

Draft Report

St. Lucie River and Estuary Watershed Water Quality Modeling

for the

St. Lucie River and Estuary
Basin Management Action Plan

Prepared by

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EXECUTIVE SUMMARY

A watershed water quality model (WaSh) has been developed for the St. Lucie River and Estuary Watershed (SLREW). The model domain covers the C-23 basin, C-24 basin, C-44/S-153 basin, Ten Mile Creek basin, North Fork, South Fork, Basin 4/5/6, and South Coastal basin. The model is a hydrologic, hydrodynamic, and water quality model originally developed for the unique hydrologic conditions in south Florida (URS, 2008d).

The St. Lucie River and Estuary Basin Management Action Plan (BMAP) is a part of a statewide watershed management approach to restore and protect Florida's water quality. It was adopted by the Florida Department of Environmental Protection (DEP) in June 2013 to implement the total maximum daily load (TMDL) for total nitrogen (TN) and total phosphorus (TP). The TMDL and BMAP relied on information from the WaSh model, and during BMAP development, it was determined that the model would be revised to better suit the planning purposes of the BMAP.

DEP coordinated with the South Florida Water Management District (SFWMD) to revise, enhance, and update the model, first by simulating the baseline scenario. The baseline scenario period of record is 1994 to 2016 and uses 2004, 2008, and 2012 land use data. The model was calibrated using available SFWMD data from 2001–2006 and verified with available SFWMD data from 1995–2000. Future work will evaluate two alternative scenarios over the period from 2007 to 2016: (1) the impact of large-scale BMAP projects; and (2) the impact of septic tank removal. This modeling effort will assist with drafting revised nutrient load allocations to be recommended as part of the St. Lucie BMAP 5-Year Review in June 2018.

Overall, the model was well-calibrated and verified within the periods chosen from the baseline scenario. The comparison of simulated and measured time series plots for both flow and water quality data were generally in good agreement. The comparison plots and evaluation statistics indicate that the model can predict annual TN and TP loads well. Generally, the comparison of simulated with measured data indicates that the model closely reproduces the patterns of flow and captures the variation of nutrient dynamics.

The calibrated and verified model was used to evaluate two alternative scenarios: (1) large-scale BMAP projects scenario and (2) septic tank removal scenario. The project scenario incorporated four large-scale completed BMAP projects in addition to the Florida Department of Agriculture and Consumer Services (FDACS) agricultural BMP enrollment as of December 31, 2016. The septic tank removal scenario simulated the water quality conditions without any loading from septic tanks. For the projects scenario, the model results indicated that the expected average annual reduction in total nitrogen (TN) and total phosphorus (TP) ranged from 441 to 31,041 lbs/ yr TN and 331 to 4,982 lbs/yr across the St. Lucie basin depending on the project. For the septic tank removal scenario, the computed reduction in TN ranged from approximately 50 lbs/yr to 2,300 lbs/yr depending on the location of interest.

1. Introduction

The St. Lucie River and Estuary Basin Management Action Plan (BMAP) is a part of a statewide watershed management approach to restore and protect Florida's water quality. It was adopted by the Florida Department of Environmental Protection (DEP) in June 2013. Through the BMAP development process, it was determined by both the stakeholders and the DEP that a more detailed scientific model would be necessary for the development of refined BMAP allocations (DEP, 2013). Through this process, it was also determined that the St. Lucie Estuary Watershed Model (WaSh) is the appropriate tool. Water quality models provide essential frameworks for scientific assessment in support of water quality management and decisions such as total maximum daily load (TMDL) determinations (NRC, 2001).

Starting from 2001, a version of the WaSh model was developed and applied to four basins: C-23 Basin, C-24 Basin, C44/S153 Basin, and Tidal Basin (including North Fork, South Fork, Ten Mile Creek, part of South Coastal, and Basin 4, 5, and 6). In support of the BMAP efforts, in 2014 the DEP requested the support of the South Florida Water Management District (SFWMD) to assist with further enhancements to the WaSh model. This initial work included code enhancement, geographical user interface (GUI) water quality upgrades, and calibration refinement and documentation. Since then, the model has been further refined by combining all basins into one model to allow for interbasin flow. The initial value of model parameters for this new combined model were taken from those four models for model calibration. During the calibration, manual adjustment of parameters was performed to improve the overall model predictions.

In accordance with the legislative requirements of Sections 373.4595 and 403.067, Florida Statutes (F.S.), the DEP 5-Year Review for the St. Lucie River and Estuary BMAP will be submitted to the Governor and Legislature by June 30, 2018. In 2017, the DEP coordinated with the SFWMD to complete the WaSh modeling tasks needed to support the 5-Year Review. DEP, in collaboration with the SFWMD, determined the information necessary for model input and output. DEP also provided direction for model scope and assumptions to the SFWMD. The following three periods of record (PORs) have been identified: (1) 1994 through 2006 with land use data for 2004; (2) 2007 through 2011 with land use data for 2008; and (3) 2012 through 2016 with land use data for 2012.

The current work comprises three model scenarios: the baseline scenario and two alternative scenarios. Baseline scenario is defined as the simulation of all three PORs with loading from septic tanks included. Two alternative scenarios are (1) model simulation through both the second and the third PORs with basinwide projects and septic tanks; and (2) simulation through both the second and the third PORs without septic tanks. The model was calibrated using data from 2001 through 2006 and was verified using available data from 1995 through 2000. Septic tank loading is included as point source inputs to the model, using septic tank data compiled from local and regional sources that are preprocessed into time series inputs for this simulation. The first version of this draft report for the WaSh baseline scenario (SFWMD, 2017) was made available to stakeholders for review and preliminary modeling results were presented at the BMAP public meeting in January 2018. Stakeholder comments were incorporated into this update.

This report describes the development of the WaSh model for the St. Lucie River and Estuary Watershed (SLREW) in detail, including model methodologies, study area description, data description, model calibration and verification, and simulation results of the baseline scenario.

2. Study Area Description

The SLREW is in southeastern Florida in Martin, St. Lucie, and Okeechobee Counties (**Figure 1**). The figure also shows the extent of the St. Lucie BMAP area (DEP, 2013). The St. Lucie Estuary (SLE) is a major tributary to the Southern Indian River Lagoon (SIRL). The watershed is an economically important area where water quality is affected by freshwater runoff from agricultural and urban sources in the watershed and Lake Okeechobee (SFWMD, 2015).

The SLE is one of the largest brackish waterbodies on the east coast of Florida. The main branch of the estuary extends from the St. Lucie Inlet (SLI) at the junction with the Indian River Lagoon and spreads northwest for 3.5 miles. Just past the A1A bridge, the estuary makes a turn due west, until it reaches the Roosevelt bridge at US 1 2.5 miles beyond. At US 1, the estuary branches out into the North and South Fork. The estuary width ranges from 0.62 miles at the inlet to nearly 1.24 miles east of the Roosevelt Bridge. The North Fork averages approximately 0.75 miles wide for a length of 4.5 miles, while the South Fork averages 0.43 miles wide for 3 miles. The total water surface area of the inland portion of the SLE is approximately 6.4 square miles, while the main estuary has a surface area of 4.7 square miles that extends eastward around 5 miles, where it joins the SIRL, before opening to the Atlantic Ocean at the SLI.

Historically, this area included a much smaller natural watershed that directly contributed to the river system. However, with the construction of drainage improvements in inland areas, the effective drainage area of the SLE and SIRL expanded to include almost all of Martin and St. Lucie Counties. The C-44 canal and its associated locks and structures were constructed to provide a navigable connection between the east and west coasts of Florida. The C-44 canal also serves as a flood control conveyance for Lake Okeechobee and transports water from the lake into the South Fork. Consequently, during periods of high discharge from the lake, the estuary water quality is degraded by a lowering of salinity, an increase in turbidity, and increase in nutrients from the lake (URS, 2008d). In addition, the C-44 canal transports runoff from the C-44/S-153 basin. The construction of canals C-23 and C-24 (in addition to C-44) provided connections between their respective basins. The C-23 and C-24 canals discharge to the North Fork (DEP, 2008).

The SLREW was originally divided into 6 basins for the BMAP, as follows:

- Basins 4, 5, and 6
- C-23
- C-24
- C-44 and S-153
- North Fork
- South Fork

DEP did not initially include the South Coastal basin within the BMAP area boundaries (2013). This exclusion was because of a lack of nutrient loading data in this area. Tide stage data are available at the SLI, which is treated as the downstream boundary for this modeling effort. Therefore, the South Coastal Basin is included in the final model domain in this study (**Figure 2**). A revised boundary that includes this basin will be recommended by the 5-Year Review.

The boundary of SLREW, including its basins and sub-basins, have changed slightly over the past decade. These changes were updated to geographic information system (GIS) data layers when changes were identified through the investigation of hydrologic connections across the watershed. The latest boundary GIS shapefile of the watershed is taken from Arc Hydro Enhanced Database (AHED) available in the SFWMD GIS data catalog database (most recently updated: Jul 26 2017). The area of basins and sub-basins in SLREW is presented in **Table 1**. The St. Lucie 5-Year Review summarizes boundary updates that have occurred since the original BMAP was adopted and proposes a new boundary that reflects these changes in acreage (**Figure 3**; See Section 3.2 and Appendix G in DEP, 2018 [in draft]). The maps in this report will display the sub-basins shown in **Figure 3** with the exception of the boundary changes proposed to the northeast corner of the watershed. These sub-basins are:

- Basins 4, 5, and 6
- C-23
- C-24
- C-44
- S-153
- Ten Mile Creek
- North Fork
- North Mid-Estuary
- South Fork
- South Mid-Estuary
- South Coastal

The climate of the SLREW is affected by the subtropical influences of the Atlantic Ocean and Lake Okeechobee, with annual mean temperatures of 73 degrees F. Rainfall averages about 55 inches per year, and is defined by a wet season from June through October, during which 62% of the rainfall occurs. The remaining seven months from November through May are considered the dry season. Extreme events typically occur during hurricane season, which is June through November. Annual lake evaporation is typically 50 inches, and wind speeds average 7 to 12 miles per hour (Aqua Terra and Linsley, Kereger Associates, 1997).

Water quality, water quantity, and meteorological data in the SLREW show very distinct seasonality. The dry winter months are characterized by less rainfall, lower nutrients, and higher dissolved oxygen (DO), while the wetter summer months are characterized by higher rainfall, higher nutrients, and lower DO (URS, 2008d).

Further possible degradation of the estuary could result from both the continued urbanization of the coastal regions of St. Lucie and Martin Counties, agricultural activities in the western regions of the watershed (URS, 2008d) and continued Lake Okeechobee discharges.

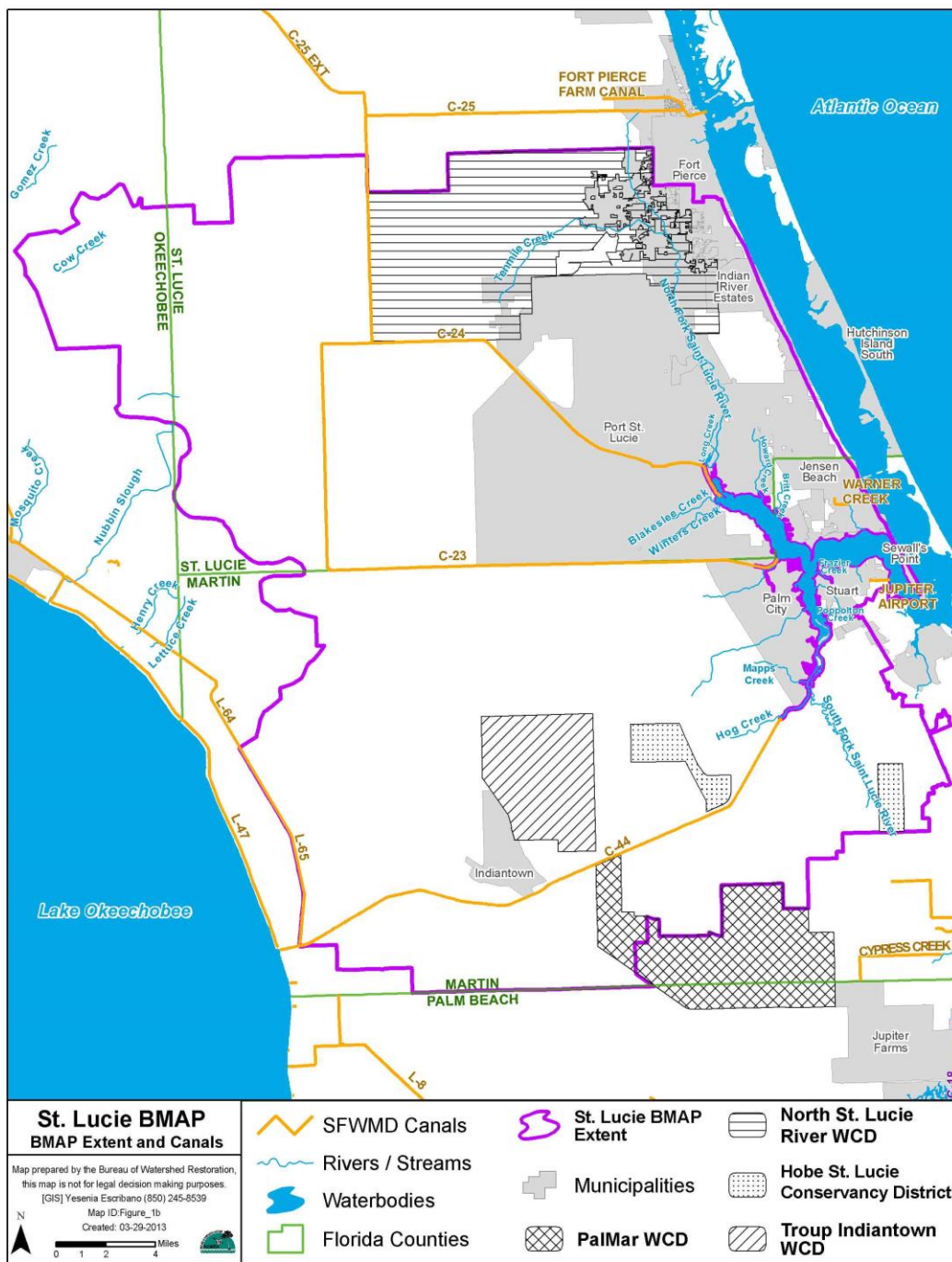
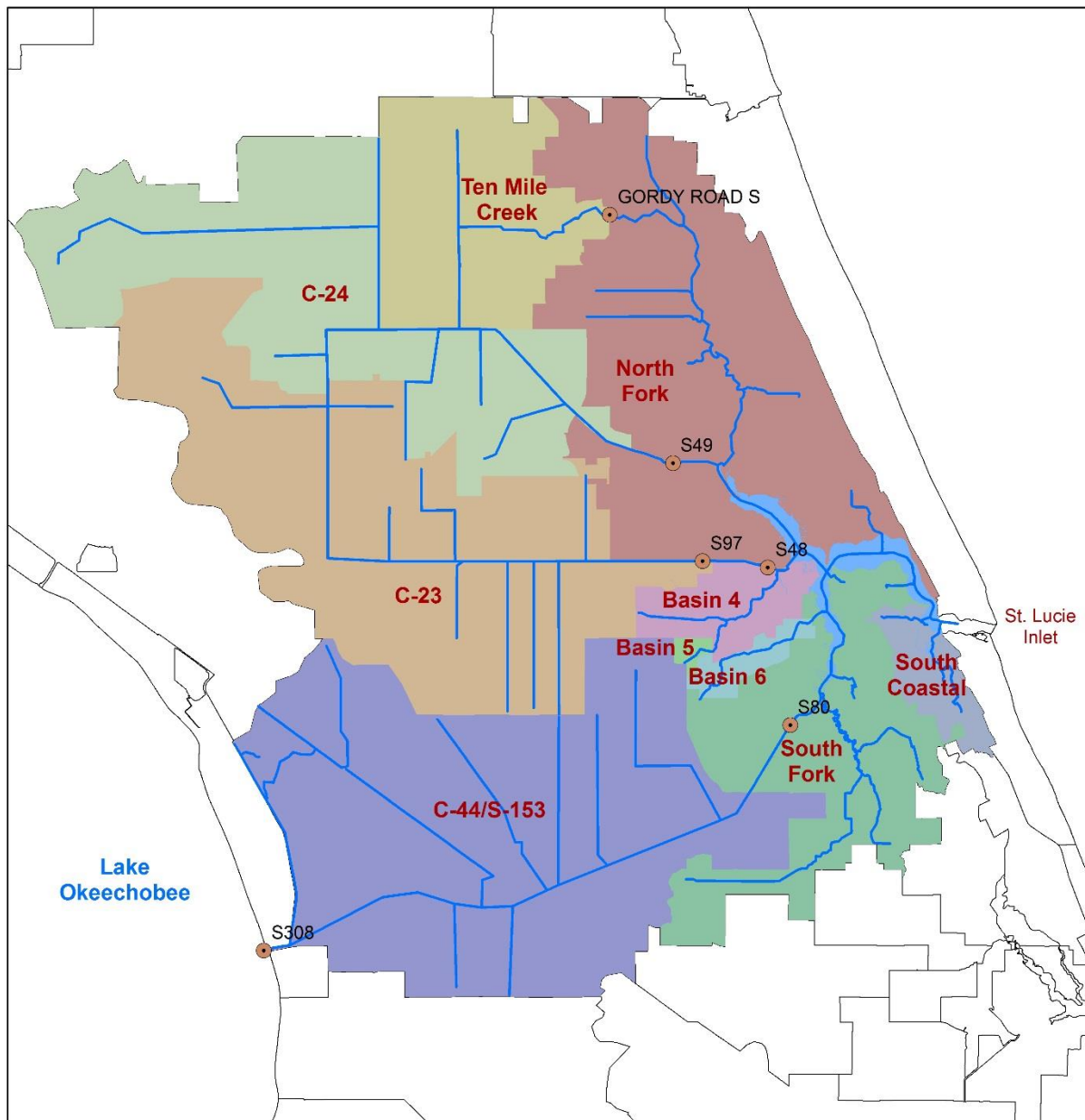


Figure 1. St. Lucie River and Estuary Basin (Source: DEP 2013).



Legend

- Structures
- Primary Canal/River
- Model Domain**
- Subbasin**
- Basin 4
- Basin 5
- Basin 6
- C-23
- C-24
- C-44/S-153
- North Fork
- South Coastal
- South Fork
- St. Lucie Estuary
- Ten Mile Creek

0 1.5 3 6 9 12 Miles

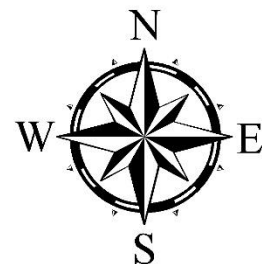


Figure 2. WaSh model domain (colored area)

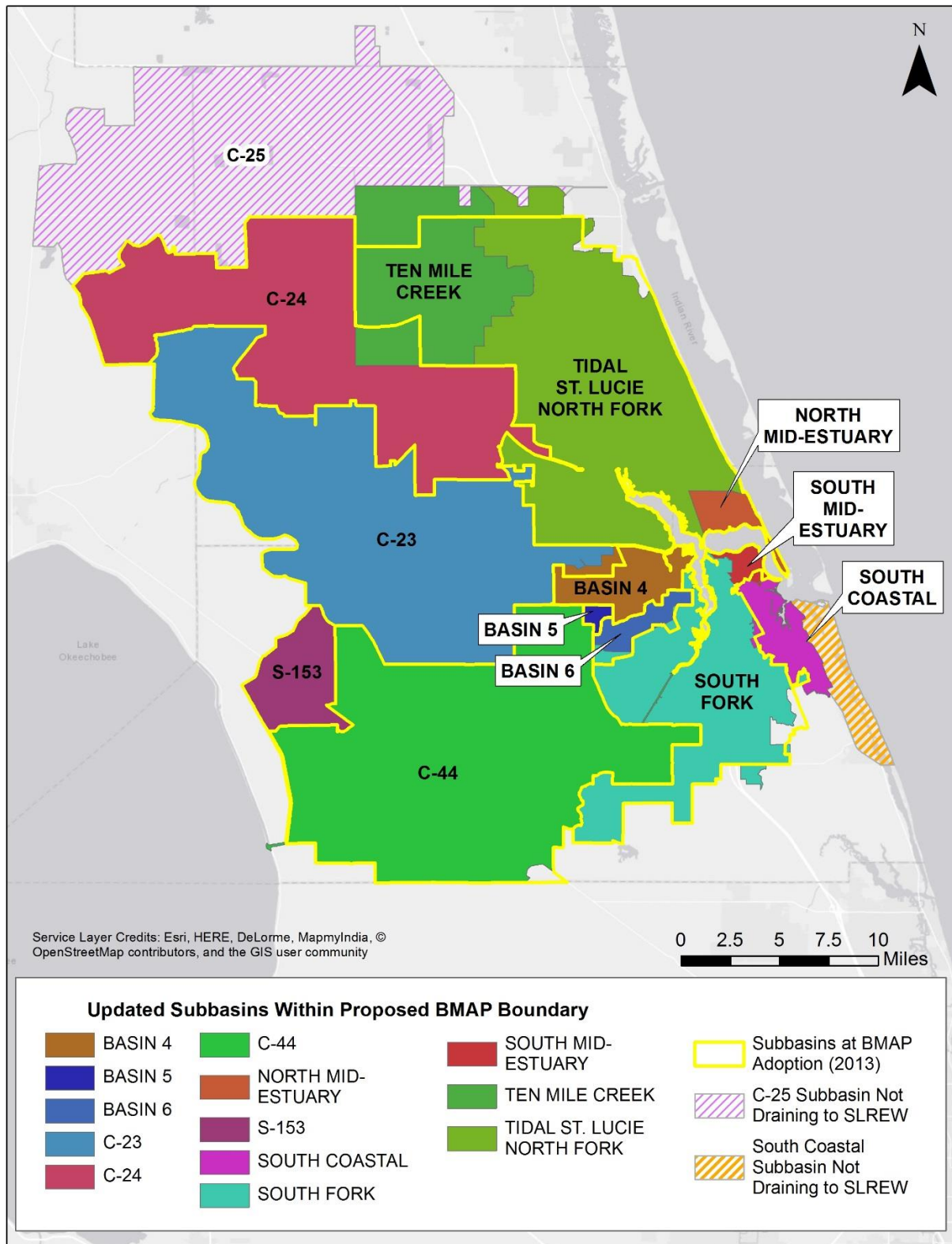


Figure 3. St. Lucie BMAP sub-basins in relation to proposed BMAP boundary

Table 1. Area of each basin/sub-basin

Basin	Sub-Basin	Area (ac)	Area (%)
C-24	C-24	83372.5	15.4%
	Subtotal	83372.5	15.4%
C-23	C-23	110874.8	20.5%
	Subtotal	110874.8	20.5%
C-44/S-153	C-44	115933.0	21.4%
	S-153	13371.1	2.5%
	Subtotal	129304.1	23.9%
Ten Mile Creek	Ten Mile Creek	41029.4	7.6%
	Subtotal	41029.4	7.6%
Tidal Basin	BASIN 4	11049.1	2.0%
	BASIN 5	959.1	0.2%
	BASIN 6	3926.2	0.7%
	ST. LUCIE ESTUARY	7113.4	1.3%
	NORTH MID- ESTUARY	4196.0	0.8%
	SOUTH COASTAL	7991.0	1.5%
	SOUTH FORK	48155.7	8.9%
	SOUTH MID- ESTUARY	2079.1	0.4%
	TIDAL ST. LUCIE NORTH FORK	90835.3	16.8%
	Subtotal	176304.8	32.6%
Total		540885.6	100.0%

3. Model Description

The WaSh is a coupled watershed hydrologic and water quality model originally developed through a joint effort between URS, Inc. (now AECOM) and the SFWMD. The model simulates both watershed quantity and quality (URS, 2008a). The WaSh Model was originally developed to simulate watershed hydrology and water quality for the SLREW, which has unique hydrologic features involving dense drainage canal systems, high water tables, and multiple irrigation sources typical of South Florida.

The model has a cell-based representation of the watershed surface where hydrology is modeled with the Hydrological Simulation Program-Fortran (HSPF) hydrology module PWATER for pervious areas and IWATER for impervious areas. The infiltrated water is routed to a diffusive wave groundwater model that represents the water table aquifer of simulated watersheds. The surface runoff is routed to a full dynamic wave drainage network model that has the capacity to simulate bidirectional flow, branches, and common flow structures.

The WaSh model consists of four basic components: (1) a cell-based representation of surface hydrology; (2) a cell-based representation of subsurface hydrology (groundwater); (3) a reach network that represents streams, rivers, estuaries, and canals; and (4) reservoirs and stormwater treatment areas (STAs). Each of these components is shown in **Figure 4**. In addition to providing

a representation of surface hydrology, each cell can optionally store surface water in a system of tertiary canals. More information is provided in URS (2008a).

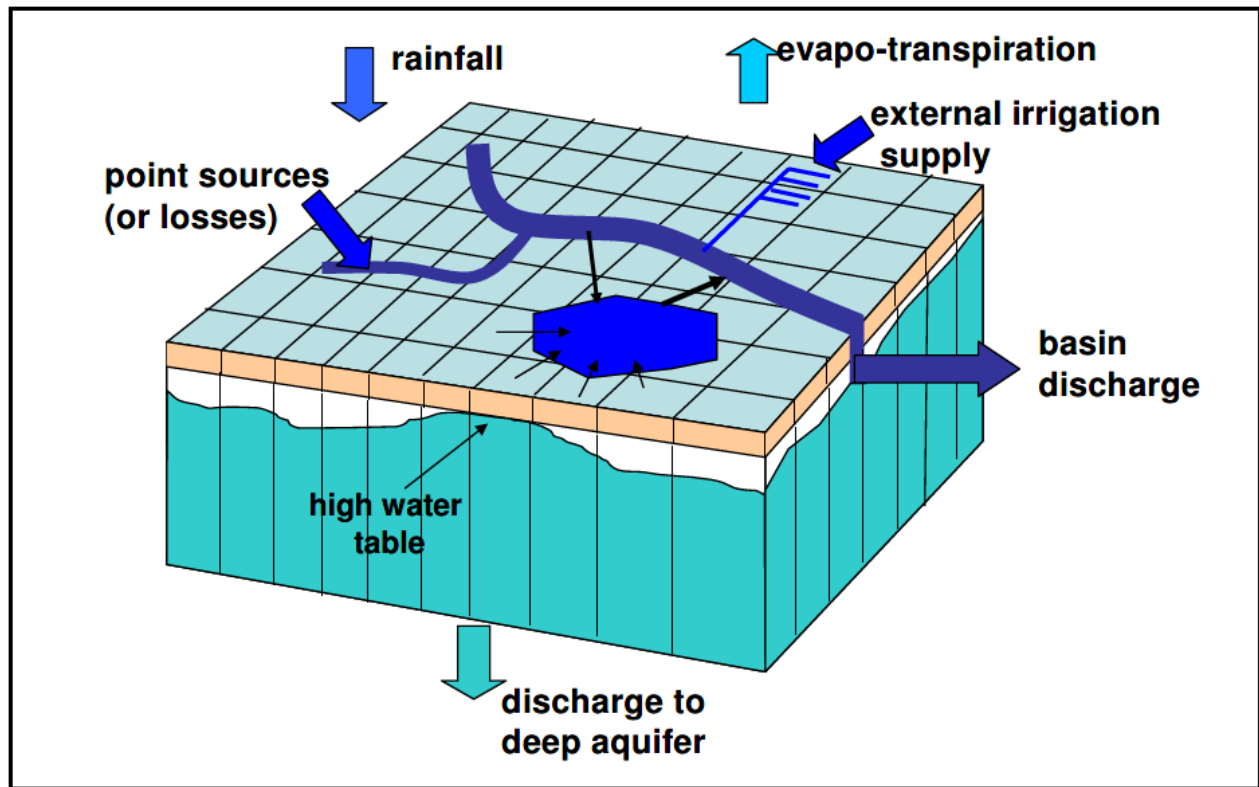


Figure 4. WaSh model system and elements (URS, 2008a)

A functional schematic of the WaSh components and how they interact is shown in **Figure 5**. This figure also serves as a summary-level block diagram of the WaSh model computer program (coded in Fortran). The computations are divided into four groups: (1) hydrology calculations, (2) cell discharge routing, (3) component interactions, and (4) individual component dynamics.

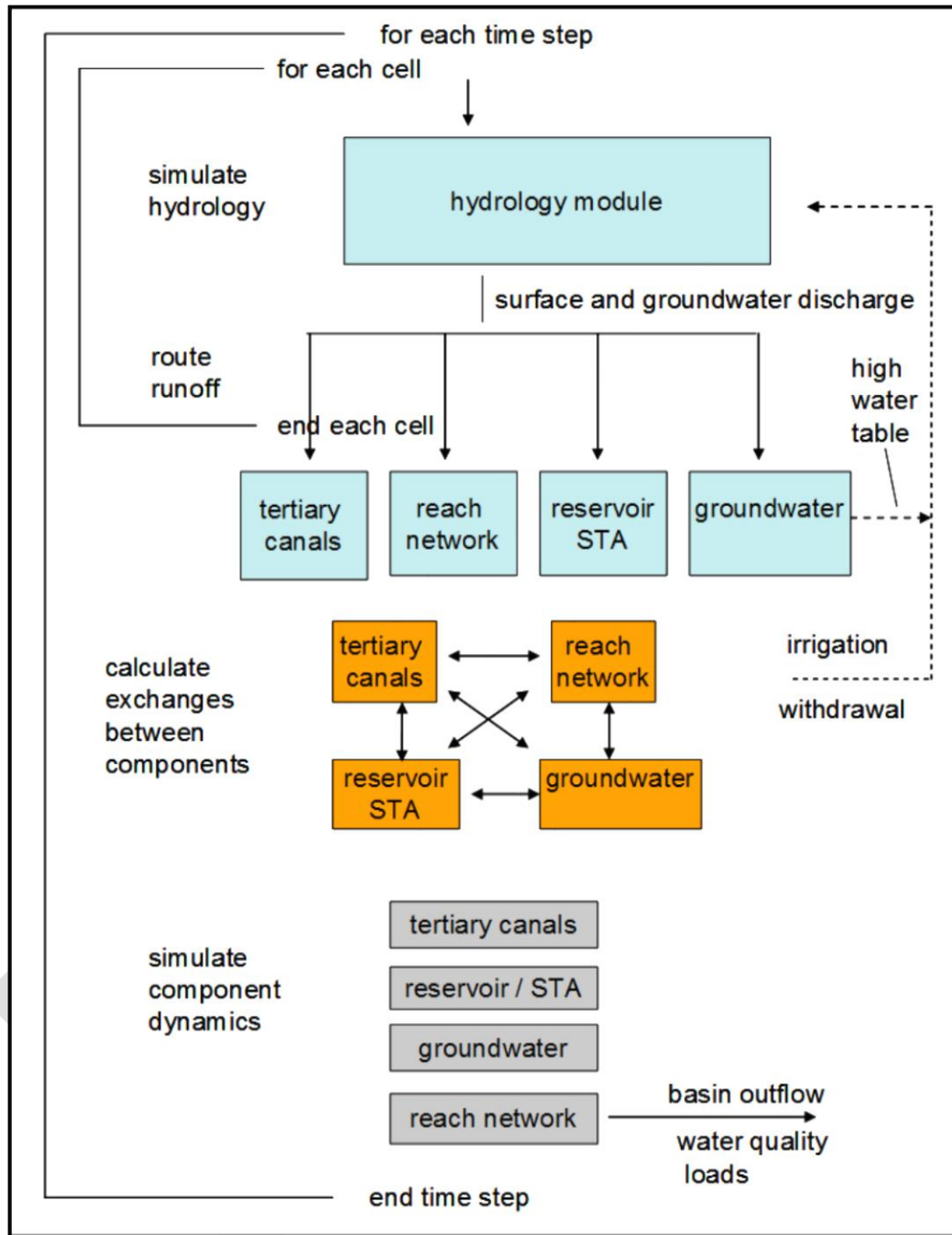


Figure 5. Flow chart for the WaSh model (URS, 2008a)

The water quality component of WaSh supports two options: (1) basic water quality and (2) advanced water quality. The basic water quality option consists of the production and transport of five constituents: total suspended solids (TSS), particulate nitrogen and phosphorus (PN and PP), and soluble nitrogen and phosphorus (SN and SP). Production is modeled using event mean concentrations (EMCs). Transport through canals and reaches, and in reservoirs is modeled using

conservation of mass and either first-order decay or settling. When settling is included, the transport model also includes a streambed simulation.

The advanced water quality option consists of simulating the production, transport, and instream processes for DO, carbonaceous biochemical oxygen demand, ammonia, nitrate, organic nitrogen, organic phosphorus and soluble phosphorus. The EMC approach is used for all constituents except for DO. Transport is modeled using conservation of mass, including settling; and instream processes are modeled using nonlinear kinetic routines adopted from the Water Quality Analysis Simulation Program (WASP) model (Ambrose et al., 1988). In this water quality modeling effort, the advanced water quality option is used.

An ArcGIS graphical user interface (GUI) has been developed to facilitate model configuration, including key watershed management strategies in South Florida such as the implementation of best management practices (BMPs), land use changes, and the operation of reservoirs or STAs.

The theory and data requirements for hydrological simulation with the WaSh model, including water quantity and water quality, are described in URS (2008a). URS (2008b) is the model user's manual providing a detailed reference for each function and feature of the WaSh model along with URS, Inc. (2008c), which contains a tutorial that demonstrates various aspects of the WaSh model application. Model components of WaSh in detail are described in URS (2008b).

4. Data Description for Current Model Development

The WaSh model is a physically based model and has a relatively high data requirement. Data required for model development include model input (driving force), data for model calibration and verification, and boundary condition data. They are described in detail below.

4.1 Rainfall

Two rainfall datasets were used in WaSh model, Next Generation Radar (NexRad) and GRIDIO rainfall data. NexRad 15-min rainfall from 1996 to 2016 with resolution of 1.24 by 1.24 miles was downloaded from the SFWMD's hydrometeorological environmental database, DBHYDRO (<https://www.sfwmd.gov/science-data/dbhydro>). GRIDIO rainfall data are binary rainfall data (daily) with a resolution of 2 by 2 miles originally generated for the South Florida Water Management Model (SFWMM) using measured data at ground surface rainfall gauge stations with the Thiessen Polygon method (SFWMD, 2012). Daily rainfall data from 1914 through 2014 are obtained from binary GRIDIO data for WaSh model development use. **Figure 6** shows the NexRad and GRIDIO grids overlaid on the SLREW. NexRad and GRIDIO rainfall are assigned to each grid cell through the ArcGIS WaSh Model GUI tool. Prior to January 1, 2000, GRIDIO rainfall data were used and NexRad data were used after January 1, 2000.

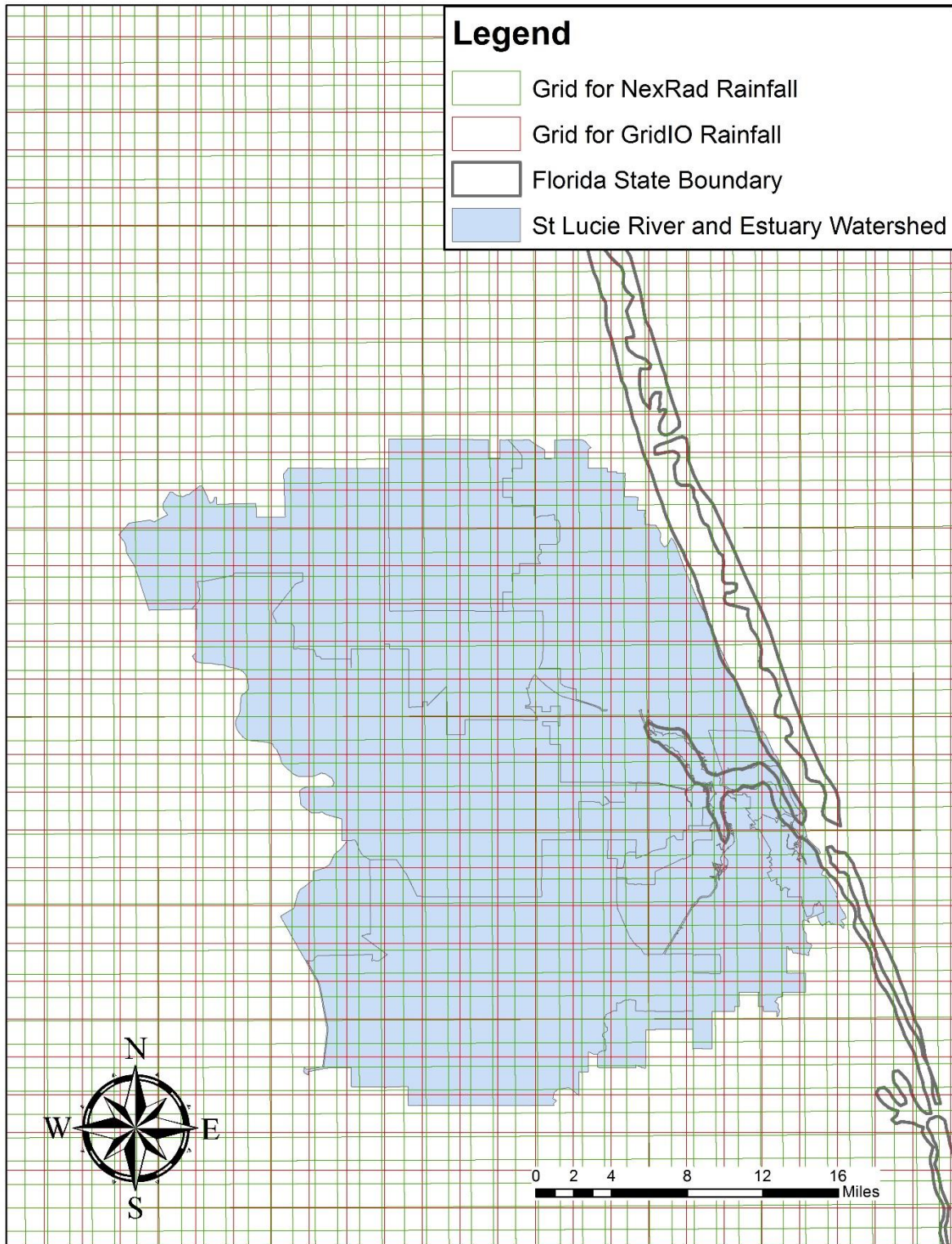


Figure 6. NEXRAD rainfall grid (2 km by 2 km) and GRIDIO rainfall grid (2 mile by 2 mile) overlaid on the SLREW

Figure 7 shows a comparison of NexRad and GRIDIO rainfall for 1999 for the entire SLREW. Generally, the difference is small; however, NexRad rainfall has better spatially variability.

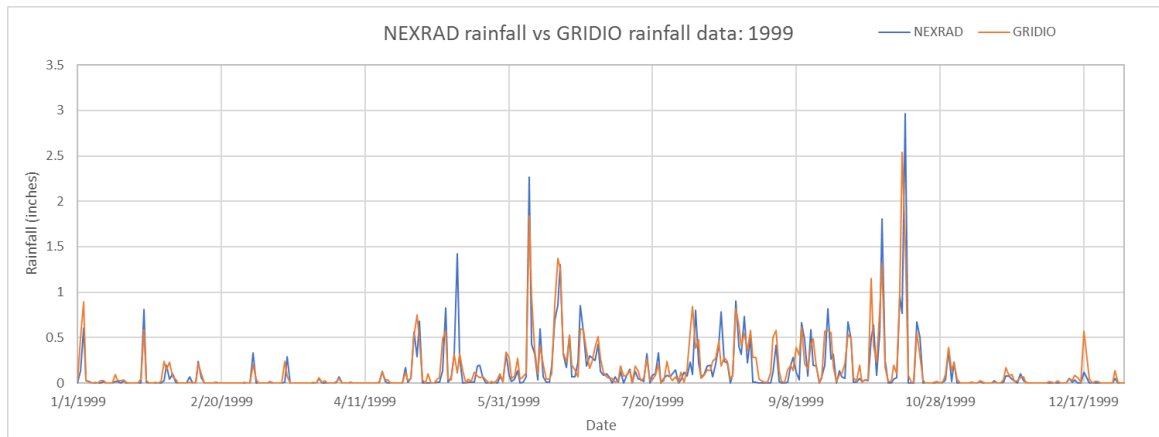


Figure 7. NexRad and GRIDIO rainfall time series (1999) comparison

4.2 Evapotranspiration

The WaSh model uses potential evapotranspiration (PET) to estimate water loss to the atmosphere. The PET data measured at Savannas Preserve Weather Station (SVWX) were downloaded from DBHYDRO for this study. Missing data were filled in with data measured at STA 1 West (STA1W) station. **Figure 8** shows the locations of SVWX and STA1W.

4.3 Solar Radiation

Solar radiation promotes algae growth through photosynthesis and by increasing water temperature. It also can affect evapotranspiration by decreasing the amount of water in the drainage system of the watershed and increasing water temperature. Daily average radiation (Langley's per day) is used in the computation of instantaneous depth-averaged light factor in the model (Ambrose et al., 1988; URS, 2008d). Due to the limited availability of monitoring stations in the watershed, one station was used to provide the input for the entire SLREW. Weather monitoring station SVWX provides the solar radiation data for the entire model calibration and verification period. Missing data were filled in with data from the Clewiston Field Station Weather Station (CFWS) (**Figure 8**), which is located outside the watershed but is likely to have similar solar radiation.

4.4 Water Temperature

Daily water temperature data collected at the HR1, Roosevelt Bridge, and A1A Bridge monitoring stations (**Figure 8**) were downloaded from DBHYDRO to input to the model. Water temperature is used in the model to adjust the value of temperature-related model parameters. For missing data from 1994 to 1997 at HR1, water temperature data measured at Roosevelt Bridge and A1A Bridge were used.

4.5 Land Use

Evapotranspiration and the hydrological cycle are highly linked to the distribution of vegetation in the watershed, which is largely correlated with land use. The SFWMD developed land use and land cover data through photointerpreting aerial photography and digital orthophotographic quarter quadrangles approximately every 4 to 5 years. These land use GIS data are available in the SFWMD GIS Data Catalog. In support of the BMAP, land use data for 2004, 2008, and 2012 were downloaded and processed to derive the percentage of major land use types for SLREW and to simulate the periods from 1995 through 2006, 2007 through 2011, and 2012 through 2016, respectively. **Table 2** lists the acreage of land use types in each sub-basin in the watershed, and **Table 3** summarizes the area and percentage of land use type at the basin level – the three major canal basins and the tidal basin which consists of the rest of the sub-basins grouped together. **Figures 9a, 9b, and 9c** are the 2004, 2008, and 2012 land use maps, respectively. The biggest change in land use is that, from 2004 to 2008, urban area increased ~2.6% while agriculture area decreased by ~2.3%. For the 2012 land use dataset, agricultural land use is the dominant land cover in the C-23, C-24, and C-44/S-153 basins, with citrus groves and improved and unimproved pastures being the most extensive. In the tidal basin, urban is the dominant land use, followed by agriculture mainly in the Ten Mile Creek basin. Overall, for the entire watershed in 2012, 52% is agriculture, 19% urban, 11% wetland, 7% upland forest, 5% water, 4% rangeland, and the remainder are transportation, communication, and utilities (2%), and barren land (1%). Based on land use data of 2004, 2008, and 2012, significant changes also occurred within agriculture land use type (sub-category of agriculture). In C-23 Basin, land use for citrus decreased by 5521 ac from 2004 to 2008, 11884 ac from 2008 to 2012. Abandoned groves and fallow crop land increased by 5748 ac from 2004 to 2008, 10185 ac from 2008 to 2012. Unimproved pasture increased by 1598 ac from 2004 to 2008 while improved pasture increased by 1372 ac from 2008 to 2012.

In C-24 Basin, land use for citrus decreased by 3356 ac from 2004 to 2008, 6688 ac from 2008 to 2012. Abandoned groves and fallow crop land increased by 6493 ac from 2008 to 2012. Unimproved pasture increased by 1499 from 2008 to 2012 and row crops decreased by 1136 ac.

In C-44 Basin, land use for citrus decreased by 18484 ac from 2004 to 2008, 16921 ac from 2008 to 2012. Abandoned groves and fallow crop land increased by 18923 ac from 2004 to 2008, 5548 ac from 2008 to 2012.

Additionally, a large section in the southwest portion of **Figure 9a** is indicated as transportation and the same area is designated as open water in **Figures 9b and 9c**. This is due to the FPL reservoir, which the model considers as water for the entire length of the model period.

These acreage changes in land use type were incorporated into model.

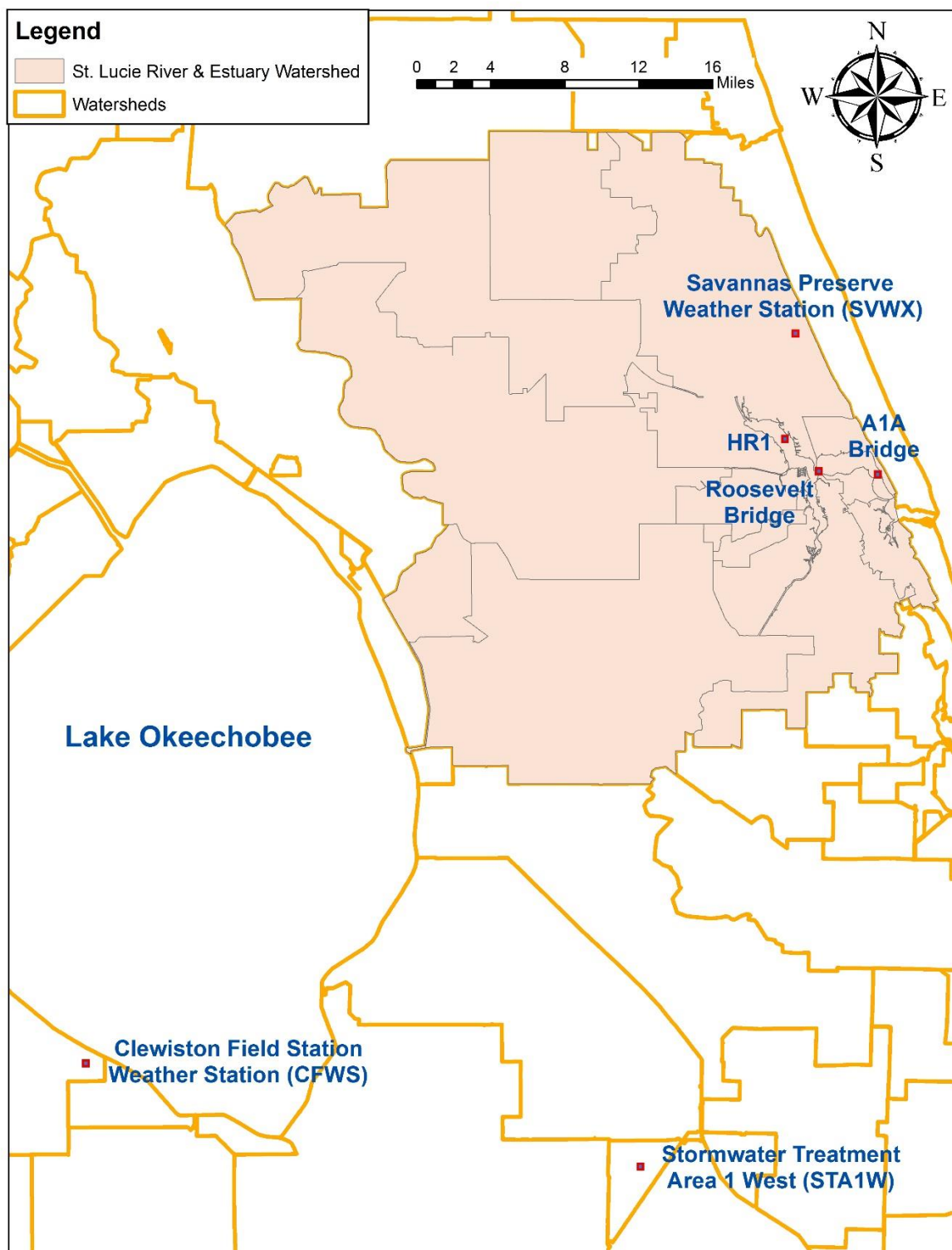


Figure 8. Map for location of Savannas Preserve Weather Station (SVWX), STA 1 West (STA1W), Clewiston Field Station Weather Station (CFWS), HR1, Roosevelt Bridge Station, and A1A Bridge Station

Table 2. Land use data for 2004, 2008, and 2012 for basins in the SLREW

Sub-basin	Year of Land Use Data	Land Use Acres							
		Urban	Agriculture	Rangeland	Upland Forest	Water	Wetland	Barren Land	Transportation, Communication, and Utilities
BASIN 4	2004	4606.9	2448.8	397.0	1634.5	323.5	1043.2	17.4	577.8
	2008	5233.9	2128.6	107.2	1727.5	424.9	915.9	58.9	452.3
	2012	5276.3	1972.6	356.3	1598.3	388.4	964.8	47.3	445.1
BASIN 5	2004	550.2	91.3		183.0	5.3	129.3		
	2008	559.1	85.5	7.7	200.3	5.3	101.2		
	2012	557.8	85.5	14.0	195.3	5.3	101.2		
BASIN 6	2004	2546.2	447.4	47.2	524.5	36.6	182.3		142.1
	2008	2557.9	455.2	47.2	498.8	40.4	185.1		141.8
	2012	2539.7	455.6	47.2	512.2	34.0	184.2	11.6	141.8
C-23	2004	3145.3	83288.5	1527.0	2690.3	1736.1	16019.0	1072.8	1325.5
	2008	2992.2	83223.9	1569.3	2615.2	1396.8	16119.2	1093.7	1794.3
	2012	3236.9	82079.0	2359.6	2709.5	1507.3	15951.4	1177.4	1783.7
C-23 CONVEYANCE CANAL	2004					46.2	0.1	23.3	0.5
	2008					46.2	0.1	23.3	0.5
	2012					46.2	0.1	23.3	0.5
C-24	2004	4364.4	63233.1	220.1	1264.5	1235.7	12155.1	296.3	603.2
	2008	6054.9	60992.2	1809.9	928.0	1352.6	11062.3	289.3	883.3
	2012	6252.2	60659.0	1944.5	935.9	1339.1	11057.3	363.2	821.4
C-44	2004	2405.3	75077.7	4833.4	9476.7	1818.6	13259.3	803.1	8258.8
	2008	2501.2	75604.1	6104.6	8668.2	8005.3	12384.4	830.9	1834.3
	2012	3298.9	73348.6	6809.6	9127.6	7974.8	12352.0	857.7	2163.9
LOWER ST. LUCIE ESTUARY	2004	14.9				543.9	0.7		0.0
	2008	14.9				529.2	15.3		0.0
	2012	14.9				529.2	15.3		0.0
MIDDLE ST. LUCIE ESTUARY	2004	3.6				2751.0	0.0		0.0
	2008	3.6				2751.0	0.0		0.0
	2012	3.6				2751.0	0.0		0.0
NORTH MID-ESTUARY	2004	2995.2		234.8	534.4	116.8	244.8		69.9
	2008	3075.3		172.9	507.6	112.7	251.9	5.7	69.9
	2012	3090.0		197.9	478.1	111.0	249.1		69.9
S-153	2004	652.8	7308.6	1550.1	2003.0	114.9	1330.2	244.8	166.5
	2008	652.3	7830.5	1142.4	2114.2	116.6	1171.5	177.1	166.5
	2012	701.6	7673.1	1181.8	2173.0	112.9	1185.1	177.1	166.5
SOUTH COASTAL	2004	5839.2	26.9	124.1	1026.8	227.7	286.7	17.6	441.8
	2008	6038.3	29.0	136.3	817.1	241.8	269.5	11.2	447.8
	2012	6052.9	10.8	160.7	803.6	231.5	273.0	8.5	453.1
SOUTH FORK	2004	10739.5	19043.2	1755.8	7436.3	1505.7	6608.6	31.0	1035.5
	2008	12898.8	17246.9	1824.6	6935.8	1365.6	6568.2	242.3	1073.4
	2012	12857.5	16256.0	2573.1	7549.6	1332.5	6360.3	153.3	1073.4
SOUTH MID-ESTUARY	2004	1410.7		5.6	220.9	33.4			408.4
	2008	1414.9		7.3	212.9	33.4			410.6
	2012	1416.8		7.3	211.6	32.9			410.6
TEN MILE CREEK	2004	3706.8	34946.8	571.3	490.1	391.2	738.5	65.3	119.3
	2008	4370.8	33242.7	1172.5	398.2	523.5	706.8	185.6	429.3
	2012	4031.2	32793.9	1703.0	528.0	525.4	710.2	209.6	528.2
TIDAL ST. LUCIE NORTH FORK	2004	52287.2	8158.5	2739.6	11214.5	3921.7	8419.0	222.5	3872.4
	2008	54286.2	6952.6	2666.3	10408.6	4176.3	7964.2	291.1	4090.0
	2012	53723.0	5940.8	4052.6	10803.8	4163.7	7920.6	257.3	3970.5
UPPER ST. LUCIE ESTUARY	2004	27.1	0.1		6.2	3612.5	152.9	0.1	0.3
	2008	27.5	0.1	0.0	6.0	3612.3	152.9	0.1	0.3
	2012	20.5	0.1	7.0	5.8	3612.4	152.9	0.1	0.3

Table 3. Summary of SLREW land use data for 2004, 2008, and 2012

		Land use Category							
Year	Sub-Basin	Urban	Agriculture	Rangeland	Upland Forest	Water	Wetland	Barren Land	Transportation, Communication, and Utilities
2004									
acres	Tidal Basin	84727.5	65163.0	5875.4	23271.3	13469.4	17806.2	353.9	6667.5
	C23	3145.3	83288.5	1527.0	2690.3	1782.3	16019.1	1096.2	1326.1
	C24	4364.4	63233.1	220.1	1264.5	1235.7	12155.1	296.3	603.2
	C44/S153	3058.1	82386.3	6383.6	11479.7	1933.5	14589.6	1048.0	8425.3
	Total	95295.3	294070.9	14006.1	38705.9	18420.9	60569.9	2794.4	17022.1
%	Tidal Basin	39.0%	30.0%	2.7%	10.7%	6.2%	8.2%	0.2%	3.1%
	C23	2.8%	75.1%	1.4%	2.4%	1.6%	14.4%	1.0%	1.2%
	C24	5.2%	75.8%	0.3%	1.5%	1.5%	14.6%	0.4%	0.7%
	C44/S153	2.4%	63.7%	4.9%	8.9%	1.5%	11.3%	0.8%	6.5%
	Total	19.0%	53.2%	3.1%	6.7%	4.6%	10.7%	0.6%	2.2%
2008									
acres	Tidal Basin	90481.2	60140.5	6141.8	21712.8	13816.5	17131.0	795.0	7115.4
	C23	2992.2	83223.9	1569.3	2615.2	1443.0	16119.3	1117.1	1794.8
	C24	6054.9	60992.2	1809.9	928.0	1352.6	11062.3	289.3	883.3
	C44/S153	3153.4	83434.7	7246.9	10782.4	8121.9	13555.9	1008.0	2000.8
	Total	102681.8	287791.2	16768.0	36038.4	24734.1	57868.5	3209.5	11794.3
%	Tidal Basin	41.6%	27.7%	2.8%	10.0%	6.4%	7.9%	0.4%	3.3%
	C23	2.7%	75.1%	1.4%	2.4%	1.3%	14.5%	1.0%	1.6%
	C24	7.3%	73.2%	2.2%	1.1%	1.6%	13.3%	0.3%	1.1%
	C44/S153	2.4%	64.5%	5.6%	8.3%	6.3%	10.5%	0.8%	1.5%
	Total	19.0%	53.2%	3.1%	6.7%	4.6%	10.7%	0.6%	2.2%
2012									
acres	Tidal Basin	89584.2	57515.3	9118.9	22686.2	13717.4	16931.5	687.7	7092.9
	C23	3236.9	82079.0	2359.6	2709.5	1553.5	15951.5	1200.7	1784.2
	C24	6252.2	60659.0	1944.5	935.9	1339.1	11057.3	363.2	821.4
	C44/S153	4000.5	81021.7	7991.3	11300.5	8087.7	13537.1	1034.8	2330.4
	Total	103073.8	281275.0	21414.3	37632.1	24697.7	57477.3	3286.4	12029.0
%	Tidal Basin	41.2%	26.5%	4.2%	10.4%	6.3%	7.8%	0.3%	3.3%
	C23	2.9%	74.0%	2.1%	2.4%	1.4%	14.4%	1.1%	1.6%
	C24	7.5%	72.8%	2.3%	1.1%	1.6%	13.3%	0.4%	1.0%
	C44/S153	3.1%	62.7%	6.2%	8.7%	6.3%	10.5%	0.8%	1.8%
	Total	19.1%	52.0%	4.0%	7.0%	4.6%	10.6%	0.6%	2.2%

St. Lucie River and Estuary Watershed 2004 Land Use Map

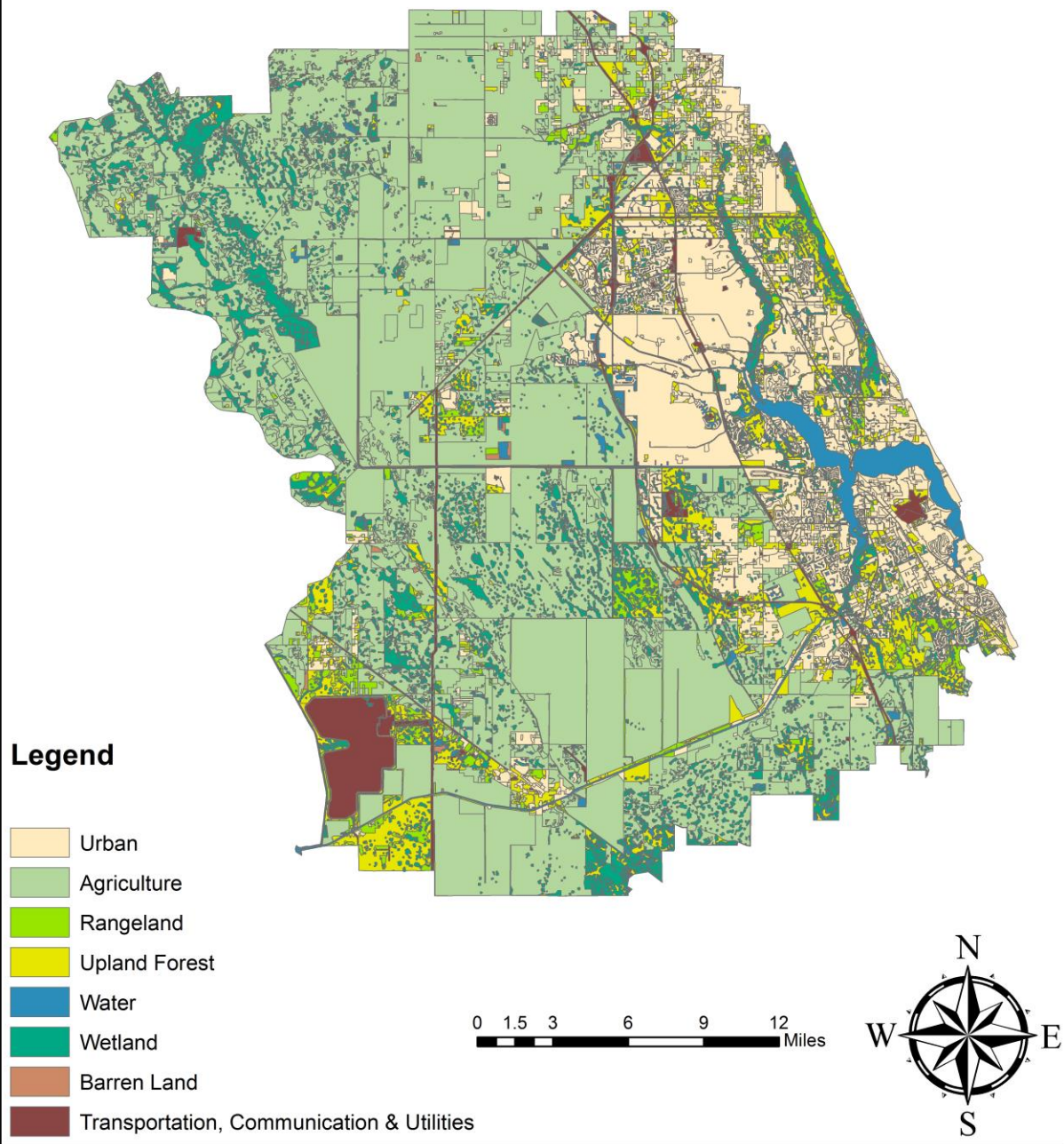


Figure 9a. 2004 land use in the SLREW

St. Lucie River and Estuary Watershed 2008 Land Use Map

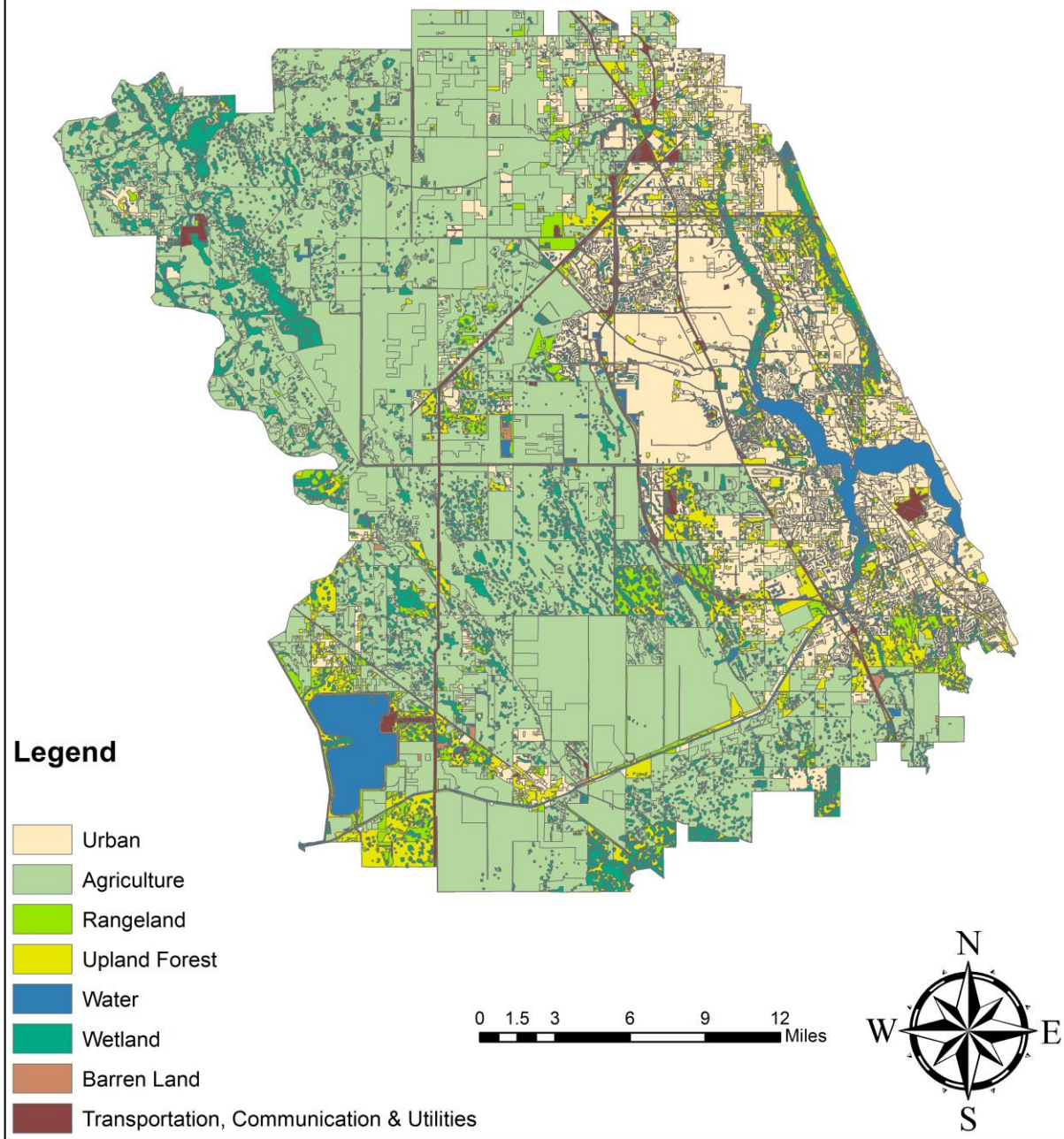


Figure 9b. 2008 land use in the SLREW

St. Lucie River and Estuary Watershed 2012 Land Use Map

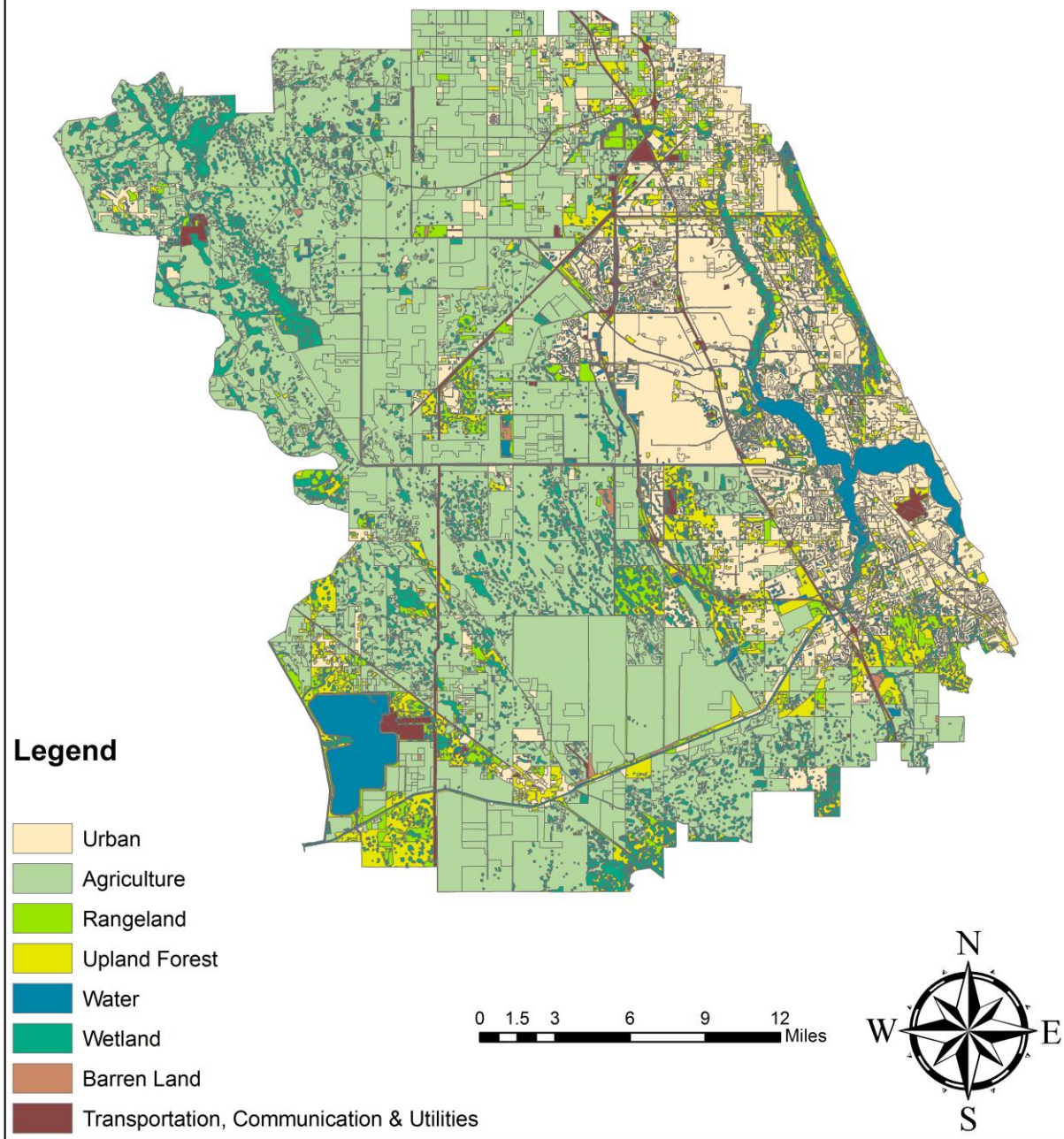


Figure 9c. 2012 land use in the SLREW

4.6 Hydrography

The primary canal and river used in the model are from the SFWMD GIS data catalog database (**Figure 2**) and were used to develop the reach network during model development. Generally, blueprints were used to calculate the dimensions for the model; if unavailable, then aerial photos and structure depth data were used. Each primary canal and river segment was then assigned a width and depth appropriate for that respective segment. The width and depth were initially taken from the models developed in 2008 (URS, 2008a). Channel hydraulic routing is implemented in this reach network.

A vast number of secondary and tertiary canals have been developed in the SLREW over the past decades, and their GIS shapefiles were also taken from the SFWMD AHED GIS database (**Figure 10**). The secondary and tertiary canal coverage total length was mapped as an attribute for each model grid cell. The secondary and tertiary canal width and bottom elevations were obtained from previously developed model by URS (2003 and 2008d) as the canal properties.

The WaSh model has the option to simulate the reach segments as a single layer or as two layers in the water quality simulation module. The two-layer option allows for better representation of deeper channels or stratified systems in which vertical mixing is inhibited and distinct upper and lower layers develop. The two-layer option is implemented for the entire reach network in this study. For the two-layer option, the water column is evenly divided into upper and lower layers. The average concentrations of the top and bottom layer were used for model calibration and validation. A vertical diffusion coefficient is used to quantify mass exchange between layers. Sediment oxygen demand only exists in the lower layer, and reaeration rate only occurs in the upper layer. This is only applied to primary canal and river system. Water from tertiary and secondary canals in a grid cell is conceptualized as ponds, and water is sent to the primary canal/river located in the most adjacent cell through a conceptualized pump or weir in the model (URS, 2008a).

4.7 Soil

Soils in the watershed range from low to high runoff potential. The dominant types are flatwood soils and soils of sloughs and freshwater marshes, both of which are poorly drained and generally level (Aqua Terra Consultants and Linsley, Kraeger Associates, 1997). Soil type determines the unsaturated zone hydrology, such as infiltration rate, interflow generation, and field capacity. In the WaSh model, hydrologic soil groups (A, B, C, and D) classified by the Soil Conservation Service (SCS) are used in determining infiltration ability. Digital soil type GIS data were obtained through the SFWMD GIS data catalog.

A detailed description of hydrologic soil group is given in Maidment (1993). **Figure 11** shows soil type classification into hydrologic soil groups based on the GIS data. Group C/D (77%) is dominant over the entire watershed, followed by Groups A/D (15%), B/D (5%), and D (3%), respectively. The area covered by water does not show soil type. This area is assumed to link directly to groundwater, and no unsaturated zone exists. Thus, no hydrologic soil group was assigned to this area.

4.8 Topography

Figure 12 shows the digital topographic elevation for the SLREW, with resolution of 100 ft by 100 ft. The western portion has a higher elevation (maximum elevation is ~ 65 ft, North American Vertical Datum of 1988 [NAVD88]), while the eastern portion has lower elevations (minimum elevation is ~ -26 ft, NAVD88). The lower elevation is the river bottom elevation near the A1A Bridge measured from digital elevation model (DEM) data. Over the entire watershed, the average slope is less than 0.0005 ft/ft. The C-24 Basin has the greatest slope, while the Tidal Basin has the smallest slope. Digital topographic elevation data were obtained from the SFWMD GIS data catalog.

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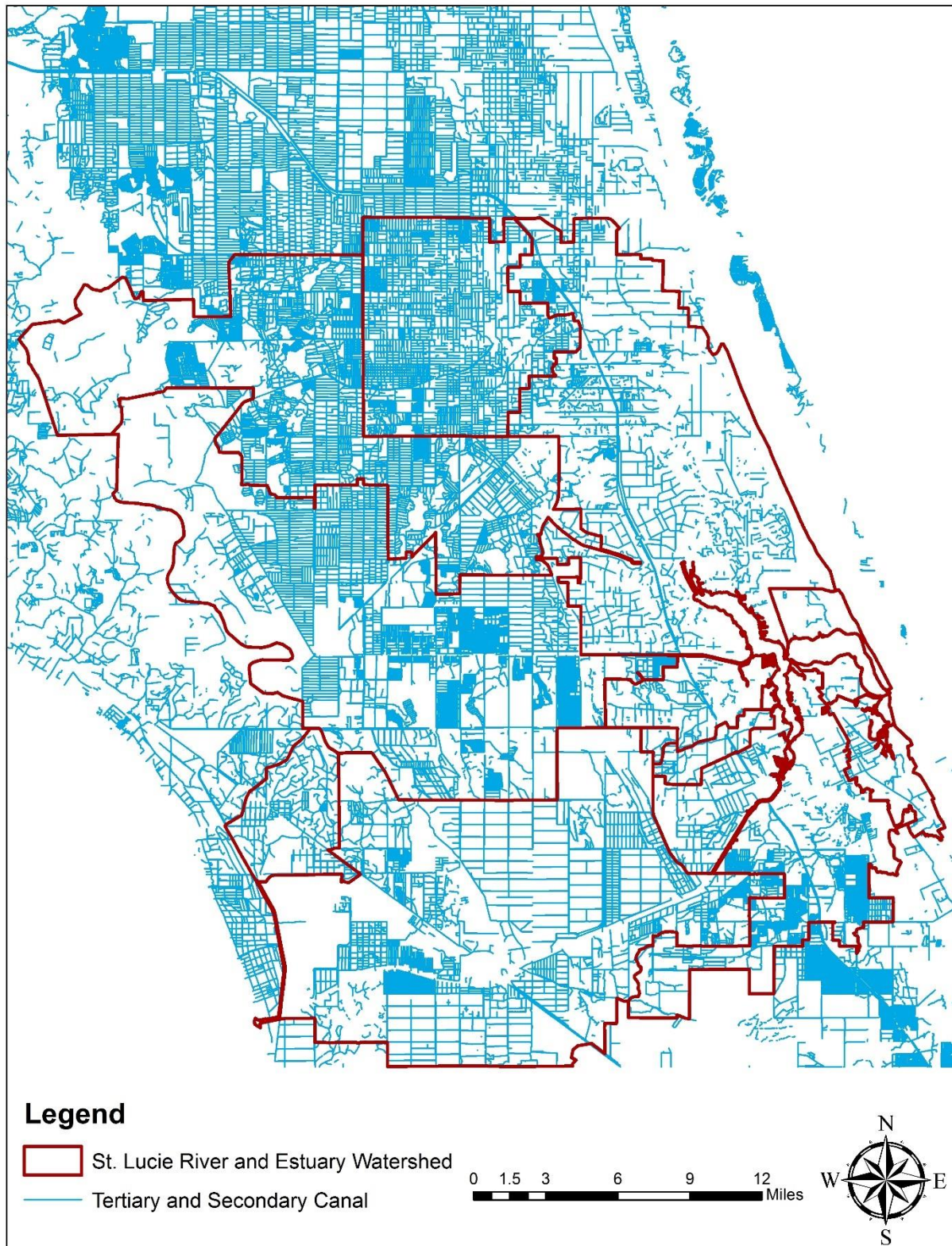


Figure 10. Tertiary and secondary canals in the SLREW

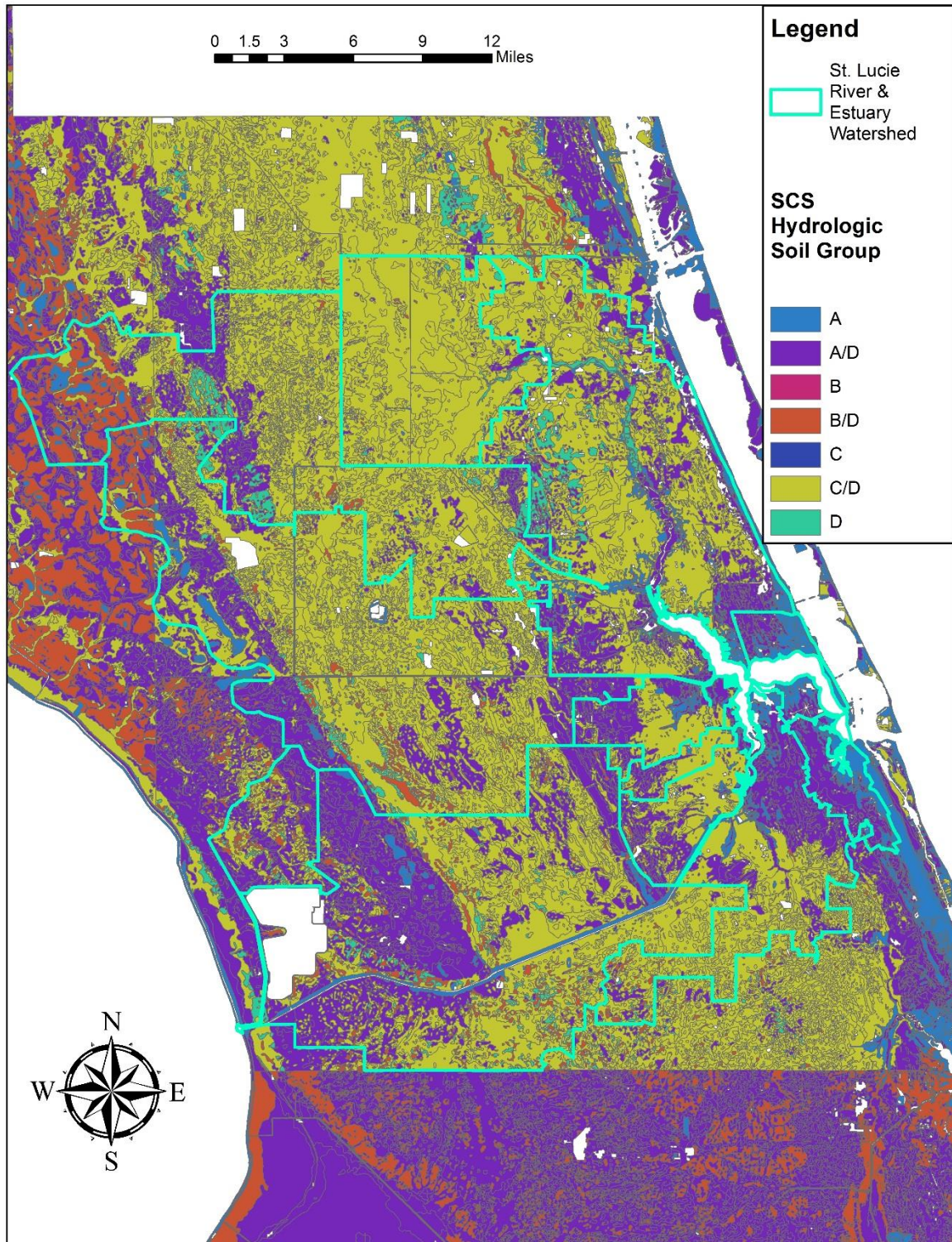


Figure 11. SCS hydrologic groups in the SLREW

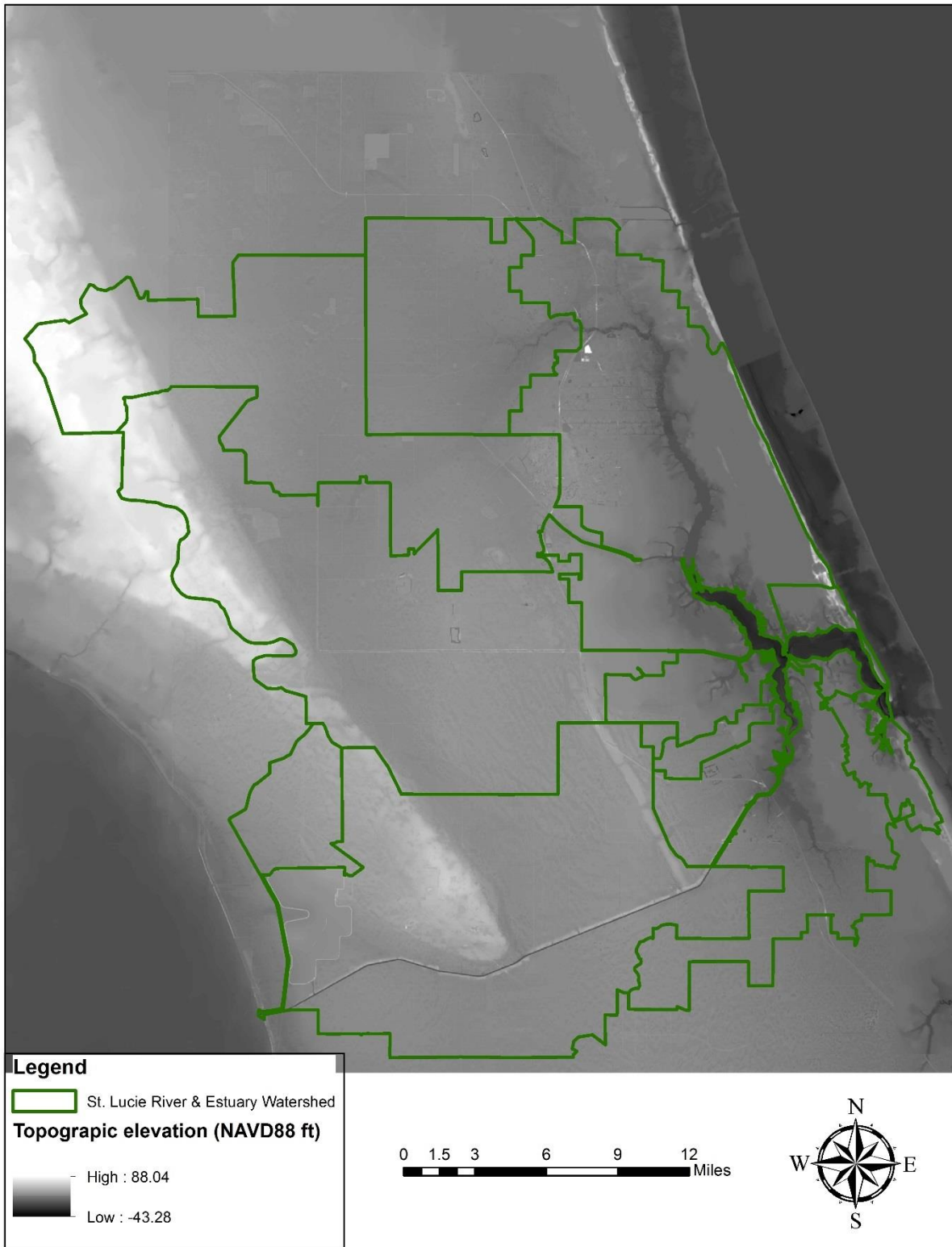


Figure 12. Topographic elevation (Unit: ft - NAVD88; Resolution: 100 ft by 100 ft).

4.9 Estuary Bathymetry

Channel depths of the estuary range up to 17.7 ft, but the average depth of the main channel is approximately 9.8 ft. **Figure 13** shows SLE bathymetry processed from raster data. The bathymetric sounding data in the Indian River Lagoon – St. Lucie Estuary Bathymetry shapefile was obtained from the SFWMD GIS catalog and converted to a raster grid with cells of 1,000 ft. The bathymetric raster data were used to calculate the bottom elevation of reach segments at the estuarine portion.

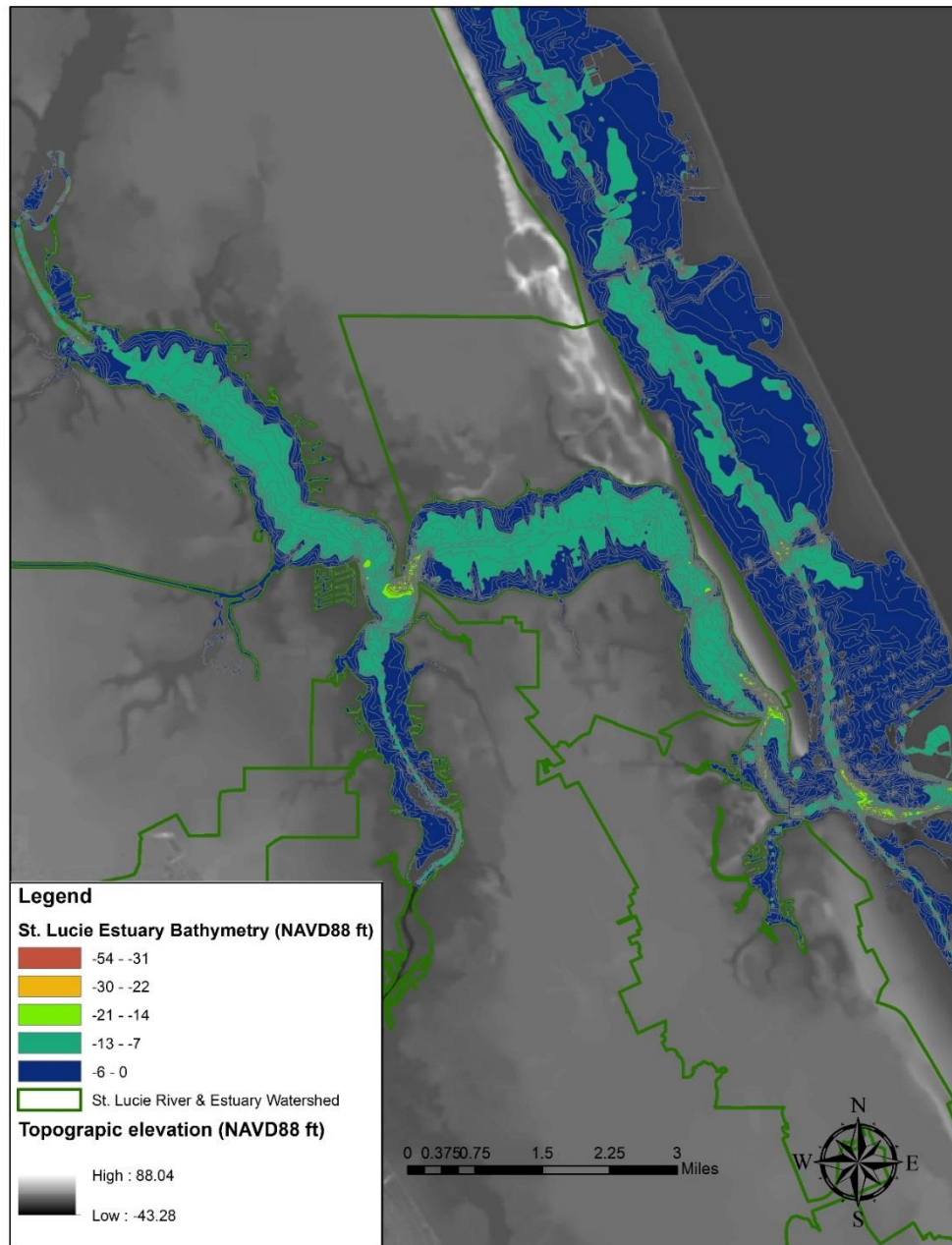


Figure 13. Bathymetry contours and topographic elevations (ft - NAVD88)

4.10 Flow

Measured daily flow data are available at S-80 (C-44/S-153 Basin outlet), S-97 (C-23 Basin outlet), S-49 (C-24 Basin outlet), Gordy Road Structure (Ten Mile Creek Basin outlet), and S308 (Lake Okeechobee outflow to C-44 Canal) and were downloaded from the SFWMD DBHYDRO database. All these measured flows were used for hydrologic module calibration and verification, except Gordy Road Structure, which was identified as a less reliable dataset.

4.11 Event Mean Concentrations

The WaSh model requires input representing runoff concentrations for nutrients (ammonia, nitrate, organic nitrogen, phosphate, and organic phosphorus), carbonaceous biochemical oxygen demand (CBOD), phytoplankton mass, and DO for water quality simulations. These data are needed to characterize the spatial distribution of runoff loadings in the watershed. Ideally, sufficient EMC data would be available to determine the spatial distribution of the loadings, as well as seasonal or higher frequency temporal variations. Few true EMC data are available for the area, and available data are not representative of all areas. EMC data are a flow-weighted-average concentration for an individual runoff event, not a true concentration. Many data sources have been identified for use in developing approximations to the EMC values needed for the WaSh model input.

The following five sources of data were found useful for the development of the land use and soil type dependent EMC values:

1. IFAS ISCO Data

The Institute for Food and Agricultural Sciences (IFAS) ISCO dataset (TN and TP concentrations using ISCO sampler) was collected from five sites through an EMC study conducted by the University of Florida periodically from 2001 to 2004. Each station was separated and analyzed based on one of two land uses: urban (residential or recreational) or agricultural.

2. DEP ISCO Data

Seven sample locations were established by DEP, and TN and TP concentration data were collected during rainfall events over three months in fall 2005. Sample locations are representative of four different land use designations: golf course, residential, agriculture-citrus, and agriculture-pastures.

3. Urban Runoff Study (SLT Station) Data

A comprehensive stormwater water quality monitoring program was conducted by the SFWMD from fall 2001 through the end of 2005. Grab sample data, including TN and TP concentrations, were collected approximately every 2 weeks from 45 stations located at St. Lucie tributaries (SLT) across the North Fork and South Fork tidal basin. The SLT stations were not originally associated with a specific land use and, therefore, the associations were established by positioning the station on the land use map. If the station appeared to be affected by multiple land uses, then it was discarded. Only the data from stations affected by one major land use type were included. These omissions are not anticipated to have an impact on the overall model results.

4. DEP BMP Study Data

DEP collected event data (TN and TP concentrations) at stations distributed throughout the SLREW from 1998 through 2000. A total of 63 sampling sites were identified, representing the major land use types in the watershed, including citrus, pasture, urban-general, urban-golf course, wetland, row crops, dairy, and residual (sludge disposal/application sites) (Graves et al., 2004). Data were collected immediately after (or during) a rainfall event when flow was occurring at the respective monitoring stations.

5. Grassy Waters Preserve Sampling Project Data

The Grassy Waters Preserve consists of nearly 13,000 acres of wetlands located in Northern Palm Beach County. In January 2004, DEP initiated the first water quality monitoring program in the Grassy Waters Preserve. Samples were collected roughly every 4 to 6 weeks and analyzed for physical parameters, DO, and nutrients. In the absence of adequate water quality data in the SLT dataset for the establishment of EMCs for wetlands, the Grassy Waters dataset was a good reference for model use.

In addition to data from these sources, data from Harper (1994; 1999), Li et al. (2016 and 2017), and DEP (2008), document EMC values in various geographic/environmental regions across the watershed and the state and were used to supplement the site-specific datasets. All these data show strong seasonality, with TN and TP concentrations typically higher during the wet season than during the dry season. Generally, approximate EMC values for the WaSh model were developed from the site-specific data, and then the regional or literature values were used to fill in missing data or replace values from the site-specific data that were suspect, either because of outliers or an insufficient number of samples. EMC development is described in detail in Sections 2.2.4 and 3.9.1 of URS (2008d).

4.12 Water Quality

Monthly or biweekly concentrations of ammonia, nitrite, nitrate, chlorophyll *a*, orthophosphate, total Kjeldahl nitrogen (TKN), total nitrogen (TN), total phosphorus (TP), and DO were downloaded from the SFWMD DBHYDRO database for the estuary stations (HR1, SE01, SE02, SE03, SE08, and SE11) and structures (S-308, S-80, S-48, S-49). These data were used for water quality module calibration and verification. **Figure 14** shows the location of all of stations except S-308, which is the outlet of Lake Okeechobee to the C-44 Canal. Flow and nutrients measured at S-308 are considered a point source input to the segment of the C-44 Canal immediately downstream of S-308. Chlorophyll *a* was measured at S-308 after 2006. Prior to 2006, chlorophyll *a* was measured at Station CLV10A, located approximately 2,500 feet south of S-308 inside Lake Okeechobee.

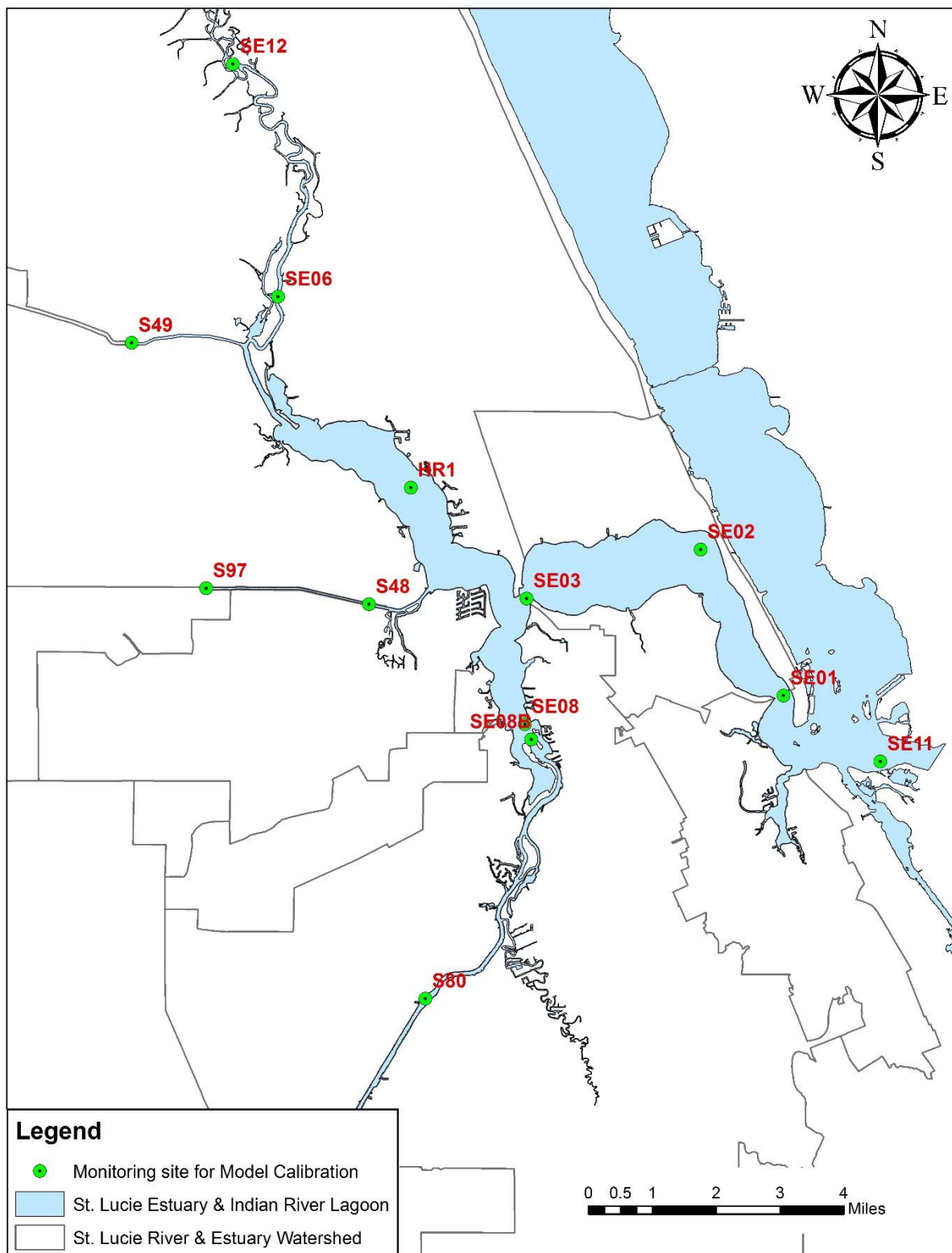


Figure 14. Location of sites used for model calibration and verification

4.13 Septic Tanks

More than 50,000 known septic tanks identified by the Florida Department of Health and located in SLREW (**Figure 15a**) have been efficiently incorporated into the model. Of these known septic tanks, those within a 328-foot (100-meter) buffer zone of the main reach network were selected and used for tank number estimation. This buffer distance was selected since the amount of load is affected in part by the distance the effluent travels before it reaches the waterbody. More denitrification occurs over longer distances, and studies in south Florida have shown that a majority of the nitrogen reaching waterbodies is when the flow path ranges from 50 meters to 150 meters (Tetra Tech Inc., 2017; Ye and Sun, 2013).

Estimated nitrogen loading values (lbs/yr/tank) were assigned by sub-basin based on previous studies completed in Martin County (Ye and Sun, 2013). An overall load from each sub-basin was then calculated, except for the South Fork sub-basin, which was grouped into four general areas with septic tanks. This led to a total of 14 point sources that were used as model input (**Figure 15b**), keeping the number of point source inputs and ultimately the overall model run time manageable.

Time series of water quality data were created for each of the 14 points. Because some septic-to-sewer conversion projects had been completed around 2012, the time series represents the change in loading after 2013. Total flow per point source input was calculated by multiplying 200 gallons per day per septic tank (from the Ye and Sun, 2013) by the number of tanks aggregated for that point source input. Using these flows and the overall loadings previously calculated, TN concentrations were calculated. The TN concentrations were then divided among the various species of nitrogen based on literature values in Ye and Sun (2013), an unpublished study in Brevard County, and discussions with DEP staff who work regularly on loading from septic systems. The septic tank input time series include flow, TN, ammonia, nitrate, and organic nitrogen. The aggregated septic tank data for 14 points as point source input in the model are shown in **Table 4a** (prior to January 2013) and **Table 4b** (after January 2013).

Table 4a. Aggregated septic tank data as point source input (prior to January 2013)

Name (in Point Shapefile)	TN Loading (lbs/yr) (Buffer = 100m) (Septic Type =Known)	# of Tanks	Flow per tank (cfs)	Total Flow - Basin (cfs)	TN (mg/L)	NH4 (mg/L) [10% of TN]	NOX (mg/L) [85% of TN]	ON (mg/L) [5% of TN]
Basin 4	6,072	552	0.00031	0.1712	18.01	1.80	15.31	0.90
Basin 5	22	2	0.00031	0.0006	18.01	1.80	15.31	0.90
Basin 6	576	64	0.00031	0.0199	14.74	1.47	12.53	0.74
C-24	270	45	0.00031	0.0140	9.83	0.98	8.35	0.49
C-44	102	17	0.00031	0.0053	9.83	0.98	8.35	0.49
North Mid Est	2,826	314	0.00031	0.0974	14.74	1.47	12.53	0.74
S-153	24	4	0.00031	0.0012	9.83	0.98	8.35	0.49
South Fork A	837	93	0.00031	0.0288	14.74	1.47	12.53	0.74
South Fork B	180	20	0.00031	0.0062	14.74	1.47	12.53	0.74
South Fork C	477	53	0.00031	0.0164	14.74	1.47	12.53	0.74
South Fork D	3,969	441	0.00031	0.1368	14.74	1.47	12.53	0.74
South Mid Est	558	62	0.00031	0.0192	14.74	1.47	12.53	0.74
Ten Mile Creek	18	3	0.00031	0.0009	9.83	0.98	8.35	0.49
North Fork	4,038	673	0.00031	0.2088	9.83	0.98	8.35	0.49

Table 4b. Aggregated septic tank data as point source input (after January 2013)

Name (in Point Shapefile)	TN Loading (lbs/yr) (Buffer = 100m) (Septic Type =Known)	# of Tanks	Flow per tank (cfs)	Total Flow - Basin (cfs)	TN (mg/L)	NH4 (mg/L) [10% of TN]	NOX (mg/L) [85% of TN]	ON (mg/L) [5% of TN]
Basin 4	1,221	111	0.00031	0.0344	18.01	1.8	15.31	0.9
Basin 5	22	2	0.00031	0.0006	18.01	1.8	15.31	0.9
Basin 6	576	64	0.00031	0.0199	14.74	1.47	12.53	0.74
C-24	270	45	0.00031	0.014	9.83	0.98	8.35	0.49
C-44	102	17	0.00031	0.0053	9.83	0.98	8.35	0.49
North Mid Est	2,826	314	0.00031	0.0974	14.74	1.47	12.53	0.74
S-153	24	4	0.00031	0.0012	9.83	0.98	8.35	0.49
South Fork A	837	93	0.00031	0.0288	14.74	1.47	12.53	0.74
South Fork B	180	20	0.00031	0.0062	14.74	1.47	12.53	0.74
South Fork C	180	20	0.00031	0.0062	14.74	1.47	12.53	0.74
South Fork D	3,969	441	0.00031	0.1368	14.74	1.47	12.53	0.74
South Mid Est	423	47	0.00031	0.0146	14.74	1.47	12.53	0.74
Ten Mile Creek	18	3	0.00031	0.0009	9.83	0.98	8.35	0.49
North Fork	3,156	526	0.00031	0.1632	9.83	0.98	8.35	0.49

For the purpose of computing total septic tank loading values (under baseline as well as alternate scenarios), the aggregation points tabulated above were assigned to specific model result output locations. **Table 5** shows the aggregation point, corresponding model output location, along with the total number of septic tanks being accounted for. For aggregation points that related to multiple model output locations, the number of septic tanks in that basin was split between the two model locations.

Table 5. Model Output Location, Aggregation Points and Number of Septic Tanks

Model Output Location	Aggregation Points	# of Tanks (prior to Jan 2013)	# of Tanks (after Jan 2013)
S-153	S-153	2	2
SE-08	S. Fork A & B	113	113
SLT_7_Basin6	S. Fork D, Basin 6	284	284
S80	C-44,S-153	19	19
SLT-9_Basin4_5	Basin 4,5	228	58
SE01	South and North. Mid Est.	219	204
SE03	S. Fork C, D, Basin 4	600	296
SE02	North Mid. Est.	157	157
HR-1	C-24	23	23
S49	C-24	22	22
SE06	Tidal St. Lucie N. Fork	224	175
SE12	Tidal St. Lucie N. Fork	224	175
SE13	Tidal St. Lucie N. Fork	225	176
GRS	Ten Mile Creek	3	3

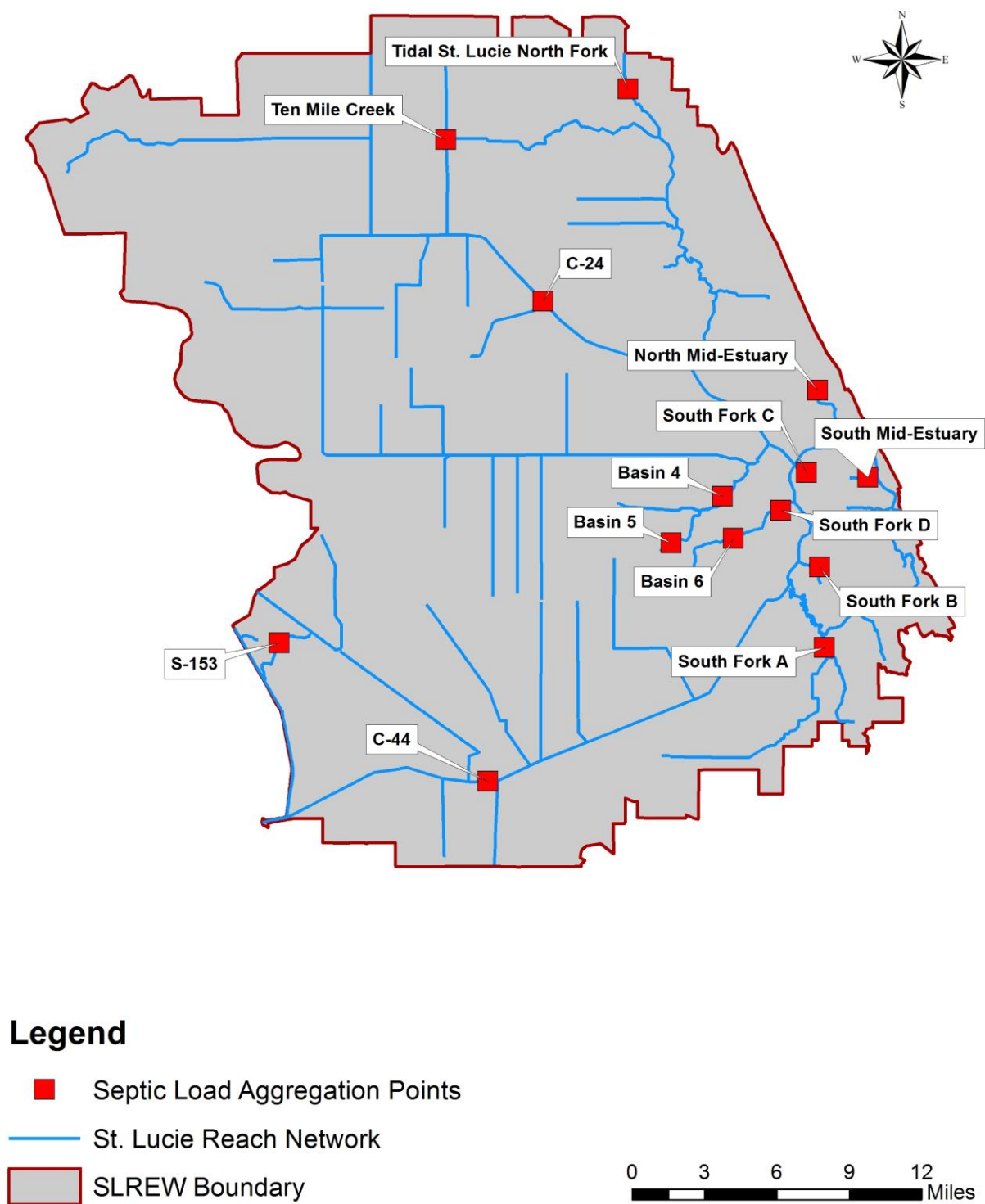


Figure 15a. Location of septic tank sites and aggregation load points in the WaSh model.

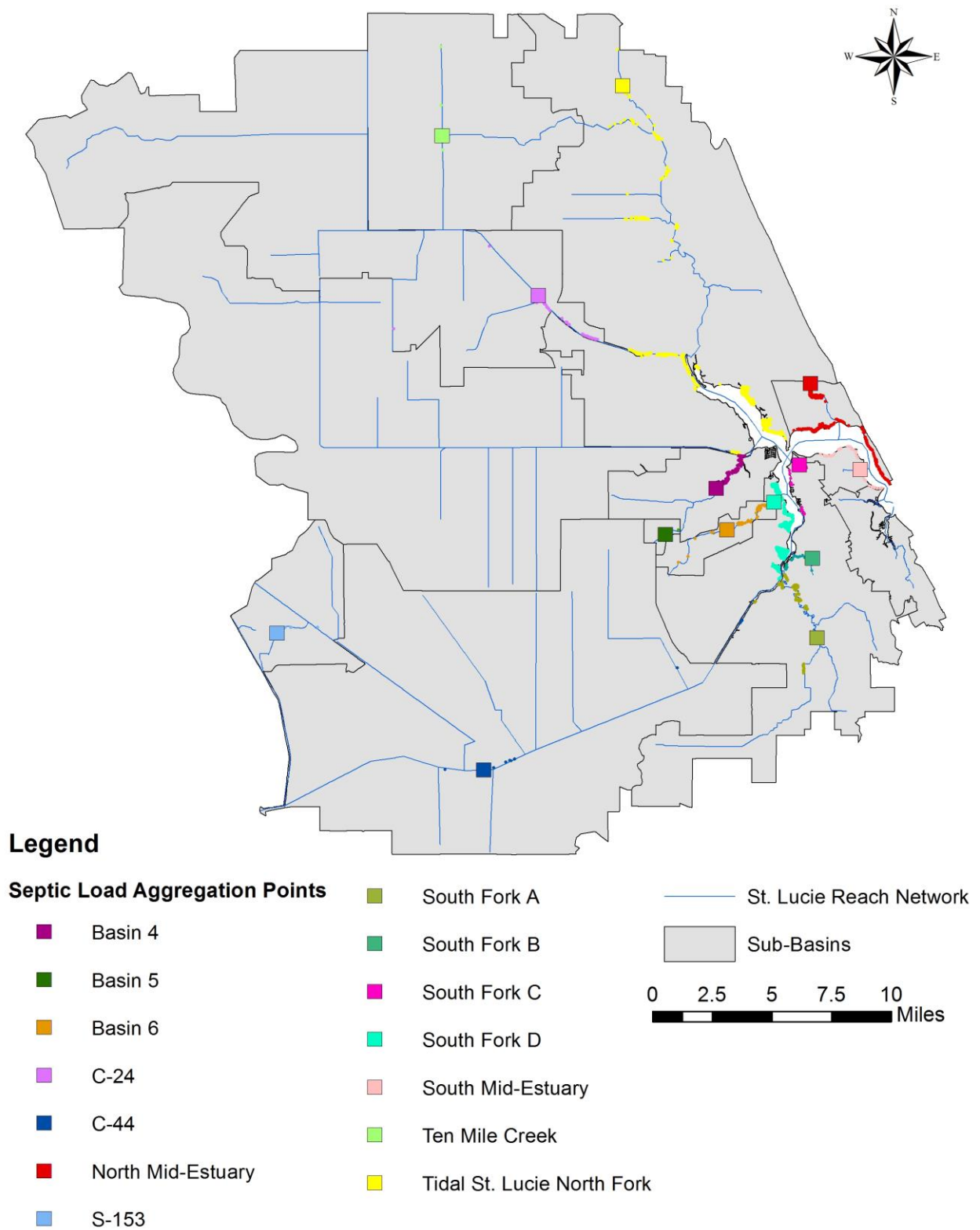


Figure 15b. Location of septic tank aggregation load points in the WaSh model.

4.14 Flow Pumped into FPL Reservoir from C-44 Canal

The Florida Power and Light (FPL) reservoir in the C-44 basin comprises 6,495 acres and, because of its relatively large size, is explicitly represented in the model configuration. The reservoir provides cooling water for FPL operations. Major water loss in the reservoir is through evaporation and infiltration. Flow is pumped into the FPL reservoir from the C-44 canal to maintain enough water for cooling. The pumping flow data were obtained from FPL and treated as an internal boundary condition in the model to simulate the water withdrawn from the C-44 canal.

4.15 Tide Stage at SLI

The SLI is set as a downstream boundary in the model, using measured tide stage as a boundary condition. Tide stage data from September 2011 to December 31, 2016, at SLI were downloaded from the DEP website (<http://www.fldep-stevens.com/data-8722375.php>). Data prior to September 2011 were assembled by the SFWMD using a tide harmonic analysis approach to predict tide stage at SLI.

4.16 Operation Rules for Flow Control Structure

Operation rules for flow control structures S-97, S-49, S-80, and S-153 are available on the structure information site at the SFWMD website (www.sfwmd.gov). These operation rules are set up in the model to simulate the flow through the structures. **Table 6** summarizes the operation rules.

Table 6. Structure operation rules (Unit: NAVD88 - ft)

Structure	Open Criteria ¹		Close Criteria ²	
	May - Oct	Nov-Apr	May - Oct	Nov-Apr
S-97	20.73	21.73	19.03	20.73
S-49	18.72	19.72	17.02	18.02
S-80	12.55	13.55	11.55	12.55
S-153	17.87	17.87	17.37	17.37

1. Gate will be opened if head water is higher than this stage; 2. Gate is closed if head water is lower than this stage.

5. Model Calibration and Verification

The model simulation includes the following PORs: 1995 through 2006 with land use data for 2004; 2007 through 2011 with land use data for 2008; and 2012 through 2016 with land use data for 2012. The model was calibrated from 2001 through 2006 to use the most recent period for calibration and verified from 1995 through 2000. The model was run starting in 1994; this allows one year to warm up the model so that it has the proper initial conditions for 1995. The 1994 result was not involved in the model evaluation and analysis.

5.1 Watershed Discretization and Canal/River Segmentation

To implement the WaSh model, the SLREW was discretized into 6,121 grid cells with a 2,000 ft by 2,000 ft resolution. The primary reach network (main channel/river and tributaries) was discretized into 943 segments with a length of 2,000 ft (**Figure 16**).

The spatial model input data described in Section 4 were overlaid on the grid cells. These overlaid data include topographic elevation, land use data, and soil type data. Model parameters for each cell were initialized based on those data and the knowledge obtained from previous model applications for the St. Lucie Estuary Watershed (USR, 2003 and 2008d). Rainfall data and PET data were assigned to each grid cell through the ArcGIS WaSh Model GUI tool. GRIDIO rainfall data were used from 1995 through 2000 to verify, while NexRad rainfall data were used from 2001 through 2006.

Hydrologic module PWATER/IWATER is applied to each grid cell. Surface runoff resulting from rainfall is routed to ponds or canals with Chezy-Manning equation. A part of water which directly infiltrates moves to groundwater in saturated zone, and the remaining either stays in un-saturated zone or moves to canal as interflow (Crawford and Linsley, 1966). Groundwater moving between grid cells is simulated by two-dimensional diffusive wave equation. The interaction between groundwater and surface water is simulated with Darcy's law. Natural hydrologic connection does not exist between basins. Thus, no inter-basin surface flow is allowed in the model. However, groundwater flow can move between basins next each other. One-dimensional full dynamic hydraulic routing is applied to simulate the flow between adjacent segments.

St. Lucie River and Estuary Watershed Model Discretization (Grid Cells and Canal/River Segments)

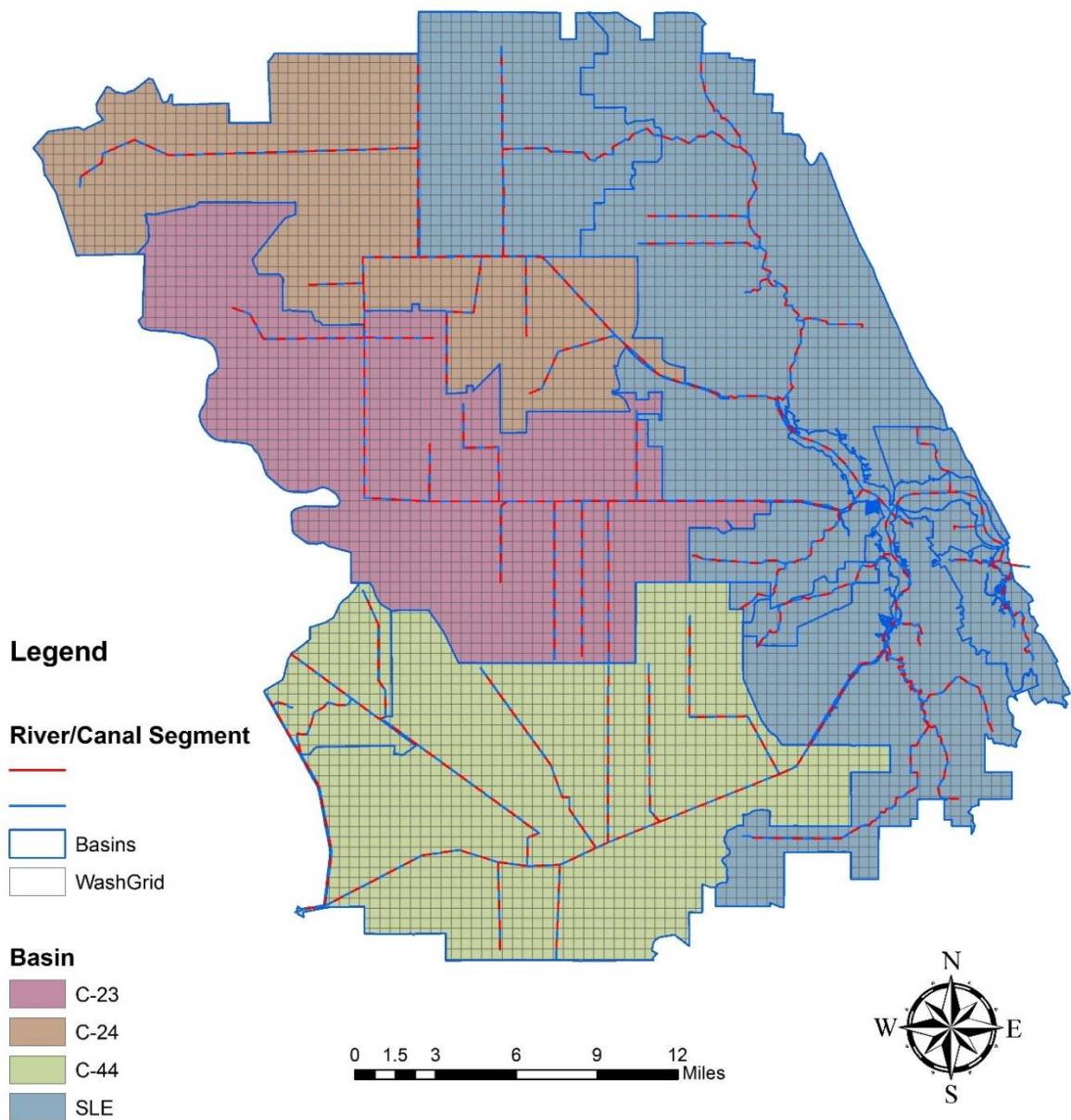


Figure 16. Model discretization for the St. Lucie River and Estuary Watershed (grid cell size: 2000 ft by 2000 ft and length of canal or river: 2000 ft) and structures set in model

5.2 Model Calibration

Calibration and verification of the hydrologic and water quality models are necessary before using them to evaluate the impacts of climate, land use, and crop management practices on the quantity and quality of land and water resources. Calibration is the process of adjusting model parameter values within reasonable ranges, determined from site-specific studies or literature values, until the simulated results closely match the observed data (Zeckoski et al, 2015). Verification is the process by which a calibrated model is shown to be capable of reproducing a set of field observations or predicting future conditions without further adjustment to the calibrated parameters (Zheng et al., 2012). Although model performance criteria have been investigated and studied for decades (Thomann, 1980; ASTM, 1984; Moriasi et al., 2007 and 2012), no single standard is established (Duda et al., 2012). For this modeling effort, we adapted the criteria established by Donigian (2002) for HSPF (Hydrological Simulation Program – Fortran, EPA model) as the following (a part of Table 3 in Moriasi et al., 2015) as model performance rating (Table 7).

Table 7. Criteria for model performance evaluation (Donigian, 2002; Moriasi et al., 2015)

Model (and Reference)	Response Output	Performance Evaluation Criteria				
BASINS/HSPF (Duda et al., 2012)		Difference between Simulated and Recorded Values (%)				
		Very Good	Good	Fair		
	Hydrology/flow	<10	10 to 15	15 to 25		
	Sediment	<20	20 to 30	30 to 45		
	Water temperature	<7	8 to 12	13 to 18		
	Water quality/nutrients	<15	15 to 25	25 to 35		
	Pesticides/toxics	<20	20 to 30	30 to 40		
		Statistical Evaluation Criteria				
	Hydrology/flow	Statistic	Very Good	Good	Fair	Poor
	Daily	R	≥0.89 ^[a]	≥0.84	≥0.77	<0.77
	Monthly	R	≥0.92	≥0.87	≥0.81	<0.81
	Daily	R ²	≥0.80	≥0.70	≥0.60	<0.60
	Monthly	R ²	≥0.85	≥0.75	≥0.65	<0.65

In the model performance evaluation, the five goodness-of-fit statistics for evaluation of model performance [coefficient of determination (R^2), bias, percent of bias (PBIAS), root mean square error (RMSE), and relative RMSE (RRE)] were calculated (formulae given at the end of this section). In Table 7, the difference between simulated and recorded values (%) is not specifically given. PBIAS and RRE were used to represent this difference for rating purposes. Therefore, for flow calibration and verification, the model is rated by PBIAS, RRE, and R^2 for both daily and monthly data, while water quality simulation is rated by PBIAS and RRE (see highlight with yellow color in the above table) for daily data. RRE was previously used to assess water quality modeling for the SLE (Wan et al., 2012).

Flow calibration and verification were conducted using measured data at Sites S-97, S-49, and S-80, while the water quality module was calibrated and verified with the measured water quality data at HR1, SE01, SE02, SE03, SE06, SE08(SE08B), SE11, S-48, S-49, and S-80 (see Figure 14). Site SE08 was moved upstream around 1,400 ft in late 2003 with the revised name SE08B and data measurements began in early 2004. They are combined as one station.

From 1995 to 1998, the HSPF model was applied to the St. Lucie Estuary Watershed (Aqua Terra and Linsley, Kraeger Associates, 1997). Starting from 2001, the WaSh model was developed and applied to four basins in the SLREW: C-23 Basin Model, C-24 Basin Model, C-44/S-153 Basin Model, and Tidal Basin Model (including North Fork, South Fork, Ten Mile Creek, part of South Coastal, and Basin 4, 5, and 6), by URS (2003 and 2008d) and refined later by AECOM (2016). Consequently, four basin models were developed under WaSh. In this effort, only one large combined model was developed to cover the entire watershed previously covered by the four models.

The major disadvantages of the four-model set for entire SLREW are that (1) interbasin groundwater flow is not allowed, which is not the case under actual conditions; and (2) it needs to run four models for each scenario. The initial values for the model parameters for this new larger model was taken from those four models for model calibration. During the calibration, the parameters were manually adjusted to improve the overall model predictions. The five goodness-of-fit statistics for evaluation of model performance as well as visual examination were used to refine parameter estimates. The comparison between the observed and model simulations was made. The goodness-of-fit statistics for model evaluation are calculated as follows:

1. Bias

$$BIAS = \frac{1}{n} \sum_{i=1}^n Q_{m,i} - \frac{1}{n} \sum_{i=1}^n Q_{s,i}$$

2. Percent Bias

$$PBIAS (\%) = \frac{\frac{1}{n} \sum_{i=1}^n Q_{m,i} - \frac{1}{n} \sum_{i=1}^n Q_{s,i}}{\frac{1}{n} \sum_{i=1}^n Q_{m,i}} \times 100$$

3. Root Mean Square Error (RMSE)

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (Q_{m,i} - Q_{s,i})^2}{n}}$$

4. Relative RMSE (RRE)

$$RRE (\%) = \frac{RMSE}{(Q_{max} - Q_{min})}$$

5. Coefficient of Determination (R^2)

$$R^2 = \left[\frac{\sum_{i=1}^n (Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s)}{\sqrt{\sum_{i=1}^n (Q_{m,i} - \bar{Q}_m)^2 \sum_{i=1}^n (Q_{s,i} - \bar{Q}_s)^2}} \right]^2$$

Where:

$Q_{m,i}$ = *i*th measured value

$Q_{s,i}$ = *i*th simulated value

$\overline{Q}_m$ = mean of measured values

$\overline{Q}_s$ = mean of simulated values

Q_{max} = maximum of measured value

Q_{min} = minimum of measured value

5.2.1 Calibration for Hydrology

The model calibration was conducted in two parts: hydrology and water quality. Calibration for both parts is complicated because of the complexity of the watershed system, meaning a large number of model parameters are involved in the calibration process. Model calibration is a global optimization of model parameters. Hydrology calibration was conducted focusing on matching simulated flow measured at three flow control structures: S-49 (C-23 basin), S-97 (C-24 basin), and S-80 (C-44/S-153 basin), using data from 2001 to 2006, with land use data from 2004.

The model-calibrated parameters are from three modules: surface hydrologic (PWater/IWater), river hydraulic, and groundwater flow. Initial model parameters for the surface hydrologic model were obtained from the St. Lucie Estuary Water Quality Model (URS, 2008d). Specifically, calibrations were mainly focused on the model parameters in **Table 8**. For complete information about these parameters, refer to Bricknell et al. (1997), Crawford and Linsley (1966), Hydrocomp Inc. and Aqua Terra Consultants (1996), and URS (2008a). **Appendix B** presents the values for the final model parameters.

The other two modules are canal/river roughness and groundwater hydraulic conductivity, for which 0.03 and 25 ft/day, respectively, were used in the final model calibration. For model calibration, an R script was developed to implement a dynamically dimensioned search algorithm (Tolson and Shoemaker, 2007), a model auto-calibration tool to assist in manual calibration. The comparison plots between measured and simulated flow for all three structures (S-49, S-97, and S-80), including daily, monthly, and annual flow calibration, are shown in **Appendix A** (see calibration period from 2001 to 2006).

For an evaluation of model performance in flow calibration, R^2 , bias, PBIAS, RMSE, and RRE were computed using daily, monthly, and annual flow data, as presented in **Table 9** (showing statistics resulting from daily and monthly data). Model performance is rated by R^2 , PBIAS, and RRE. For daily flow calibration, model performance is fair for S-49 and S-97 in terms of R^2 (0.69 and 0.64, respectively) and very good for S-80 ($R^2 = 0.84$). $PBIAS \leq 6.6\%$ and $RRE \leq 7\%$ for daily data indicate that the model has very good performance. From the monthly data, all statistics of the model evaluation shows very good model performance ($R^2 \geq 0.89$, $-1.7\% \leq PBIAS \leq 6.7\%$, and $RRE \leq 6.0\%$).

Similarly, the model performs at a relatively good level in simulating annual average data (not shown in **Table 9**; comparison plots are provided in **Appendix A**). Daily flows through structures

S-49, S-97, and S-80 were simulated in the model using their operation criteria (**Appendix E**), which is purely based on head water and tail water stage. Under real-world conditions, other factors are involved in the actual operations, such as rainfall occurring in areas upstream a few hours ahead of when operations are issued, as well as the experience of staff making the operational decisions (personal communication, Dr. Zhiming Chen, SFWMD, October 2017). However, it is difficult to incorporate such factors beyond the documented criteria into the model. Thus, daily structure flow simulation is not as good as monthly flow simulation. This is why there is only a fair R^2 for daily simulation at S-49 and S-97, but monthly flow values are much better. No poor ratings for flow calibration were produced.

Table 8. Calibrated surface hydrologic and hydraulic module parameters and descriptions

Model Parameter	Description
CEPSC	Interception storage capacity (inches)
UZSN	Upper zone nominal storage (inches)
NSUR	Manning's n for land surface
IRC	Interflow recession constant
INTFW	Interflow coefficient
LZETP	Lower zone evaporation potential (fraction)
LZSN	Lower zone nominal storage (inches)
INFILT	Infiltration rate (inches per hour [/hr])
INFEXP	Parameter in infiltration function
INFILD	Parameter in infiltration function
CONDUCTANCE	Primary canal and river bed conductance (ft/day)
PET Coefficient	Evaporation scale factor (fraction)
CANPMPPARM	Land use tertiary canal drainage pump rate (inches/hr)
PMP_UC	Tertiary canal depth for triggering pump (ft)
PMP_LC	Tertiary canal depth for stopping pump (ft)
CAN_CONDUCTANCE	Tertiary canal bed conductance (ft/day)

Table 9. Model performance for flow calibration

Evaluation Statistics	S-49	Rating	S-97	Rating	S-80	Rating
R^2 (Daily)	0.69	F	0.64	F	0.84	VG
BIAS (Daily, cfs)	11.3		13.7		-12.0	
PBIAS (Daily, %)	5.8	VG	6.6	VG	-1.7	VG
RMSE (Daily, cfs)	239.7		285.7		470.0	
RRE (Daily, %)	5.87	VG	5.53	VG	6.99	VG
R^2 (Monthly)	0.89	VG	0.90	VG	0.95	VG
BIAS (Monthly, cfs)	11.4		13.9		-11.7	
PBIAS (Monthly, %)	5.8	VG	6.7	VG	-1.7	VG
RMSE (Monthly, cfs)	119.6		118.7		243.3	
RRE (Monthly, %)	5.9	VG	6.0	VG	4.6	VG

5.2.2 Calibration for Water Quality

Measured water quality data in the system indicate a strong seasonal variation in nutrient distribution and phytoplankton in both the upstream watershed (e.g., at S-49, S-48, and S-80) and the intraestuary (Doering, 1996; Qian et al., 2006, 2007a and 2007b; Wan et al., 2017; Li et al., 2016 and 2017) following the same seasonal pattern existing in flow. Six years of data, collected from 2001 to 2006, that adequately capture the seasonal variation were used for water quality calibration. This period covers various climatic conditions, including a dry year (e.g., 2006), a wet year (e.g., 2005), and an average year (e.g., 2004). Calibrating the model with these years ensures that the calibrated model is capable of simulating water quality variations resulting from a range of hydrologic and climatic conditions.

Comparisons were made between eight simulated and measured water quality variables, including ammonia (NH₃), nitrate (NO₃), inorganic phosphorus (IP), chlorophyll *a* (CHLA, only available for estuary sites; measured data unavailable for basin outlets at S-48, S-49, and S-80), organic nitrogen (ON), DO, TP, and TN at 10 sites, i.e., S-48, S-49, S-80, HR1, SE01, SE02, SE03, SE6, SE08, and SE11 (**Figure 14**). The same five evaluation statistics used in flow calibration— R^2 , BIAS, PBIAS, RMSE, and RRE—were calculated for all eight water quality variables. Model performance is rated by PBIAS and RRE. R^2 was not used for rating water quality according to the rating table (**Table 7**) introduced in Section 5.2.

The model parameters involved in calibration are from four water quality processes: phytoplankton kinetics, phosphorus cycling, nitrogen cycling, and DO dynamics. **Table 10** lists the model parameters that were calibrated and their final values in the model. The initial value of these parameters was from the four models previously developed by URS (2003 and 2008d). Besides these parameters, the diffusion coefficients with 10 square feet per second (ft²/s) and 100 ft²/s were used in the advection-diffusion equation for upstream canals (C-23 Canal, C-24 Canal, C-44 Canal, and their tributaries) and Tidal Basin (St. Lucie River, estuary, and tributaries), respectively. The specific calibration process was to maximize R^2 and minimize BIAS, PBIAS, RMSE, and RRE for all nine water quality variables by adjusting water quality module parameters.

Table 10. Calibrated parameter values of water quality module[†]

Parameter Description	Notation	Values	Units
Phytoplankton kinetics			
Light extinction coefficient for all non-algae absorption	K_e^1	1	ft ⁻¹
Factor for light extinction coefficient for algae	K_e^2	0.7	ft ² /mg
Maximum algae growth rate at 20°C	G_p	2.0	day ⁻¹
Temperature coefficient for algae growth rate	θ_{GP}	1.03	-
Carbon-Chlorophyll Ratio	E_c	30	-
Saturating light intensity of phytoplankton	I_s	240	langleys/day
Half-Saturation constant for Nitrogen	K_{mN}	5.0	μg(N)/L
Half-Saturation constant for Phosphorus	K_{mP}	1.0	μg(P)/L
Endogenous respiration at 20°C	k_{1R}	0.125	day ⁻¹
Temperature coefficient for respiration	θ_{1R}	1.045	-
Phytoplankton settling Velocity	V_{s4}	0.1	ft/day
Phytoplankton death rate	k_{Dp}	0.02	day ⁻¹
Phosphorus cycle			
Phosphorus to carbon ratio	a_{PC}	0.025	mg(P)/mg(C)
Organic phosphorus mineralization at 20°C	k_{83}	0.023	day ⁻¹
Temperature coefficient for phosphorus mineralization	θ_{83}	1.08	-
Half saturation constant for phytoplankton limitation of phosphorus recycle	K_{mPc}	1	mg(C)/L
Fraction of dead and respired phytoplankton recycled to the organic phosphorus pool	f_{OP}	0.35	-
Organic phosphorus settling velocity	V_{s2}	0.007	ft/day
Fraction dissolved organic phosphorus in water column	f_{D8}	0.95	-
inorganic phosphorus settling velocity	V_{s6}	0.007	ft/day
Fraction dissolved inorganic phosphorus in water column	f_{D6}	0.95	-
Nitrogen cycle			
Nitrogen to carbon ratio	a_{NC}	0.25	mg(N)/mg(C)
Organic Nitrogen mineralization at 20°C	k_{71}	0.05	day ⁻¹
Temperature coefficient for nitrogen mineralization	θ_{71}	1.08	-
Nitrification rate at 20°C	k_{12}	0.05	day ⁻¹
Temperature coefficient for nitrification	θ_{12}	1.08	-
Half Saturation constant for oxygen limitation of nitrification	K_{NIT}	2.0	mg(O ₂)/L

Parameter Description	Notation	Values	Units
Denitrification rate at 20°C	k_{2D}	0.05	day ⁻¹
Temperature Coefficient of Denitrification rate	θ_{2D}	1.045	-
Michaelis constant for denitrification	k_{NO3}	0.1	mg(O ₂)/L
Fraction of dead and respired phytoplankton recycled to organic nitrogen pool	f_{ON}	0.5	-
Organic nitrogen settling velocity	V_{s3}	0.007	m/day
Fraction of dissolved organic nitrogen	f_{D7}	0.9	-
Oxygen balance			
Oxygen to carbon ratio	a_{OC}	32/12	mg(O ₂)/mg(C)
Deoxygenation rate at 20°C	k_D	0.15	day ⁻¹
Temperature coefficient of deoxygenation rate	θ_D	1.047	-
Half saturation constant for oxygen limitation	K_{BOD}	0.9	mg(O ₂)/L
Sediment Oxygen Demand	SOD	1.8	g/(ft ² day)
SOD Temperature coefficient	θ_{SOD}	1.03	-
BOD settling velocity	V_{s5}	0.007	ft/day
Fraction dissolved CBOD	f_{D5}	0.05	-
Reaeration Rate	k_2	0.15	day ⁻¹
Endogenous Respiration Temperature coefficient	θ_{1R}	1.045	-
Endogenous Respiration	k_{1R}	0.15	day ⁻¹

†Detail descriptions of these model parameters and their literature values can be found in Ambrose et al. (1988) and URS (2008a).

Table 11 lists the final evaluation statistics and ratings of model performance by PBIAS and RRE. If PBIAS or RRE > 35%, which is not included in the rating table (**Table 7**), then the model performance was rated as poor. Among a total of 154 ratings, 87.7% (135) are good or very good, 8.4% (13) are fair, and 3.9% (6) are poor. Poor ratings are from the simulation of chlorophyll *a*, nitrate, and ammonia. The comparison plots of water quality variables between measured and simulated data are presented in **Appendix C** (see plots for the calibration period from 2001 to 2006).

Both evaluation statistics and comparison plots suggest that the model performance in water quality calibration is generally good. Most ratings of poor or fair performance occur in chlorophyll *a* and nitrate. Nitrate is extremely reactive in water, and bio-ecological processes with high complexity are involved in phytoplankton kinetics. These two factors can probably explain why the model does not have good performance for these two variables.

Although R^2 is not involved in rating metrics of model performance for the water quality calibration in **Table 7** adapted from Donigan (2002), R^2 was calculated for this effort (**Table 11**), as it can be indicative of model performance in water quality simulation. As shown in the table, 64% of R^2 are greater than 0.35 (i.e., $R \sim 0.6$) and 48% are greater than 0.4, suggesting good model performance for water quality calibration. Low R^2 is found in chlorophyll *a*, ammonia, and nitrate,

indicating that the model has fair performance on these three water quality variables. This is consistent with the rating result by PBISAS and RRE.

Table 11. Model performance for water quality calibration

Monitoring Station	Statistics	NH3	NO3	IP	DO	ON	TP	TN	CHLA
S-48	R ²	0.55	0.02	0.4	0.35	0.34	0.39	0.42	
	BIAS (mg/L)	-0.01	-0.04	0.01	0.76	-0.13	-0.02	-0.2	
	PBIAS(%)	-6.9	-28.5	3.4	12.5	-11.2	-5.4	-14.3	
	Rating	VG	F	VG	VG	VG	VG	VG	
	RMSE (mg/L)	0.07	0.15	0.14	1.83	0.34	0.17	0.4	
	RRE (%)	16.1	29.1	16.5	17.7	15.9	19.9	18.4	
	Rating	G	F	G	G	G	G	G	
S-49	R ²	0.49	0.1	0.27	0.51	0.23	0.43	0.31	
	BIAS (mg/L)	-0.02	-0.05	0.01	0.27	-0.04	-0.01	-0.13	
	PBIAS(%)	-16.7	-46.9	6.8	5.4	-3.5	-5.4	-9.7	
	Rating	G	P	VG	VG	VG	VG	VG	
	RMSE (mg/L)	0.07	0.13	0.13	1.83	0.4	0.13	0.42	
	RRE (%)	18.6	25.5	16.6	17.6	8.0	15.3	8.2	
	Rating	G	F	G	G	VG	G	VG	
S-80	R ²	0.38	0.68	0.48	0.32	0.19	0.3	0.4	
	BIAS (mg/L)	-0.02	0.01	0	0.54	-0.04	-0.02	-0.05	
	PBIAS(%)	-38.8	1.9	3.1	8.9	-4.1	-10.2	-3.4	
	Rating	P	VG	VG	VG	VG	VG	VG	
	RMSE (mg/L)	0.05	0.12	0.06	1.68	0.4	0.08	0.45	
	RRE (%)	14.3	14.2	15.6	16.9	20.1	21.7	16.8	
	Rating	VG	VG	G	G	G	G	G	
HR1	R ²	0.52	0.2	0.43	0.47	0.26	0.53	0.44	0.1
	BIAS (mg/L)	-0.01	-0.03	0.01	0.75	-0.01	0.02	-0.05	3.32
	PBIAS(%)	-10.7	-58.2	7.1	11.2	-1.2	7.2	-4.7	25.6
	Rating	VG	P	VG	VG	VG	VG	VG	F
	RMSE (mg/L)	0.08	0.08	0.1	1.46	0.34	0.11	0.35	12.3
	RRE (%)	13.2	20.4	11.8	18.4	20.2	11.1	18.7	14.0
	Rating	VG	G	VG	G	G	VG	G	VG
SE01	R ²	0.41	0.74	0.85	0.43	0.23	0.78	0.44	0.04
	BIAS (mg/L)	0.01	-0.02	0	-0.02	0.01	-0.01	0.02	0.07
	PBIAS(%)	16.9	-26.3	4.9	-0.3	1.9	-4.0	2.1	1.2
	Rating	G	F	VG	VG	VG	VG	VG	VG
	RMSE (mg/L)	0.07	0.06	0.03	0.87	0.37	0.06	0.37	5.68

Monitoring Station	Statistics	NH3	NO3	IP	DO	ON	TP	TN	CHLA
SE02	RRE (%)	16.0	10.0	10.2	19.1	16.9	10.5	13.5	19.6
	Rating	G	VG	VG	G	G	VG	VG	G
	R ²	0.46	0.61	0.74	0.36	0.28	0.7	0.48	0.04
	BIAS (mg/L)	0.01	-0.04	0	0.13	-0.1	-0.02	-0.11	86.75
	PBIAS(%)	12.0	-36.6	-3.6	2.1	-13.6	-9.6	-11.9	90.9
	Rating	VG	P	VG	VG	VG	VG	VG	P
	RMSE (mg/L)	0.07	0.09	0.05	1.22	0.39	0.07	0.41	96.65
	RRE (%)	18.7	14.2	10.4	20.8	20.3	12.7	16.0	58.2
	Rating	G	VG	VG	G	G	VG	G	P
SE03	R ²	0.39	0.63	0.75	0.37	0.26	0.71	0.41	0.1
	BIAS (mg/L)	0.01	-0.03	0	0.28	-0.06	0	-0.08	0.13
	PBIAS(%)	11.9	-26.9	0.4	4.4	-7.5	-1.9	-8.0	1.4
	Rating	VG	F	VG	VG	VG	VG	VG	VG
	RMSE (mg/L)	0.07	0.09	0.05	1.3	0.38	0.07	0.43	7.12
	RRE (%)	18.7	14.3	12.9	22.8	18.9	13.8	16.2	16.8
	Rating	G	VG	VG	G	G	VG	G	G
SE06	R ²	0.39	0.28	0.36	0.47	0.08	0.57	0.25	0
	BIAS (mg/L)	-0.02	-0.01	0.03	-0.02	0	0.04	-0.02	3.84
	PBIAS(%)	-26.6	-22.7	18.6	-0.3	-0.1	16.6	-1.8	28.4
	Rating	F	G	G	VG	VG	G	VG	F
	RMSE (mg/L)	0.07	0.06	0.09	1.36	0.39	0.09	0.4	12.05
	RRE (%)	13.0	23.2	15.7	17.7	29.7	15.2	22.5	24.6
	Rating	VG	G	G	G	F	G	G	G
SE08	R ²	0.2	0.77	0.69	0.37	0.26	0.49	0.45	0.05
	BIAS (mg/L)	0.01	0	0	0.63	0.06	0.02	0.05	0.69
	PBIAS(%)	11.8	0.0	0.0	9.4	5.6	7.5	3.7	7.2
	Rating	VG	VG	VG	VG	VG	VG	VG	VG
	RMSE (mg/L)	0.07	0.09	0.04	1.45	0.4	0.08	0.45	7.5
	RRE (%)	20.6	13.1	14.9	21.5	17.8	17.2	15.5	20.6
	Rating	G	VG	VG	G	G	G	G	G
SE11	R ²	0.37	0.59	0.67	0.17	0.15	0.73	0.26	0.04
	BIAS (mg/L)	0.01	-0.01	0.02	0.25	0.14	0.01	0.16	1.28
	PBIAS(%)	10.5	-18.8	26.7	3.8	23.4	7.5	22.7	34.1
	Rating	VG	G	F	VG	G	VG	G	F
	RMSE (mg/L)	0.06	0.05	0.04	1.05	0.32	0.04	0.34	3.64
	RRE (%)	16.0	13.5	15.5	12.9	27.0	13.7	25.7	23.5
	Rating	G	VG	G	VG	F	VG	F	G

As annual nutrient loads are of the most concern in the St. Lucie BMAP, annual TP and TN loads were calculated based on simulated and measured data from the calibration period from 2001 to 2006. **Appendix D** presents the comparison between simulated and measured TP and TN loads (the third column), the annual average flow (the first column), and TN and TP concentrations (the second column). The evaluation statistics were also calculated and are listed in **Table 12**. From the table, $R^2 \geq 0.9$, -19.3% (TP of S-80) $\leq$ PBIAS $\leq 10.9\%$ (TP of S-48), and $RRE \leq 12.4\%$ (TP of S-48 and S-49) indicate good agreement between measured and simulated TN/TP loads. Based on evaluation statistics, the model appears to simulate annual TN load better than annual TP load. Overall, the model performs very well both in annual TN and TP simulation.

Table 12. Model performance in simulation of annual TP and TN loads from 2001 to 2006 (calibration)

Statistics	S-48		S-49		S-80	
	TP Load	TN Load	TP Load	TN Load	TP Load	TN Load
R ²	0.90	0.95	0.90	0.92	0.98	1.0
BIAS (metric tons)	7.5	-2.3	5.2	2.18	-22.3	-77.4
PBIAS (%)	10.9	-0.9	10.5	0.9	-19.3	-7.8
RMSE (metric tons)	13.8	32.2	9.7	35.3	39.7	132.5
RRE (%)	11.9	7.0	12.4	9.2	12.4	5.1

5.3 Model Verification

Another independent flow and water quality dataset from 1995 to 2000 under different external conditions was used for model verification. Essentially, model verification is the subsequent testing of a calibrated model to a second independent dataset to further examine the model prediction ability. Model parameter values were kept unchanged in the model verification.

5.3.1 Verification for Hydrology

During model verification, the model was run from 1995 through 2000. **Table 13** lists the evaluation statistics for model verification of hydrology. For daily data, R^2 is 0.6 and 0.66 for S-49 and S-97, respectively, meaning fair model performance, while R^2 is 0.93 for S-80, showing very good model performance in this structure. Although relatively low R^2 of S-49 and S-97 in daily data, both -19.5% (S-97) $\leq$ PBIAS $\leq -7.6\%$ (S-80) and $RRE \leq 6.3\%$ (S-49) show that model performance is good or very good. For monthly data, model performance is generally good or very good for all three statistics ($R^2 \geq 0.82$, -19.7% [S-97] $\leq$ PBIAS $\leq -7.6\%$ [S-80], and 8.2% [S-49]). PBIAS < 0 is found at all three structures, which means that the model overestimates of flow during the verification period though the range of error are acceptable. Evaluation statistics were also computed for annual average flow which has good performance (not shown in **Table 13**). The comparison plots of daily, monthly, and annual flow are presented in **Appendix A** (see the verification period from 1995 through 2000). Overall, the model performance in verification is similar to model calibration, indicating that the model calibration is robust and reliable.

Table 13. Model performance for flow verification

Evaluation Statistics	S-49	Rating	S-97	Rating	S-80	Rating
R ² (Daily)	0.60	F	0.66	F	0.93	VG
BIAS (Daily, cfs)	-31.9		-33.8		-60.1	
PBIAS (Daily, %)	-17.5	G	-19.5	G	-7.6	VG
RMSE (Daily, cfs)	279.1		284.0		395.7	
RRE (Daily, %)	6.32	VG	6.24	VG	4.56	VG
R ² (Monthly)	0.82	VG	0.87	VG	0.99	VG
BIAS (Monthly, cfs)	-32.1		-34.1		-59.8	
PBIAS (Monthly, %)	-17.6	G	-19.7	G	-7.6	VG
RMSE (Monthly, cfs)	121.9		113.8		166.8	
RRE (Monthly, %)	8.2	VG	6.4	VG	2.3	VG

5.3.2 Verification for Water Quality

Evaluation statistics for model verification of water quality using 1995–2000 data were computed for 10 sites (**Table 14**). Comparison plots between measured and simulated are shown in **Appendix C**. In the rating metrics shown in **Table 14**, among a total of 154 model performance ratings, 84.4% (130) are good or very good, 11.0% (17) are fair, and 4.5% (7) are poor. Similar to model calibration, the simulation of chlorophyll *a*, nitrate, and ammonia had poor ratings. Generally, the error between the measured and simulated results in water quality verification were similar to those obtained in the model calibration period (**Appendix C** shows both calibration and verification plots together for a visual comparison of the error level in calibration and verification). This suggests that the calibrated model is applicable to other climatic and hydrologic conditions. From comparison plots between simulated and measured data at 10 sites shown in **Appendix C**, the model is able to generally capture the seasonal variation of simulated nutrients, except for nitrate at S-48 and S-49 and chlorophyll *a* at SE02.

Annual TP and TN loads at three outlets of the upstream basin (S-48, S-49, and S-80) were calculated based on simulated and measured data for the model verification period. Comparison plots of annual TN and TP loads between simulated and measured results are provided in **Appendix D** (see verification period 1995 to 2000), which also shows the annual average flow and TN and TP concentrations. The evaluation statistics were also calculated (**Table 15**). In the table, $R^2 \geq 0.83$, 26.3% (TP of S-49) $\leq$ PBIAS $\leq 0.4\%$ (TN of S-80), and $RRE \leq 25.6\%$ (TN of S-48) suggests that the model is verified in simulating nutrient loads with a reasonable range.

Table 16 lists the water budget for model simulation through the entire model development POR (i.e., 1995–2006). Irrigation is applied to citrus only in the model as it is the only land use with significant irrigation. Urban area has a much higher runoff depth than other land uses since it is impervious area. Wetland holds the highest actual evapotranspiration because it accounts for significant transpiration of vegetation with sufficient water.

Table 14. Model performance for water quality verification

Monitoring Station	Statistics	NH3	NO3	IP	DO	ON	TP	TN	CHLA
S-48	R ²	0.29	0.02	0.19	0.37	0.24	0.27	0.34	
	BIAS (mg/L)	0	-0.02	-0.02	0.52	-0.09	-0.05	-0.12	
	PBIAS(%)	0.1	-14.5	-9.4	9.5	-7.4	-15.3	-7.9	
	Rating	VG	VG	VG	VG	VG	G	VG	
	RMSE (mg/L)	0.09	0.14	0.14	1.52	0.41	0.18	0.45	
	RRE (%)	13.0	20.1	22.9	15.0	13.6	17.7	13.7	
	Rating	VG	G	G	G	VG	G	VG	
S-49	R ²	0.33	0.09	0.14	0.4	0.05	0.23	0.11	
	BIAS (mg/L)	-0.07	-0.05	-0.02	0.19	0.07	-0.06	-0.06	
	PBIAS(%)	-75.2	-58.7	-10.7	4.1	5.2	-22.4	-3.8	
	Rating	P	P	VG	VG	VG	G	VG	
	RMSE (mg/L)	0.1	0.12	0.11	1.69	0.41	0.15	0.44	
	RRE (%)	29.9	20.5	20.9	17.4	18.2	19.9	24.8	
	Rating	F	G	G	G	G	G	G	
S-80	R ²	0.21	0.36	0.4	0.46	0.02	0.25	0.1	
	BIAS (mg/L)	-0.03	0.04	-0.01	0.49	-0.13	-0.04	-0.11	
	PBIAS(%)	-58.7	14.1	-8.0	8.0	-11.5	-26.2	-7.7	
	Rating	P	VG	VG	VG	VG	F	VG	
	RMSE (mg/L)	0.07	0.13	0.05	1.3	0.48	0.08	0.52	
	RRE (%)	15.2	21.1	15.6	15.8	22.9	27.2	24.6	
	Rating	G	G	G	G	G	F	G	
HR1	R ²	0.11	0.11	0.44	0.55	0.11	0.58	0.2	0.05
	BIAS (mg/L)	0	0	0.01	0.61	0.1	-0.01	0.06	1.1
	PBIAS(%)	4.5	-2.5	5.4	9.2	9.5	-5.5	5.5	9.8
	Rating	VG	VG	VG	VG	VG	VG	VG	VG
	RMSE (mg/L)	0.09	0.12	0.06	1.18	0.44	0.07	0.46	9.64
	RRE (%)	22.8	18.1	15.6	16.0	20.0	18.3	21.6	16.8
	Rating	G	G	G	G	G	G	G	G
SE01	R ²	0	0.49	0.63	0.42	0.15	0.63	0.39	0.05
	BIAS (mg/L)	0.05	-0.01	-0.01	-0.07	0.11	-0.03	0.03	0.62
	PBIAS(%)	42.5	-7.8	-15.8	-1.2	12.6	-27.9	2.6	7.9
	Rating	P	VG	G	VG	VG	F	VG	VG
	RMSE (mg/L)	0.09	0.08	0.04	0.83	0.43	0.06	0.43	8.57
	RRE (%)	31.1	17.8	12.4	13.8	19.9	19.3	16.8	16.1
	Rating	F	G	VG	VG	G	G	G	G

Monitoring Station	Statistics	NH3	NO3	IP	DO	ON	TP	TN	CHLA
SE02	R ²	0.08	0.39	0.56	0.44	0.05	0.67	0.22	0.05
	BIAS (mg/L)	0.02	-0.01	-0.02	-0.01	0	-0.04	0.01	73.18
	PBIAS(%)	23.7	-9.4	-18.0	-0.1	0.4	-28.2	1.1	87.5
	Rating	G	VG	G	VG	VG	F	VG	P
	RMSE (mg/L)	0.08	0.09	0.05	0.97	0.44	0.07	0.47	88.86
	RRE (%)	18.2	21.4	15.6	16.3	24.2	20.7	22.8	53.2
	Rating	G	G	G	G	G	G	G	P
SE03	R ²	0.07	0.33	0.47	0.54	0.16	0.52	0.29	0.03
	BIAS (mg/L)	0.03	-0.01	0	-0.05	0.01	-0.02	0.03	-0.38
	PBIAS(%)	29.0	-6.9	1.7	-0.9	1.4	-10.0	2.3	-3.7
	Rating	F	VG	VG	VG	VG	VG	VG	VG
	RMSE (mg/L)	0.12	0.12	0.05	0.93	0.39	0.07	0.44	9.29
	RRE (%)	14.5	16.7	14.8	16.4	20.7	18.6	20.6	19.6
	Rating	VG	G	VG	G	G	G	G	G
SE06	R ²	0.15	0.12	0.43	0.57	0.06	0.37	0.12	0.01
	BIAS (mg/L)	0	0.04	0.05	-0.48	0.2	0.04	0.2	1.66
	PBIAS(%)	-1.4	33.5	25.1	-10.1	19.6	14.8	16.7	14.4
	Rating	VG	F	F	VG	G	VG	G	VG
	RMSE (mg/L)	0.07	0.15	0.08	1.1	0.46	0.1	0.51	11.35
	RRE (%)	19.3	12.9	20.0	13.6	31.0	15.3	24.9	25.4
	Rating	G	VG	G	VG	F	G	G	F
SE08	R ²	0.2	0.6	0.51	0.39	0.01	0.24	0.17	0.07
	BIAS (mg/L)	0	0.01	0.01	1.12	0.14	0.01	0.13	-0.08
	PBIAS(%)	1.2	7.1	4.6	15.9	12.4	3.7	9.7	-0.7
	Rating	VG	VG	VG	G	VG	VG	VG	VG
	RMSE (mg/L)	0.06	0.09	0.05	1.57	0.48	0.08	0.5	8.45
	RRE (%)	16.8	17.0	20.8	25.2	30.2	19.5	19.6	20.6
	Rating	G	G	G	F	F	G	G	G
SE11	R ²	0.12	0.53	0.63	0.26	0.16	0.55	0.18	0.06
	BIAS (mg/L)	0.01	-0.01	0	-0.25	0.25	-0.01	0.22	1.76
	PBIAS(%)	22.4	-11.1	5.8	-4.1	31.8	-10.5	26.6	37.1
	Rating	G	VG	VG	VG	F	VG	F	P
	RMSE (mg/L)	0.06	0.05	0.03	0.78	0.47	0.04	0.47	4.52
	RRE (%)	27.4	17.5	13.9	15.3	27.6	15.8	24.1	20.9
	Rating	F	G	VG	G	F	G	G	G

Table 15. Model performance in simulation of annual TP and TN loads from 1995–2000 (verification)

Statistics	S-48		S-49		S-80	
	TP Load	TN Load	TP Load	TN Load	TP Load	TN Load
R ²	0.84	0.83	0.91	0.90	1.0	0.99
BIAS (metric tons)	-12.0	-62.5	-10.6	-37.9	-26.9	3.9
PBIAS (%)	-24.0	-28.5	-26.3	-15.5	-23.7	0.36
RMSE (metric tons)	16.6	84.6	11.9	50.9	29.6	105.8
RRE (%)	21.1	25.6	24.3	16.8	12.8	4.4

Table 16. Water budget for various land use types (1995– ~2006)

Land Use (level 3 code)	Rainfall (in)	Total Irrigation (in)	External Irrigation (in)	Irrigation from Canal (in)	ET (in)	Runoff (in)	Interflow Outflow (in)	Infiltration (in)
100	53.89	0.00	0.00	0.00	22.09	13.37	14.35	4.05
200	51.44	0.00	0.00	0.00	28.75	3.40	14.09	5.13
221	51.25	6.82	2.50	4.22	33.63	1.11	13.27	9.92
300	51.40	0.00	0.00	0.00	32.65	2.97	11.75	3.97
400	53.02	0.00	0.00	0.00	32.72	3.33	12.60	4.30
500	55.17	0.00	0.00	0.00	30.09	6.23	16.54	2.29
600	52.16	0.00	0.00	0.00	39.43	0.25	11.32	1.17
700	45.40	0.00	0.00	0.00	20.61	3.47	17.22	4.08
800	48.61	0.00	0.00	0.00	29.34	5.63	10.42	3.20

Note: The description of each land code shown in the table is as follows:

- 100 - Urban
- 200 - Agriculture (excluding Citrus)
- 221 - Citrus
- 300 - Rangeland
- 400 - Upland Forest
- 500 - Water
- 600 - Wetland
- 700 - Barren Land
- 800 - Transportation, Communication & Utilities

5.4 Additional Baseline Simulation PORs

The verified model was subsequently setup to simulate two additional PORs outside of the calibration and verification timeframe. The first POR simulated in the model was from 2007 through 2011 using the 2008 land use data as the base land use, while the second POR simulated in the model was from 2012 through 2016 using the 2012 land use data. The rainfall, evapotranspiration, temperature, solar radiation, and other boundary conditions were adjusted to accordingly to represent observed values during the simulated POR.

Figure 17 through **Figure 19** show the simulated and observed values for the entire 10 years (from 2007 through 2016) of additional baseline simulation at structures S-48, S-49, and S-80. From the

figures it can be seen that the simulated time-series generally matches the annual variability observed in the flow and water quality dataset, thereby, providing reasonable assurance for the adequacy of the model for use in scenario analysis.

From approximately 2006 to 2007, several BMAP large projects (primarily wet/dry detention ponds and flow control structures) were implemented in St. Lucie River Watershed. These projects were not incorporated into the additional baseline simulation. However, it is not expected that the output of this baseline simulation be close to the measured data. Actually, both flow and nutrient concentrations/loads of the baseline simulation appear to be higher than measurements, particularly for S-48 and S-49 (**Figures 17 and 18**, respectively). The reason is that the measured data reflects the effect of those large projects, including more ET due to the detention ponds and lower nutrient concentrations/loads resulting from treatment by the projects. Simulation of S-80 (**Figure 19**) does not show similar overestimation as S-48 and S-49. This is because the large portion of inflow at S-80 is from Lake Okeechobee, with the upper boundary condition of C-44 canal at S-308 using measured data (both flow and nutrient concentrations). As additional BMAP projects are set up in the model, the simulated variables are expected to be closer to the measurements. The baseline simulation is used for comparison with the simulation of project scenarios (see Section 7).

6. Model Sensitivity Analysis

A sensitivity test and analysis of the model parameters provide important insight into the studied system and a better understanding of the characteristics of the watershed. Ideally, the sensitivity of all model parameters (there are more than 71 major parameters in the WaSh model) should be investigated. The sensitivity of the parameters involved in the PWATER module of HSPF has been well studied in the literature (e.g., Iskra and Droste, 2008; Fonseca, 2014; Fonseca et al., 2014). It is commonly recognized that potential evapotranspiration coefficient, infiltration rate (INFILT), and lower zone nominal soil moisture storage (LZSN) are sensitive parameters in flow modeling. Those parameters are directly related to climatic conditions, land use conditions, precipitation patterns, and soil characteristics. These conclusions are also applicable to the SLREW, according to experience gained through manual calibration.

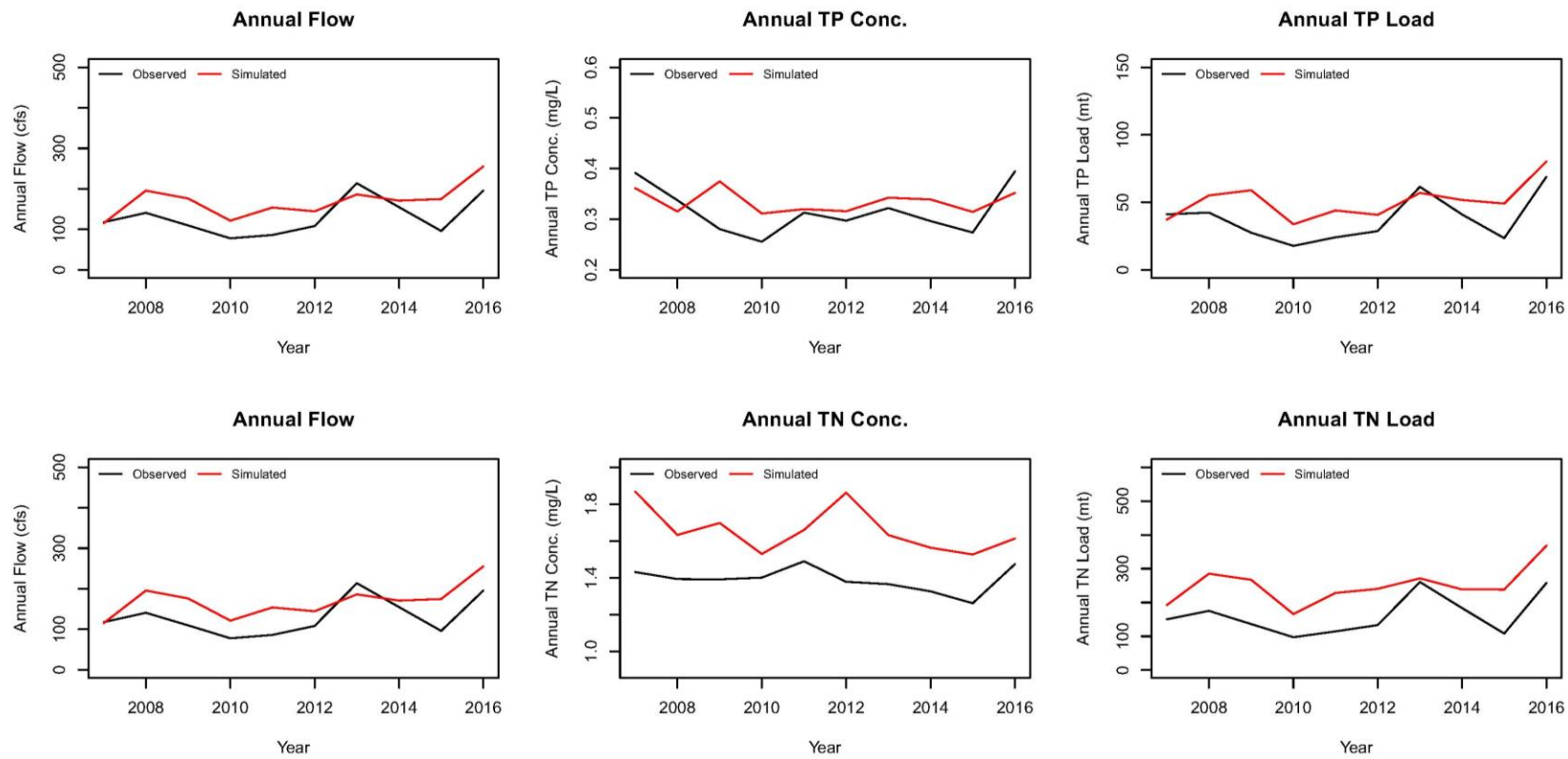
With limited time in this modeling effort, the sensitivity analysis focused on some key parameters of the water quality model. In previous WaSh model applications to the watershed, the sensitivity of BOD values in EMCs and SOD was investigated (URS, 2008d). The investigation was focused on DO dynamics and oxygen balance processes in the water column. The investigation showed that a 50% reduction of biological oxygen demand (BOD) input in the EMC caused an 8% increase in DO value. These results indicate a low sensitivity of DO to BOD in overland flow, likely caused by the high BOD generated by the decaying phytoplankton mass in the simulation.

The model simulates the in-stream production of BOD in tertiary, secondary, and primary canals as well as estuary rivers. This production yields significantly more BOD than from overland flow resulting directly from rainfall on the land surface. The other finding is that a 50% decrease in SOD leads to a 12% increase in DO in the water column. This suggests that DO has a relatively low sensitivity to SOD. Most likely, the vast network of tertiary and secondary canals provides a

large reservoir of BOD because of phytoplankton production and has a larger impact on DO than SOD.

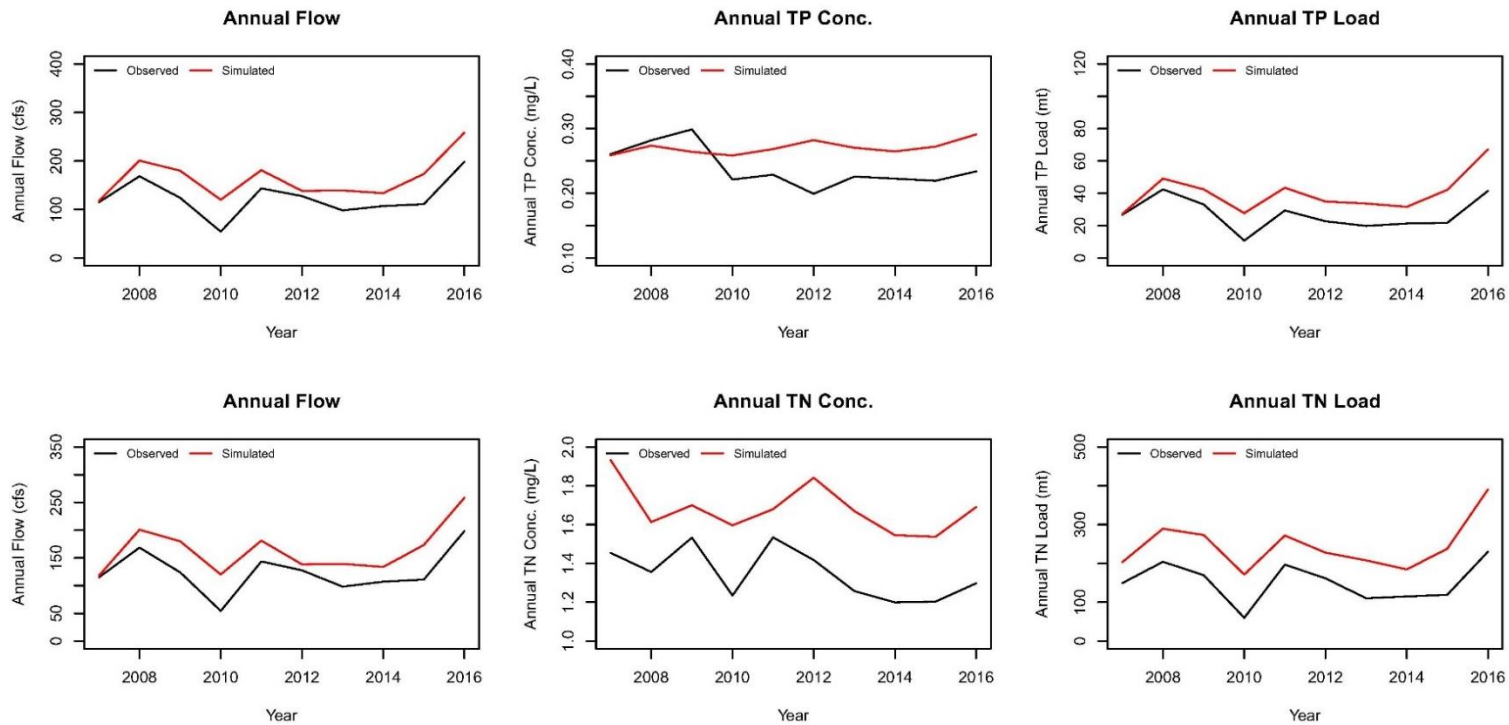
To identify the sensitivity of the diffusion term in the water quality process, the diffusion coefficient was increased by 50% in the model and was run from 1995 to 2006. All water quality variables at SE03 had a decrease within a range of 1.4% (inorganic phosphorus) to ~0.3% (ammonia). This indicates that the impact of diffusion is very minor in the St. Lucie canal and river system.

Extra effort was made to test parameters involved in phytoplankton kinetics. Three parameters picked for the sensitivity test were phytoplankton maximum growth rate (G_p), extinction coefficient because of nonalgal light attenuation (K_e^1), and extinction coefficient because of algal self-shading light attenuation (K_e^2) (**Table 10**).



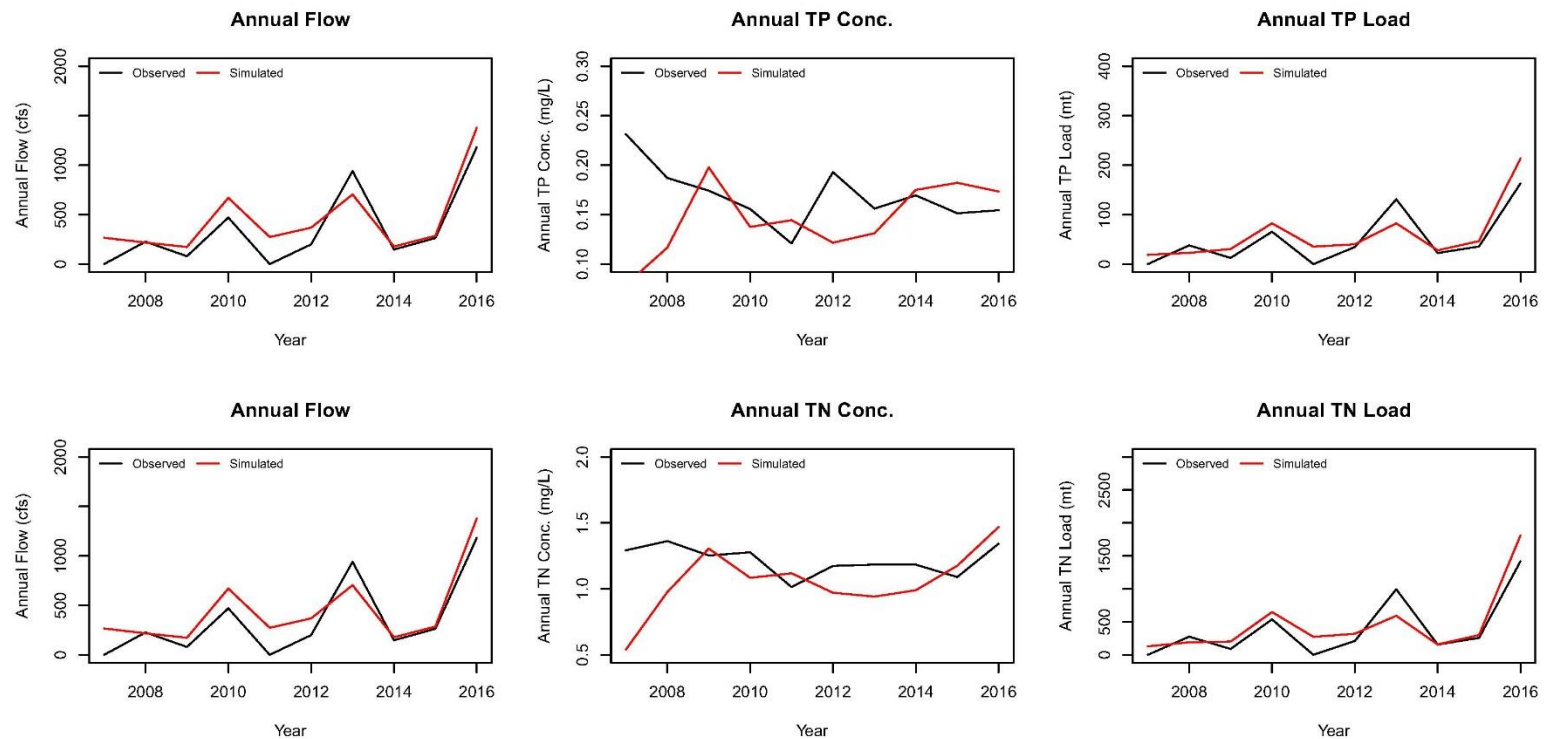
Comparison plots of observed vs simulated flow, concentration, and load at S48

Figure 17. Comparison plots of observed vs. simulated flow and concentrations at S48



Comparison plots of observed vs simulated flow, concentration, and load at S49

Figure 18 Comparison plots of observed vs. simulated flow and concentrations at S49



Comparison plots of observed vs simulated flow, concentration, and load at S80

Figure 19. Comparison plots of observed vs. simulated flow and concentrations at S80

Increasing G_p by 50% leads to a 44% increase in CHLA, a 52% decrease in NO₃, a 33% decrease in NH₃, and in other variables the magnitude of the change was not more than 4% (increase or decrease). Increasing K_e^1 by 50% results in a 37% decrease in CHLA, a 55% increase in NO₃, and an 11% increase in NH₃. This indicates that phytoplankton growth rate and nonalgal light attenuation are critical in phytoplankton kinetics and the nitrogen cycle, but do not appear to be critical for the phosphorus cycle.

Increasing K_e^2 by 50% causes a 16% increase in NO₃ and a 12% decrease in CHLA; all other variables change less than 6%. This suggests algal self-shading attenuation does not play a very sensitive role in the system.

Lastly, the endogenous respiration rate (k_{1R}) in **Table 10** was tested. Increasing k_{1R} by 50% causes a 63% decrease in CHLA and a 66% increase in NO₃. Changes in other variables are less than 6%. This reveals that respiration rate is a very sensitive factor in phytoplankton kinetics. Determination of its value is critical in model development.

7. Alternative Scenarios

The following two alternative scenarios were simulated using the verified WaSh model for the POR from 2007 through 2016.

1. Model simulation with five large-scale BMAP projects and all septic tanks (Projects scenario)
2. Model simulation without septic tanks (No Septic Tanks scenario)

7.1 Projects Scenario

The projects scenario involved incorporating five water quality projects that were selected by FDEP in an effort to quantify their water quality benefits. The following paragraphs provide a brief summary of the projects and how they were incorporated in the model. Each project has a project number identifier that is consistent with its listing in the St. Lucie BMAP.

7.1.1. Agricultural BMP Enrollment Project

Figures 20a and **20b** show the extents of the agriculture BMP enrollment project as of December 31, 2011 and December 31, 2016 respectively. The project involves improving water quality through a series of agricultural BMPs. Agricultural BMPs are individual or combined practices determined through research, field testing, and expert review to be the most effective and practicable means for improving water quality on agriculture landscapes that take into account economic and technological considerations. The Florida Department of Agriculture and Consumer Services (FDACS) Office of Agricultural Water Policy (OAWP) recruits and works with producers in the St. Lucie River and Estuary Basin to submit notices of intent (NOIs) and enroll in adopted BMP programs to implement the BMPs applicable to their operations. The NOIs will document the estimated total number of acres on which applicable BMPs are implemented. The project included in this scenario represents the BMP enrollment in the basin as of December 31, 2016.

To simulate the BMPs in the WaSh model, the project extents were overlaid on model grid cells and intersected to determine fractional extent of each BMP enrollment for a model grid cell. The TN/TP event mean concentrations (EMCs) reduction percentage received from FDEP (**Table 17**) is applied to each grid cell by multiplying the area percentage. For example, if the enrollment area partially (e.g. 80%) covers a grid cell (i.e. the area percentage is 80%, assuming the TN EMC is 2 mg/L and reduction percentage is 10%), then the TN EMC for post-implementation is $80\% * (1 - 10\%) * 2 + 20\% * 2 = 1.84$ mg/L. TN/TP EMCs for all 6,121 cells are processed in this way and these new calculated TN EMCs (i.e., 1.84 mg/L) are used in model. The processing is applied to model simulation of 2007 through 2011 and simulation of 2012 through 2016 respectively.

The results from the inclusion of the agricultural BMPs program in the model are combined with the results of the other four projects in this scenario.

Table 17. TN/TP event mean concentrations (EMCs) reduction percentage for FDACS BMP enrollment project

FLUCCS (LEVEL 3)	Land Use	TP Efficiency (%)	TN Efficiency (%)
211	Improved Pasture	11	17
212	Unimproved Pasture	7	11
213	Woodland Pasture	4	4
330	Mixed Rangeland	4	4
214	Row Crops	30	30
215	Field Crops	15	15
242	Sod Farms	20	20
251	Horse Farm	20	30
221	Citrus	12	10
223	Other Groves	12	10
241	Tree Nurseries	32	25
243	Ornamentals	32	25
252	Dairies	9	20
250	Specialty Farm	20	30

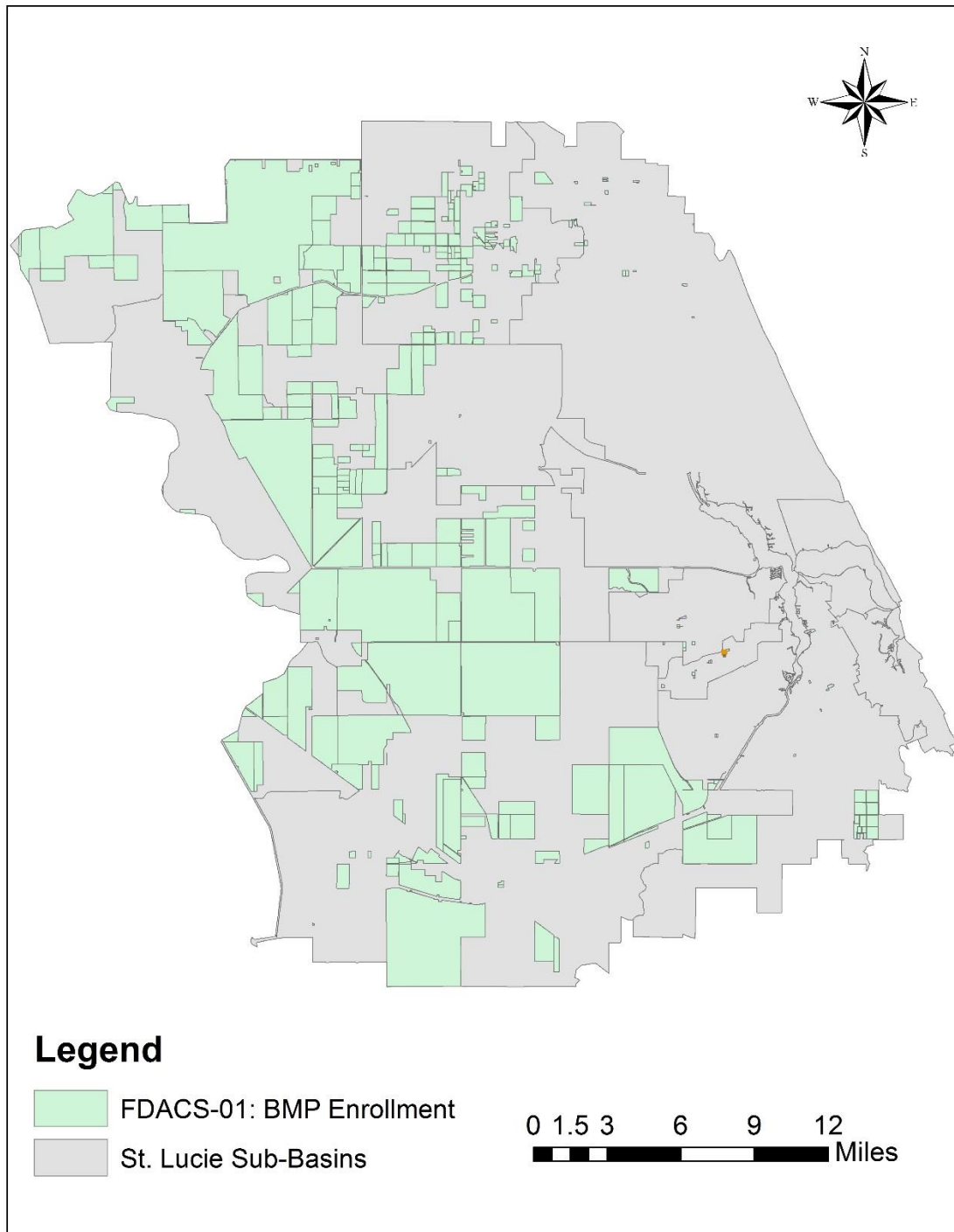


Figure 20a. FDACS Agricultural BMP Enrollment as of December 31, 2011

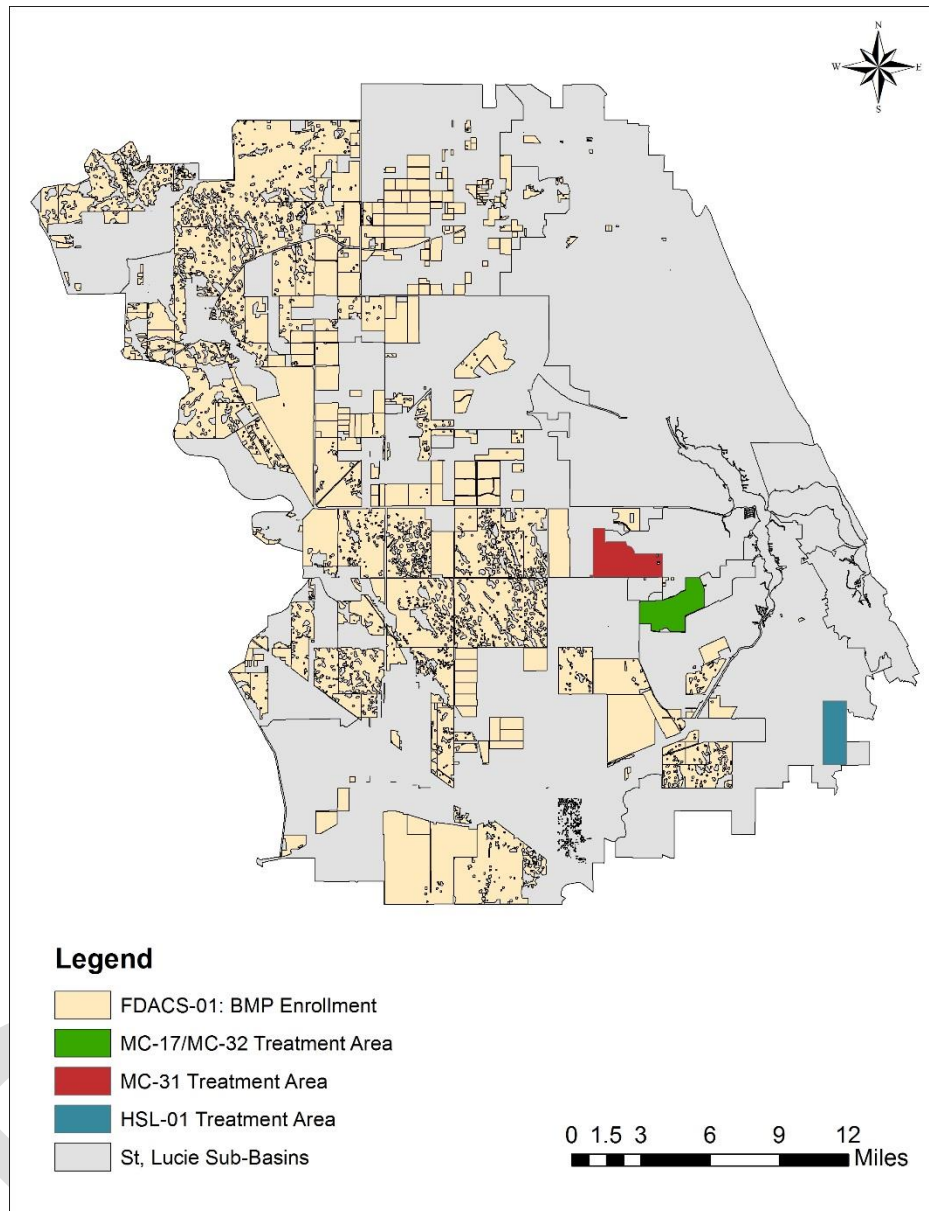


Figure 20b. FDACS Agricultural BMP Enrollment as of December 31, 2016

7.1.2. HSL-01: Hobe Sound Polo Club Wet and Dry Detention Treatment Train

The Hobe Sound Polo Club project located in Martin County covers an area of about 1,160 acres and provides water quality benefits by wet and dry detention. The project area is split into five basins (named 1 through 5, see **Figure 21**) with Basin 1 providing water quality treatment via a wet detention pond while Basins 2 through 5 have dry detention swales to provide water quality benefits. **Table 18** list the characteristics of the individual basins.

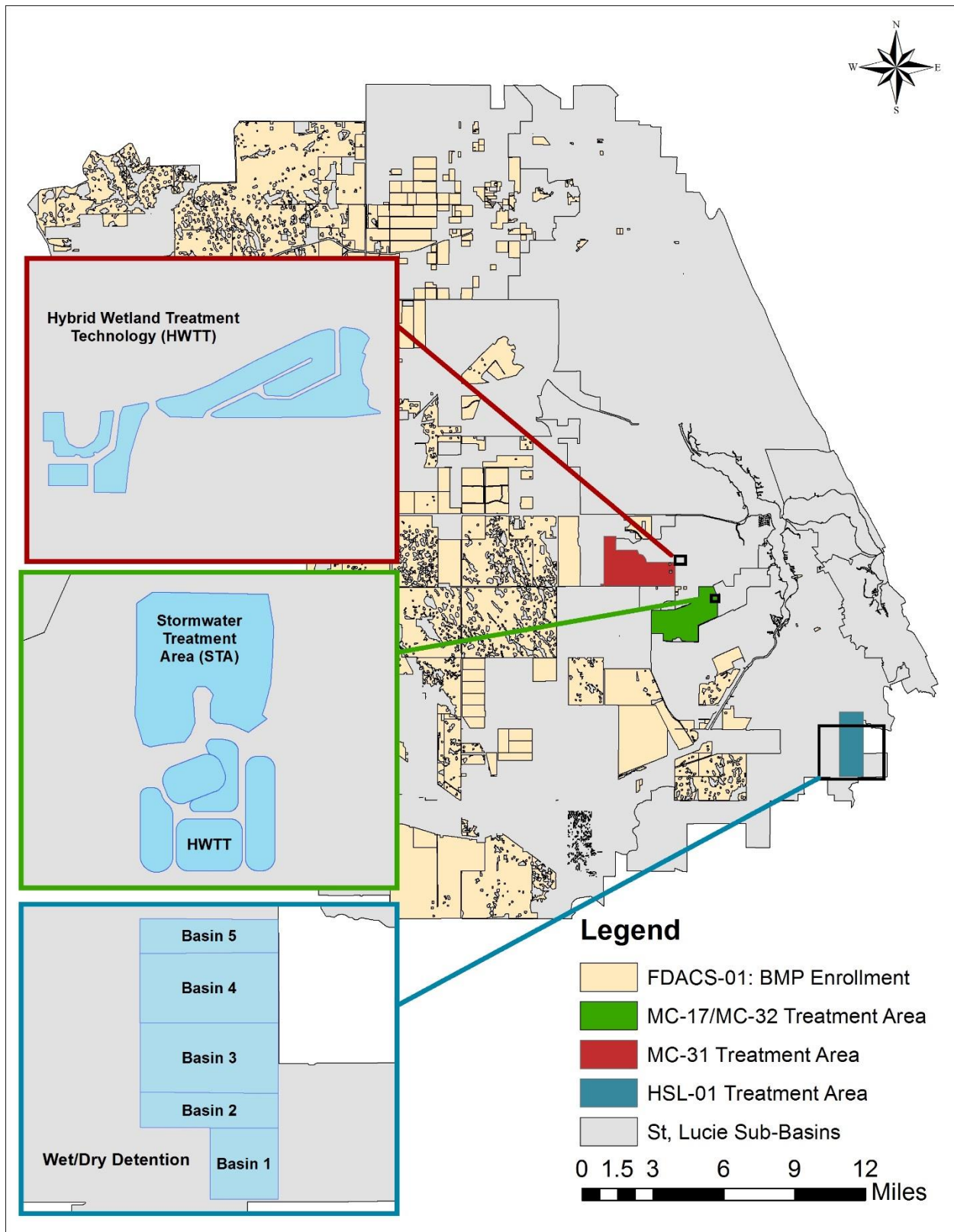


Figure 21. Details of projects simulated in WaSh alternative scenario model

Table 18. HSL Basin Characteristics

Basin	Area (ac)	Volume (ac-ft)	Treatment
Basin 1	169.82	21.23	Wet Pond
Basin 2	168.25	17.53	Dry Detention
Basin 3	328.02	34.17	Dry Detention
Basin 4	328.05	34.17	Dry Detention
Basin 5	165.64	17.25	Dry Detention

The outflow from the wet pond and dry detention swales will be individually routed via a V-Notch weir to the existing outfall canal which is also proposed to be replaced with two parallel 60” pipes. Several other conveyance-related modifications, such as routing offsite flows through a single riser system instead of currently present two 24” flashboard riser systems and changes in the connection of the offsite discharge location to the main discharge pipes (parallel 60”) are also proposed.

To incorporate this project into the WaSH model, the model domain covering the project area was modified explicitly to split contributing area for each of the five basins and add an outflow structure at each basin’s outfall location. **Figure 22** shows the updated model schematics due to incorporation of the HSL-01 project. The characteristics, i.e., size, bottom elevation, and outflow control elevation, of detention pond in Basin 1 were available and were set up into model. These structure characteristics for dry detention swales in Basins 2 through 5 were not available. They were simulated in the model as dry detention ponds (i.e., invert elevation of outflow structure is set to equal to the bottom elevation of pond) with approximately 1 foot of depth. The area of the detention pond was adjusted such that the overall treatment volume at each basin very closely matched the volume that is proposed (**Table 19**). Additionally, all V-notch weirs were simulated using general weir flow equation.

$$Q = CWH^b$$

where:

Q is weir flow

C is weir coefficient

W is width of weir

H is height of water above weir crest

b is weir exponent

The weir coefficient and exponent was modified such that the overall discharge rating curve from the proposed V-notch and simulated sharp-crested weir stay the same. **Figure 23** shows an example comparison of the flow rating curve for V-Notch weir in Basin 1 versus the simulated sharp-crested weir. **Table 20** compiles the proposed and simulated weir characteristics.

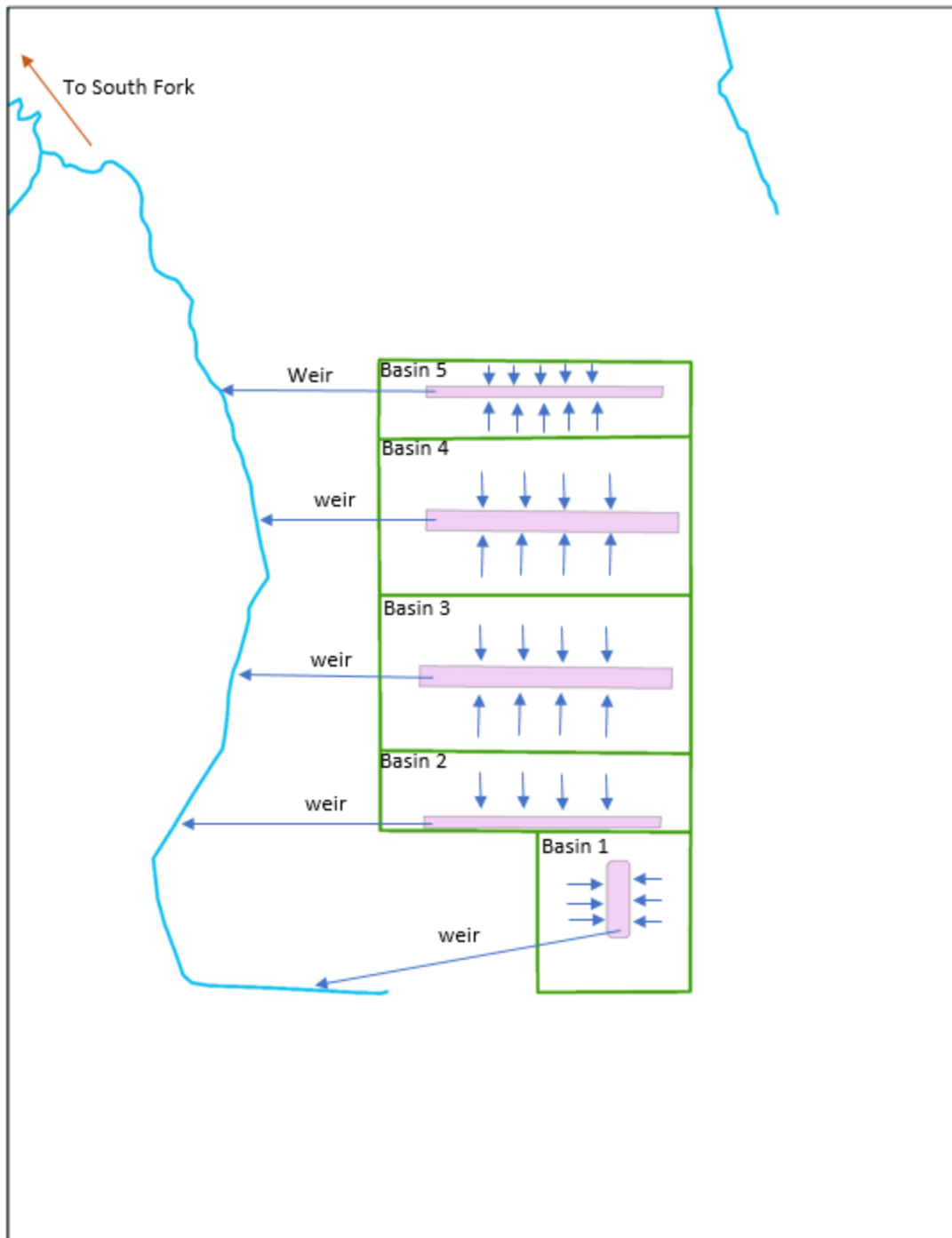


Figure 22. Model schematics accounting for HSL-01 project.

Table 19. Detention Pond Setup in WaSh

Basin	Detention Pond Area (ac)	Pond Depth (ft)	Volume Treated(ac-ft)
Basin 2	17.62	1	17.62
Basin 3	34.46	1	34.46
Basin 4	34.46	1	34.46
Basin 5	17.40	1	17.40

¹ The area was adjusted to approximately match the volume, so that the model represents TN and TP reasonably.

² Basin 1 was modeled based on depth multiplied by area, rather than the documented volume.

Table 20. V-Notch and Weir Characteristics

Basin	V-Notch Desc.	Invert El. (ft -NAVD88)	Weir Width (ft)	Weir Coeff.	Weir Exponent
Basin 1	12'X1.7', 85 deg	10.73	1	2.275	2.5
Basin 2	35 deg	10.73	1	0.775	2.5
Basin 3	63 deg	10.73	1	1.525	2.5
Basin 4	63 deg	9.73	1	1.525	2.5
Basin 5	34 deg	9.73	1	1.525	2.2

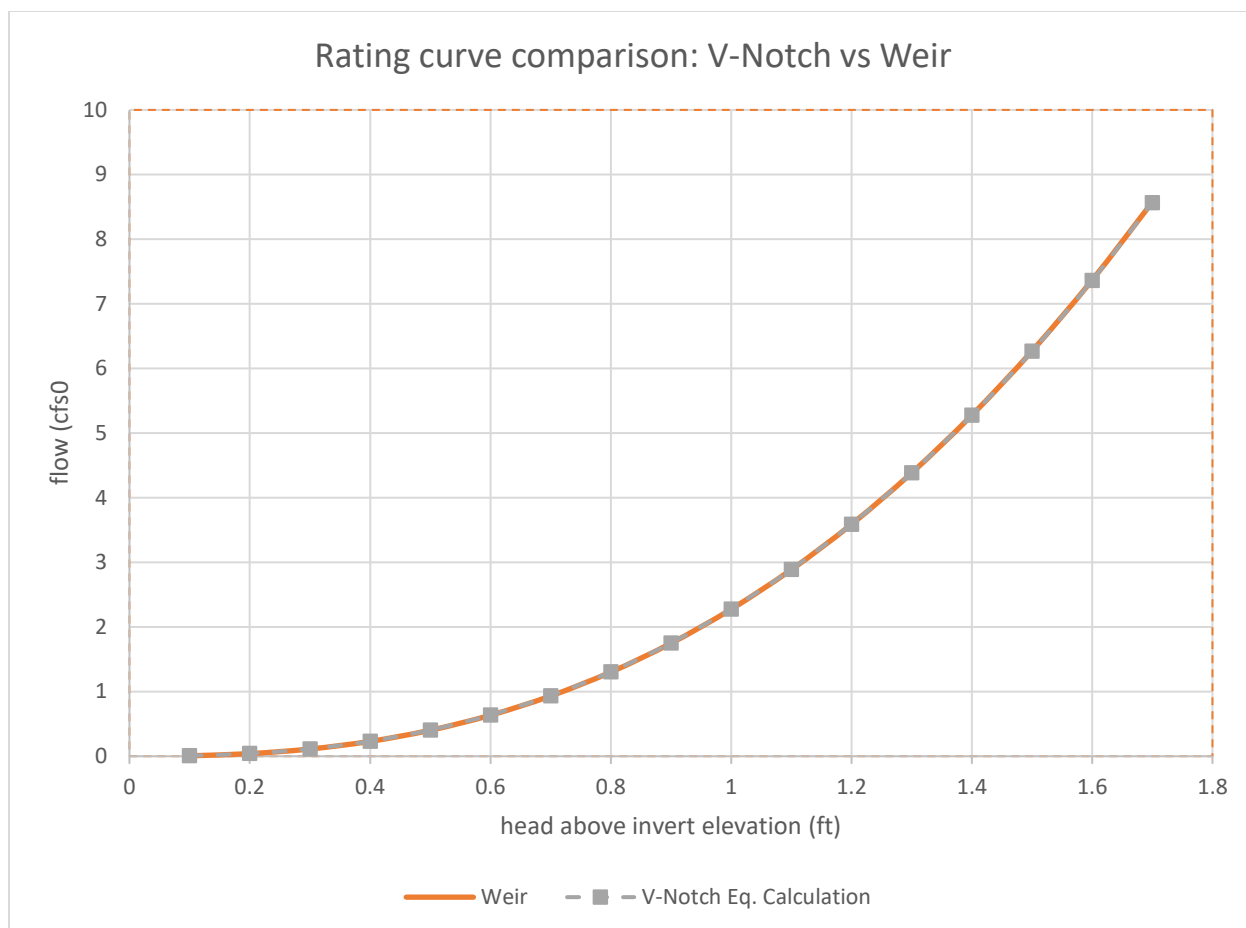


Figure 23. Example of rating curve comparison between V-Notch and Weir Setup in WaSh Model

7.1.3. MC-17: Danforth Creek Phase I Stormwater Treatment Area (STA)

The Danforth Creek Phase I STA project located in Martin County aims to provide water quality improvements by routing flow from Danforth Creek through an 8.15-acre STA with bottom elevation of 0 ft (NAVD88) and a residence time of about 11 days. The STA detains the stormwater and ultimately releases it back to Danforth Creek via a control structure (**Figure 20**). The project provides stormwater treatment and groundwater recharge for stormwater that would otherwise flow directly downstream into the South Fork of the St. Lucie River.

The project is designed to let Danforth Creek flow through the STA with a 6'W X 3' H rectangular notch with invert elevation of 13 ft NAVD88 (control elevation). The flow out of the STA back into Danforth Creek is controlled by a 100-foot wide sharp-crested weir set at an elevation of 16 ft NAVD88. The design pond efficiency is expected to be about 31.5% for TN removal and about 60.3% for TP removal.

To incorporate this project in the WaSh model, a weir with crest elevation of 13 ft (NGVD88) was set in the end of the segment from where water is diverted into the STA with critical flow of 0 cfs

and flow fraction of 1 (representing 100% of flow diversion). The outflow was simulated using a weir connection with weir elevation of 16 ft NAVD88 and a width of 100 ft. The weir coefficient was set at 2.65 while the weir exponent was 1.5. **Figure 24** shows the updated model schematics indicating the flow diversion and weir locations.

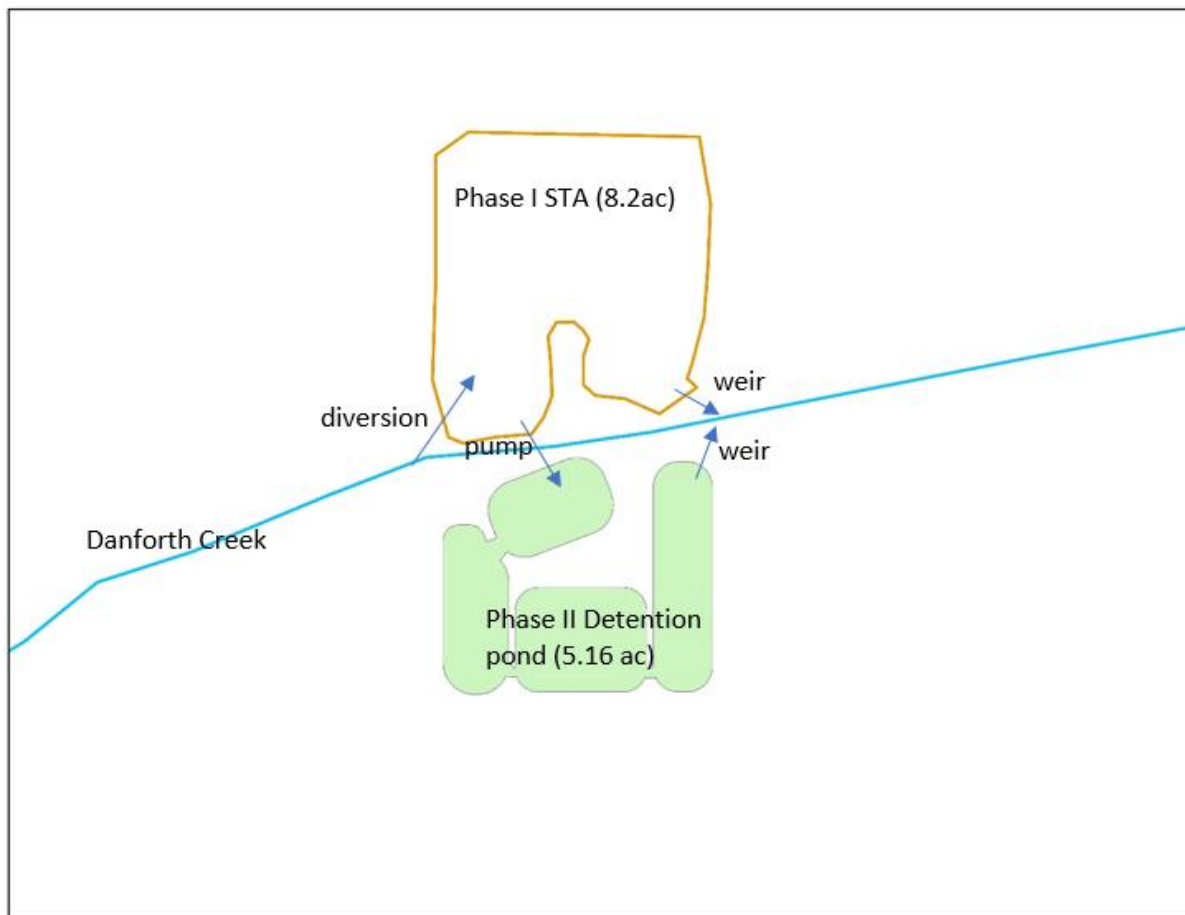


Figure 24. Model schematics accounting for MC-17 and MC-32 projects

7.1.4. MC-32: Danforth Creek Hybrid Wetland Treatment Technology (HWTT) Facility

The Danforth Creek HWTT facility located in Martin County, immediately south of the previously described project MC-17, is a hybrid wetland and a wet detention pond (**Figure 21**). The water to the facility is pumped from the STA constructed on the north side of the Danforth Creek (Project MC-17). The water is dosed with alum as it moves through a contact pond and then a settling pond. The flow then continues through floating aquatic vegetation and submerged aquatic vegetation ponds before being discharged to a downstream marsh. The entire project is expected to have a 41% removal efficiency for TN and about a 78% removal efficiency for TP. The outflow back into Danforth Creek from the facility occurs via a weir at an elevation of 13.54 ft NAVD88 with a top width of 10 ft.

Inflow of the Danforth Creek HWTT facility is from Danforth Creek Phase I STA through a pump which was setup in the WaSh model. The pump has normal flow of 5 cfs and maximum of 20 cfs, however, we were not able to obtain operation of the pump and the following operation rule is assumed and setup in model:

16.05 ft – NAVD88, 5 cfs

17.00 ft – NAVD88, 20 cfs

16.00 ft – NAVD88, 0 cfs.

The outflow from the facility was simulated using a sharp crested weir set at 13.54 ft NAVD88. The weir coefficient was set at 2.9 while the weir exponent was 1.5. **Figure 24** shows the specified model schematic.

7.1.5. MC-31: Bessey Creek HWTT Facility

The Bessey Creek HWTT facility located in Martin County is a hybrid wetland and a wet detention pond (**Figure 21**). The water in the facility is pumped from Bessey Creek and dosed with alum as it moves through a contact pond. The water then flows through a settling pond, floating aquatic vegetation and submerged aquatic vegetation ponds before discharging to a downstream marsh. The entire project is expected to have a 53% removal efficiency for TN and about a 86% removal efficiency for TP. The outflow from the facility goes into an existing mitigation area with a flow-through marsh which eventually reconnects with Bessey Creek downstream. The outflow is controlled by a V-shaped weir (10 ft in total length) set at an elevation of 15.53 ft NAVD88.

The pump from Bessey Creek to the project's detention pond is triggered with the following rules

12.53 ft – NAVD88, 0.5 cfs

15.53 ft – NAVD88, 20 cfs

12.03 ft – NAVD88, 0 cfs.

To simulate the project in the WaSh model, this operation rules were setup into model. The outfall structure from the HWTT facility was set up using the sharp-crested weir set-up in the model with an elevation of 15.53 ft NAVD88 and a width of 10 ft. The coefficient and exponent of the weir was specified to be 2.9 and 1.5 respectively. **Figure 25** shows the model schematics of the project that were specified in the WaSh model.

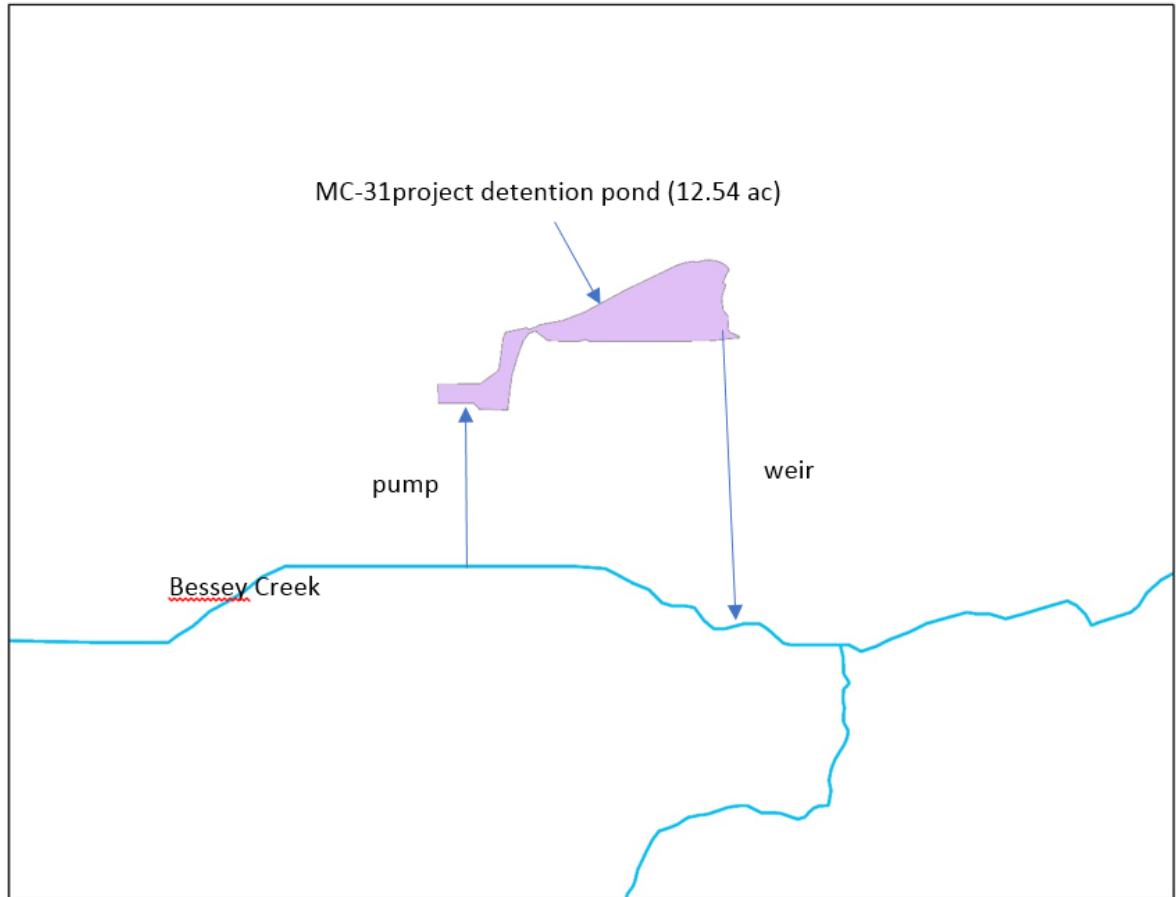


Figure 25. Model schematics accounting for MC-31 project.

Detention ponds in projects MC-17, MC-31, MC-32, and HSL-01 were simulated using reservoir module in WaSh model. Advanced water quality in the reservoirs module is simulated in a simplified approach that retains some of the characteristics of the WASP EUTRO algorithms, but allows for easier calibration to water quality data typically measured for reservoirs. These data typically can be expressed in a percent or load reduction in nutrients. The equation for the water quality constituents, ammonia, nitrate, organic nitrogen, inorganic phosphorus, organic phosphorus and carbonaceous biological oxygen demand is:

$$\frac{\partial C}{\partial t} = -kC$$

where C is the water quality constituent concentration and k is a user-specified decay rate coefficient.

Calibration efforts were made to achieve designed TN/TP removal efficiency by tuning decay rates of water variables with data from 2007 to 2011, then verification was conducted with data from 2012 to 2016. The model simulates the entire decay process of each nutrient component instead of simulating individual chemical and biological processes in detention pond. All these decay processes are reflected in decay rates. **Table 21** shows the calibration and verification results for

TN/TP removal efficiency. Please note, the agricultural BMP enrollment project described in **Section 7.1.1** was included in the model first prior to the inclusion of the other projects.

Table 21. TN and TP removal efficiency in model performance and designed performance.

Project	Model Performance				Designed Performance	
	2007 - 2011		2012 - 2016		TN Removal Efficiency	TP Removal Efficiency
	TN Removal Efficiency	TP Removal Efficiency	TN Removal Efficiency	TP Removal Efficiency		
MC-31	53%	87%	53%	87%	53%	86%
MC-17	31%	61%	30%	58%	32%	60%
MC-32	41%	78%	42%	79%	41%	78%
HSL-01/Basin1	38%	69%	20%	57%	39%	68%
HSL-01/Basin2	11%	11%	4%	4%	10%	10%
HSL-01/Basin3	10%	10%	2%	3%	10%	10%
HSL-01/Basin4	10%	10%	4%	3%	10%	10%
HSL-01/Basin5	11%	11%	2%	1%	10%	10%

From the table, we can see that MC-17, MC-31, MC-32 have consistent TN/TP removal efficiency between 2007-2011 (calibration) and 2012-2016 (verification), which are very close to designed TN/TP removal efficiency. For project HSL-01, model performance shows that model calibration period (2007 – 2011) has good agreement with designed values on TN/TP removal efficiency. Model verification period (2012 – 2016) has lower TN/TP removal efficiencies than the calibration period, because land use type in the area covered by project HSL-01 has changed from citrus and sod farm to other, such as fallow crop land, abandoned groves, and improved pastures. The inflow nutrient concentrations are less and then the lower nutrient efficiency with same decay rates.

7.1.6. Projects Scenario Results

The aforementioned five projects were incorporated into the verified WaSh model for PORs of 2007-2011 and 2012 - 2016. The model was run for both PORs. The simulated water quantity and quality results from the projects scenario run at specified observation locations were compared against the simulated time-series for the baseline model runs to quantify expected water quality improvements. **Table 22** shows the specific project scenario and the corresponding observation locations that were used to extract results. These results will be used to compare load reduction estimates for each project in the BMAP once estimated project reductions are recalculated using the updated model. **Appendix E** and **F** are plots of simulation results for 2007-2011 and 2012 - 2016 respectively, including pond depth, inflow, outflow, TN/TP load in inflow and outflow, TN/TP concentration in pond for projects MC-31, MC-17, MC-32, and four basins of HSL-01.

Table 22. Annual average load reduction for select projects

Modeled (2007-2016)		
Projects	Avg. Annual TN Red. (lbs/yr)	Avg. Annual TP Red. (lbs/yr)
MC-31	2924	796
MC-17	2163	1056
MC-32	319	79
HSL-01(B1)	145	87
HSL-01(B2)	143	27
HSL-01(B3)	129	26
HSL-01(B4)	141	26
HSL-01 (B5)	150	28

¹ The results for these projects also include the impact of the agricultural BMP enrollment project for which the results were not isolated.

To evaluate benefit of these five projects, comparison plots of TN/TP concentrations and loads between baseline and project scenarios were generated (**Appendix G**) at selected locations: S-48, S-49, S-80, Gordy Road Structure (GRS), Basin 6 outlet, and Basin 4/5 outlet. The TN and TP load reductions at these locations are presented in **Table 23**.

Table 23. Total TN and TP loads/concentrations reduction at different model output locations for 2007-2016

Location	TN Load Reduction (lbs/yr)	TP Load Reduction (lbs/yr)
S48	31,041	4,982
S49	29,101	3,616
S80	27,822	4,872
GRS	3,571	661
Basin 6 outlet	441	331
Basin 4/5 outlet	1,808	661

Except for the FDACS BMP enrollment project, the other four projects are located in tidal basins (HSL-01 in South Fork, MC-31 in Basin 6, and MC-17/MC32 in Basin4/5). Thus, the TN/TP reductions at sites S-48, S-49, S-80, and GRS (Gordy Road Structure) represent the benefits of FDACS project implementation in the C-23, C-24, C-44/S-153, and Ten Mile Creek sub-basins. These four sub-basins have TN/TP reductions in percentage as follows: 5.3%/4.3%, 5.1%/3.9%, 2.7%/3.5%, and 2.7%/2.5%, resulting from FDACS BAP enrollment program. The TN/TP reductions in percentages are 2.1%/8.1% for Basin 6, and 6.6%/10.9% for Basin 4/5. Basin 4,5, and 6 have very small agriculture land use, and these TN/TP reductions are due to detention pond implemented in the basins. We can also see that the detention ponds generally have more efficiency than the BMP enrollment program in TN/TP reduction.

Sites SE 01, SE 02, SE 06, and SE 08 are within in the estuary. The changes in TN/TP concentrations are attributed to the both the FDACS BMP enrollment project and the detention

ponds in the model. Their TN concentration reduced in a range of 0.01 to 0.03 mg/L while TP concentration reduced in a range of 0.003-0.006 mg/L.

7.2 Septic Tank Removal Scenario

As described in **Section 4.13**, loading from all relevant septic tanks were aggregated into 14 different locations across the entire model domain (see **Figure 15b** and **Table 5**) and the corresponding model output locations were assigned to different aggregation points for the purpose of extracting results for the baseline conditions. For the septic tank removal scenario, septic loading to all 14 aggregation locations was completely turned off and the WaSH model was run for two PORs. The first POR that was simulated was from 2007 through 2011 using the hotstart conditions from the baseline model run for POR 1995 through 2006 (note: the septic tanks were active during this period). The second POR from 2012 through 2016 was subsequently simulated using the hotstart conditions from the end of the first POR run.

The water quality output at a reach location by the WaSH model has time-series data for simulated flows and concentrations for various water quality parameters for the simulated POR. The concentrations for both the upper and lower section of the channel are provided. For computing total nitrogen values for both baseline and septic tank removal simulations, the flow was assumed to be equally divided between upper and lower sections of the channel. Thus, half of the simulated flow value was multiplied by the corresponding concentration values to generate loads. The computed loads in the upper and lower section of the channel were summed and reported as a single value for reporting and graphing.

Appendix H show the TN annual load reductions between the baseline scenario and no septic tanks scenarios. **Table 24** shows the average annual TN load reduction computed at the model output locations for the 10-year POR (2007 through 2016).

Table 24. Annual Average TN Load Reduction at Select Model Output Locations

Model Output Location	Avg. Annual TN Load Reduction (lbs/yr)
S-153	65
SE-08	611
SLT_7_Basin6	267
S80	311
SLT-9_Basin4_5	823
SE01	1936
SE03	830
SE02	2344
HR-1	946
S49	485
SE06	856
SE12	57
SE13	894
GRS	38

8. Conclusions and Recommendations

A watershed water quality model has been developed for the SLREW. The model domain covers the C-23 basin, C-24 basin, C-44/S-153 basin, Ten Mile Creek basin, North Fork, South Fork, Basin 4/5/6, and South Coastal basin. The model is a hydrologic, hydrodynamic, and water quality model originally developed for the unique hydrologic conditions in South Florida (URS, 2008d). The model was based on the previously developed four sub-basin models by URS (2003 and 2008d). The water quality simulation represents the physical processes affecting DO, BOD, and chlorophyll *a* in the SLE. In support of the BMAP, the model was calibrated using available SFWMD data from 2001 through 2006 and verified with available SFWMD data from 1995 through 2000.

Overall, the model was well calibrated and verified. The simulated daily, monthly, and annual flows show good agreement with the measured data. The monthly variation was well simulated with $R^2 \geq 0.82$, $-19.7\% \leq \text{PBIAS} \leq 6.7\%$, and $\text{RRE} \leq 8.2\%$.

The comparison of simulated and measured time series plots for the water quality data were generally in good agreement. The rating metrics in calibration and verification based on statistics PBIAS and RRE for model performance were 86% good or very good, 9.7% fair, and 4.3% poor for daily data. The poor performance that was observed for chlorophyll *a*, ammonia, and nitrate can mostly likely be attributed to the lack of reliable chlorophyll *a* EMC data in addition to extremely reactive ammonia and nitrate. However, since the primary objective of the model simulations was to provide accurate estimates of TN and TP only, the poor model performance for chlorophyll *a*, ammonia, and nitrate is not expected to have any impact on the final loading or the load reduction estimates that were developed from the model output.

Annual TN and TP loads from 1995 to 2006 were also calculated using simulated and measured data and the results were compared. The comparison plots and evaluation statistics indicate that the model can predict annual TN and TP loads well. Generally, the comparison of simulated with measured data indicates that the model reasonably and closely reproduced the flow patterns and captured the variation in nutrient dynamics. As the alternative scenarios continue to be evaluated, the results may be used in the future to support restoration activities in the St. Lucie BMAP.

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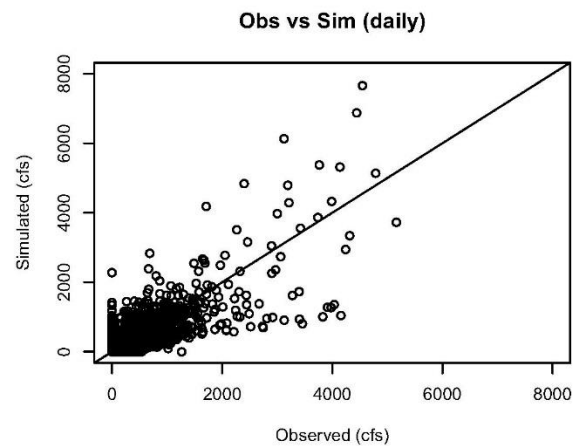
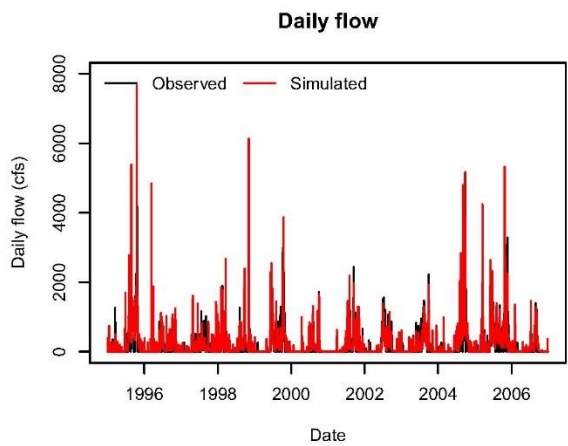
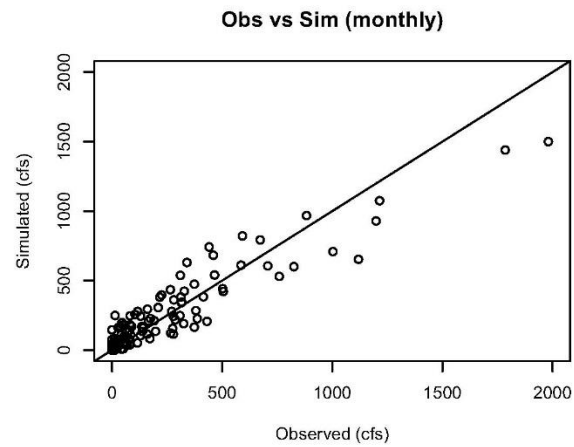
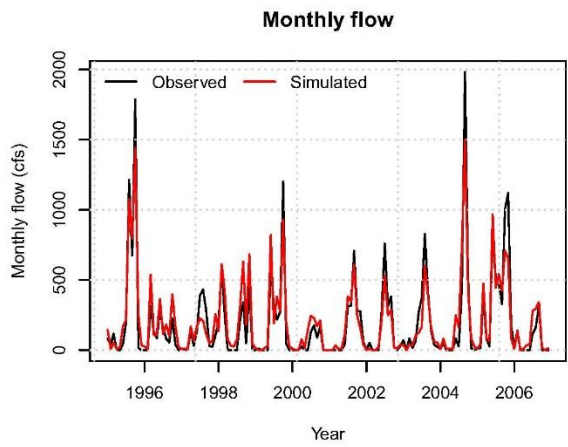
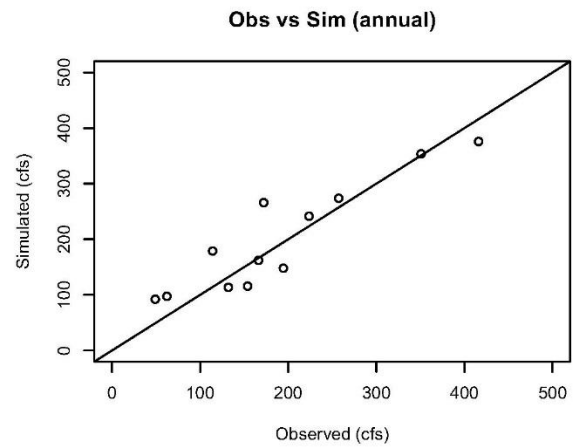
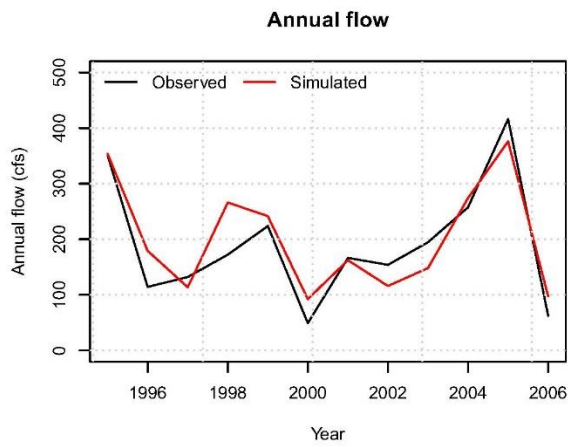
Appendices

Appendix A: Flow calibration plots of comparison between measured and simulated flow

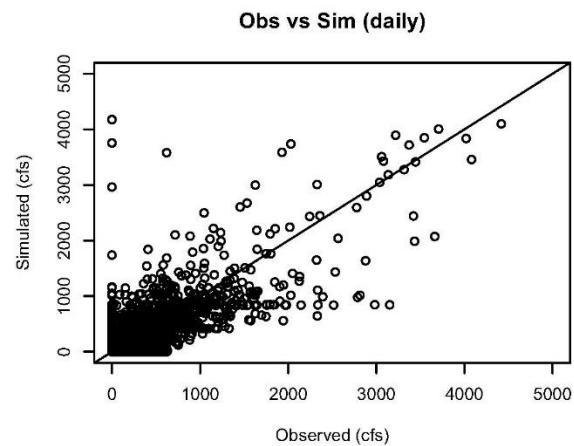
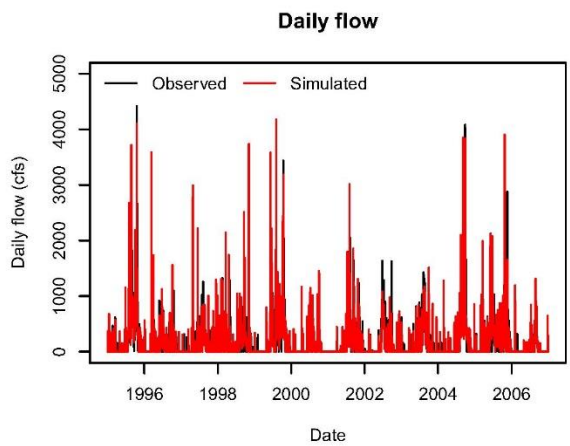
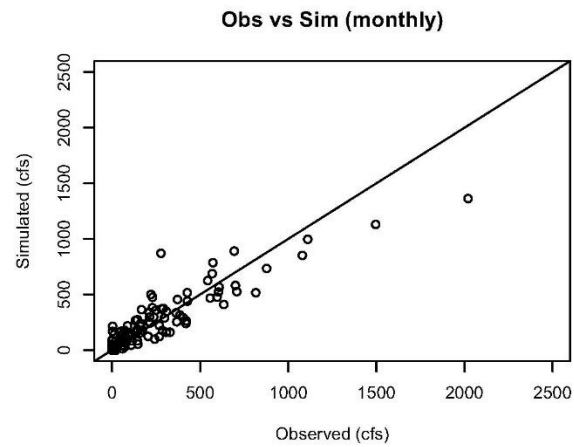
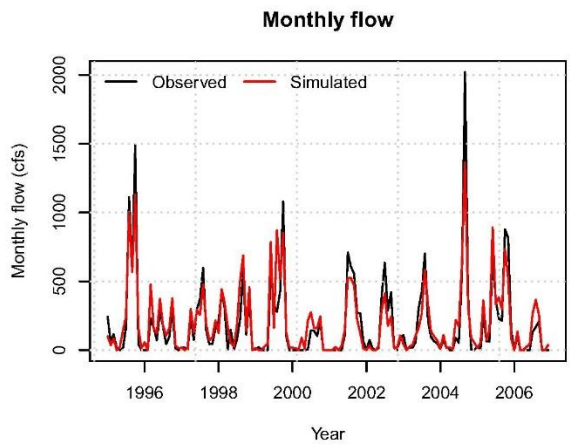
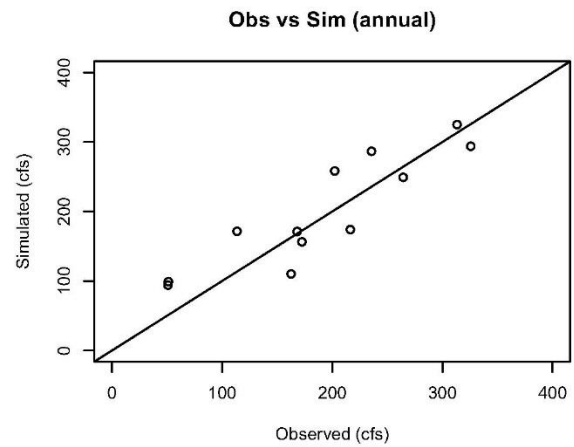
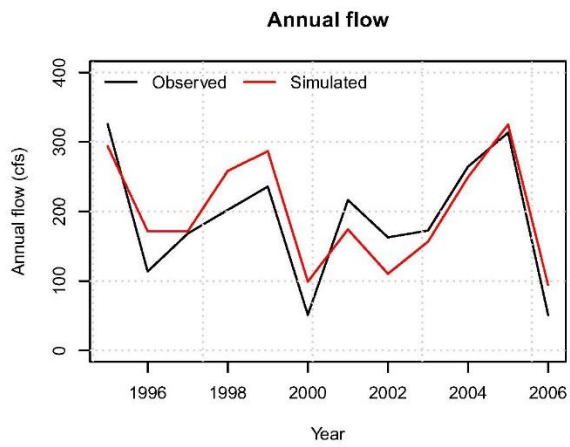
Model Calibration: 2001–2006

Model Verification: 1995–2000

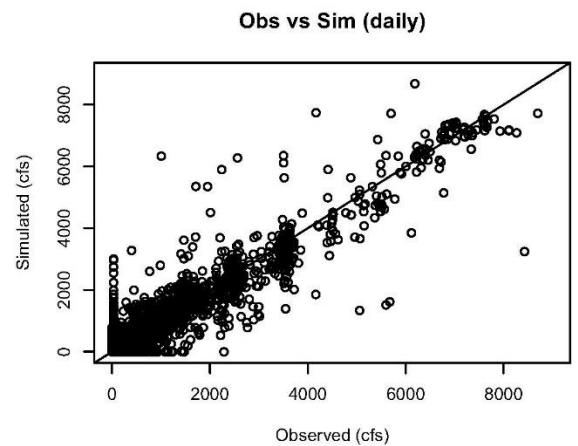
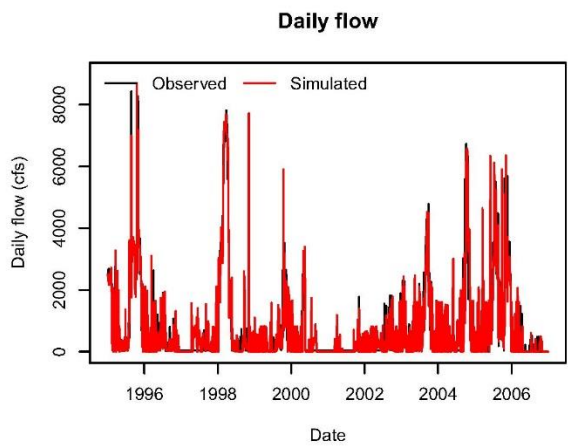
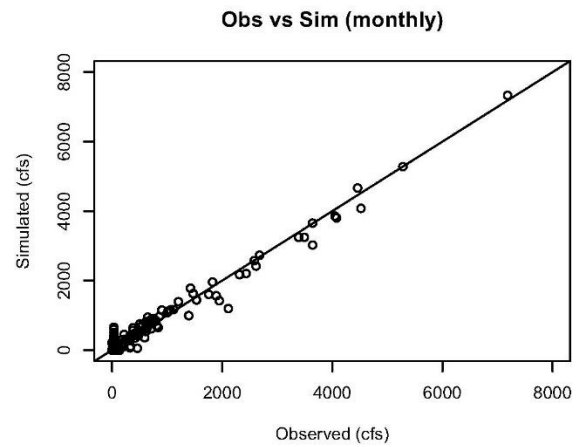
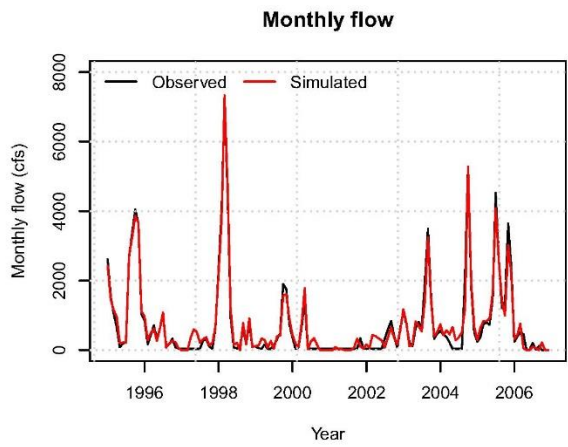
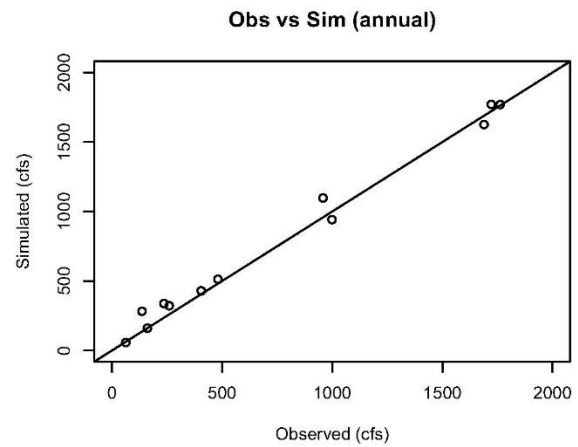
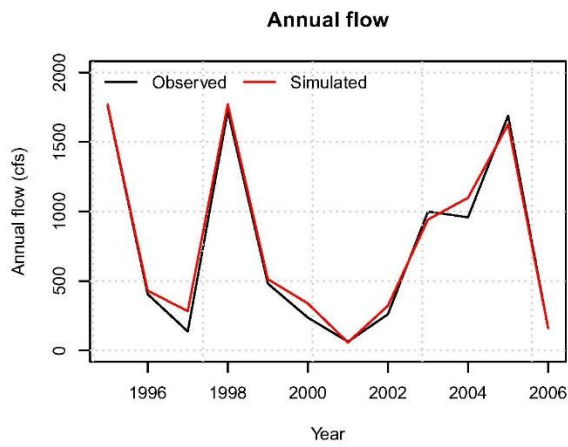
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Comparison plots of observed vs simulated flow at S-97



Comparison plots of observed vs simulated flow at S-49



Comparison plots of observed vs simulated flow at S-80

Appendix B: Model parameters and their values resulting from flow calibration

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Table B-1. Hydrologic model parameter

Land use	UZSN	LSZN	NSUR	LZETP	INFILT	INFILD	CEPSC	IRC	INTFW	CANPMPARM	PMP_UC	PMP_LC
Urban	0.08	0.7	0.25	0.28	0.01	2	0.1	0.1	2	0.33	4.125	1.375
General Agriculture	0.25	2.1	0.4	0.95	0.01	2	0.1	0.1	2	0.3225	6	2
Citrus	0.25	2.1	0.4	0.95	0.03	2	0.15	0.2	1	0.3	6	2
Rangeland	0.23	1.9	0.4	0.76	0.01	2	0.1	0.1	2	0.2475	4.125	1.375
Upland Forests	0.23	1.9	0.4	0.76	0.01	2	0.1	0.1	2	0.2175	4.125	1.375
Water	0.07	0.6	0.07	0.24	0.01	2	0.03	0.1	0	0.165	0.75	0.25
Wetland	0.23	3	0	0	0.001	2	0.1	0.1	0	0.165	0.75	0.25
Barren land	0.05	0.4	0.4	0.16	0.01	2	0.1	0.1	2	0.165	4.125	1.375
Transportation, Communication, Utilities	0.14	1.2	0.4	0.48	0.01	2	0.1	0.1	2	0.285	4.125	1.375
Range in literature*	0.05-2.0	2.0-15	0.05-0.5	0.1-0.9	0.001-0.5	1.0-3.0	0.001-0.4	0.3-0.85	1.0-10	-	-	-

* This range is from EPA (2000), which was synthesized based on parameter values for model applications in over 40 watersheds in 14 states prior to 1999.

Table B-2. ET pan coefficient, river roughness, and canal bed conductance

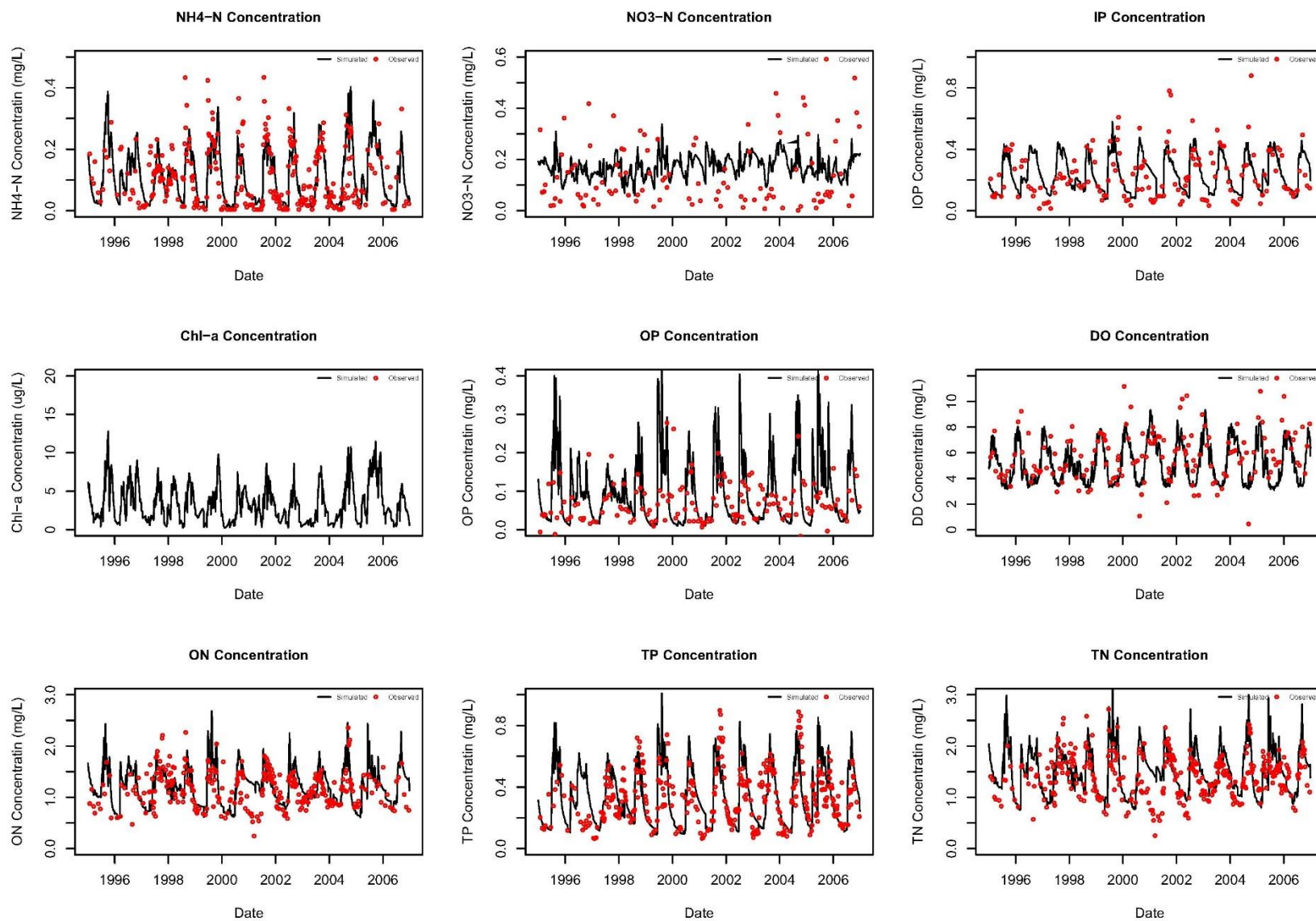
Basin	Land Use	PAN Coefficient	River roughness (Manning's n)	Tertiary canal conductance	Primary canal/river conductance
C-23	Urban	0.80	0.03	0.1	0.1
	Agriculture	0.76			
	Rangeland	0.92			
	Upland Forests	0.95			
	Water	1.42			
	Wetland	1.20			
	Transportation, Communication, Utilities	0.75			
C-24	Urban	0.8	0.03	0.1	0.1
	Agriculture	0.73			
	Rangeland	0.92			
	Upland Forests	0.89			
	Water	1.32			
	Wetland	1.20			
	Barren Land	0.79			
C-44/S-153	Urban	0.80	0.03	0.1	0.1
	Agriculture	0.78			
	Rangeland	0.98			
	Upland Forests	1.01			
	Water	1.42			
	Wetland	1.2			
	Barren	0.79			
	Transportation, Communication, Utilities	0.81			
Tidal Basin	Urban	0.75	0.03	0.1	0.1
	Agriculture	0.75			
	Rangeland	0.86			
	Upland Forests	0.89			
	Water	1.32			
	Wetland	1.20			
	Transportation, Communication, Utilities	0.81			

Appendix C: Comparison plots of observed and simulated water quality constituents

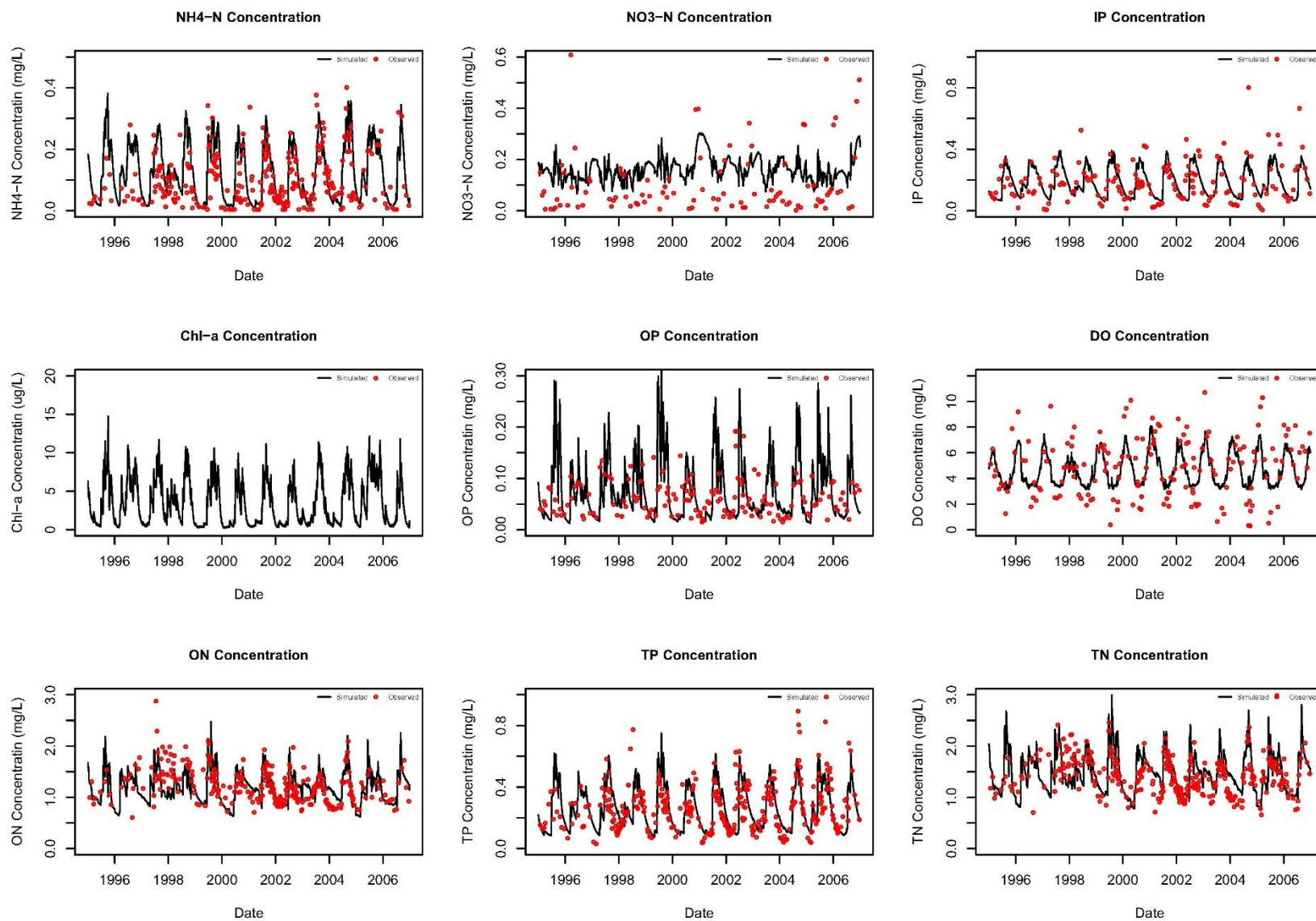
Model calibration: 2001–2006 (evaluation statistics for model performance, see **Table 10**)

Model verification: 1995–2000 (evaluation statistics for model performance, see **Table 13**)

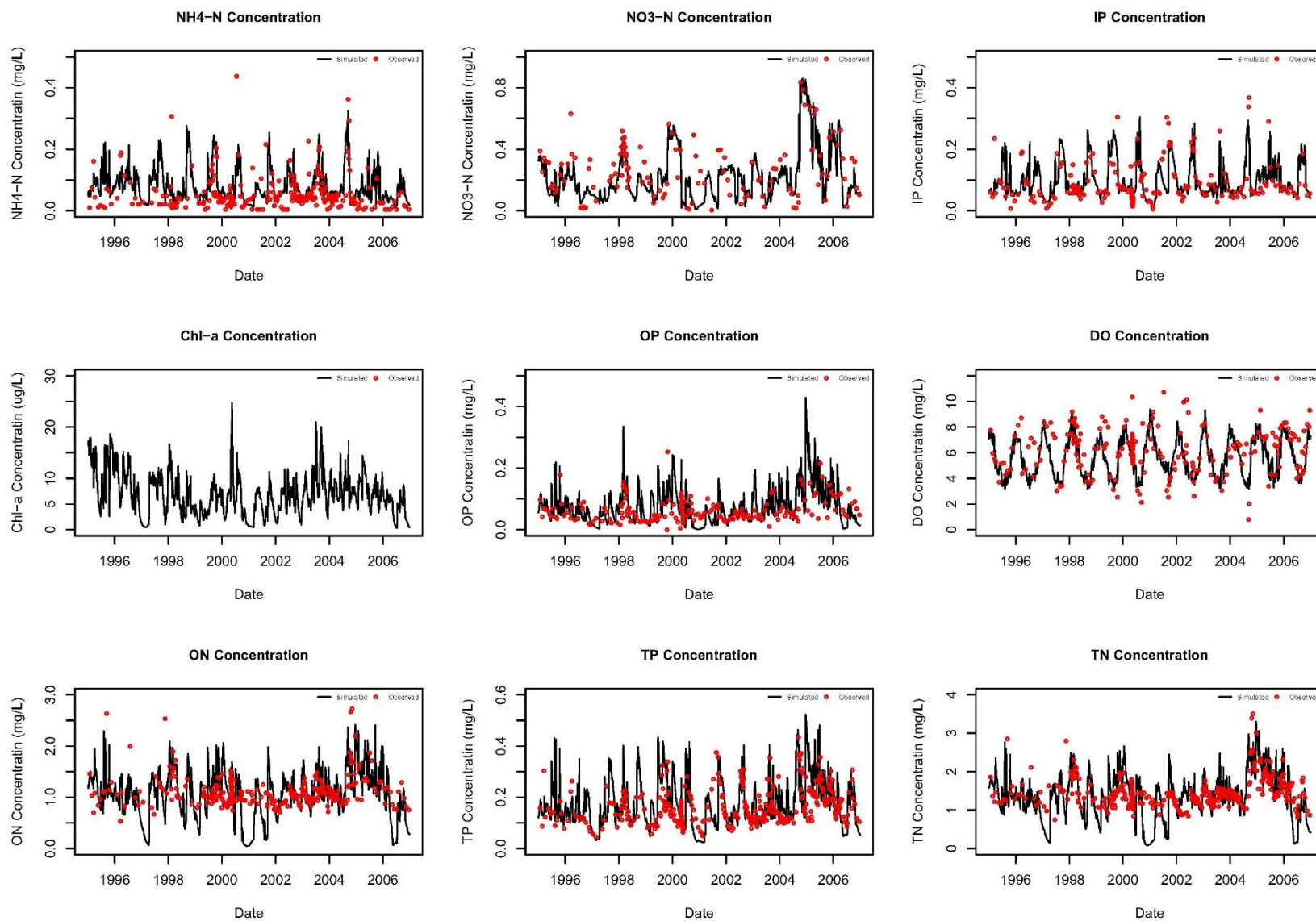
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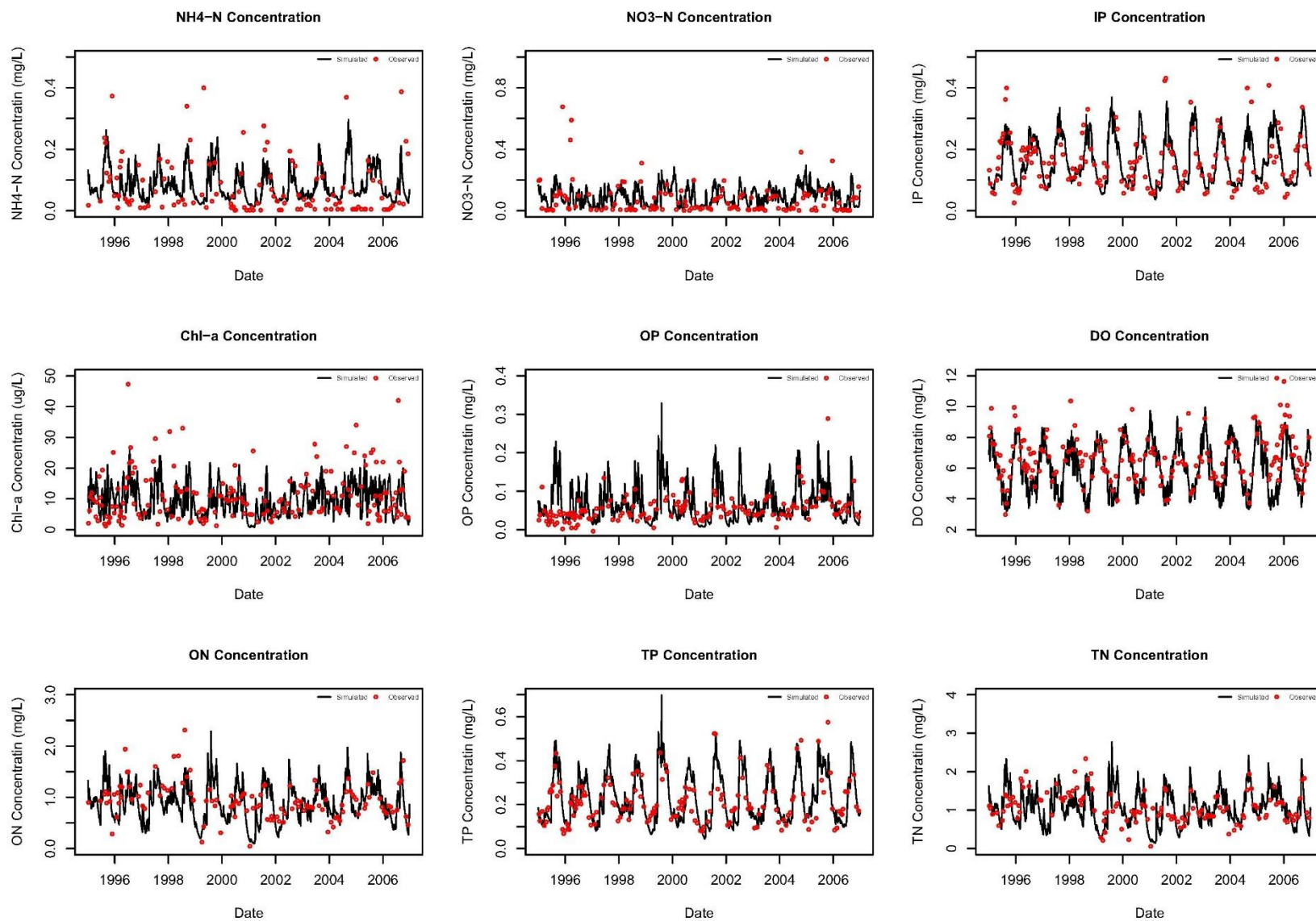
Comparison plots of observed vs simulated constituent at S-48



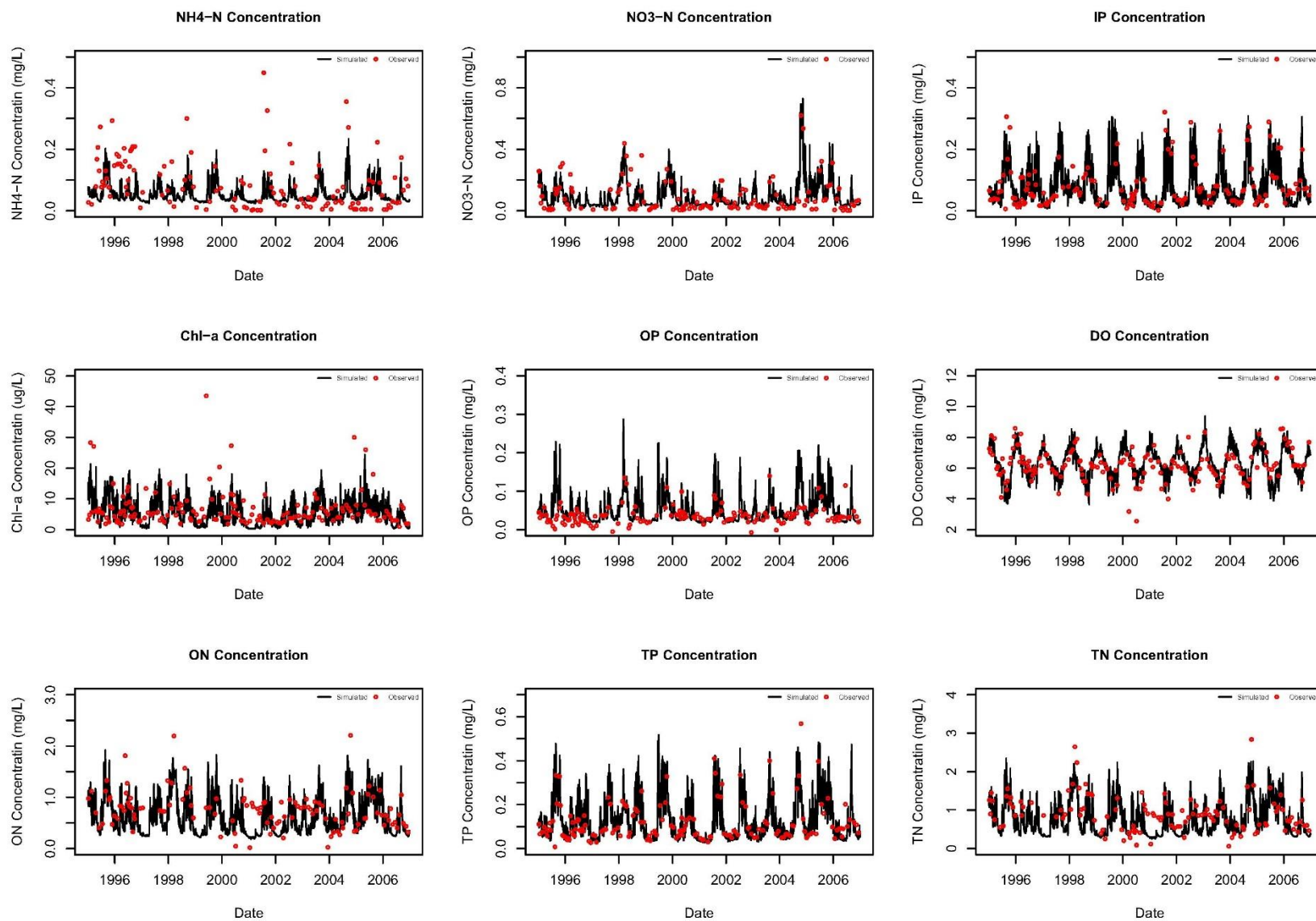
Comparison plots of observed vs simulated constituent at S-49



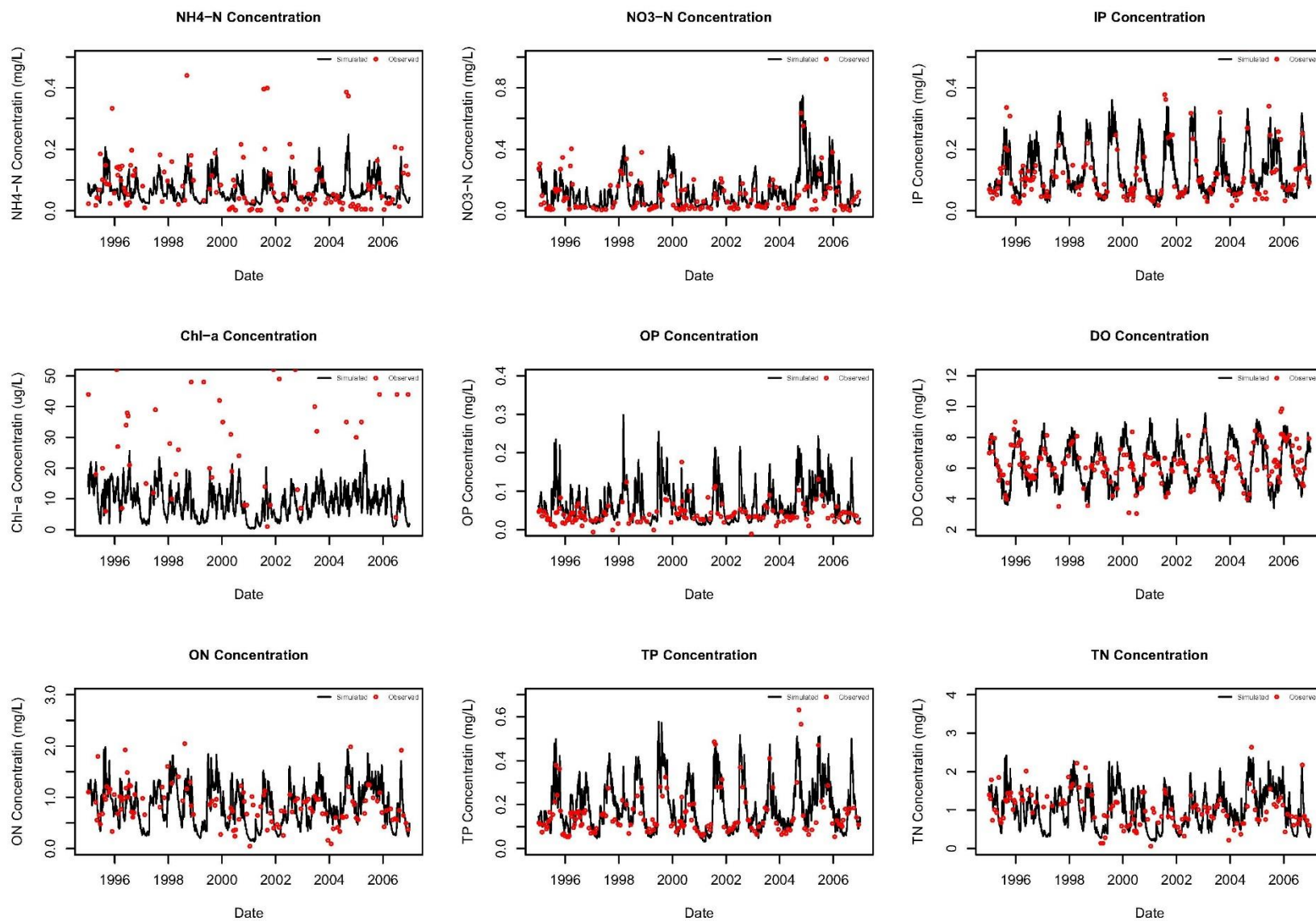
Comparison plots of observed vs simulated constituent at S-80



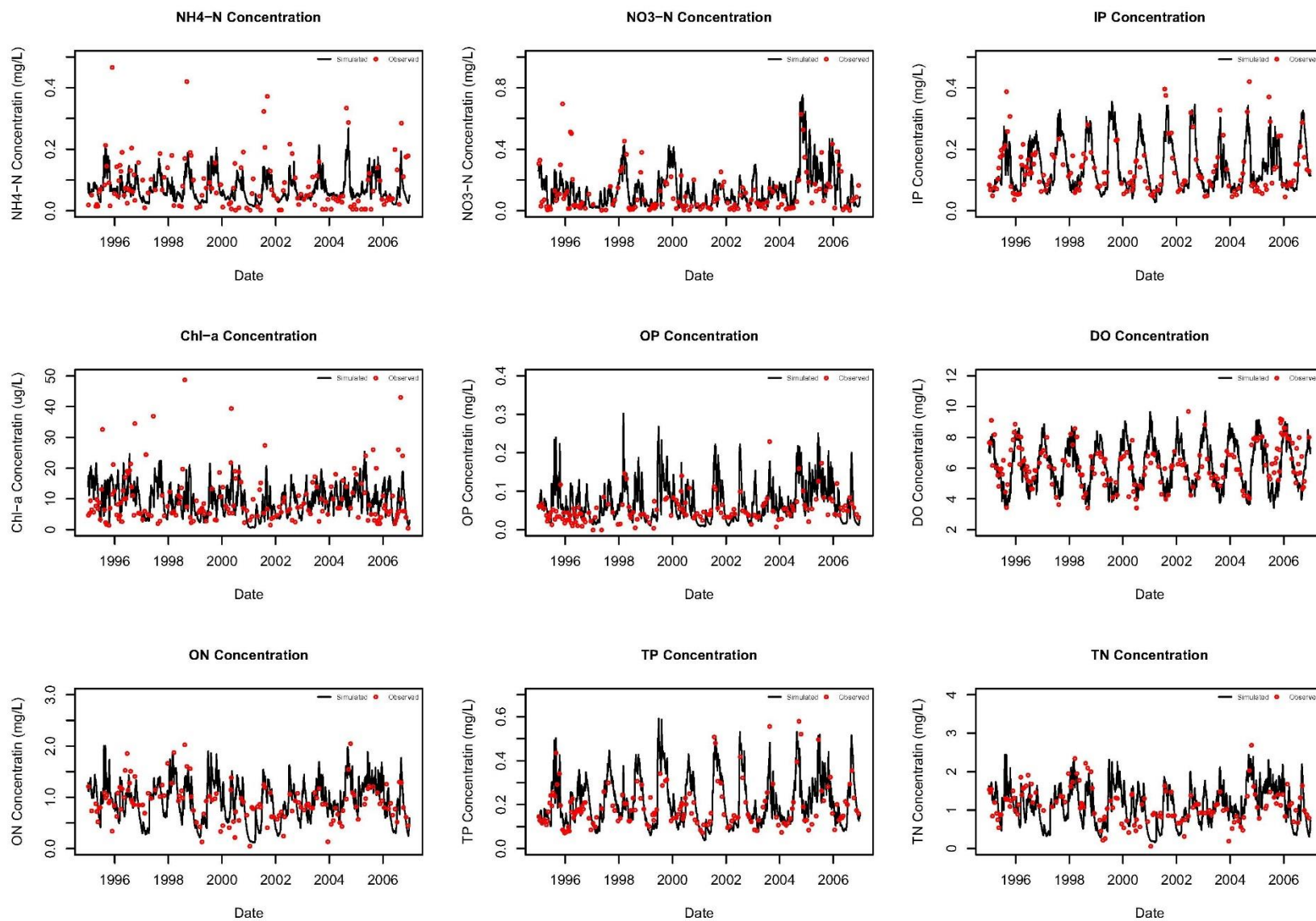
Comparison plots of observed vs simulated constituent at HR1



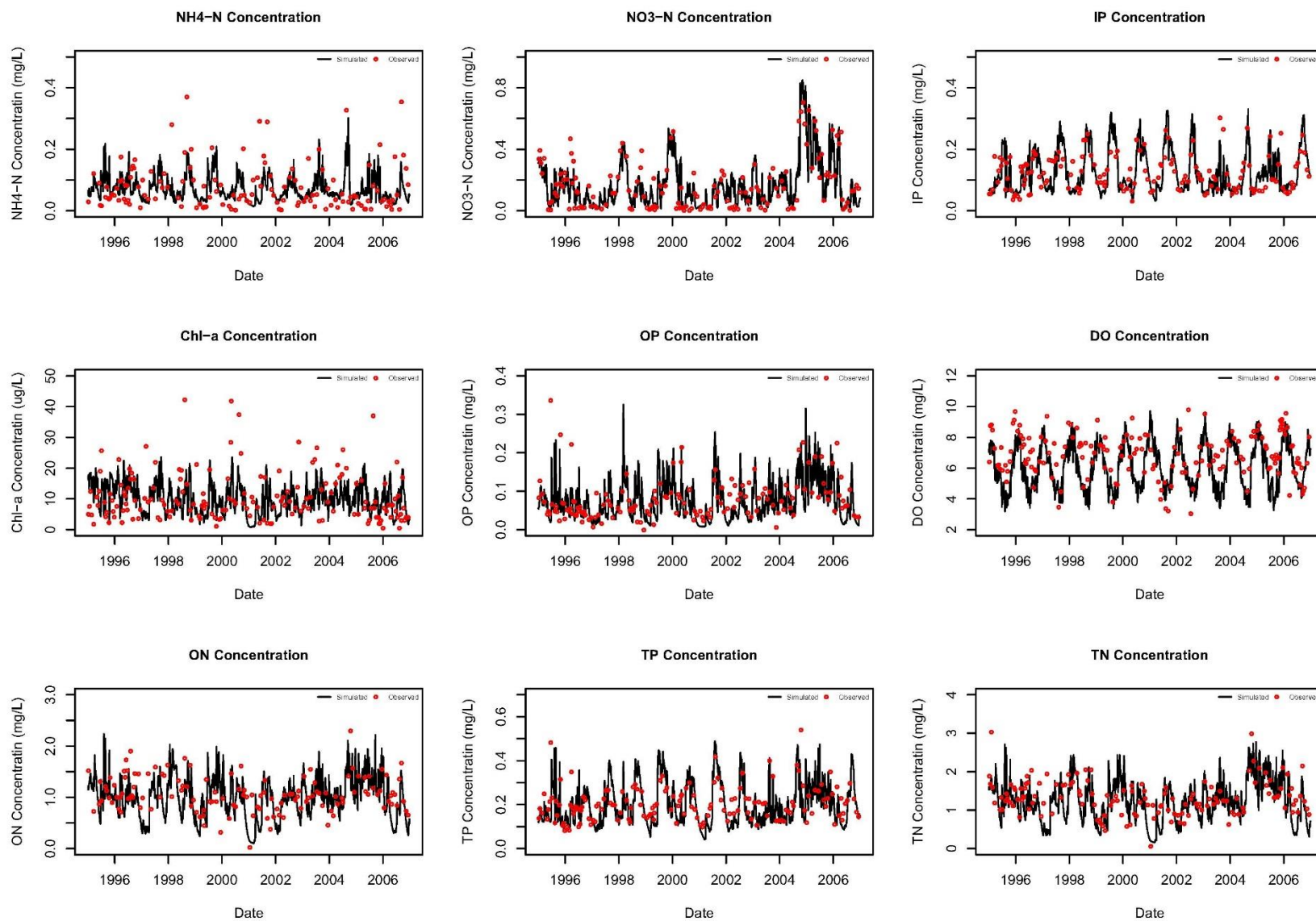
Comparison plots of observed vs simulated constituent at SE01



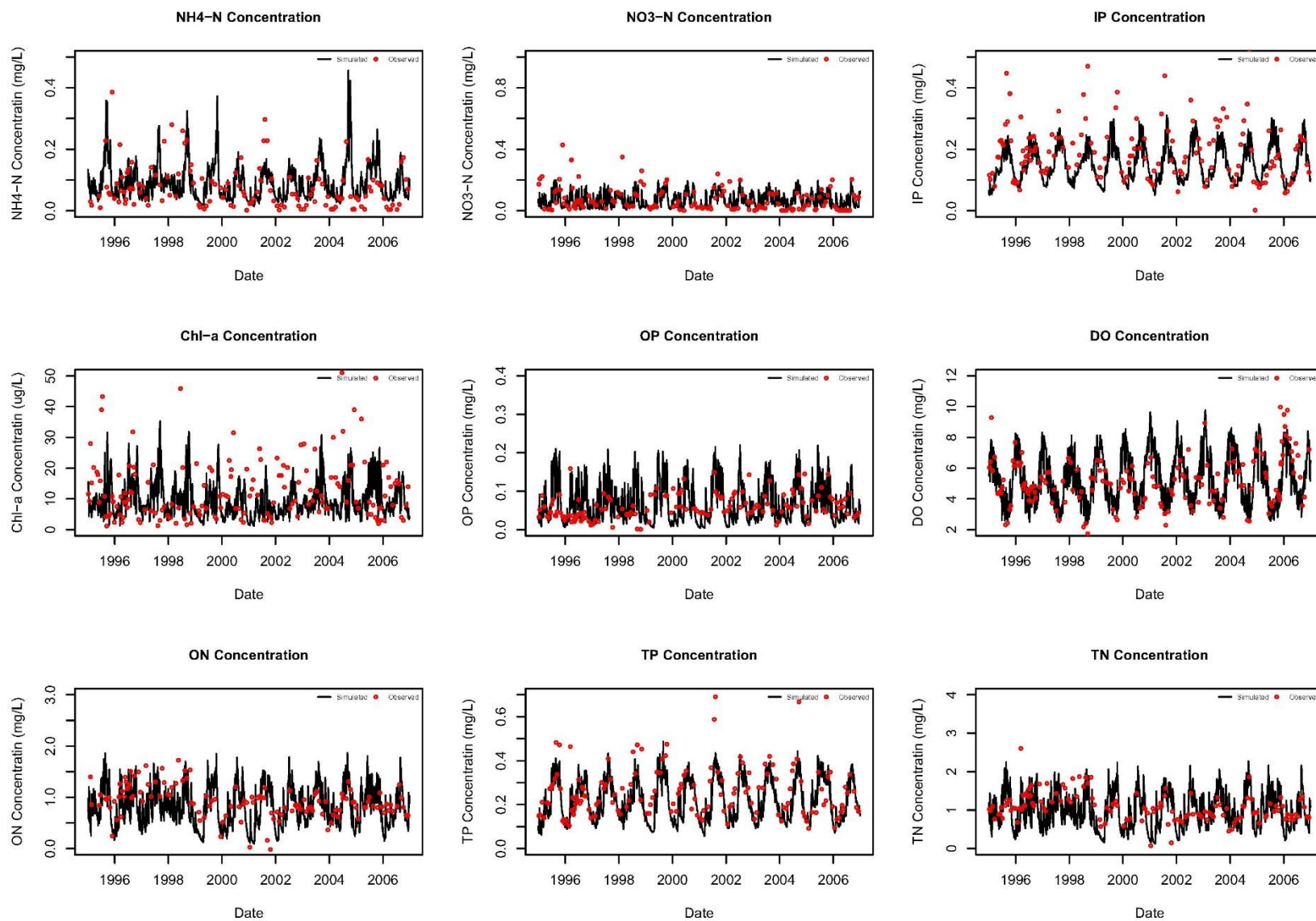
Comparison plots of observed vs simulated constituent at SE02



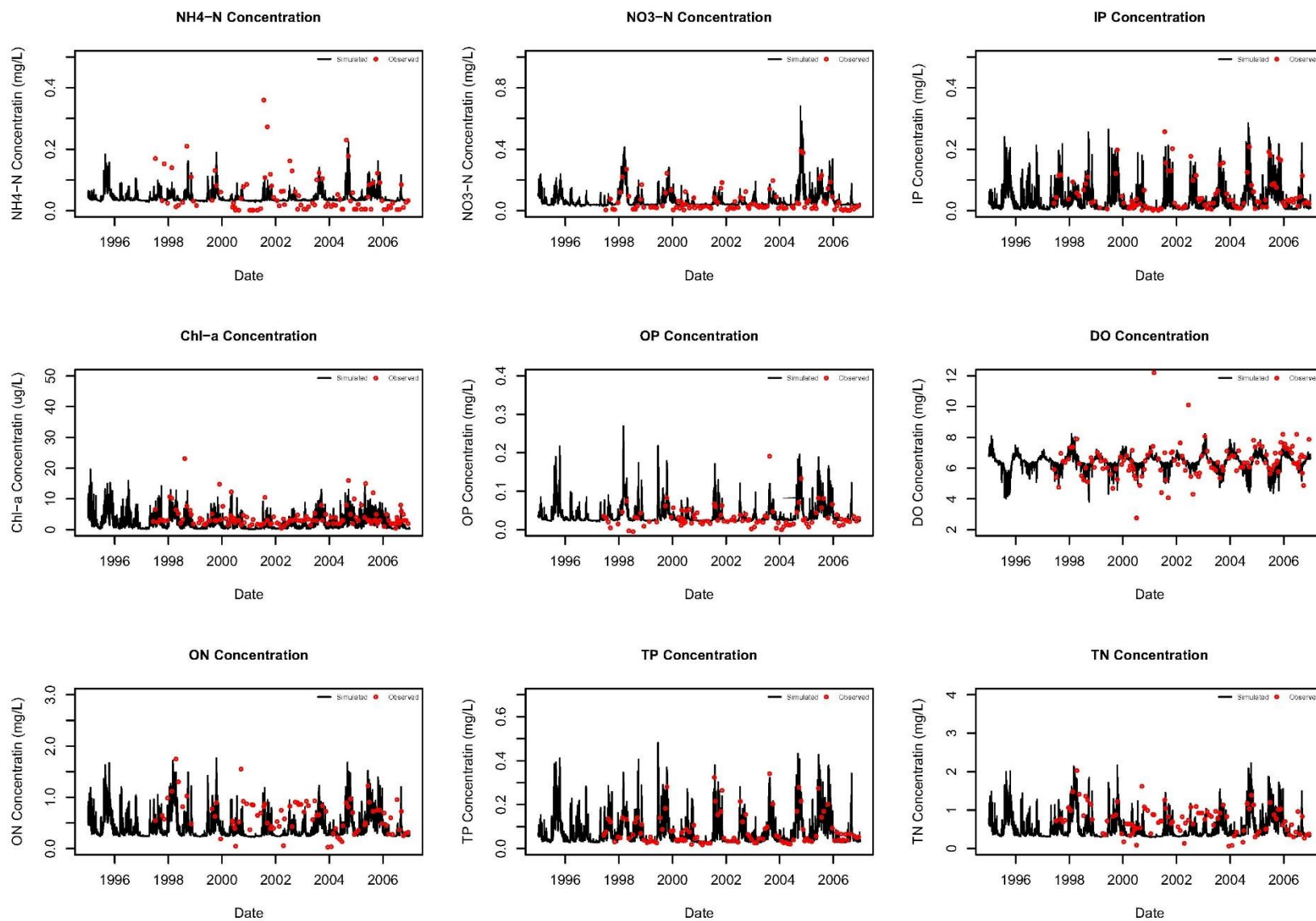
Comparison plots of observed vs simulated constituent at SE03



Comparison plots of observed vs simulated constituent at SE08



Comparison plots of observed vs simulated constituent at SE06

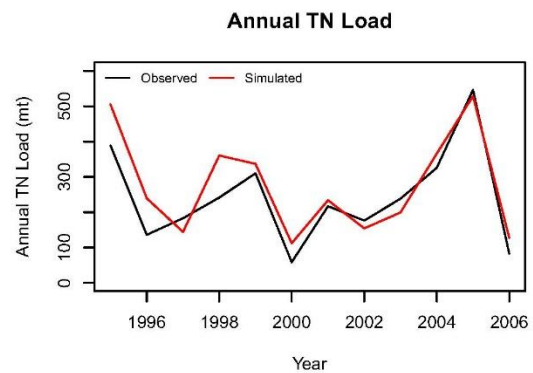
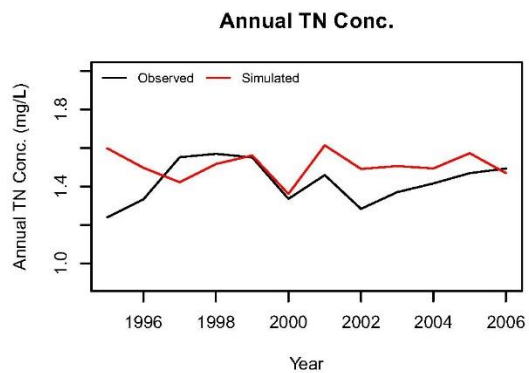
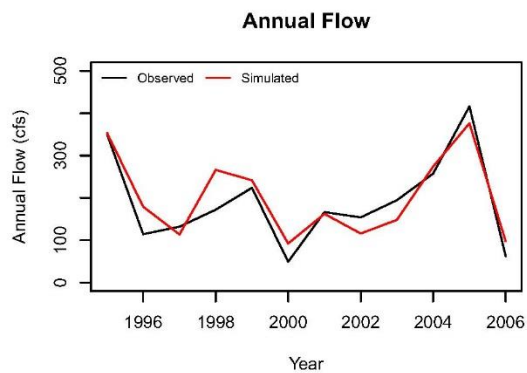
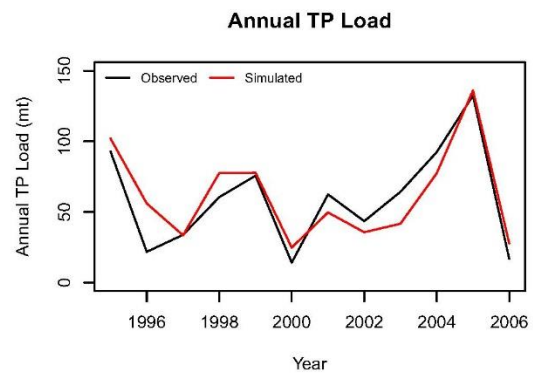
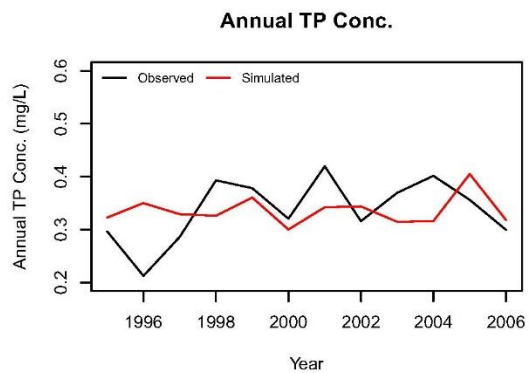
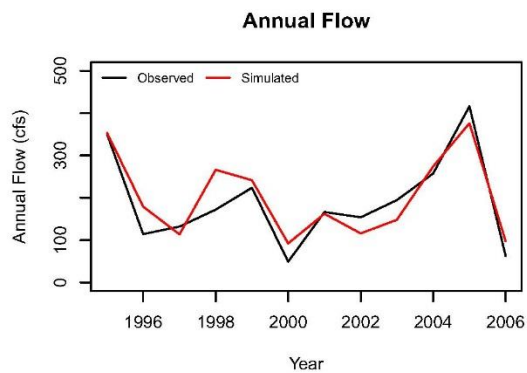


Comparison plots of observed vs simulated constituent at SE11

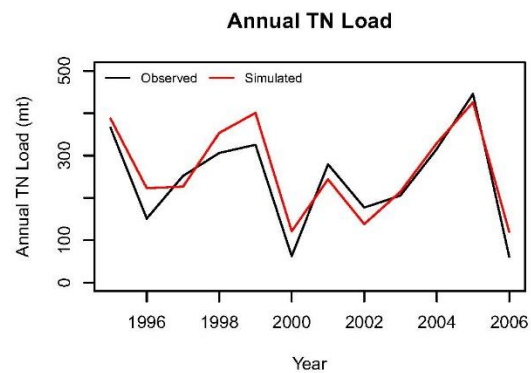
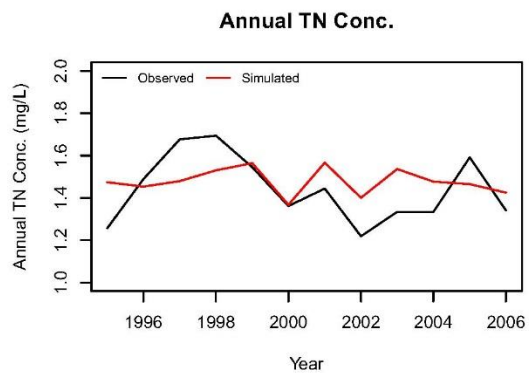
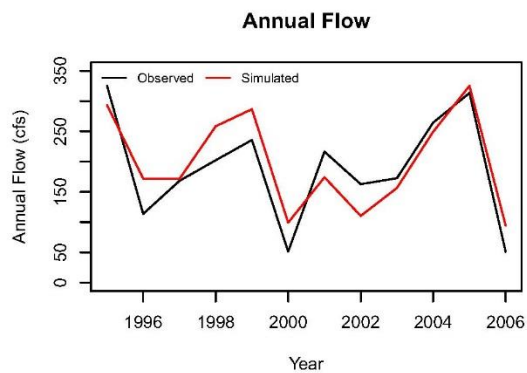
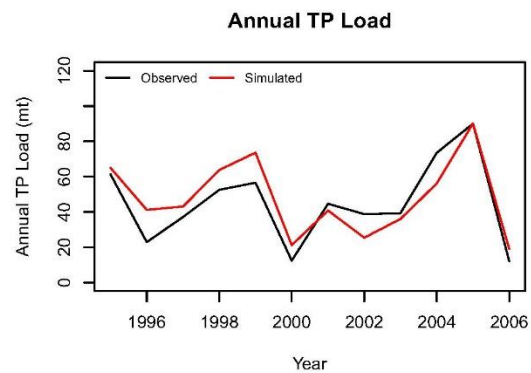
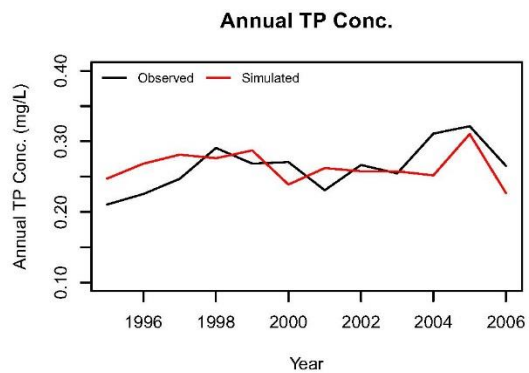
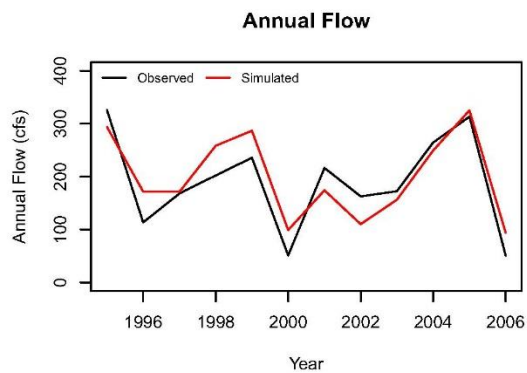
Appendix D: Comparison plots of observed and simulated annual TP and TN loads.

For evaluation statistics of TP and TN loads, see **Table 11** (calibration) and **Table 14** (verification).

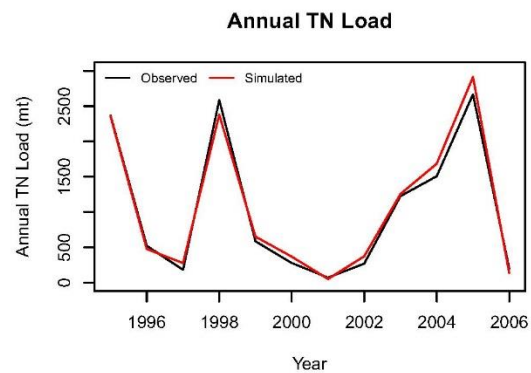
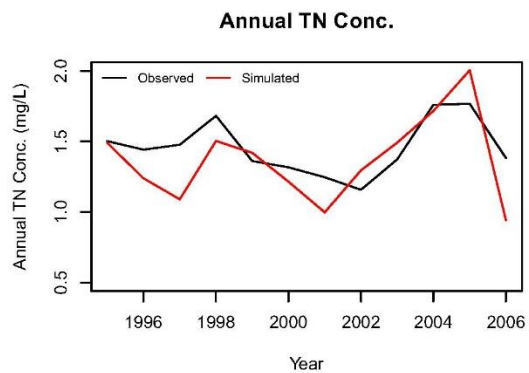
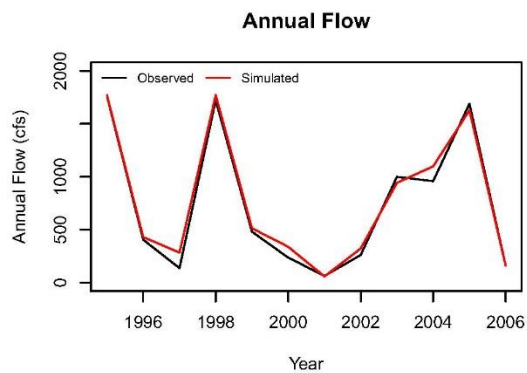
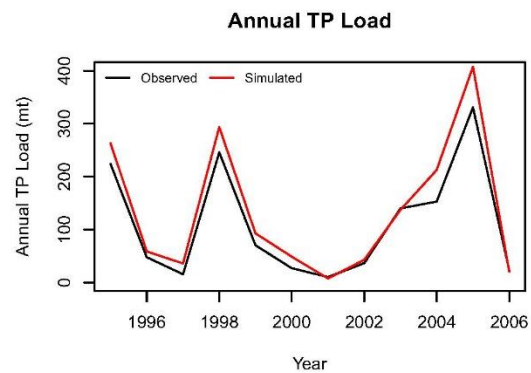
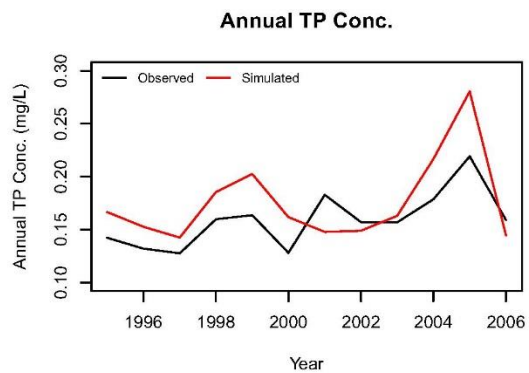
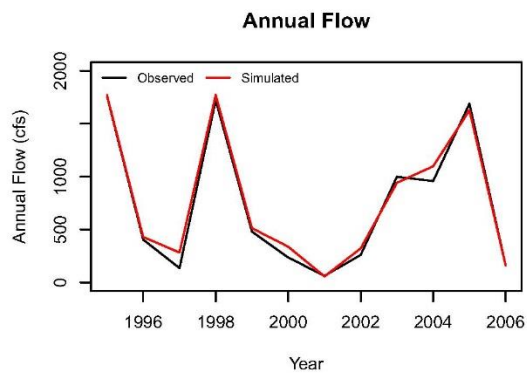
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Comparison plots of observed vs simulated flow, concentration, and load at S48



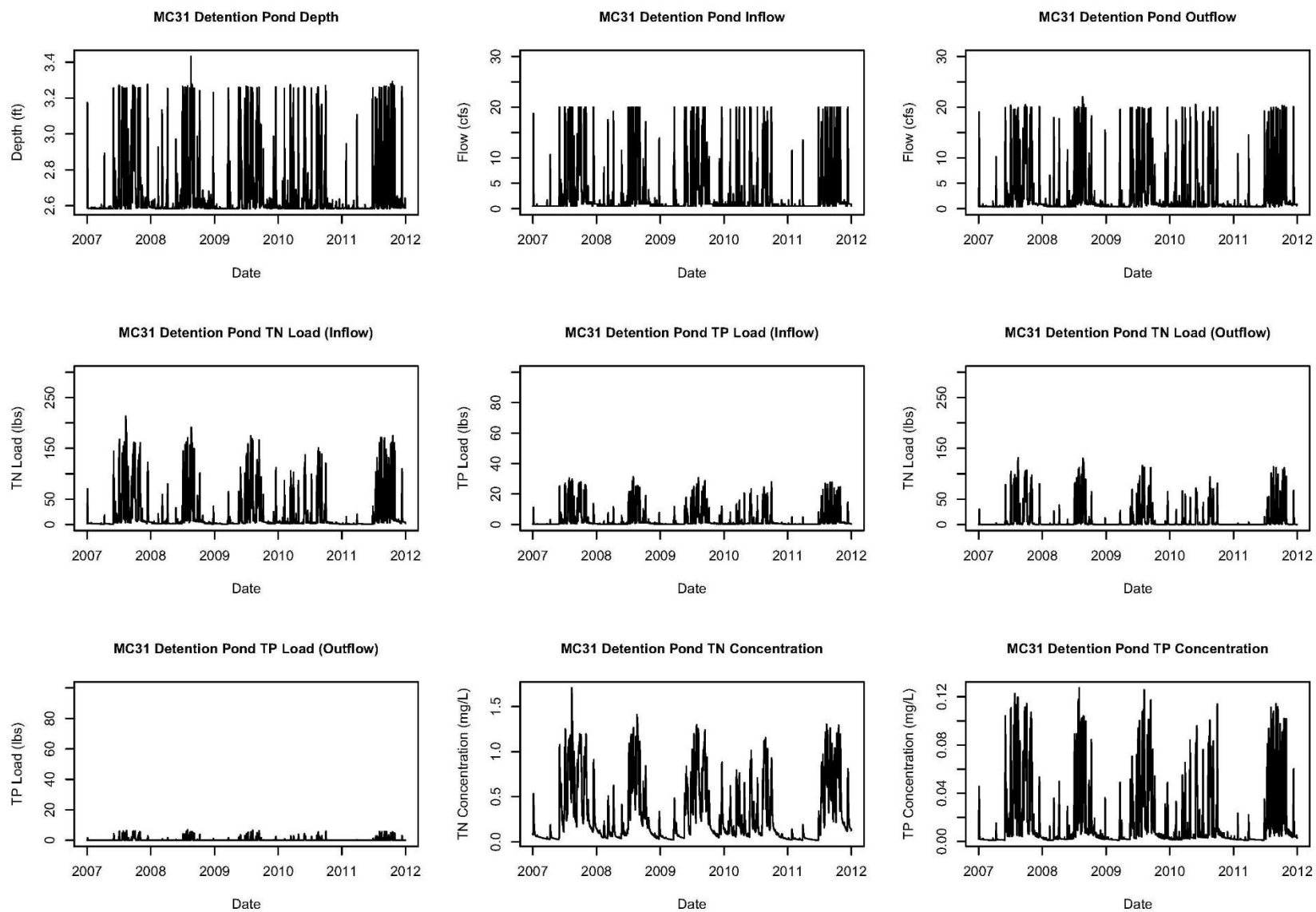
Comparison plots of observed vs simulated flow, concentration, and load at S49



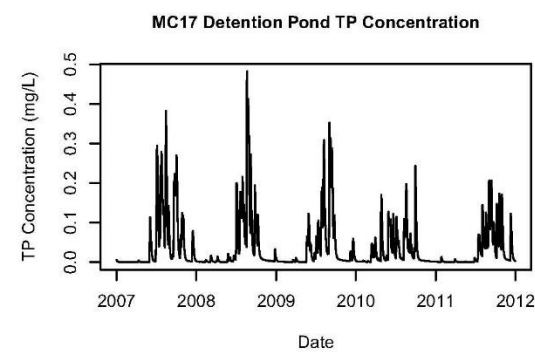
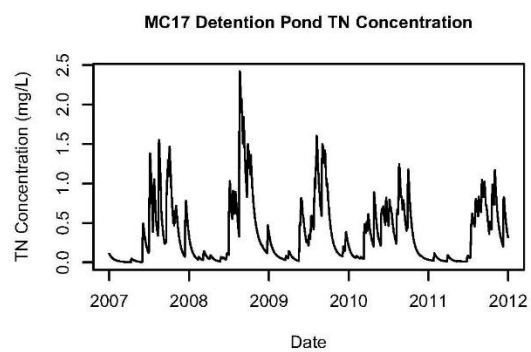
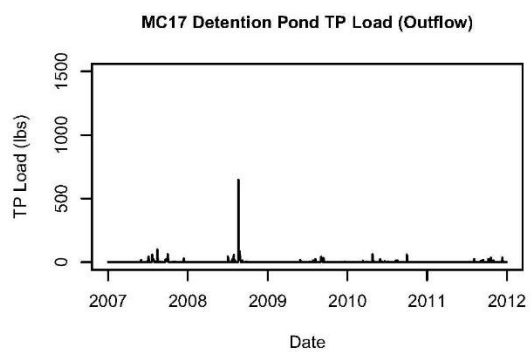
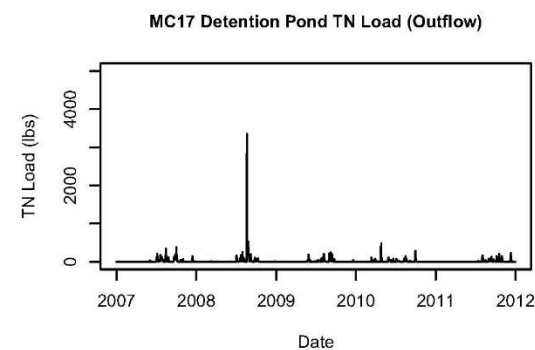
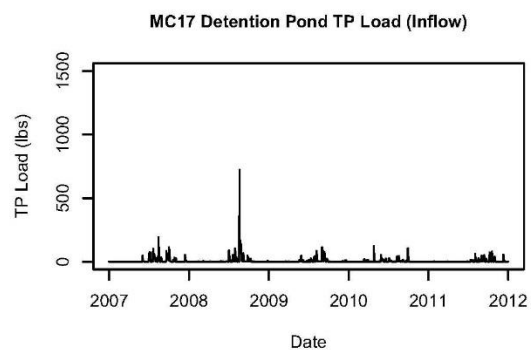
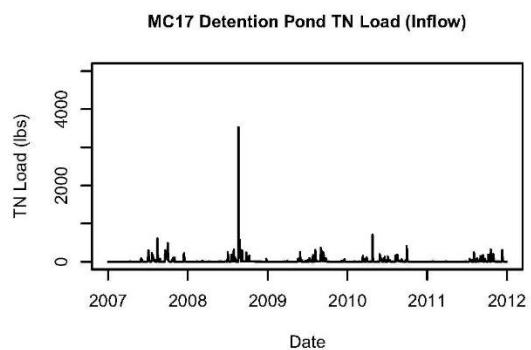
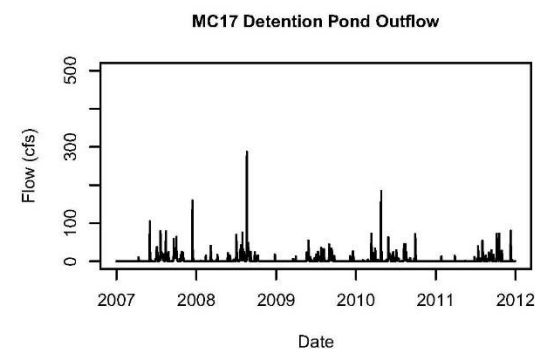
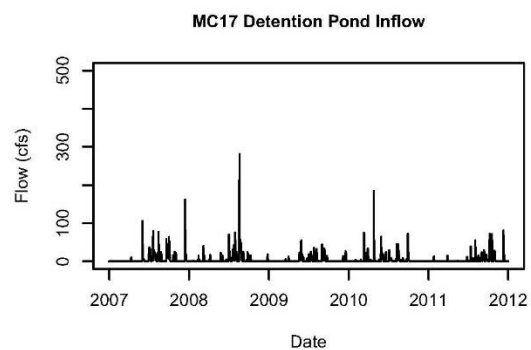
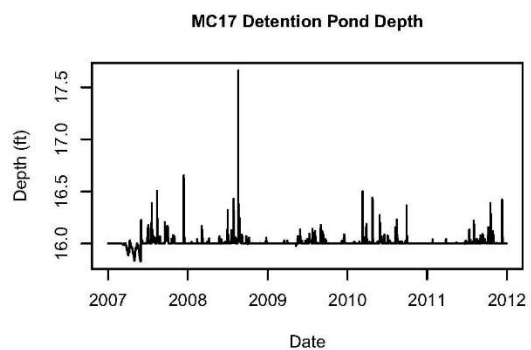
Comparison plots of observed vs simulated flow, concentration, and load at S80

Appendix E: Plots of simulation results for projects MC-31, MC-17, MC-32, and HSL-01 (2007 – 2011).

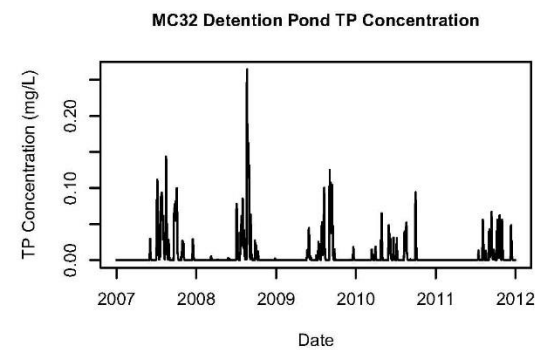
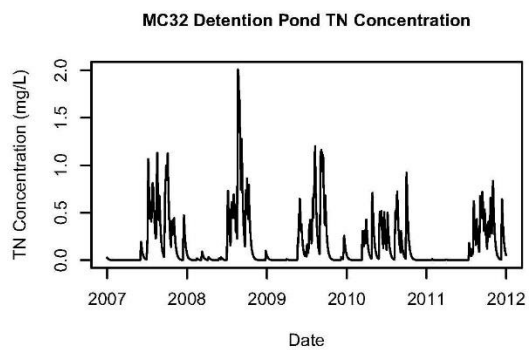
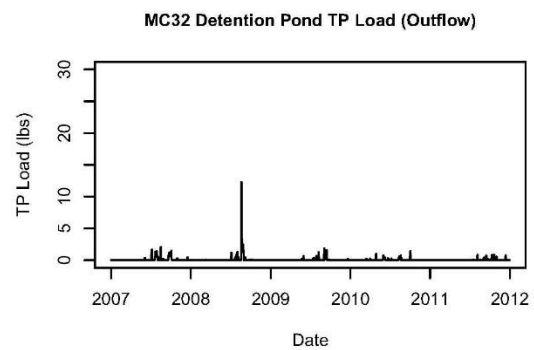
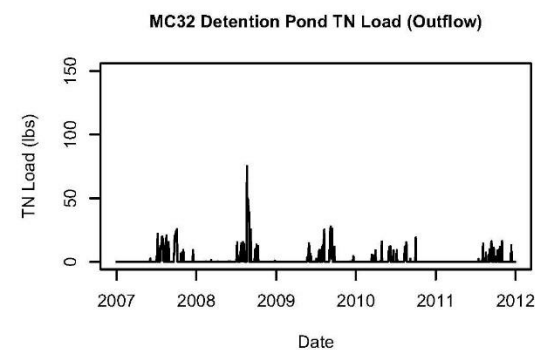
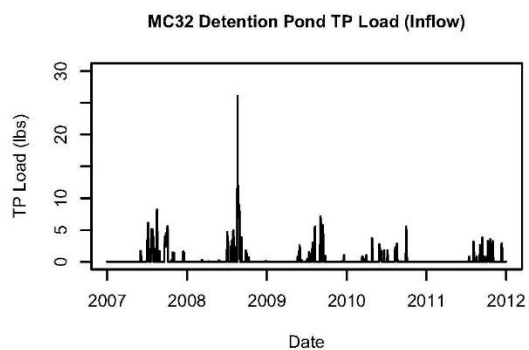
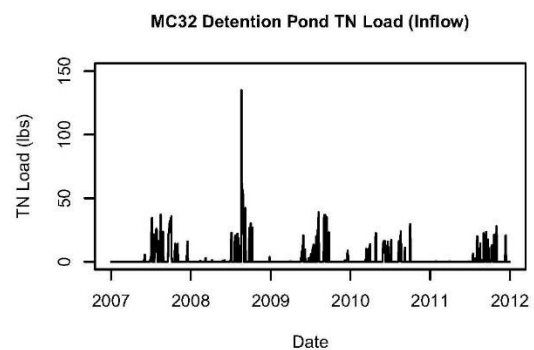
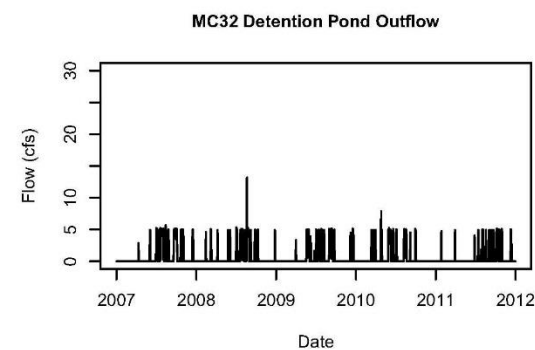
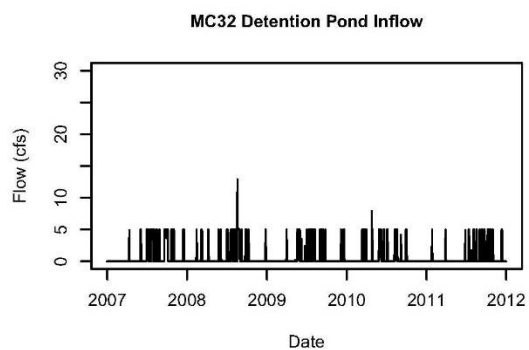
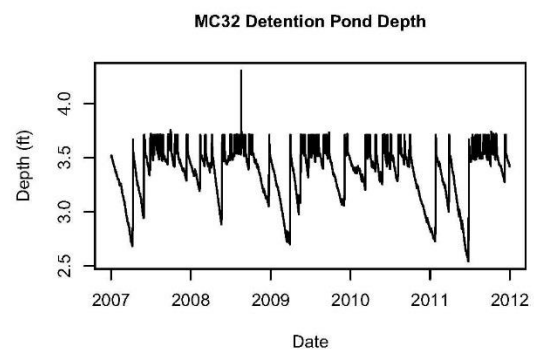
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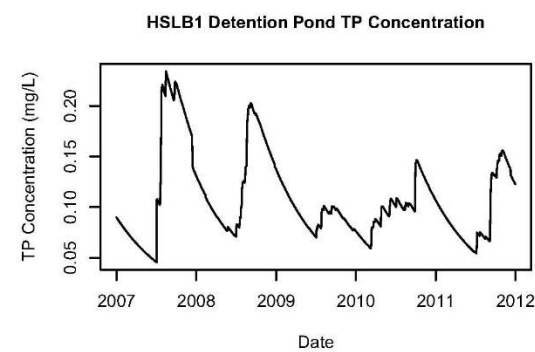
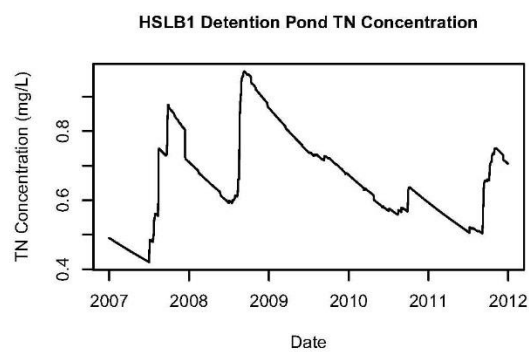
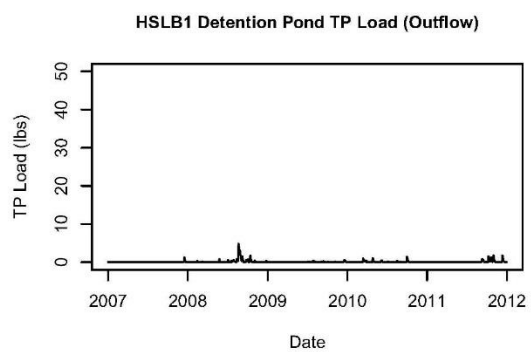
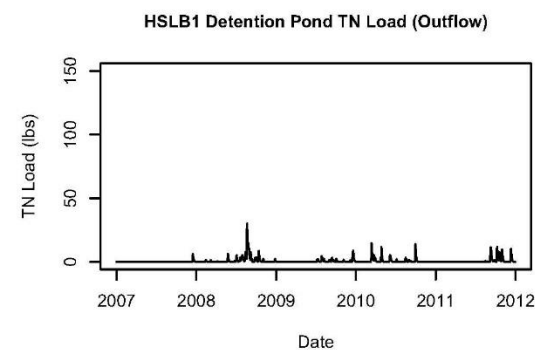
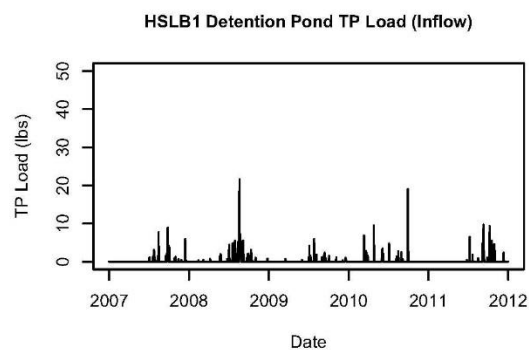
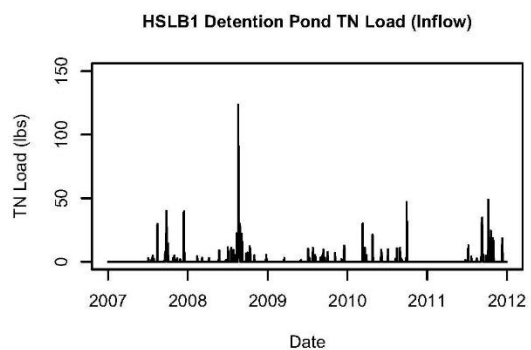
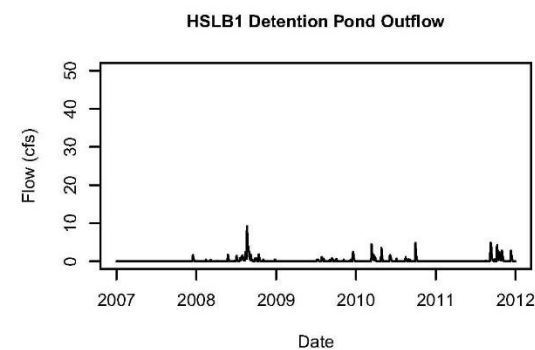
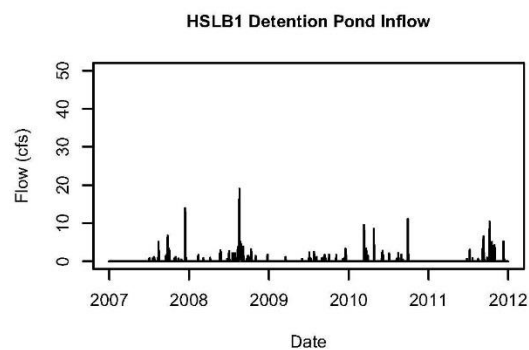
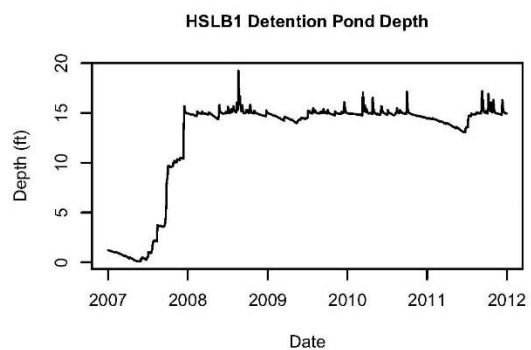
Plots of variables for detention pond of MC31



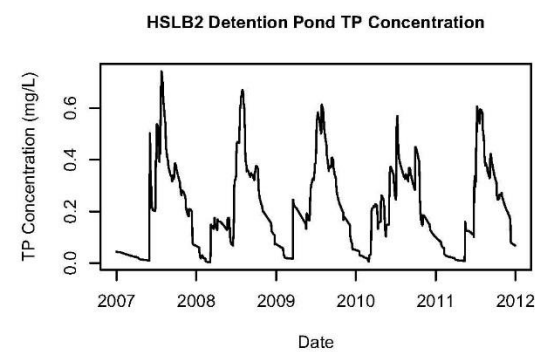
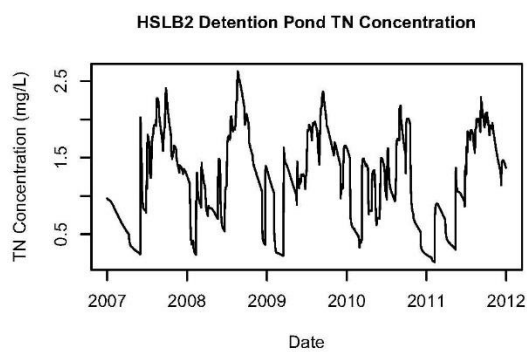
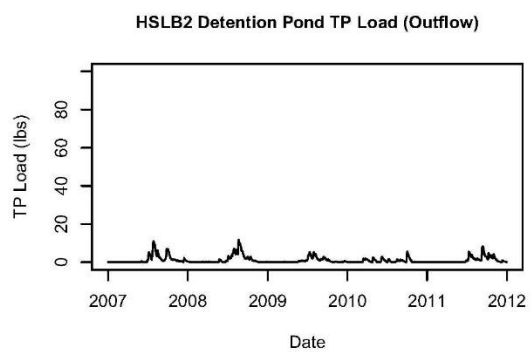
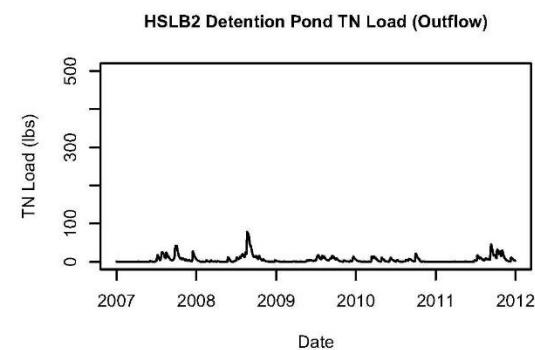
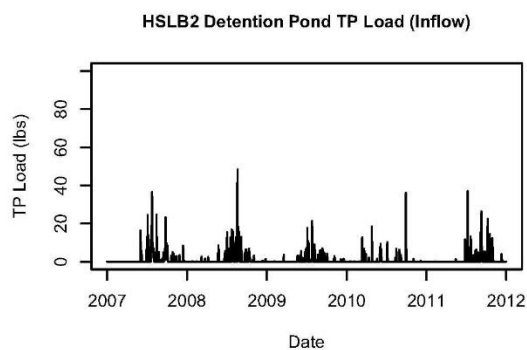
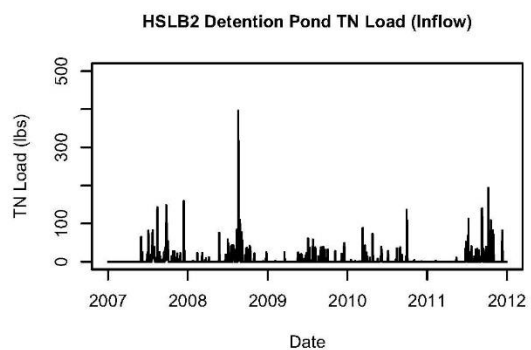
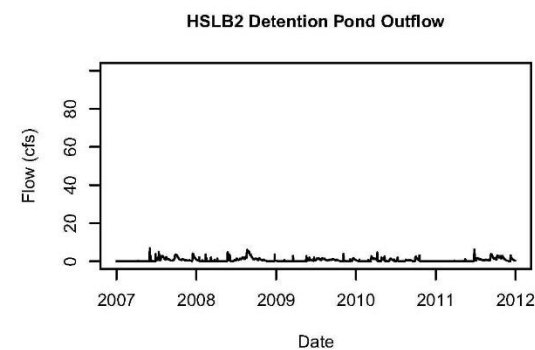
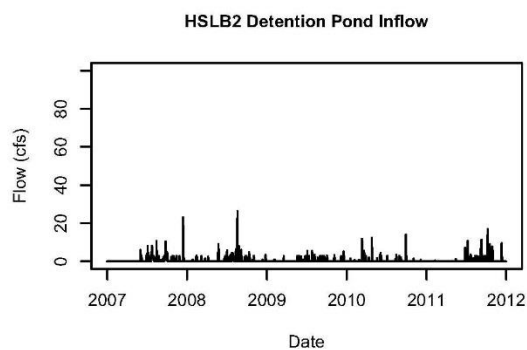
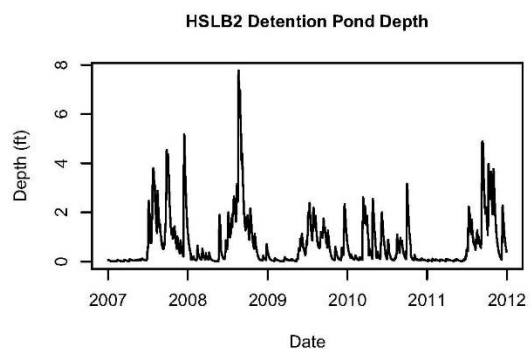
Plots of variables for detention pond of MC17



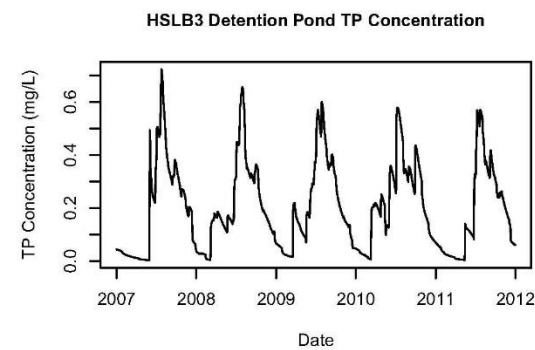
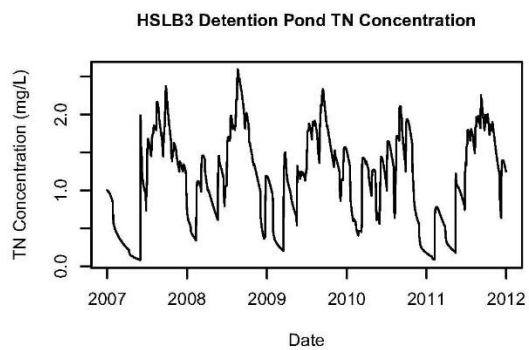
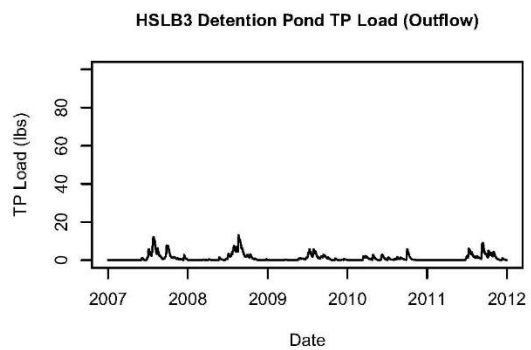
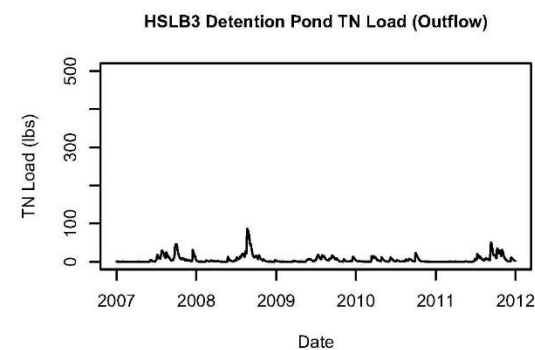
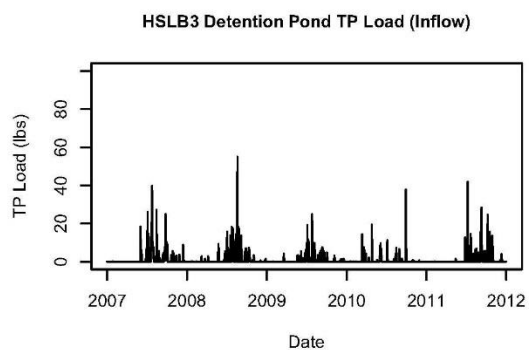
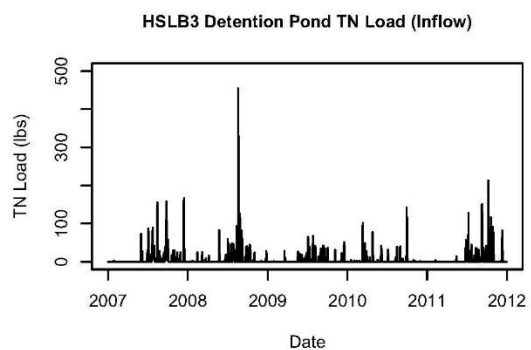
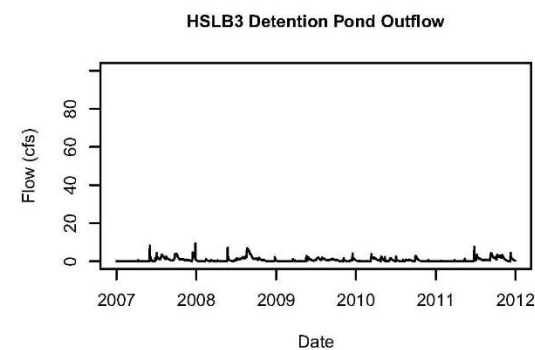
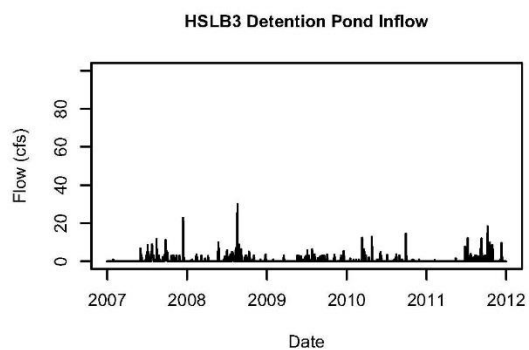
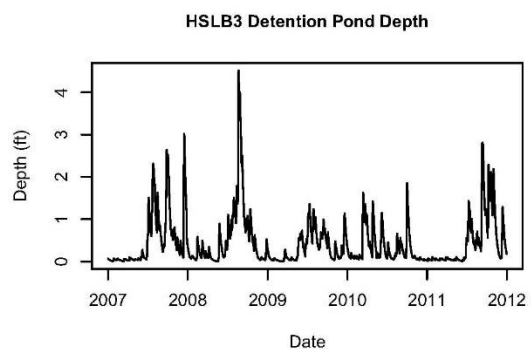
Plots of variables for detention pond of MC32



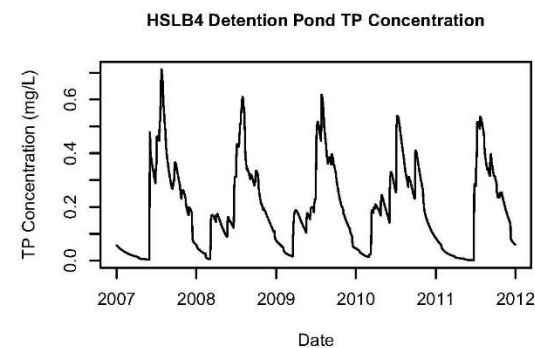
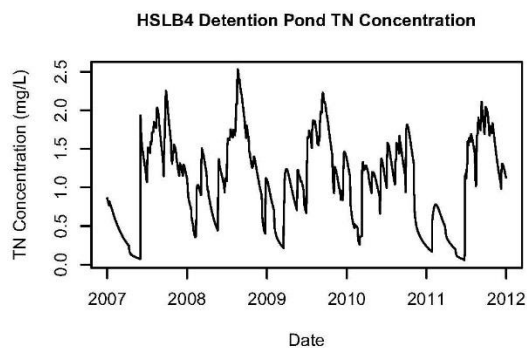
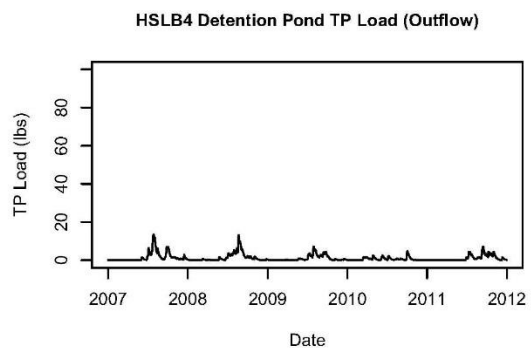
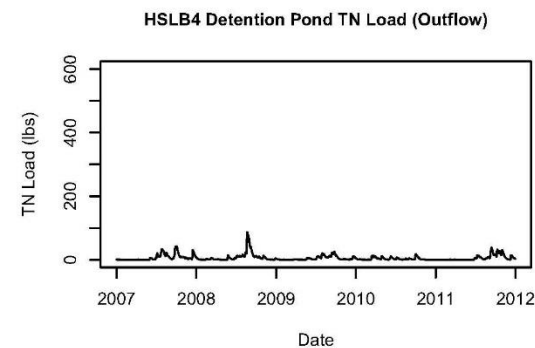
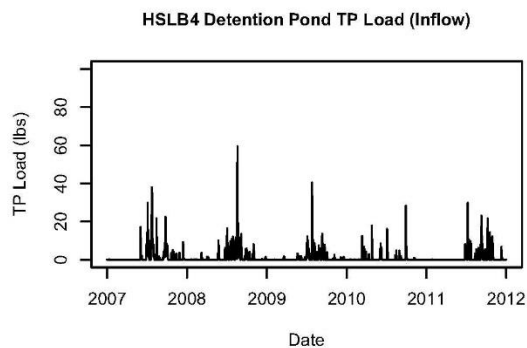
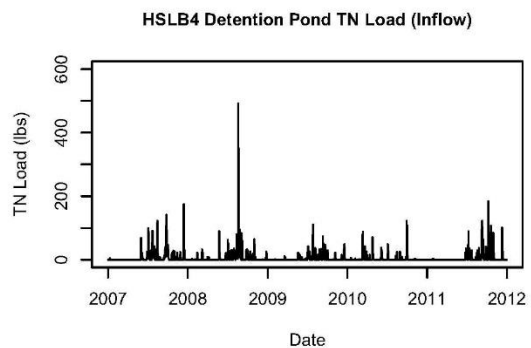
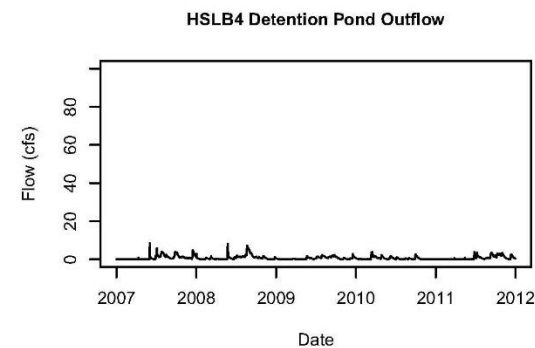
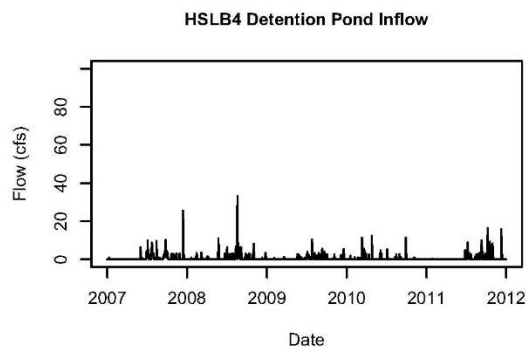
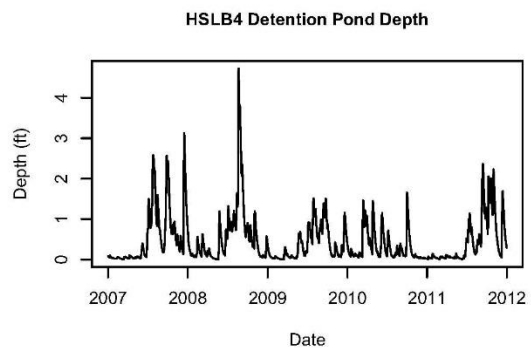
Plots of variables for detention pond of HSLB1



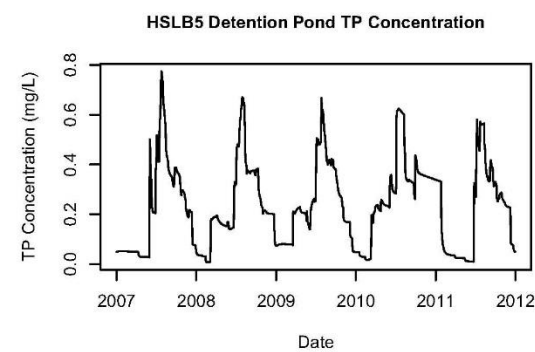
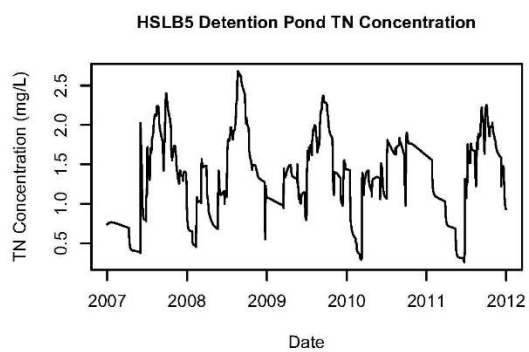
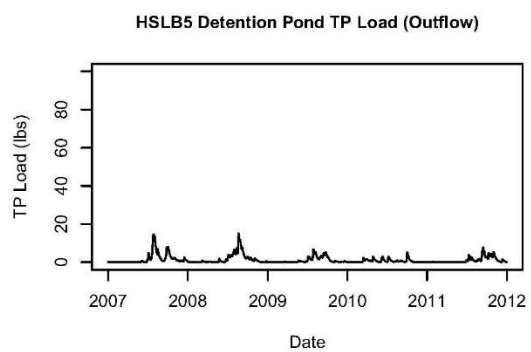
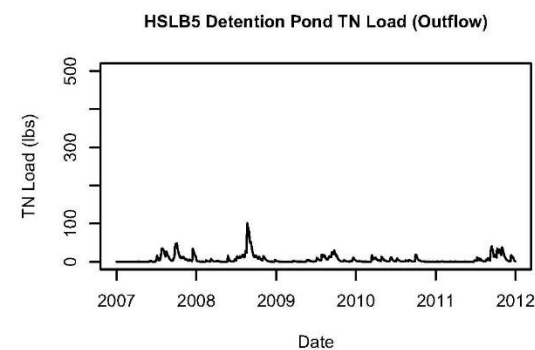
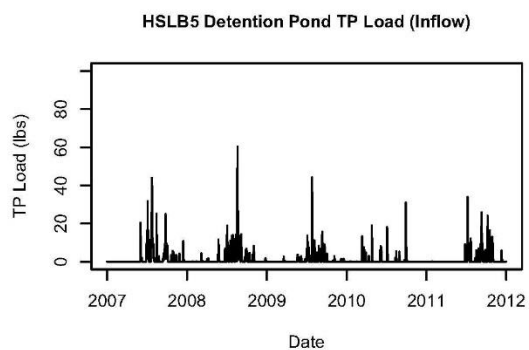
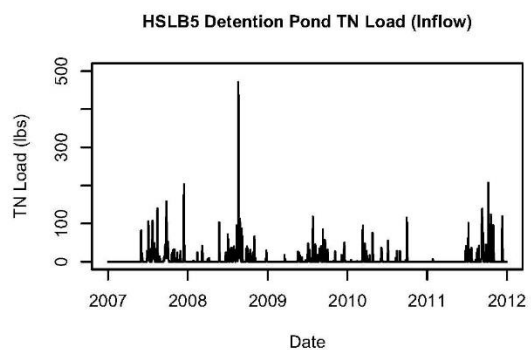
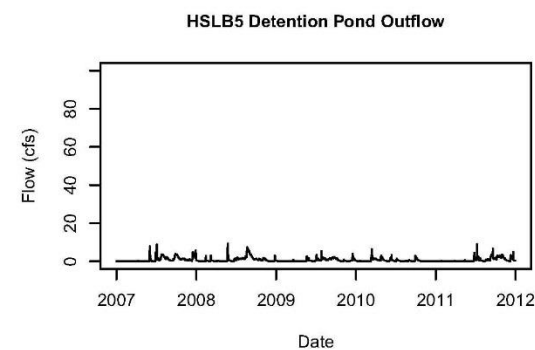
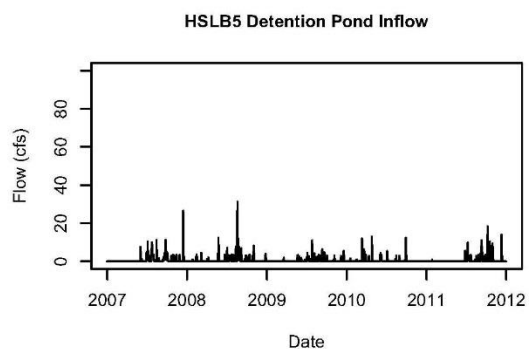
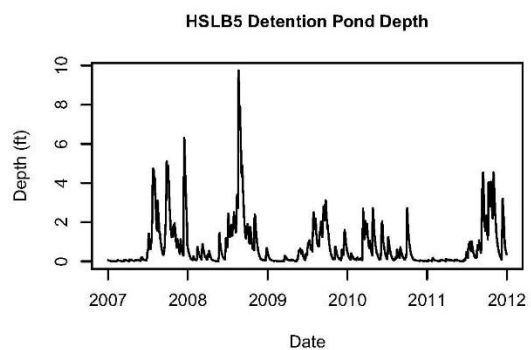
Plots of variables for detention pond of HSLB2



Plots of variables for detention pond of HSLB3



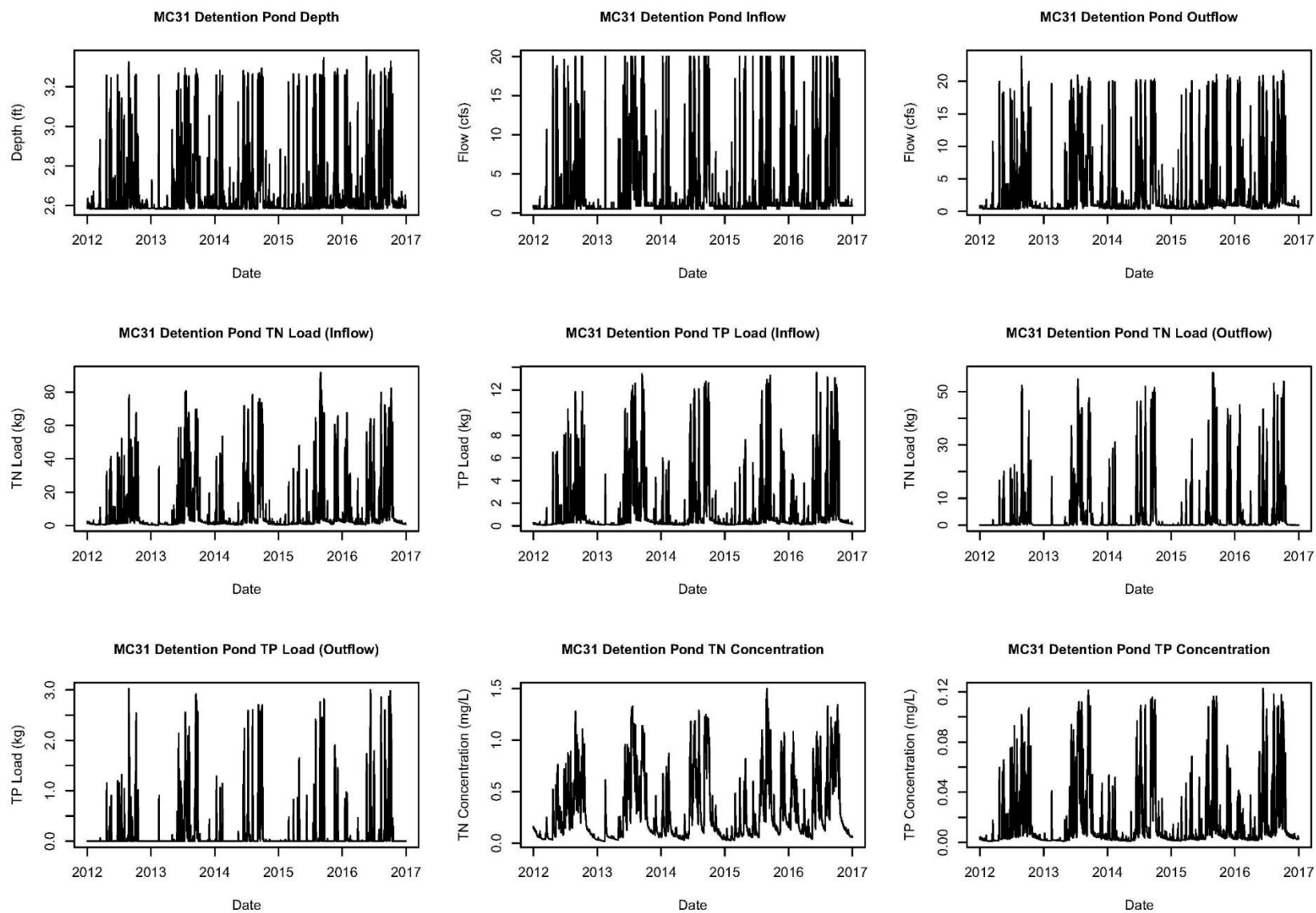
Plots of variables for detention pond of HSLB4



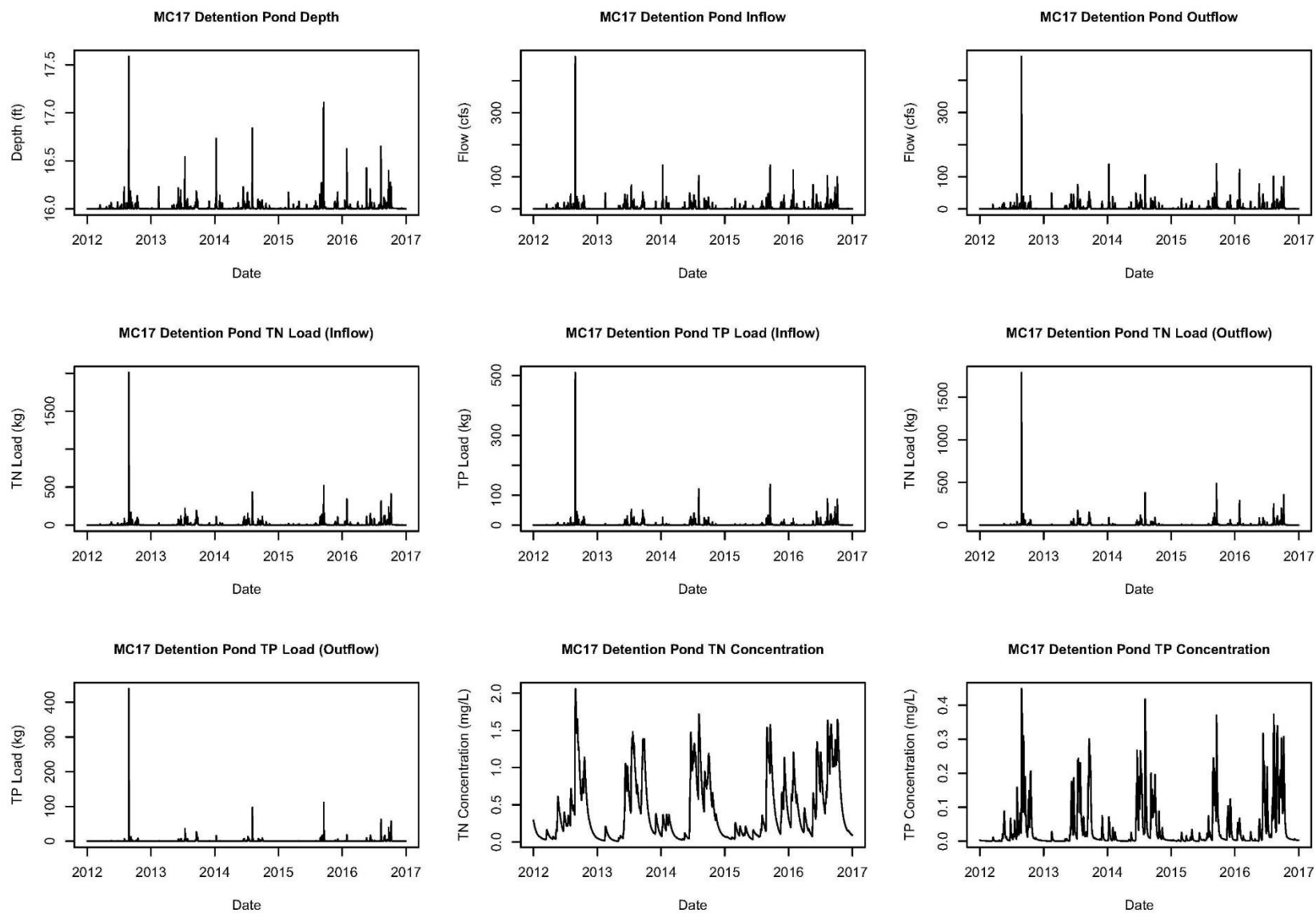
Plots of variables for detention pond of HSLB5

Appendix F: Plots of simulation results for projects MC-31, MC-17, MC-32, and HSL-01 (2012– 2016).

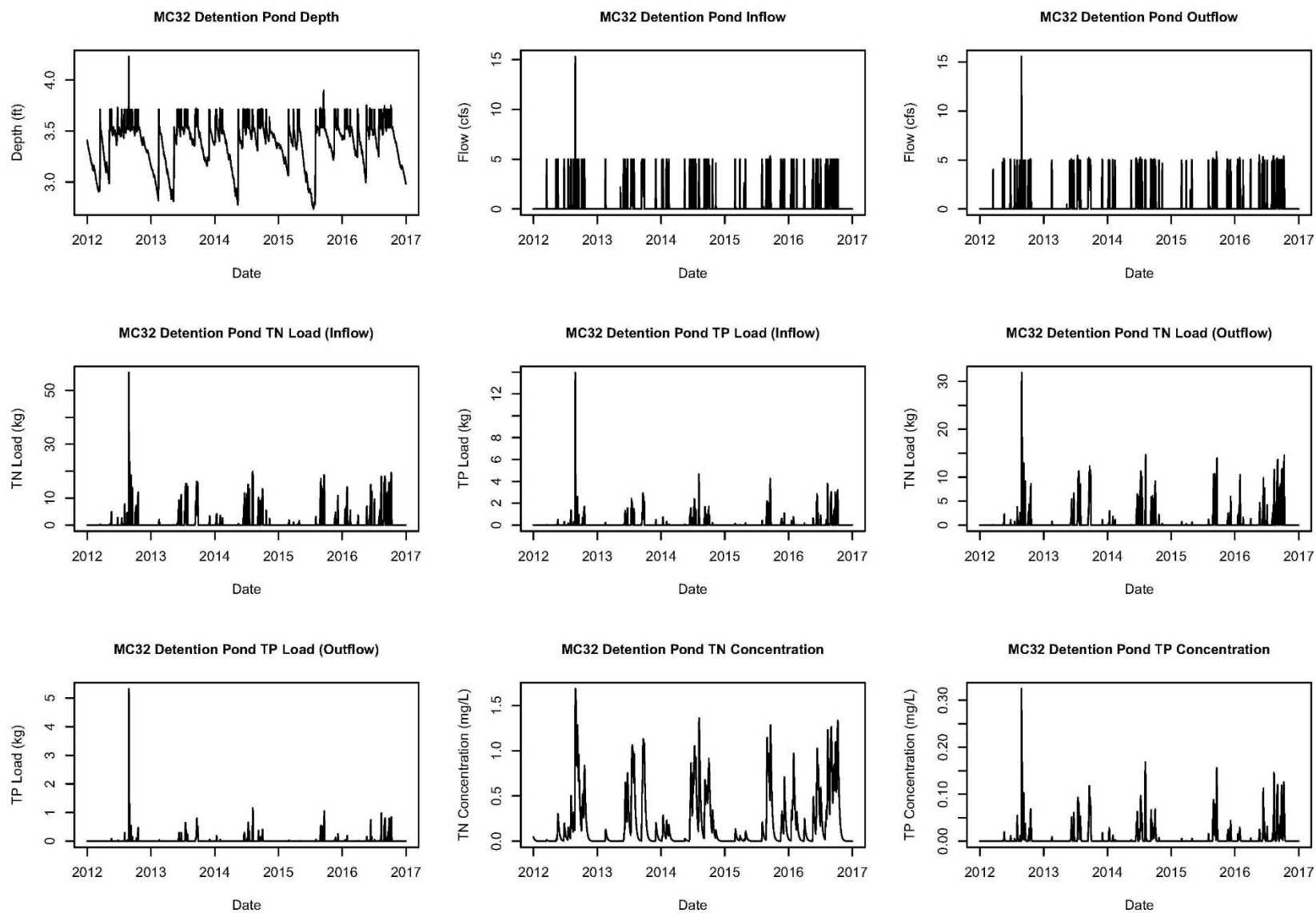
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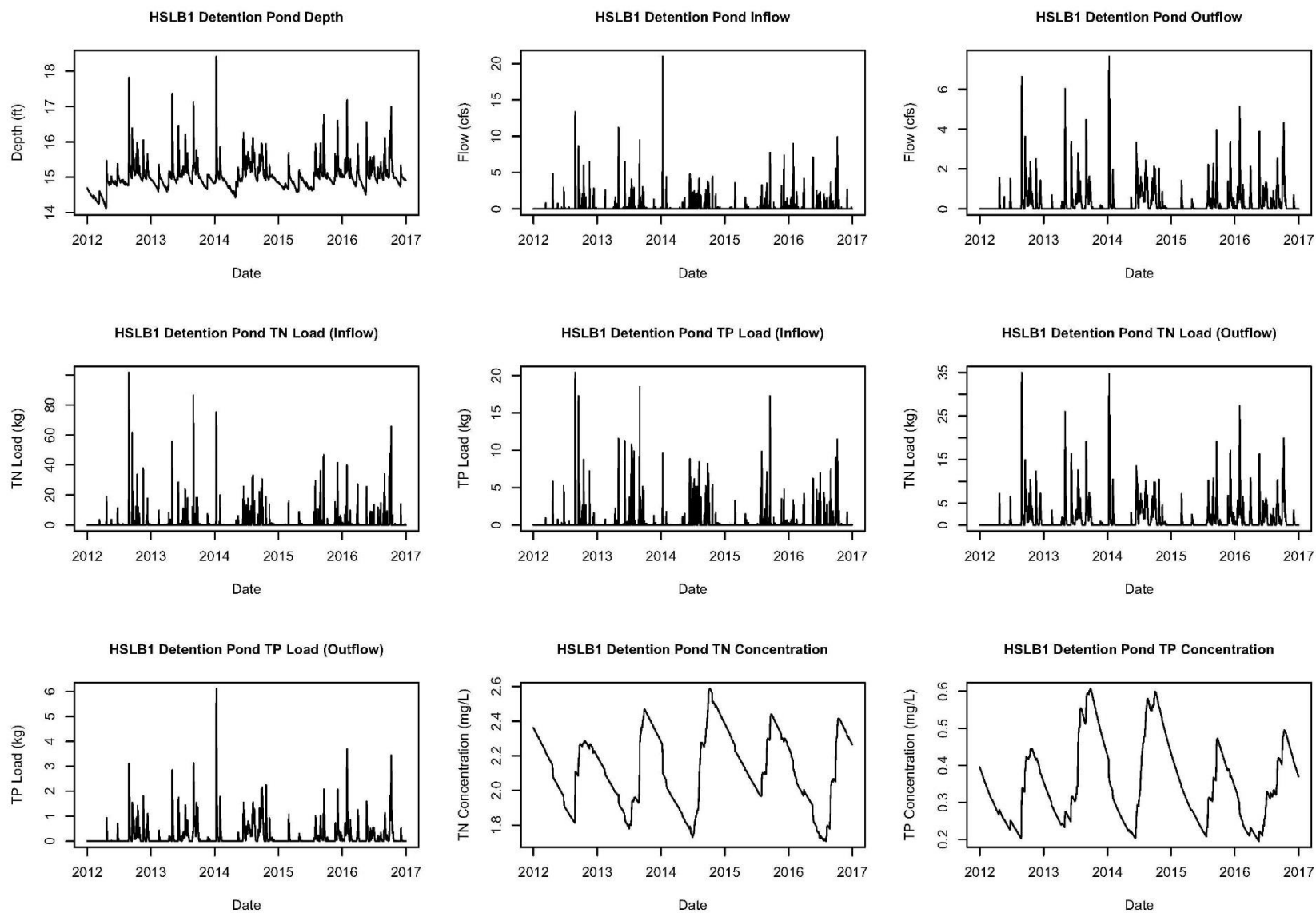
Plots of variables for detention pond of MC31



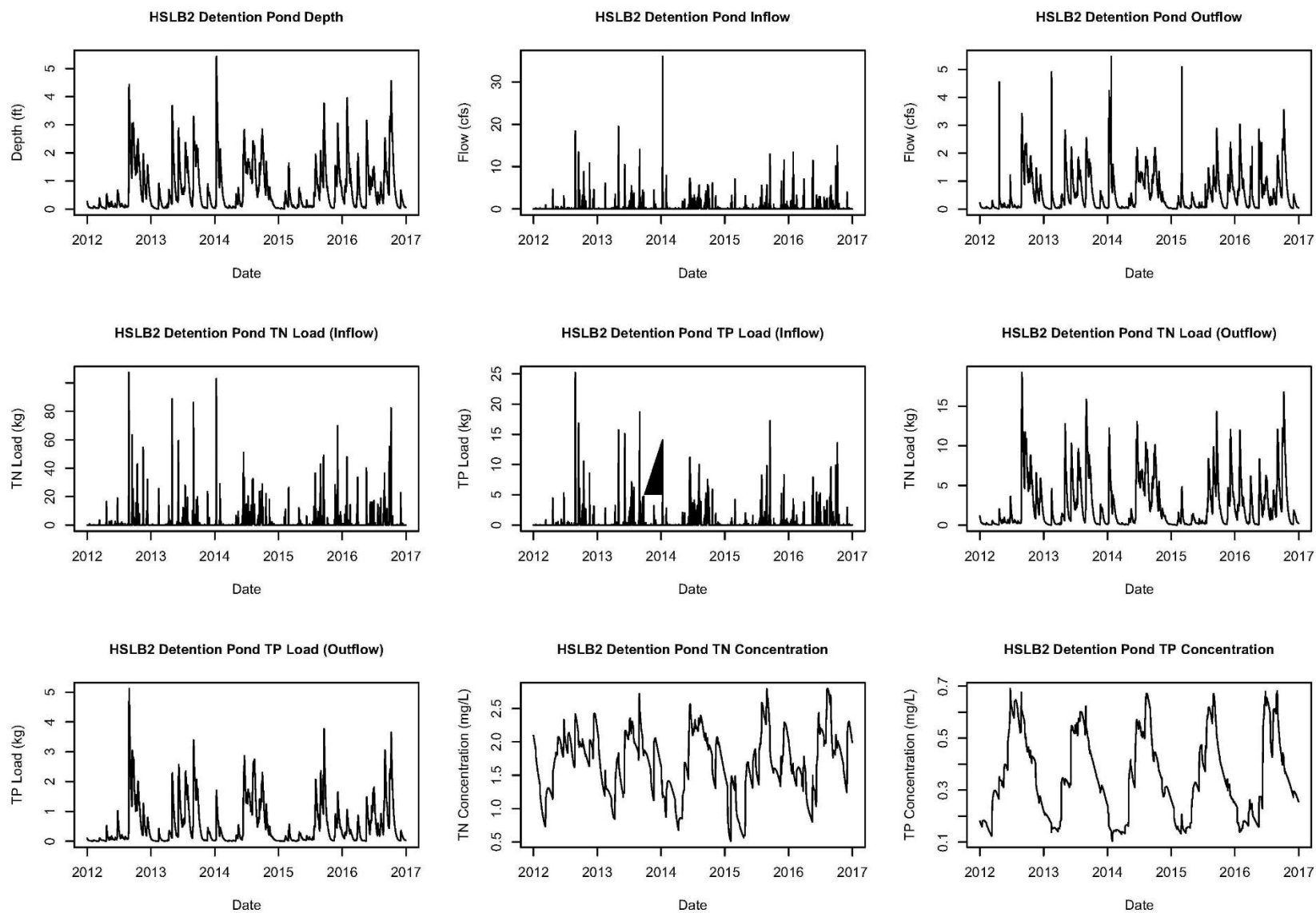
Plots of variables for detention pond of MC17



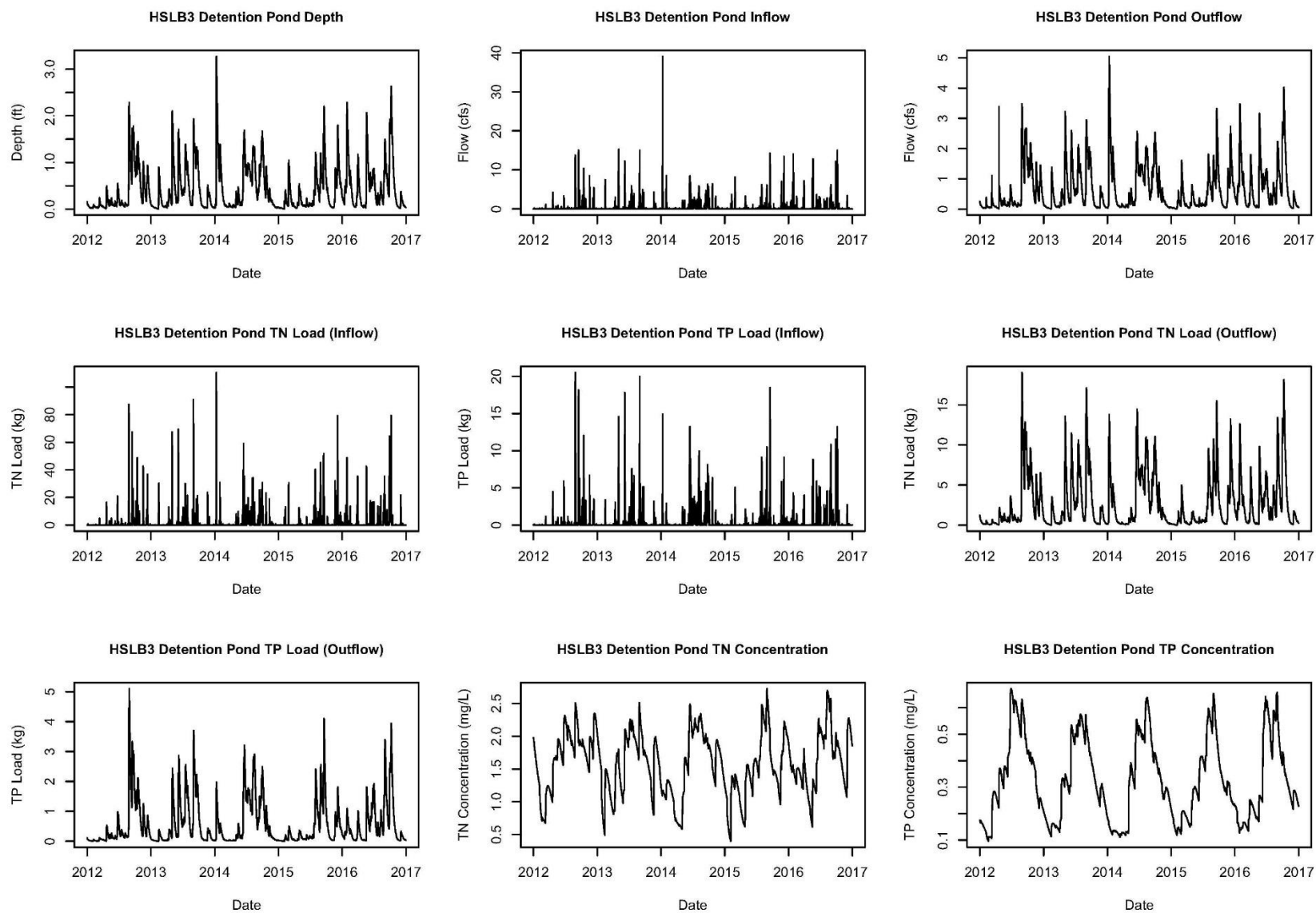
Plots of variables for detention pond of MC32



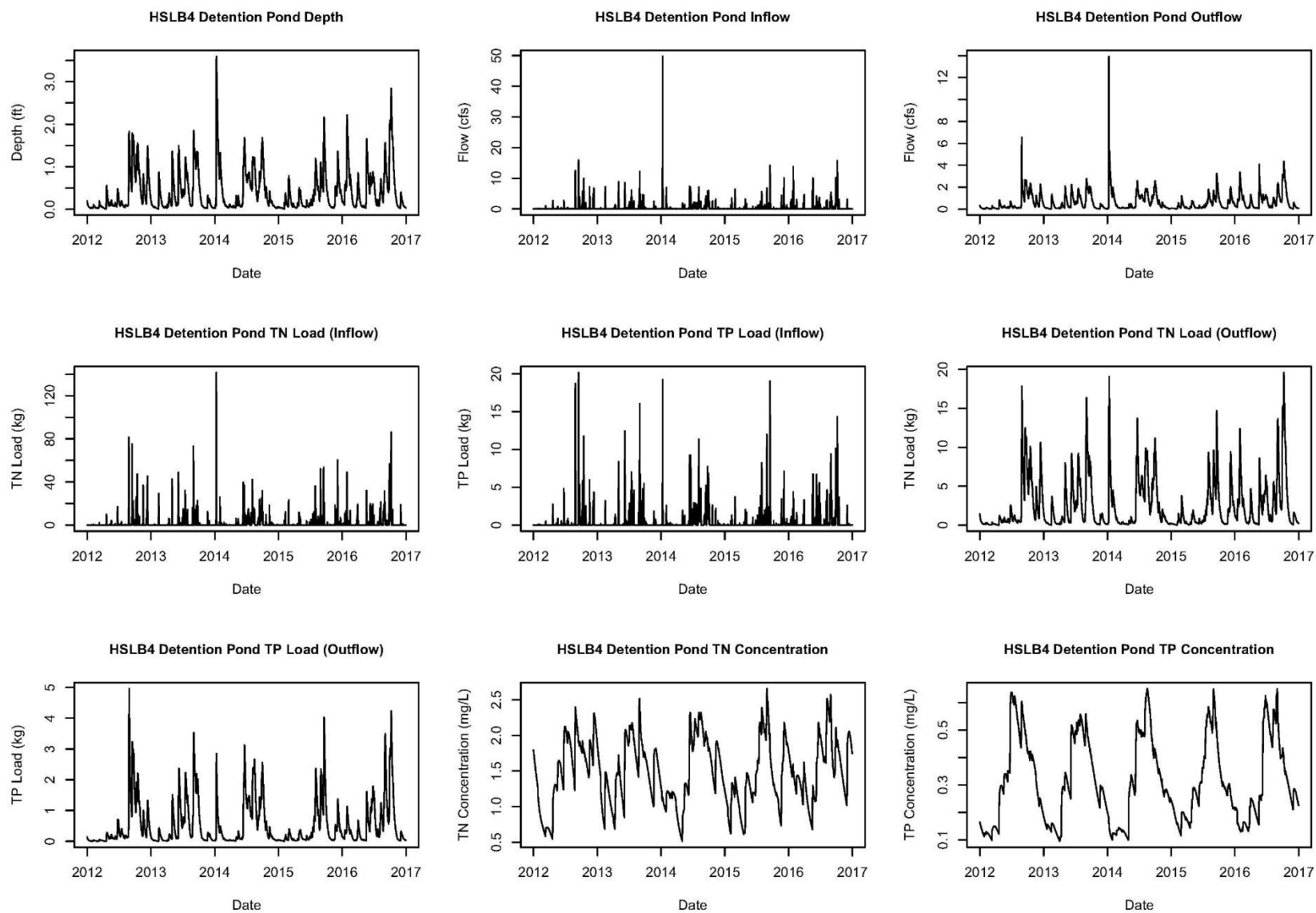
Plots of variables for detention pond of HSLB1



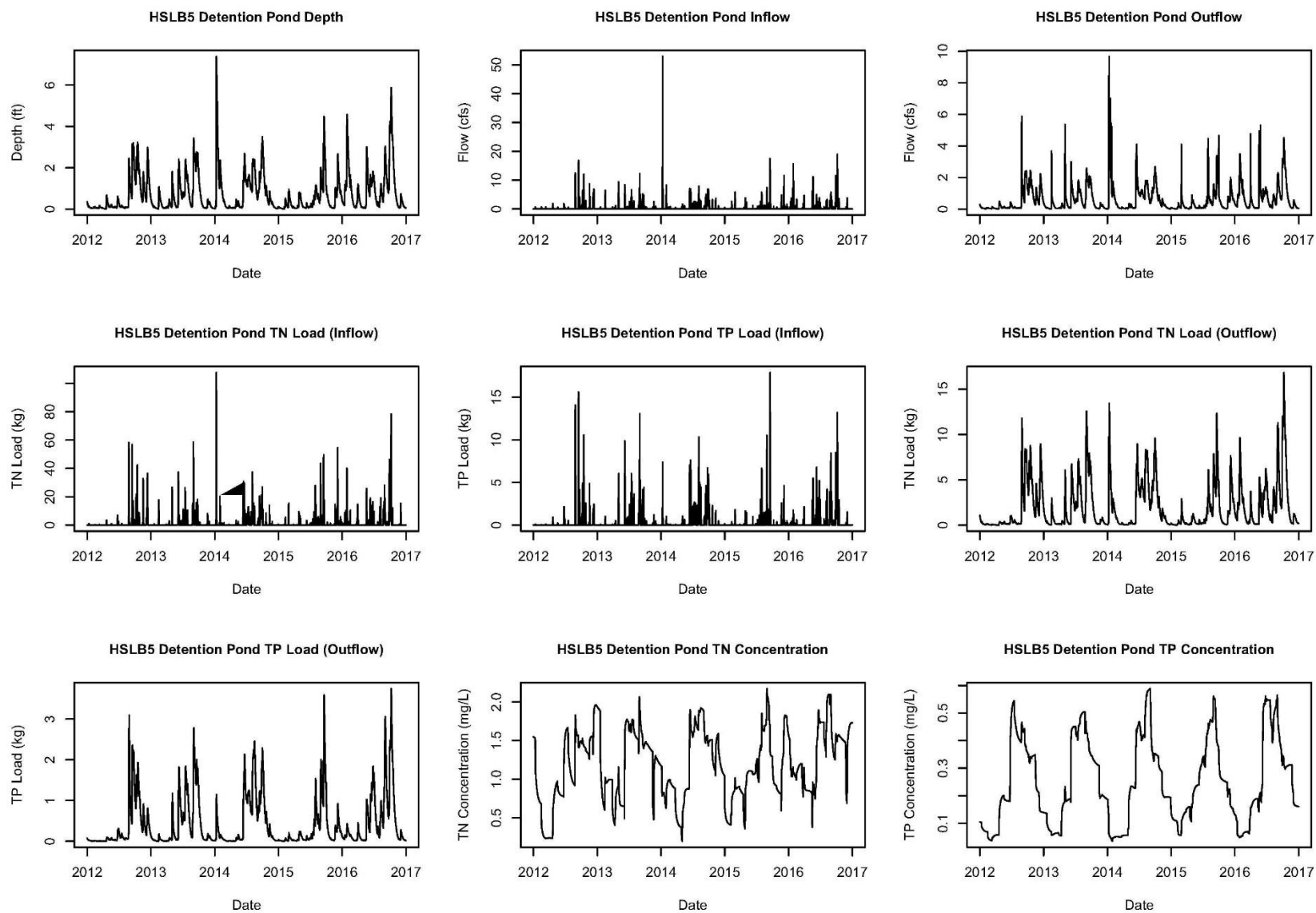
Plots of variables for detention pond of HSLB2



Plots of variables for detention pond of HSLB3



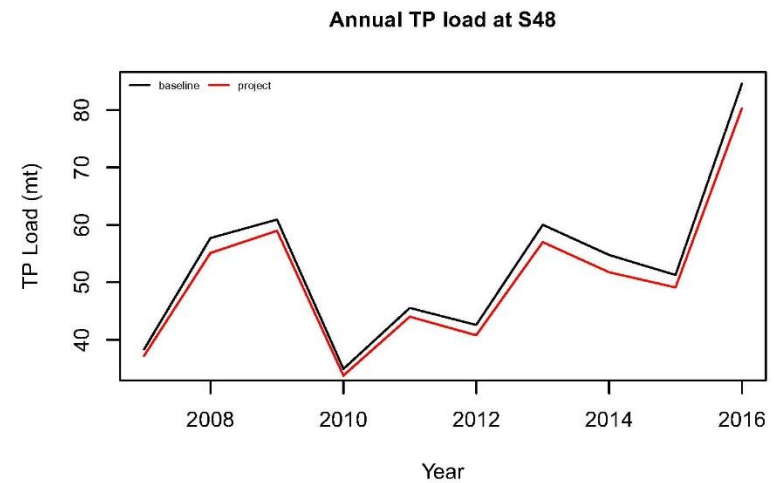
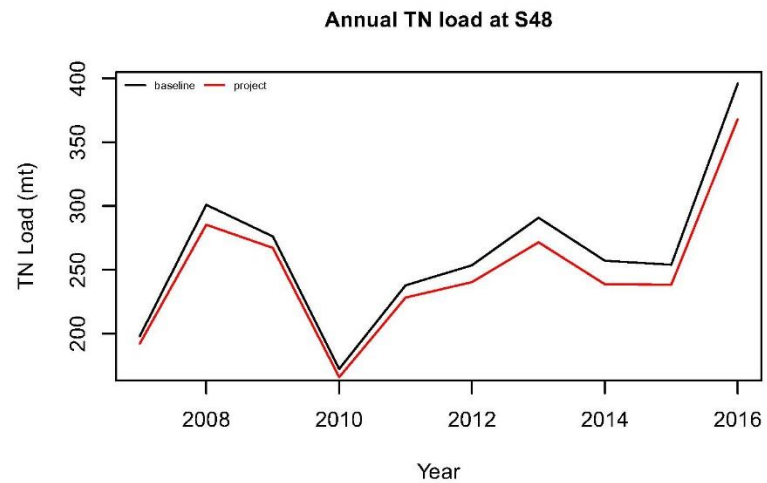
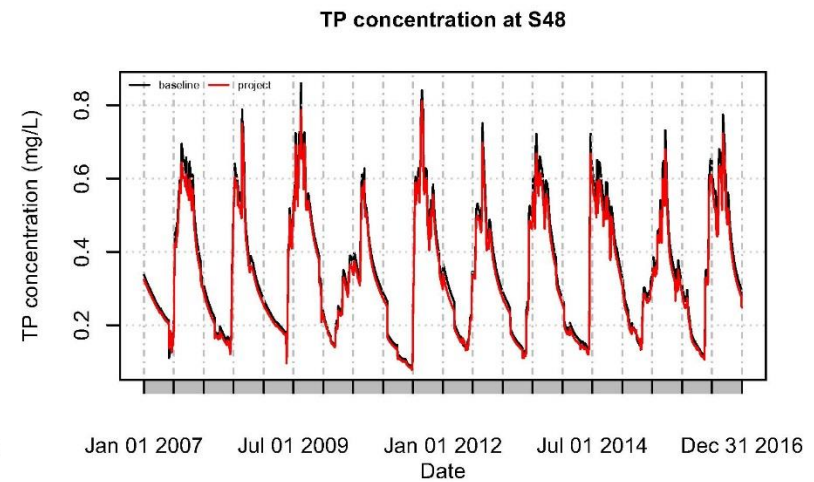
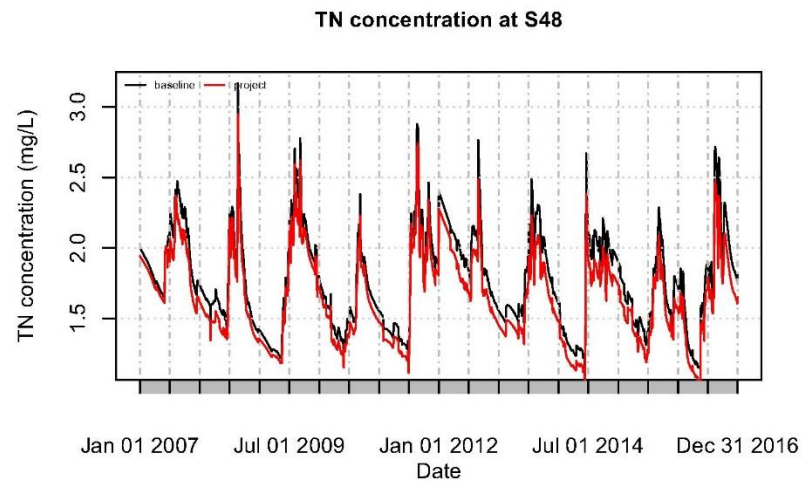
Plots of variables for detention pond of HSLB4



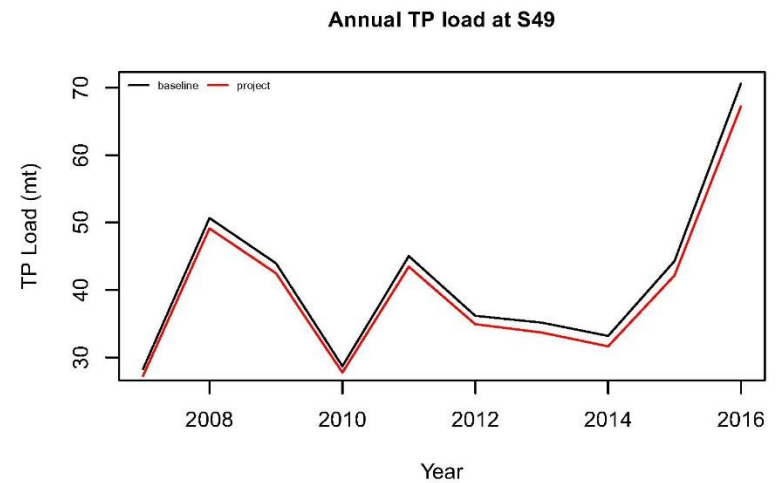
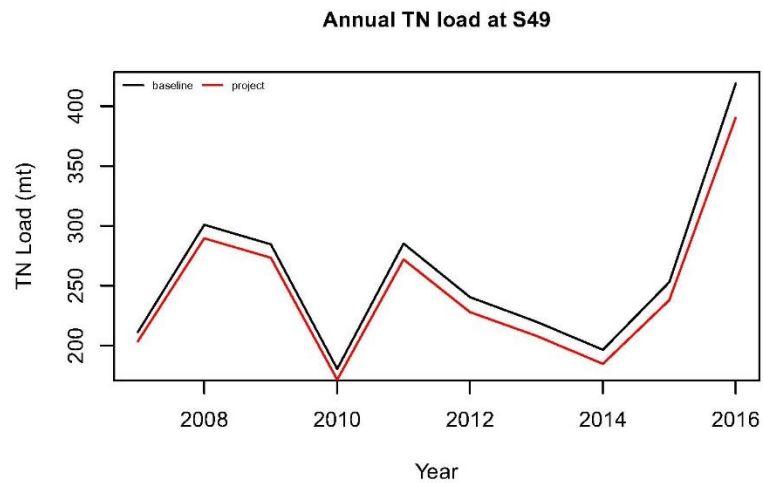
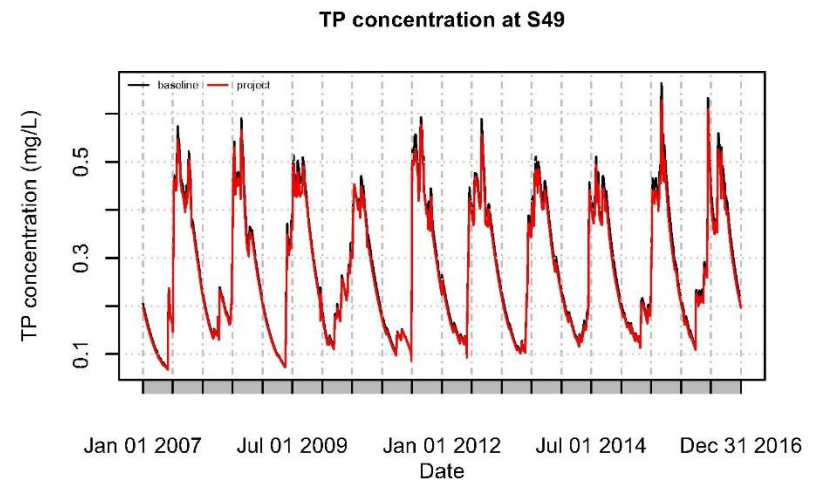
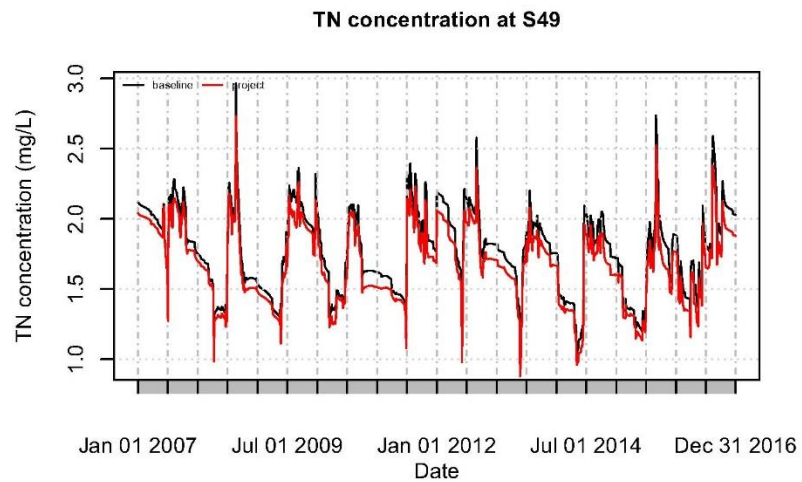
Plots of variables for detention pond of HSLB5

Appendix G: Plots of TN/TP concentrations/loads between baseline and project scenarios at selected locations: S-48, S-49, S80, GRS, Basin6 outlet, and Basin 4/5 outlet.

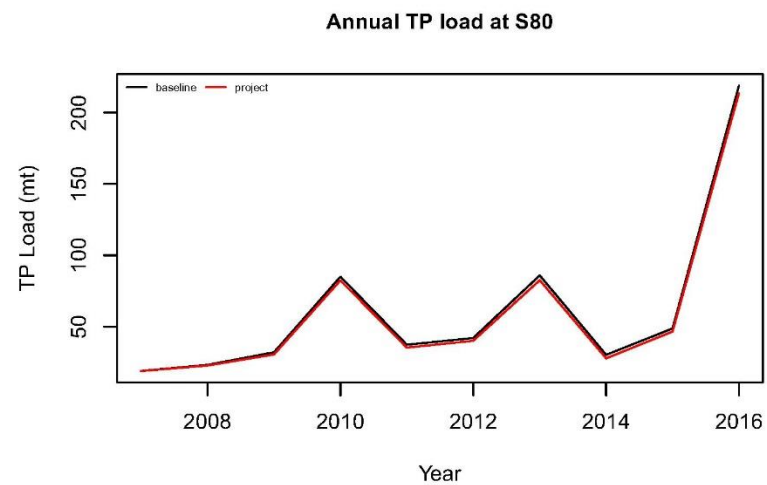
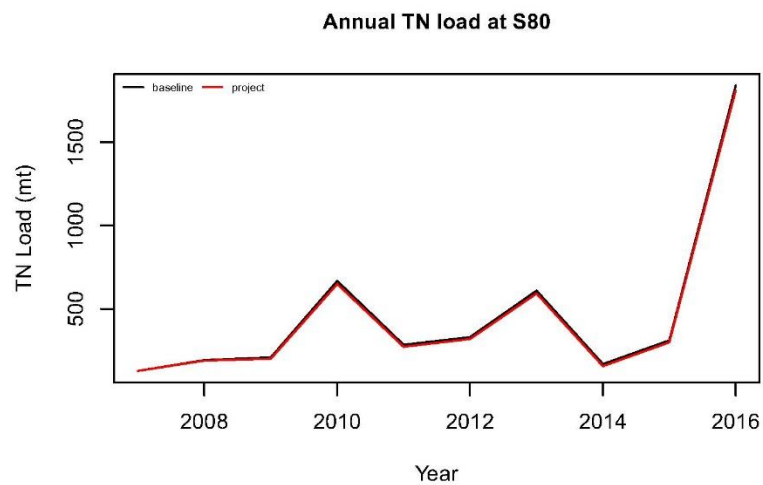
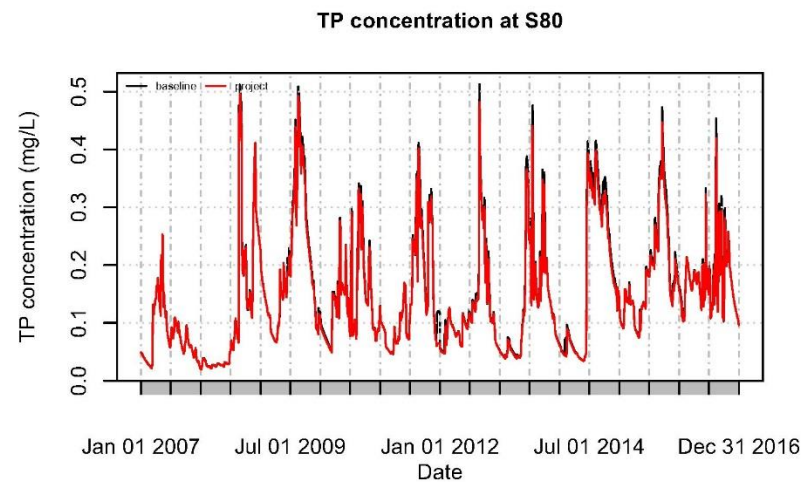
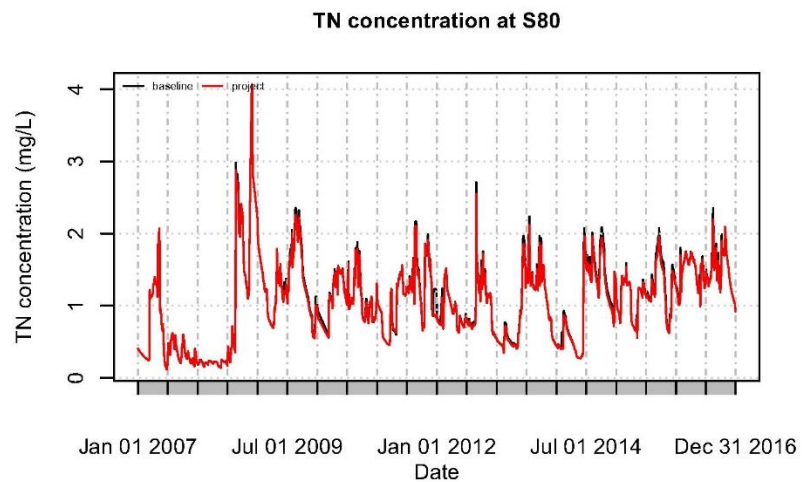
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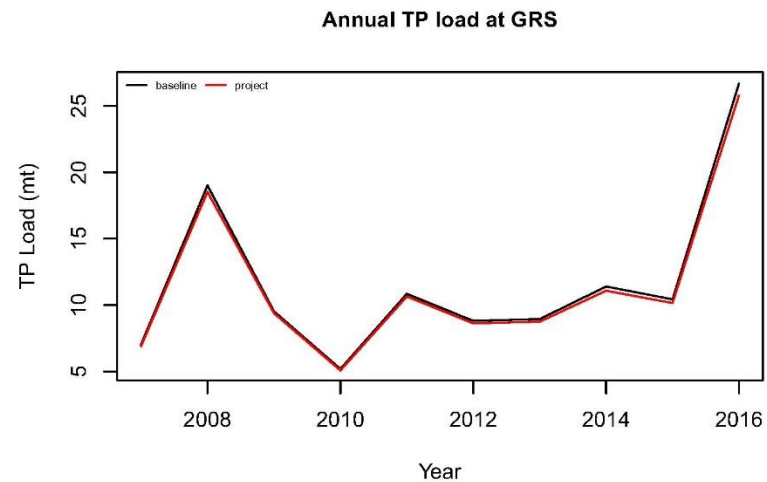
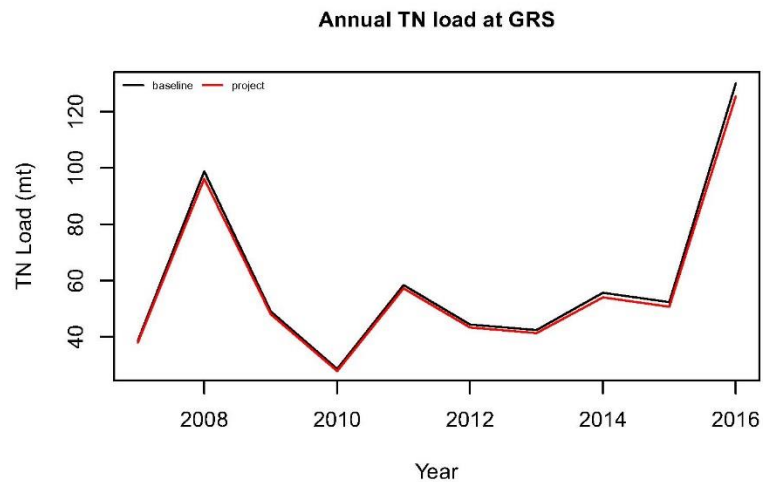
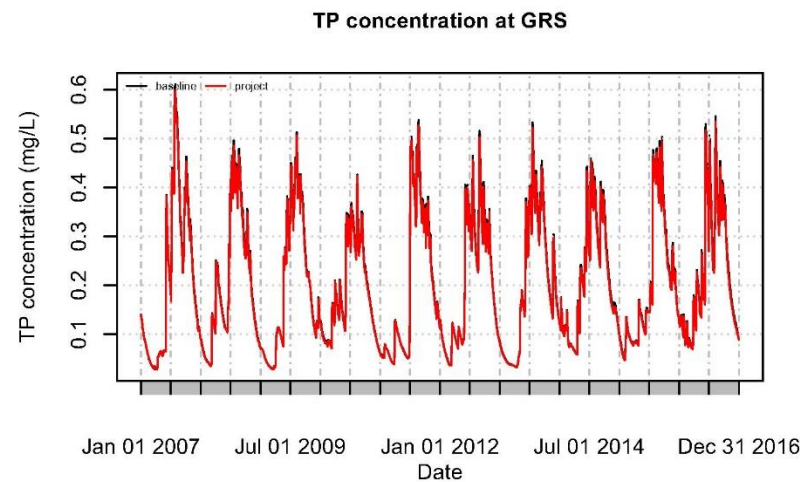
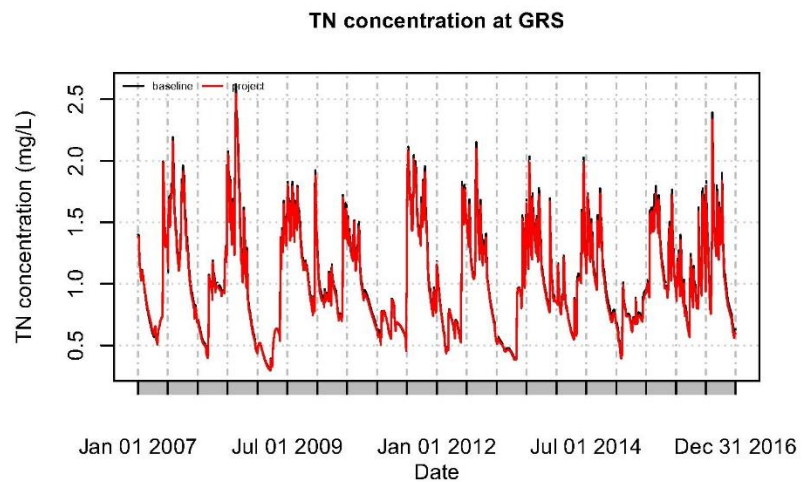
Comparison plots of TN/TP concentrations/loads between baseline and project scenarios at S-48



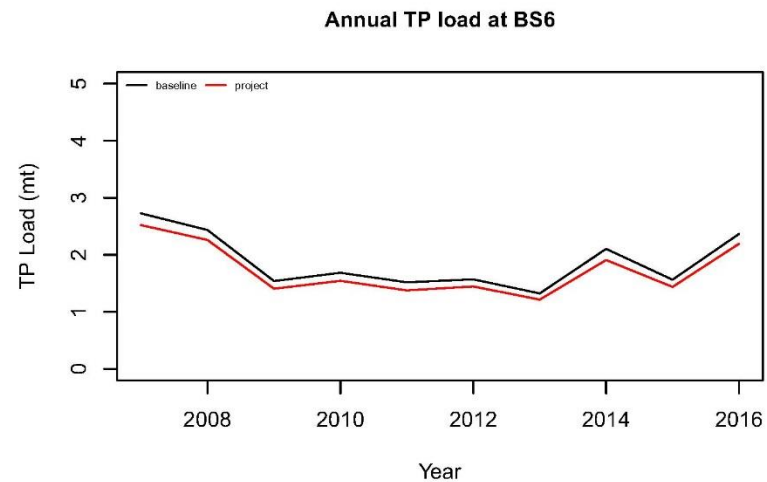
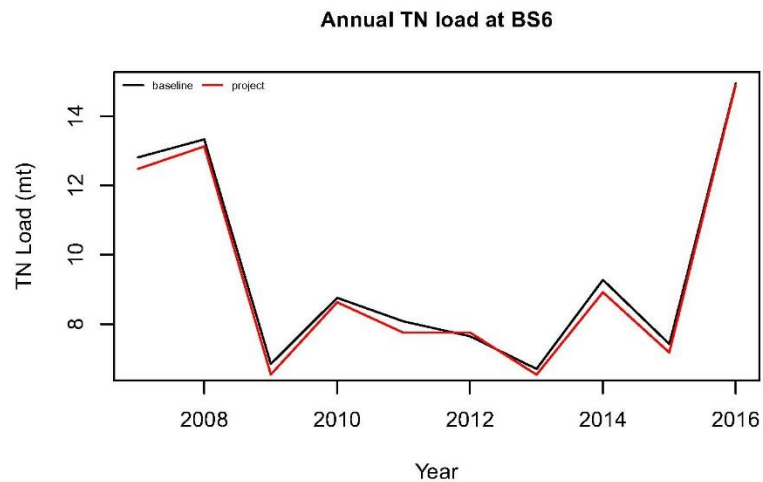
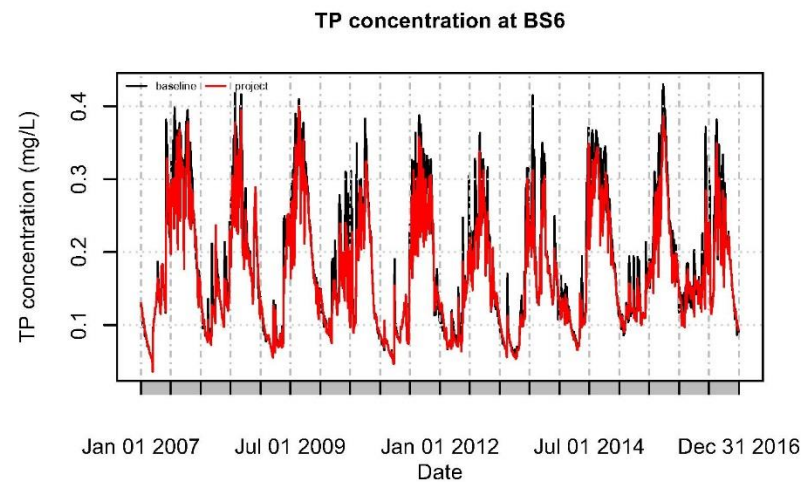
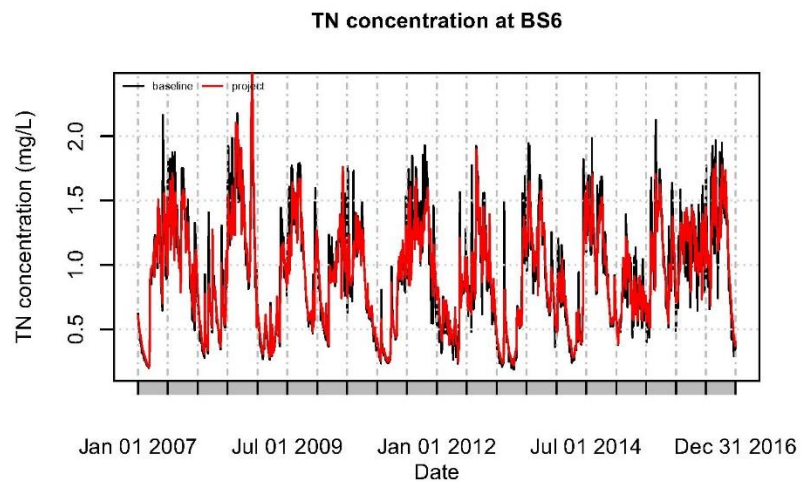
Comparison plots of TN/TP concentrations/loads between baseline and project scenarios at S-49



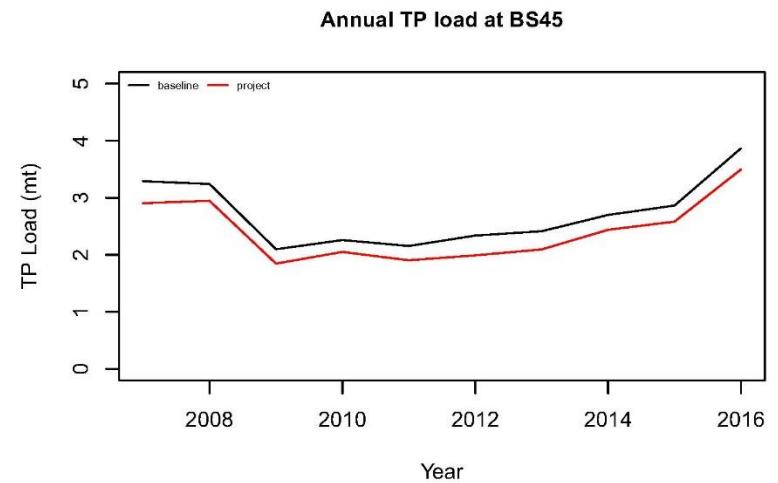
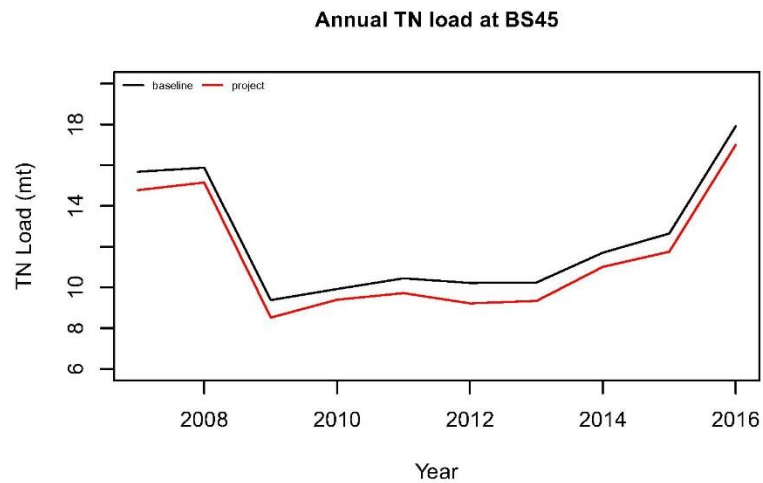
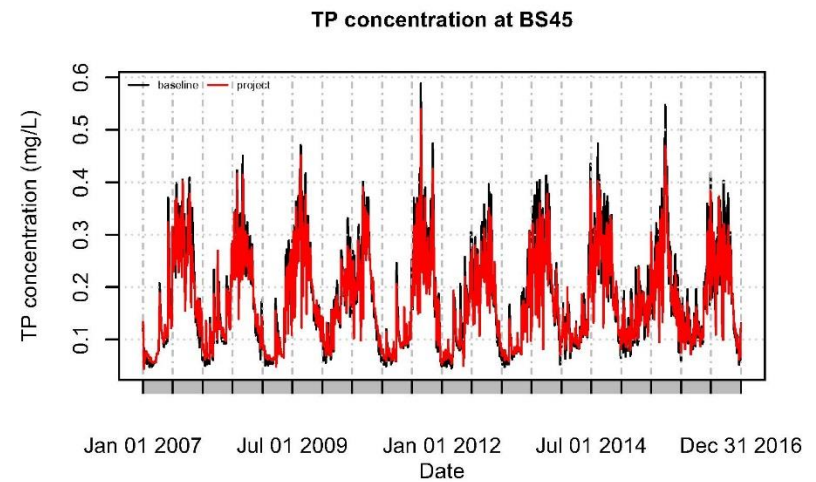
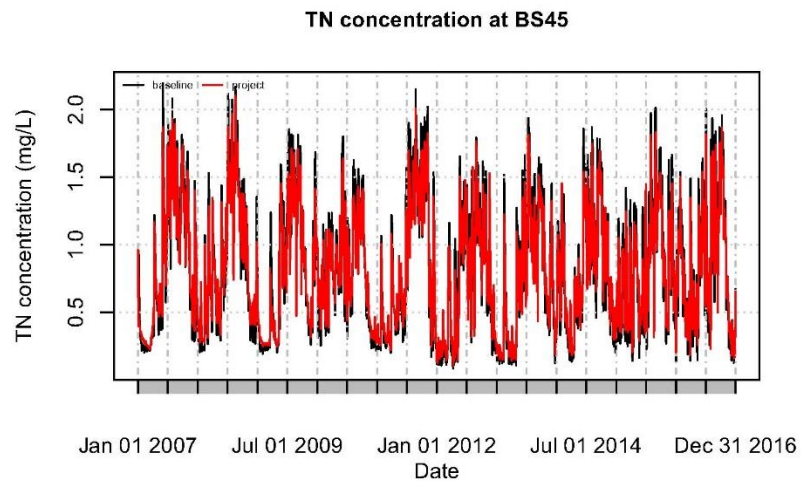
Comparison plots of TN/TP concentrations/loads between baseline and project scenarios at S-80



Comparison plots of TN/TP concentrations/loads between baseline and project scenarios at GRS



Comparison plots of TN/TP concentrations/loads between baseline and project scenarios at Basin 6 outlet



Comparison plots of TN/TP concentrations/loads between baseline and project scenarios at Basin 4/5 outlet

Appendix H: Annual TN Load Reductions for Septic Tanks Removal Scenario

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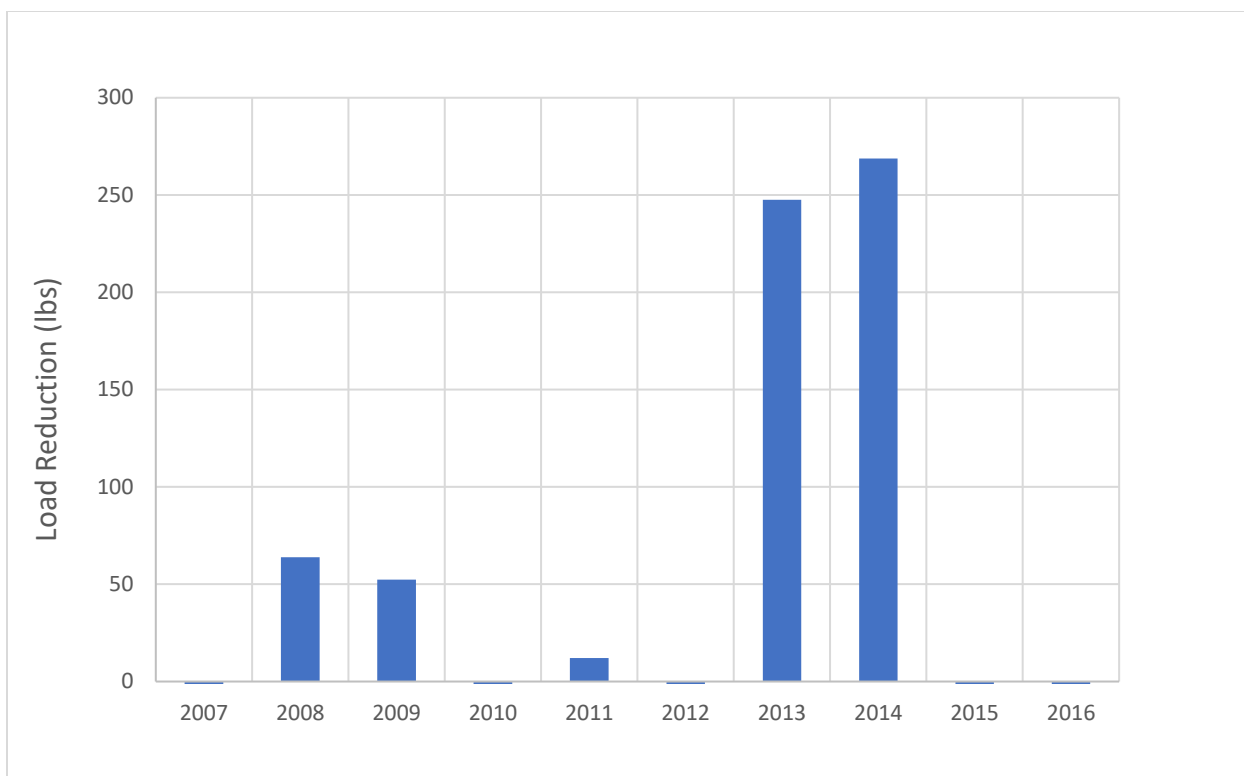


Figure H1. Annual TN Load Reduction for S-153

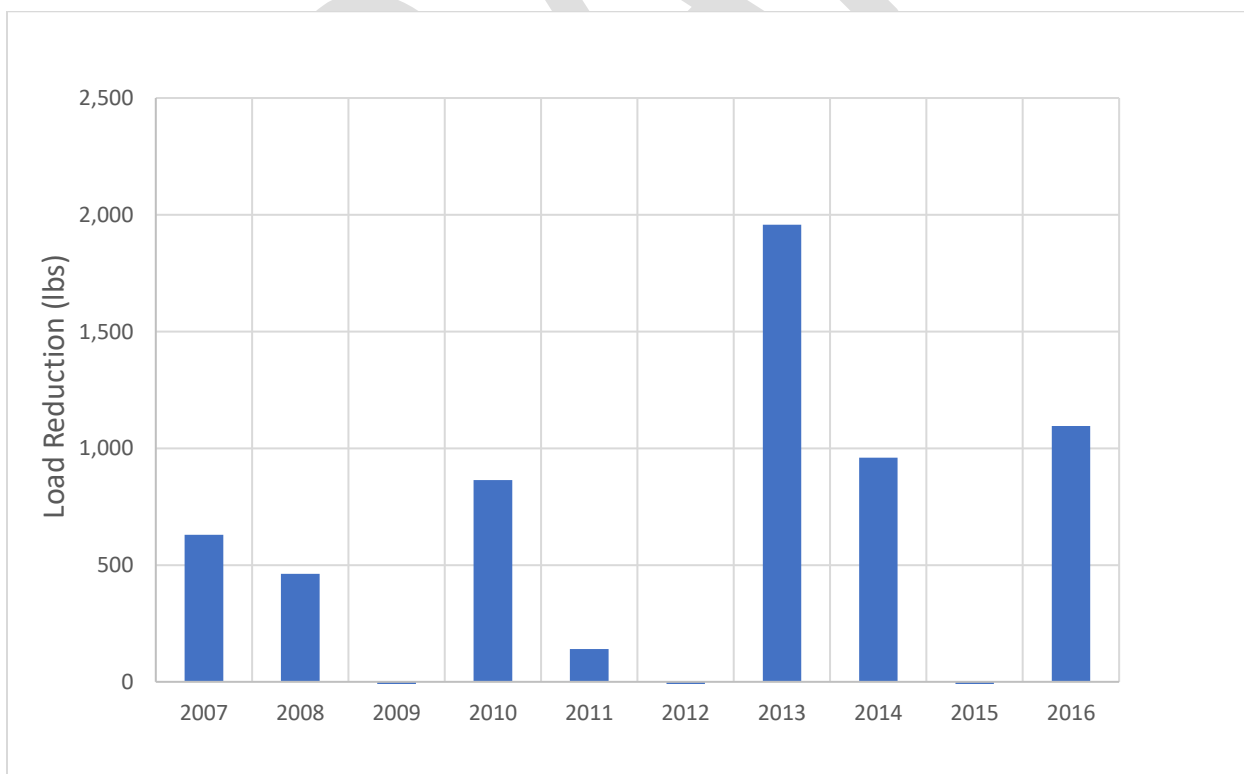


Figure H2. Annual TN Load Reduction for SE-08

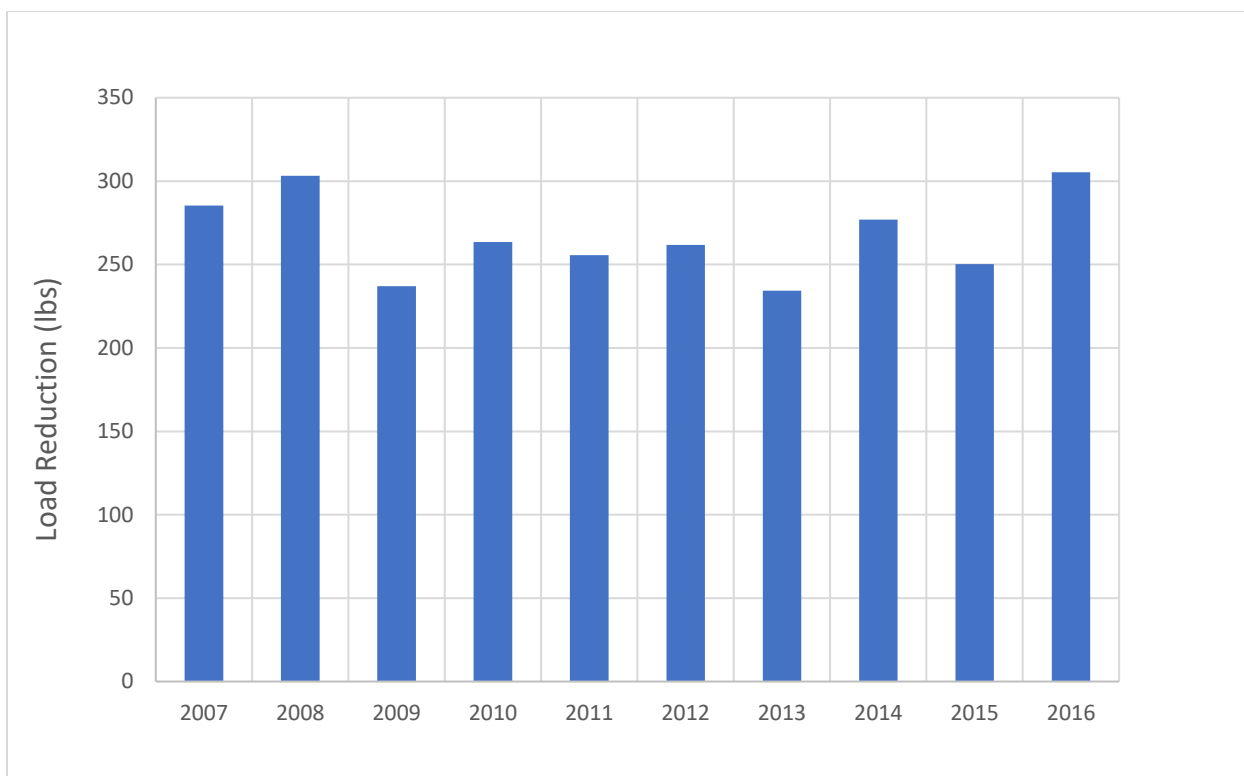


Figure H3. Annual TN Load Reduction for SE-LT-7_Basin6

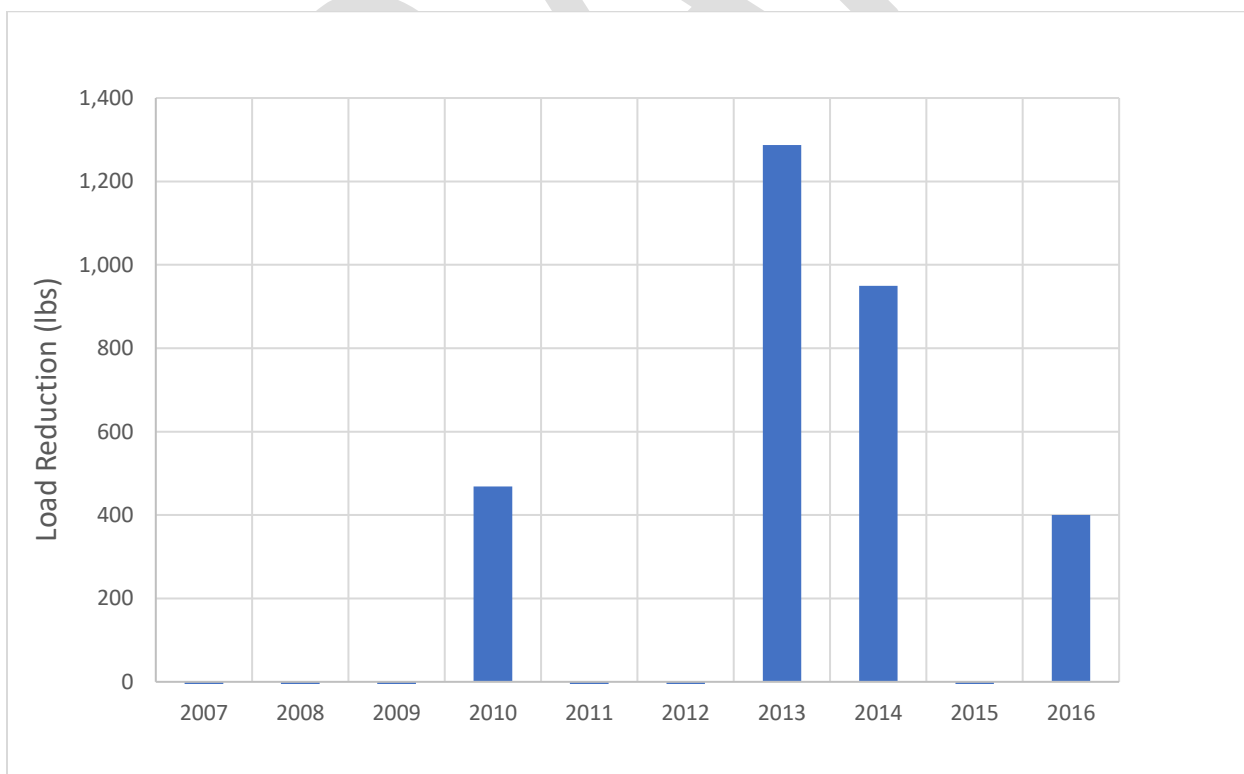


Figure H4. Annual TN Load Reduction for S-80

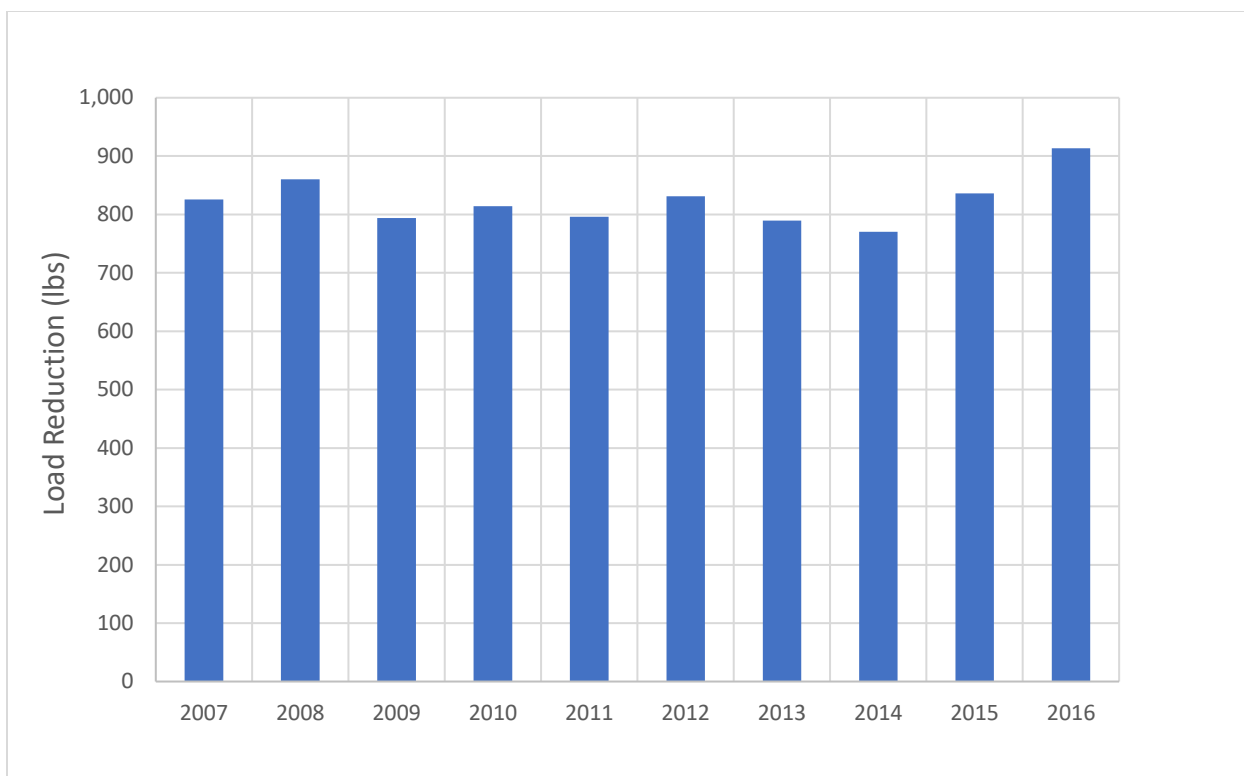


Figure H5. Annual TN Load Reduction for SLT-9_Basin4_5

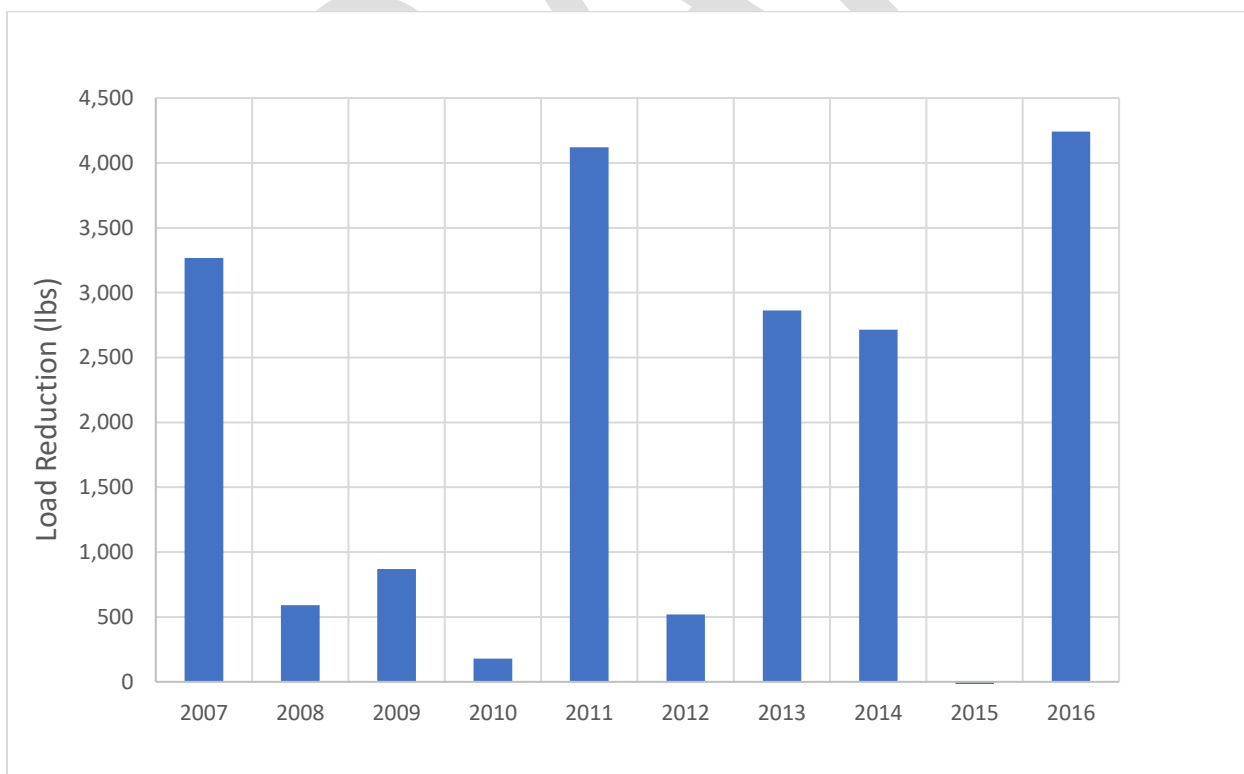


Figure H6. Annual TN Load Reduction for SE-01

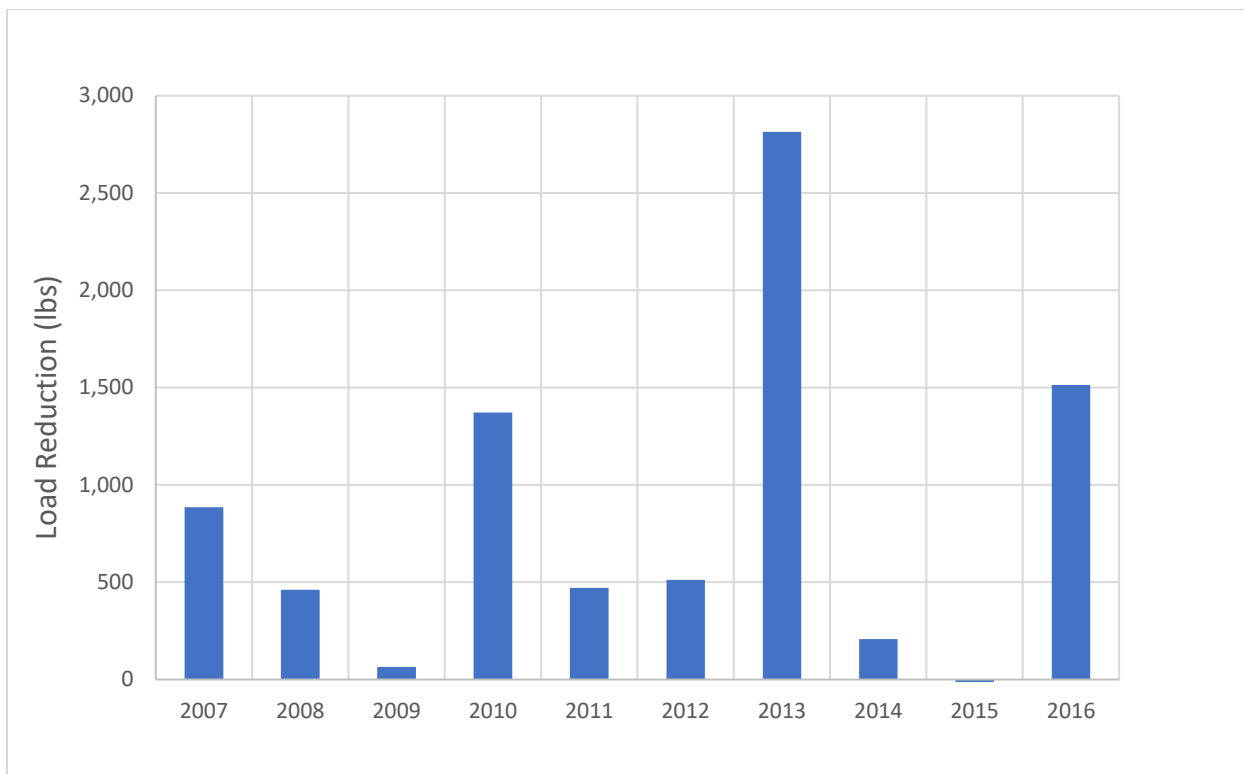


Figure H7. Annual TN Load Reduction for SE-03

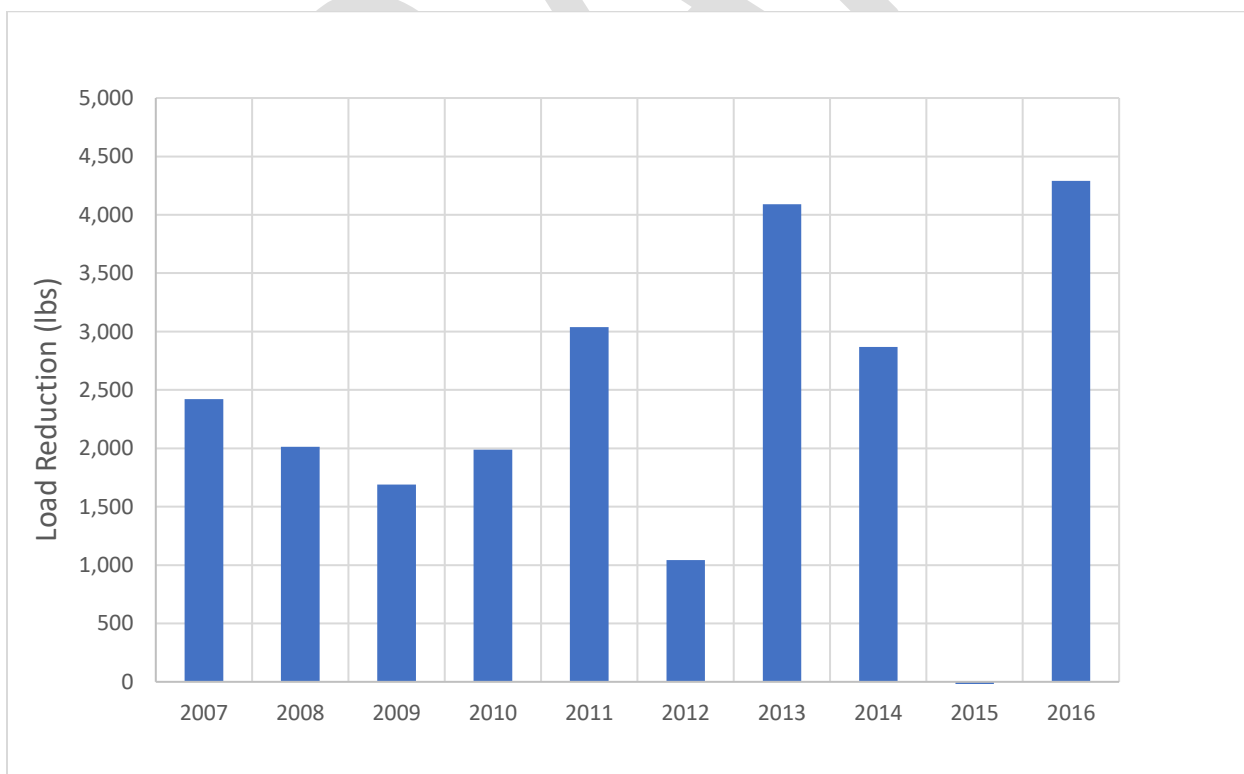


Figure H8. Annual TN Load Reduction for SE-02

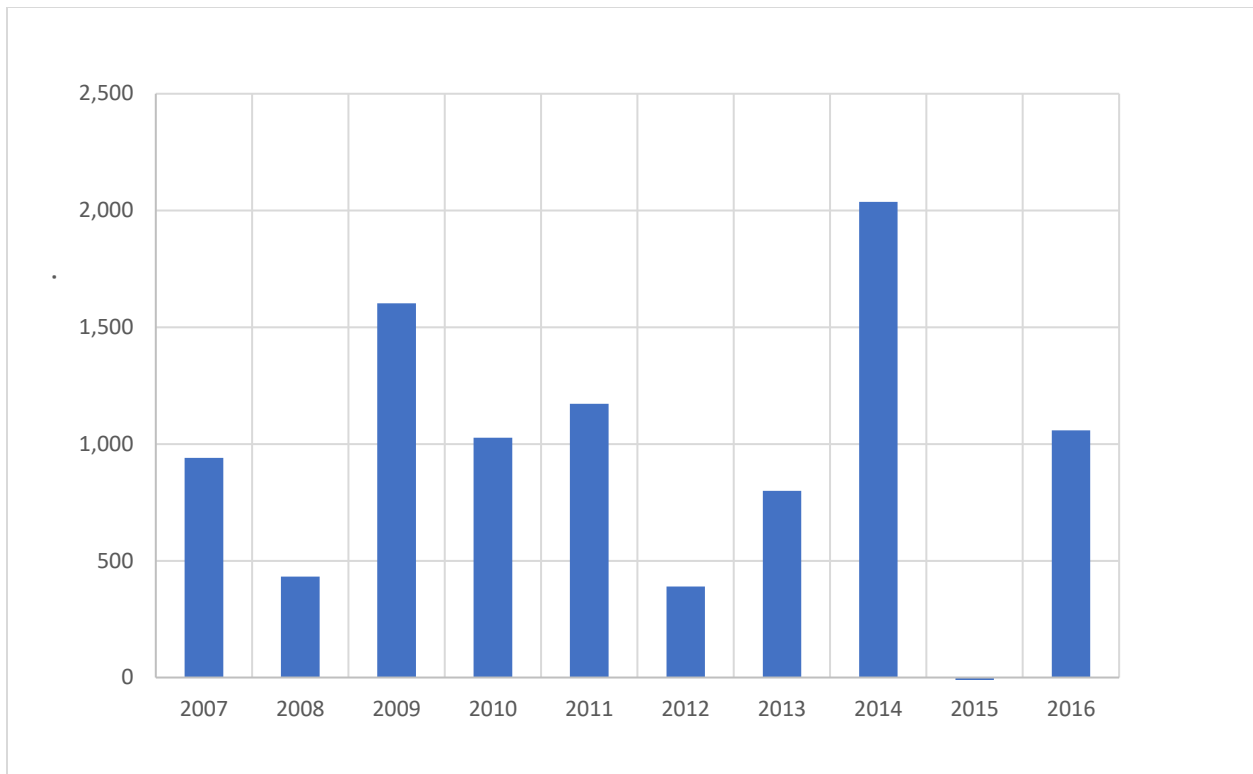


Figure H9. Annual TN Load Reduction for HR-1

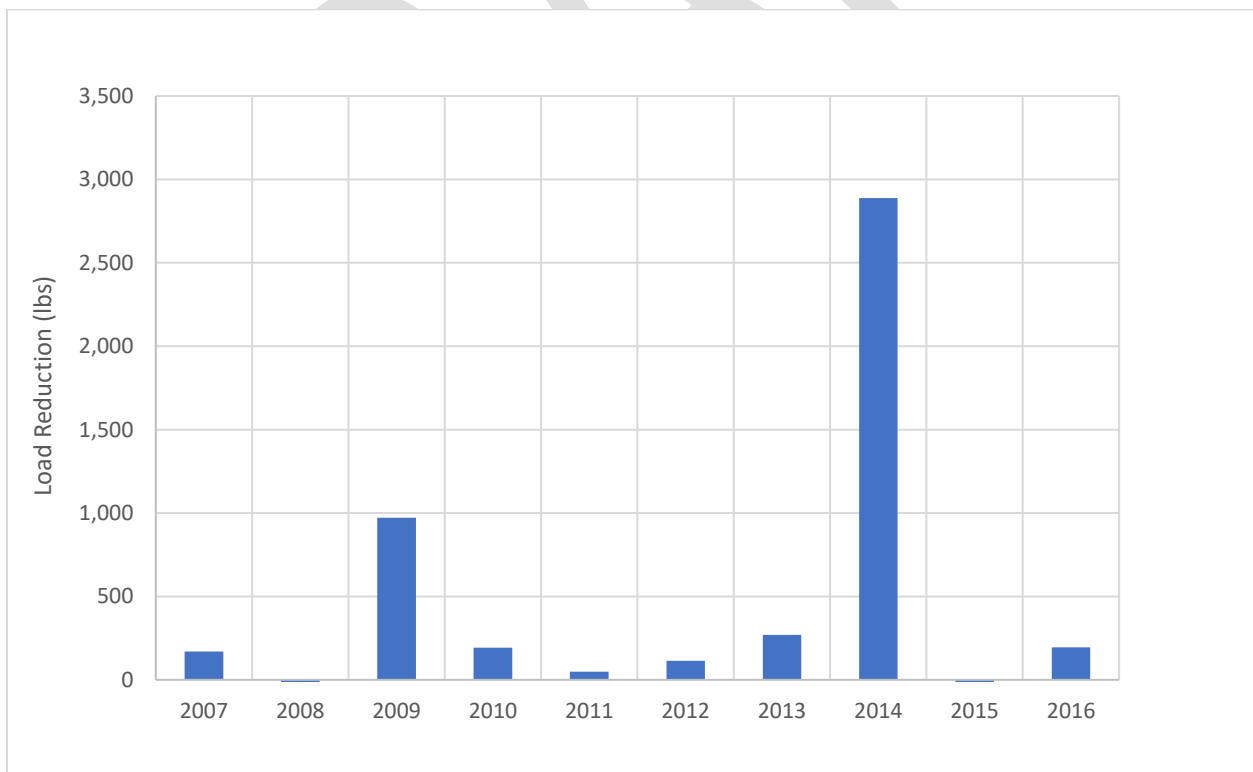


Figure H10. Annual TN Load Reduction for S-49

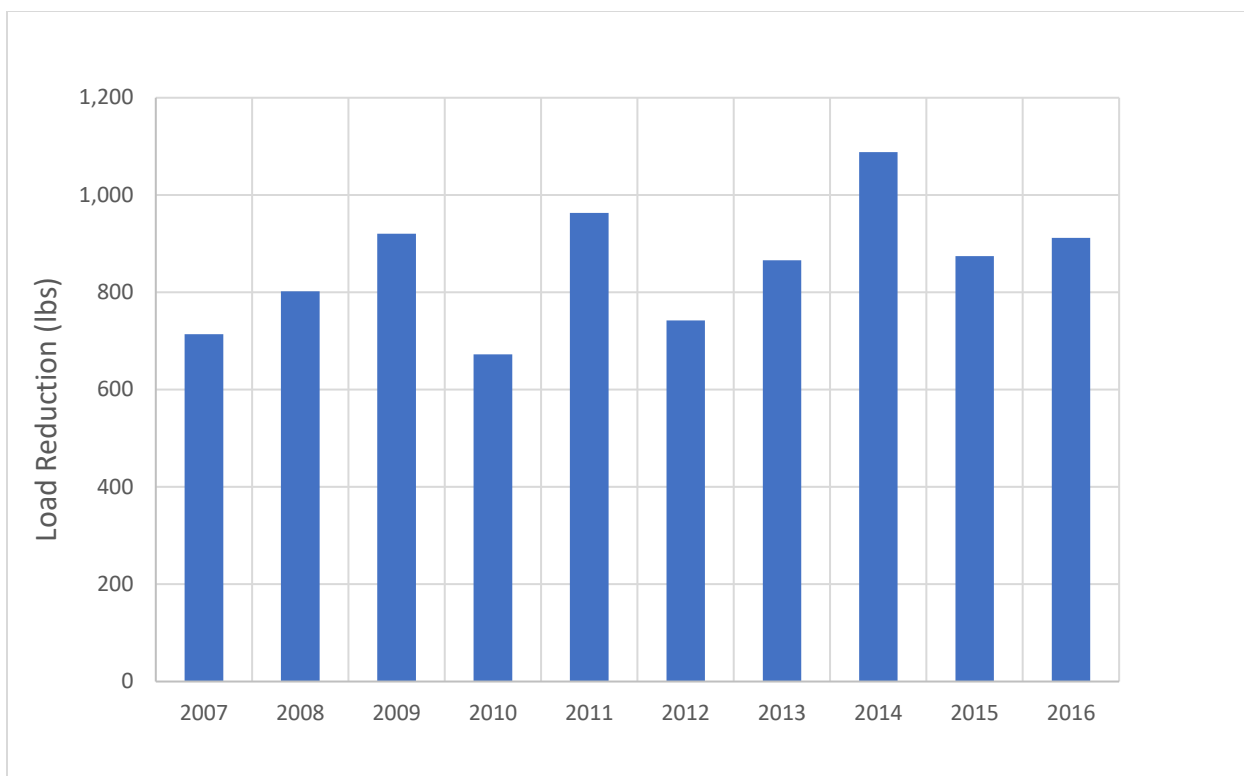


Figure H11. Annual TN Load Reduction for SE-06

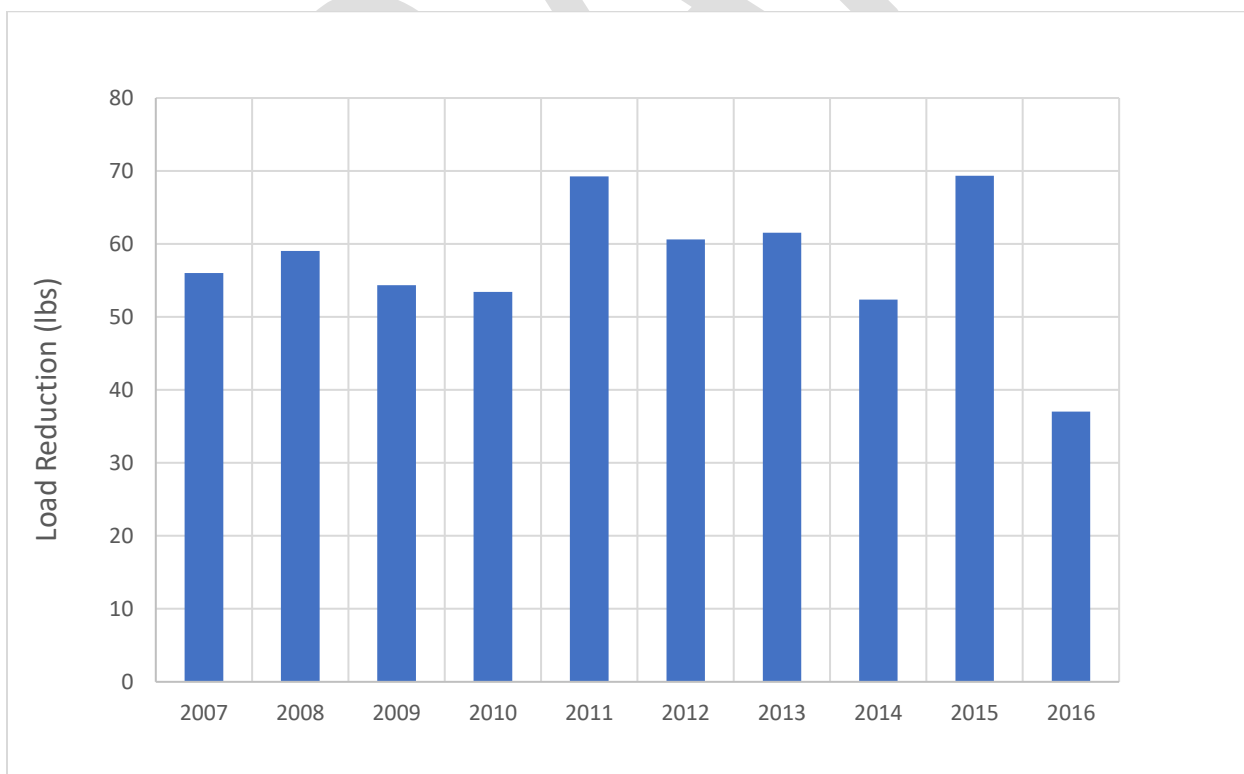


Figure H12. Annual TN Load Reduction for SE-12

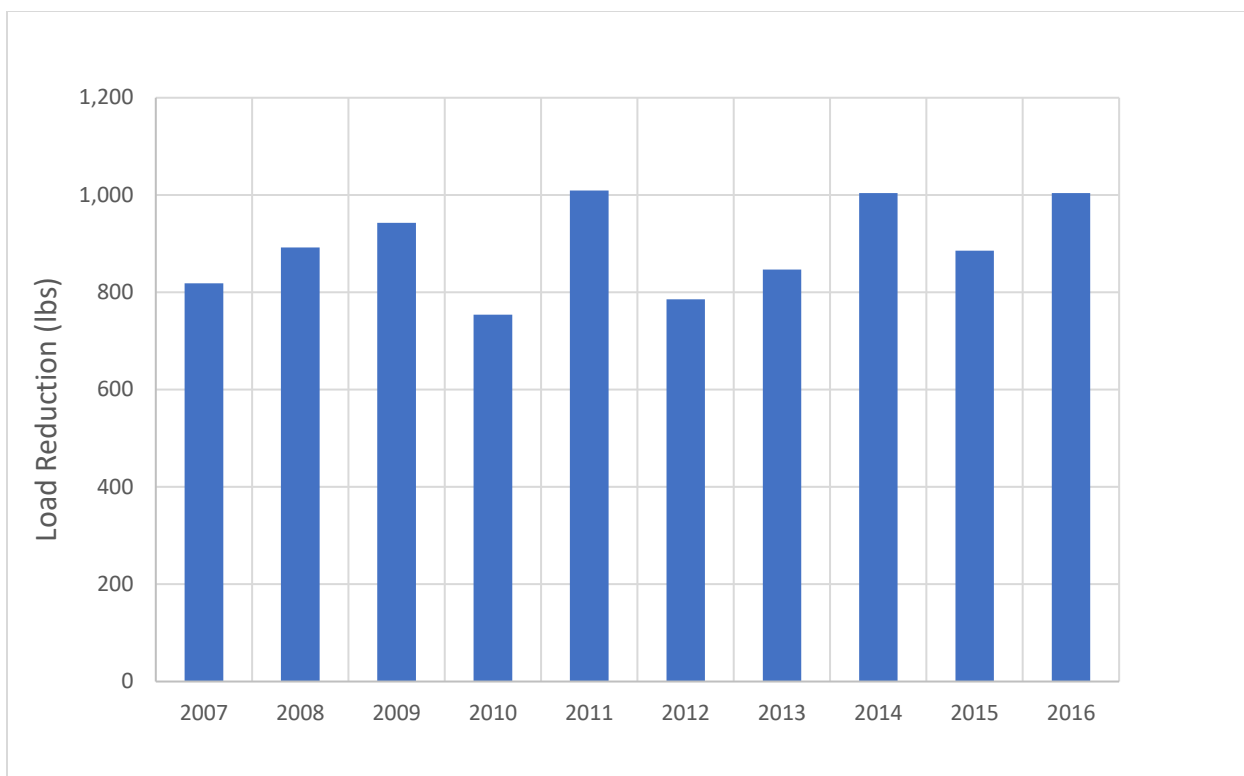


Figure H13. Annual TN Load Reduction for SE-13

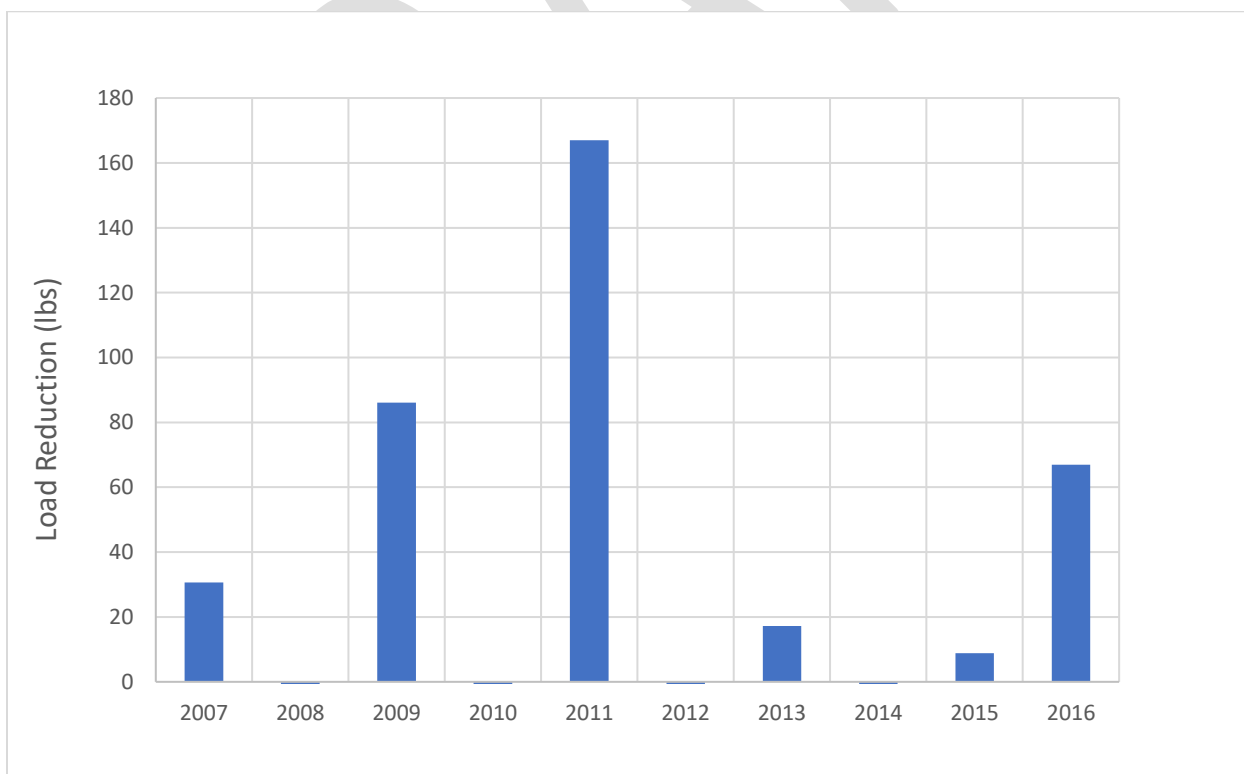


Figure H14. Annual TN Load Reduction for GRS

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