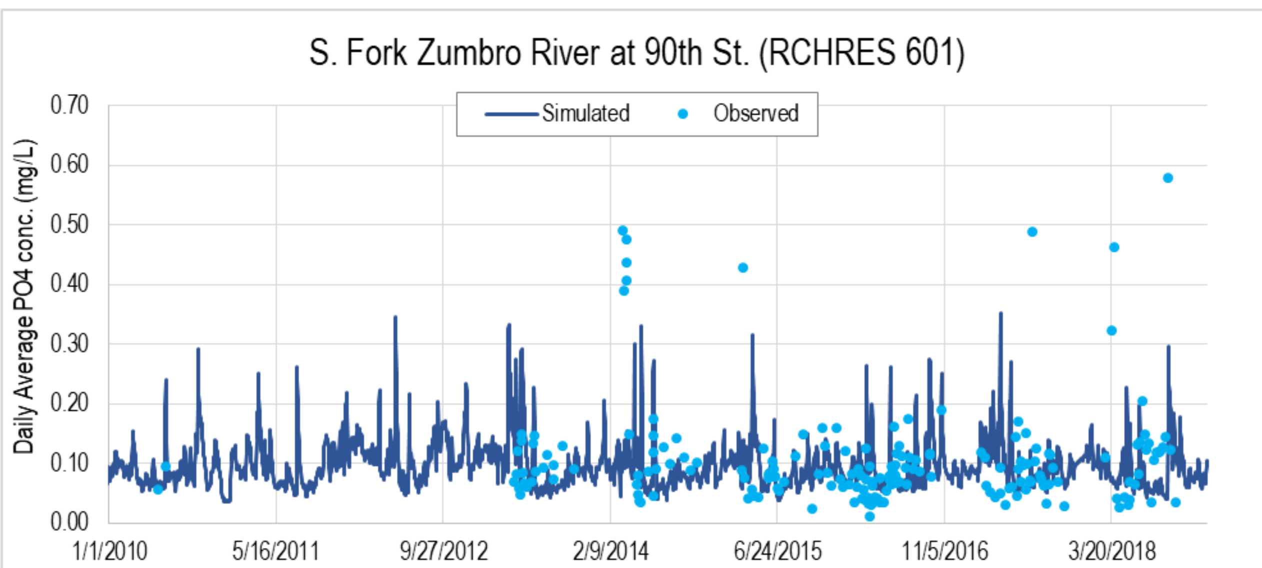

Figure 17: Observed and simulated daily average PO_4 concentrations for South Fork Zumbro River at 90th Street

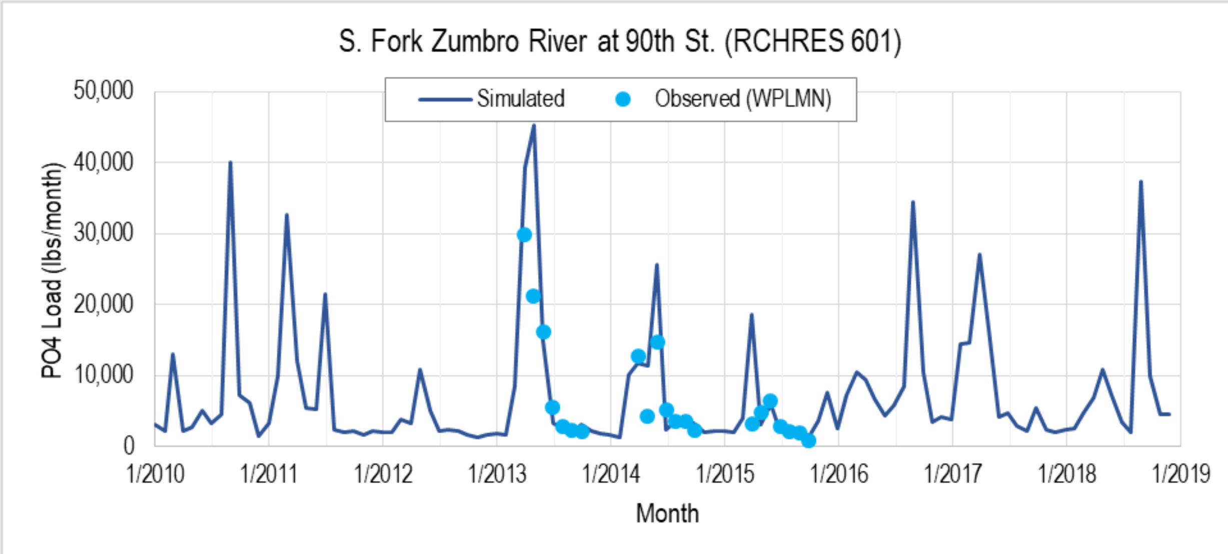

Figure 18: Observed and simulated monthly PO_4 loads for South Fork Zumbro River at 90th Street

Other Water Quality Calibration

The model calibration for other water quality constituents, including water temperature, nitrate plus nitrate (NO_{23}), total nitrogen (TN), and dissolved oxygen (DO), was reevaluated primarily using the additional observational datasets available for the 2010-2018 model extension period. This included monthly nitrogen loads from the WPLMN for the watershed outlet and four upstream locations, which were not yet available during previous phases of ZRWHSPF modeling work. Model performance for the extension period was also evaluated using grab sample concentrations at the five WPLMN locations and other, secondary locations throughout the watershed. Based on the new data and information available to support the revision of the water quality calibration, the following ZRWHSPF model inputs were modified:

- Landside accumulation rates for NO_{23}; and
- Landside interflow and groundwater NO_{23} and organic nitrogen concentrations.

Summary performance statistics for the other water quality constituents are shown in Tables 4 and 5. Visual comparisons of observed and simulated concentrations and monthly loads are shown in Figures 19 to 24, for the Zumbro River at Kellogg and in Appendix C for the other primary calibration locations. Summary performance statistics for the validation period are provided in Table B-3. The overall model performance for other water quality constituents in the current model can be summarized as:

- The relative percent difference between observed and simulated monthly TN and NO_{23} loads are “good” to “very good” at all five WPLMN locations;
- The relative percent difference between observed and simulated water temperature, TN, NO_{23}, DO concentrations are “good” to “very good” at all primary locations; and
- Visual inspection of the time series plots suggests that overall, the model was able to reproduce the range, timing, and magnitude of observations for the other water quality constituents.
- Figure 23 shows infrequent model simulation results with very low DO concentrations, less than 6 mg/L, during late summer conditions. It’s not uncommon to see temporary instabilities in the DO

simulation in HSPF. Without any DO observations lower than 6 mg/L, we expect model instabilities are resulting in these low results rather than “real-world” phenomenon.

Table 4: Model performance evaluation statistics for TN loads, TN concentrations, NO_{23} loads, and NO_{23} concentrations for the 2010-2018 model extension period

Station Name	Monthly TN loads		TN concentrations		Monthly NO_{23} loads		NO_{23} concentrations	
	Count	RPD	Count	RPD	Count	RPD	Count	RPD
Zumbro at Kellogg	84	-11%	320	23%	84	-6%	330	14%
S. Fork at 90th St.	16	5%	167	15%	16	12%	194	3%
S. Br. M. Fork near Oronoco	32	-6%	137	16%	32	5%	139	6%
M. Fork near Oronoco	33	-13%	159	-1%	33	-7%	160	-10%
N. Fork near Mazeppa	33	-18%	151	13%	33	-10%	153	2%

Table 5: Model performance evaluation statistics for water temperature and dissolved oxygen concentration for the 2010-2018 model extension period

Station Name	Water Temp.		DO concentration	
	Count	RPD	Count	RPD
Zumbro at Kellogg	188	-2%	120	-8%
S. Fork at 90th St.	186	-3%	168	-13%
S. Fork at 75th St.	49	-2%	17	-3%
S. Fork at 55th St.	19	-4%	18	-4%
S. Fork at 37th St.	168	-3%	25	-11%
S. Br. M. Fork near Oronoco	126	1%	124	-21%
M. Fork near Oronoco	151	2%	147	-17%
N. Fork near Mazeppa	141	4%	138	-13%

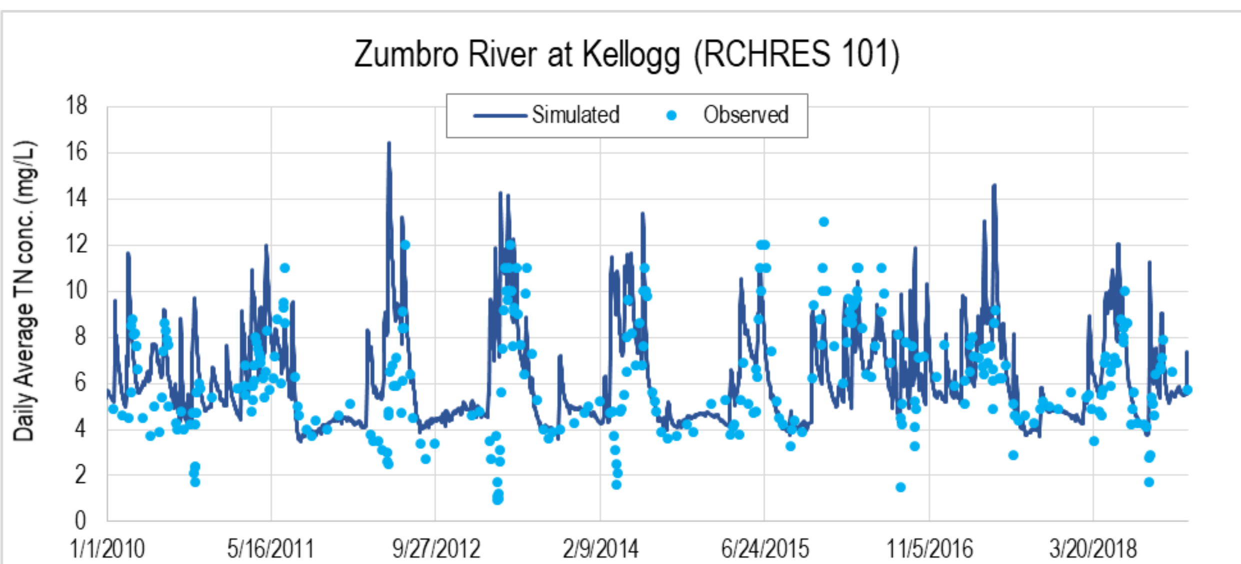

Figure 19: Observed and simulated daily average TN concentrations for Zumbro River at Kellogg

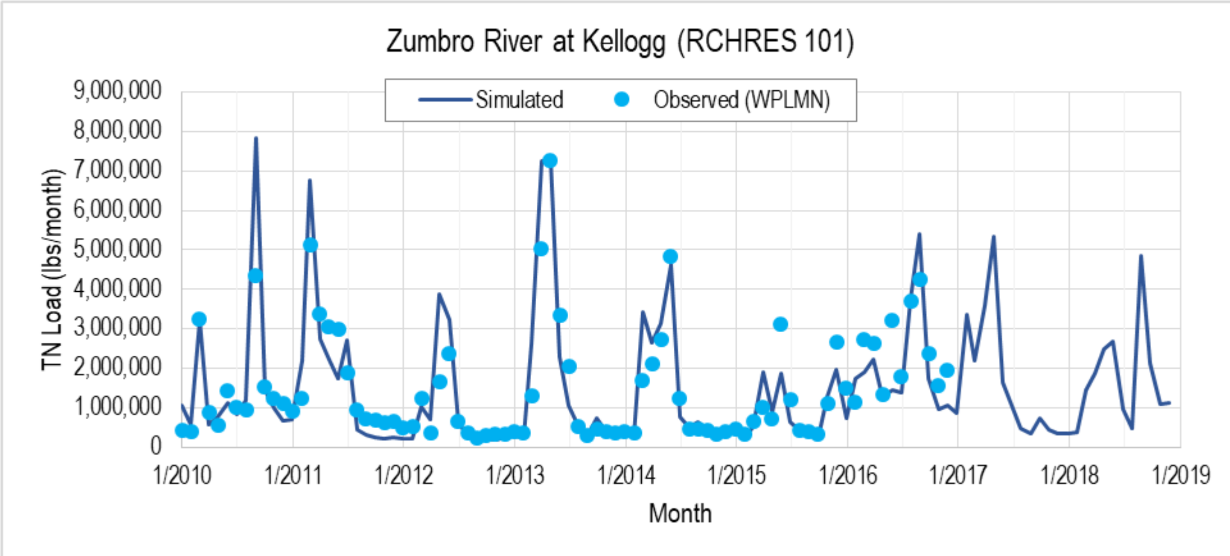

Figure 20: Observed and simulated monthly TN loads for Zumbro River at Kellogg

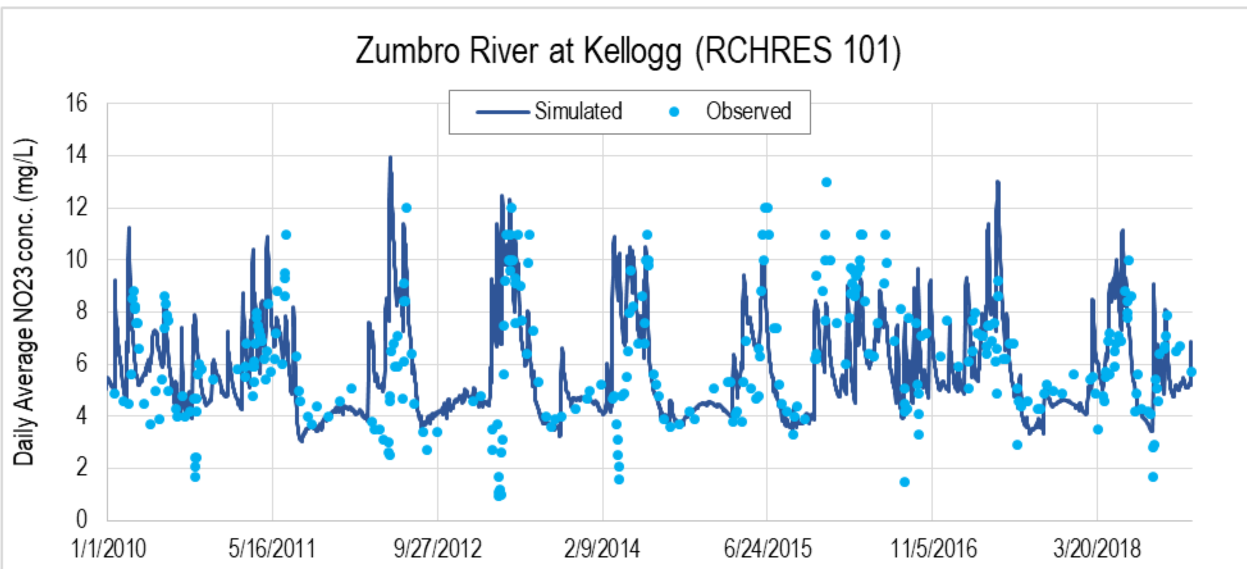

Figure 21: Observed and simulated daily average NO_{23} concentrations for Zumbro River at Kellogg

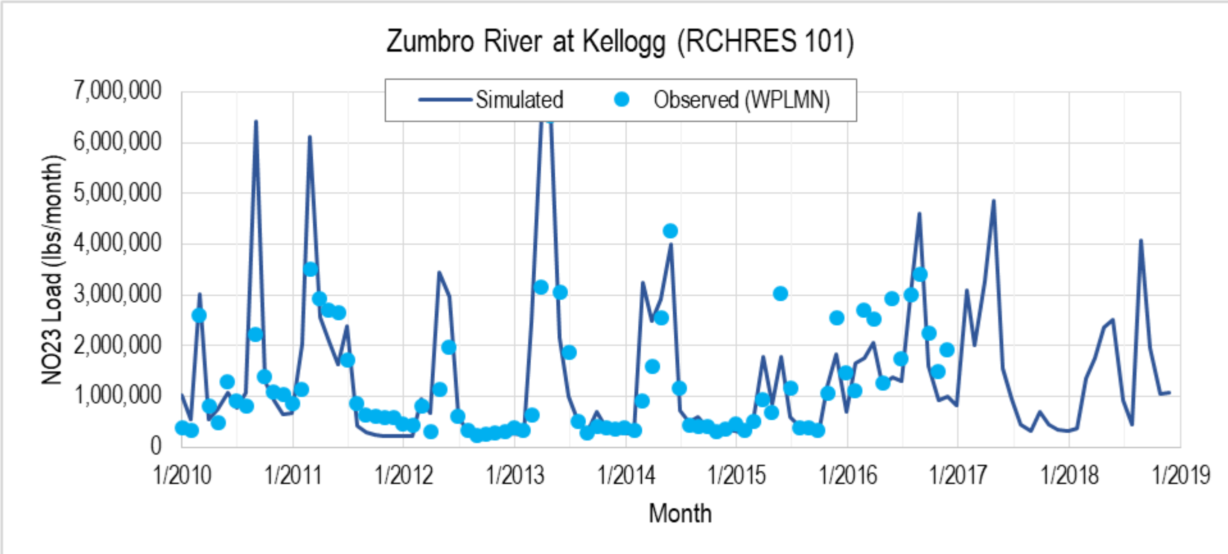

Figure 22: Observed and simulated monthly NO_{23} loads for Zumbro River at Kellogg

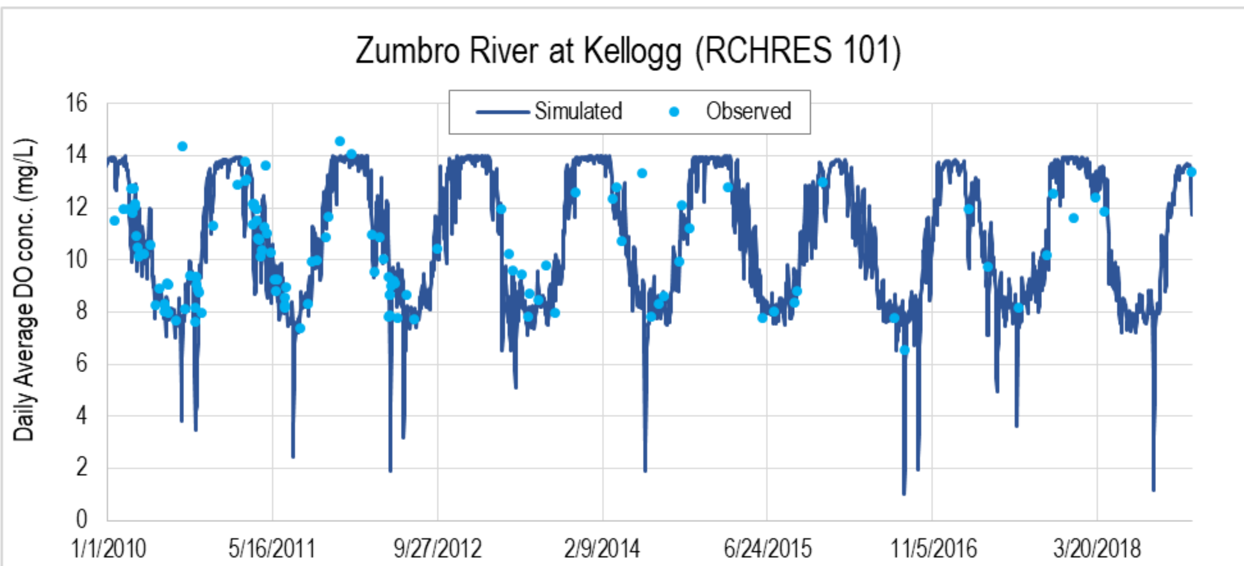

Figure 23: Observed and simulated daily average DO concentrations for Zumbro River at Kellogg

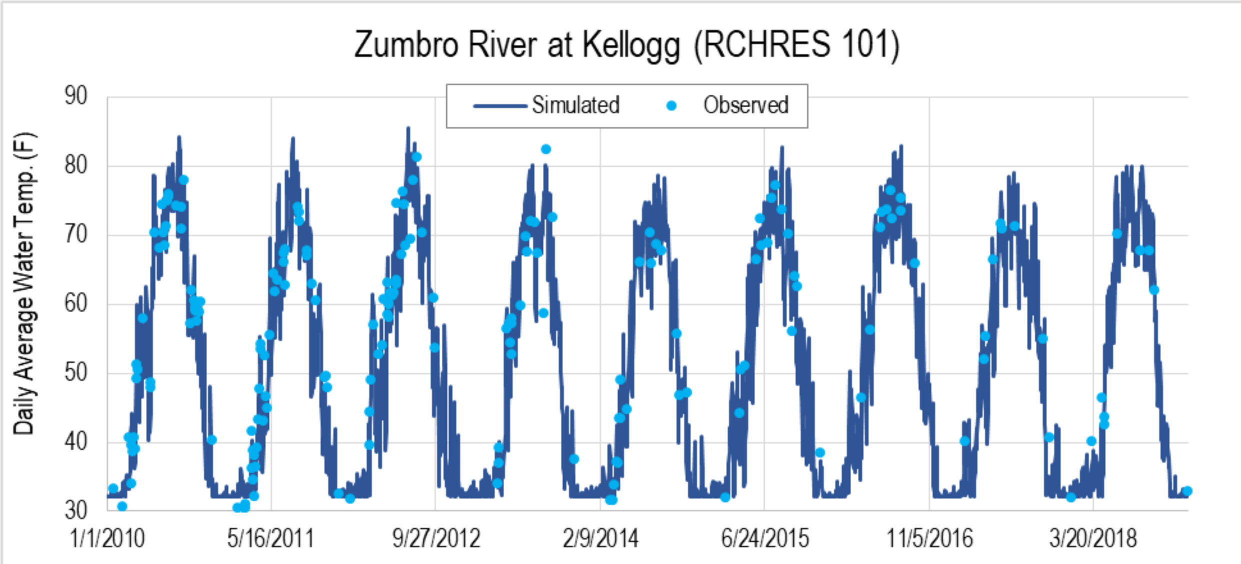

Figure 24: Observed and simulated daily average water temperature for Zumbro River at Kellogg

Model Application

Following completion of the model extension and recalibration efforts, the next objective was to apply the ZRWHSPF model to assess various management scenarios. The purpose of this objective was to evaluate the effects of potential future nonpoint source management actions and hypothetical point source phosphorus wasteload allocations (WLAs).

Management Scenario Overview

LimnoTech worked with MPCA to define the combination of nonpoint source best management practices (BMPs) and hypothetical point source phosphorus WLAs to represent in the ZRWHSPF model scenarios. The selected scenarios are summarized in Table 6 and described in greater detail in the subsequent text.

Table 6: List of management scenarios simulated with ZRWHSPF model

No.	Scenario	Description
1	Baseline	Historic non-point and point source conditions
2	Non-point only	WRAPS BMPs
3	Non-point & WLA1	WRAPS BMPs; Rochester WRP at AWWDF & 0.8 mg-P/L; Other point sources at AWWDF and existing limits or historic concentrations if no limits
4	Non-point & WLA2	WRAPS BMPs; Rochester WRP at 70% AWWDF & 0.8 mg-P/L; Other point sources at AWWDF and existing limits or historic concentrations if no limits
5	Non-point & WLA3	WRAPS BMPs; Rochester WRP at 70% AWWDF & 0.6 mg-P/L; Other point sources at 70% AWWDF and existing limits or historic concentrations if no limits
6	Non-point & WLA4	WRAPS BMPs; Rochester WRP at 70% AWWDF & 0.4 mg-P/L; Other point sources at 70% AWWDF and existing limits or historic concentrations if no limits

Non-Point Source Scenario Details

The potential future nonpoint source management actions simulated in the ZRWHSPF model scenarios were intended to be reflective of strategies described in the Zumbro River Watershed WRAPS report (Wotzka and Watkins, 2017), with an emphasis on the phosphorus reduction BMPs described in Table 19 of the report. The example strategies and levels of adoption were constructed during the WRAPS process by watershed stakeholders and resource managers focused on nonpoint source nutrient reductions. The "fall corn fertilization to pre-plant/starter" BMP was not simulated because of both challenges in practically representing the effects in HSPF and an overall low acreage of implementation assumed at <1% of total cropland acreage for the two HUC-10s where it was listed.

The percentages of total cropland acres assumed to receive the various WRAPS BMPs shown in Table 7 below was constructed by dividing the individual acres of implementation by the total cropland acres for a given HUC-10 basin. These percentages were then used to modify ZRWHSPF model inputs. The Middle Fork Zumbro River HUC-10 (0704000403) was assumed to have the same percentages of implementation as the South Branch Middle Fork Zumbro River HUC-10 (0704000402).

Table 7: Percent of total cropland acres assumed to receive BMPs for phosphorus reduction (computed from Table 19 of the Zumbro WRAPS report)

Management Practice	South Fork	S. Branch Middle Fork	Middle Fork	North Fork	Lower Zumbro
Target P_2O_5 rate	72.0%	74.0%	74.0%	61.0%	66.0%
Use reduced tillage on corn, soy, and small grains	3.4%	8.6%	8.6%	16.8%	24.0%
Riparian buffers, 50 ft. wide, 100 ft. treated	5.4%	4.3%	4.3%	6.4%	7.5%
Perennial crop % of marginal corn & soybean land	2.5%	0.3%	0.3%	0.0%	3.1%
Rye cover crop on corn & soybean acres	5.2%	17.6%	17.6%	8.3%	5.5%
Short season crops planted to a rye cover crop	3.4%	2.6%	2.6%	2.7%	4.1%
Controlled drainage	0.0%	0.5%	0.5%	0.0%	0.0%
Alternative tile intakes	0.5%	0.0%	0.0%	0.0%	0.0%
Inject/incorporate manure	4.0%	5.9%	5.9%	2.6%	5.4%

The overall strategy for representing the effects of these BMPs in HSPF was to modify the model hydrology, sediment, and/or nutrient related parameters that best translated to the real-world physical changes expected with their implementation. Four of these practices (reduced tillage, cover crops, riparian buffers, and conversion of marginal cropland to perennials) were modeled in previous Zumbro and Cannon River Watershed HSPF scenario modeling applications (LimnoTech, 2015; LimnoTech, 2016). The approach used in those efforts set precedence for the parameter changes implemented during this phase. The additional four practices (reduced N and P_2O_5 fertilizer application rates, controlled drainage, alternative tile intakes, and manure injection) were assumed to have limited effect on surface hydrology and sediment erosion, and therefore only nitrogen and phosphorus related parameters were modified. Although controlled drainage will also impact hydrology for artificially drained fields, the hydrology impacts were not represented due to both challenges in practically representing the effects in HSPF and an overall low acreage of implementation. HSPF input parameters modified for each BMP are described in greater detail below and summarized in Table 8.

Cover Crops and Conservation Tillage

The effects of cover crops and conservation tillage were represented in the model by first constructing new PERLND segments with modified parameterization and then updating the SCHEMATIC block to decrease areas from the baseline cropland segments and increasing areas for the new BMP scenario segments according to the percentages specified in the Zumbro WRAPS. Parameter adjustments for conservation tillage included increasing monthly values of interception storage (MON-INTERCEP), nominal upper zone soil moisture storage capacity (MON-UZSN), the soil cover factor (MON-COVER), the coefficients in the equations that simulate soil washoff (KSER) and gully erosion (KGER), and nitrogen and phosphorus concentrations in interflow (MON-IFLW-CONC) and groundwater (MON-GRND-CONC). The same parameters were adjusted for representing cover crops as well as the index to lower zone evapotranspiration (MON-LZETPARM).

Perennials and Riparian Buffers

The effects of converting marginal cropland to perennial vegetation and implementing the 2015 Minnesota buffer initiative (MNDNR, 2015) were represented by decreasing areas of baseline cropland segments and increasing areas for grassland segments according to the percentages specified in the Zumbro WRAPS. In addition to the land cover change, the 50 ft buffers were also assumed to have some additional water quality benefit due to the ability to reduce contaminants in surface runoff from adjacent cropland. The edge-of-field removal efficiencies of the buffers were assumed to be 80% for sediment, 60% for phosphorus, and 40% for nitrogen. The primary source of information used to determine these values was the Agricultural BMP Handbook for Minnesota, with reported reduction efficiencies of 56 – 86% for sediment, 39 – 78% for phosphorus, and 27 – 66% for nitrogen (Miller et al., 2012). For a given subbasin, it was assumed that 25% of the cropland surface runoff would be treated by these new perennial vegetated filter strips. The other 75% was assumed to be untreated because of concentrated flow across the buffers, gully formation, and short-circuiting. Because all cropland in a given subbasin is modeled as one unit, the following "effective" removal efficiencies were computed and used via adjustments to scale factors in the MASS-LINK block: 20% for sediment, 15% for phosphorus, and 10% for nitrogen. These effective removal efficiencies account for both (1) the buffer removal efficiencies for the 25% of cropland assumed to be treated and (2) the 75% of cropland assumed to be untreated [example for sediment: 25% treated*80% removal + 75% untreated*0% removal = effective 20% removal].

Nutrient Management and Drainage Water Management

The fertilizer and manure management BMPs (reduced N and P_2O_5 fertilizer application rates and manure injection/incorporation) were represented by decreasing phosphorus potency factors (POTFW), nitrate-nitrogen accumulation (MON-ACCUM) and storage limits (MON-SQOLIM), and decreasing nitrogen and phosphorus concentrations in interflow (MON-IFLW-CONC) and groundwater (MON-GRND-CONC). The alternative tile intakes and controlled drainage BMPs were represented by decreasing nitrogen and phosphorus concentrations in interflow (MON-IFLW-CONC) and groundwater (MON-GRND-CONC).

Magnitude of Landside Parameter Adjustments

The magnitude of adjustment for the various parameters was determined by the following criteria:

1. Parameters were only adjusted by an amount that was reasonable relative to values for other land uses. For example, the assumed soil cover factor increase to represent conservation tillage was not as high as the soil cover factors for forest and grassland.
2. Parameters were adjusted until the edge-of-field runoff, sediment, TP, and TN reductions relative to the baseline scenario were generally in agreement with values reported in literature or guidance manuals for BMPs. The Agricultural BMP Handbook for Minnesota provided the primary source of information with reported reduction efficiencies (Miller et al., 2012).
3. Interflow and groundwater concentrations of nitrogen and phosphorus were reduced using the default, long-term interflow and groundwater reduction efficiencies reported in the Scenario Application Manager for HSPF BMP reference manual (RESPEC, 2017).

For the BMPs where a SCHEMATIC modification was not made, "effective" interflow and groundwater phosphorus and nitrogen reduction factors were computed for each cropland model segment based on (1) the assumed reduction percentage and (2) the assumed level of adoption. Similar to the strategy described above for deriving scale factors for the MASS-LINK block for cropland routed through riparian buffers, this approach results in an effective nutrient mass reduction that accounts for a higher reduction from areas treated by the BMPs and no reduction from untreated areas. For example, if 80% of the cropland in a subwatershed were to receive the target P_2O_5 rate, and the assumed groundwater TP concentration reduction for this BMP was 4%, then the effective groundwater TP concentration reduction implemented was 3.2% [80% treated*4% reduction + 20% untreated*0% reduction = effective 3.2% reduction]. The final step involved computing a cumulative reduction factor for each cropland segment based on the sum of the individual, effective reduction factors. This strategy enabled a feasible representation of the combined effects of multiple BMPs.

Bed Sediment Concentrations

As a final step in representing the long-term effects of adopting the Zumbro WRAPS BMPs, an initial model simulation was completed with the above-described changes to inform one additional model input modification: bed sediment phosphorus concentrations (NUT-BEDCONC). This parameter modification assumes that the baseline sediment phosphorus concentrations are relatively elevated, reflective of long-term legacy phosphorus losses from the landscape that have accumulated in the riverine system. It also assumes that with reduced phosphorus loading into the waterways, over time the bed sediment phosphorus concentrations would also be reduced. The average annual phosphorus load reductions simulated with the initial model run were used to inform the magnitude of the bed sediment phosphorus concentrations for the "final" WRAPS scenario run and subsequent scenarios reflecting implementation of the WRAPS BMPS.

Table 8: HSPF parameter changes to represent BMPs for phosphorus reduction

Parameter	Reduced Tillage	Cover Crops	Riparian Buffers	Perennials	N and P_2O_5 rates	Manure injection	Controlled Drainage	Tile Intakes	Combined Effects
Hydrology Inputs									
CEPSC	X	X							
UZSN	X	X							
LZETP		X							
Sediment Inputs									
KSER	X	X							
KGER	X	X							
COVER	X	X							
Phosphorus Inputs									
POTFW					X	X			
IFW conc	X	X			X	X	X	X	
GW conc	X	X			X	X	X	X	
Nitrogen Inputs									
ACCUM					X	X			
SQOLIM					X	X			
IFW conc	X	X			X	X	X	X	
GW conc	X	X			X	X	X	X	
Other Inputs									
SCHEMATIC[1]			X	X					
MASS-LINK[2]			X						
NUT-BEDCONC									X

1 - Schematic modifications were used for representing cropland converted to buffers or perennials (assumed as grassland)

2 - Mass-Link modifications were used to decrease surface sediment, P, and N loads from cropland routed through buffers

Point Source Scenario Details

MPCA provided phosphorus WLA scenarios to represent in the ZRWHSPF model (Wasley, 2020). The assumed flow and TP concentrations for municipal facilities for these four scenarios (WLA1 through WLA4) are summarized in Table 9, and the assumptions for industrial dischargers are summarized in Table 10. Concentrations for other water quality constituents were held constant for all scenarios and were assumed based on an analysis of relatively recent (i.e., 2010-2018) observed data, if available.

The general strategy for most municipal facilities was to use the AWWDF and existing permit concentration or load limit for WLA1 and WLA2, and then to reduce June-September loads by 30% for WLA3 and WLA4 via holding the TP concentration constant and decreasing flow to 70% of AWWDF. Industrial facility WLAs were held constant across all scenarios assuming AWWDF and a TP concentration based on either an existing limit or historic data. There are several exceptions to this approach:

- Rochester WRP had unique TP loads for each of the four WLA scenarios;
- Kasson WWTP TP loads were held constant for all four WLA scenarios due to a relatively restrictive existing limit, which meant increasing the TP concentration for WLA3 and WLA4 to compensate for the 30% decrease in flow to maintain a constant load across all four WLA scenarios;
- For facilities downstream of Lake Zumbro without an existing TP limit, the assumed TP concentration was based on historic data;
- The potential future Oronoco WWTF was assumed to have a relatively restrictive Jun-Sep effluent TP concentration limit, therefore it was given a higher Oct-May TP concentration at 1 mg/L;
- Facilities with stabilization ponds were assigned unique flow distribution time series. A total annual flow estimate was computed based on an analysis of historic average number of days discharging per year and the design discharge rate. This total annual flow was then distributed in a daily flow time series based on a second analysis of the frequency of historic discharges by these facilities within the allowable discharge periods (Apr 1-Jun 15 and Sep 15-Dec 31). See LimnoTech (2017b) for additional details;
- Flows for Milestone Golberg Quarry were maintained at historic reported discharges rather than the design flow, which is approximately double the actual average flow. This was done to avoid artificial dilution of South Fork Zumbro River; and
- Although the Milestone North Quarry has a permit and specified design flow of 11 million gallons per day (MGD), this industrial facility was not represented to avoid artificial dilution because dewatering discharges have never occurred over the historic period and are uncertain in the future.

Table 9: TP concentrations and flows for municipal facilities (Jun-Sep) for WLA scenarios[1]

Municipal Facility	WLA 1		WLA 2		WLA 3		WLA 4	
	conc. (mg/L)	flow (mgd)	conc. (mg/L)	flow (mgd)	conc. (mg/L)	flow (mgd)	conc. (mg/L)	flow (mgd)
Bellechester WWTP [2]	2.0		2.0		2.0		2.0	
Byron WWTP	0.8	1.400	0.8	1.400	0.8	0.980	0.8	0.980
Camp Victory WWTP	5.0	0.027	5.0	0.027	5.0	0.019	5.0	0.019
Claremont WWTP	1.0	0.206	1.0	0.206	1.0	0.144	1.0	0.144
Dodge Center WWTP	1.0	0.973	1.0	0.973	1.0	0.681	1.0	0.681
Goodhue WWTP	5.0	0.099	5.0	0.099	5.0	0.069	5.0	0.069
Hallmark Terrace Inc. [2]	2.0		2.0		2.0		2.0	
Hammond WWTP	5.0	0.023	5.0	0.023	5.0	0.016	5.0	0.016
Hayfield WWTP	0.5	0.780	0.5	0.780	0.5	0.546	0.5	0.546
Kasson WWTP	0.27	2.070	0.27	2.070	0.39	1.449	0.39	1.449
Kellogg WWTP [2]	2.0		2.0		2.0		2.0	
Kenyon WWTP	3.5	0.357	3.5	0.357	3.50	0.250	3.5	0.250
Mazeppa WWTP	5.0	0.073	5.0	0.073	5.00	0.051	5.0	0.051
Pine Island WWTP	1.0	0.705	1.0	0.705	1.00	0.494	1.0	0.494
Rochester WRP	0.8	23.85	0.8	16.695	0.6	16.695	0.4	16.695
Wanamingo WWTP	3.5	0.458	3.5	0.458	3.5	0.321	3.5	0.321
West Concord WWTP	1.0	0.473	1.0	0.473	1.0	0.331	1.0	0.331
Zumbro Falls WWTP [2]	2.0		2.0		2.0		2.0	
Zumbro Ridge Estates MHP	3.5	0.025	3.5	0.025	3.5	0.018	3.5	0.018
Zumbrota WWTP	2.0	1.110	2.0	1.110	2.0	0.777	2.0	0.777
Oronoco WWTF [3]	0.3	0.638	0.3	0.638	0.3	0.447	0.3	0.447

[1] - Facilities were set at WLA1 flows and concentrations for Oct-May for all scenarios, except for Oronoco WWTF
[2] - Pond facility flows were estimated as the average number of discharge days per year times the design flow
[3] - Oronoco WWTF was set to 1.0 mg/L in Oct-May

Table 10: WLAs for industrial facilities used in all point source scenarios

Industrial Facility	TP conc. (mg/L)	Flow (mgd)
AMPI - Rochester	0.15	0.64
Franklin Heating Station	0.50	1.356
Kemps - Milk Plant	0.50	0.072
Kerry Inc.	0.10	0.90
Milestone - Golberg Quarry	0.025	Historic
Rochester Athletic Club	2.0	0.02
Seneca Foods - Rochester	0.60	0.99
Stussy - Mantorville Quarry	0.05	0.54
DFA - Zumbrota	0.30	0.50

Management Scenario Results

Post-processing of the scenario results included computing annual average loading, flow-weighted mean concentrations (FWMCs), and time-weighted mean concentrations (TWMCs). FWMCs and TWMCs (i.e., straight-averages) were summarized for the June-September period for Lake Zumbro inflow model reaches, "whole-lake" computations, and exclusion of the top 15% flows (per the Lake Zumbro site specific standard). Post-processing also summarized scenario results for the South Branch Middle Fork Zumbro River model segments (reach 07040004-978). A comparison of average annual sediment, TP, and TN loading for the baseline run and five hypothetical scenario runs over the 1996-2018 simulation period is provided in Table 11 below. Annual time series plots of sediment, TP, and TN loading for the South Fork Zumbro River for a subset of the years simulated are shown in Figures 25 to 27. Figure 28 shows the distribution of seasonal June-September FWMCs without the top 15% flows for Lake Zumbro inflow model reaches, and Table 12 lists the FWMCs for each season simulated. Additional FWMC and TWMC are available in the attached Excel file.

Table 11: Average annual sediment, TP, and TN loading for the 1996-2018 period for the baseline simulation and five scenarios.

Scenario	Sediment Loading		TP Loading		TN Loading	
	tons/year	change	lbs/year	change	lbs/year	change
Baseline	210,100		762,300		16,479,000	
WRAPS	168,600	-19.8%	520,200	-31.8%	13,274,000	-19.4%
WRAPS & WLA1	170,200	-19.0%	547,500	-28.2%	14,358,000	-12.9%
WRAPS & WLA2	169,900	-19.1%	543,800	-28.7%	14,198,000	-13.8%
WRAPS & WLA3	169,800	-19.2%	539,600	-29.2%	14,155,000	-14.1%
WRAPS & WLA4	169,800	-19.2%	537,600	-29.5%	14,154,000	-14.1%

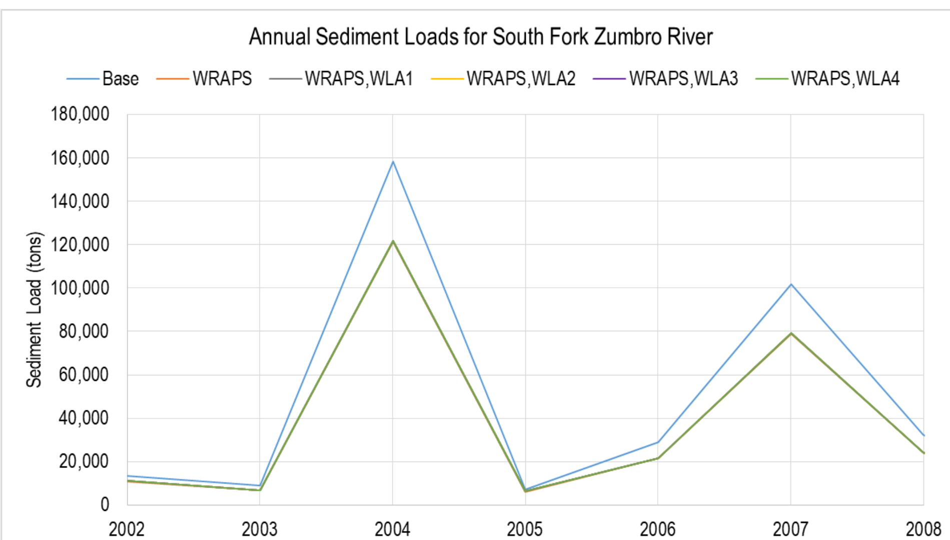

Figure 25: Annual sediment loading for the South Fork Zumbro River at 90th St. for the baseline and management scenarios (2002-2008).

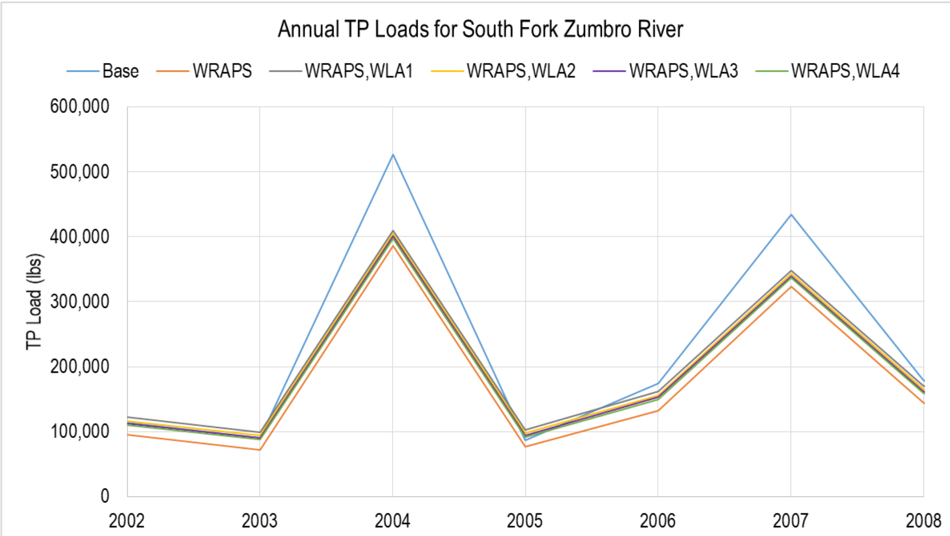

Figure 26: Annual TP loading for the South Fork Zumbro River at 90th St. for the baseline and management scenarios (2002-2008).

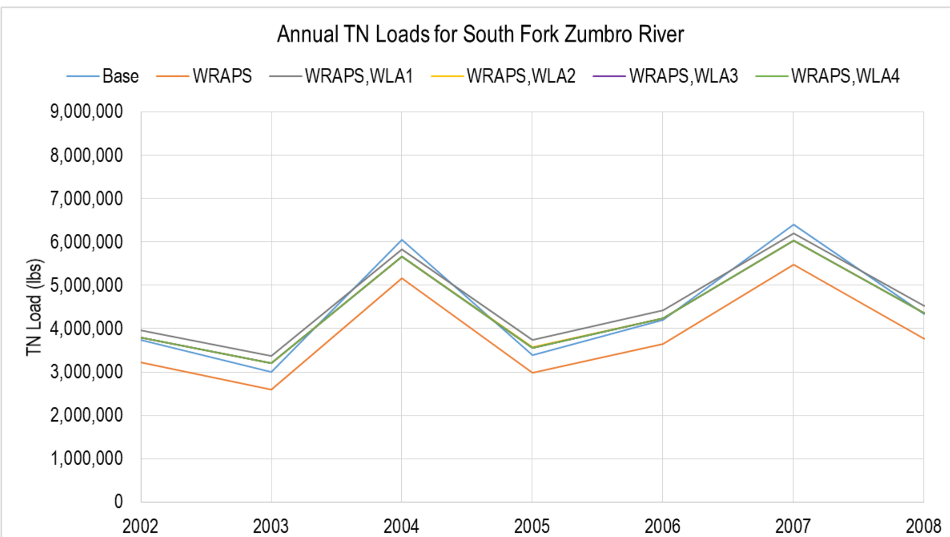

Figure 27: Annual TN loading for the South Fork Zumbro River at 90th St. for the baseline and management scenarios (2002-2008).

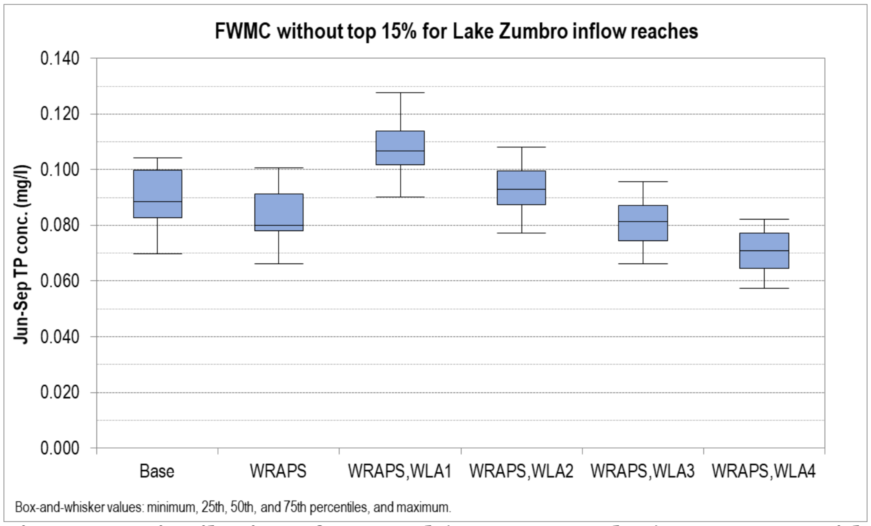

Figure 28: Distribution of seasonal (June-September) TP FWMCs without the top 15% of flows for the combined reach inflows into Lake Zumbro (1996-2018).

Table 12: Estimated June-September flow-weighted mean TP concentrations with the top 15% of daily flows removed for six scenarios for the combined inflow to Lake Zumbro from the South Fork Zumbro River and Middle Fork Zumbro River.

Period	Baseline	WRAPS	WRAPS & WLA1	WRAPS & WLA2	WRAPS & WLA3	WRAPS & WLA4
Jun-Sep 1996	0.079	0.076	0.106	0.088	0.073	0.061
Jun-Sep 1997	0.104	0.092	0.114	0.104	0.092	0.082
Jun-Sep 1998	0.079	0.075	0.102	0.087	0.074	0.064
Jun-Sep 1999	0.088	0.083	0.094	0.082	0.072	0.065
Jun-Sep 2000	0.091	0.085	0.115	0.100	0.088	0.077
Jun-Sep 2001	0.088	0.080	0.108	0.094	0.082	0.072
Jun-Sep 2002	0.104	0.094	0.114	0.101	0.089	0.080
Jun-Sep 2003	0.084	0.079	0.113	0.092	0.076	0.062
Jun-Sep 2004	0.104	0.092	0.107	0.095	0.085	0.077
Jun-Sep 2005	0.089	0.084	0.114	0.096	0.081	0.069
Jun-Sep 2006	0.090	0.079	0.103	0.091	0.080	0.071
Jun-Sep 2007	0.104	0.092	0.115	0.100	0.088	0.079
Jun-Sep 2008	0.083	0.080	0.107	0.090	0.076	0.065
Jun-Sep 2009	0.104	0.101	0.128	0.108	0.096	0.082
Jun-Sep 2010	0.100	0.093	0.114	0.099	0.087	0.077
Jun-Sep 2011	0.079	0.074	0.098	0.084	0.072	0.063
Jun-Sep 2012	0.090	0.091	0.125	0.103	0.086	0.071
Jun-Sep 2013	0.070	0.066	0.090	0.077	0.066	0.058
Jun-Sep 2014	0.082	0.076	0.099	0.086	0.075	0.066
Jun-Sep 2015	0.087	0.079	0.107	0.093	0.081	0.070
Jun-Sep 2016	0.099	0.088	0.107	0.097	0.087	0.080
Jun-Sep 2017	0.081	0.078	0.099	0.085	0.074	0.065
Jun-Sep 2018	0.089	0.079	0.102	0.091	0.081	0.074

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Appendix A: Performance Metric Equations and Tolerances

Nash-Sutcliffe Efficiency (NSE):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$$

Percent Bias (PBIAS):

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - S_i) * (100)}{\sum_{i=1}^{n}(O_i)}\right]$$

Mean Relative Percent Difference (RPD):

$$RPD = \frac{1}{n}\sum_{i=1}^{n}\frac{S_i - O_i}{\frac{1}{2}(S_i + O_i)} \times 100$$

where:

n is the number of samples
O_i is the observed value
$\bar{O}$ is the mean observed value
S_i is the simulated value

Table A-1: Model performance ratings for R-squared, NSE, PBIAS, RPD and RPE

Performance Rating	R-squared for streamflow (Duda et al., 2012)		NSE for annual and monthly streamflow (Parajuli et al., 2009)	PBIAS for monthly streamflow (Moriasi et al., 2007)	RPD (Duda et al., 2012)		
	Daily	Monthly			Streamflow	Sediment	Water Quality
Excellent			> 0.90				
Very good	>0.80	> 0.85	0.75 – 0.89	< ±10	<10%	<20%	<15%
Good	0.70-0.80	0.75-0.85	0.50 – 0.74	±10 – ±15	10 – 15%	20 – 30%	15 – 25%
Fair / Satisfactory	0.60-0.70	0.65-0.75	0.25 – 0.49	±15 – ±25	15 – 25%	30 – 45%	25 – 35%
Poor	<0.60	0.55-0.65	0.00 – 0.24		>25%	>45%	>35%
Unsatisfactory		< 0.55	< 0.00	> ±25			

Appendix B: Additional Model Performance Evaluation Statistics

Table B-1: Model performance evaluation statistics for secondary hydrology calibration locations for the 2010-2018 model extension period

Time Interval	Statistic	South Fork at US-14	South Fork at CR-104	Middle Fork Pine Island	S. Branch M. Fork near Post Town	North Fork at Wanamingo
		2010-2018	2011-2018	2011-2018	2011-2017	2010-2018
Annual	*Count*	9	8	8	7	8
	R-Squared	0.86	0.92	0.93	0.95	0.87
	NSE	0.73	0.92	0.88	0.85	0.72
	RPD	-10.9%	3.6%	3.1%	-3.5%	-5.8%
Monthly	*Count*	88	79	77	56	77
	R-Squared	0.85	0.85	0.85	0.89	0.86
	NSE	0.83	0.85	0.85	0.84	0.84
	P-Bias	11.49	0.42	2.23	9.79	11.29
	RPD	-12.3%	12.5%	14.4%	13.6%	-2.0%
Daily	*Count*	2462	2309	2205	1534	2130
	R-Squared	0.71	0.74	0.69	0.76	0.67
	RPD	-13.7%	13.2%	12.1%	14.6%	2.0%

Table B-2: Model performance evaluation statistics for primary (Zumbro at Kellogg, South Fork at 37th St.) and secondary hydrology calibration locations for the 1996-2009 model validation period

Time Interval	Statistic	Zumbro at Kellogg	South Fork at 37th Street	South Fork at US-14	Middle Fork Pine Island	North Fork at Wanamingo
		2007-2009	1996-2009	1998-2009	2007-2008	1998-2007
Annual	*Count*	3	14	12	2	10
	R-Squared	0.82	0.90	0.92	1.00	0.76
	NSE	0.69	0.85	0.88	0.92	0.75
	RPD	6.0%	7.9%	-2.4%	-28.3%	-1.4%
Monthly	*Count*	23	168	107	11	82
	R-Squared	0.78	0.78	0.78	0.96	0.68
	NSE	0.42	0.76	0.78	0.87	0.68
	P-Bias	-6.79	-6.80	6.44	16.34	1.22
	RPD	-5.0%	8.6%	3.9%	1.2%	12.4%
Daily	*Count*	627	5113	2805	256	2184
	R-Squared	0.68	0.71	0.62	0.87	0.53
	RPD	-8.3%	5.4%	3.9%	15.7%	20.8%

Table B-3: Model performance evaluation statistics for primary water quality calibration locations for the 1996-2009 model validation period

Parameter	Zumbro River at Kellogg			S. Fork Zumbro River at 90th St			S. Fork Zumbro River at 75th St		
	Range	Count	RPD	Range	Count	RPD	Range	Count	RPD
TSS conc.	2007-2009	128	-33%	2007-2009	51	-24%	2000-2009	69	-6%
TP conc.	2007-2009	121	2%	2007-2009	51	9%	2000-2008	64	3%
PO_4 conc.	2007-2009	98	14%	2007-2009	37	13%	2003-2007	28	-1%
TN conc.	2007-2009	97	26%	2007-2009	39	12%	-	-	-
NO_{23} conc.	2007-2009	119	40%	1999-2009	91	11%	-	-	-
Water Temp.	2008-2009	77	-5%	2005-2009	70	-9%	1996-2009	270	-6%
DO conc.	2008-2009	71	-2%	-	-	-	1996-2009	70	6%

Appendix C: Additional Calibration Plots

Hydrology

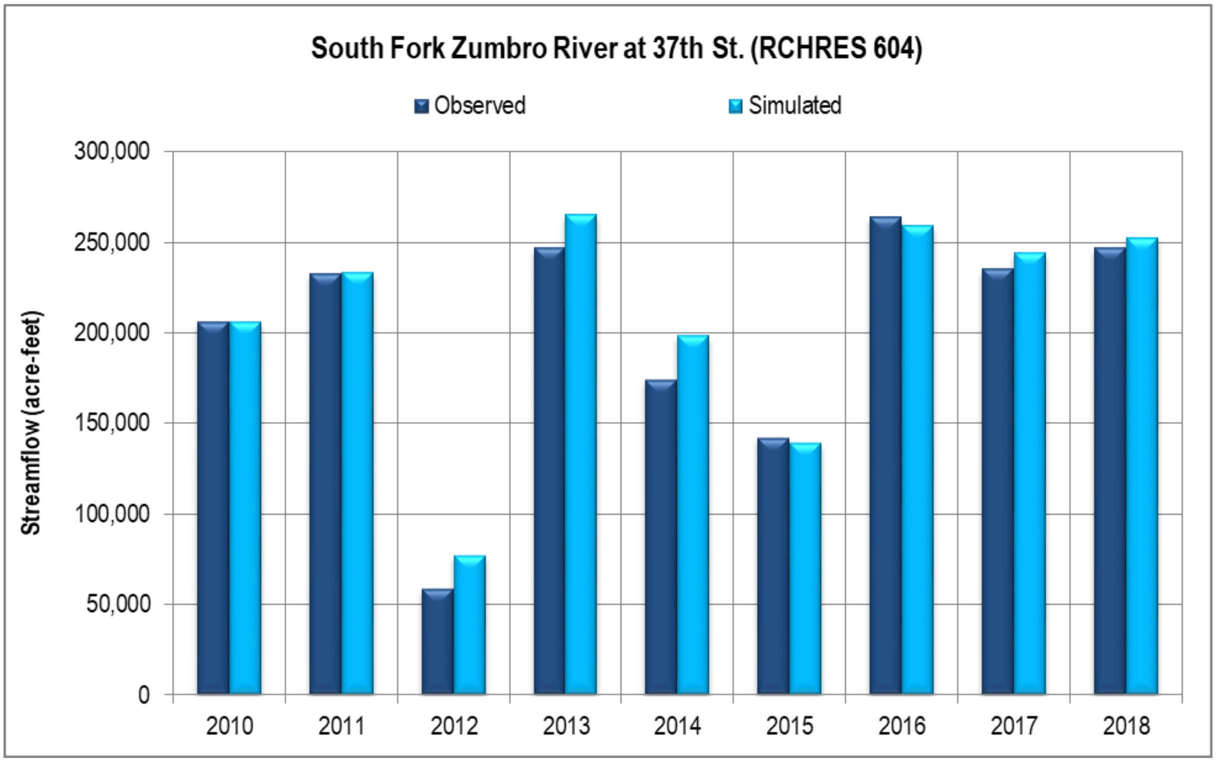

Figure C-1: Observed and simulated annual streamflow for South Fork Zumbro River at 37th St.

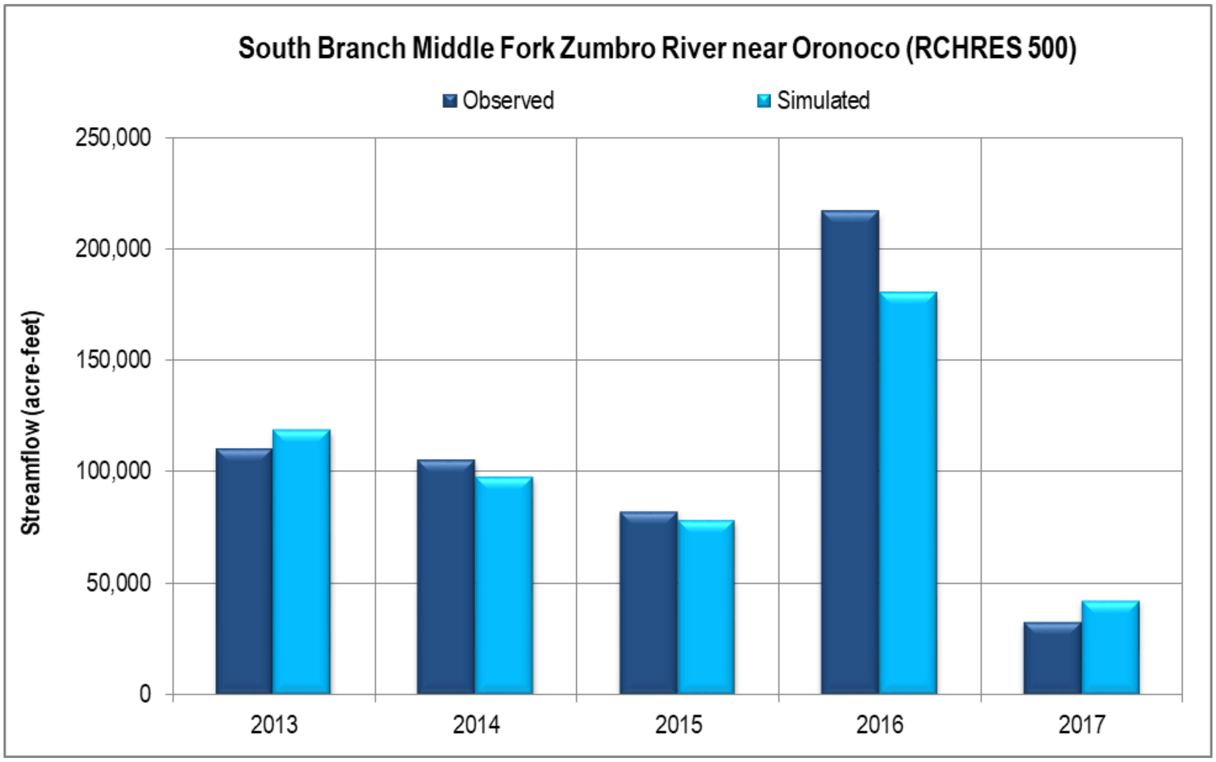

Figure C-2: Observed and simulated annual streamflow for South Branch Middle Fork Zumbro River near Oronoco

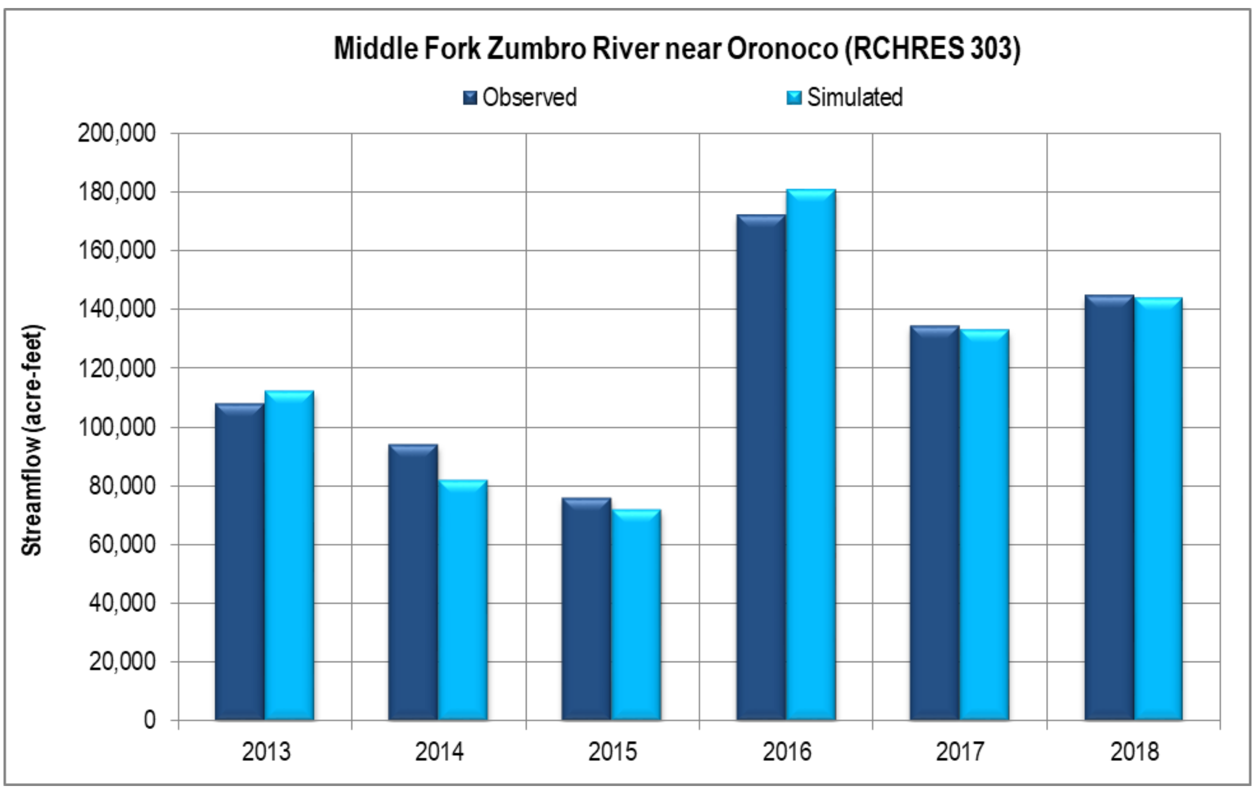

Figure C-3: Observed and simulated annual streamflow for Middle Fork Zumbro River near Oronoco

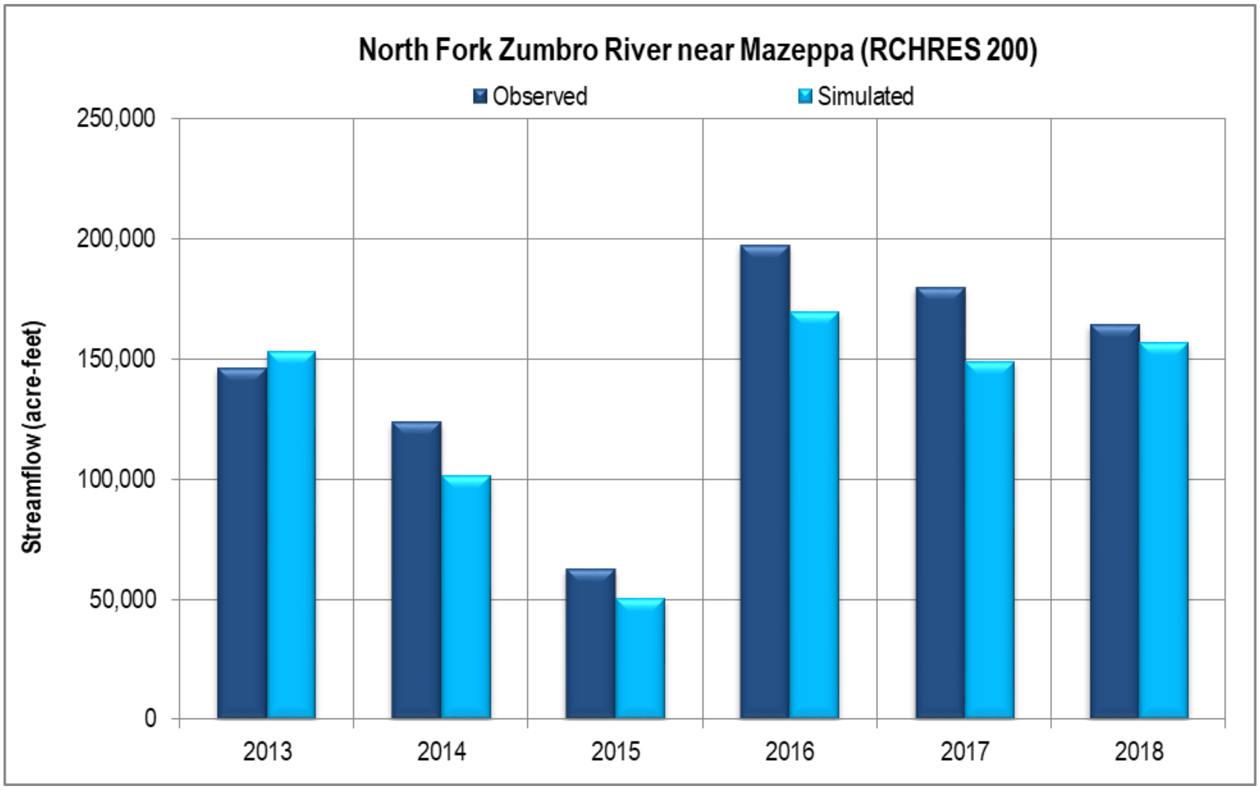

Figure C-4: Observed and simulated annual streamflow for North Fork Zumbro River near Mazeppa

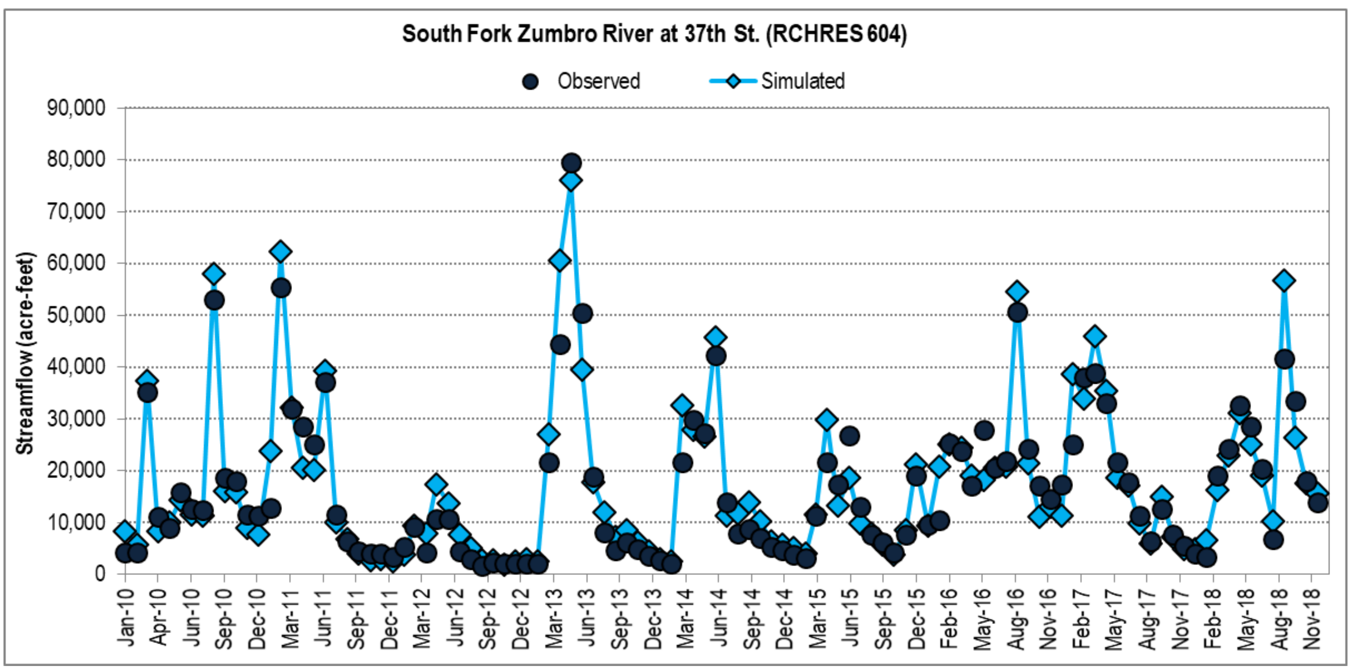

Figure C-5: Observed and simulated monthly streamflow for South Fork Zumbro River at 37th St.

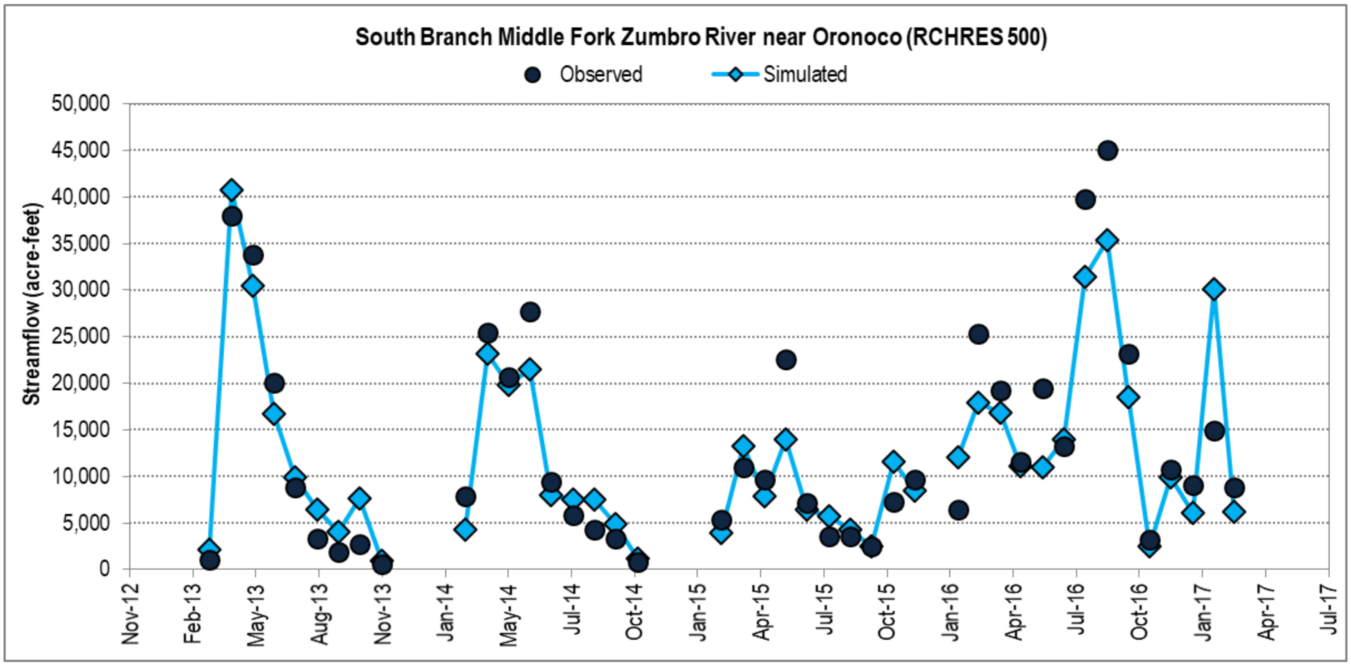

Figure C-6: Observed and simulated monthly streamflow for South Branch Middle Fork Zumbro River near Oronoco

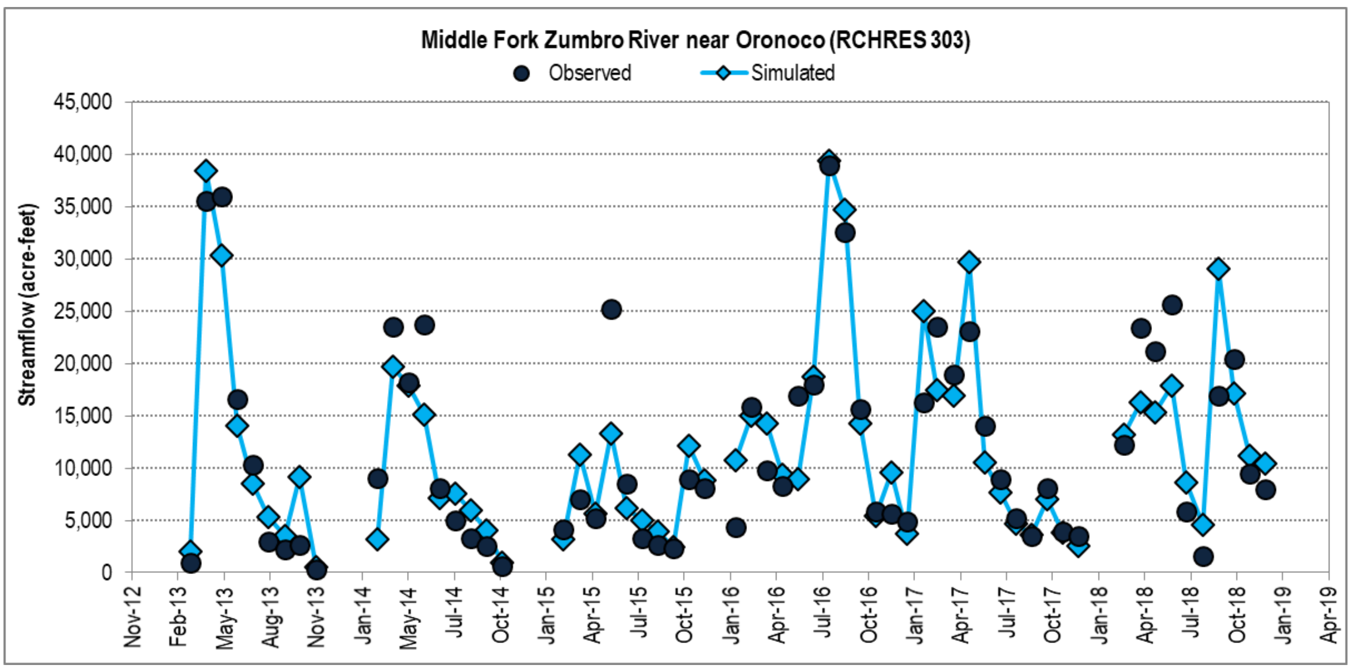

Figure C-7: Observed and simulated monthly streamflow for Middle Fork Zumbro River near Oronoco

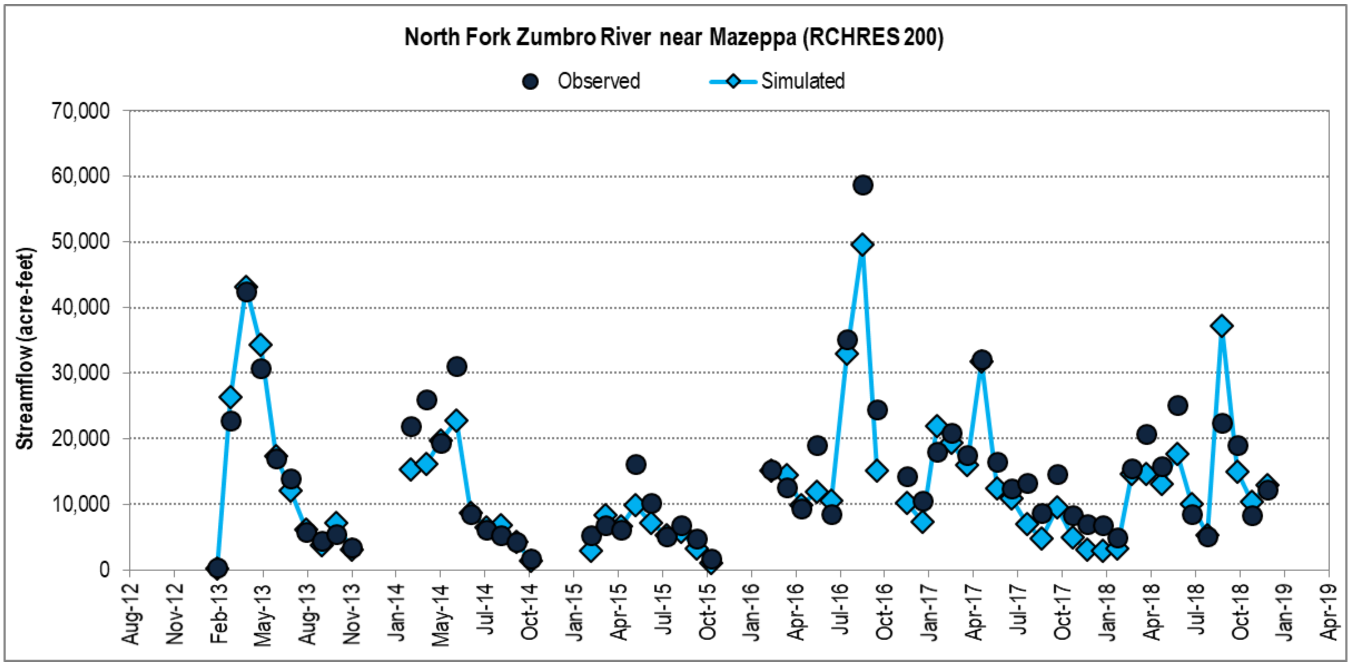

Figure C-8: Observed and simulated monthly streamflow for North Fork Zumbro River near Mazeppa

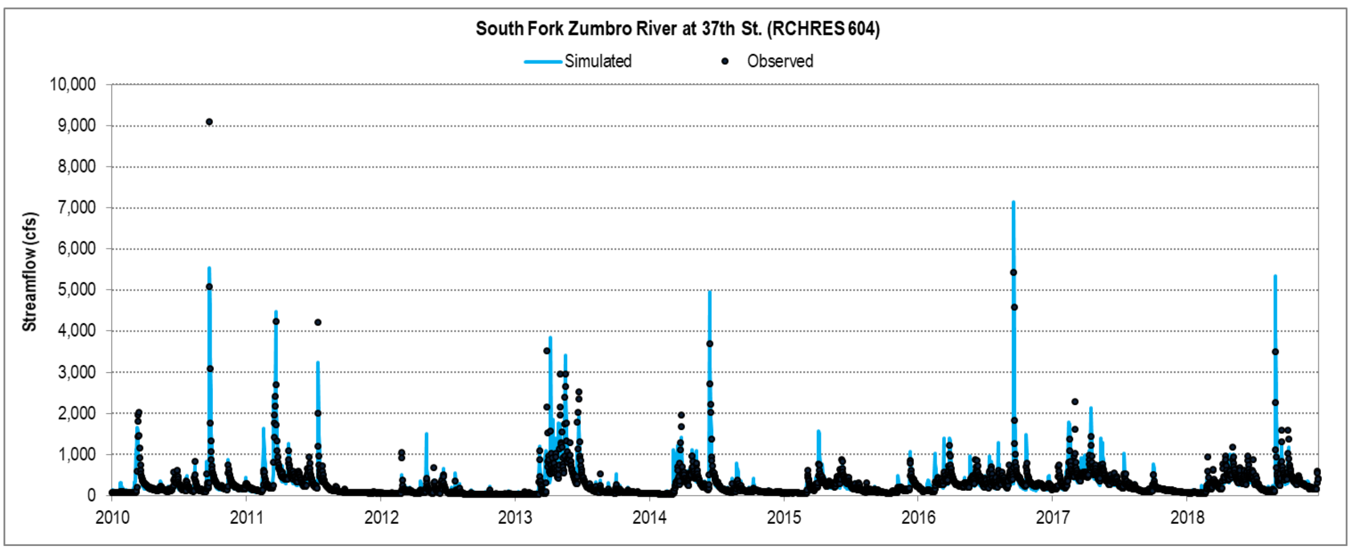

Figure C-9: Observed and simulated daily average streamflow for South Fork Zumbro River at 37th St.

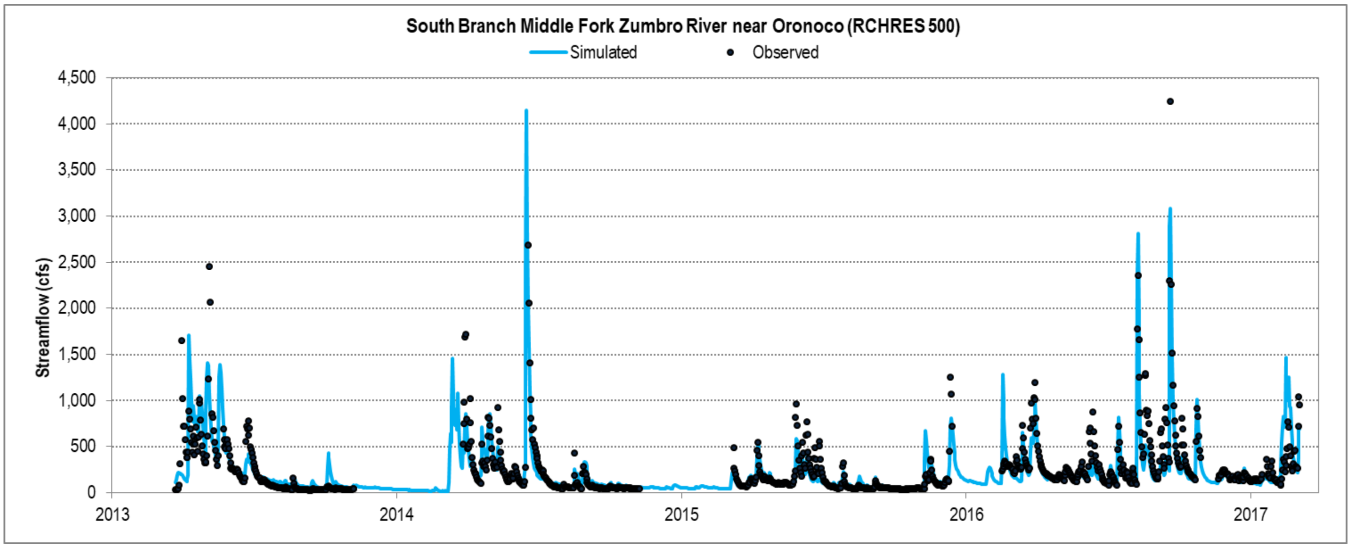

Figure C-10: Observed and simulated daily average streamflow for South Branch Middle Fork Zumbro River near Oronoco

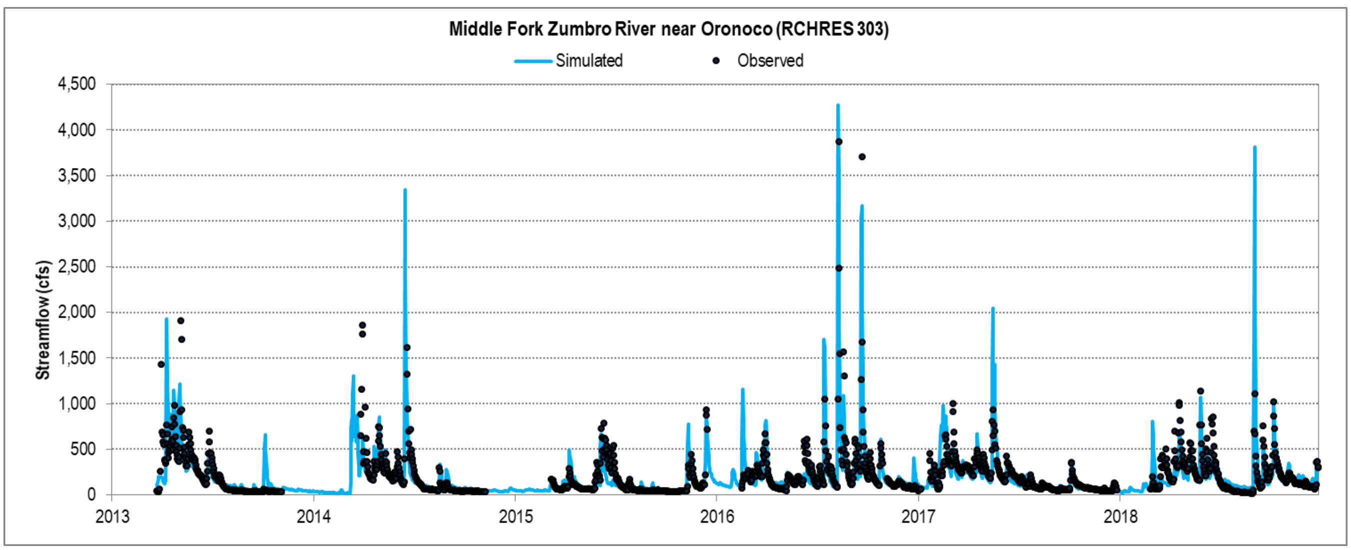

Figure C-11: Observed and simulated daily average streamflow for Middle Fork Zumbro River near Oronoco

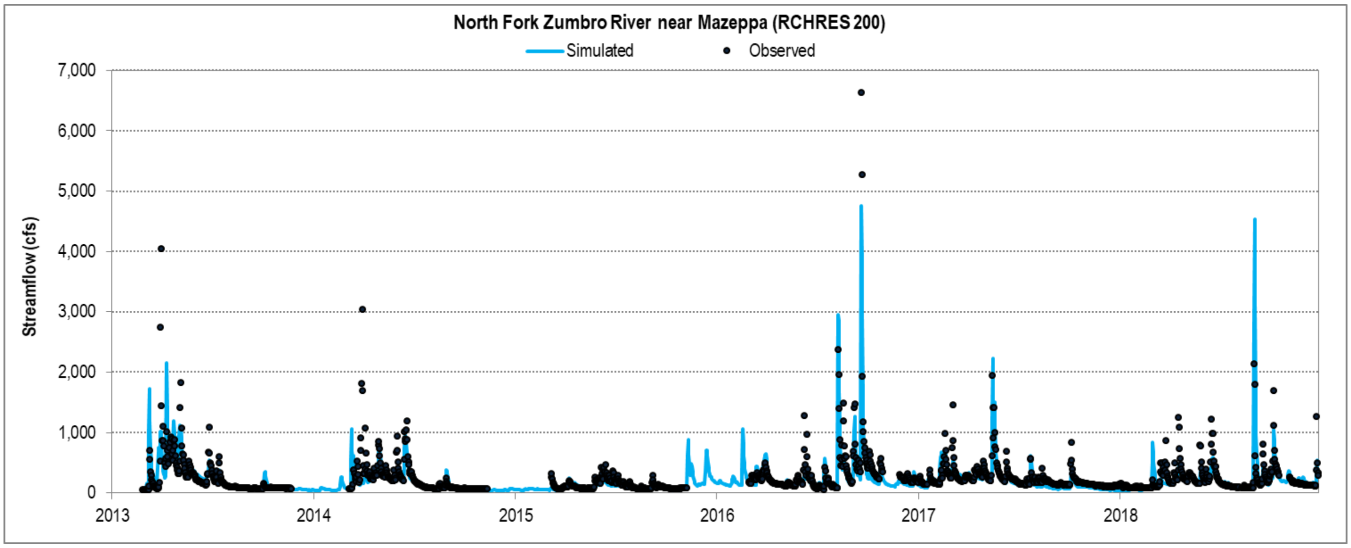

Figure C-12: Observed and simulated daily average streamflow for North Fork Zumbro River near Mazeppa

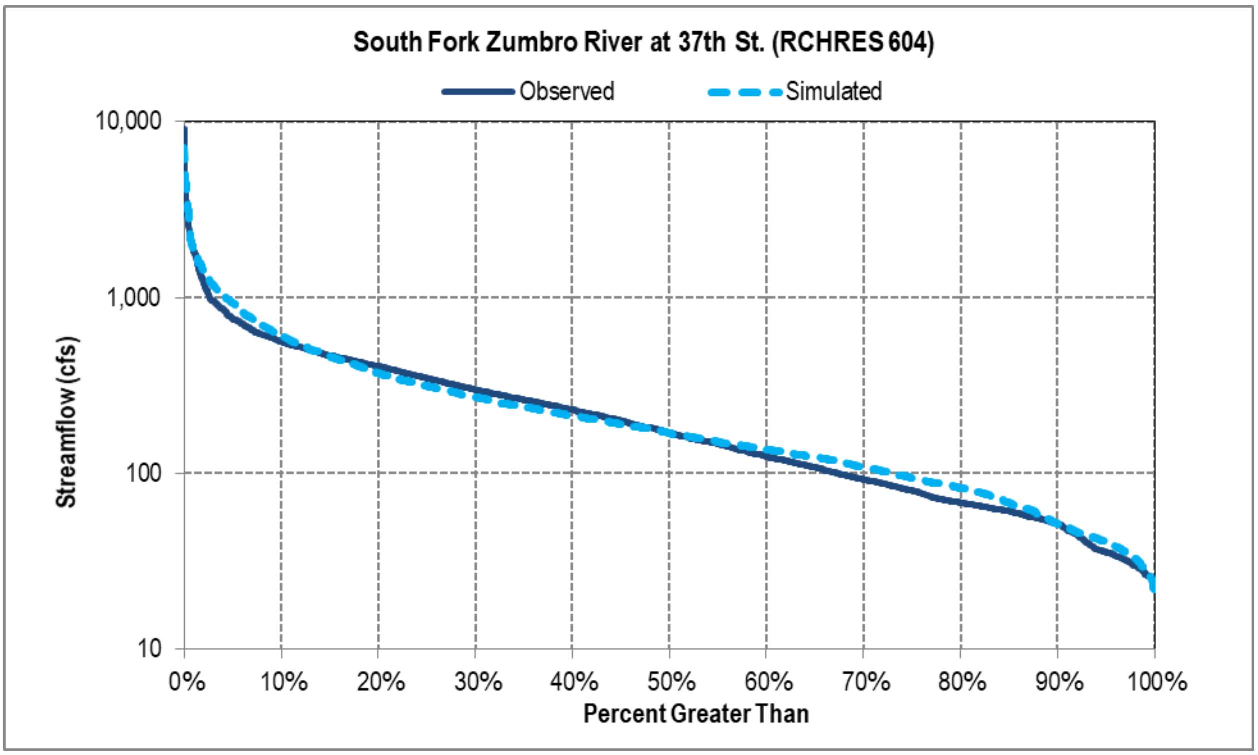

Figure C-13: Observed and simulated daily streamflow cumulative frequency distribution for South Fork Zumbro River at 37th St.

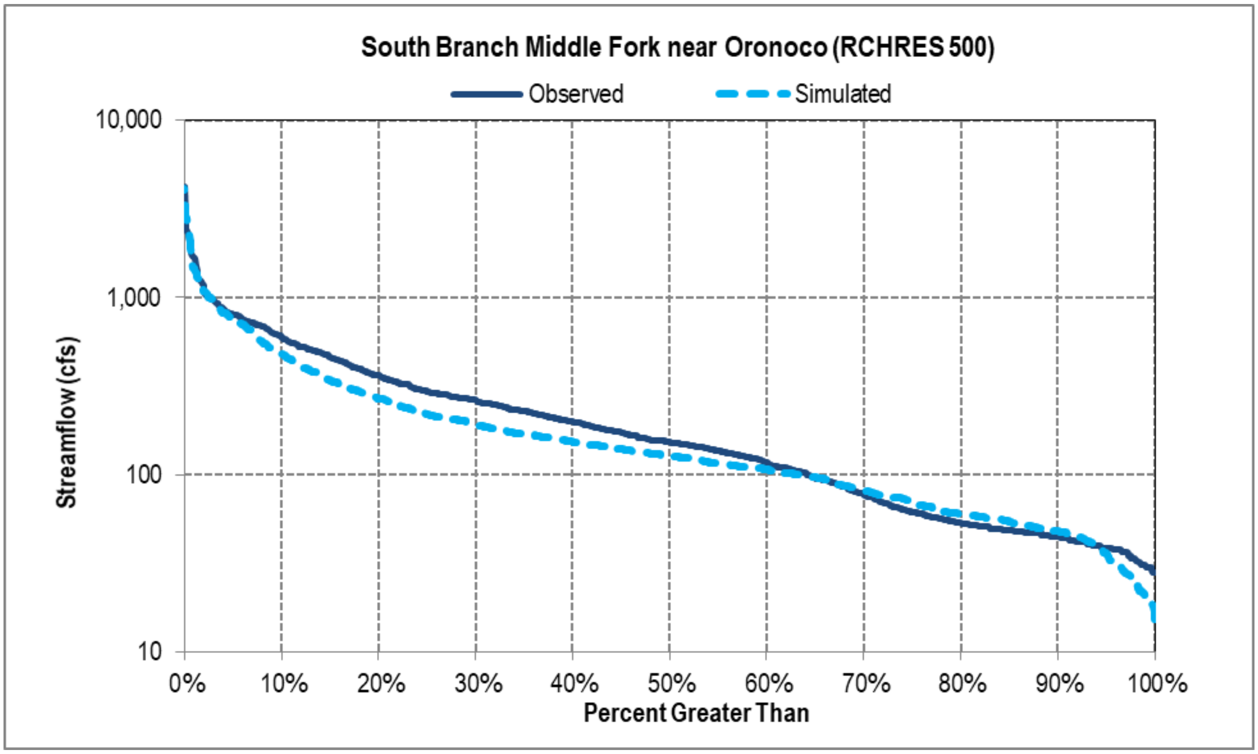

Figure C-14: Observed and simulated daily streamflow cumulative frequency distribution for South Branch Middle Fork Zumbro River near Oronoco

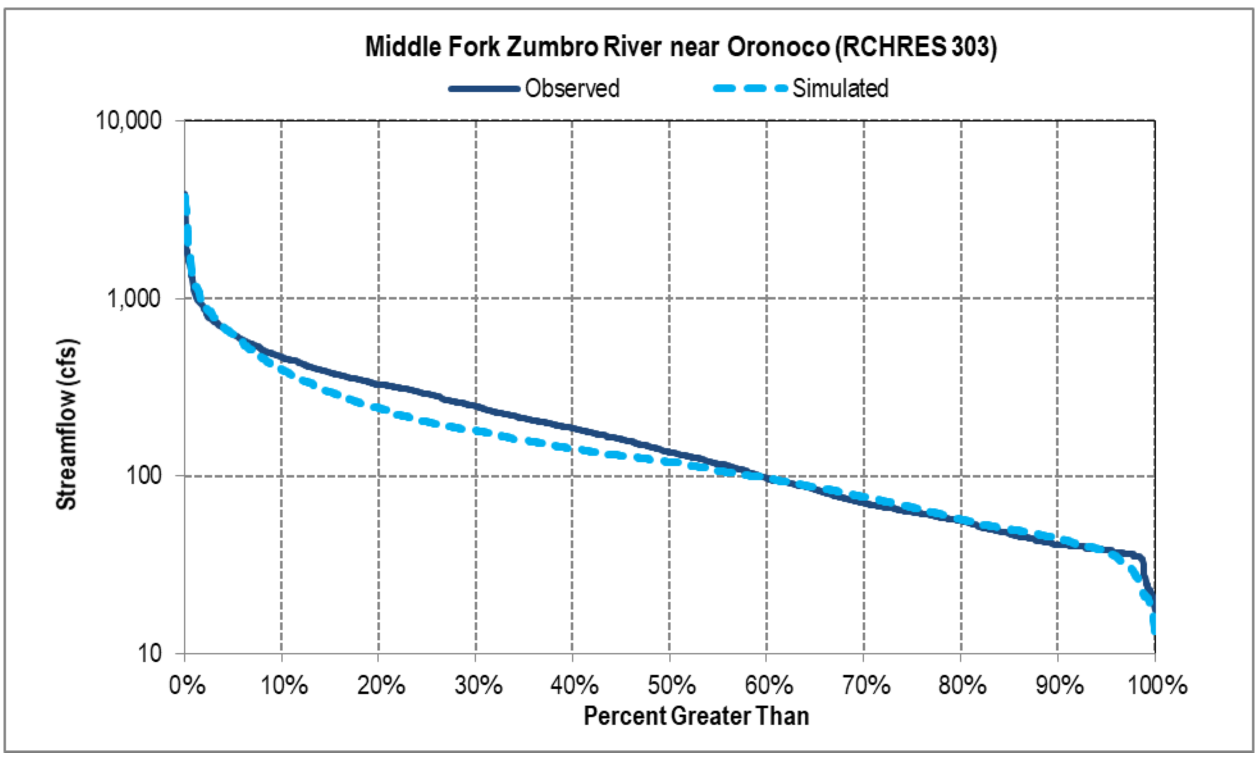

Figure C-15: Observed and simulated daily streamflow cumulative frequency distribution for Middle Fork Zumbro River near Oronoco

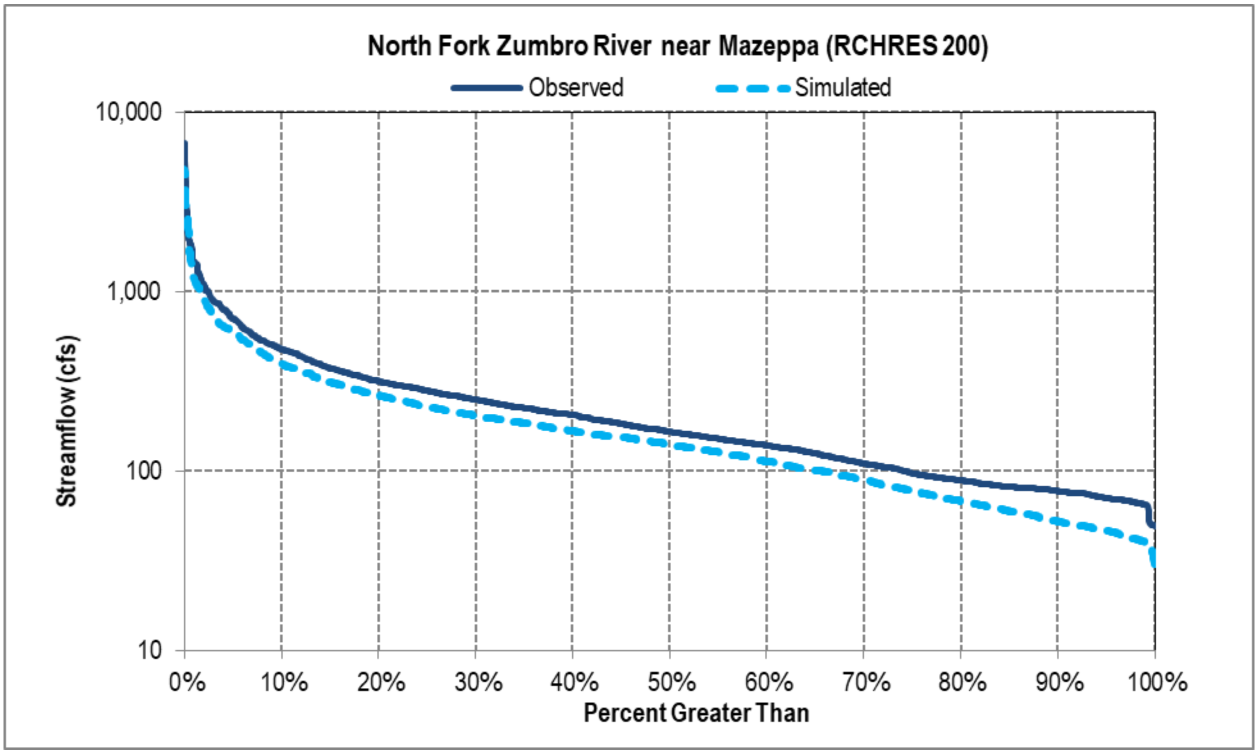

Figure C-16: Observed and simulated daily streamflow cumulative frequency distribution for North Fork Zumbro River near Mazeppa

Sediment

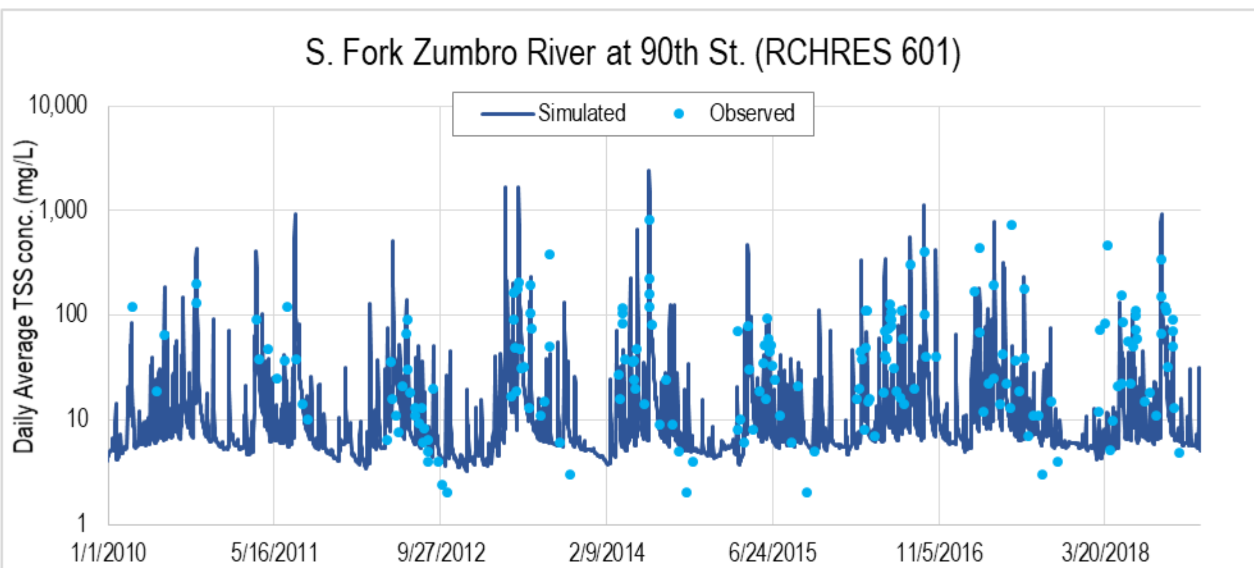

Figure C-17: Observed and simulated daily average TSS concentrations for South Fork Zumbro River at 90th Street

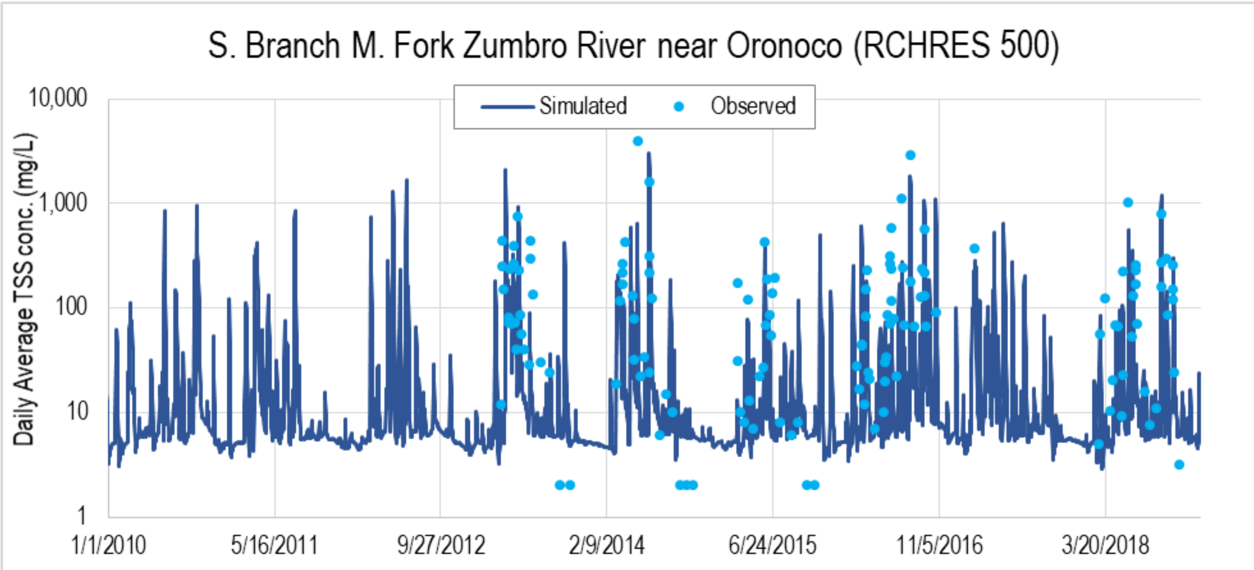

Figure C-18: Observed and simulated daily average TSS concentrations for South Branch Middle Fork Zumbro River near Oronoco

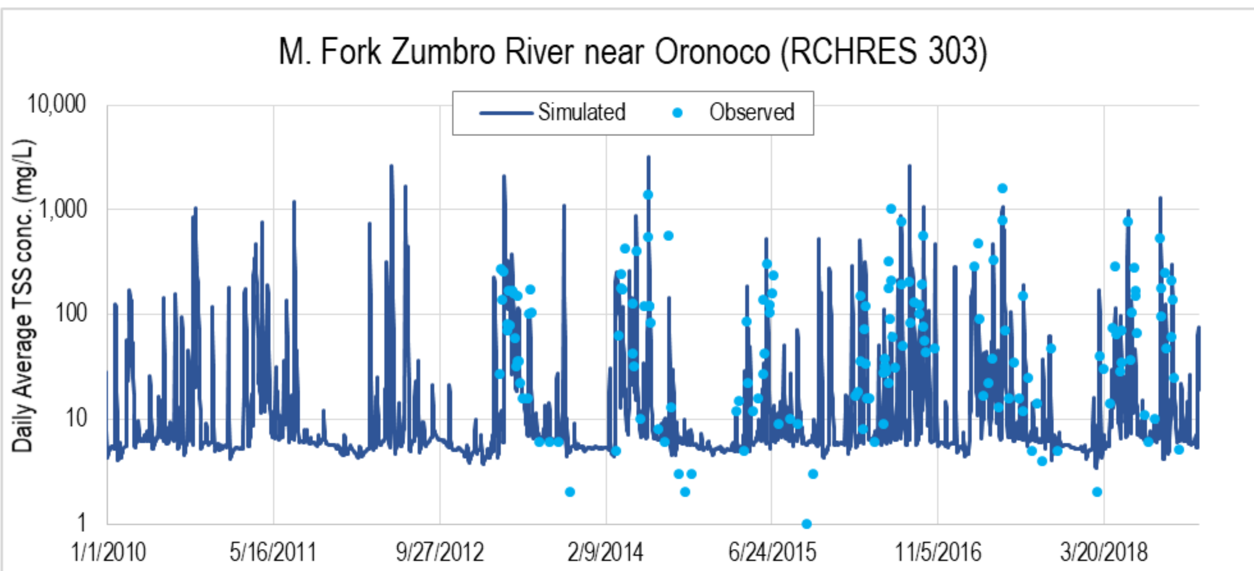

Figure C-19: Observed and simulated daily average TSS concentrations for Middle Fork Zumbro River near Oronoco

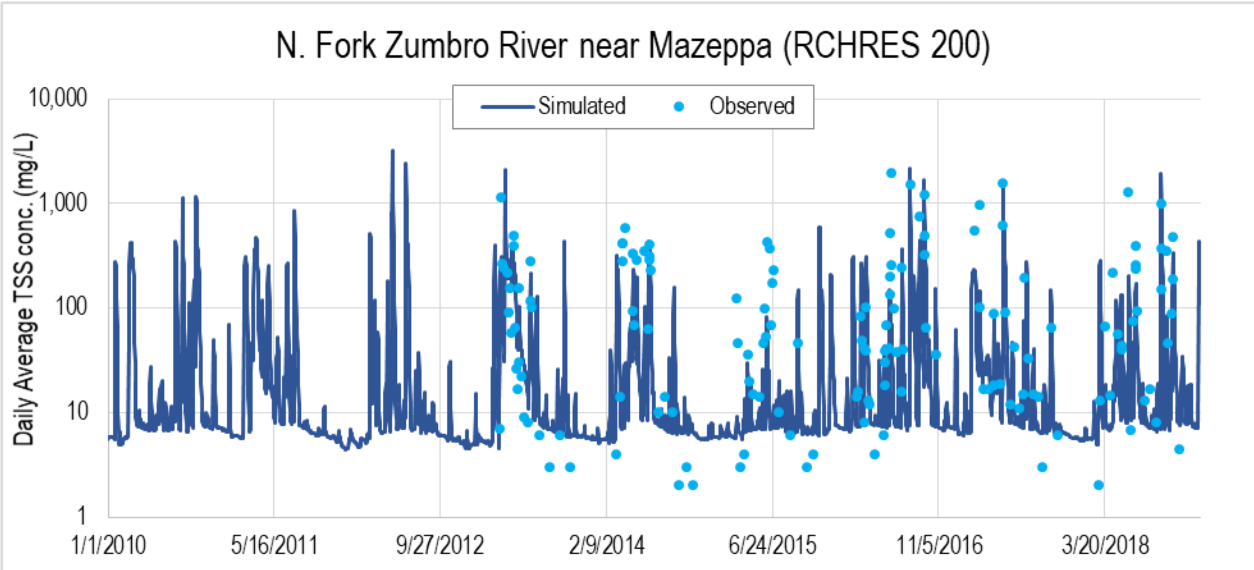

Figure C-20: Observed and simulated daily average TSS concentrations for North Fork Zumbro River near Mazeppa

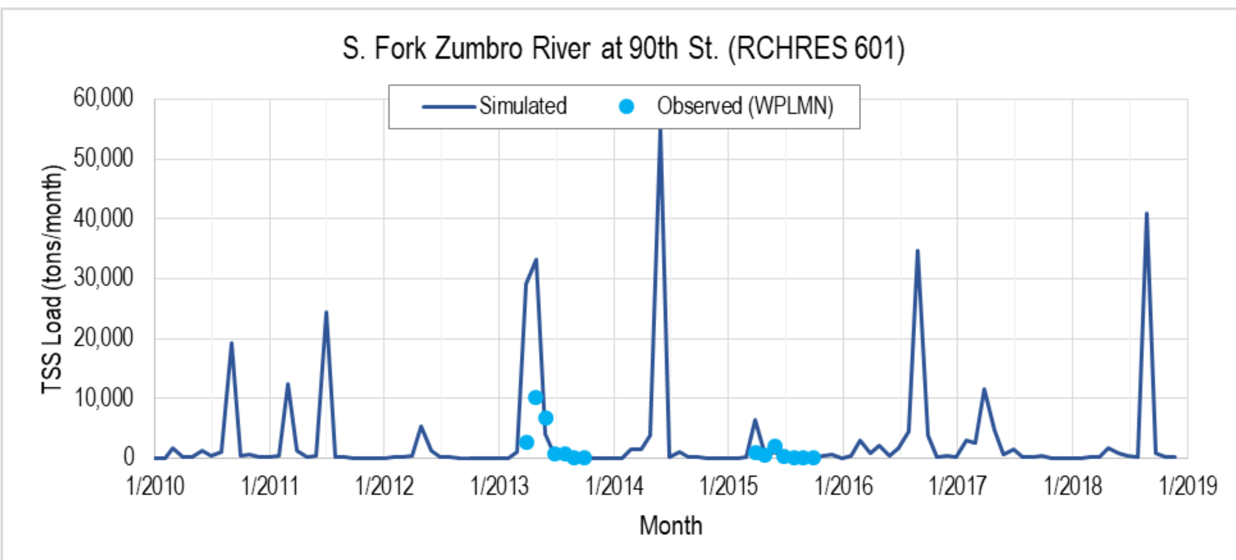

Figure C-21: Observed and simulated monthly TSS loads for South Fork Zumbro River at 90th Street

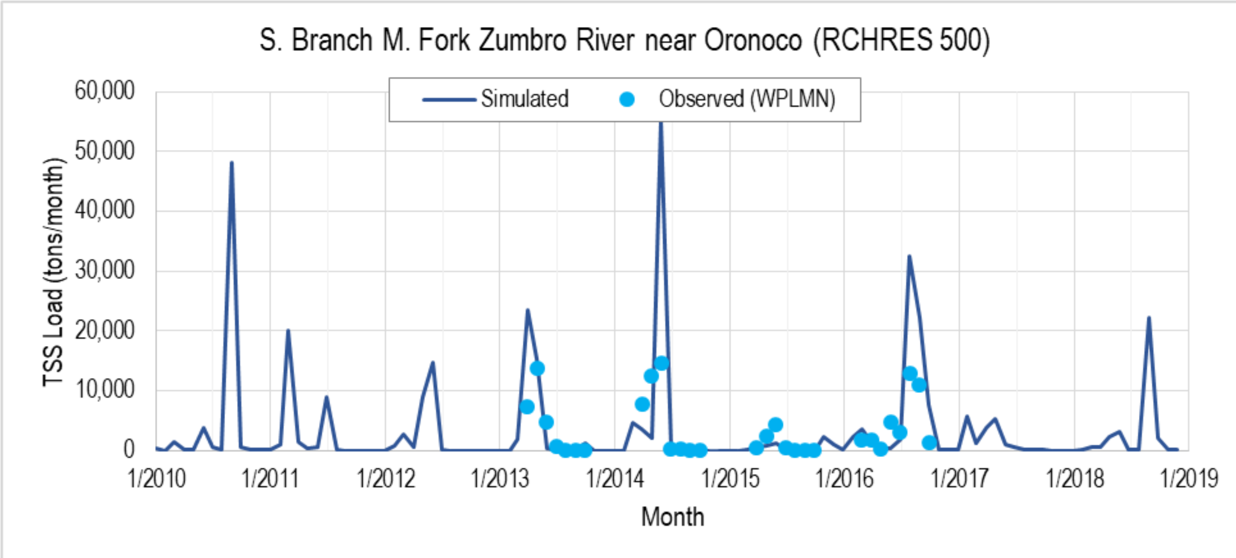

Figure C-22: Observed and simulated monthly TSS loads for South Branch Middle Fork Zumbro River near Oronoco

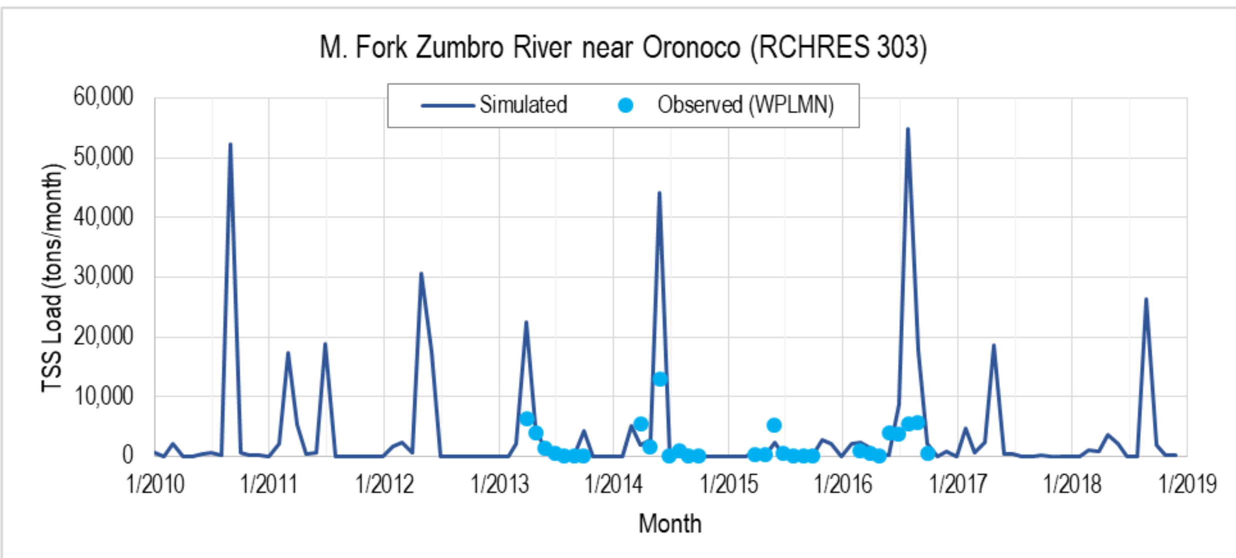

Figure C-23: Observed and simulated monthly TSS loads for Middle Fork Zumbro River near Oronoco

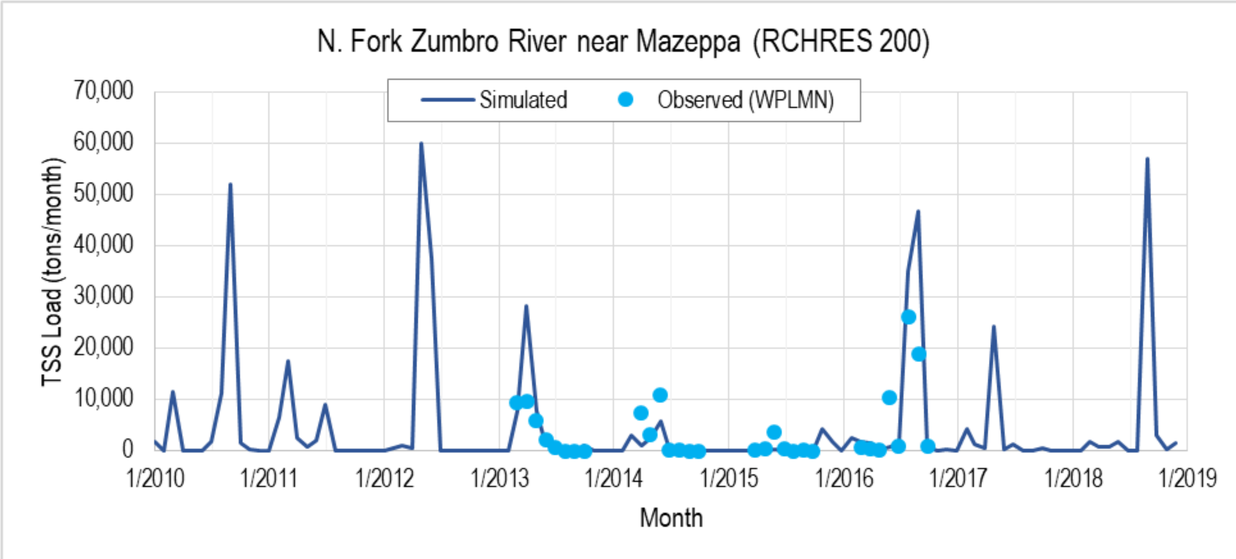

Figure C-24: Observed and simulated monthly TSS loads for North Fork Zumbro River near Mazeppa

Total Phosphorus

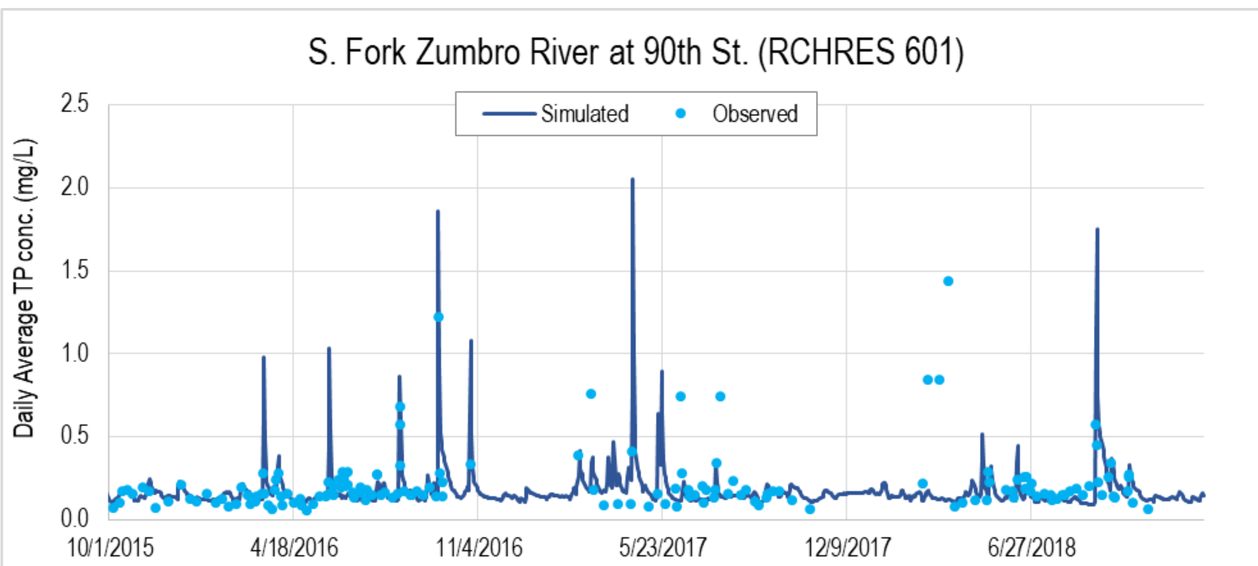

Figure C-25: Observed and simulated daily average TP concentrations for South Fork Zumbro River at 90th Street

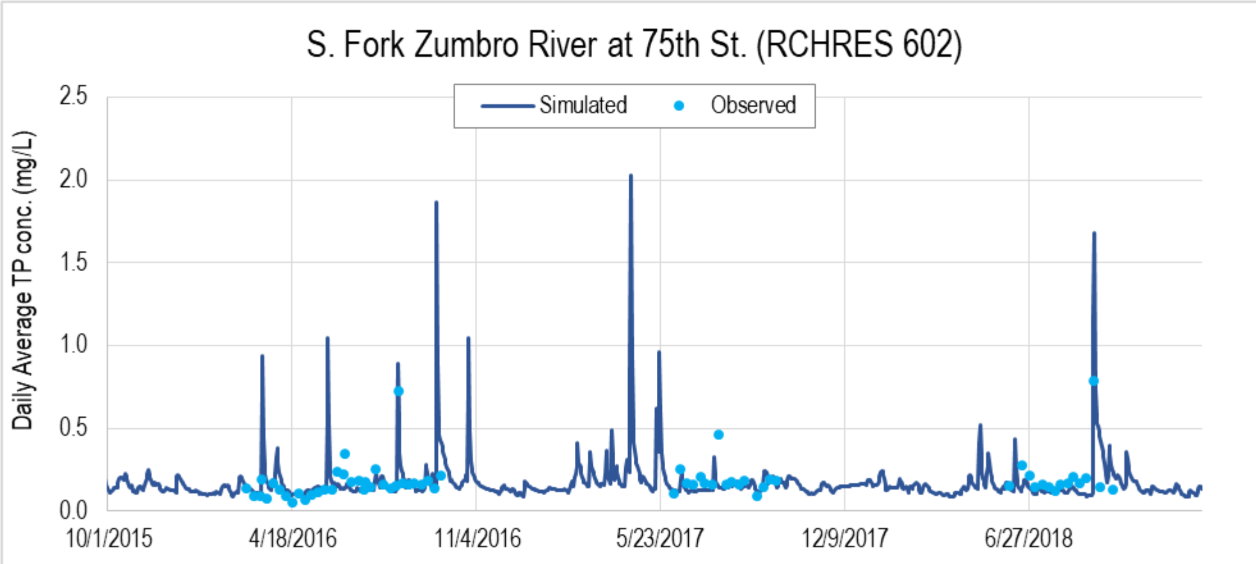

Figure C-26: Observed and simulated daily average TP concentrations for South Fork Zumbro River at 75th Street

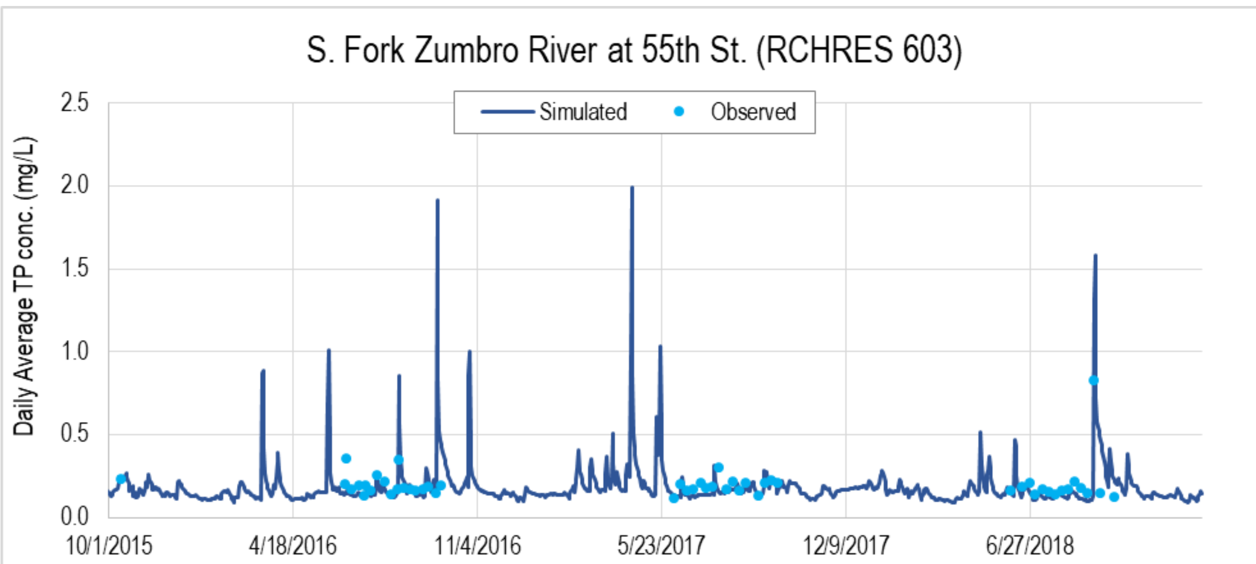

Figure C-27: Observed and simulated daily average TP concentrations for South Fork Zumbro River at 55th Street

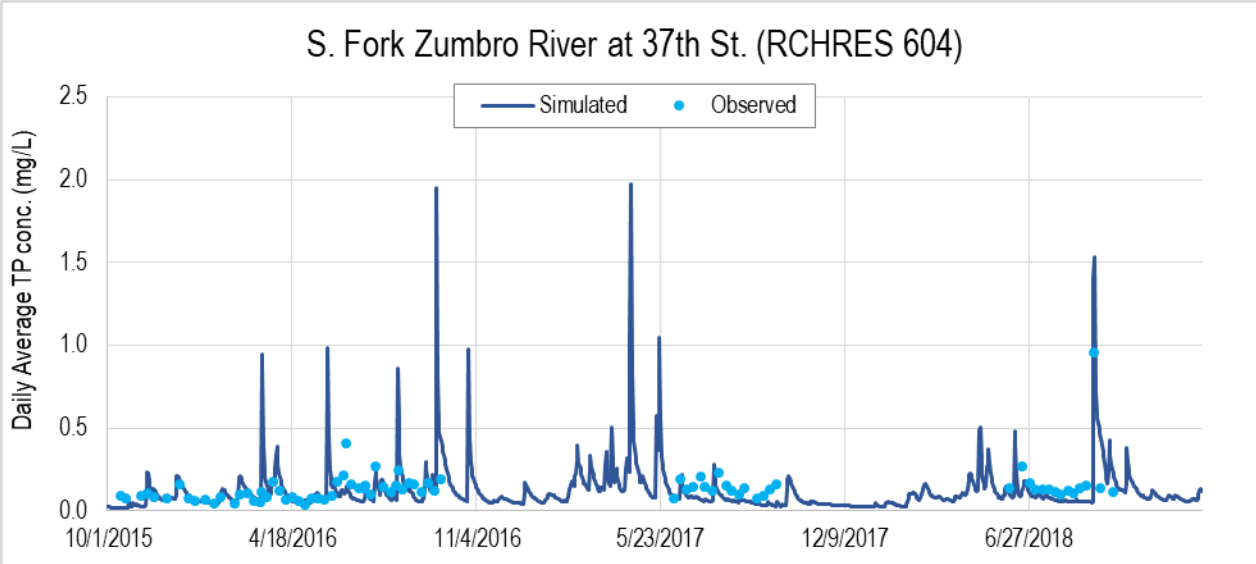

Figure C-28: Observed and simulated daily average TP concentrations for South Fork Zumbro River at 37th Street

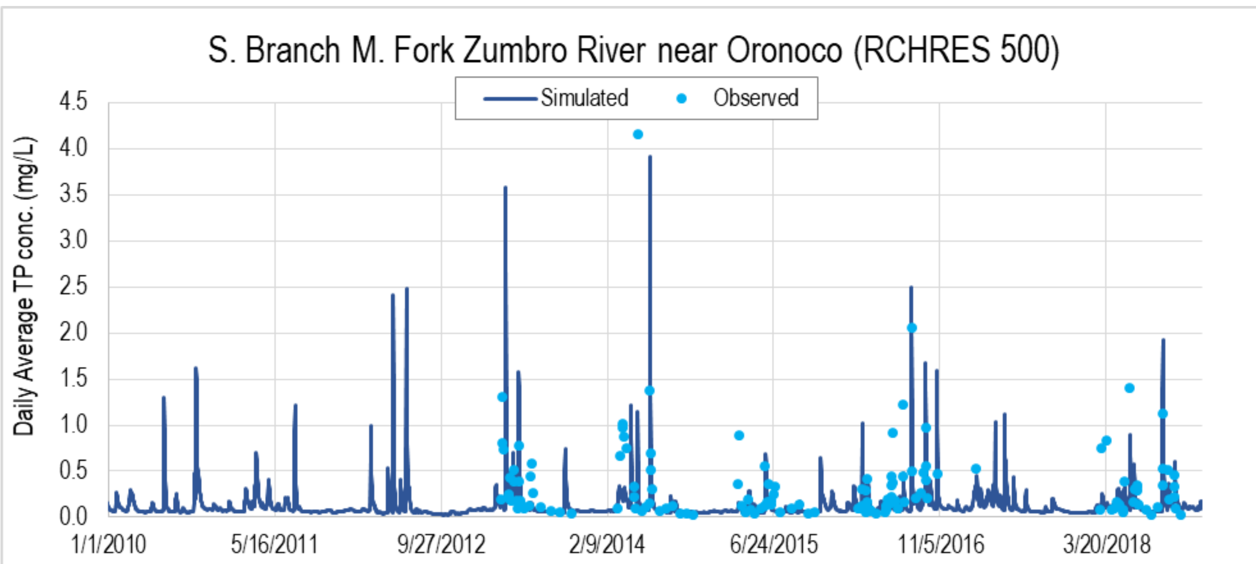

Figure C-29: Observed and simulated daily average TP concentrations for South Branch Middle Fork Zumbro River near Oronoco

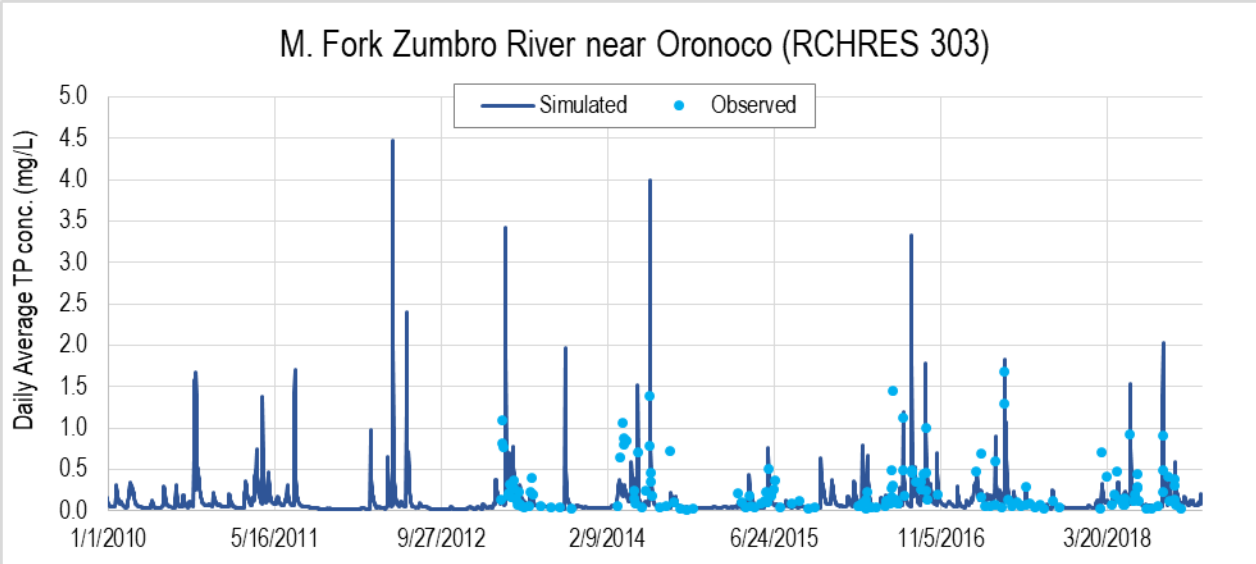

Figure C-30: Observed and simulated daily average TP concentrations for Middle Fork Zumbro River near Oronoco

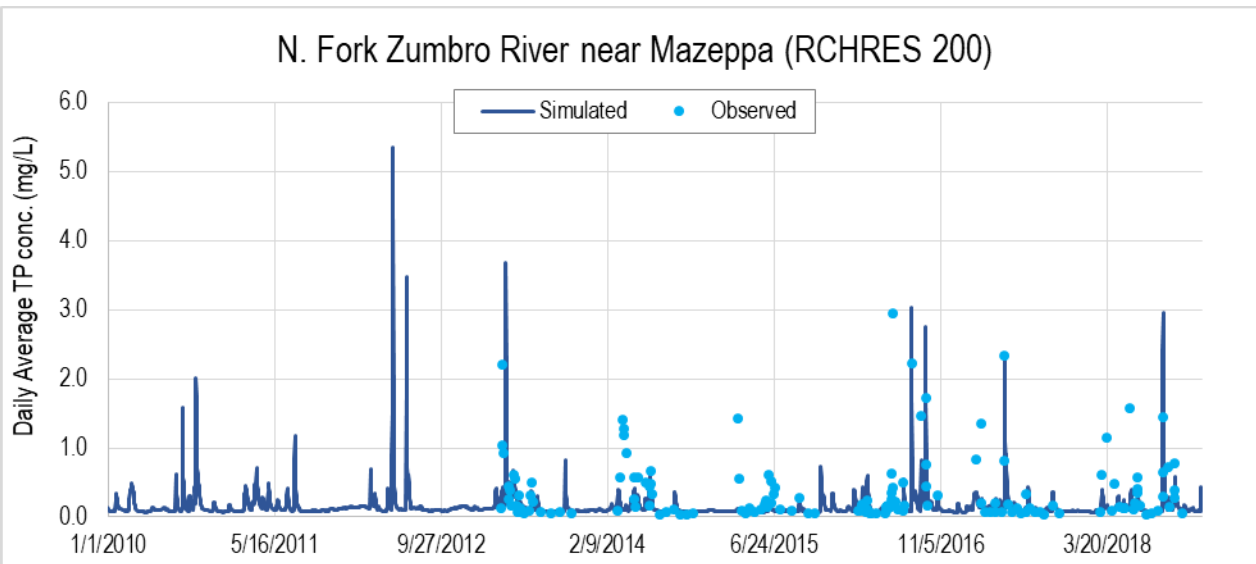

Figure C-31: Observed and simulated daily average TP concentrations for North Fork Zumbro River near Mazeppa

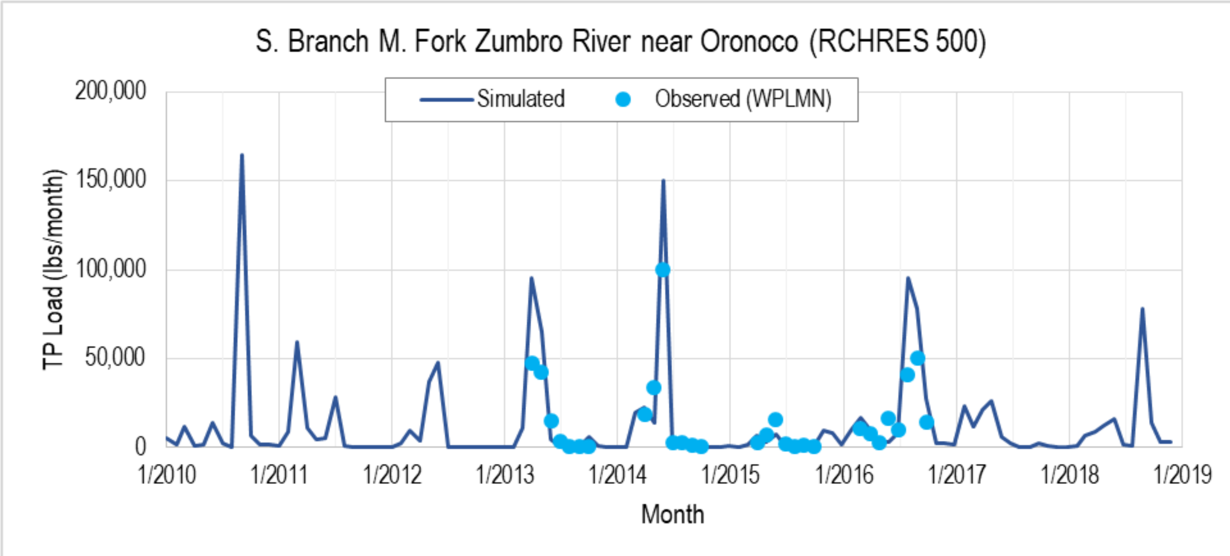

Figure C-32: Observed and simulated monthly TP loads for South Branch Middle Fork Zumbro River near Oronoco

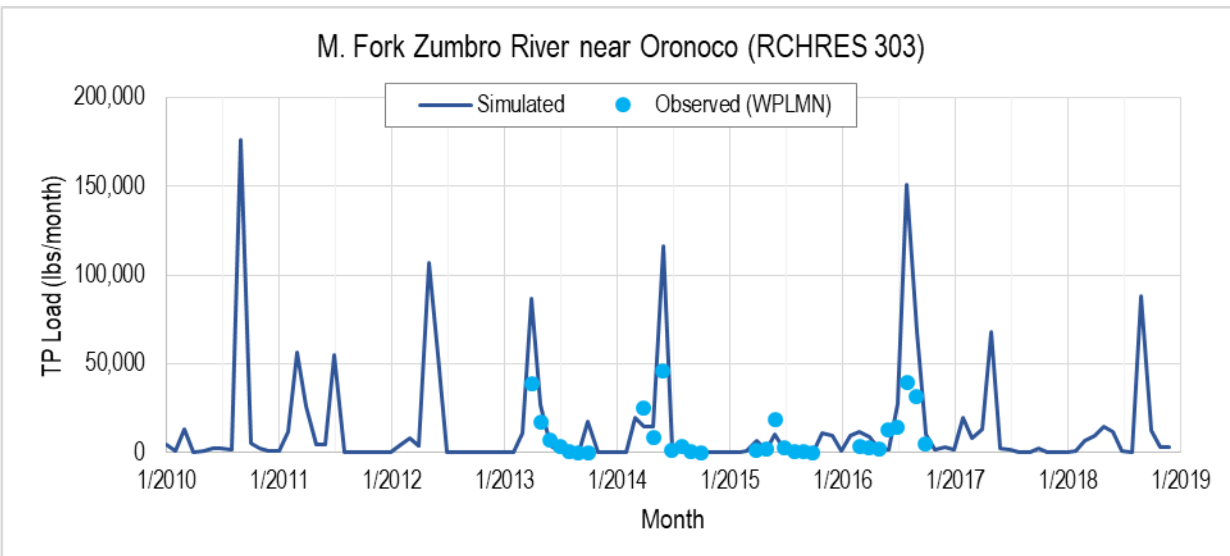

Figure C-33: Observed and simulated monthly TP loads for Middle Fork Zumbro River near Oronoco

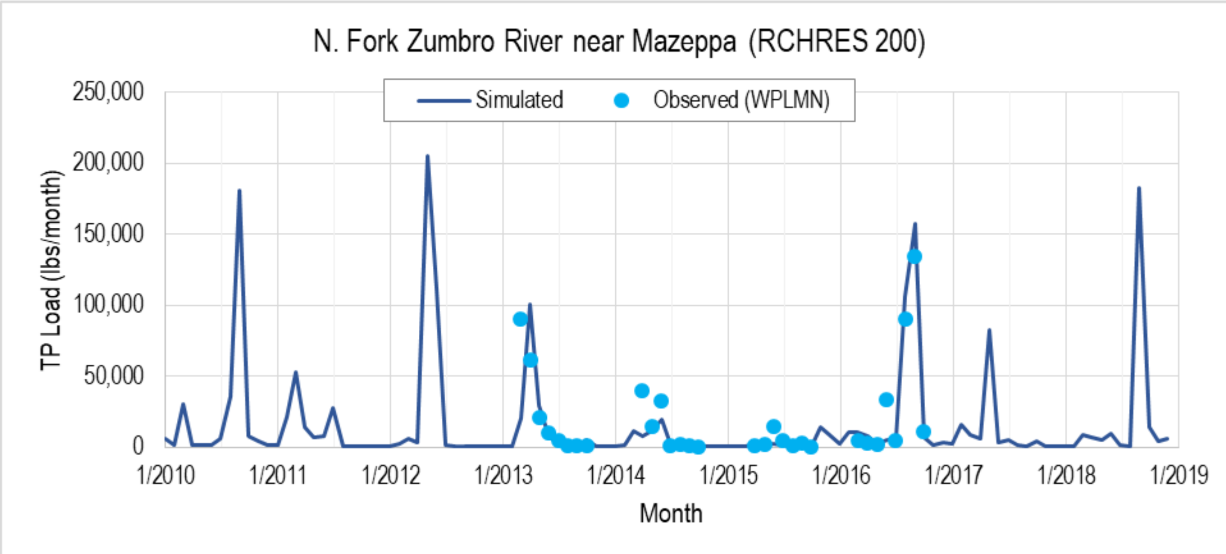

Figure C-34: Observed and simulated monthly TP loads for North Fork Zumbro River near Mazeppa

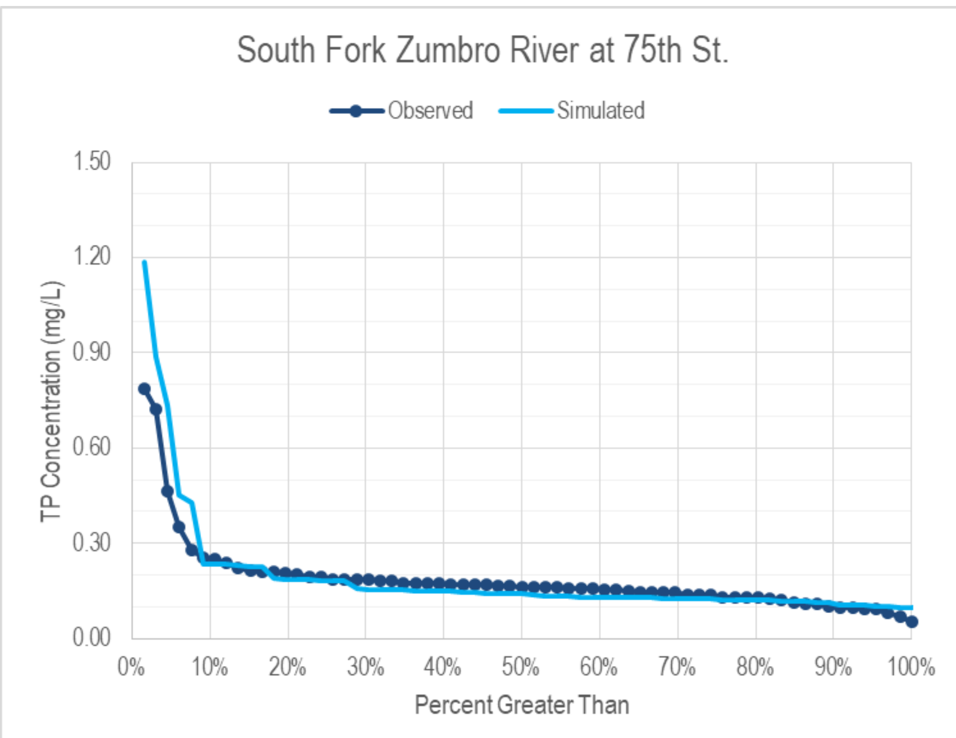

Figure C-35: Observed and simulated TP concentration cumulative frequency distributions for South Fork Zumbro River at 75th Street for the 2010-2018 model extension period

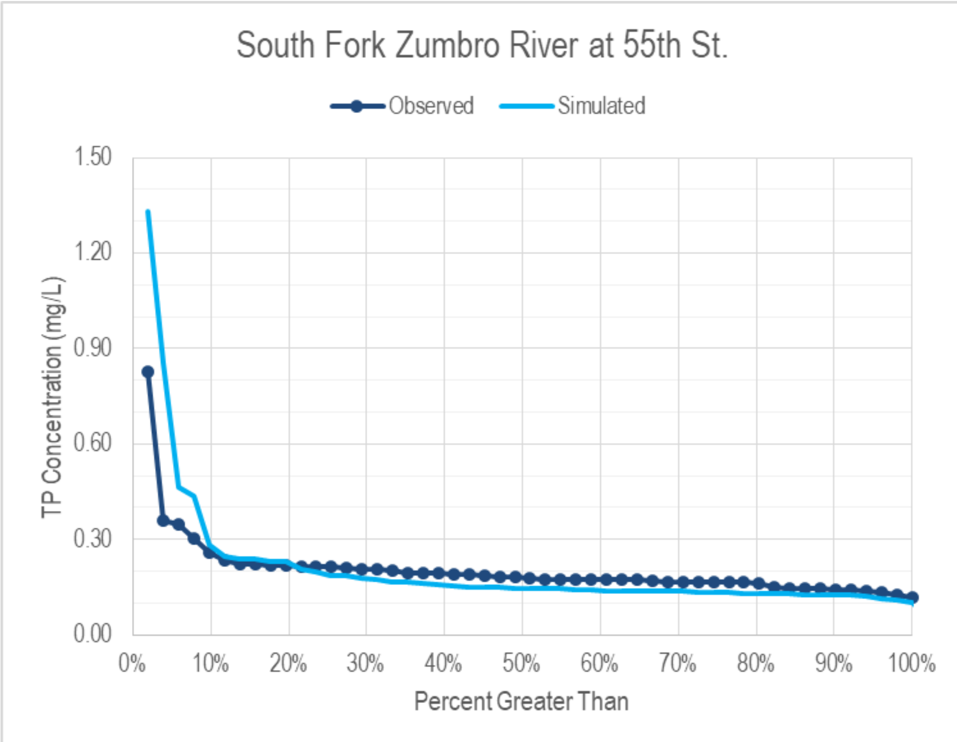

Figure C-36: Observed and simulated TP concentration cumulative frequency distributions for South Fork Zumbro River at 55th Street for the 2010-2018 model extension period

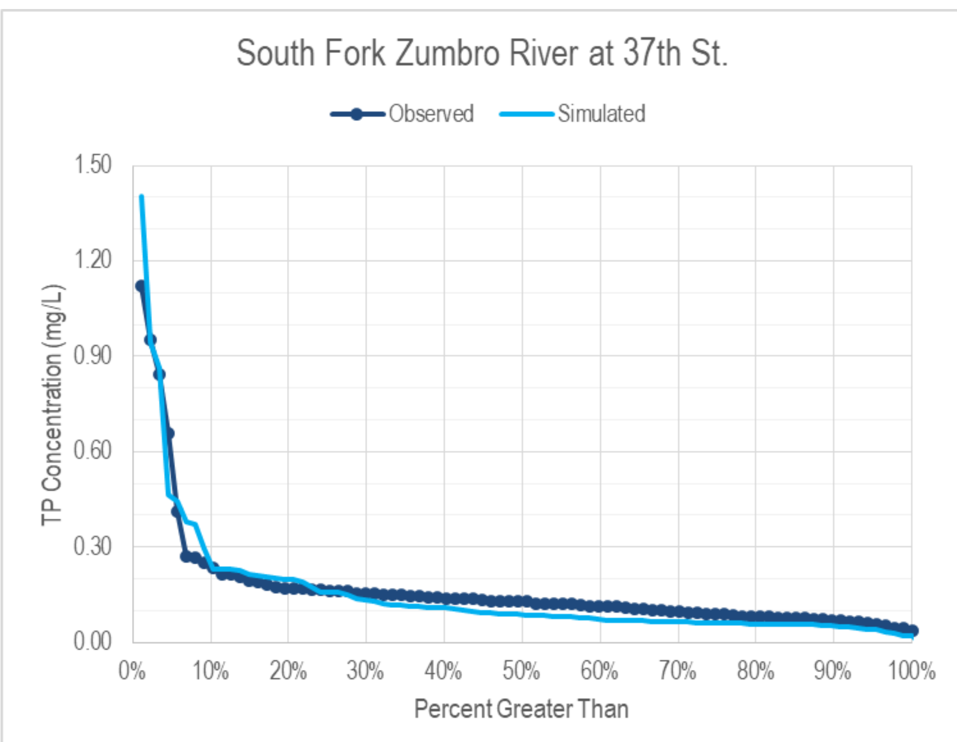

Figure C-37: Observed and simulated TP concentration cumulative frequency distributions for South Fork Zumbro River at 37th Street for the 2010-2018 model extension period

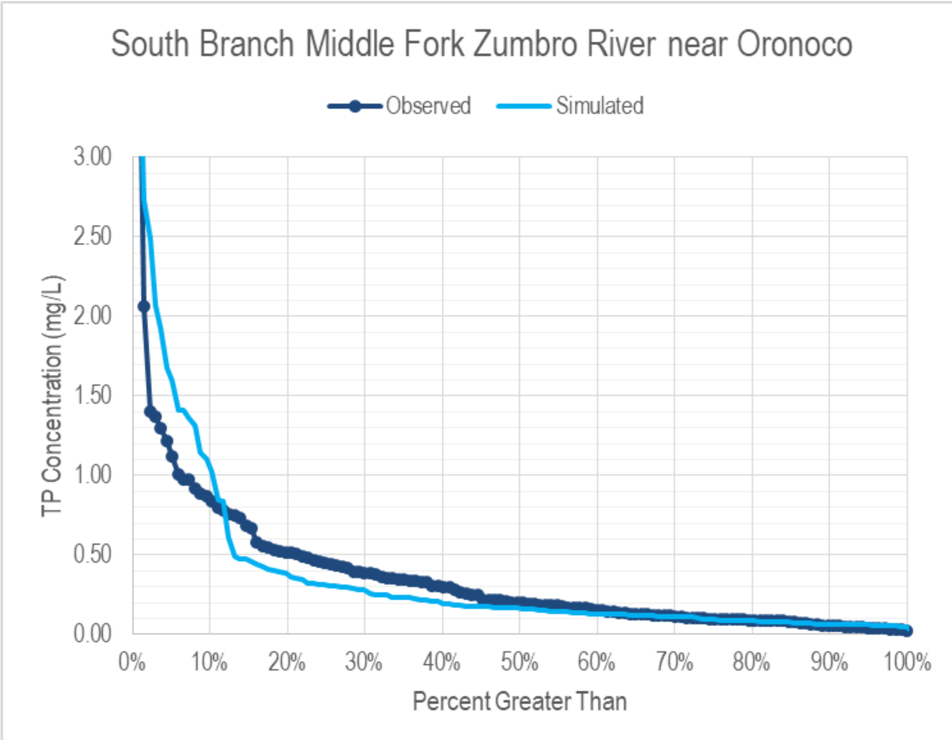

Figure C-38: Observed and simulated TP concentration cumulative frequency distributions for South Branch Middle Fork Zumbro River near Oronoco for the 2010-2018 model extension period

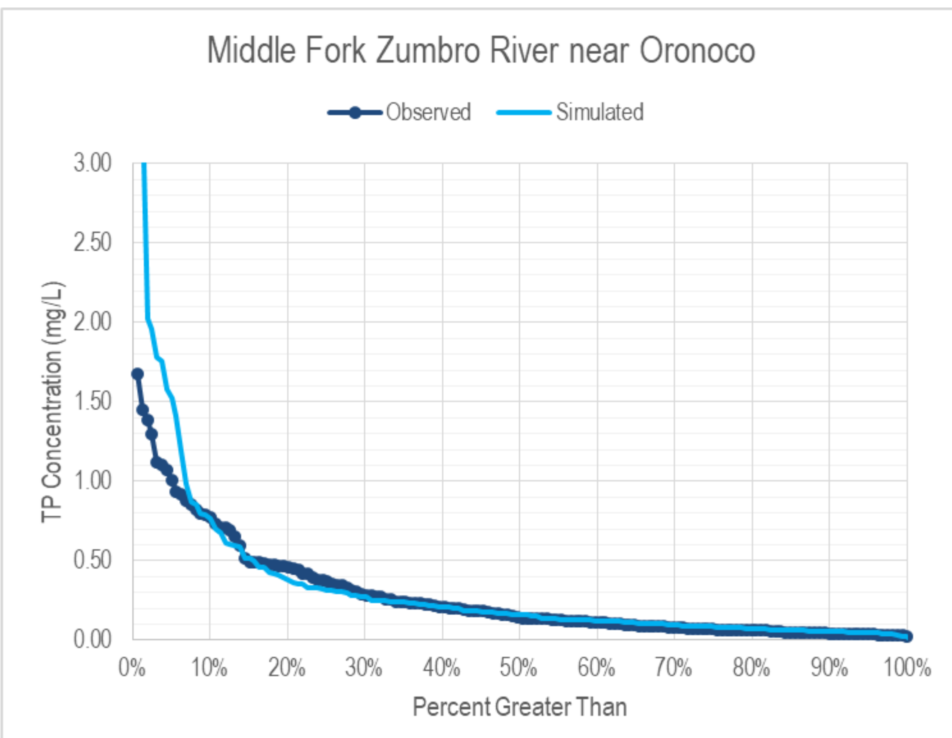

Figure C-39: Observed and simulated TP concentration cumulative frequency distributions for Middle Fork Zumbro River near Oronoco for the 2010-2018 model extension period

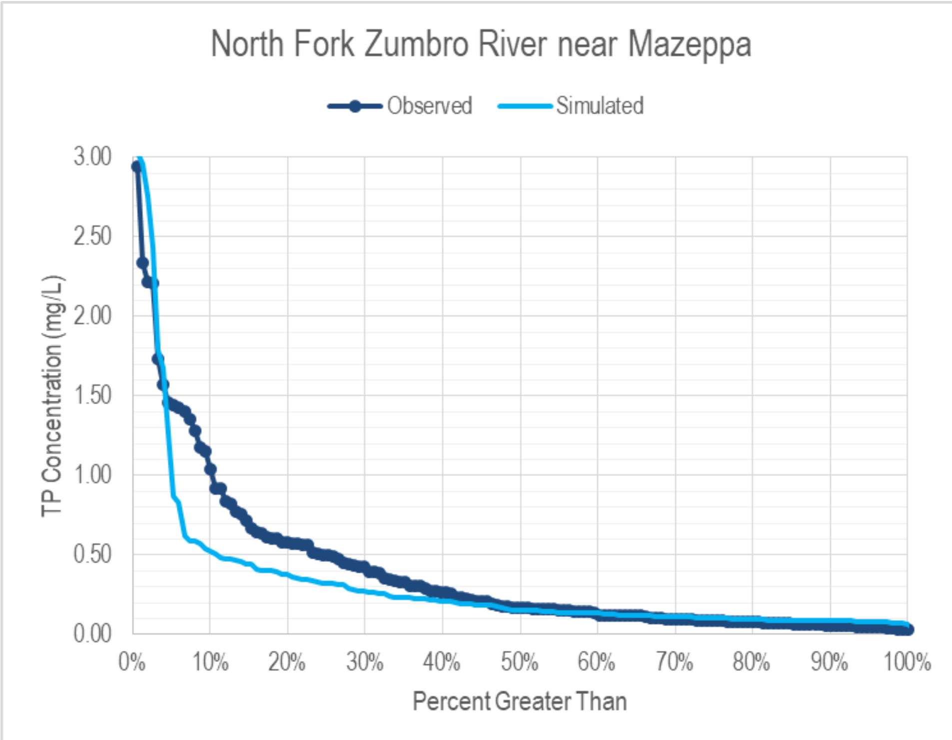

Figure C-40: Observed and simulated TP concentration cumulative frequency distributions for North Fork Zumbro River near Mazeppa for the 2010-2018 model extension period

Dissolved Orthophosphorus

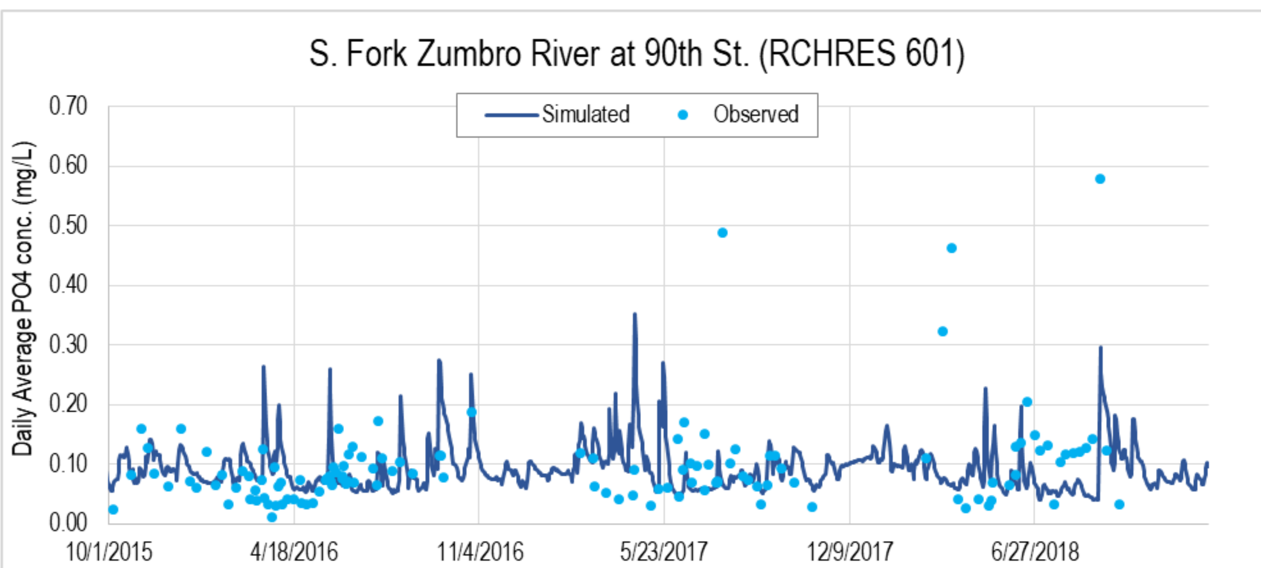

Figure C-41: Observed and simulated daily average PO_4 concentrations for South Fork Zumbro River at 90th Street

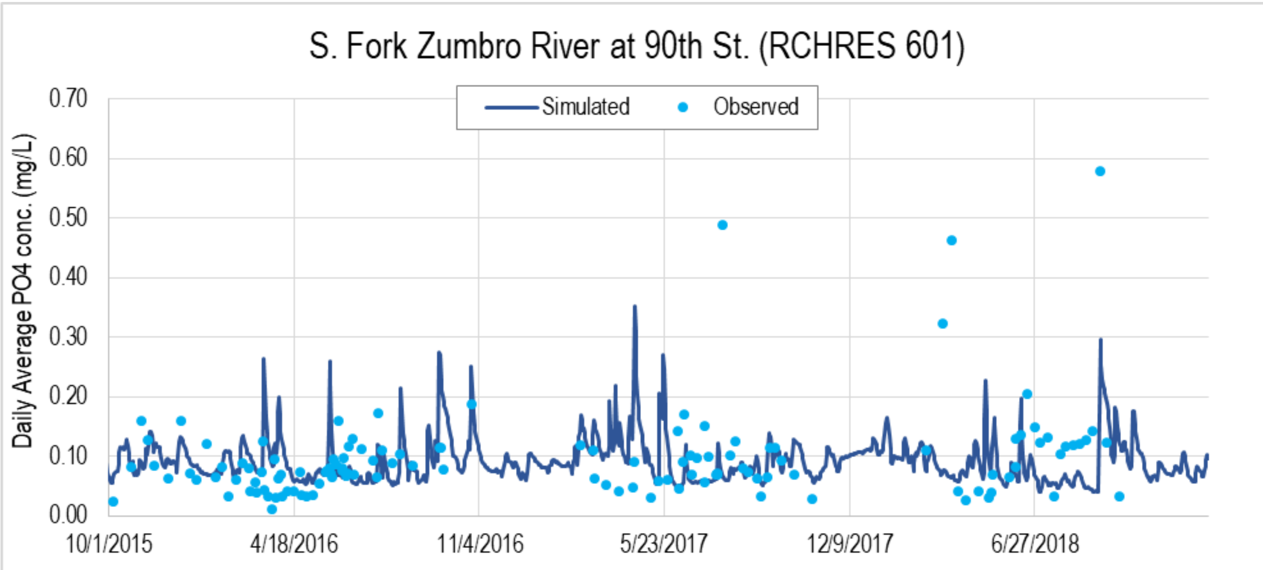

Figure C-42: Observed and simulated daily average PO_4 concentrations for South Fork Zumbro River at 75th Street

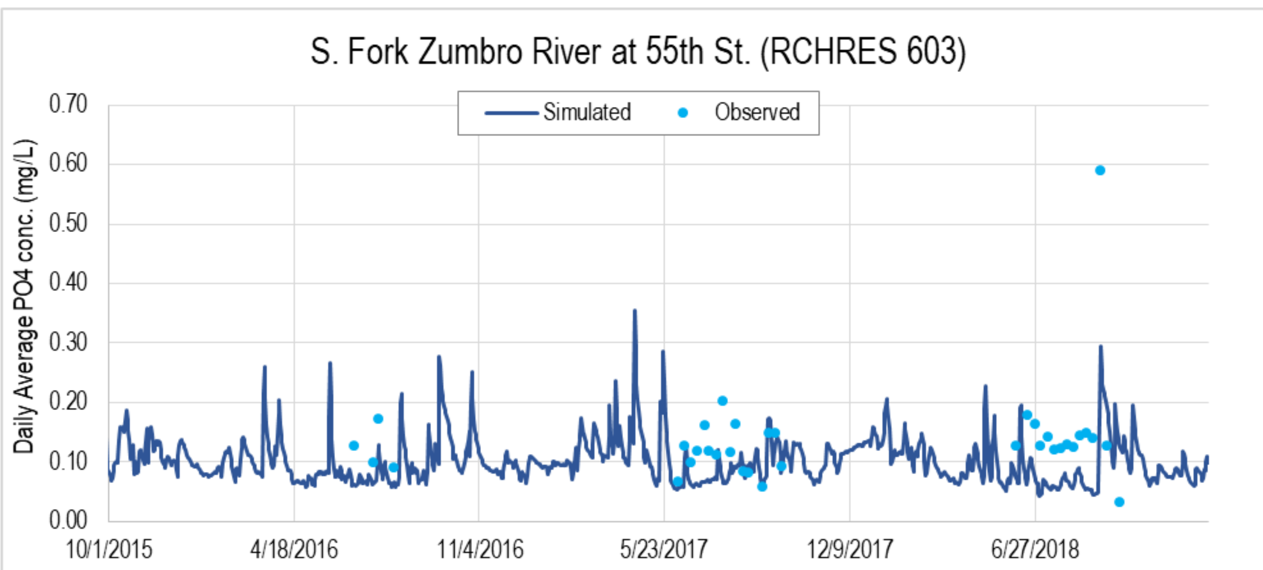

Figure C-43: Observed and simulated daily average PO_4 concentrations for South Fork Zumbro River at 55th Street

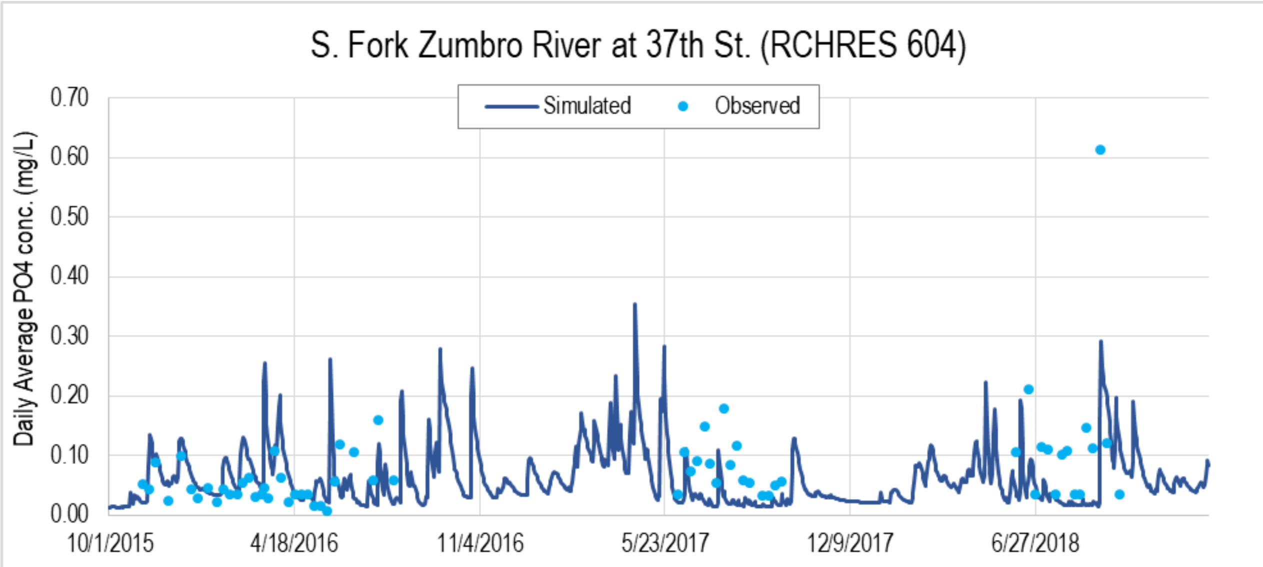

Figure C-44: Observed and simulated daily average PO_4 concentrations for South Fork Zumbro River at 37th Street

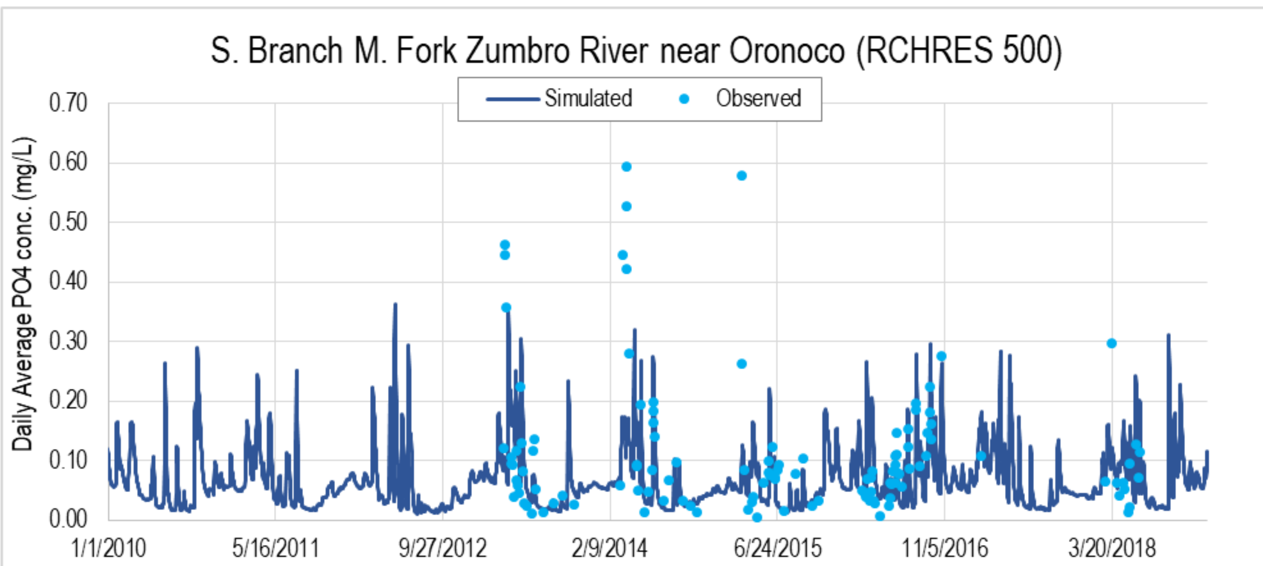

Figure C-45: Observed and simulated daily average PO_4 concentrations for South Branch Middle Fork Zumbro River near Oronoco

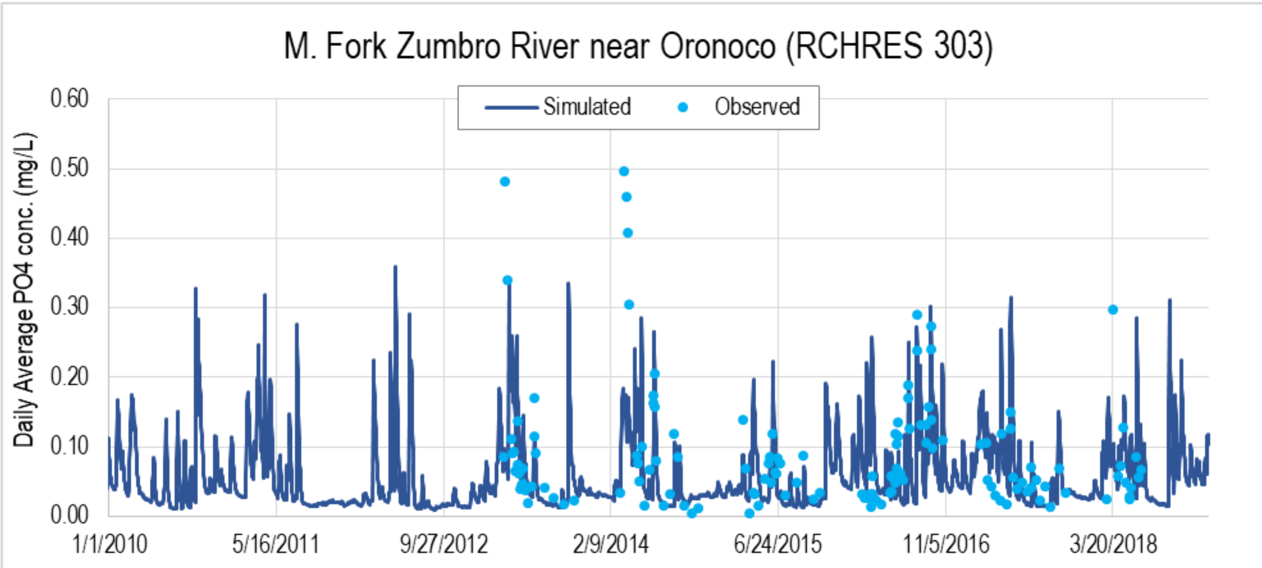

Figure C-46: Observed and simulated daily average PO_4 concentrations for Middle Fork Zumbro River near Oronoco

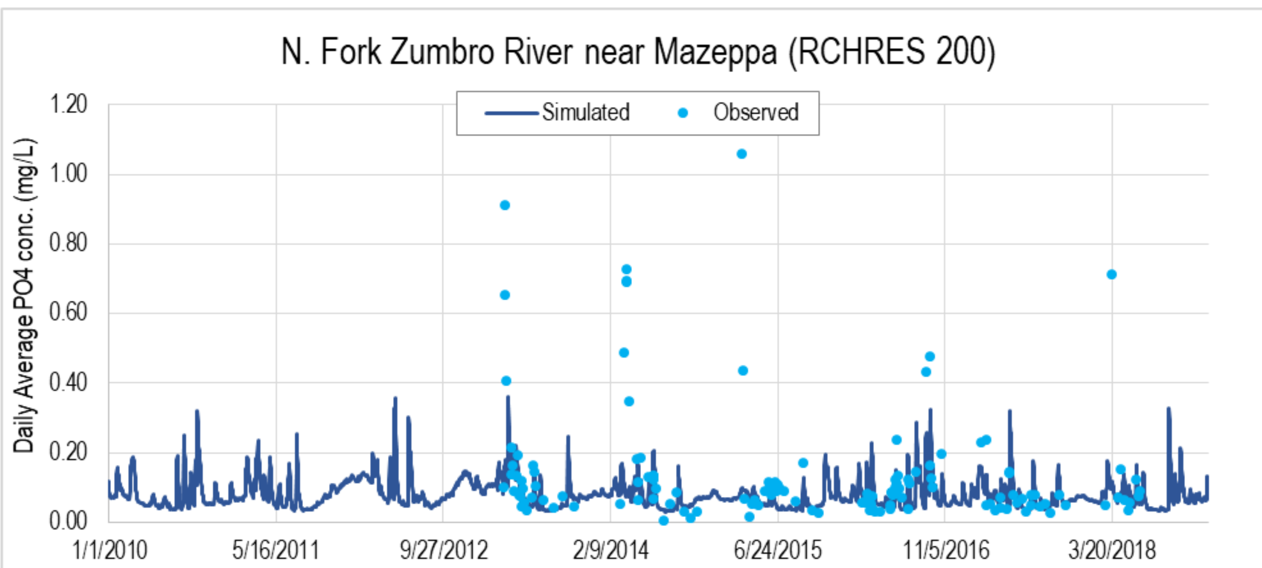

Figure C-47: Observed and simulated daily average PO_4 concentrations for North Fork Zumbro River near Mazeppa

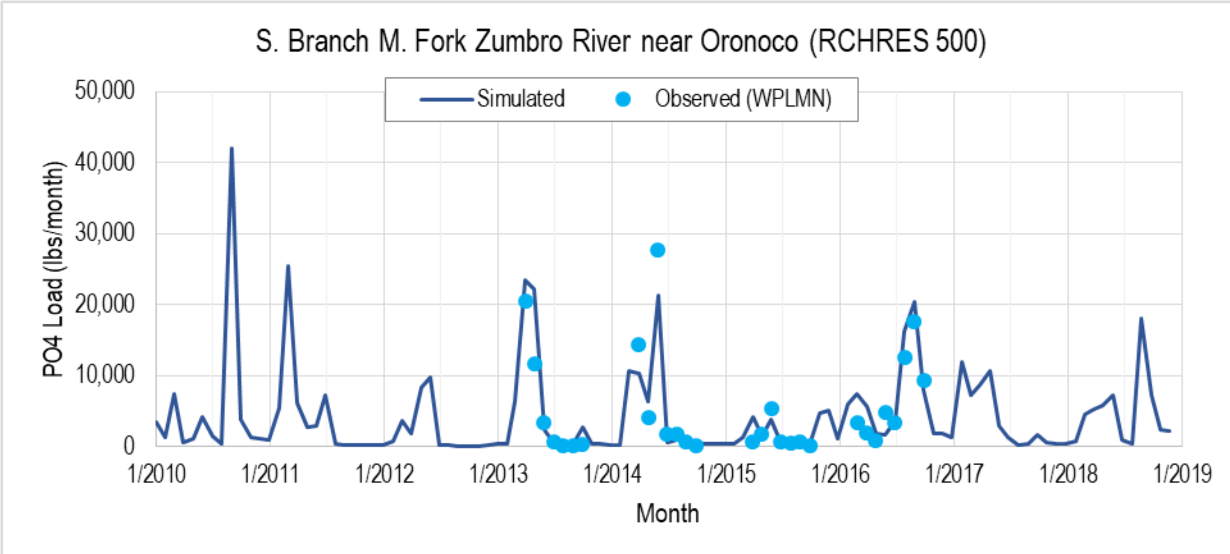

Figure C-48: Observed and simulated monthly PO_4 loads for South Branch Middle Fork Zumbro River near Oronoco

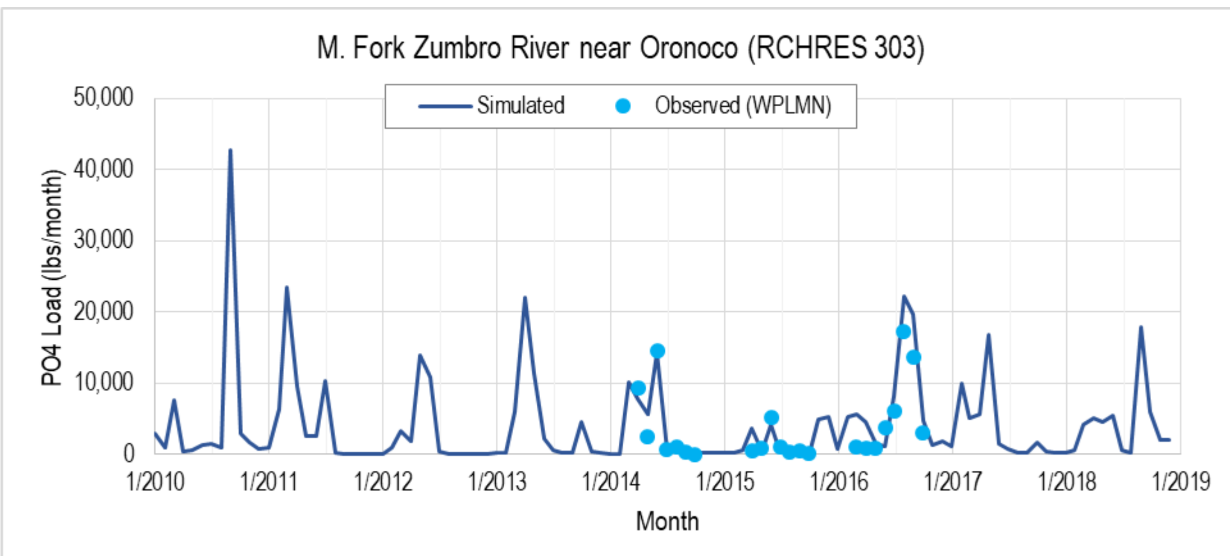

Figure C-49: Observed and simulated monthly PO_4 loads for Middle Fork Zumbro River near Oronoco

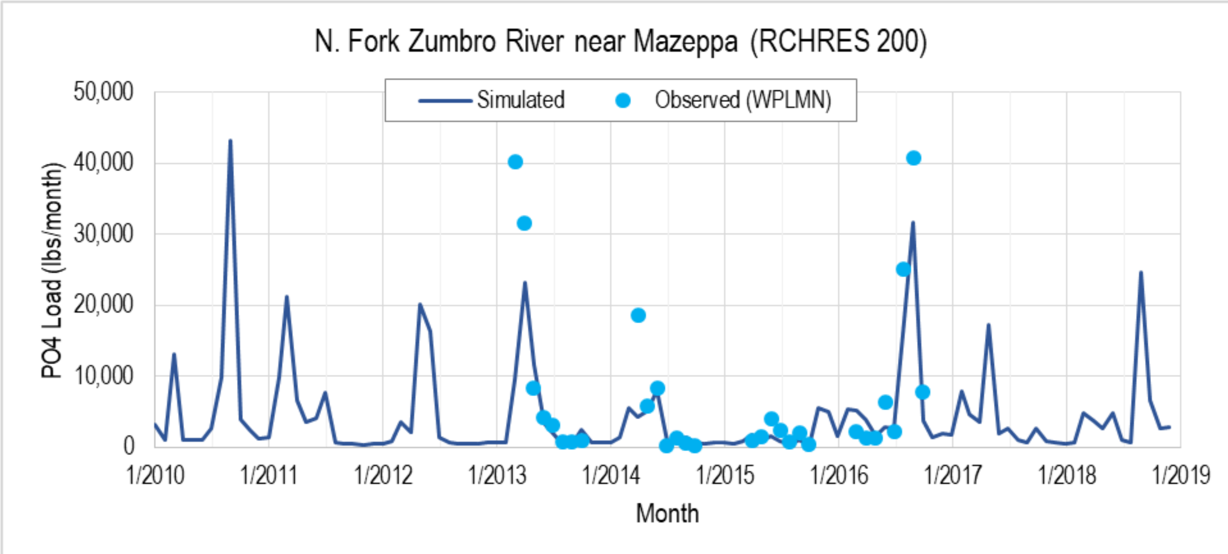

Figure C-50: Observed and simulated monthly PO_4 loads for North Fork Zumbro River near Mazeppa

Total Nitrogen

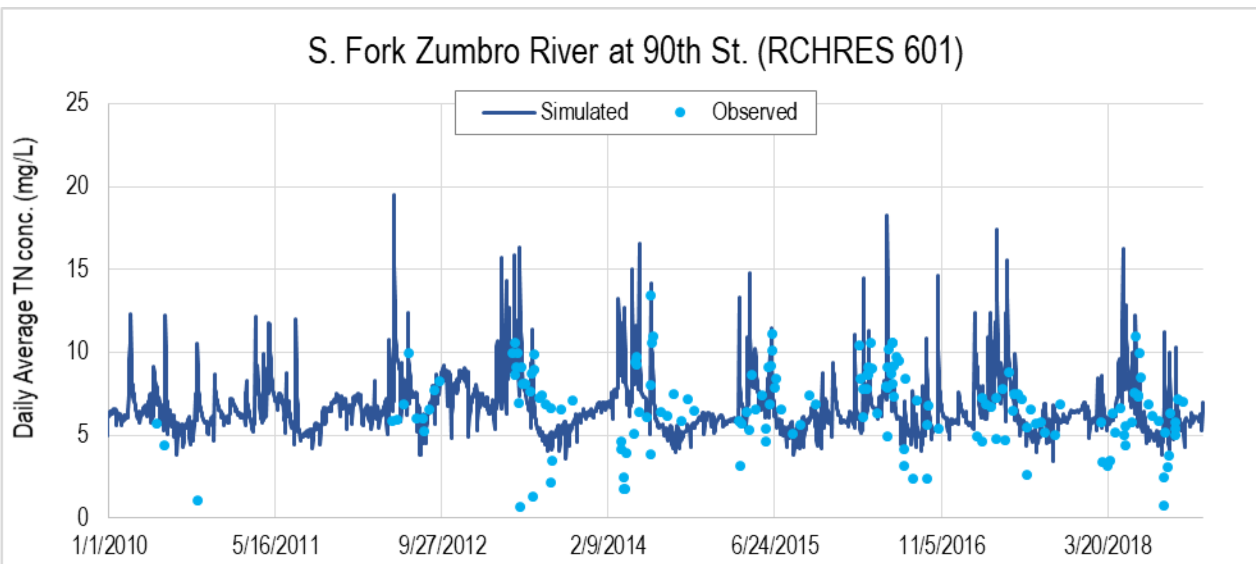

Figure C-51: Observed and simulated daily average TN concentrations for South Fork Zumbro River at 90th Street

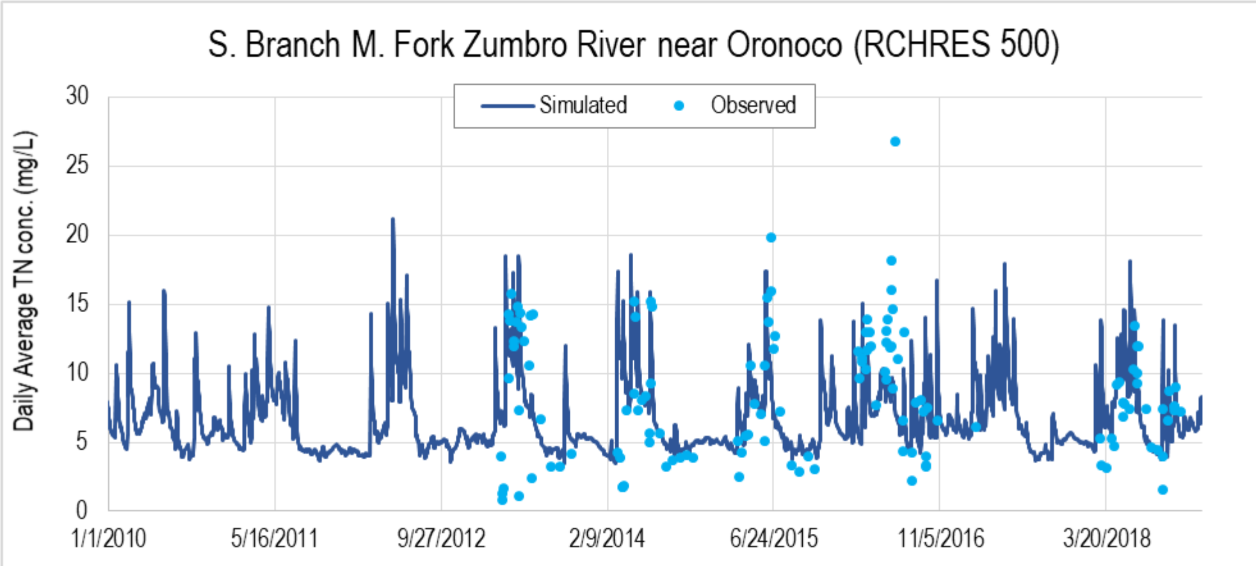

Figure C-52: Observed and simulated daily average TN concentrations for South Branch Middle Fork Zumbro River near Oronoco

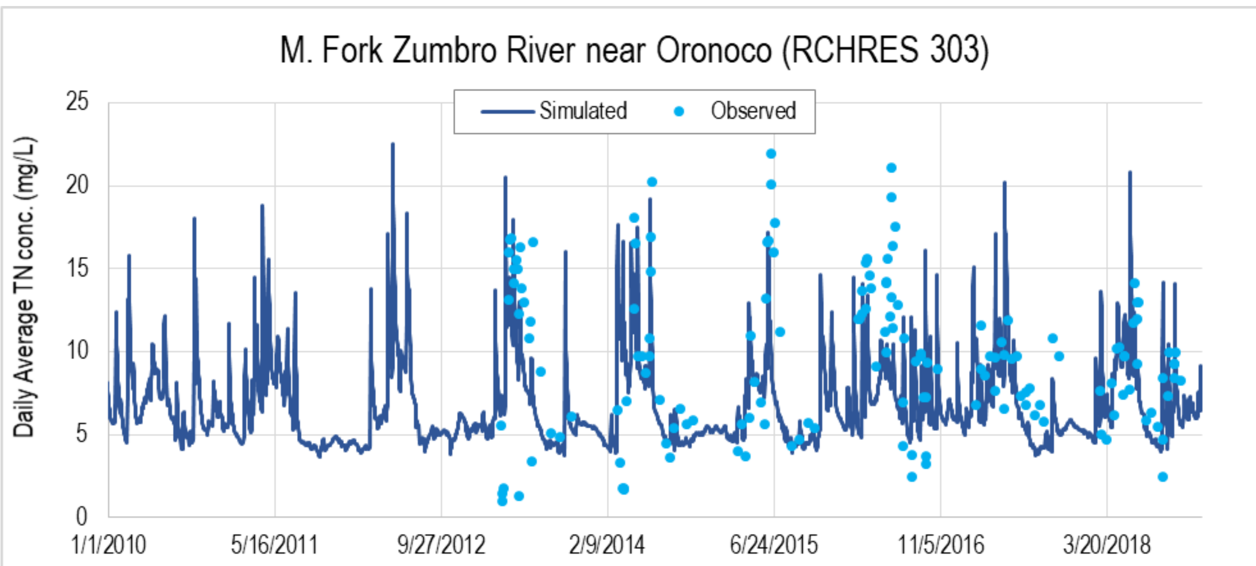

Figure C-53: Observed and simulated daily average TN concentrations for Middle Fork Zumbro River near Oronoco

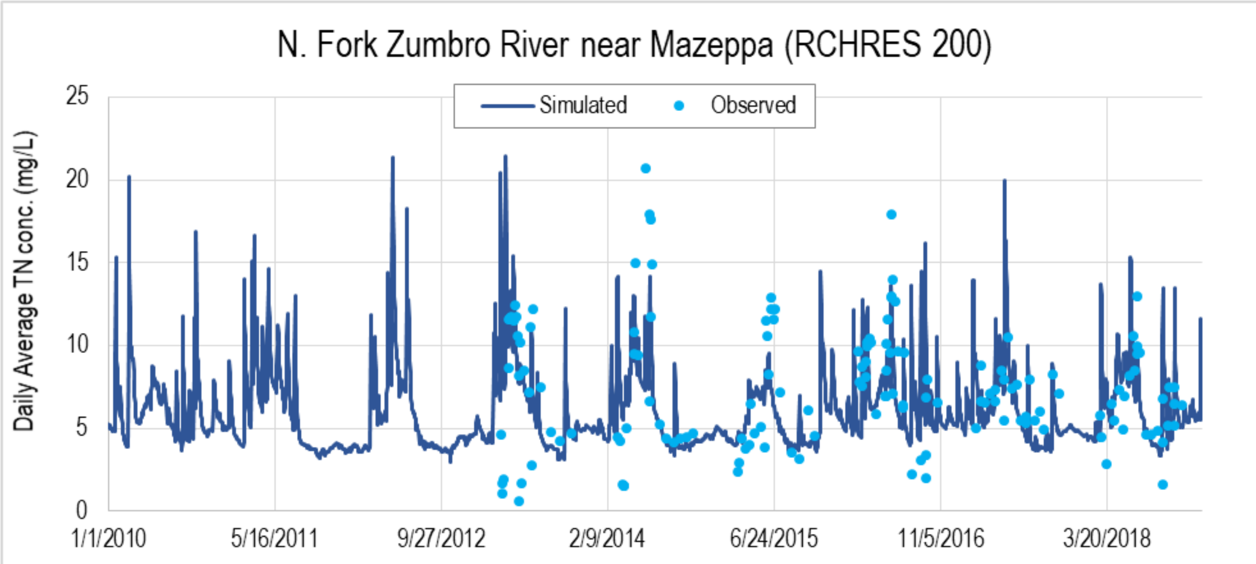

Figure C-54: Observed and simulated daily average TN concentrations for North Fork Zumbro River near Mazeppa

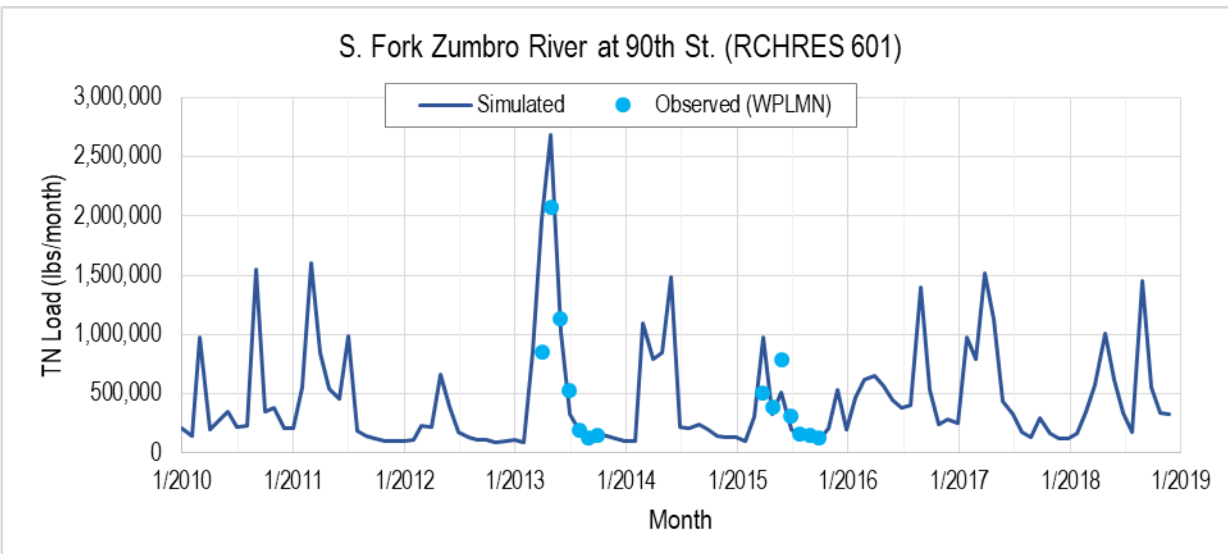

Figure C-55: Observed and simulated monthly TN loads for South Fork Zumbro River at 90th Street

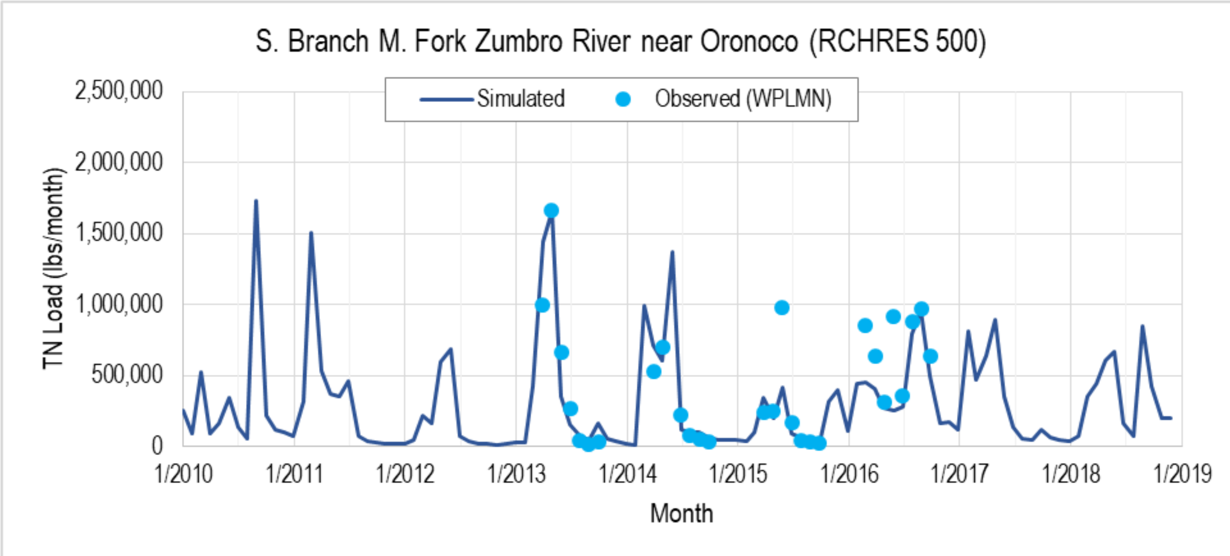

Figure C-56: Observed and simulated monthly TN loads for South Branch Middle Fork Zumbro River near Oronoco

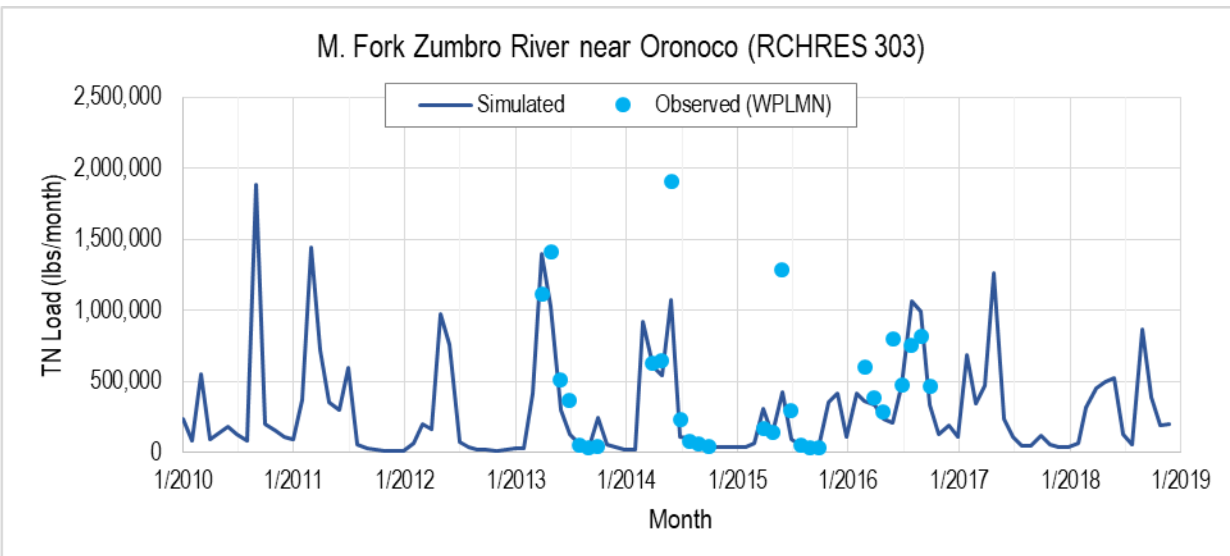

Figure C-57: Observed and simulated monthly TN loads for Middle Fork Zumbro River near Oronoco

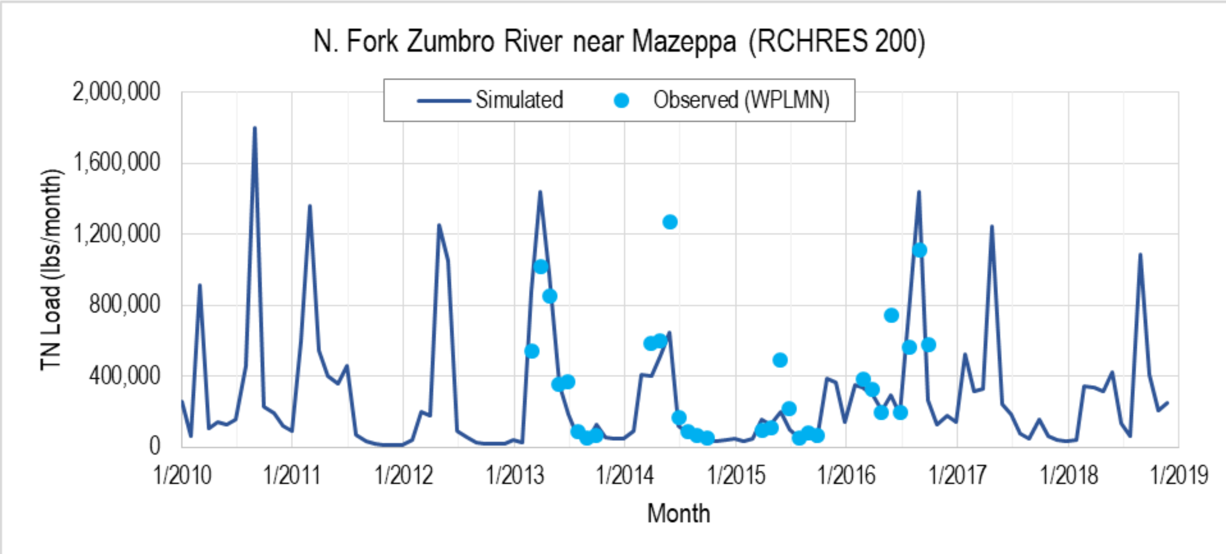

Figure C-58: Observed and simulated monthly TN loads for North Fork Zumbro River near Mazeppa

Nitrate + Nitrite

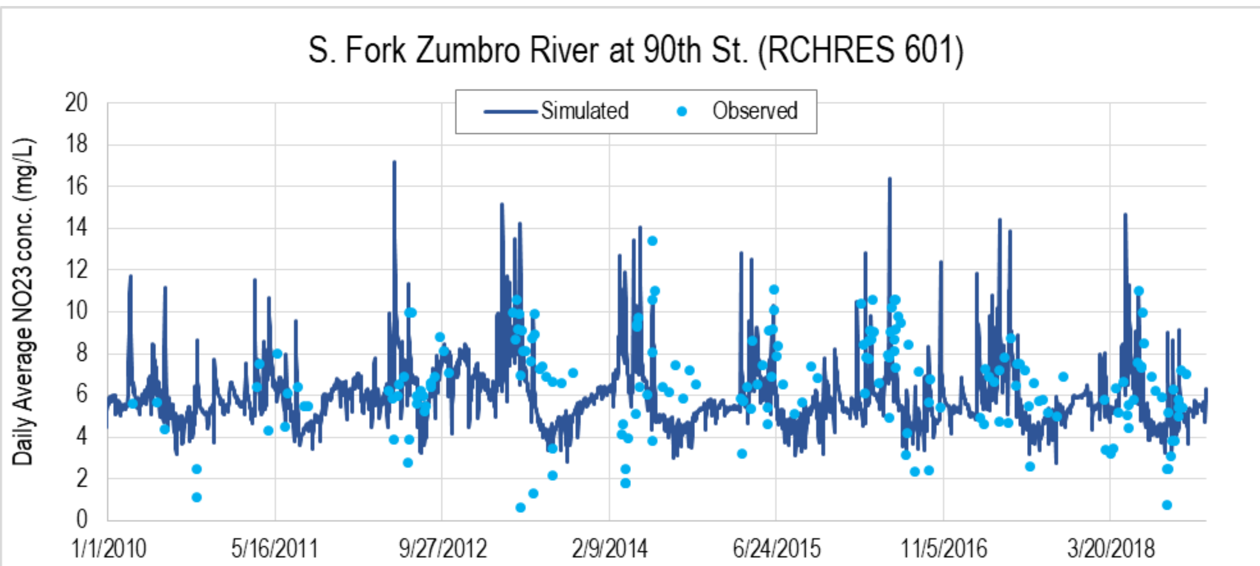

Figure C-59: Observed and simulated daily average NO_{23} concentrations for South Fork Zumbro River at 90th Street

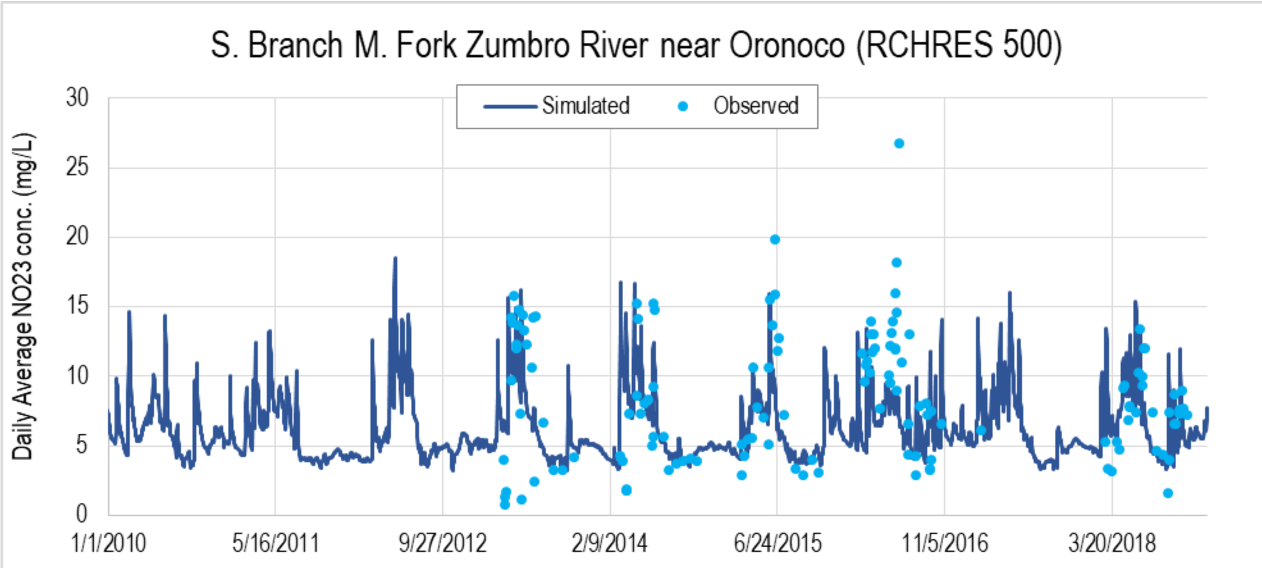

Figure C-60: Observed and simulated daily average NO_{23} concentrations for South Branch Middle Fork Zumbro River near Oronoco

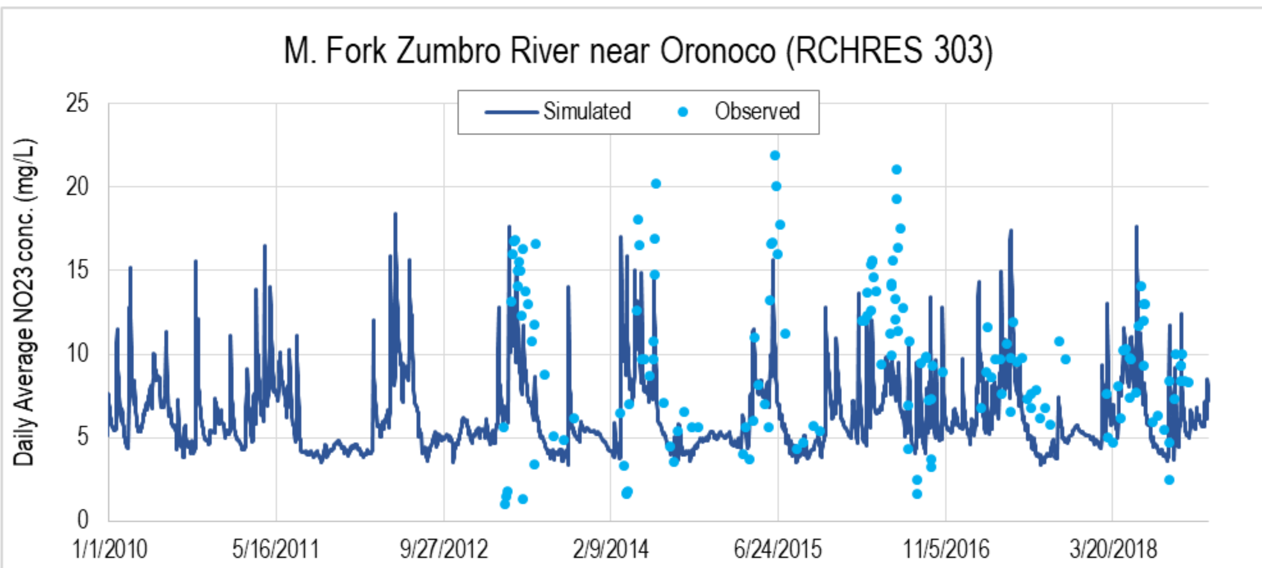

Figure C-61: Observed and simulated daily average NO_{23} concentrations for Middle Fork Zumbro River near Oronoco

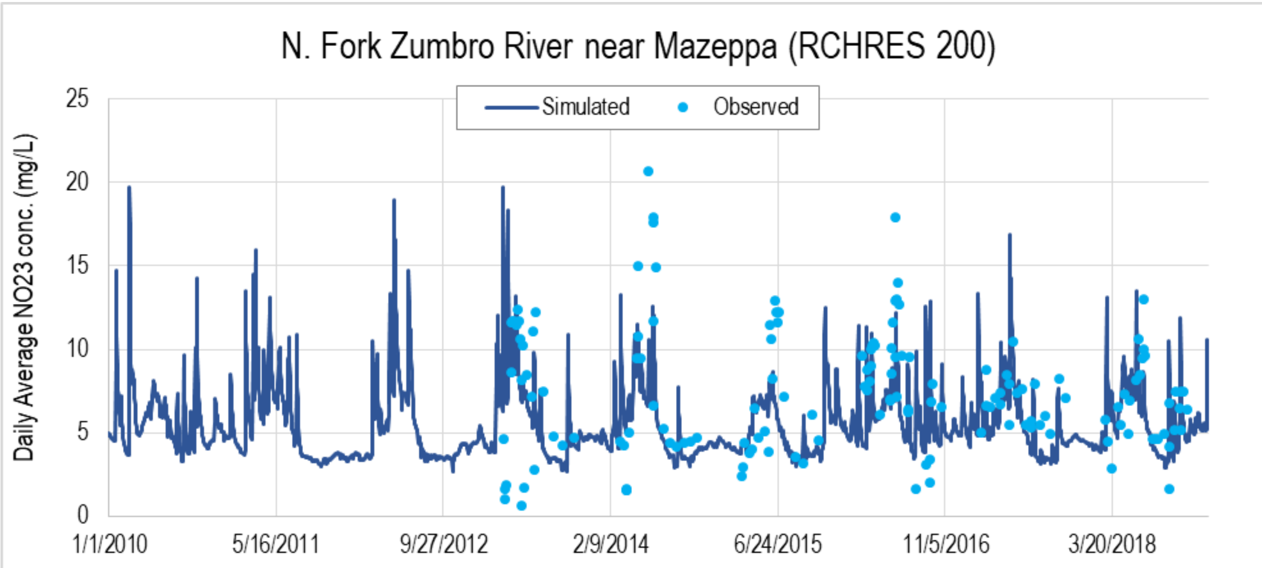

Figure C-62: Observed and simulated daily average NO_{23} concentrations for North Fork Zumbro River near Mazeppa

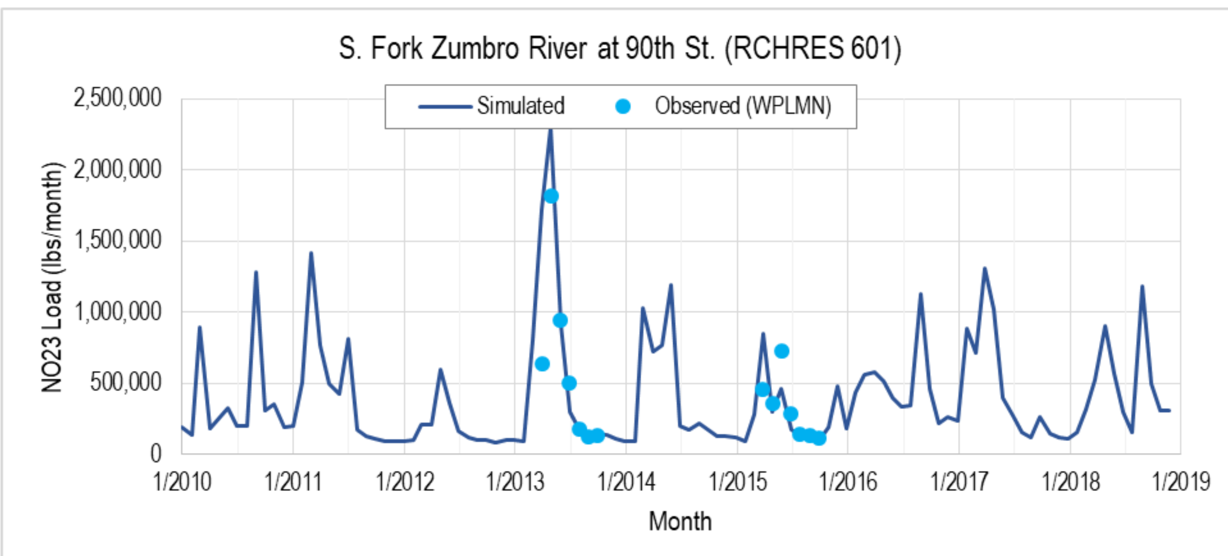

Figure C-63: Observed and simulated monthly NO_{23} loads for South Fork Zumbro River at 90th Street

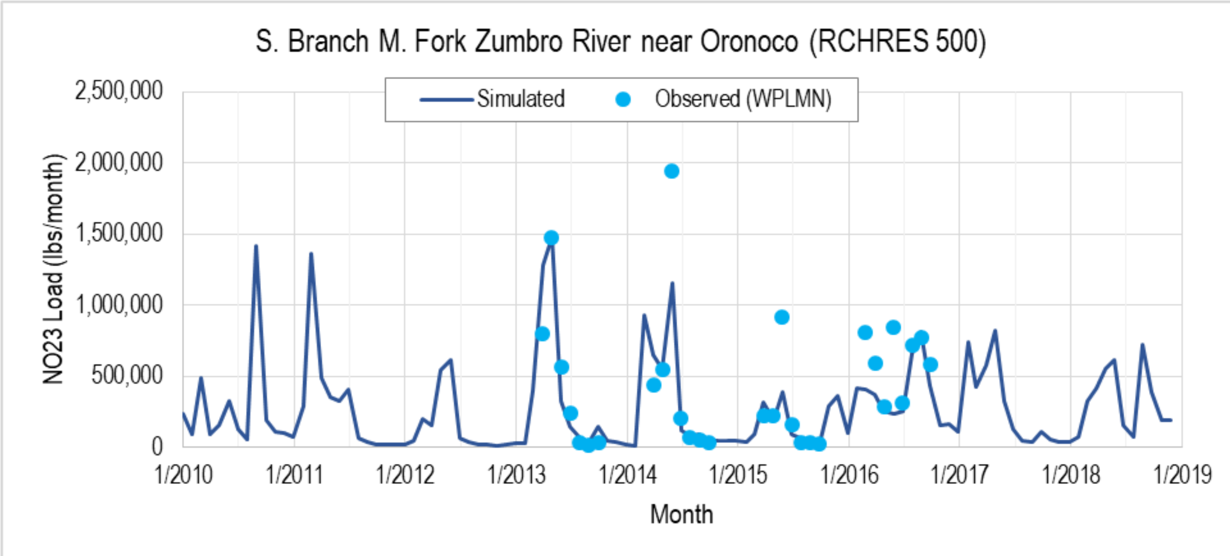

Figure C-64: Observed and simulated monthly NO_{23} loads for South Branch Middle Fork Zumbro River near Oronoco

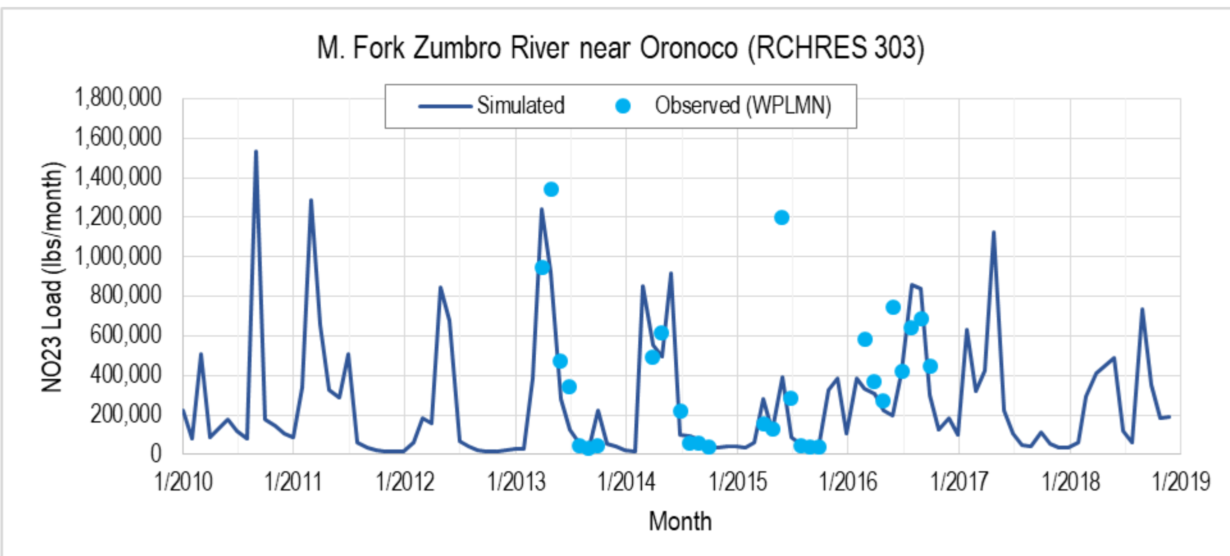

Figure C-65: Observed and simulated monthly NO_{23} loads for Middle Fork Zumbro River near Oronoco

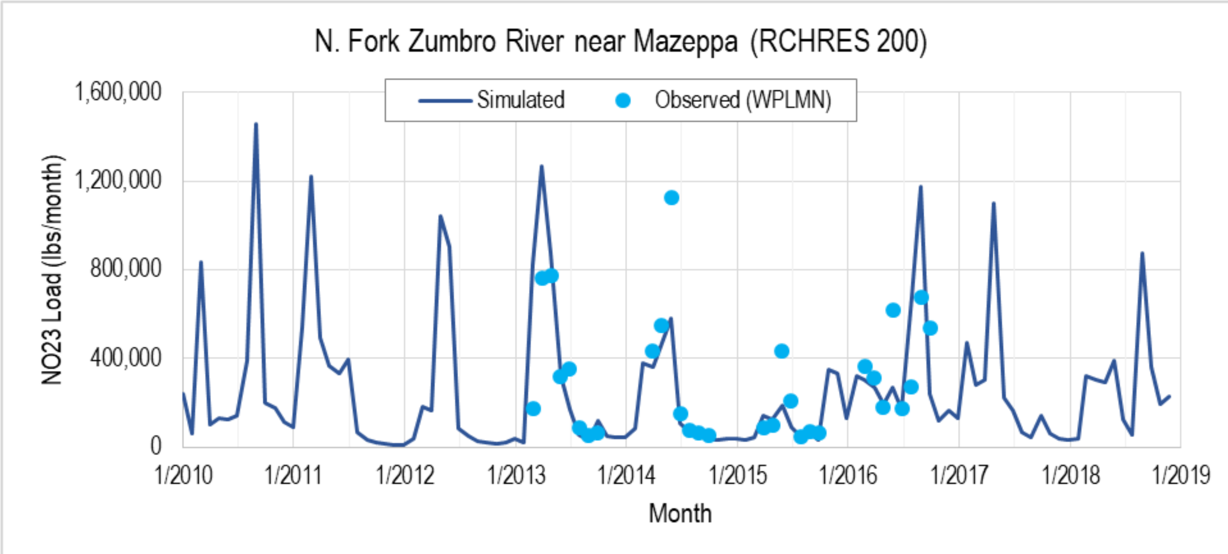

Figure C-66: Observed and simulated monthly NO_{23} loads for North Fork Zumbro River near Mazeppa

Dissolved Oxygen

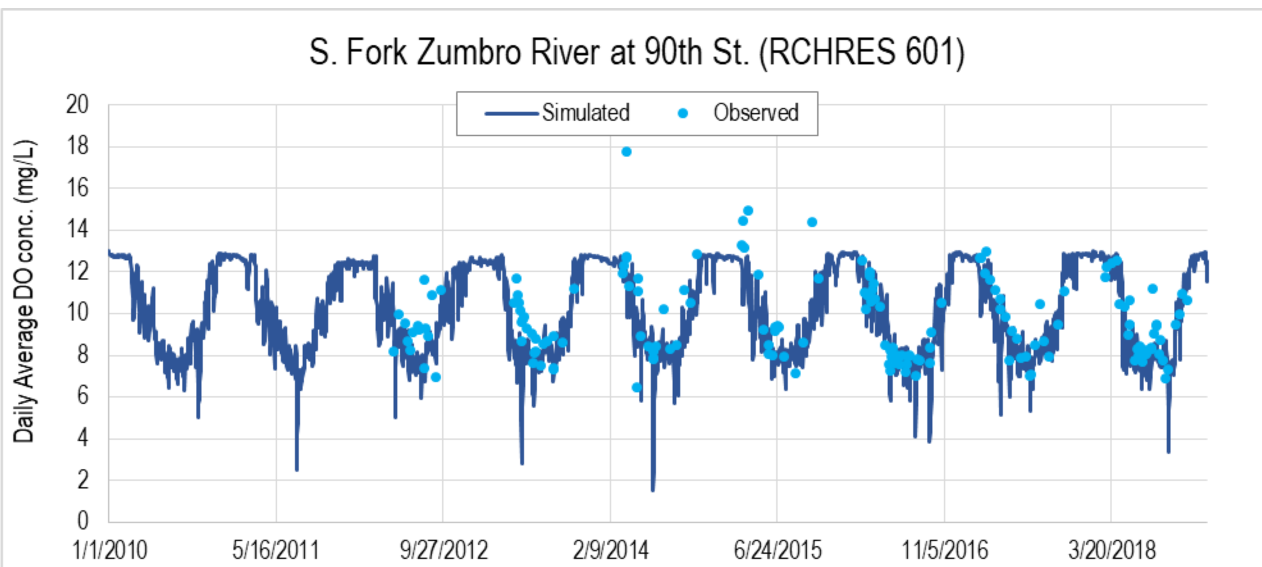

Figure C-67: Observed and simulated daily average DO concentrations for South Fork Zumbro River at 90th Street

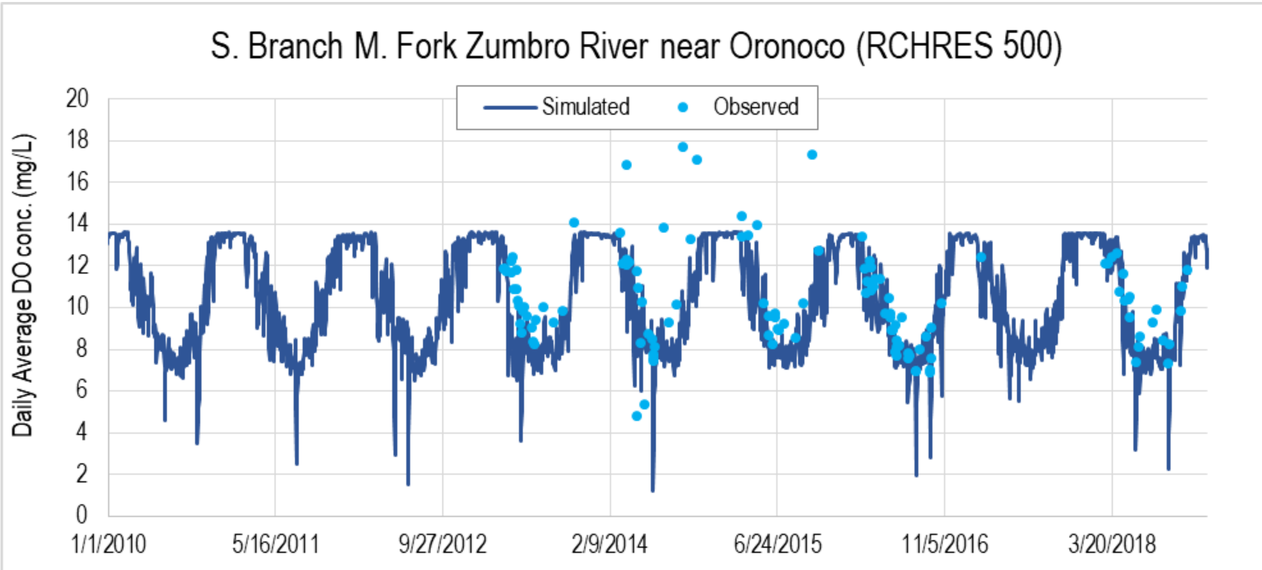

Figure C-68: Observed and simulated daily average DO concentrations for South Branch Middle Fork Zumbro River near Oronoco

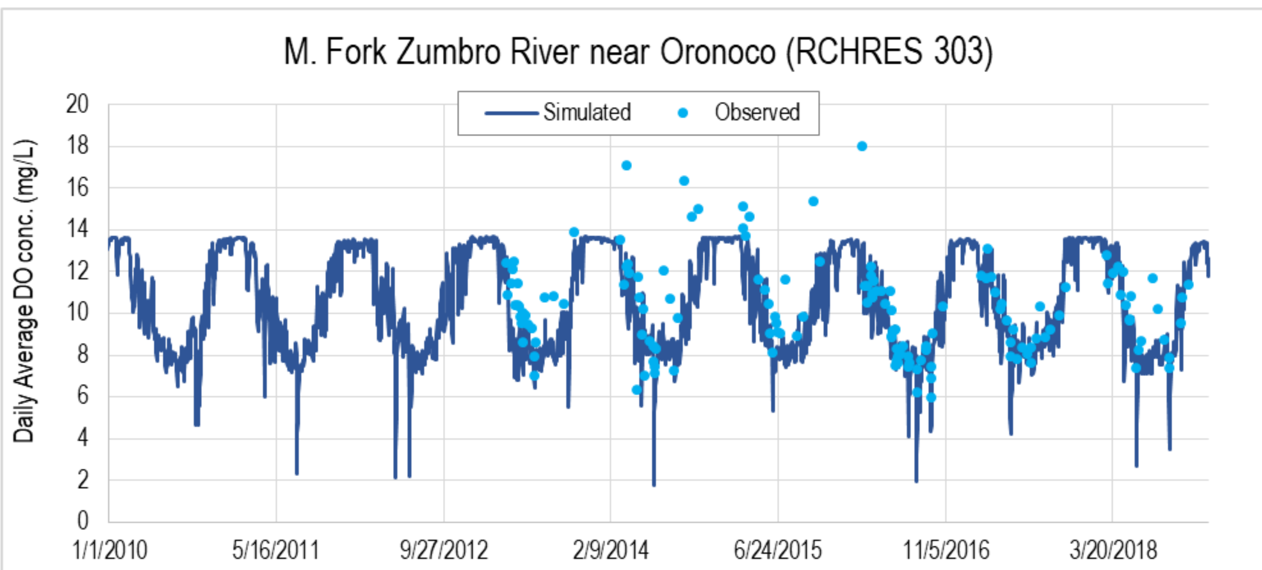

Figure C-69: Observed and simulated daily average DO concentrations for Middle Fork Zumbro River near Oronoco

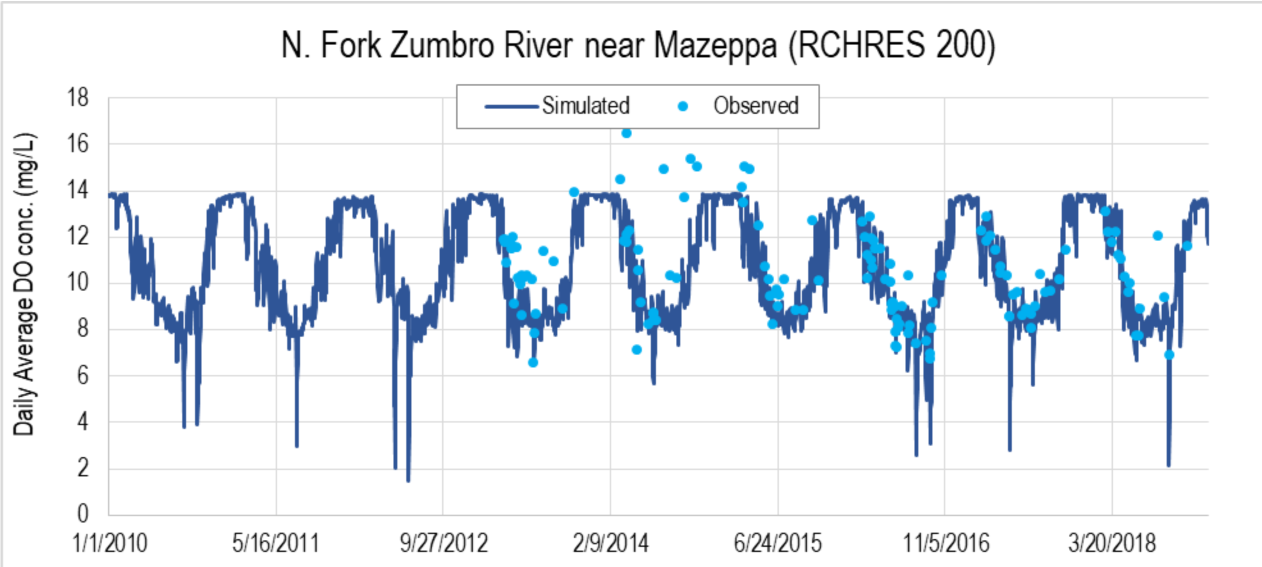

Figure C-70: Observed and simulated daily average DO concentrations for North Fork Zumbro River near Mazeppa

Water Temperature

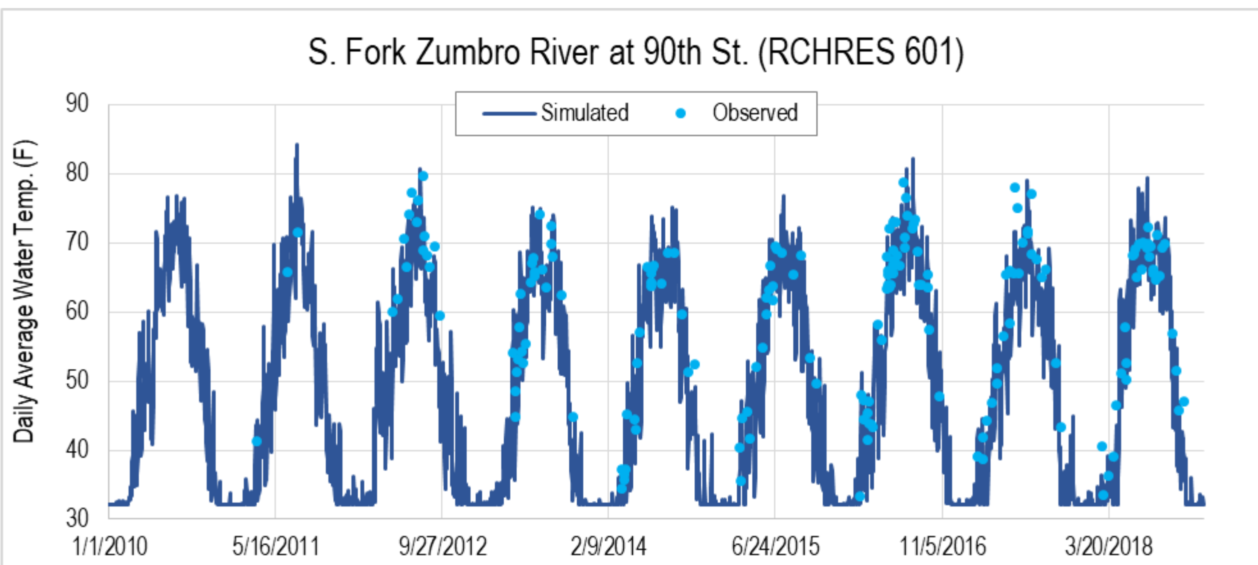

Figure C-71: Observed and simulated daily average water temperature for South Fork Zumbro River at 90th Street

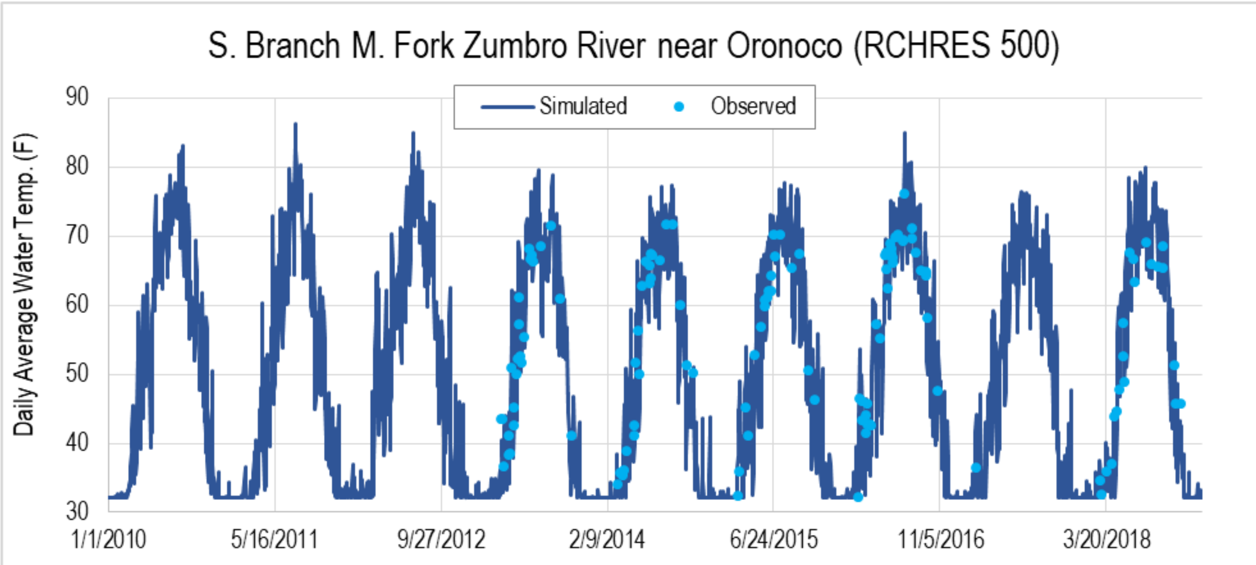

Figure C-72: Observed and simulated daily average water temperature for South Branch Middle Fork Zumbro River near Oronoco

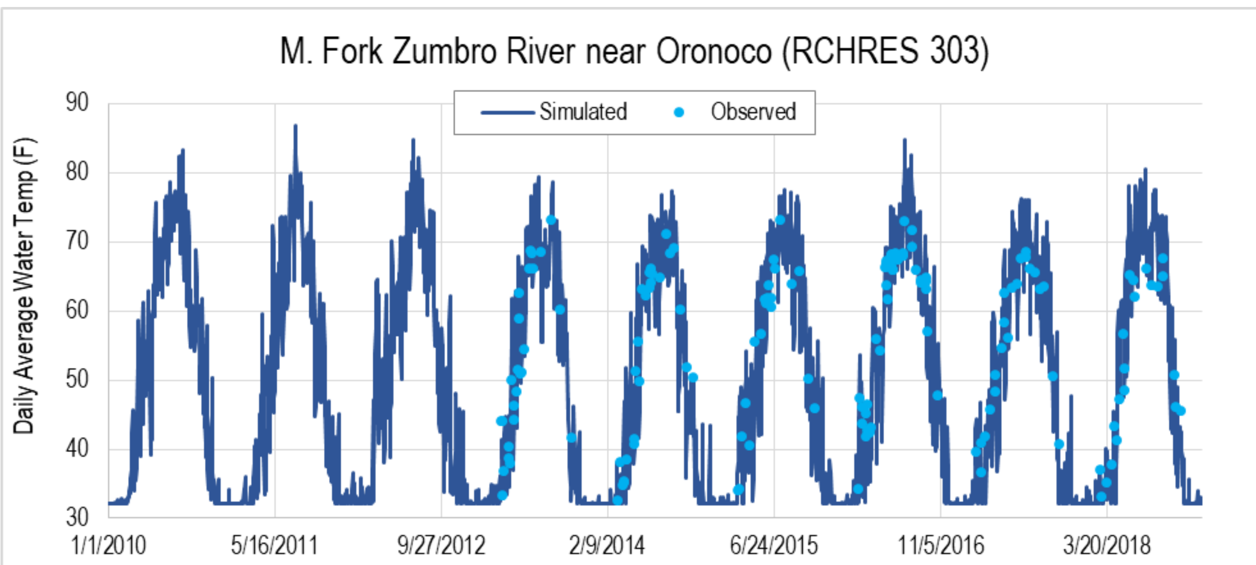

Figure C-73: Observed and simulated daily average water temperature for Middle Fork Zumbro River near Oronoco

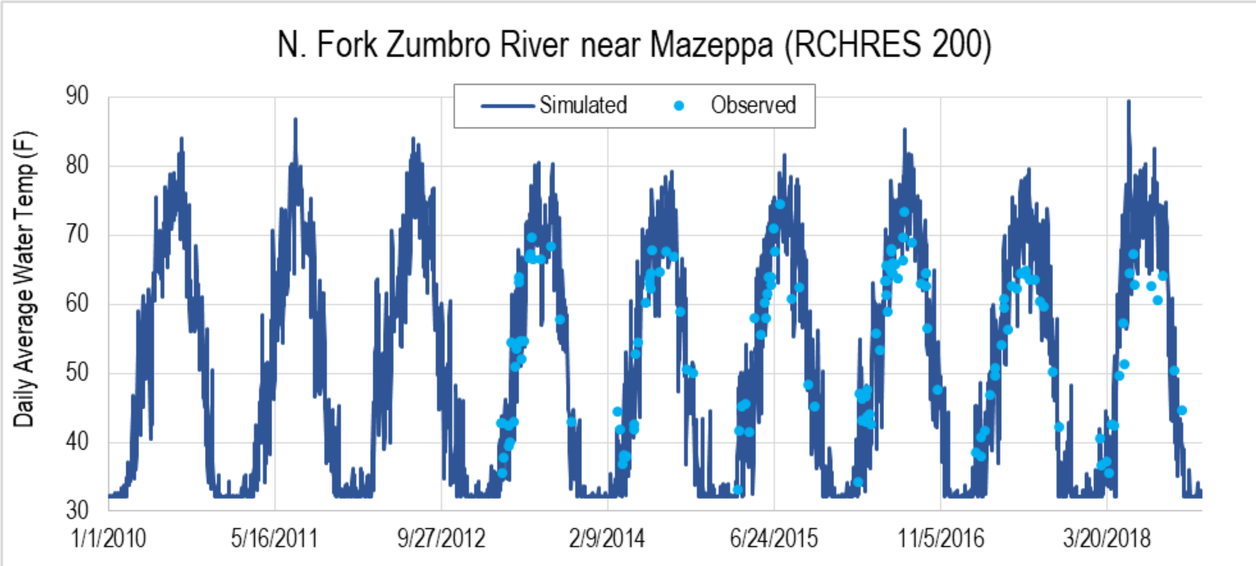

Figure C-74: Observed and simulated daily average water temperature for North Fork Zumbro River near Mazeppa