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MEMORANDUM

To:	Chuck Regan and Mark Evenson (MPCA)
Cc:	Jon Butcher, Sam Sarkar and Jennifer Olson (Tetra Tech)
From:	Michelle Schmidt
Date:	7/13/2018
Subject:	Mississippi River – Grand Rapids HSPF Model Recalibration
Project Number:	100-IWM-T36278.13

1.0 BACKGROUND

The Minnesota Pollution Control Agency (MPCA) has facilitated the development of linked Hydrologic Simulation Fortran Models (HSPF) for HUC8 watersheds of the Upper Mississippi River Basin. The original models were created in 2011-12 and ran through 2009. In 2016, RESPEC was contracted to make refinements to the HUC8-level HSPF models. During this phase land use was updated in several of the models using the University of Minnesota's Remote Sensing and Geospatial Analysis group's Minnesota Land Cover Classification and Impervious Surface Area by Landsat and LiDAR (2013 update – Version 1; RESPEC, 2016) land use coverage. RESPEC also extended all the models in time to simulate the period of 1/1/1995 – 12/31/2015. However, not all the models were recalibrated following these updates. Tetra Tech has been tasked with recalibrating the linked Upper Mississippi River basin models, and the recalibration of the Mississippi River – Grand Rapids (MR-GR) watershed model is discussed in this memorandum.

The Upper Mississippi River originates in the Headwaters watershed, which joins with the outflow from the Leech Lake HUC8 watershed and flows eastward into the Grand Rapids watershed near Grand Rapids, MN, and then southward to the Brainerd watershed. This memorandum documents the hydrology and water quality recalibration of the Mississippi River – Grand Rapids (HUC 07010103) watershed HSPF model, and additional memorandums are being prepared for the other models being recalibrated sequentially.

The northern lakes and forest ecoregion covers most of northeastern Minnesota, including the MR-GR watershed. White pine was historically logged in this region, however, more than half of the MR-GR

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drainage area remains densely forested (primarily coniferous species). Some streams were rerouted or incised to support logging endeavors, although most streams continue to flow naturally. Wetlands, including those formed through beaver damming activity, span approximately 36% of the watershed. There are several lakes dispersed throughout the MR-GR watershed and because most of the land remains relatively undisturbed (agricultural, grassland, pasture, and urban areas combine to be less than 12% of land in the watershed) many of the lakes remain in pristine condition. Recent intensive monitoring found that nearly all lakes sampled met aquatic life standards, and several lakes exhibited exceptional fish communities (MPCA, 2018). Most streams in the MR-GR watershed remain in good condition. Sections of the Prairie River, Tamarack River, and Willow River, three major tributaries, provide healthy habitats for fish and invertebrates, and are classified as Exceptional Use streams.

There are lakes, particularly in the southern portion of the watershed, that exhibit elevated phosphorus, chlorophyll *a*, and/or excessive turbidity. Big Sandy Lake and Lake Minnewawa are listed as impaired for excessive nutrients, and are the subject of a Total Maximum Daily Load (TMDL; Aitkin County SWCD, 2013). Low dissolved oxygen or have biology dominated by taxa that thrive in low dissolved oxygen waters have been observed in a few streams. Part of the Sandy River is impaired for low dissolved oxygen. Low dissolved oxygen is also an issue in Moose River, although it is believed to be a naturally occurring phenomenon.

2.0 HYDROLOGY

Refining the water quality simulation based on monitoring data collected for the extension period (and full simulation period) was the primary focus of this work. However, a strong hydrologic foundation is critical for representing water quality dynamics well, and several areas for improvement were identified after the model was received. Many of the identified refinements were implemented prior to the sediment recalibration. First, the water balance was reviewed and excessive potential evapotranspiration was addressed. NLDAS gridded data was used to derive new potential evapotranspiration time series, and evapotranspiration was then recalibrated in comparison to SSEBop (Simplified Surface Energy Balance), a gridded data product from USGS (Savoca, et al, 2013). The snow accumulation and melt simulation method used by RESPEC was converted from degree day to a mechanistic energy balance method, as recommended for One Water models (AQUA TERRA, 2012), and gridded snow water equivalent data from SNODAS informed the snow recalibration. The hydrologic recalibration was then further tuned using flow records at several key gages dispersed throughout the watershed. Potential future refinements to the representation of mining features and operations (e.g., excavated, closed pits and associated dewatering activities) in the Mesabi Range region were documented in a separate memorandum (Tetra Tech, 2018).

2.1 WATER BALANCE

During the recalibration of the Sauk and Crow watershed HSPF models it was discovered that the potential evapotranspiration inputs were excessive for this region (expected evaporation/precipitation ratio range: 0.6 - 0.7), which resulted in the models misrepresenting the overall water balance in these watersheds (Tetra Tech, 2017a). The same issue was present in the MR-GR model. To amend this, potential evapotranspiration was recalculated from gridded NLDAS hourly meteorological time series using the Penman Pan method as recommended by AQUA TERRA (2012). The same approach was used to update the potential evapotranspiration time series for hydrozones in the MR-GR model. The annual water balances simulated by the model pre- and post-recalibration are provided in Figure 2-1 and

Figure 2-2. In the recalibrated model a more representative fraction of precipitation is evaporated, either by vegetative canopy interception, evaporation from soil zone layers, baseflow or groundwater evaporation (wetlands only), or snow pack evaporation (previously not included). Groundwater is the primary contributor of flow to the stream network, followed by interflow, as expected for such a densely forested and wetland watershed. Surface runoff, deep groundwater recharge, and surface storage are relatively small components of the modeled water balance.

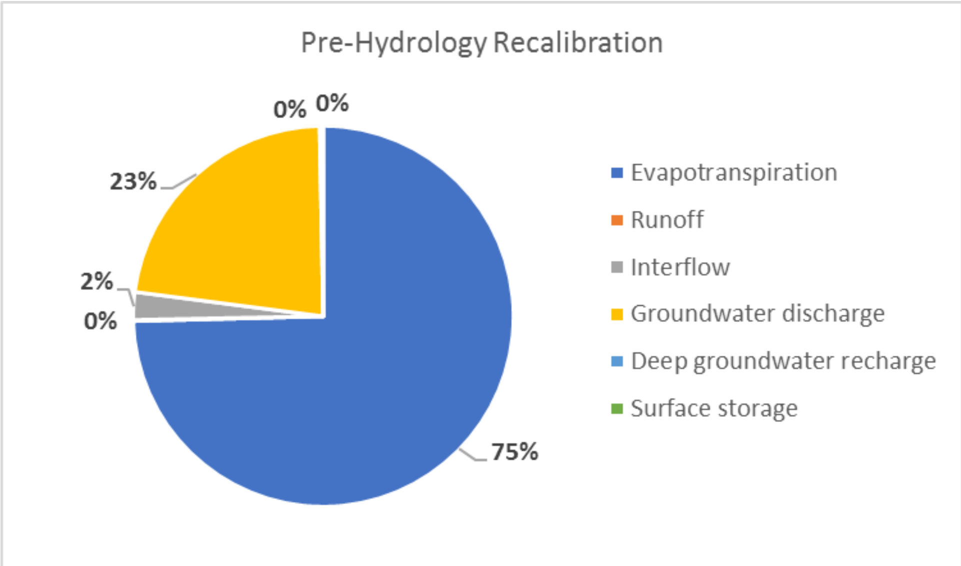


Figure 2-1. Annual Average Water Balance for the Upper Mississippi – Grand Rapids Watershed HSPF Model (Pre-Hydrology Recalibration)

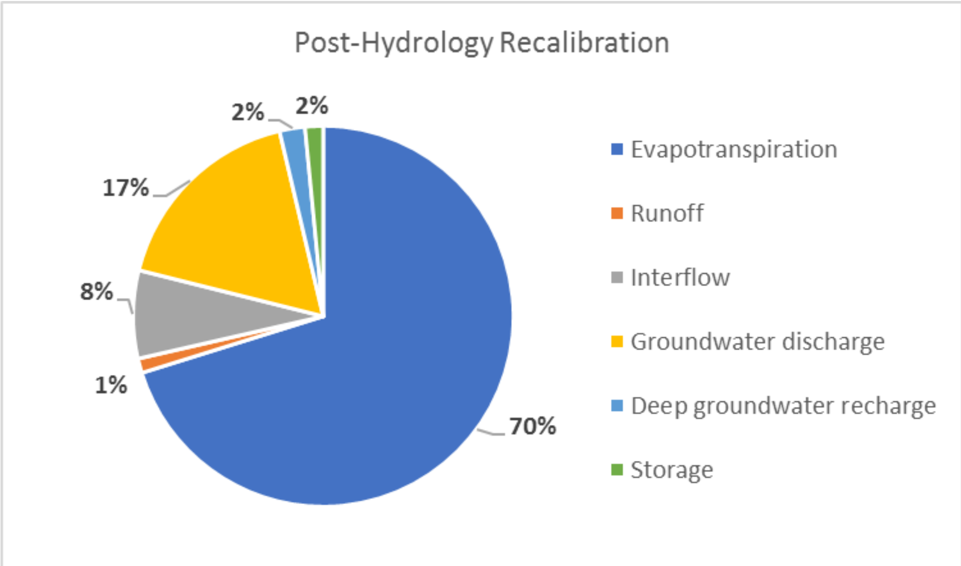


Figure 2-2. Annual Average Water Balance for the Upper Mississippi – Grand Rapids Watershed HSPF Model (Post-Hydrology Recalibration)

Simulated evapotranspiration was compared to SSEBop estimates (Savoca, et al, 2013) by hydrozone and the model was recalibrated accordingly (e.g., monthly interception and lower soil zone evapotranspiration parameters were adjusted). Summary statistics that demonstrate the fit between SSEBop and HSPF simulated evapotranspiration are provided for the hydrozones in the MR-GR model (Table 2-1). HSPF simulated evapotranspiration resembles that of SSEBop and monthly Nash Sutcliffe Coefficients (NSE) are quite good (> 0.90 for all hydrozones). Example calibration plots are also provided for hydrozone 17 in Figure 2-3 - Figure 2-5.

Table 2-1. Summary Statistics for Comparison to SSEBop Evapotranspiration

Hydrozone	Relative Error	Monthly R^2	Monthly Nash Sutcliffe Coefficient
1	-3.6%	0.91	0.92
3	5.7%	0.92	0.92
5	-4.8%	0.91	0.92
7	-10.1%	0.90	0.93
9	4.5%	0.92	0.92
11	0.3%	0.91	0.91
13	-10.3%	0.91	0.93
15	-10.9%	0.90	0.92
17	2.1%	0.92	0.93
19	-5.2%	0.90	0.91
21	5.0%	0.91	0.92
23	-7.7%	0.91	0.92
25	-7.6%	0.90	0.92
31	-5.5%	0.91	0.93

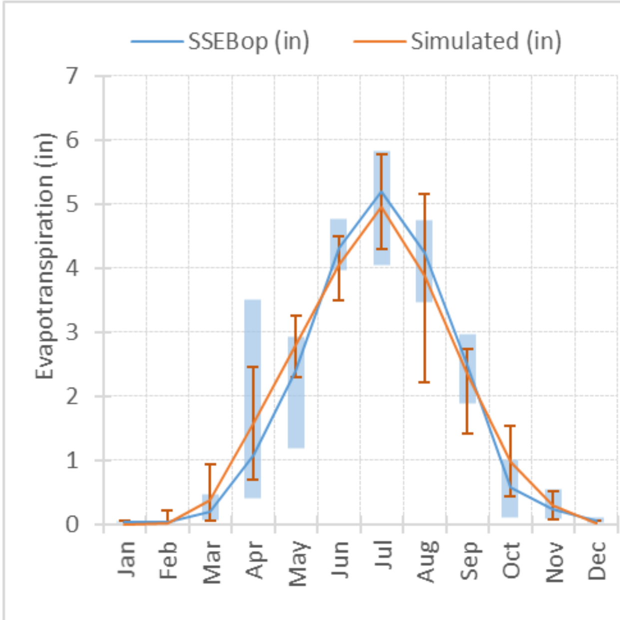


Figure 2-3. Comparison of SSEBop and Simulated Monthly Evapotranspiration for Hydrozone 17

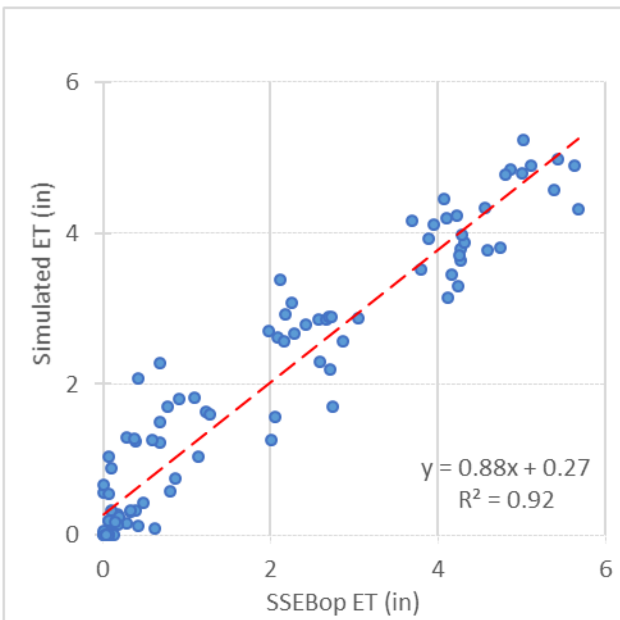


Figure 2-4. Scatter Plot of SSEBop and Simulated Monthly Evapotranspiration for Hydrozone 17

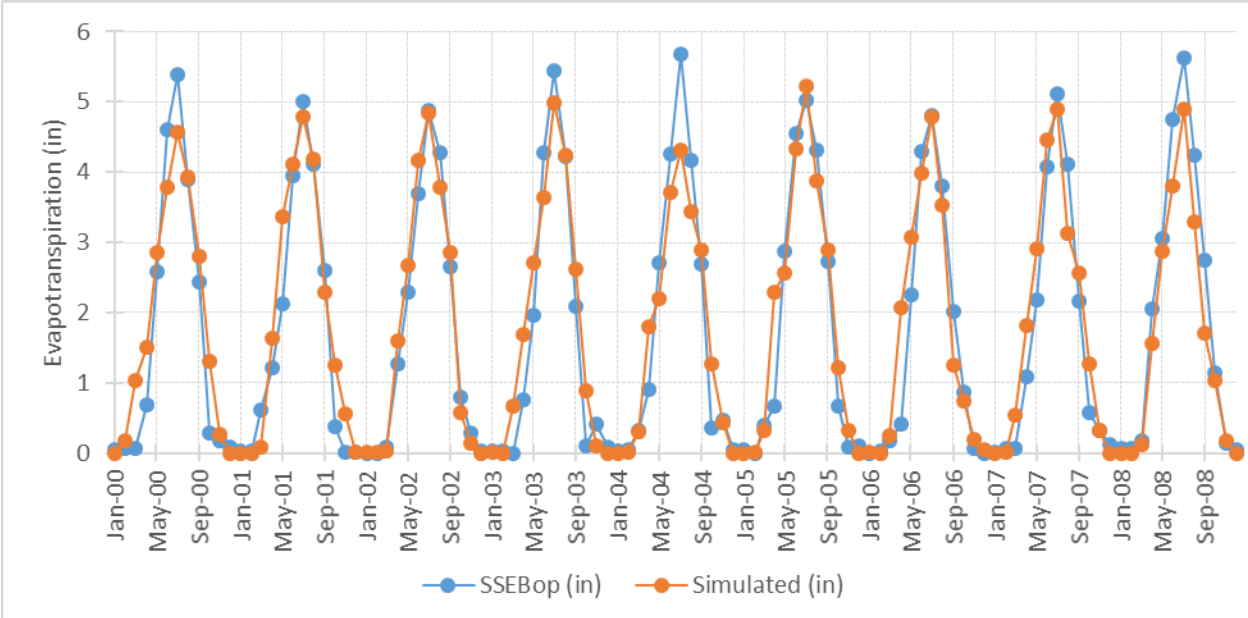


Figure 2-5. Time Series Plot of SSEBop and Simulated Evapotranspiration for Hydrozone 17

2.2 SNOW

The dominate form of precipitation in the winter in the Grand Rapids watershed is snow, and peak flows often follow the spring melt period. Therefore, a good representation of snow processes is a critical component of watershed model. The RESPEC version of the MR-GR model utilized the degree day method for simulating snow accumulation and melt in the watershed. However, the energy balance method is preferable (AQUA TERRA, 2012) as it accounts for net radiation, convection and condensation heat exchanges that are computed from meteorological inputs (e.g., solar radiation, wind). The MR-GR model was converted to the energy balance method. Gridded snow water equivalent data from SNODAS were aggregated to the hydrozone level and used to support the snow recalibration. Most of the snow parameters required recalibration following the switch to the energy balance method. The final snow simulation is representative of SNODAS snow water equivalent, as shown by the summary statistics in Table 2-2 and sample calibration plots for hydrozone 17 in Figure 2-6 - Figure 2-8.

Table 2-2. Summary Statistics for Comparison to SNODAS Snow Water Equivalent

Hydrozone	Relative Error	Monthly R^2	Monthly Nash Sutcliffe Coefficient
1	6.5%	0.93	0.87
3	4.7%	0.93	0.85
5	-4.7%	0.93	0.86
7	-2.1%	0.94	0.89

Hydrozone	Relative Error	Monthly R^2	Monthly Nash Sutcliffe Coefficient
9	-7.0%	0.90	0.81
11	-2.6%	0.95	0.90
13	0.1%	0.90	0.81
15	-1.6%	0.92	0.85
17	-5.7%	0.92	0.85
19	2.4%	0.91	0.82
21	-5.3%	0.89	0.78
23	4.9%	0.91	0.80
25	4.3%	0.83	0.66
31	3.3%	0.87	0.75

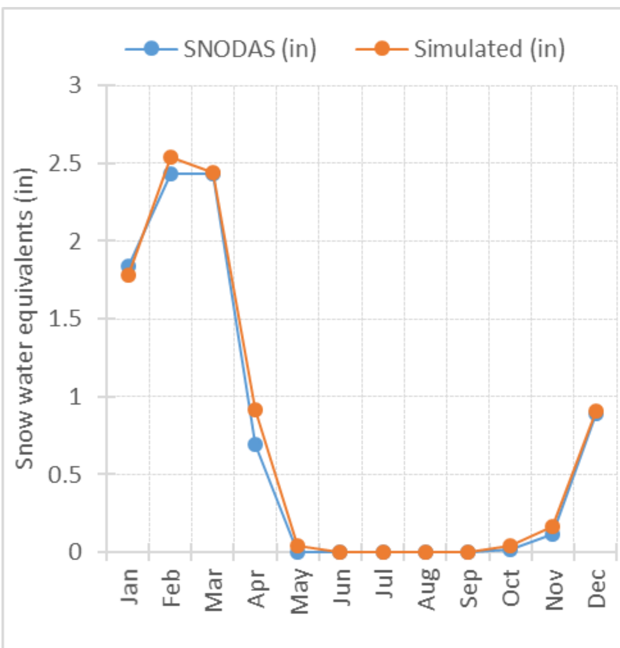


Figure 2-6. Comparison of SNODAS and Simulated Monthly Snow Water Equivalent for Hydrozone 17

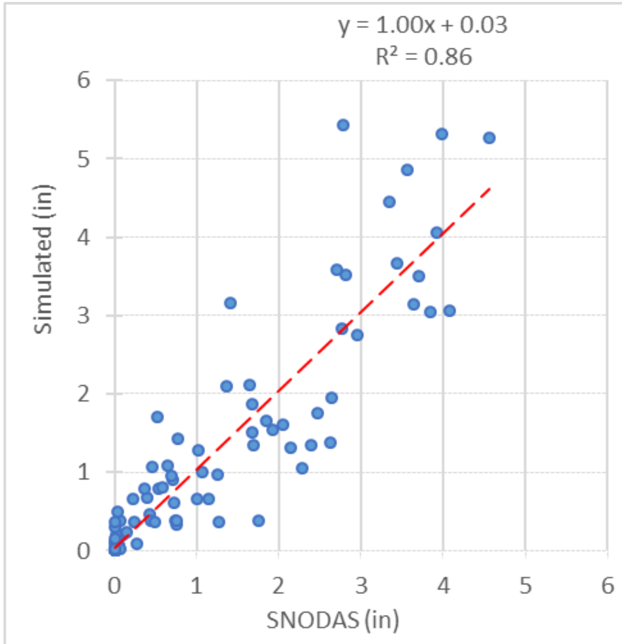


Figure 2-7. Scatter Plot of SNODAS and Simulated Monthly Snow Water Equivalent for Hydrozone 17

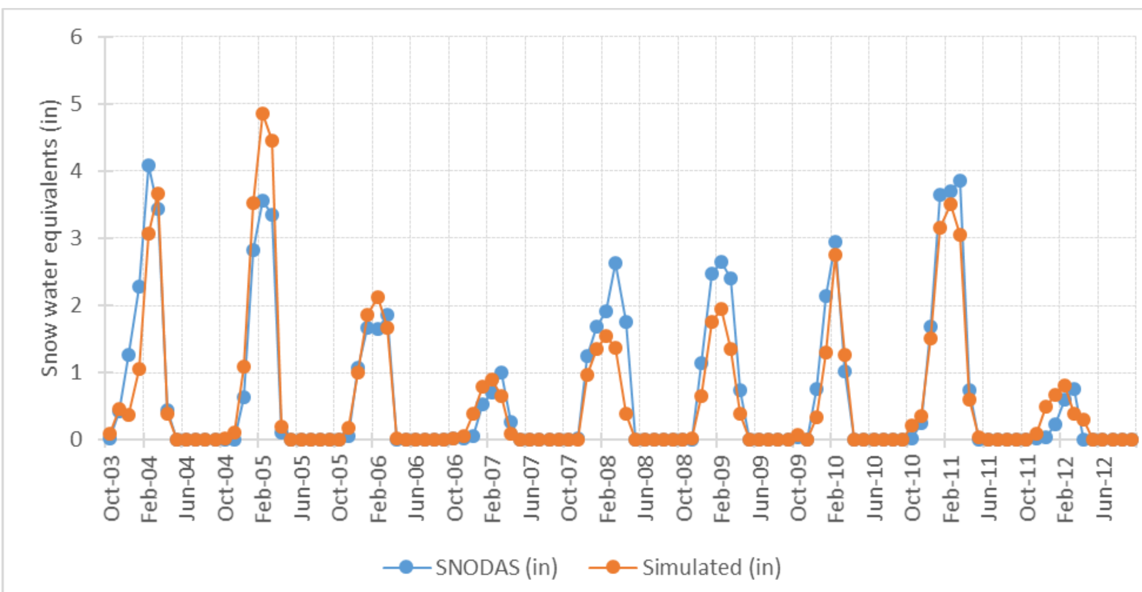


Figure 2-8. Time Series Plot of SNODAS and Simulated Snow Water Equivalent for Hydrozone 17

2.3 LAKE LEVELS

Stage dynamics were reviewed for simulated lakes in the MR-GR watershed as part of the hydrology recalibration. Lake surface elevation data was extracted from the Minnesota Lake Finder and compared to simulated lake stage. Example comparison plots are provided for Lake Minnewawa, Prairie Lake, and Swan Lake in Figure 2-9 - Figure 2-11. The model does a reasonable job of representing lake level dynamics. Improvements to the representation of Mesabi Range mining features and operations (e.g., closed pits and dewatering processes) in the HSPF model may improve the representation of Swan Lake, and downstream river segments. Suggested improvements are discussed in a separate memorandum (Tetra Tech, 2018).

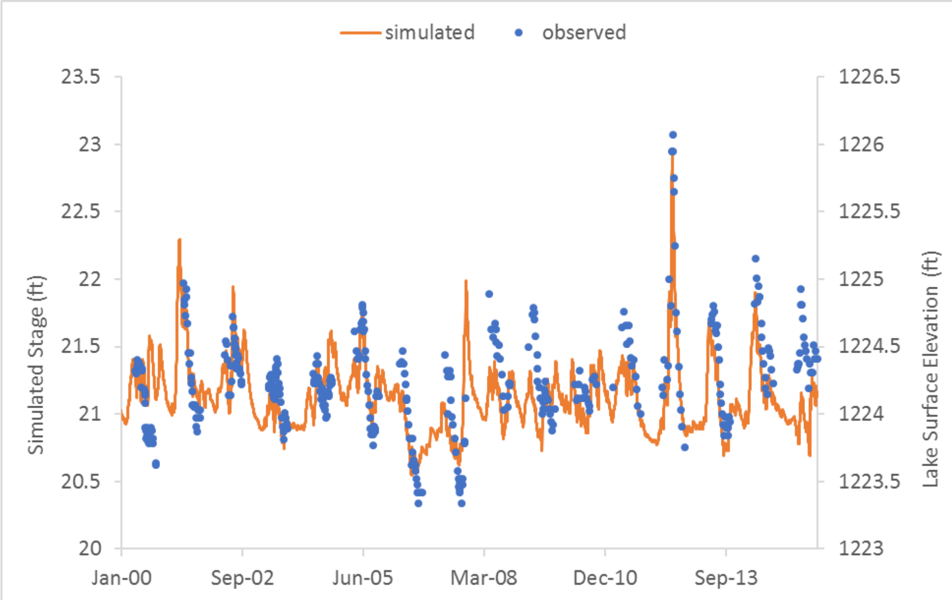


Figure 2-9. Stage Calibration for Lake Minnewawa (R434)

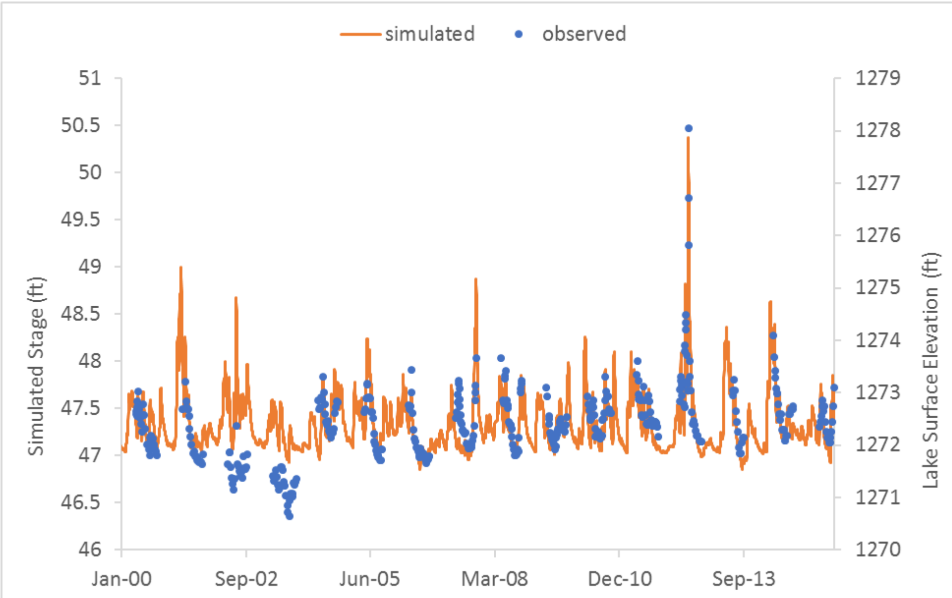


Figure 2-10. Stage Calibration for Prairie Lake (R404)

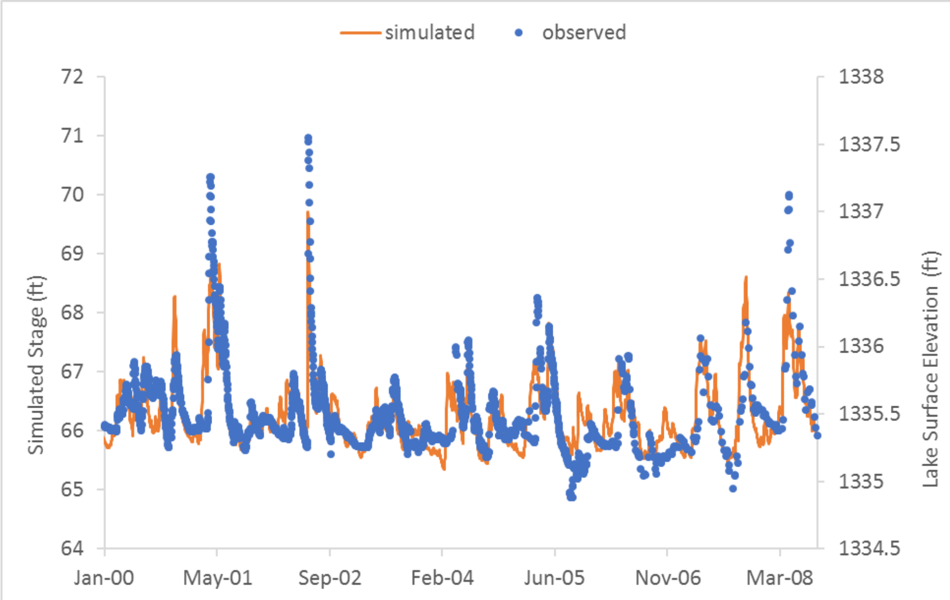


Figure 2-11. Stage Calibration for Swan Lake (R282)

2.4 FLOW

Summary statistics for flow gages prior to and following the hydrology recalibration are provided in Table 2-3. For most sites error in total volume improved with the recalibration. The fit at Swan River near Jurgenson was, and remains, relatively poor. The recalibration did improve the representation of flow somewhat; however, uncertainty in representation of mining features in the Swan River drainage area appear to result in an overestimation of the full flow profile. The original fit was exceptionally poor at Prairie River near McGregor. Qualitative notes regarding the flow data at this HYDSTRA site specify that records are of poor or fair quality for years 2008-2015, which partially explains the misfit of the model at this site. Better representation of wetland hydrology improved the fit at this site, although the overestimation of flow by the model at this location was not fully resolved. Recalibration efforts reduced volume errors and improved daily flow fit for Willow River, a major tributary stream in the western MR-GR watershed. Example calibration plots for Willow River are provided in Recalibration of the upstream Headwaters and Leech watersheds improved the representation of the mainstem Mississippi River near Grand Rapids, Minnesota.

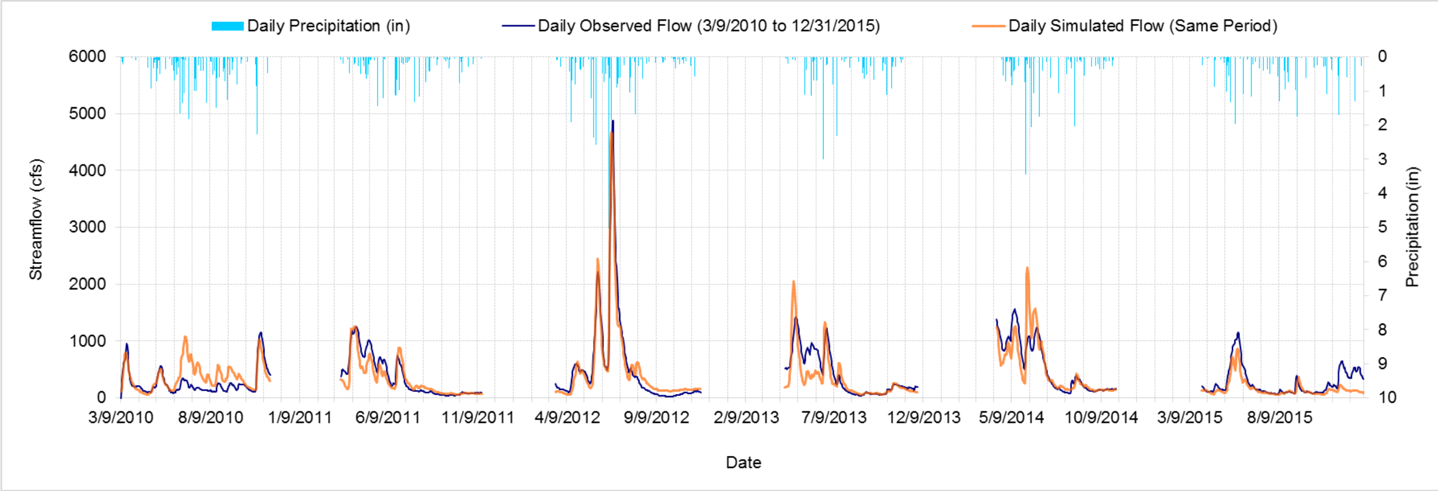
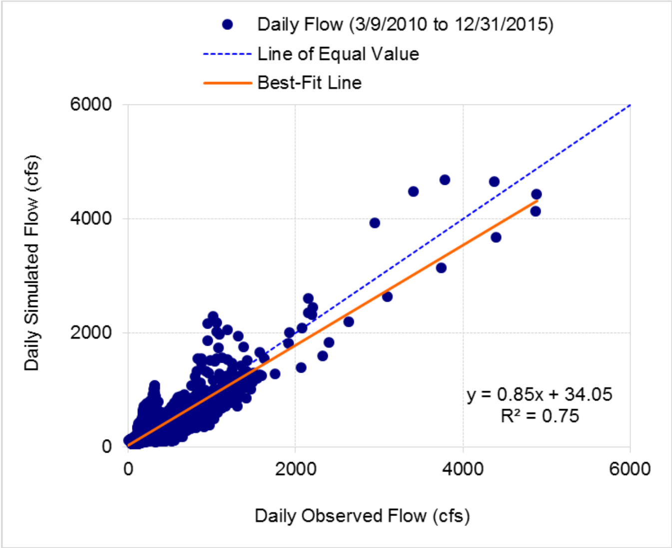


Figure 2-12. Time Series of Simulated and Observed Streamflow at Willow River (R690)



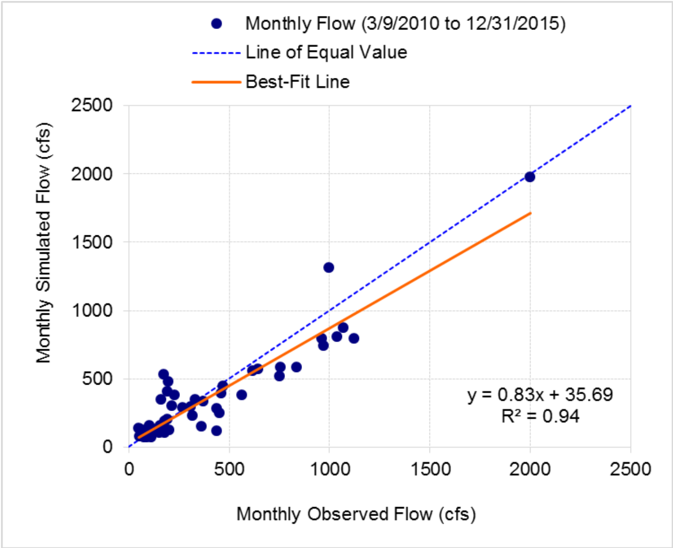


Figure 2-13. Simulated vs Observed Daily (Left) and Monthly (Right) Flow

Table 2-3. Summary Statistics for Flow Pre- and Post-Hydrology Recalibration

Location	Error in Total Volume	Error in 50% lowest flows	Error in 10% highest flows	Nash-Sutcliffe Efficiency	
				Daily	Monthly
Prior to hydrology recalibration					
Prairie River near Taconite, MN (H09020001; R150)	-11.9	-40.4	-7.12	0.768	0.844
Mississippi River at Grand Rapids, MN (H09064001; R220)	-10.8	-12.4	-4.35	0.761	0.887
Swan River near Jurgenson, Charter Dam Rd (H09052001; R287)	31.0	26.3	28.3	0.548	0.655
Swan River near Jacobson, CR438 (H09065001; R309)	0.97	-3.25	6.04	0.826	0.885
Prairie River near McGregor, at South Balsam TWP Rd (H09079001; R431)	81.4	454	95	-1.118	-0.261
Big Sandy Lake near McGregor (H01006200; R462)	0.00	0.12	-0.02	1.000	1.000
Willow River near Palisade, CSAH5 (H09118001; R690)	-11.8	-27.5	-3.56	0.792	0.842
Post hydrology recalibration					
Prairie River near Taconite, MN (H09020001; R150)	0.13	12.0	-13.7	0.740	0.832
Mississippi River at Grand Rapids, MN (H09064001; R220)	-9.77	-10.4	-3.51	0.778	0.904
Swan River near Jurgenson, Charter Dam Rd (H09052001; R287)	24.2	20.0	20.9	0.581	0.723
Swan River near Jacobson, CR438 (H09065001; R309)	-9.99	-24.4	4.28	0.767	0.853
Prairie River near McGregor, at South Balsam TWP Rd (H09079001; R431)	62.9	924	46.2	-0.010	0.360
Big Sandy Lake near McGregor (H01006200; R462)	0.00	0.12	-0.02	1.000	1.000
Willow River near Palisade, CSAH5 (H09118001; R690)	-5.71	8.19	-1.11	0.806	0.855

3.0 SEDIMENT

The sediment simulation was refined following the hydrology recalibration. There were nine model reaches with 75 or more TSS samples collected during the model period, and these were selected as the primary calibration sites. Updates to the sediment simulation included:

- Establishment of critical shear stress parameters for deposition and scour following the hydrology recalibration
- Revisions to upland sediment parameterization (e.g., monthly vegetation cover patterns refined based on adjacent St. Louis River watershed) and recalibration of upland loading rates
- Incorporation of clay load with active groundwater outflow
- Recalibration of instream sediment parameterization based on long-term net sediment bed balance and instream suspended sediment data

Sediment loading rates for the Minnesota River Basin in southern Minnesota range from less than 100 to more than 500 lb/ac/yr (https://mrbdc.mnsu.edu/sites/mrbdc.mnsu.edu/files/public/pdf/askexpert/sediment_overview.pdf). Most land in the Minnesota River Basin is utilized for crop production, and soils are susceptible to erosion where there is a lack of perennial vegetation and poor field management practices (e.g., tillage). Sediment loading rates are expected to be lower for the forested land uses in the MR-GR watershed, where there is substantial cover and root mats to hold the soil in place. Sediment loading rates estimated for the entire MR – GR watershed based on instream TSS concentrations from 2007-2012 range from 22.1 – 48 lb/ac/yr (University of Minnesota, 2015). The mean annual sediment loading rate for the MR – GR model is well within this range at 31.5 lb/ac/yr. Sediment loading rates for forests and wetlands were 44.6 and 6.1 lb/ac/yr. Rates from agriculture and urban areas (about 5% of the watershed combined) were higher, at 56.2 and 45.8 lb/ac/yr.

Change in simulated sediment bed depth (which, in the one-dimensional reach representation used by SWAT, is a surrogate for total near-channel sediment source load due to meandering, widening, or incision), was also assessed to ensure that long-term net scour and deposition is reasonable in model reaches. Simulated change in bed depth is presented for model reaches in Figure 3-1. The largest change is 1.35 ft for R100, which equates to < 1 in/yr, which is reasonable because this is a lake segment that is likely to be accumulating sediment. Summary statistics for the instream sediment calibration are listed in Table 3-1. As shown in the table, adjustments to the hydrology calibration paired with the original sediment parameterization resulted in a poor representation of suspended sediment in the model. This was significantly improved through the recalibration of upland and instream sediment parameters. For most sites, sediment load errors are lower post-recalibration compared to pre-recalibration. Instream calibration plots are provided for Prairie River, Sandy River, and Willow River in **Error! Reference source not found.** - Figure 3-13. The sediment recalibration achieved a good fit at most sites in the watershed.

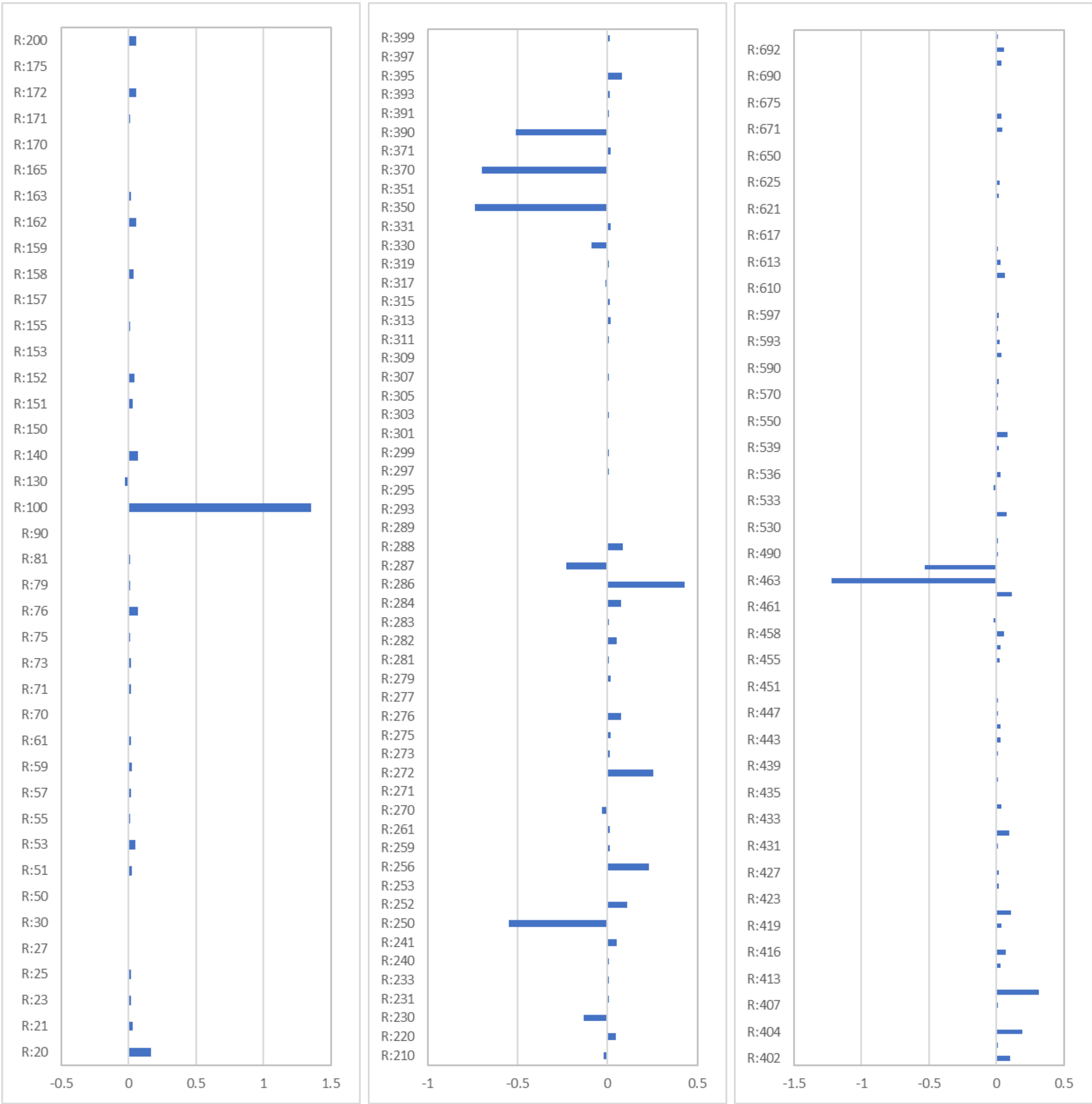


Figure 3-1. Simulated Change in Sediment Bed Depth

Table 3-1. Summary Statistics for the Sediment Calibration

Location	Average Observed Concentration (mg/L)	Average Simulated Concentration (mg/L)			Relative Concentration Error Average (Median)			Average Observed Load (tons/day)	Average Simulated Load (tons/day)			Relative Load Error Average (Median)		
		Pre Hydro Recal	Post Hydro Recal	Post Sed Recal	Pre Hydro Recal	Post HydroRecal	Post Sed Recal		Pre Hydro Recal	Post Hydro Recal	Post Sed Recal	Pre Hydro Recal	Post Hydro Recal	Post Sed Recal
R230	2.96	4.53	4.58	3.39	53.0% (-9.2%)	54.8% (-8.4%)	14.7% (-9.3%)	10.3	24.6	24.8	16.0	137% (-7.4%)	139.8% (-5.3%)	51.2% (-9.9%)
R240	3.79	3.64	9.90	4.74	-4.0% (-17.6%)	161% (16.9%)	25.1% (-22.6%)	17.8	19.2	56.8	25.1	16.8% (-5.9%)	221.5% (9.1%)	39.8% (-9.3%)
R309	4.73	3.05	8.23	4.00	-35.6% (-28.2%)	75.1% (-9.6%)	-15.5% (-15.7%)	3.7	2.9	10.3	3.6	-21.5% (-7.0%)	189% (-2.2%)	0.3% (-2.8%)
R397	4.12	3.62	14.1	7.39	-12.1% (2.5%)	242% (105%)	79.6% (61.3%)	0.5	0.3	1.4	0.5	-36.5% (0.5%)	199% (24%)	-1.8% (13.7%)
R405	5.74	4.30	9.43	4.50	-25.1% (-14.8)	64.4% (13.2%)	-21.4% (-19.2%)	1.4	2.1	3.9	1.5	23.4% (-1.7%)	180% (3.0%)	8.5% (-2.5%)
R431	6.71	5.41	13.5	6.34	-19.4% (-25.5%)	102% (17.8%)	-5.5% (-12.3%)	5.4	7.0	15.4	5.5	29.0% (-2.0%)	196% (4.5%)	5.9% (-3.4%)
R453	6.57	4.35	13.1	7.81	-33.9% (-42.8%)	98.6% (-31.0%)	18.9% (-22.0%)	1.8	1.5	5.8	2.7	-17.4% (-13.4%)	271% (-13.6%)	73.3% (-9.8%)
R470	16.3	3.74	8.74	6.99	-77.0% (-68.5%)	-46.3% (-49.9%)	-57.0% (-46.5%)	110	26.1	52.2	40.7	-76.0% (-33.3%)	-52.5% (-16.0%)	-63.4% (-15.5%)
R690	6.00	5.98	24.5	8.03	-0.3% (-30.1%)	307.5% (19.4%)	33.7% (-5.9%)	7.1	7.2	40.4	9.3	0.5% (-6.6%)	485.8% (6.5%)	34.9% (-3.5%)

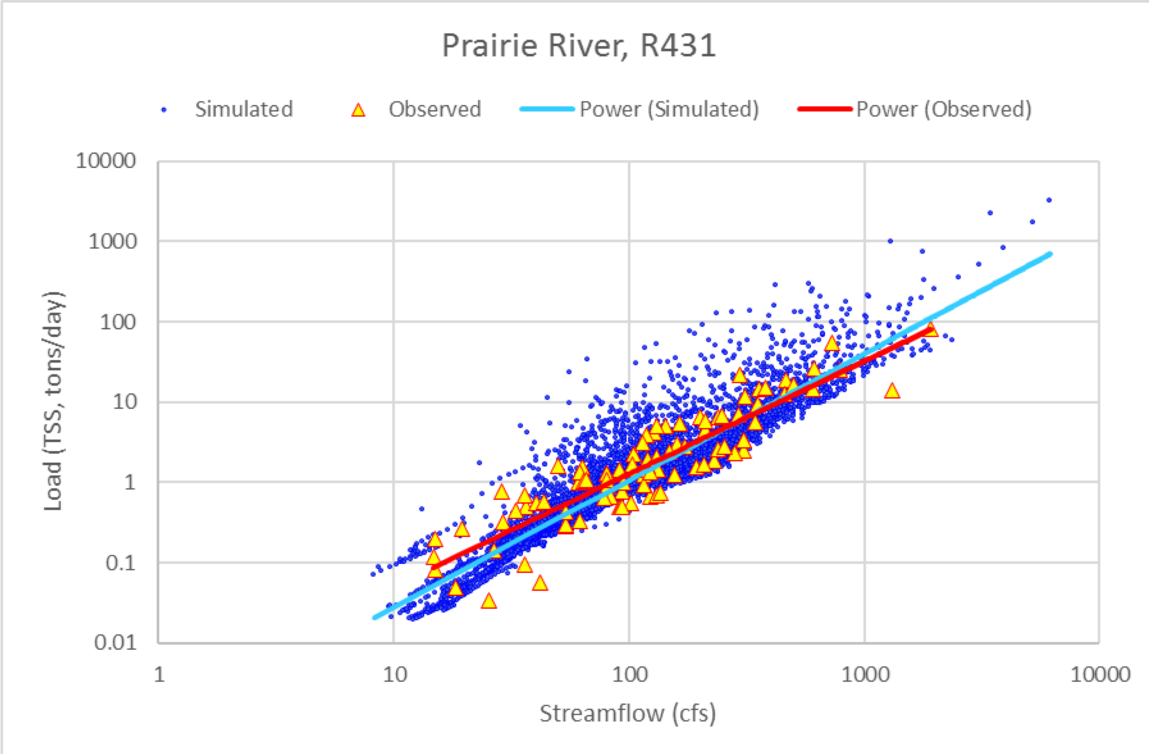


Figure 3-2. Sediment Load vs Streamflow for Prairie River near McGregor

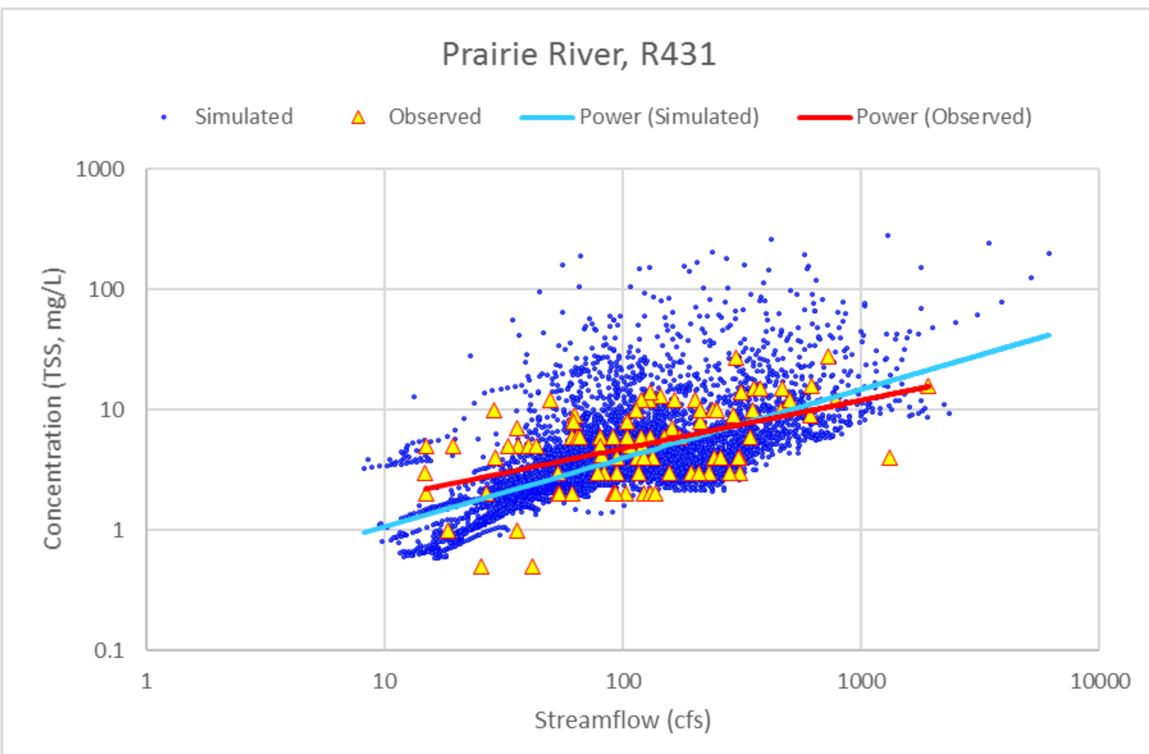


Figure 3-3. Sediment Concentration vs Streamflow for Prairie River

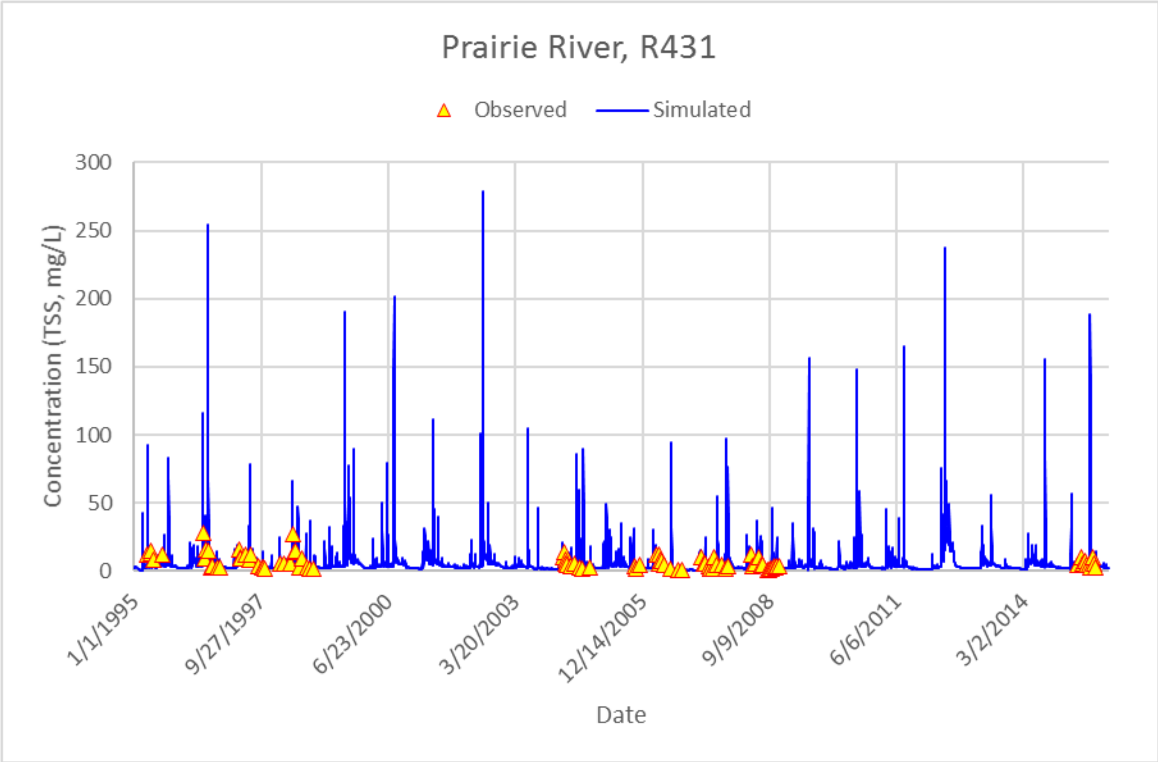


Figure 3-4. Sediment Concentration Time Series for Prairie River near McGregor

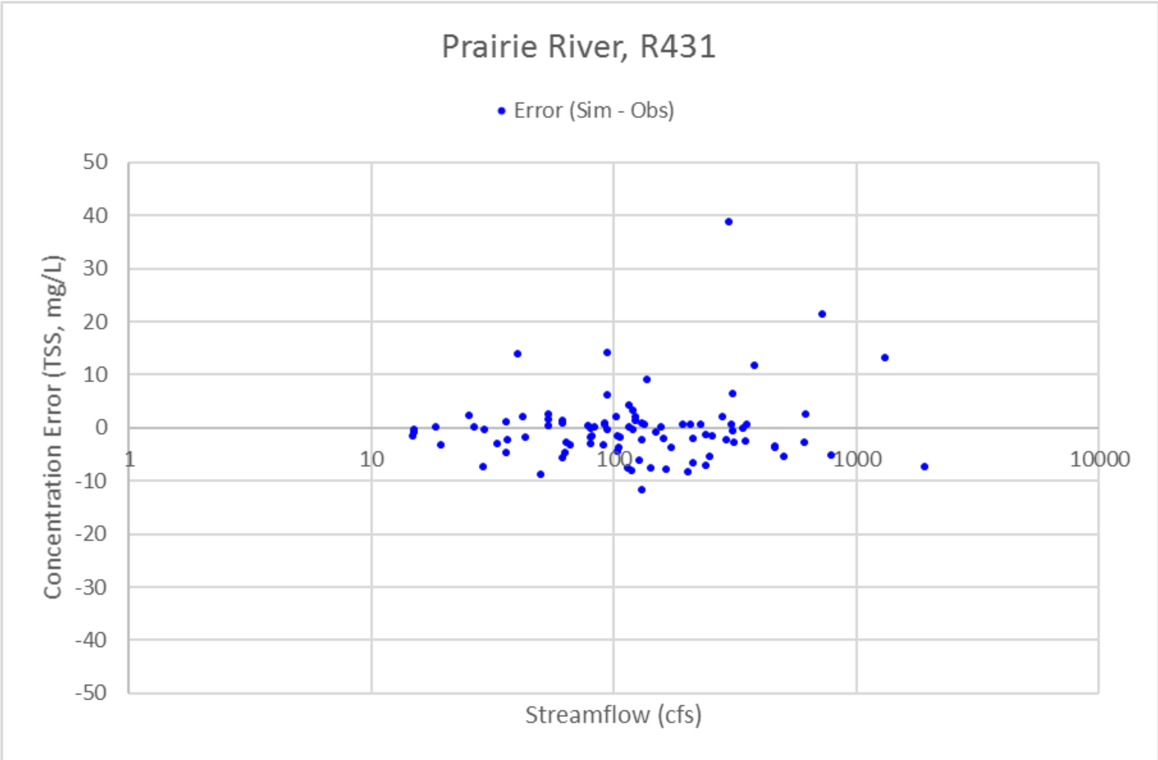


Figure 3-5. Concentration Error for Prairie River near McGregor

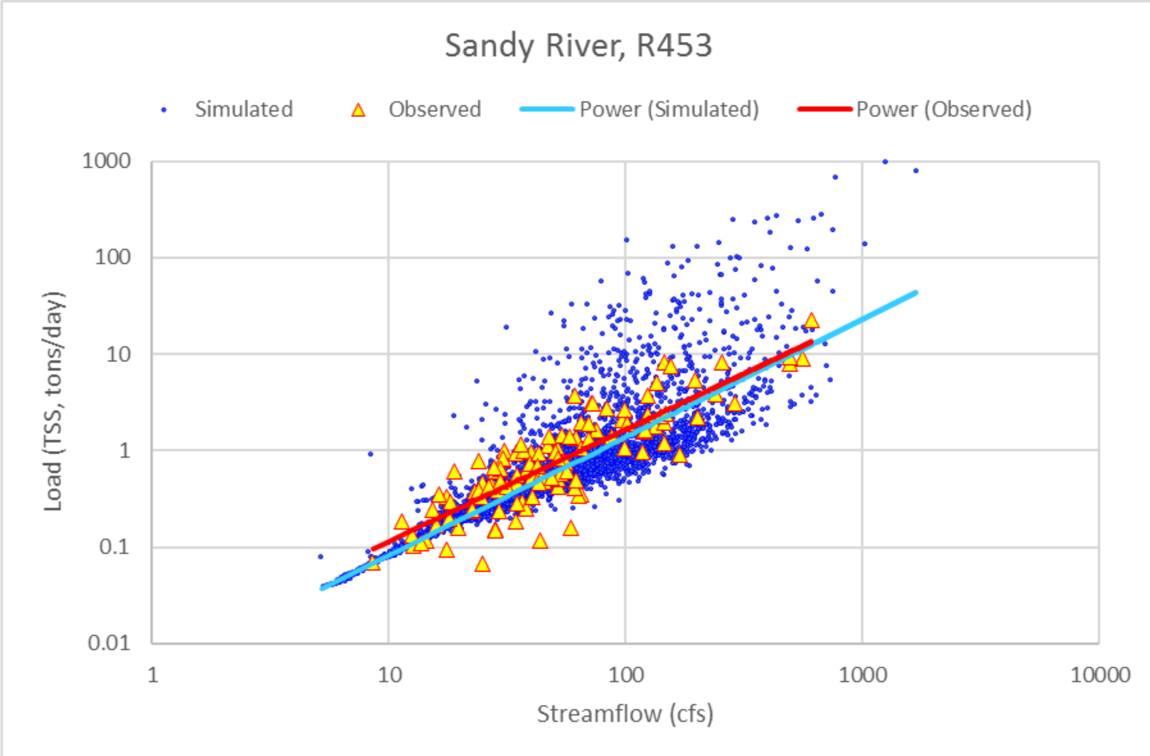


Figure 3-6. Sediment Load vs Flow at Sandy River

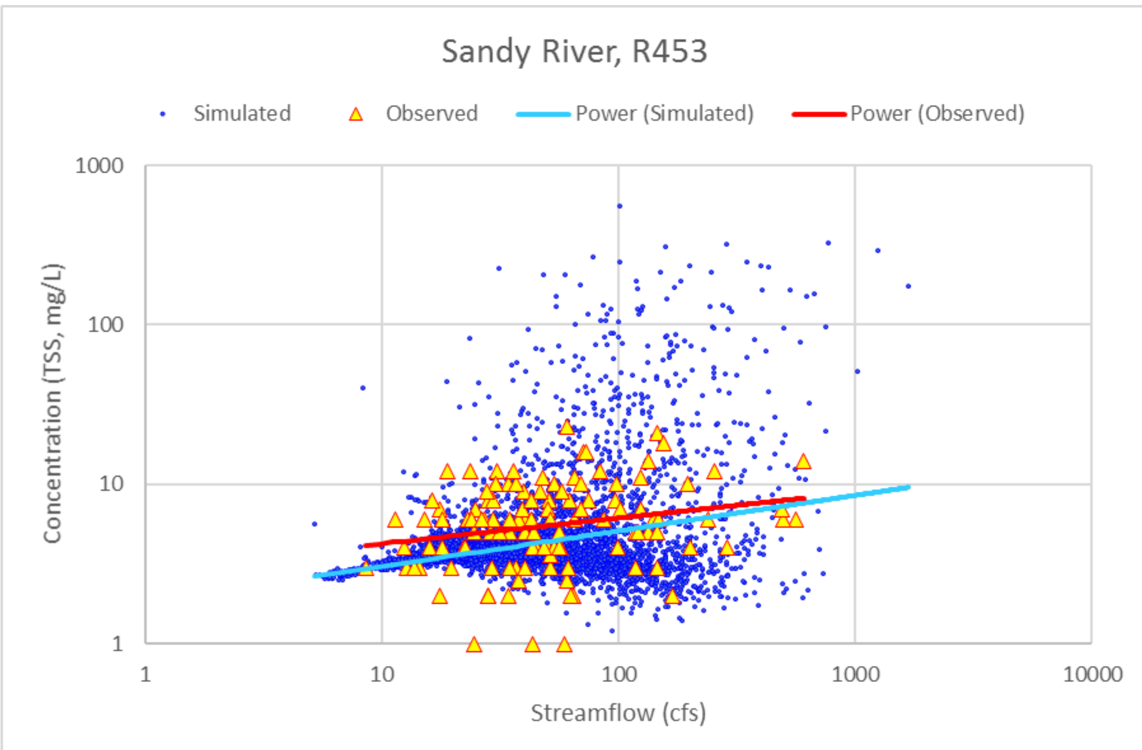


Figure 3-7. Sediment Load vs Concentration at Sandy River

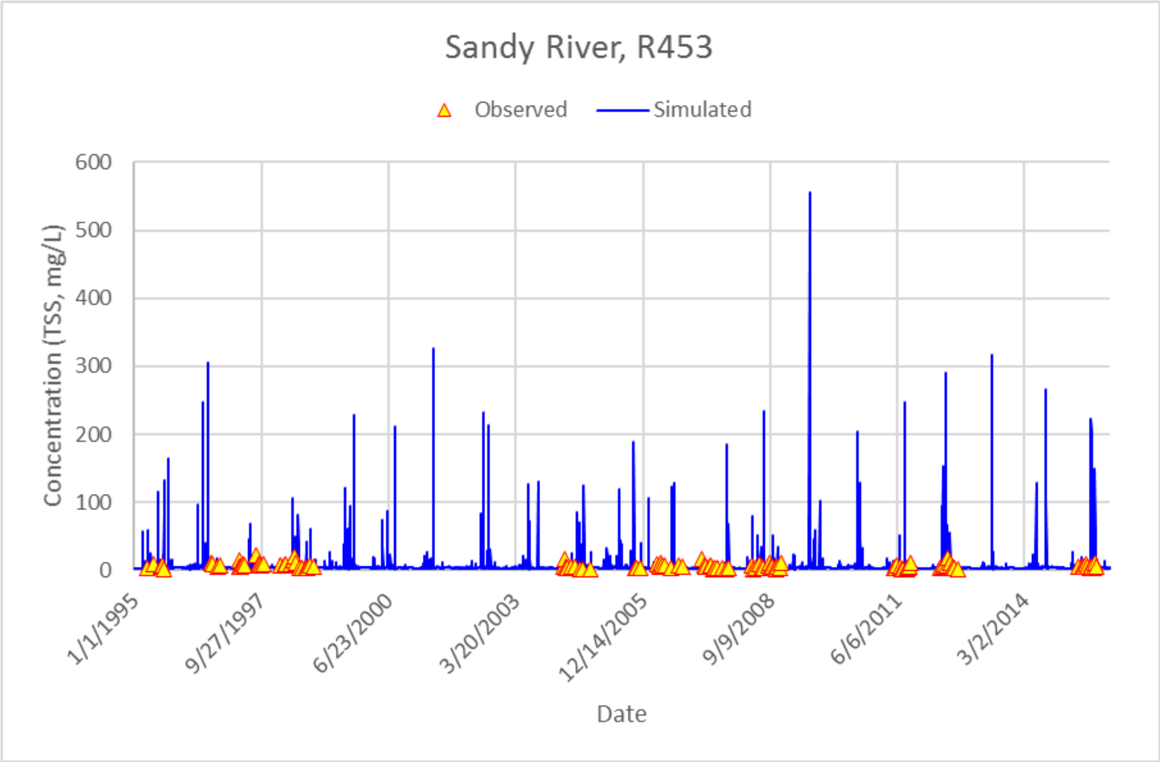


Figure 3-8. Sediment Concentration Time Series for Sandy River

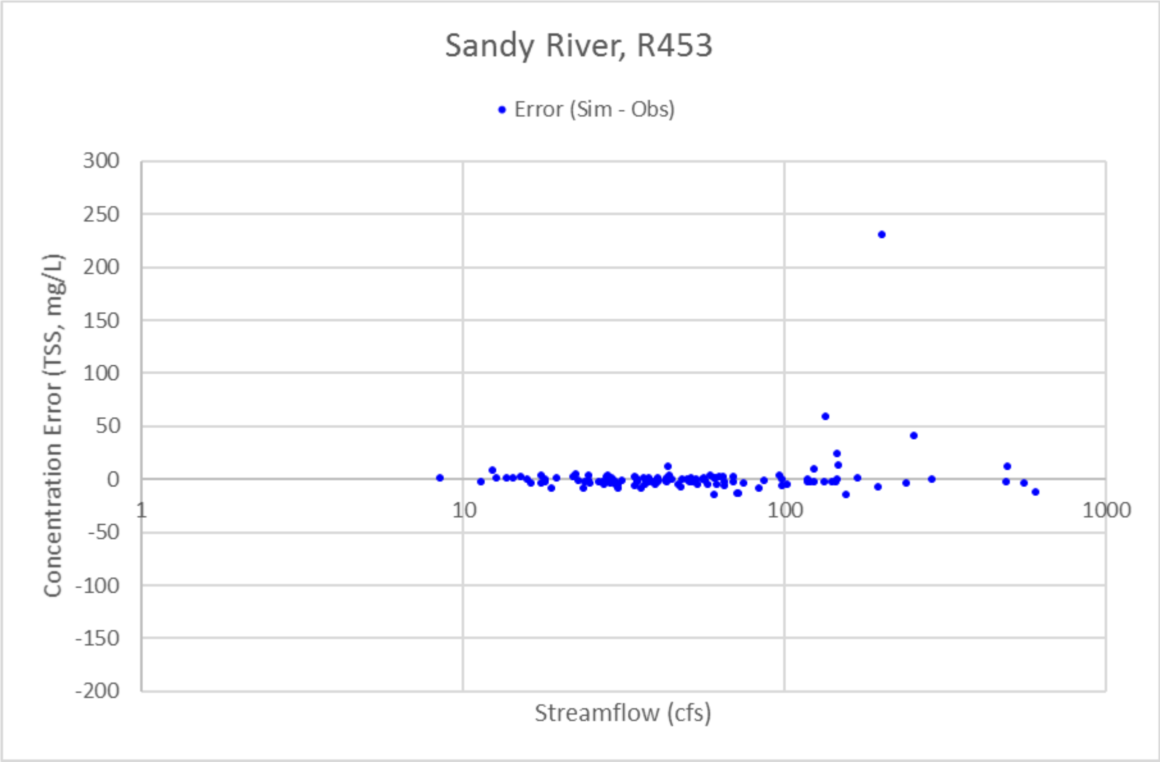


Figure 3-9. Concentration Error for Sandy River

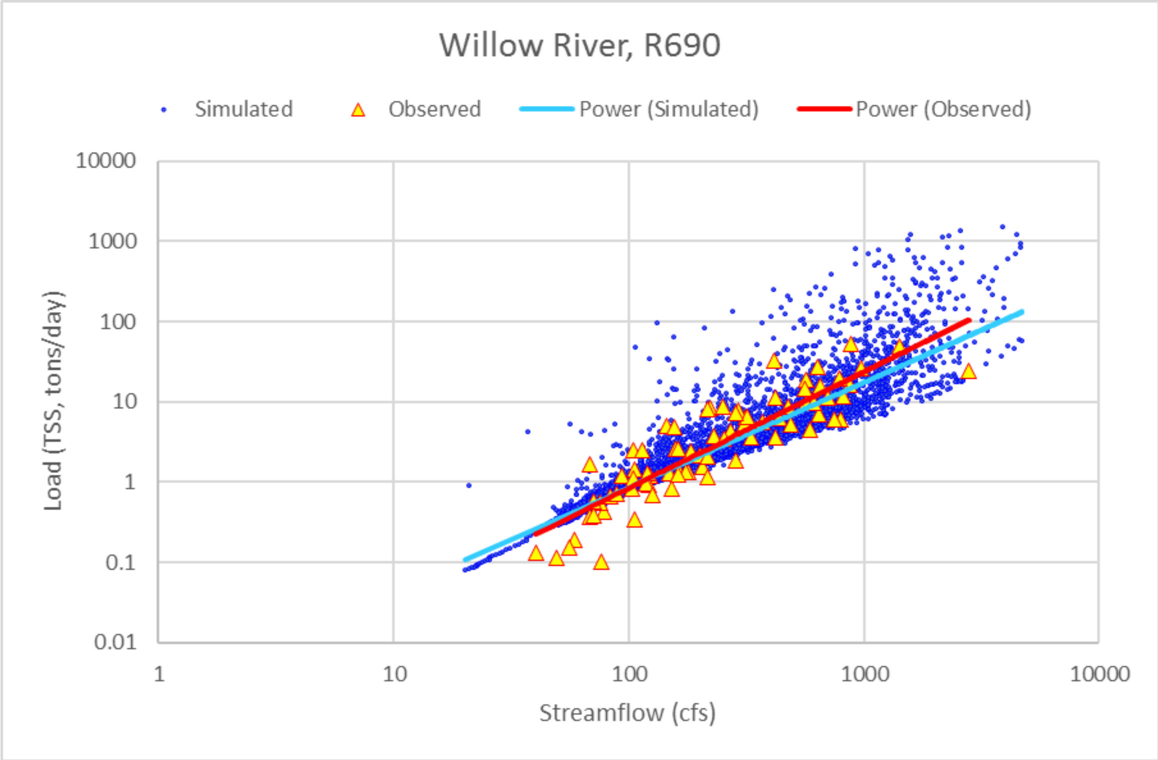


Figure 3-10. Sediment Load vs Flow at Willow River

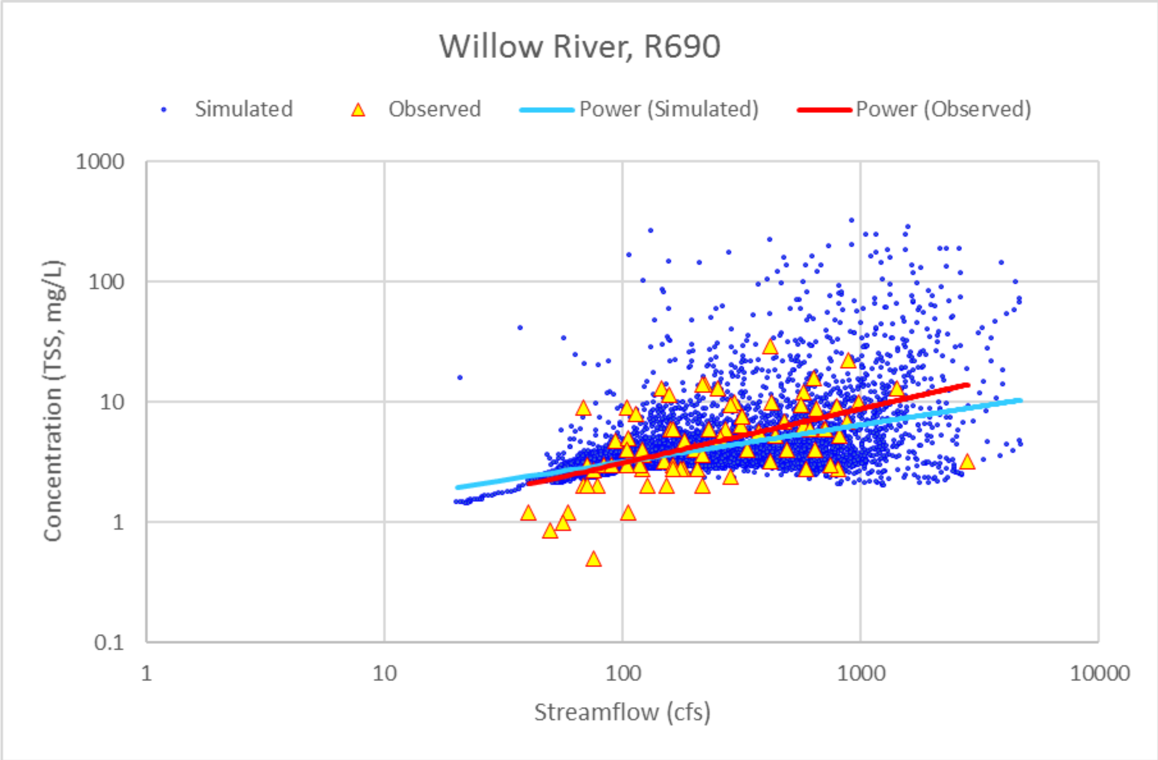


Figure 3-11. Sediment Concentration vs Flow at Willow River

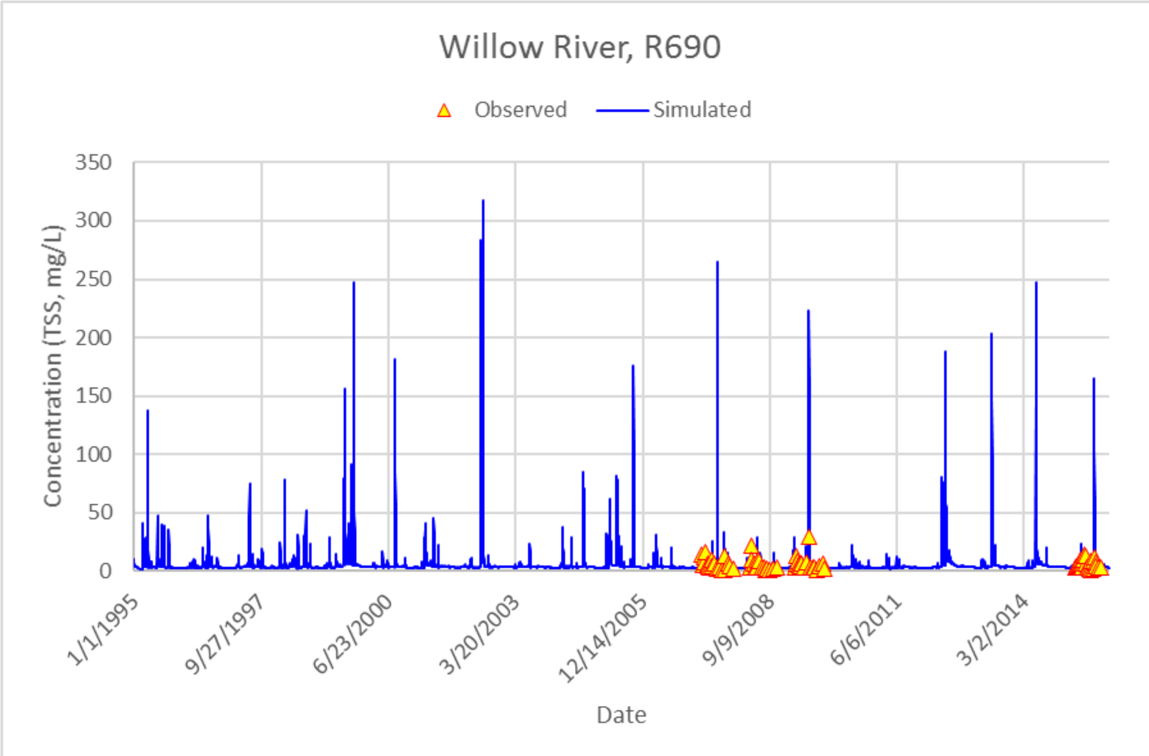


Figure 3-12. Sediment Concentration Time Series for Willow River

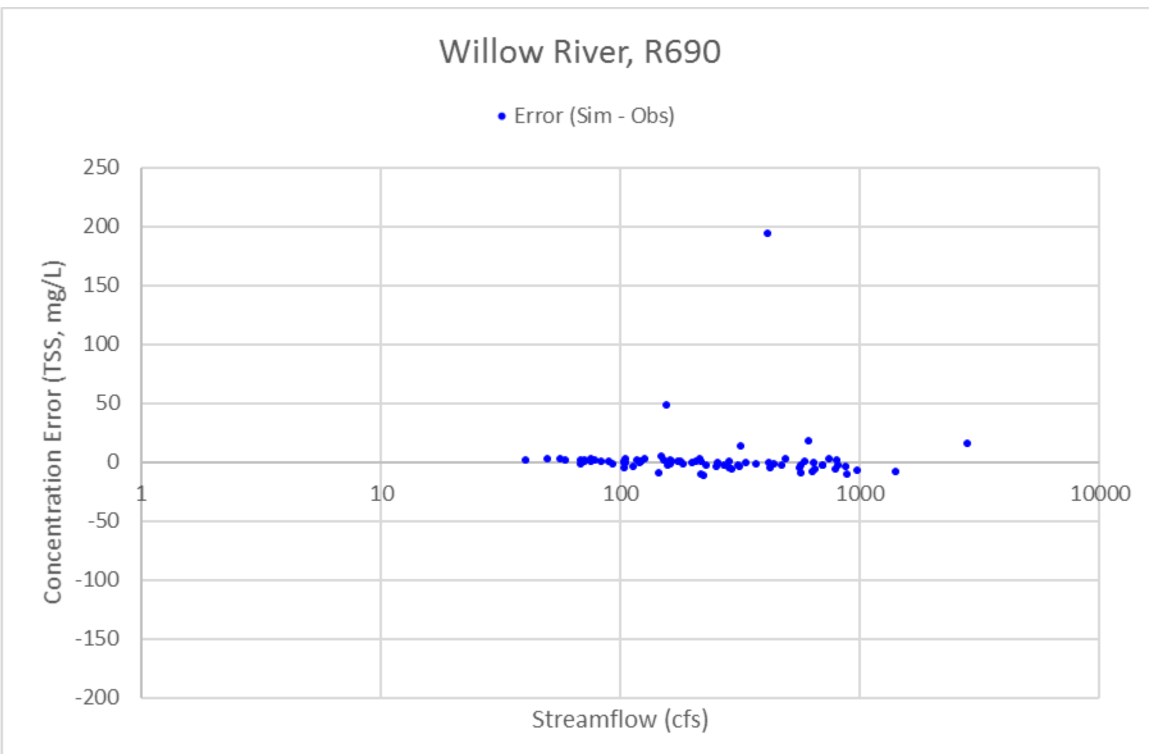


Figure 3-13. Concentration Error for Willow River

4.0 NUTRIENTS AND LAKE CHLOROPHYLL-*A*

4.1.1 Upland Nutrient Loading Rates

Upland Total Nitrogen (TN) and Total Phosphorus (TP) loading rates were tuned following the sediment recalibration. Nitrogen loading rates in the MR – GR watershed estimated from monitoring data range from 0.01 – 2.50 lb-N/ac/yr (MPCA, 2013), and phosphorus rates range from 0.001 – 0.093 lb-P/ac/yr (MPCA, 2014). Reference rates by land use category are listed in Table 4-1, and were used as a guide. The average annual TN and TP loading rates simulated by the MR – GR model are comparable to expected ranges at 0.7 and 0.1 lb/ac/yr, respectively (Figure 4-1 - Figure 4-2). TN loading rates for many of the land uses represented in the model are below reference rates listed in Table 4-1. Initially upland loading rates were constrained to the reference range and this resulted in a very poor representation of nutrients in the streams and lakes. Because monitoring data indicates that TN loading rates for Grand Rapids are quite low (as low as 0.01 lb-N/ac/yr), the rates were reduced to better represent dynamics in this particular watershed. TP loading rates also tend to be slightly below reference ranges, but are on the high end of monitoring-based estimates.

Table 4-1. Reference Ranges for Nutrient Loading Rates by Land Use Category

Land Use	TN (lb-N/ac/yr)	TP (lb-P/ac/yr)	Source
Forest	1.97 – 4.2	0.05 – 5	Clesceri et al., 1986; Loehr et al., 1989; MPCA, 2013, MPCA, 2004; Reckhow et al., 1980
Wetland	0.5 – 5	0	MPCA, 2013; MPCA, 2004
Pasture	6.1 – 23	0.11 – 0.43	Clesceri et al., 1986; McFarland and Hauck, 2001; MPCA, 2013; MPCA 2004
Crop	7.5 – 23	0.11 – 1.7	Clesceri et al., 1986; Loehr et al., 1989, MPCA, 2013; MPCA 2004
Developed (pervious)	2 – 17	0.8 – 1.02	Loehr et al., 1989; MPCA, 2013; MPCA, 2004; Reckhow et al., 1980
Developed (impervious)	2 – 17	0.8 -1.02	Loehr et al., 1989; MPCA, 2013; MPCA, 2004; Reckhow et al., 1980
Barren	0.5 - 5	ND	MPCA, 2013
Shrub	0.5 - 5	0.05 – 0.12	MPCA, 2013; MPCA, 2004
Feedlots	89 -1,427	8.9 - 553	Loehr et al., 1989

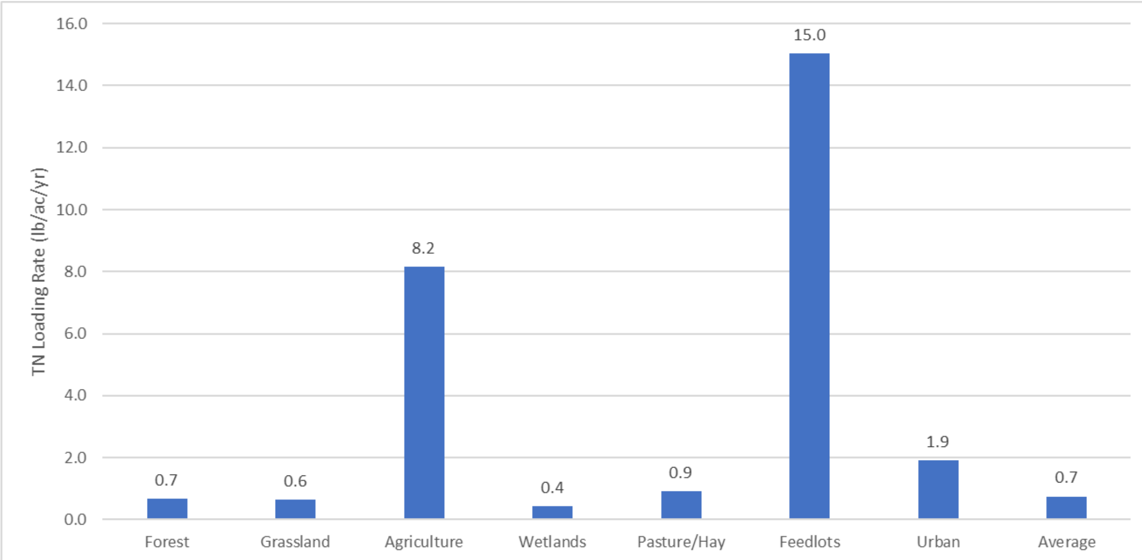


Figure 4-1. Mean Annual Upland Total Nitrogen Loading Rates

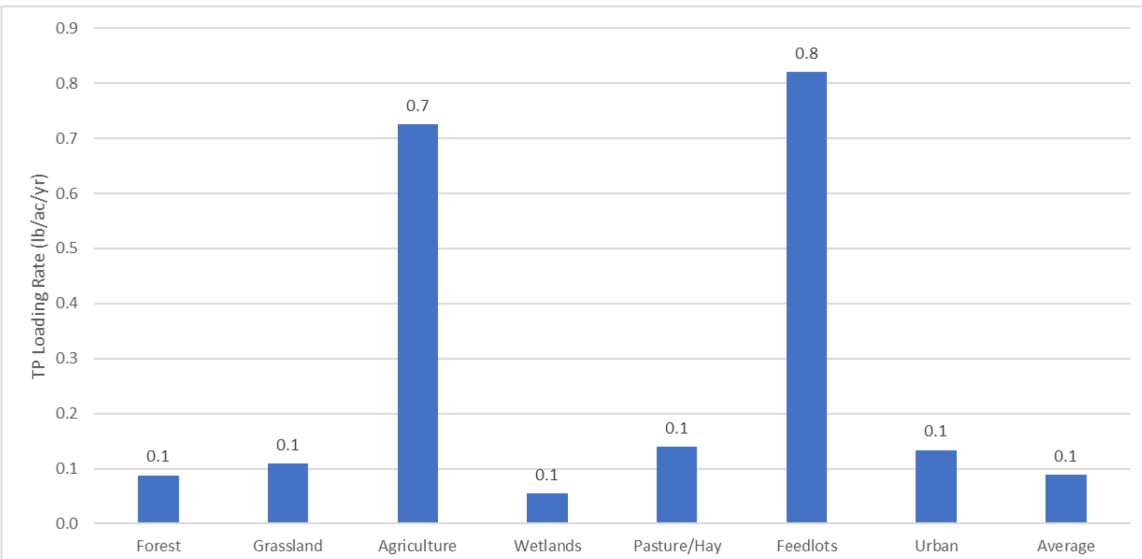


Figure 4-2. Mean Annual Upland Total Phosphorus Loading Rates

4.1.2 Lake Calibration

Chlorophyll *a* and phosphorus monitoring records were available for calibrating water quality in several lakes in the watershed. A broad review prior to the recalibration revealed excessive total phosphorus concentrations in the lakes. Monitoring data from the watershed indicates that organic P is the dominant component of TP. In the model (total organic P is comprised of refractory organic P, phytoplankton biomass P, and the P component of labile organic matter expressed as BOD). In several lakes, phytoplankton chlorophyll *a* was underrepresented and organic P was overestimated with phytoplankton being the largest component of organic P in these cases. This was largely due to unrepresentative stoichiometric relationships in the model. To address this, the C:P stoichiometric ratio was adjusted for lakes from 106 (Redfield ratio) to 200 based on a study that assessed 130 small lakes in North America

(Sterner, 2008). The C:N ratio was also reassigned from 16 (Redfield ratio) to 22 for explicitly simulated lakes. In addition, the ratio of chlorophyll *a* content of biomass to phosphorus content was recalibrated based on monitoring data. Other key recalibration parameters included benthic release rates of ammonia and orthophosphate, algae growth and settling rates, and BOD release and setting rates. Calibration of the lakes paralleled that of the free-flowing reaches in an effort to appropriately represent both lake and instream water quality dynamics.

Prior to the recalibration Balsam (R76), an approximately 714 acre lake in the northwest portion of the drainage area, exhibited unstable chlorophyll *a* that spiked mid-simulation and dropped to a negligible concentration (Figure 4-3). The recalibration alleviated this issue and simulated chlorophyll *a* is within range of observed values. In addition, the recalibration reduced overestimated total phosphorus concentrations in Balsam Lake. Improvements were also made to Island Bay (Figure 4-4) and Minnewawa lakes (Figure 4-6). Chlorophyll *a* simulated by the HSPF model for both of these lakes is now more in range with observed concentrations, although peak chlorophyll-*a* concentrations remain underestimated.

Big Sandy Lake is of particular interest since it exceeds aquatic recreation indicators of TP and chlorophyll *a*. Several modifications were tested for Big Sandy and, although minor improvements were made, the HSPF model continues to poorly represent algae dynamics in this expansive, deep lake. A lake model (e.g., BATHTUB) could be developed and paired with HSPF output (i.e., loads from the lake's drainage area) for Big Sandy and/or other lakes of interest to better support application studies.

A summary of lake TP and chlorophyll *a* concentrations for the Grand Rapids watershed are provided in Table 4-2.

Pre-recalibration **Post-recalibration**

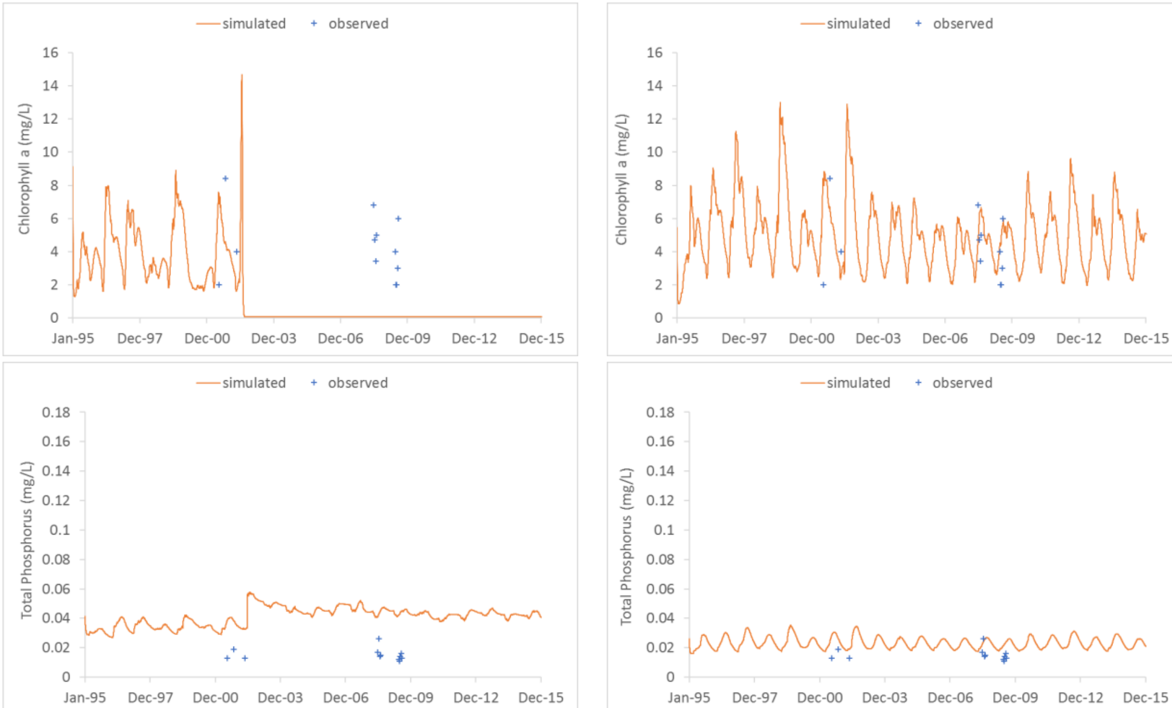


Figure 4-3. Pre- and Post-recalibration of Chlorophyll-*a* and Total Phosphorus for Balsam (R76)

Pre-recalibration **Post-recalibration**

Figure 4-4. Pre- and Post-recalibration of Chlorophyll-*a* and Total Phosphorus for Swan Lake (R282)

Pre-recalibration **Post-recalibration**

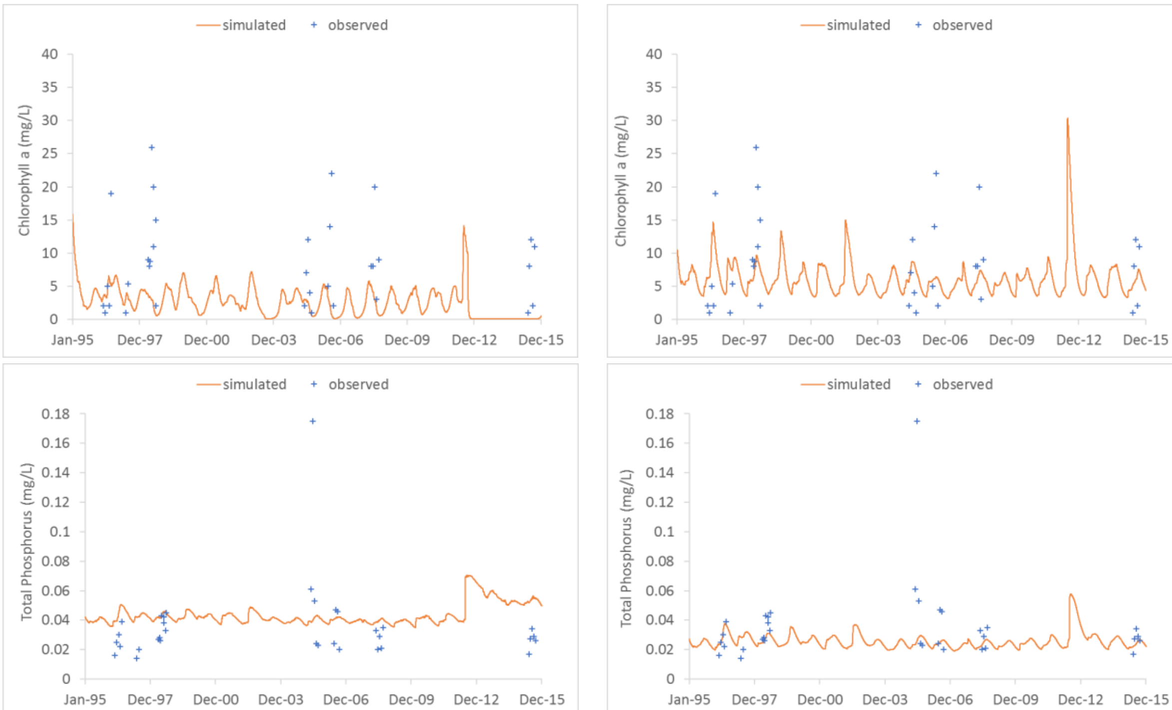


Figure 4-5. Pre- and Post-recalibration of Chlorophyll-*a* and Total Phosphorus for Island Bay (R414)

Pre-recalibration **Post-recalibration**

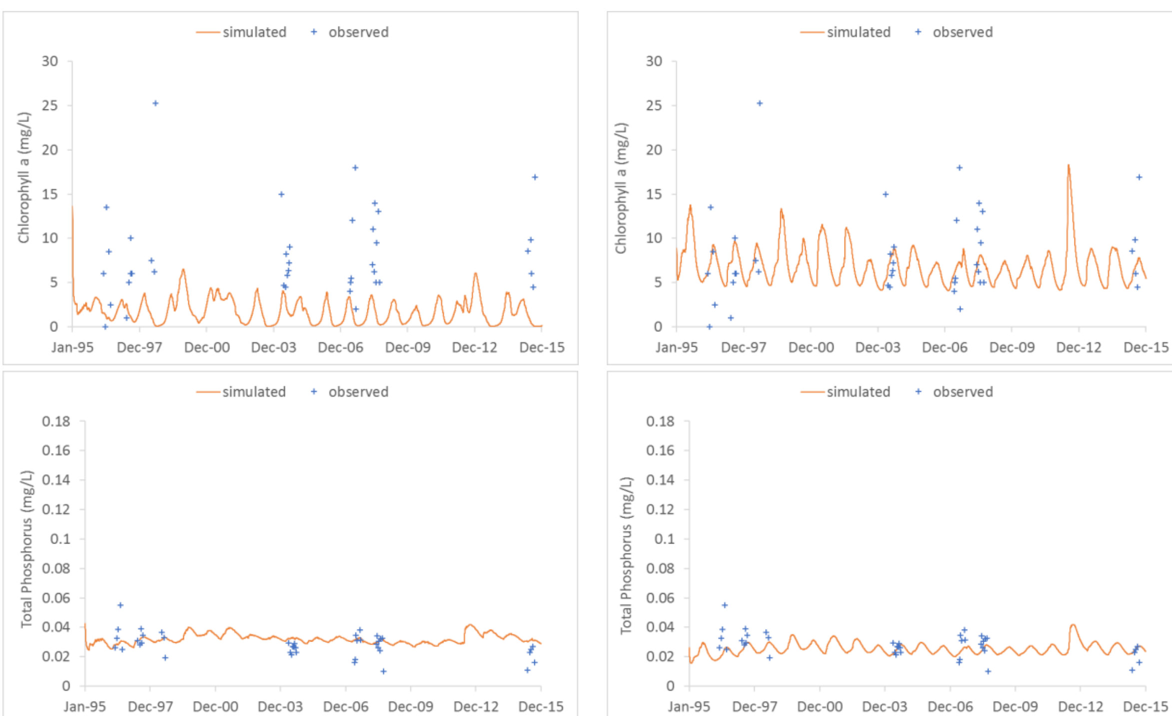


Figure 4-6. Pre- and Post-recalibration of Chlorophyll-*a* and Total Phosphorus for Minnewawa (R434)

Pre-recalibration **Post-recalibration**

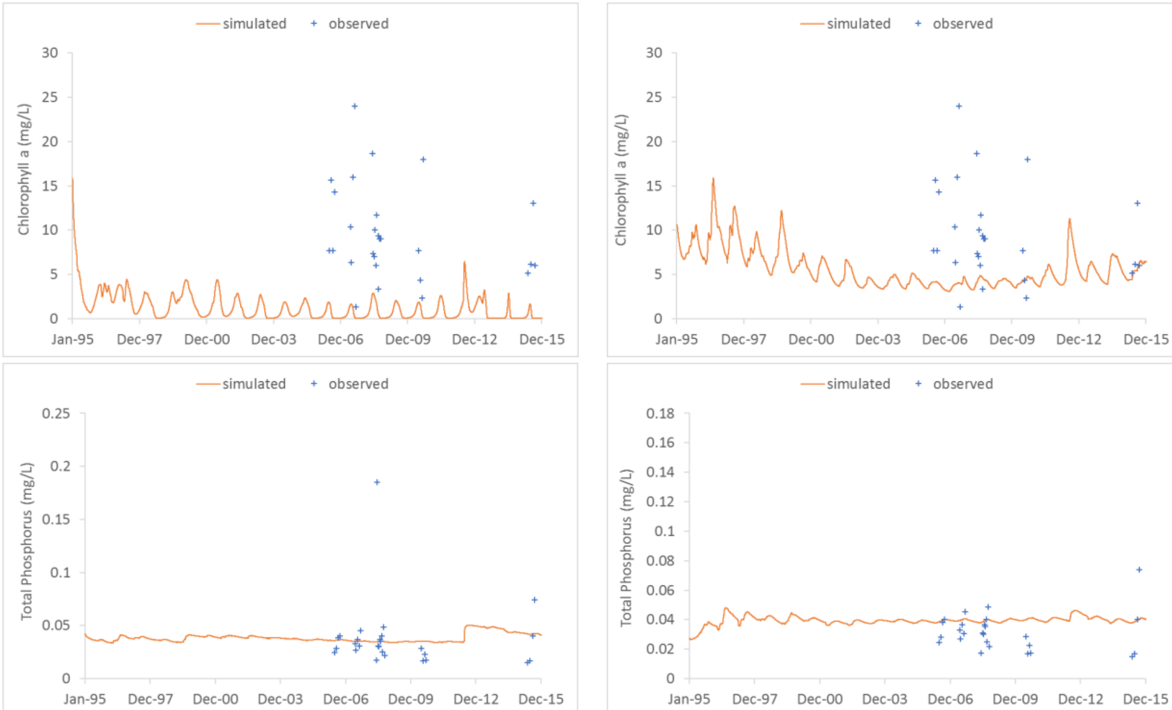


Figure 4-7. Pre- and Post-recalibration of Chlorophyll-*a* and Total Phosphorus for Big Sandy (R462)

Table 4-2. Lake TP and Chlorophyll-*a* Concentrations

Model Reach	Lake Name	TP (mg/L)		Chlorophyll-*a*	
		Observed	Simulated	Observed	Simulated
76	BALSAM	0.016	0.024	4.3	5.5
536	BIG RICE	0.020	0.022	3.0	6.6
462	BIG SANDY	0.037	0.040	9.3	4.5
100	CROOKED	0.018	0.045	5.1	14.7
412	EAGLE	0.030	0.025	10.8	4.3
612	HILL (MAIN BASIN)	0.025	0.026	9.3	3.7
284	HOLMAN	0.010	0.016	2.0	1.4
432	HORSESHOE	0.047	0.064	21.2	0.7
416	ISLAND (NORTH BAY)	0.031	0.062	11.3	18.9

Model Reach	Lake Name	TP (mg/L)		Chlorophyll-*a*	
		Observed	Simulated	Observed	Simulated
414	ISLAND (SOUTH BAY)	0.035	0.027	8.8	7.5
140	LAWRENCE	0.020	0.044	7.8	17.8
434	MINNEWAWA	0.029	0.026	8.1	7.6
404	PRAIRIE	0.028	0.053	10.2	0.9
152	Spider	0.009	0.016	5.4	3.3
256	SPLIT HAND	0.043	0.023	23.6	4.9
20	STINGY	0.018	0.023	7.6	3.0
282	SWAN (MAIN BASIN)	0.020	0.063	7.0	15.6
422	TAMARACK	0.031	0.051	8.3	10.9
532	THUNDER	0.012	0.023	4.0	2.4
288	TROUT	0.023	0.024	3.3	1.8
158	TROUT	0.007	0.055	1.5	0.1
162	WABANA	0.008	0.052	2.9	1.3
414	ISLAND (SOUTH BAY)	0.035	0.027	8.8	7.5
140	LAWRENCE	0.020	0.044	7.8	17.8

4.1.3 Instream Nutrient Recalibration

Monitoring locations used to recalibrate instream nutrients are listed in Table 4-3, and mean observed concentrations of ammonia, nitrite + nitrate, organic N, ortho P, and organic P are listed in Table 4-4. Average concentration errors are listed by constituent and calibration location pre-recalibration (as model was received after RESPEC extended the model through 2015) and post-recalibration in Table 4-5. Similarly, median concentration errors are reported in Table 4-6.

The model drastically overestimated inorganic N, yet exhibited a reasonable fit for inorganic and organic P, at most sites prior to the recalibration. A better balance between N and P was achieved though the model recalibration. The key adjustments were:

- Recalibration of upland nitrogen and phosphorus loading rates (Section 4.1.1)
- Recalibration of nutrient and algae dynamics in explicitly simulated lakes (Section 4.1.2)
- Correction of unit for wet deposition of ammonia and nitrate (discussed in Tetra Tech, 2017a)
- Added wet atmospheric deposition of ortho P (10.7 µg/L) to reaches based on the 2007 update to *Detailed Assessment of Phosphorus Sources to Minnesota Watersheds - Atmospheric Deposition* (Twaroski, et al. 2007)
- Removed multipliers in upland-to-reach Mass-Links that reduced ortho P from interflow and groundwater (previously 0.67 and 0.50, respectively)
- Adjusted several instream parameters governing biochemical transformations and fluxes (e.g., nitrification and denitrification rates (dissolved oxygen concentration threshold for denitrification previously set high (8 mg/L) due to excessive nitrate, threshold was reduced to 4 mg/L), algae inorganic N preference, setting rates for refractory matter, BOD, and phytoplankton, etc.)

Except for Sandy River (R453) and Savanna (R397), calibration sites had explicitly simulated lakes upstream. The model calibration focused on achieving a representative fit in the lakes and at free-flowing stream sampling sites. This presented a challenge in areas where lake phytoplankton were nitrogen limited, and benthic releases of ammonia improved the representation of lake chlorophyll-*a*, but resulted in excessive nitrogen at downstream monitoring sites. Iterative adjustments to lakes and free-flowing reaches resulted in major improvements to the representation of inorganic N (ammonia and nitrate), as shown by average and median concentrations errors in Table 4-5 and Table 4-6. This is especially true for Willow River (R690), Sandy River (R453), and Savanna (R397). Observed nitrate concentrations at Swan River (R309) were relatively low (Table 4-4), and most samples at this site were non-detect, and the model still overestimates nitrate at Swan River. Nitrate in Prairie River downstream of Prairie Lake and upstream of Big Sandy Lake (R431) matches observed concentrations and loads well, as shown in **Error! Reference source not found.** - Figure 4-10. Organic N, organic P, and ortho P, are also well represented at Prairie River upstream of Big Sandy. Graphical representations of the recalibration at Willow River are also provided in Figure 4-20 - Figure 4-31.

Table 4-3. Nutrient Calibration Reaches and Monitoring Site Information

Reach	Description	STORET Site Number
R230	MISSISSIPPI R AT 7TH AVE, IN GRAND RAPIDS, MINNES* MISSISSIPPI RIVER 1.0 MI S OF LA PRAIRIE, MN W CO*	S003-656 S007-333
R240	MISS R 1 MI SE OF GRAND RAPIDS, FROM FIRE#F-360 MISSISSIPPI R BR ON CR-441 1 MI SW OF BLACKBERRY	S002-636 S000-220
R309	SWAN R AT ITASCA CR-431 BRG, 4 MI NE OF JACOBSON	S001-922
R397	SAVANNA R AT CSAH-14, 7 MI NE OF SHESHABEE, MN	S002-444
R405	PRAIRIE R AT 140TH AVENUE 7 MI NE OF SHESHABEE, MN PRAIRIE R AT CR-825, 8.5 MI NNW OF WRIGHT, MN PRAIRIE R AT CSAH-51 BRG, 9.5 MI S OF FLOODWOOD PRAIRIE R, UPSTREAM OF MOEN RD, 8.5 MI NW OF CROM*	S002-445 S005-776 S001-577 S008-341
R431	PRAIRIE R AT 145TH AVENUE 6.5 MI NE OF SHESHABEE,* PRAIRIE R AT CSAH-14, 10 MI NNE OF MCGREGOR, MN	S002-446 S004-613
R453	SANDY R AT CR-62, 2.8 MI NW OF McGREGOR, MINNESOTA SANDY R AT SH-65, 0.75 MI N OF MCGREGOR	S003-306 S002-629
R470	MISS R 0.2 MI SO OF PALISADE, 1500' DS RR BRIDGE MISSISSIPPI R AT CSAH-10, 4.9 MI NE OF PALISADE, * MISSISSIPPI R AT MN-232, 0.3 MI SE OF PALISADE, MN	S002-638 S004-515 S003-663
R690	WILLOW R AT CSAH-3, 3 MI W OF PALISADE, MN WILLOW RIVER AT CSAH-5, 1.5 MI N OF PALISADE, MN	S008-442 S004-407

Table 4-4. Average Observed Nutrient Concentrations at Calibration Reaches

Reach	Average Observed Concentration (mg/L)				
	TAM	NO2+NO3	Organic N	Ortho P	Organic P
1995-2015					
R230	0.028	0.031	0.701	0.006	0.020
R240	0.038	0.091	0.531	0.007	0.026
R309	0.033	0.039	0.679	0.018	0.035
R397	0.043	0.038	0.707	0.008	0.032
R405	0.027	0.024	0.651	0.008	0.030
R431	0.034	0.033	0.822	0.012	0.042
R453	0.132	0.067	1.266	0.015	0.057
R470	0.031	0.112	0.757	No data	No data
R690	0.037	0.074	0.882	0.014	0.037

Table 4-5. Average Relative Concentration Error (Simulation – Observed) Pre- and Post-recalibration

Reach	Average Concentration Error				
	TAM	NO2+NO3	Organic N	Ortho P	Organic P
Prior to recalibration (as received)					
R230	383%	11,931%	-52%	113%	112%
R240	325%	2,426%	-27%	56%	89%
R309	218%	1,253%	-23%	-79%	-5%
R397	563%	210%	-7%	66%	12%
R405	187%	592%	-6.1%	-23.1%	-7%
R431	304%	771%	-26%	-52%	-31%
R453	64%	706%	-35%	108%	-5%
R470	-33%	875%	-37%	No data	No data
R690	188%	213%	-28%	-40%	-15%
Post recalibration					
R230	30%	586%	-20%	102%	29%
R240	-13%	165%	-20%	-12%	24%
R309	145%	3,767%	-21%	-86%	1%
R397	92%	-25%	-7.2%	139%	44%
R405	-37%	-26%	-15%	194%	-26%
R431	40%	247%	-18%	-23%	-11%
R453	-73%	41%	-20%	-46%	25%
R470	-14%	144%	-25%	No data	No data
R690	24%	-39%	-12%	-44%	29%

Table 4-6. Median Relative Concentration Error (Simulation – Observed) Pre- and Post-recalibration

Reach	Median Concentration Error				
	TAM	NO2+NO3	Organic N	Ortho P	Organic P
Prior to recalibration (as received)					
R230	385%	11,271%	-50%	98%	98%
R240	312%	2,416%	-30%	44%	58%
R309	213%	1242%	-19%	-61%	3.7%
R397	472%	203%	-12%	77%	12%
R405	187%	531%	1%	3%	6%
R431	182%	495%	-22%	-45%	-22%
R453	54%	494%	-32%	22%	-4%
R470	-28%	914%	-40%	No data	No data
R690	218%	234%	-27%	-53%	-15%
Post recalibration					
R230	31%	477%	-21%	86%	27%
R240	2%	149%	-19%	-24%	20%
R309	6%	3,287%	-22%	-70%	0.4%
R397	98%	30%	-6%	123%	39%
R405	-55%	1%	-11%	209%	-32%
R431	-12%	8%	-21%	-22%	-11%
R453	-52%	59%	-24%	-37%	28%
R470	-4%	109%	-25%	No data	No data
R690	34%	-7%	-11%	-57%	35%

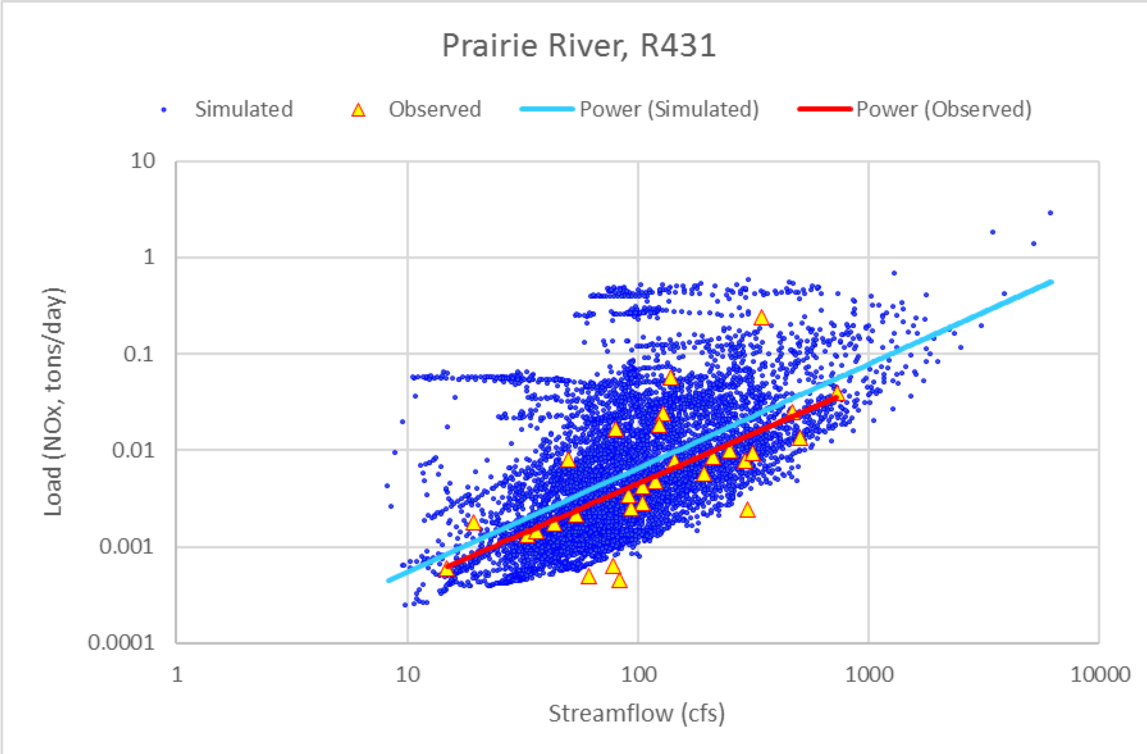


Figure 4-8. Nitrite + Nitrate Load vs Streamflow for Prairie River (R431)

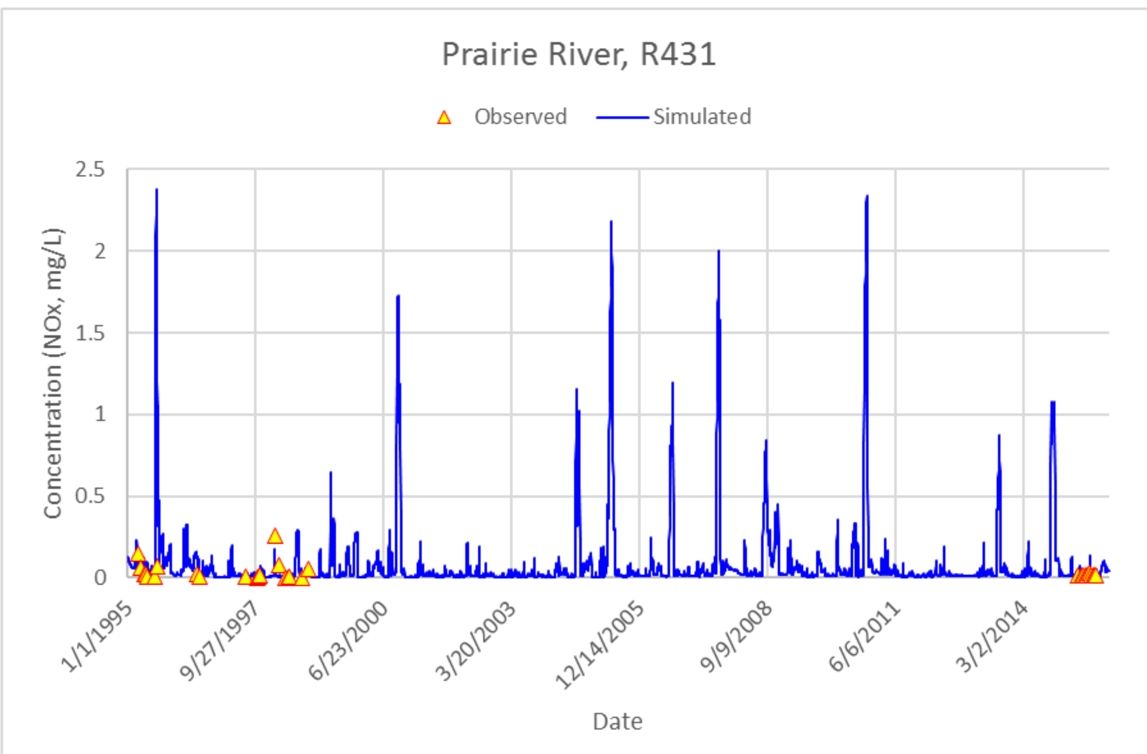


Figure 4-9. Simulated Nitrite + Nitrate Concentration for Prairie River (R431)

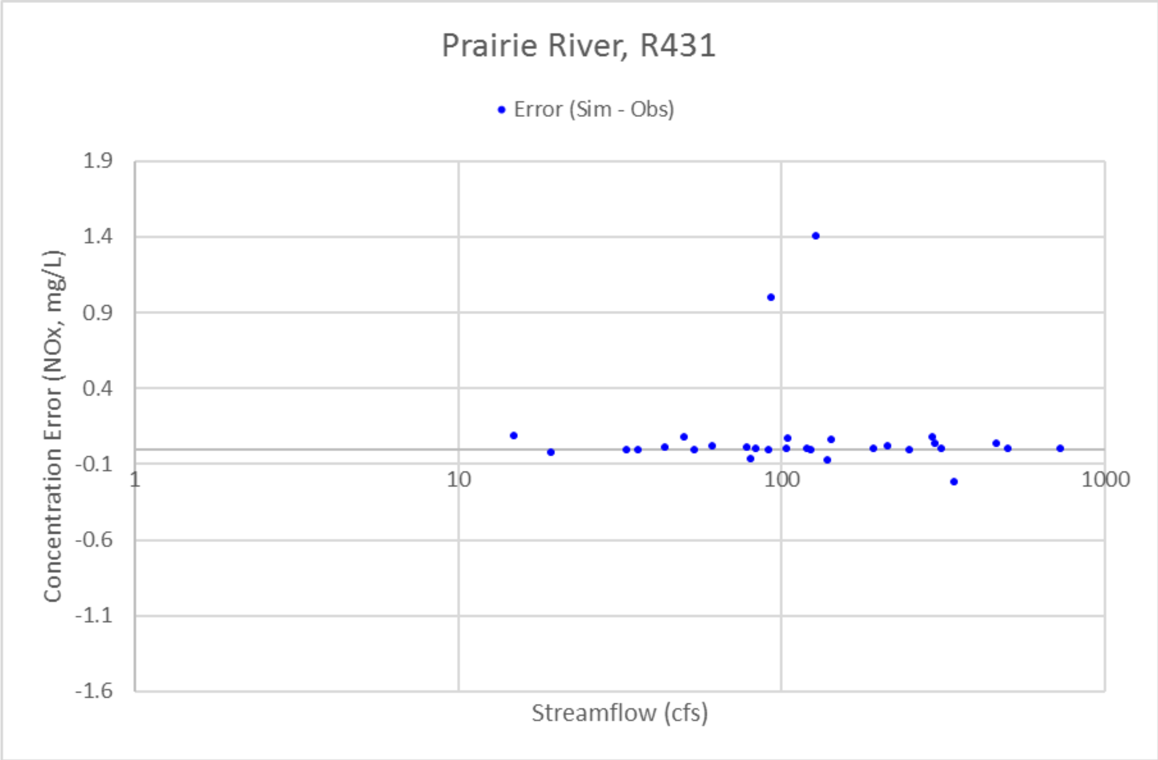


Figure 4-10. Nitrite + Nitrate Concentration Error (Simulated – Observed) for Prairie River (R431)

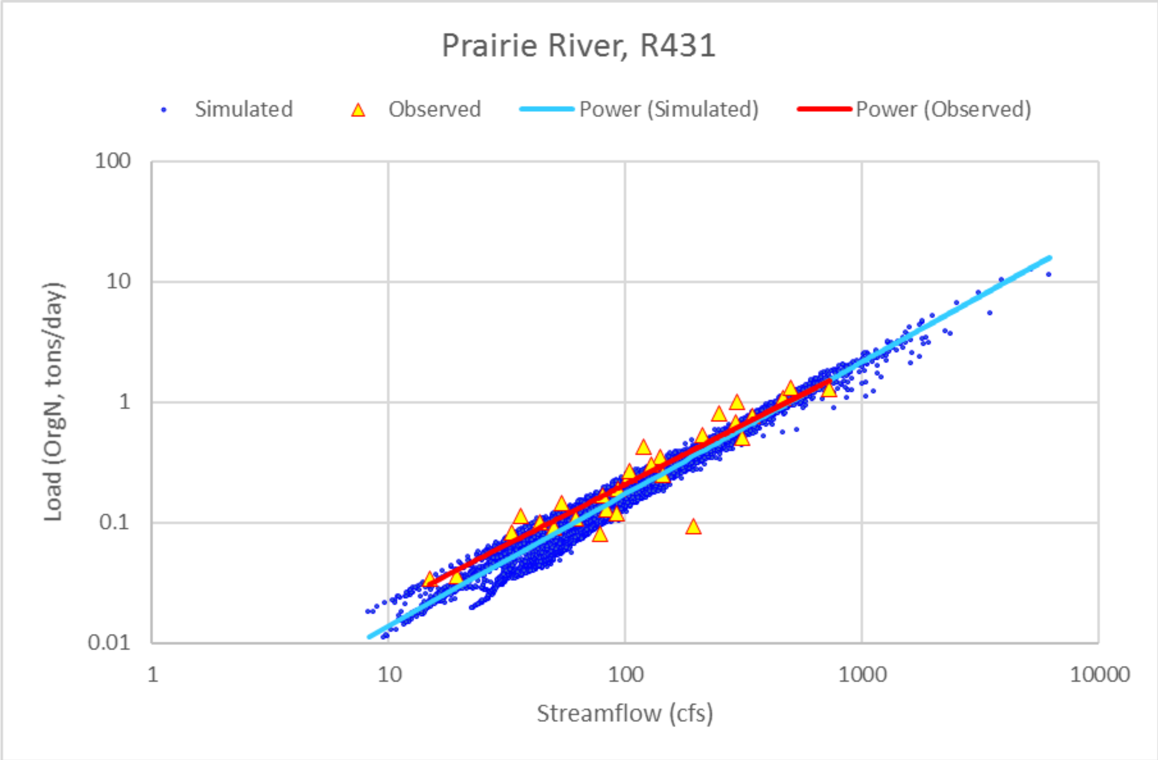


Figure 4-11. Organic N Load vs Streamflow for Prairie River (R431)

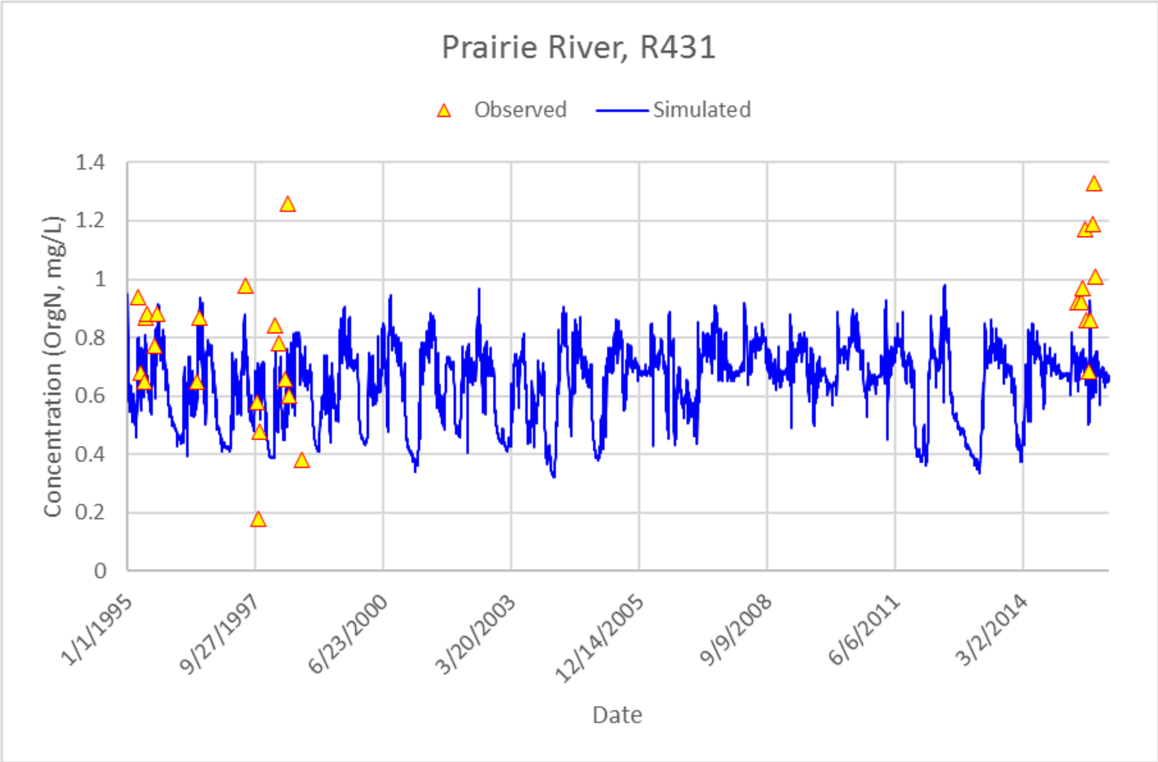


Figure 4-12. Simulated Organic N Concentration for Prairie River (R431)

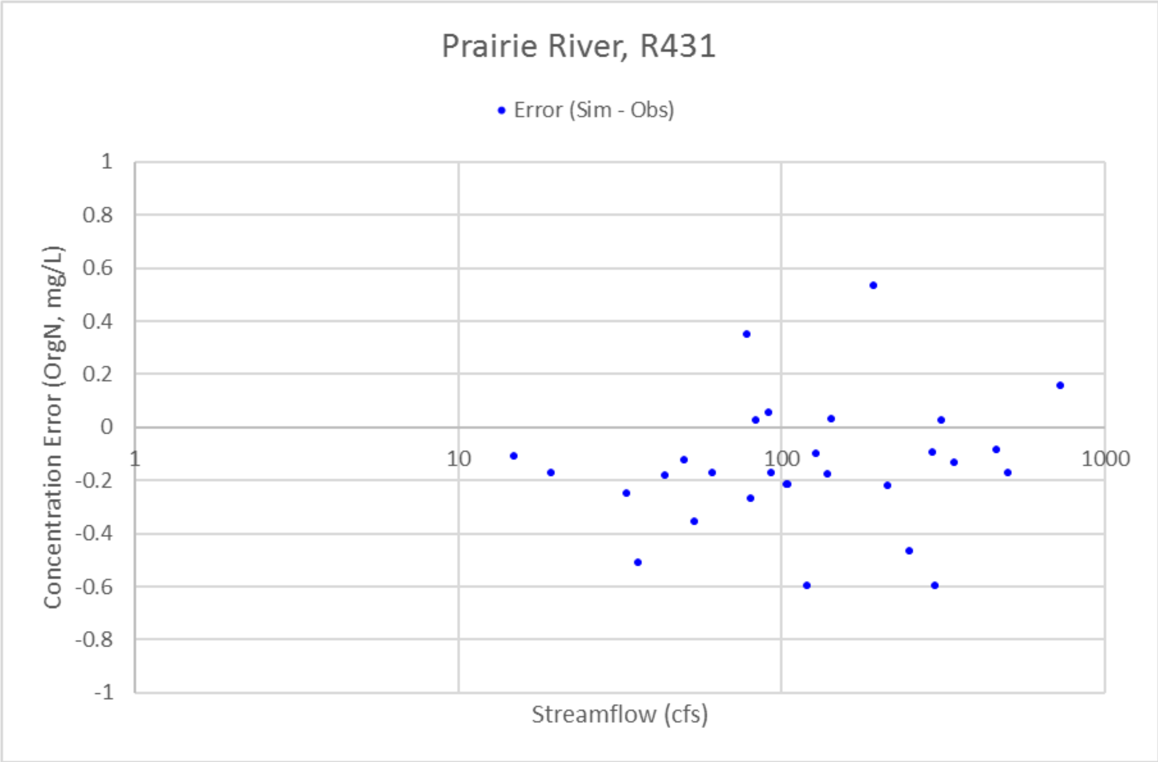


Figure 4-13. Organic N Concentration Error (Simulated – Observed) for Prairie River (R431)

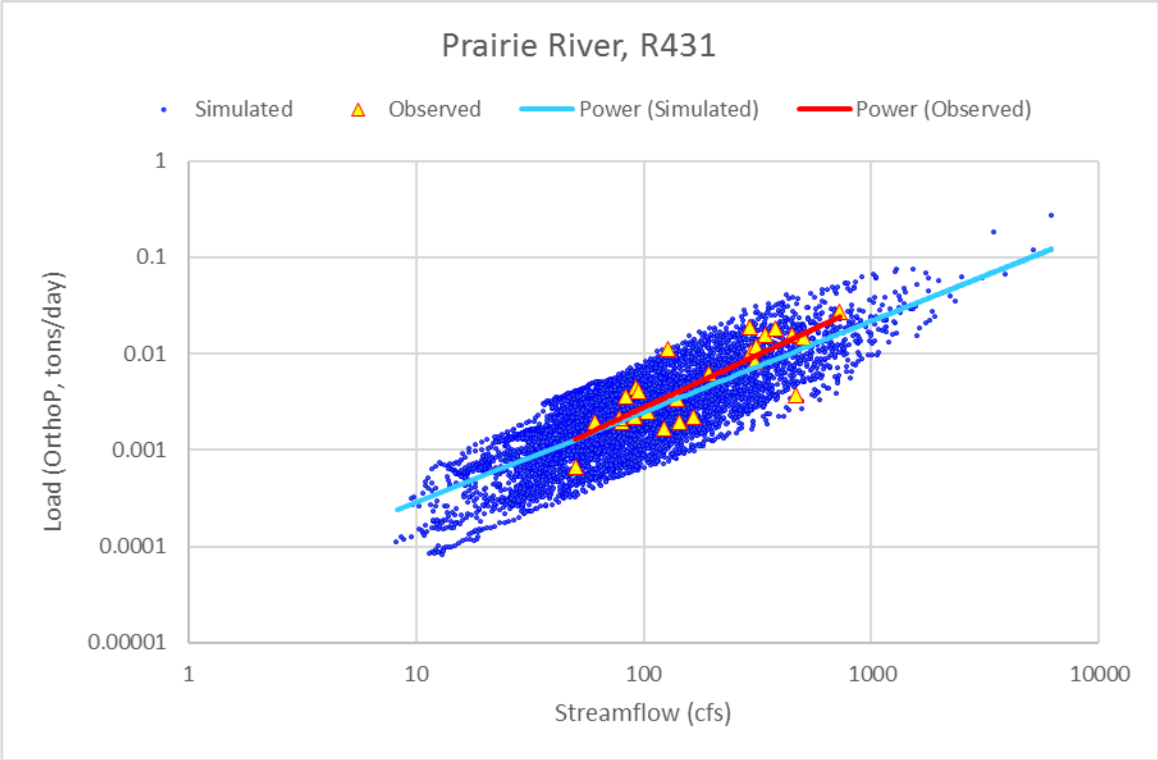


Figure 4-14. Ortho P Load vs Streamflow for Prairie River (R431)

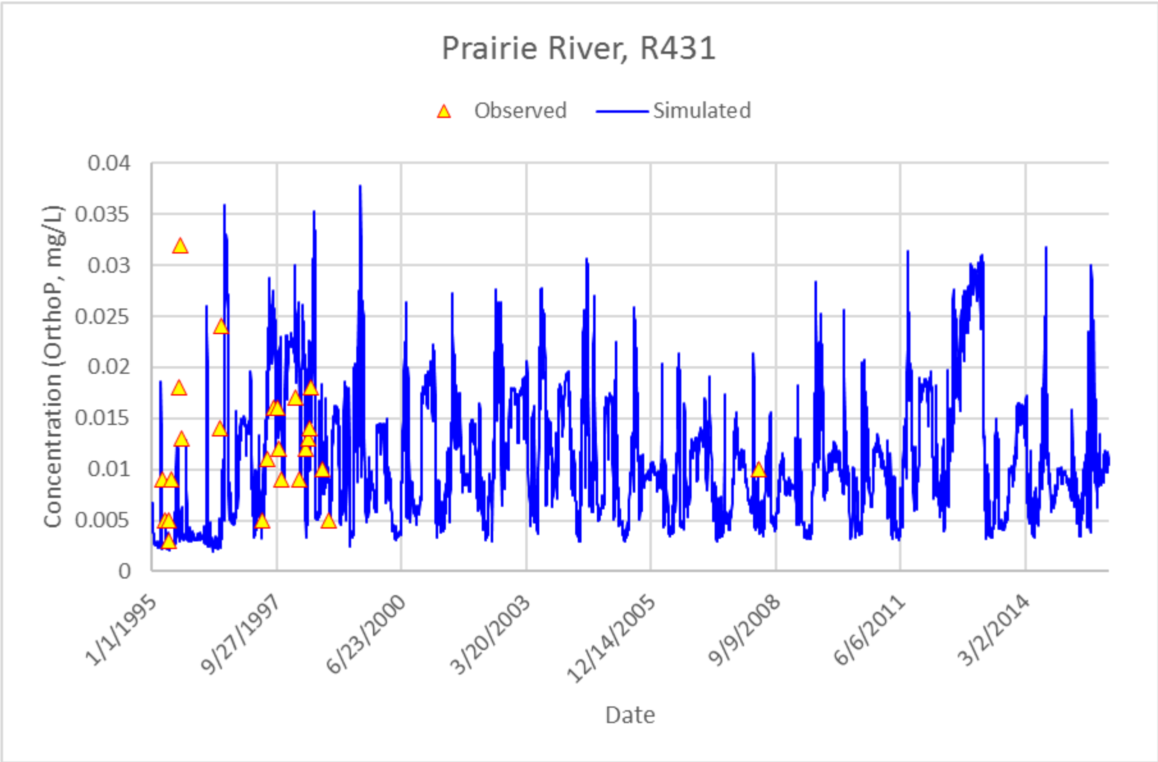


Figure 4-15. Simulated Ortho P Concentration for Prairie River (R431)

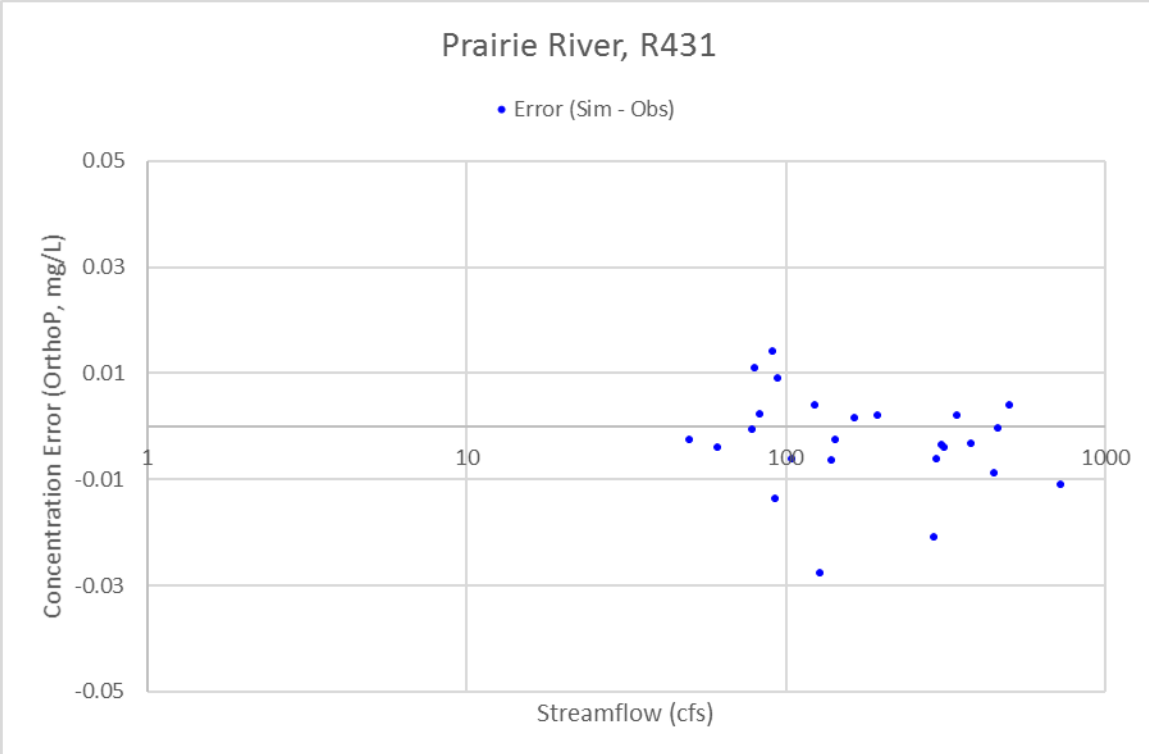


Figure 4-16. Ortho P Concentration Error (Simulated – Observed) for Prairie River (R431)

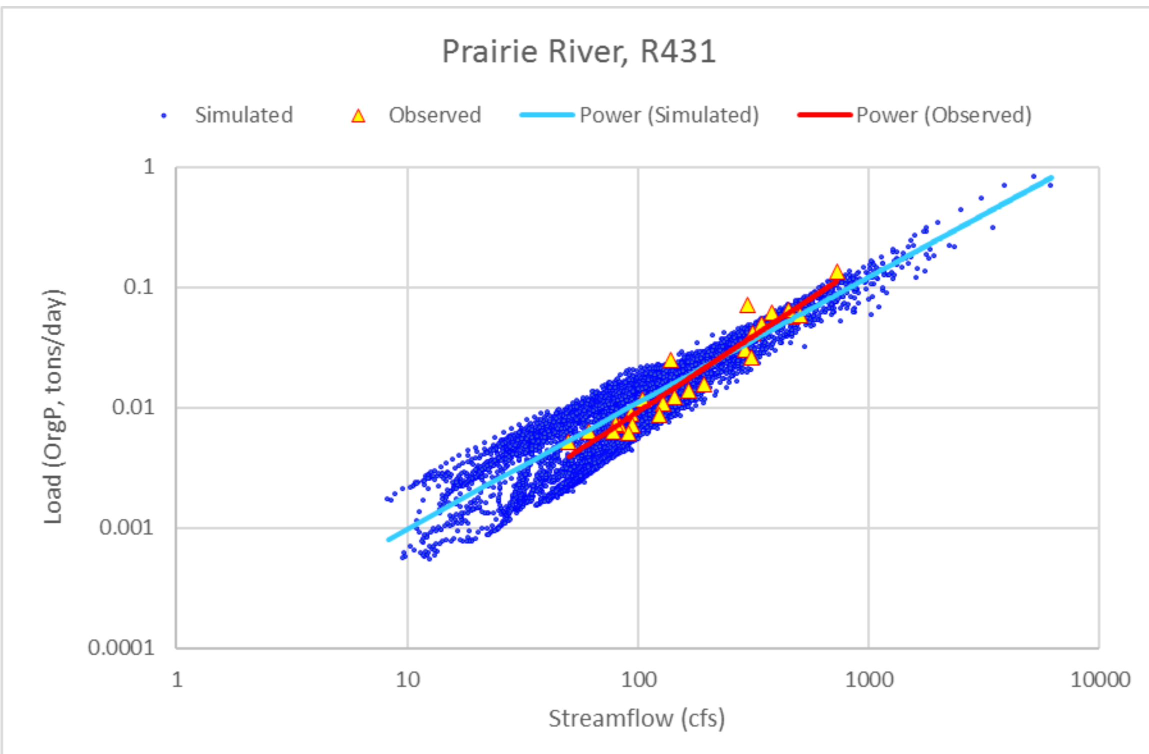


Figure 4-17. Organic P Load vs Streamflow for Prairie River (R431)

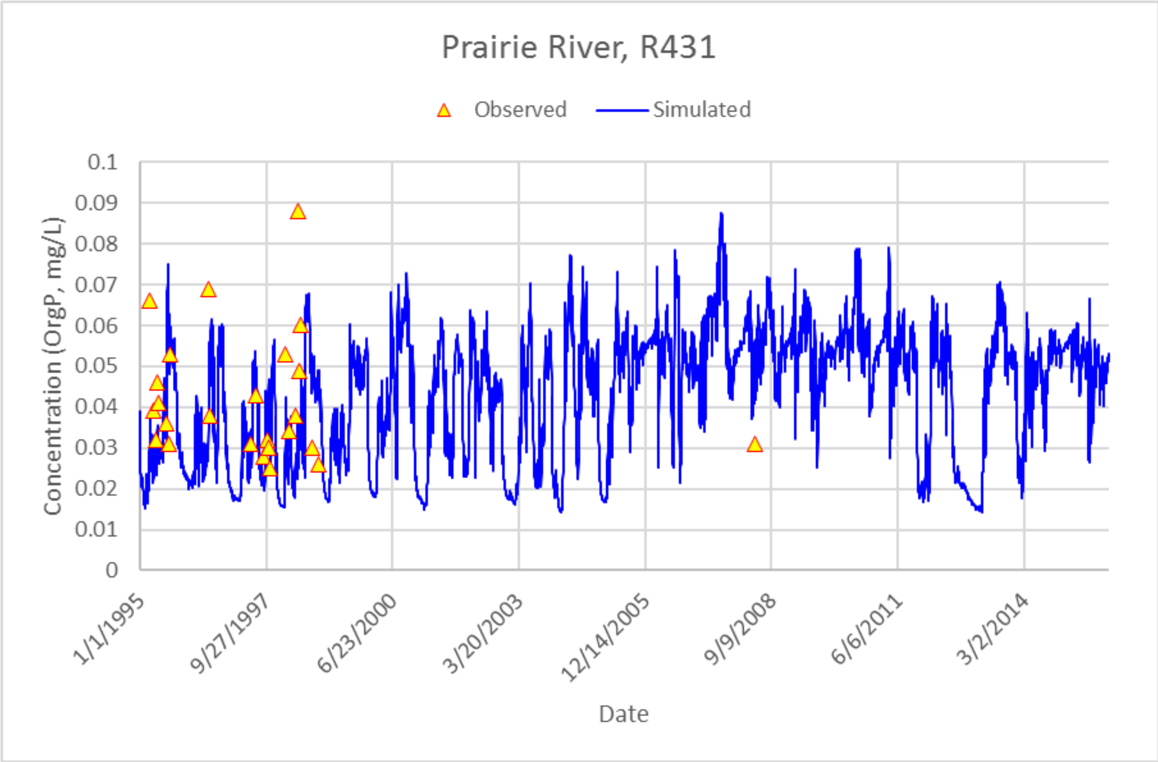


Figure 4-18. Simulated Organic P Concentration for Prairie River (R431)

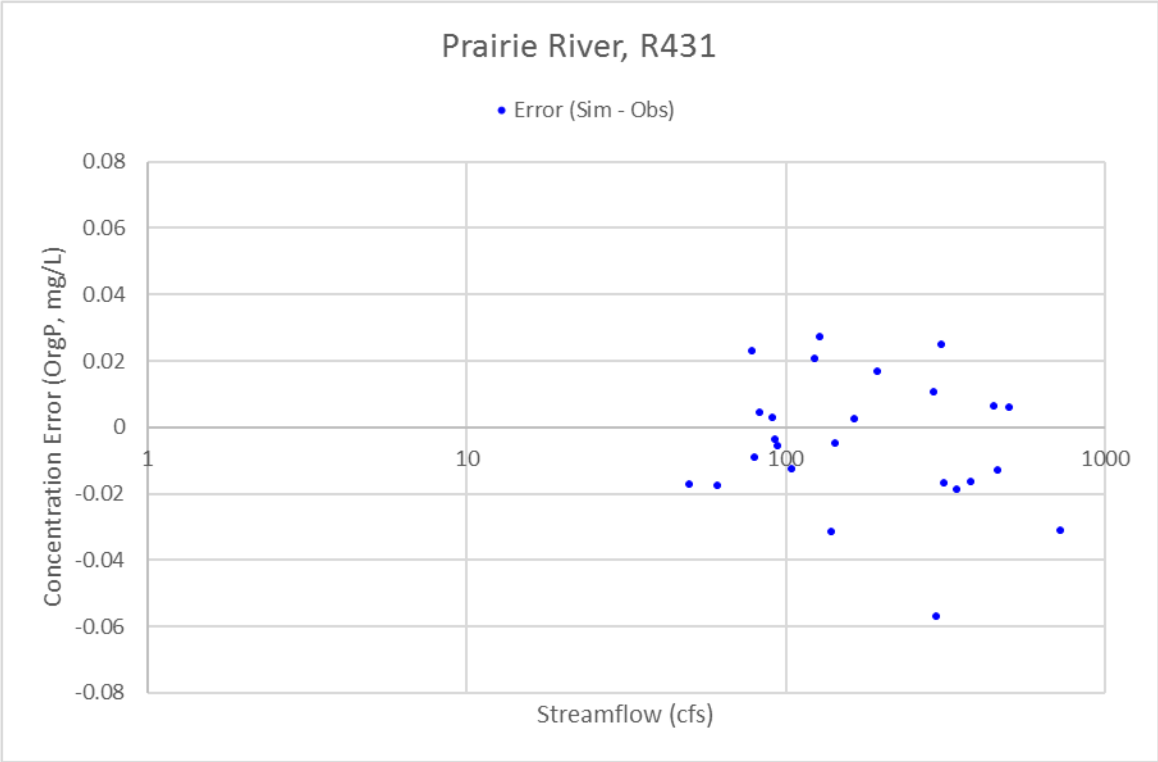


Figure 4-19. Organic P Concentration Error (Simulated – Observed) for Prairie River (R431)

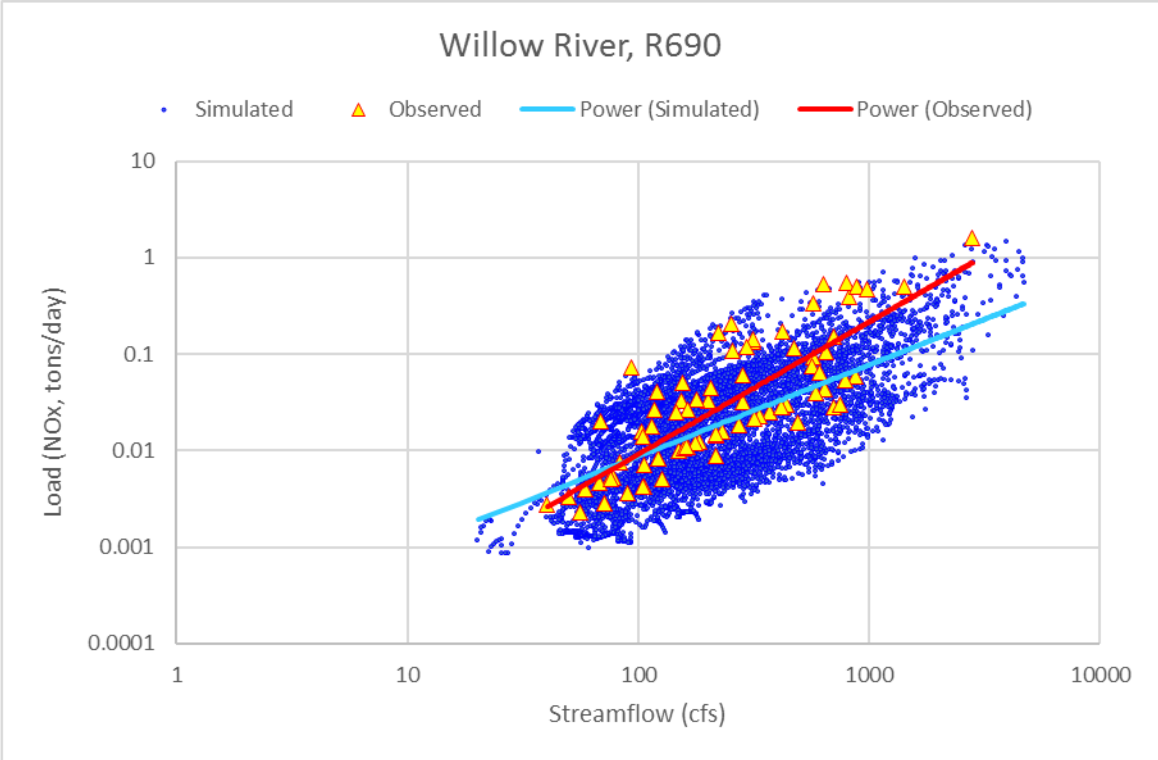


Figure 4-20. Nitrite + Nitrate Load vs Streamflow for Willow River (R690)

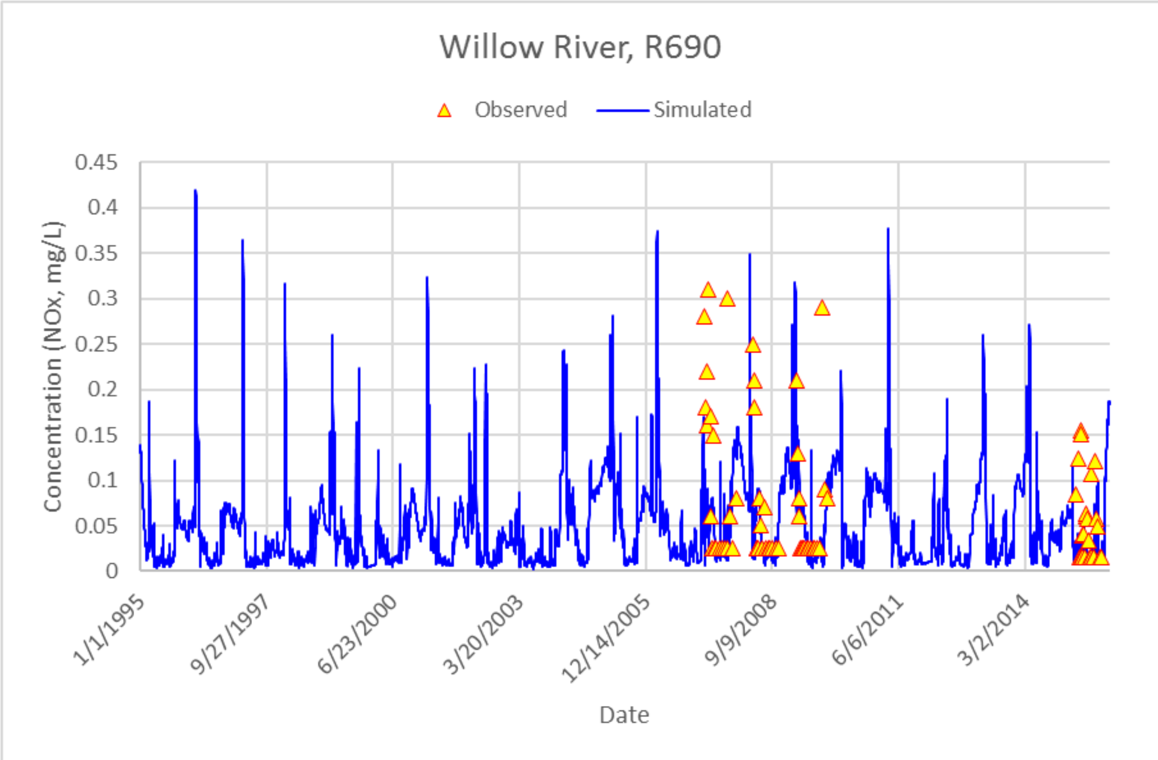


Figure 4-21. Simulated Nitrite + Nitrate Concentration for Willow River (R690)

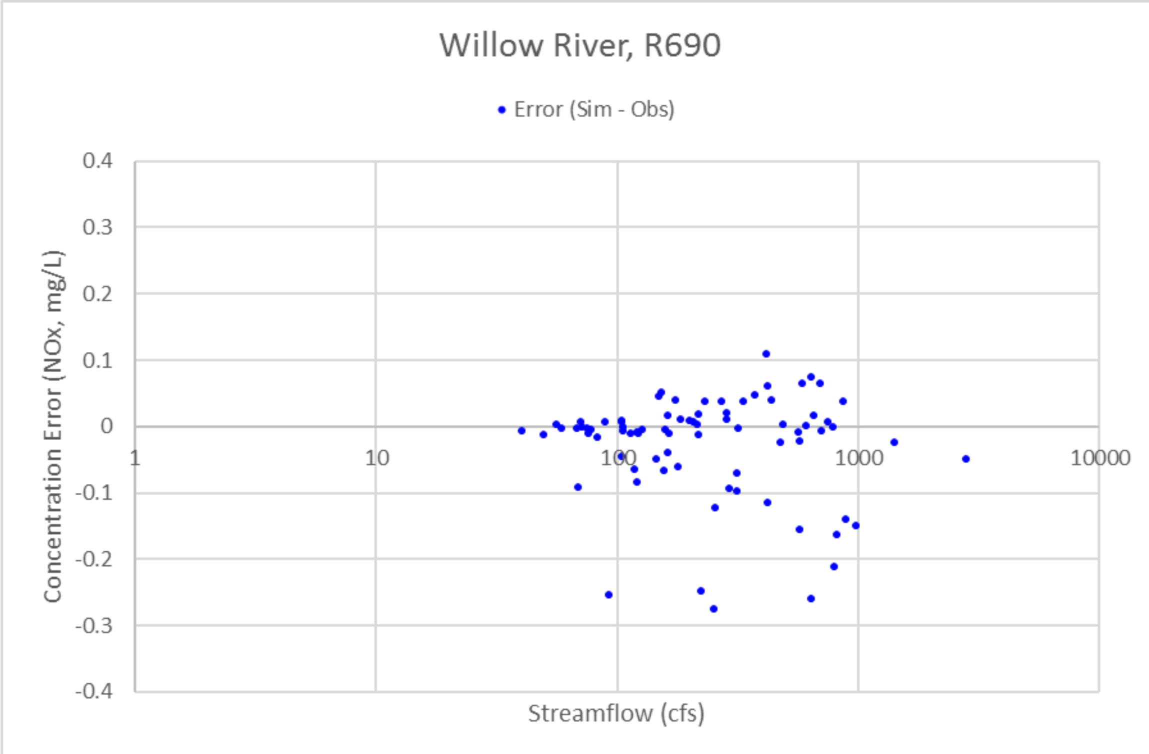


Figure 4-22. Nitrite + Nitrate Concentration Error (Simulated – Observed) for Willow River (R690)

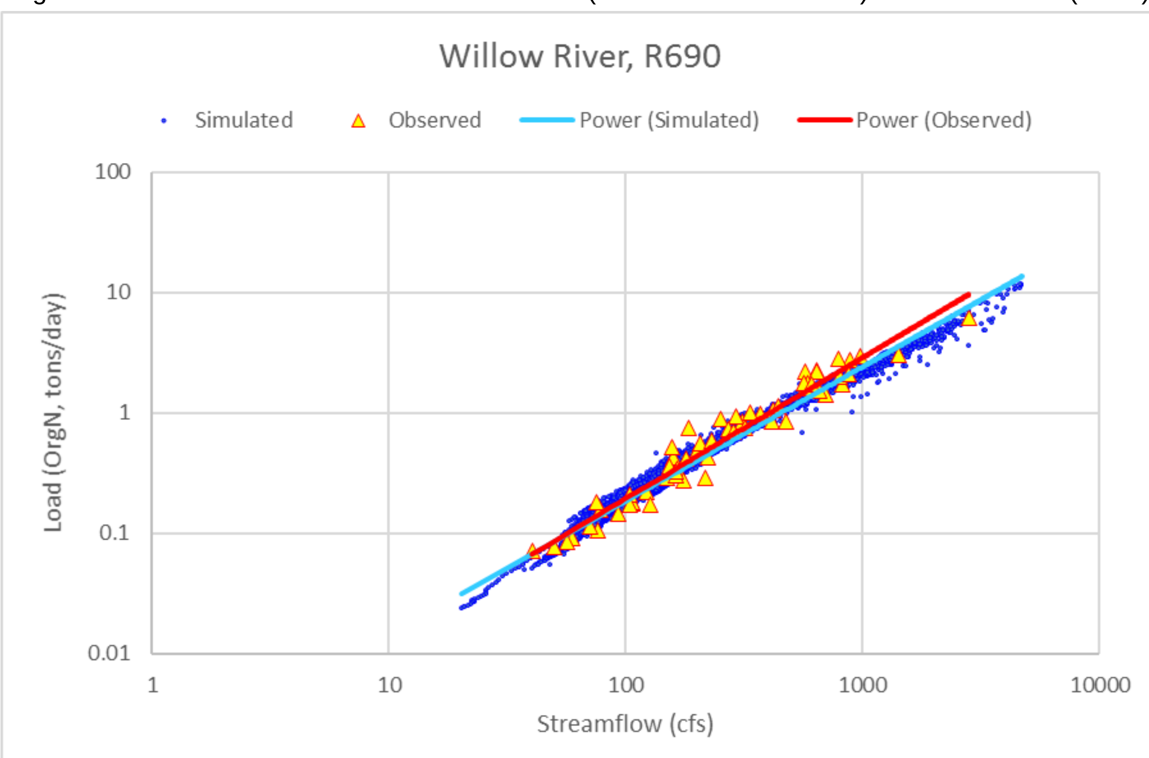


Figure 4-23. Organic N Load vs Streamflow for Willow River (R690)

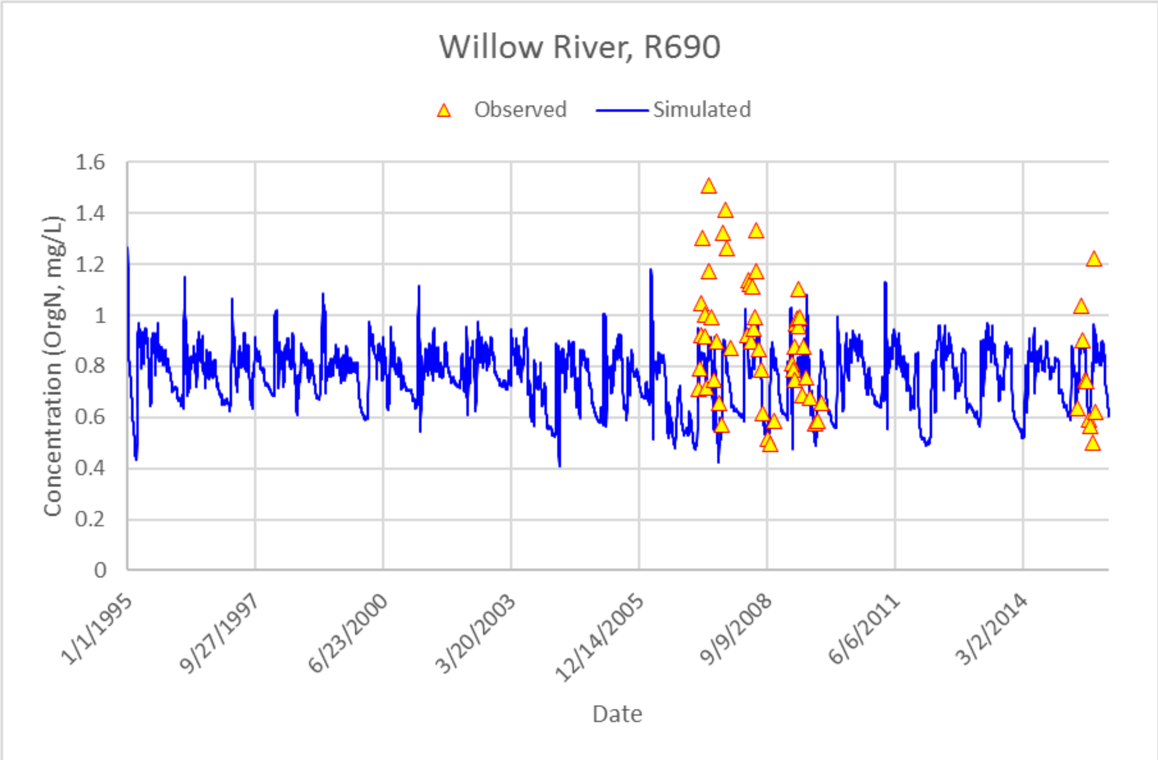


Figure 4-24. Simulated Organic N Concentration for Willow River (R690)

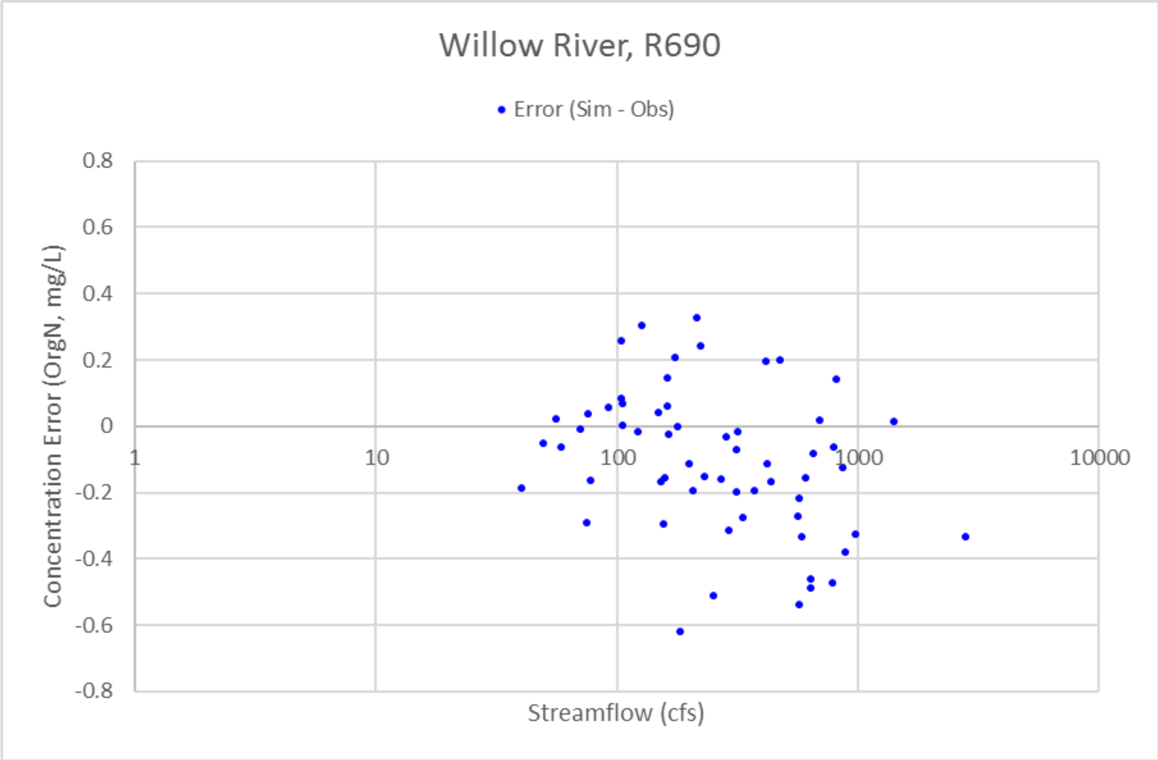


Figure 4-25. Organic N Concentration Error (Simulated – Observed) for Willow River (R690)

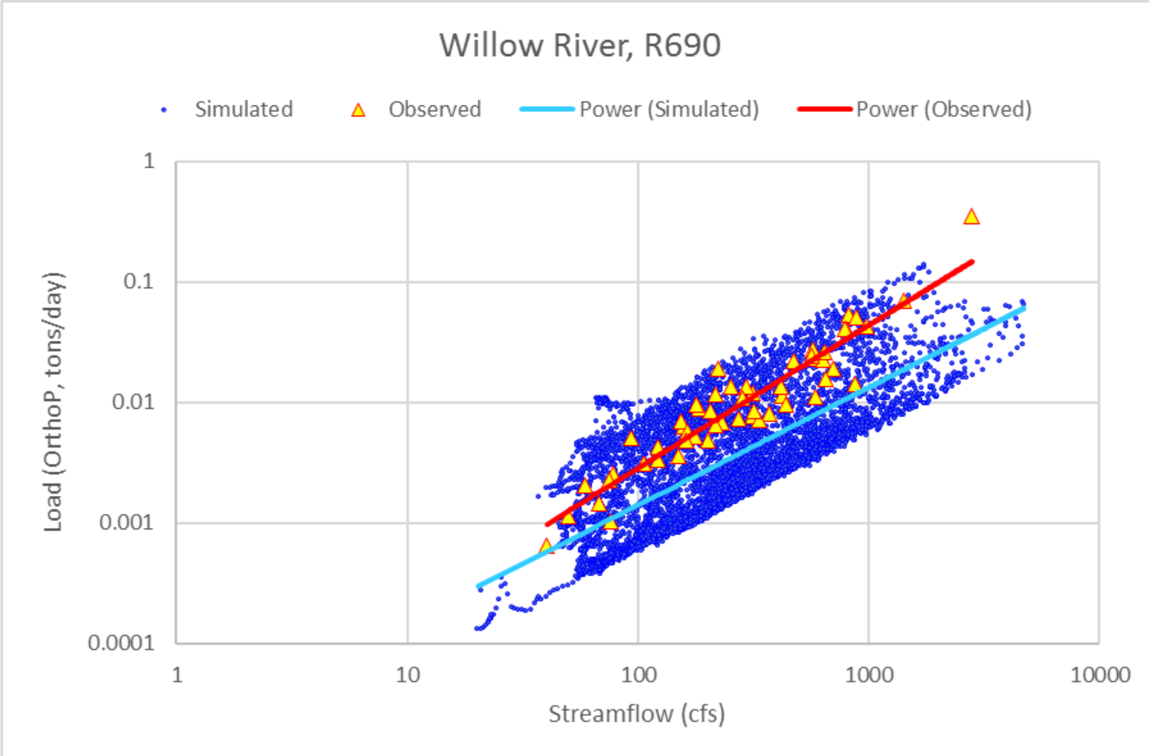


Figure 4-26. Ortho P Load vs Streamflow for Willow River (R690)

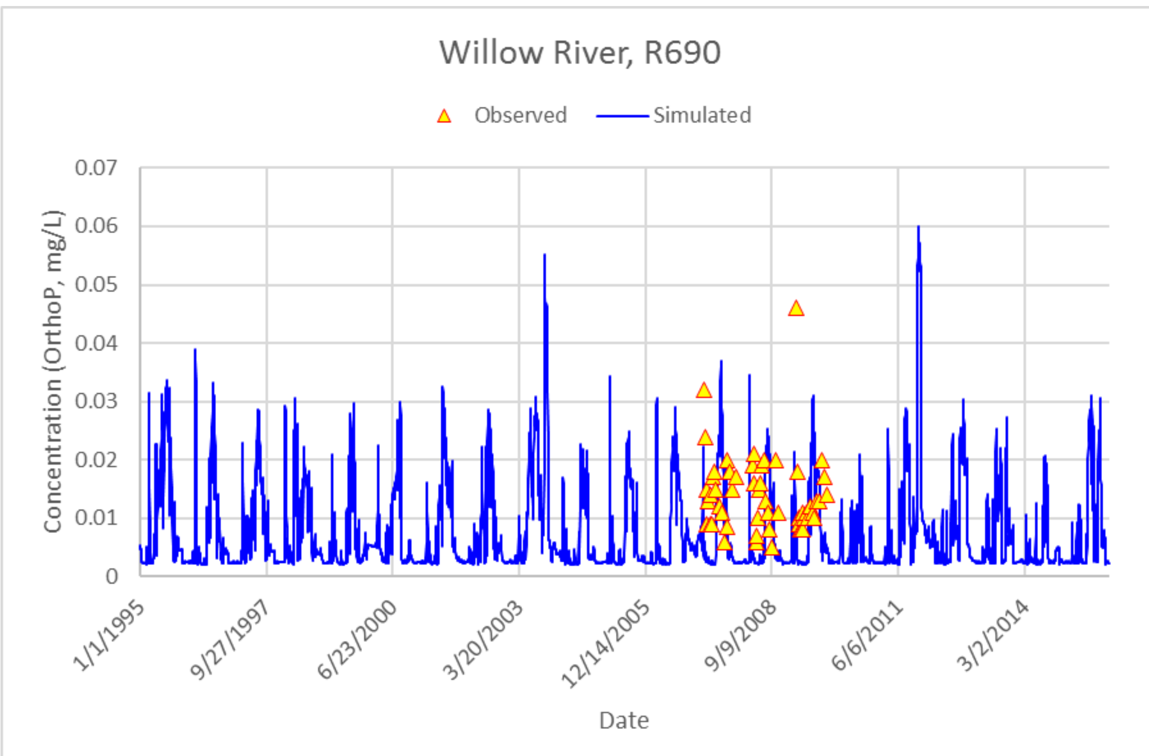


Figure 4-27. Simulated Ortho P Concentration for Willow River (R690)

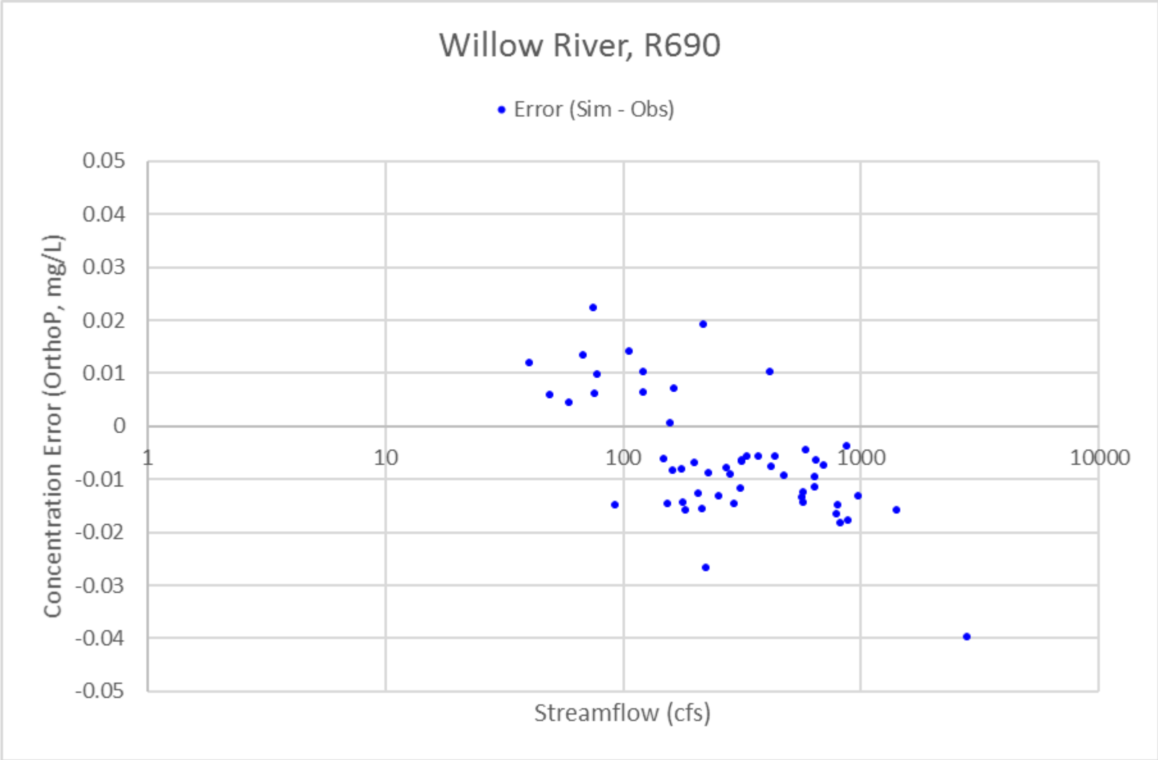


Figure 4-28. Ortho P Concentration Error (Simulated – Observed) for Willow River (R690)

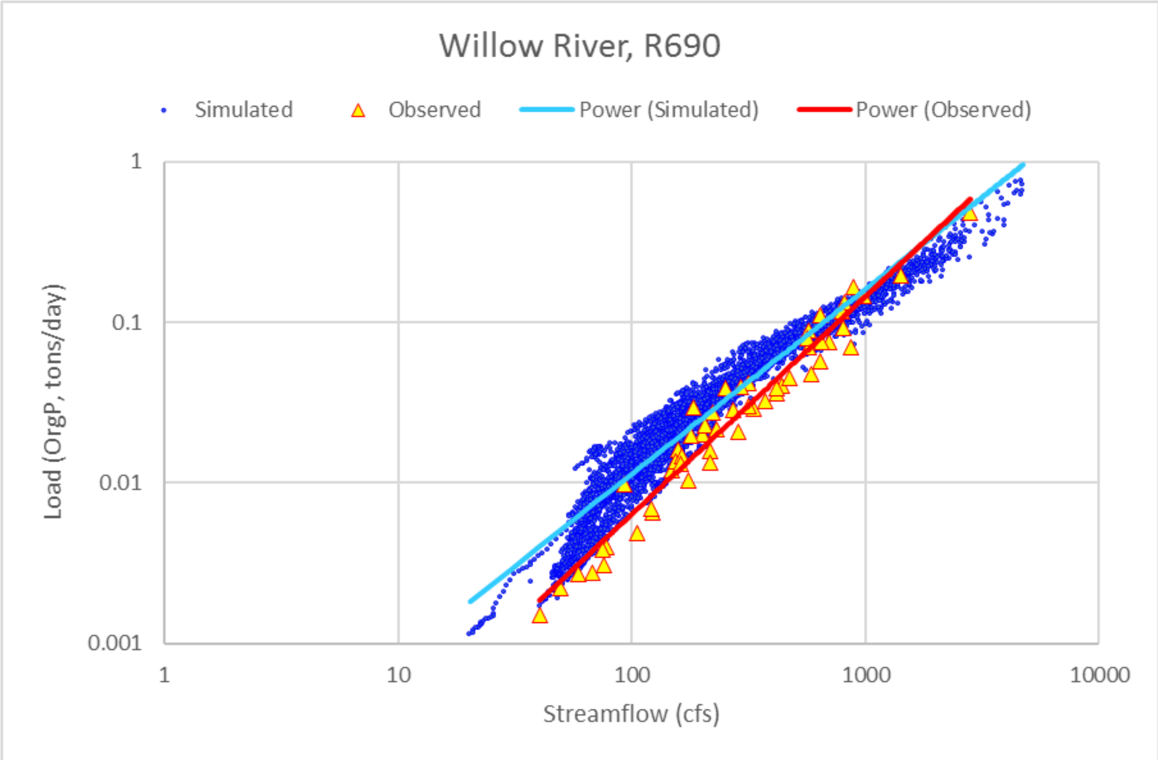


Figure 4-29. Organic P Load vs Streamflow for Willow River (R690)

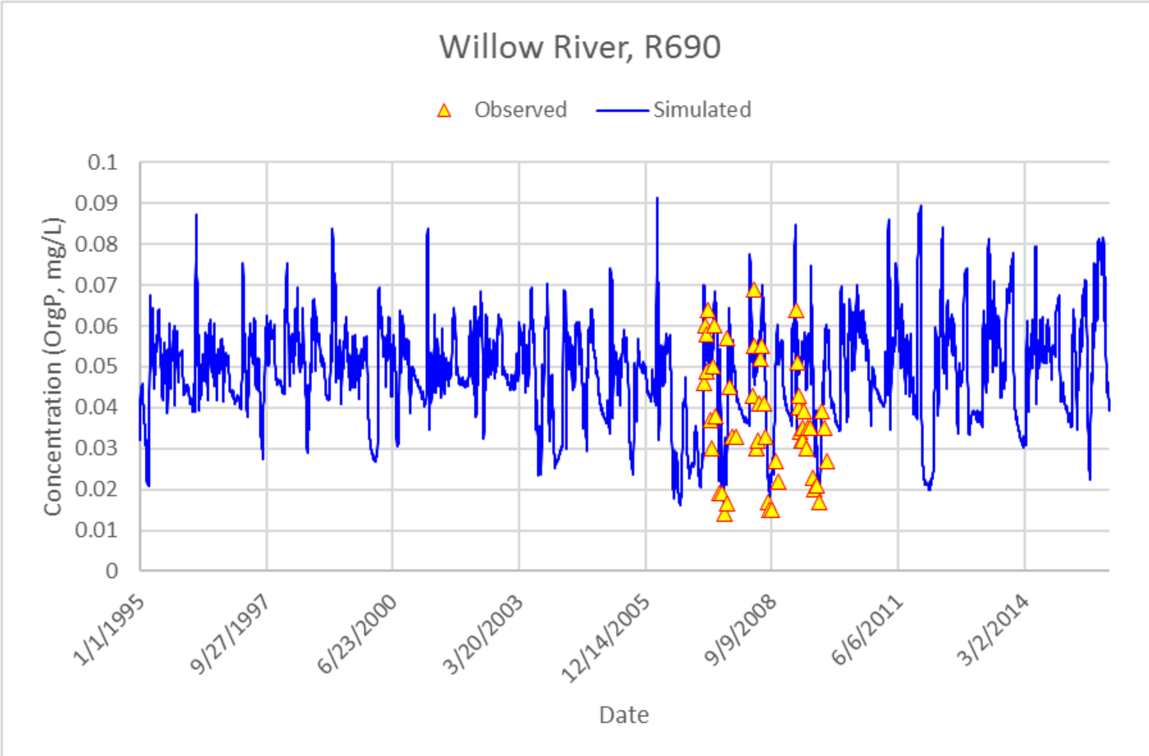


Figure 4-30. Simulated Organic P Concentration for Willow River (R690)

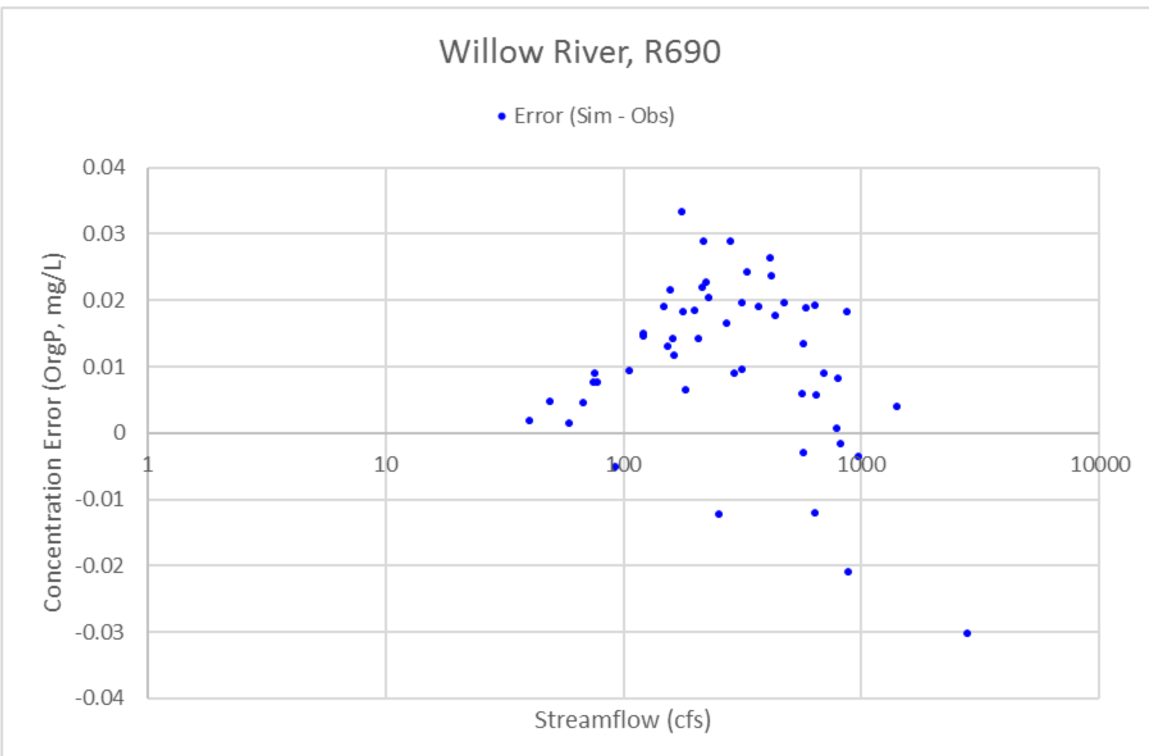


Figure 4-31. Organic P Concentration Error (Simulated – Observed) for Willow River (R690)

5.0 TEMPERATURE AND DISSOLVED OXYGEN

Monitored dissolved oxygen (DO) data was compiled for calibration reaches and used to inform the recalibration of nutrients, algae, BOD, and dissolved oxygen. Simulated times series of dissolved oxygen are presented for Swan River, Savanna River, Prairie River and Sandy River in Figure 5-1 - **Error! Reference source not found.**. In general, the model does a reasonable job of representing mean daily DO, which is largely governed by reaeration at the air-water interface and benthic oxygen demand. Diurnal DO fluctuations are primarily dependent on algae photosynthesis (DO production in daylight hours) and respiration (DO consumption in nighttime hours). The model also provides a reasonable representation of diurnal DO patterns in these reaches. Some exceptionally high or low DO records, however, are not mimicked by the model, and changes in the DO pattern from earlier years (pre-2009) to later simulation years (post-2011) are not fully resolved at Sandy River. Plots of observed and simulated water column temperature are also provided for the same locations as the DO plots. Diurnal temperature patterns are also well represented by the HSPF model, as shown in Figure 5-5 - Figure 5-8.

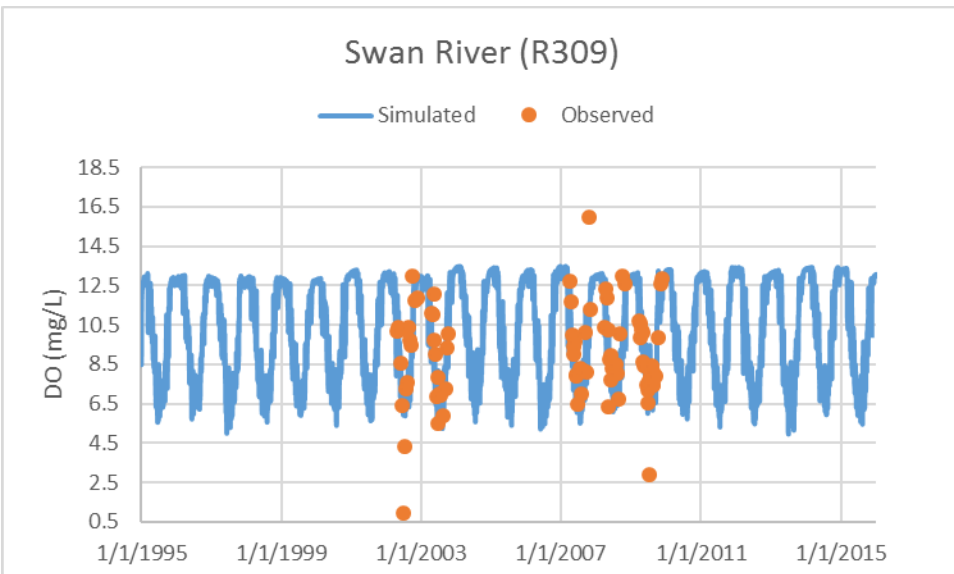


Figure 5-1. Simulated and Observed Dissolved Oxygen Concentrations at Swan River (R309)

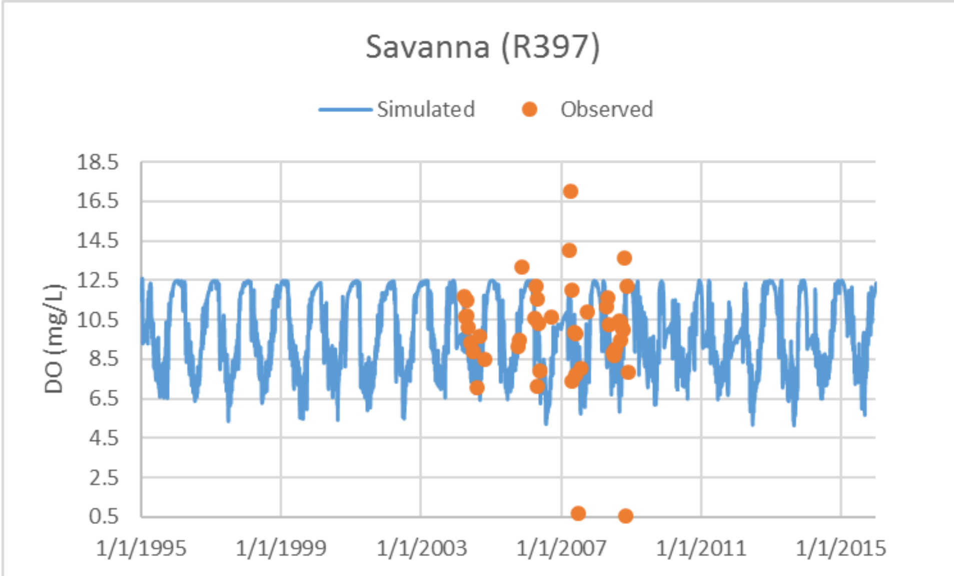


Figure 5-2. Simulated and Observed Dissolved Oxygen Concentrations at Savanna River (R397)

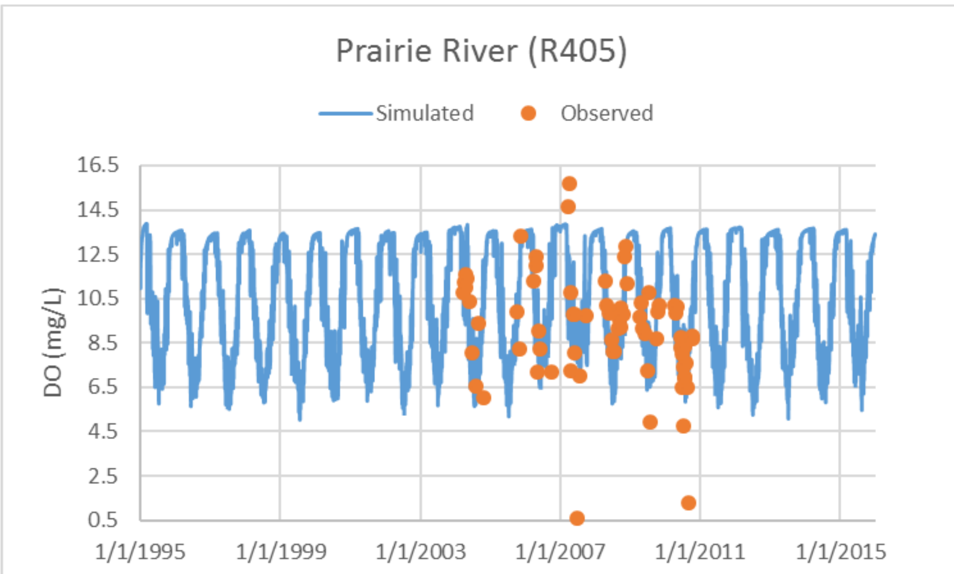


Figure 5-3. Simulated and Observed Dissolved Oxygen Concentrations at Prairie River (R405)

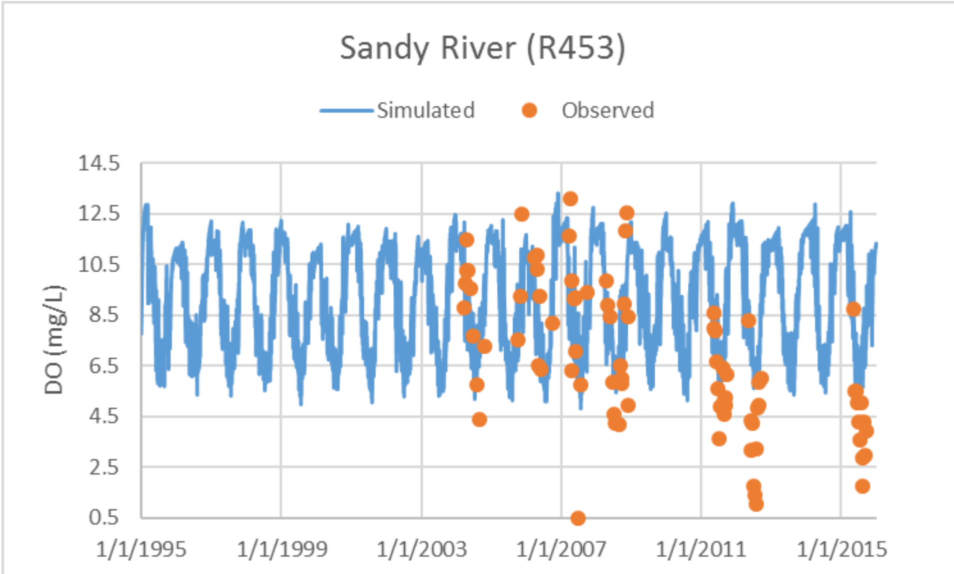


Figure 5-4. Simulated and Observed Dissolved Oxygen Concentrations at Sandy River (R453)

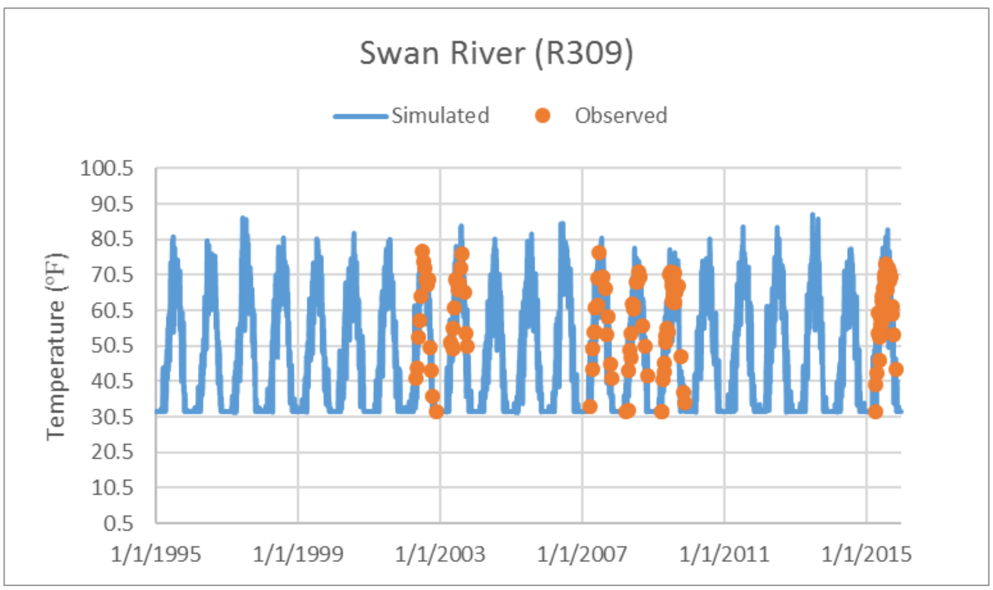


Figure 5-5. Simulated and Observed Water Temperature at Swan River (R309)

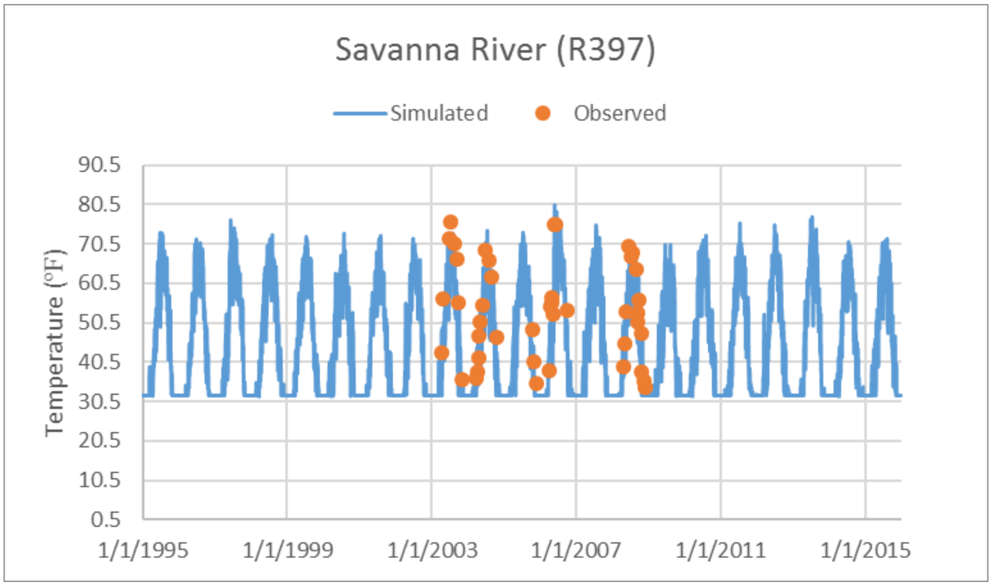


Figure 5-6. Simulated and Observed Water Temperature at Savanna River (R397)

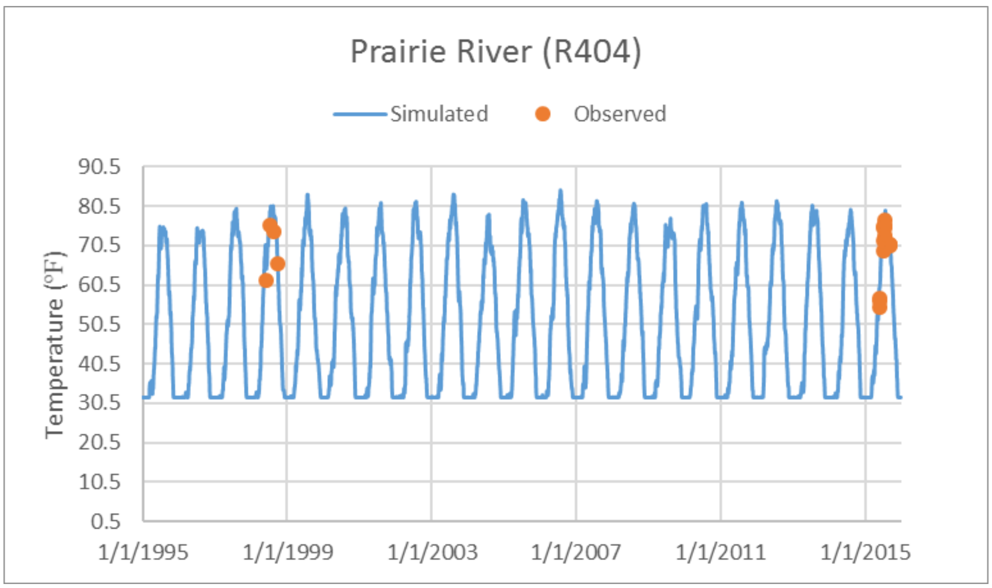


Figure 5-7. Simulated and Observed Water Temperature at Prairie River (R405)

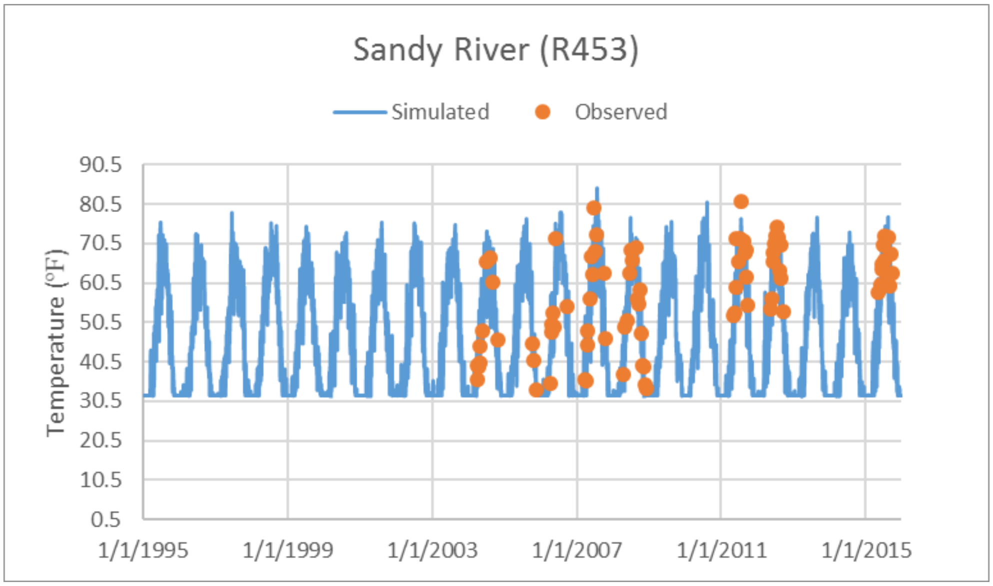


Figure 5-8. Simulated and Observed Water Temperature at Sandy River (R453)

6.0 CONCLUSIONS AND POTENTIAL MODEL ENHANCEMENTS

The recalibration of the Mississippi River – Grand Rapids watershed HSPF model following the land use updates and temporal extension through 2015 by RESPEC improved the representation of hydrology and water quality in the watershed. Key improvements to the hydrology simulation include fixing of excessively high potential evapotranspiration time series, switching to the energy balance method for snow accumulation and melt, and the multi-objective recalibration of evapotranspiration, snow water equivalent, lake level, and flow. Major improvements to the water quality simulation include fixed units on ammonia and nitrate atmospheric deposition to reaches, incorporation of wet deposition of ortho P to reaches, and an extensive recalibration of nutrients, algae, dissolved oxygen, BOD, and temperature using records available for the extended model period.

The recalibrated model does a reasonable job of representing upland and instream processes in the watershed, as indicated by comparison plots and metrics shown in the previous sections. The recalibration provides a better balance of nitrogen and phosphorus species, and chlorophyll-*a* and phosphorus concentrations simulated by the model improved for most lakes. Mean and diurnal dissolved oxygen concentrations and water temperature align well with monitoring records. Therefore, the Grand Rapids watershed model is appropriate for Waste Load Allocations (WLAs), management and future conditions scenario studies (e.g., response to changes in climate), and other planning efforts.

The recalibrated models provide a solid foundation for scenario applications. For example, impacts of forestry best management practices and conservation, rejuvenation of the logging industry, wildfires, or urban development could be assessed with the MR – GR watershed model. The model could also be used to examine the vulnerabilities of forest and wetland ecosystems to climate change, such as risk of fires, change in species composition, warming water temperatures, of other impacts of intensified floods and/or droughts.

Even though the model preforms well overall, there are still components that could be improved in the future. Iron ore deposits are extracted and processed in the Mesabi Mining Range that extends into the northeast portion of the watershed. Mine features, such as closed pits that trap water, and activities, such as pit dewatering and discharge, alter hydrologic processes in mining areas. A simple representation of mines is included in the MR - GR HSPF model that only accounts for discharges to surface waters from dewatering activities. Records from dewatering appropriation permits and discharge location information were used to characterize mining inflows to stream reaches (RESPEC, 2016). However, there are several issues with the current representation of mines that result in a poor hydrology simulation in this region of the watershed. A separate memorandum was provided that discussed methods that could be implemented to better represent mining features (e.g., identifying and disconnecting surface flows from closed pits) in the model (Tetra Tech, 2018).

Improvements could also be made to stratifying lakes. For example, chlorophyll-*a* is poorly depicted by the HSPF model for the impaired Big Sandy Lake. Big Sandy Lake is deep and likely exhibits thermal stratification in the winter and summer, with turnover periods in the spring and fall. HSPF simulates model reaches as one-dimensional, fully mixed segments, and this limitation made it a challenge to model Big Sandy Lake. An approach to represent epilimnion and hypolimnion layers of stratified lakes was developed for and implemented in the Otter Tail watershed HSPF model (Tetra Tech, 2017b), and it could be applied in the Grand Rapids model as well. We recommend that this approach only be used for a small number of lakes as it significantly extends model run time. Another option would be to develop and utilize a lake model (or models) in combination with HSPF. The HSPF model provides useful estimates of loads to Big Sandy, and it could be paired with a lake model (e.g., BATHTUB) to support management and planning efforts.

Lastly, the model recalibration results presented in this report are based on simulations and comparisons to observed data through end of 2015. Data collected in 2016 and beyond can be used to further enhance and refine the MR-GR HSPF model, and other watershed models in the Upper Mississippi Basin.

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