Appendix B

Lake Oologah Watershed Model Calibration and Validation Report

Final Draft

Lake Oologah TMDL Report

Prepared for:

Oklahoma Department of Environmental Quality
Joe A. Long, Environmental Programs Manager
Water Quality Division / Watershed Planning Section
P. O. Box 1677
Oklahoma City, OK 73101-1677
Telephone: (405) 702-8198

FY 2016/17 §106 Grant #I-00640015
Project # 5
May 31, 2017

DYNAMIC SOLUTIONS, LLC
6421 DEANE HILL DRIVE
KNOXVILLE, TENNESSEE 37919

TABLE OF CONTENTS

List of Figures

List of Tables

1. Introduction and Background

Lake Oologah is a reservoir located in northeastern Oklahoma in Rogers County near the towns of Oologah, Nowata, and Claremore. The reservoir is at the downstream end of the Middle Verdigris River Basin (HUC8: 11070103) with a contributing drainage area of 4,339 square miles that includes both Kansas and Oklahoma (USACE, Tulsa District) (Figure 1). The Lake Oologah dam (-95.679 Longitude, 36.4225 Latitude) is located on the Middle Verdigris River at river mile 90.2, about 2 miles southeast of Oologah in Rogers County, Oklahoma, and about 27 miles northeast of Tulsa in Tulsa County, Oklahoma.

Under authorization of the Flood Control Act of 1938, the reservoir was constructed by the US Army Corps of Engineers, Tulsa District. Construction began in 1950 and was completed in 1974, and the USACE continues to manage the lake. The purpose of the reservoir is flood control, water supply, navigation, recreation, and propagation of fish and wildlife. Normal pool surface area of the lake is 31,040 acres, the mean depth is 18.7 feet, and the storage volume is 553,400 acre-ft.

The City of Tulsa obtains approximately 40-50% of its water supply needs from Lake Oologah. The reservoir also serves as a raw water source for Public Service of Oklahoma, the City of Collinsville, Rural Water Districts of Rogers, Nowata, and Washington County, the City of Chelsea, and the City of Claremore (Oklahoma Department of Wildlife Conservation, Oologah Lake Management Plan, 2008). Raw water resource issues include taste and odor complaints and, beginning in 2003, the presence of zebra mussels throughout the lake and a dense accumulation of mussels in the water intake (City of Tulsa, Tulsa Comprehensive Water System Study, 2006).

The Water Body ID (WBID) for the lake is OK121510010020-00 and water quality conditions in the lake are monitored by the Oklahoma Water Resources Board (OWRB) at 7 station locations as part of the Beneficial Use Monitoring Program (BUMP). Based on data collected in 2012 and the Trophic State Index, OWRB has classified the lake as eutrophic. The Oklahoma 303(d) List of Impaired Waters for 2012 identifies impairments of Lake Oologah because of dissolved oxygen and turbidity. Within the Middle Verdigris River Basin, Big Creek and California Creek in Oklahoma are also identified as impaired for dissolved oxygen, as shown in Figure 2.

TMDL evaluations are needed for Lake Oologah to address dissolved oxygen and turbidity impairments. The TMDL evaluation requires the development of a linked watershed and lake model framework for the entire Verdigris River Basin to quantify the cause-effect relationships between external flows and pollutant loads from the watershed and in-lake water quality conditions.

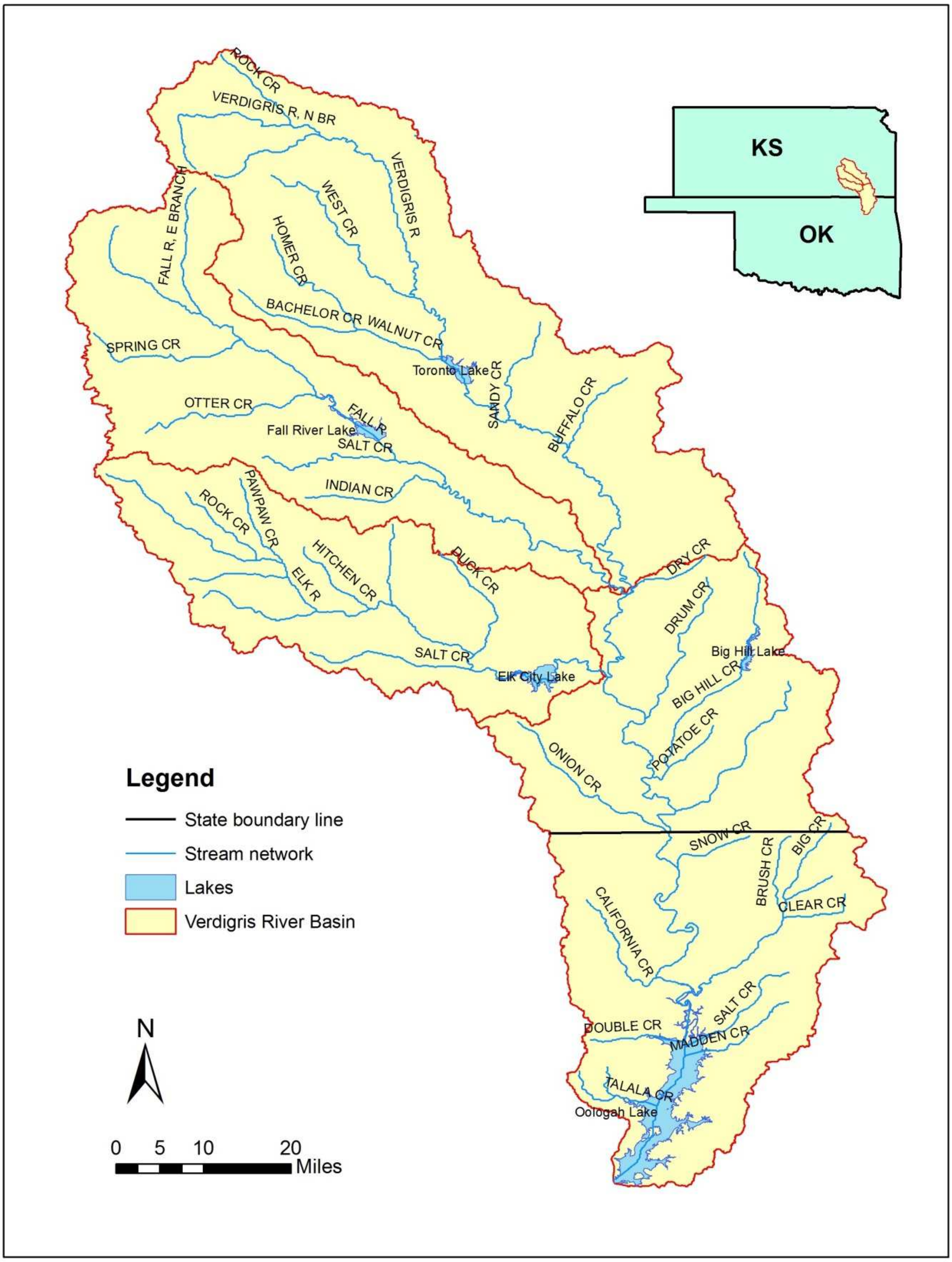

Figure 1 Location of Verdigris River Basin and Lake Oologah

Through review of existing watershed and lake models developed for the Verdigris River Basin and Lake Oologah, Hydrological Simulation Program–FORTRAN (HSPF) (Bicknell et al, 2001) has been identified and selected as the most appropriate modeling tool for development of a watershed model of the Verdigris River Basin. The Environmental Fluid Dynamics Code (EFDC) (USEPA, 2013) has been identified and selected as the most appropriate modeling tool for development of a hydrodynamic, sediment transport, water quality and sediment diagenesis model of Lake Oologah.

The data sources and data availability for the development of the watershed model using HSPF and a lake model using EFDC were documented in the previous report (DSLLC, 2015). Based on the analysis of data collection, the watershed modeling period is narrowed down to 2005 to 2007 because this period covers normal, dry and wet conditions. Since year 2006 is a dry year and year 2007 is a wet year, these two years are selected as the lake EFDC model calibration and validation periods.

This report describes the results of the watershed HSPF model calibration and validation in support of the Lake Oologah TMDL development.

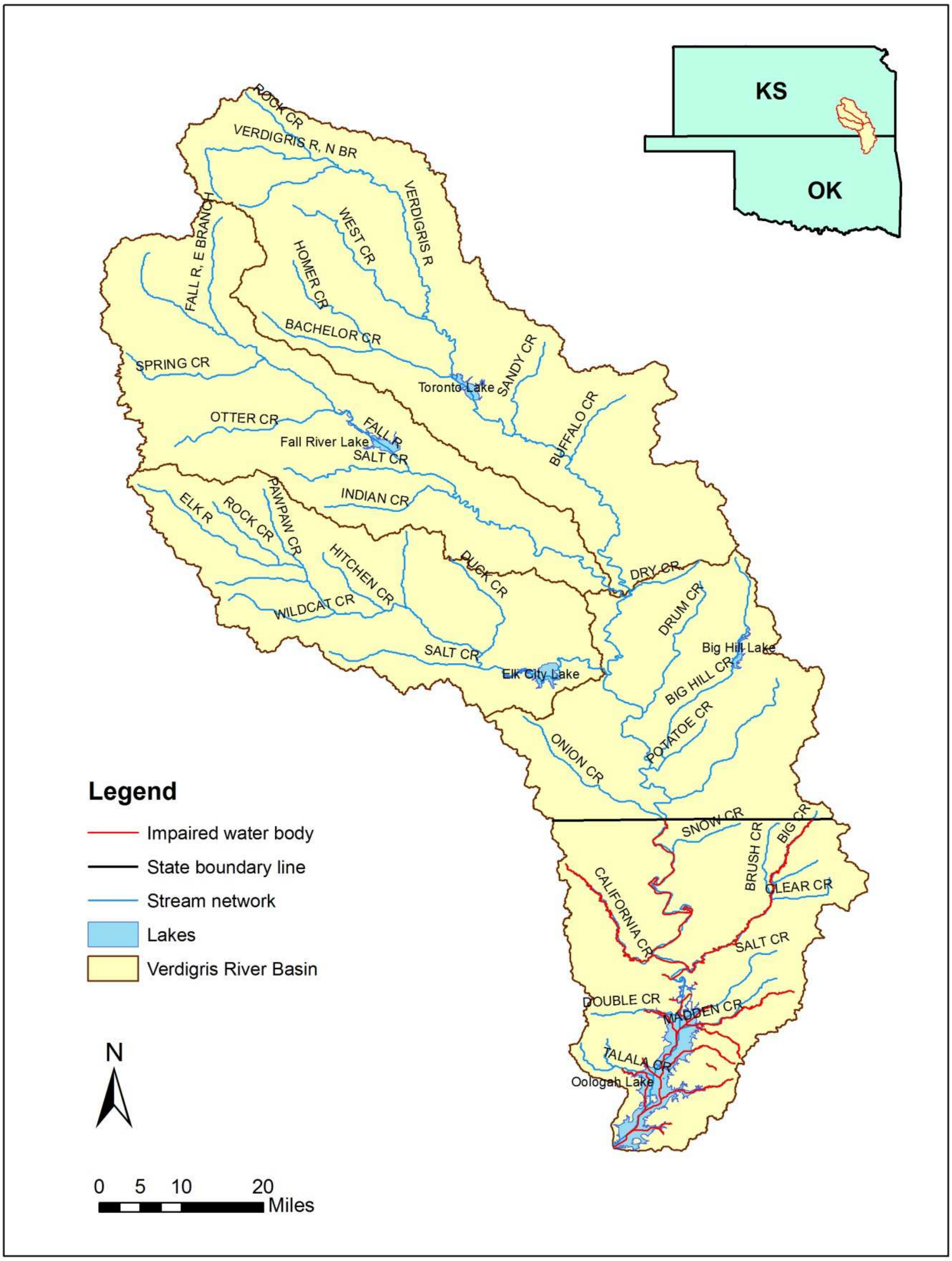

Figure 2 Impaired Water Bodies in 303(d) List in the State of Oklahoma

2. DEVELOPMENT OF HSPF MODEL

This section describes the Hydrologic Simulation Program-FORTRAN (HSPF) model setup, calibration, and validation results for Lake Oologah. Detailed description of HPSF can be found in the literature (Donigian et al., 1999; Bicknell et al., 2001; Duda et al., 2002).

The modeling domain of this project is confined to the basin area above the Lake Oologah but below the four federal reservoirs: Toronto Lake, Fall River Lake, Elk City Lake, and Big Hill Lake. The time series data of flows and water quality constituent loads from these four federal reservoirs serve as the boundary conditions of the watershed model.

2.1 Model Simulation Period

As mentioned in the section of Introduction and Background, the watershed modeling simulation period is narrowed downed to 2005 to 2007 and year 2004 will be used as spinning up to diminish the impact of the initial conditions. However, when processing the water quality data available for model calibration and validation, it was found that the water quality data are very limited. For example, there are less than 10 measured data points during 2005 to 2007 for some water quality parameters. Hence, it was decided that that second half-year of 2004 was added into model simulation period, and the first half year of 2004 was used as the model spinning up to diminish the impact of initial conditions. The model calibration period is from July 1, 2004 to December 31, 2005. The model validation period is from January 1, 2006 to December 31, 2007.

2.2 Model Constituents

The modeled constituents for Lake Oologah watershed model are given below.

- Flow
- Water temperature
- Total suspended solids (TSS)
- ultimate BOD (UBOD)
- Nitrogen (TN, -NO_2+NO_3, organic N, NH_3/NH_4)
- Phosphorus (TP, organic P, Ortho-Phosphate)
- Total organic carbon (TOC)
- Phytoplankton (as Chl-a)
- Dissolved oxygen (DO)

2.3 Model Discretization

The model requires the acreage of various land uses in each sub-watershed and the stream reach to which the land segment discharges. The United States Environmental Protection Agency (USEPA) software BASINS and Arc Hydro were used to delineate the watershed and obtain the physical characteristics of each sub-watershed such as major changes in slope, channel cross-section, and depth.

The Verdigris River watershed was delineated into 59 sub-watersheds shown in Figure 3 based on the United States Geological Survey (USGS) National Elevation Dataset. Table 1 provides the reach characteristics developed by BASINS used in the HSPF model. For subbasin 56, 57, 58, 59, 60, and 1, there are no delineated tributaries. Hence, the flow and water quality constituent loads would directly discharge into the lake.

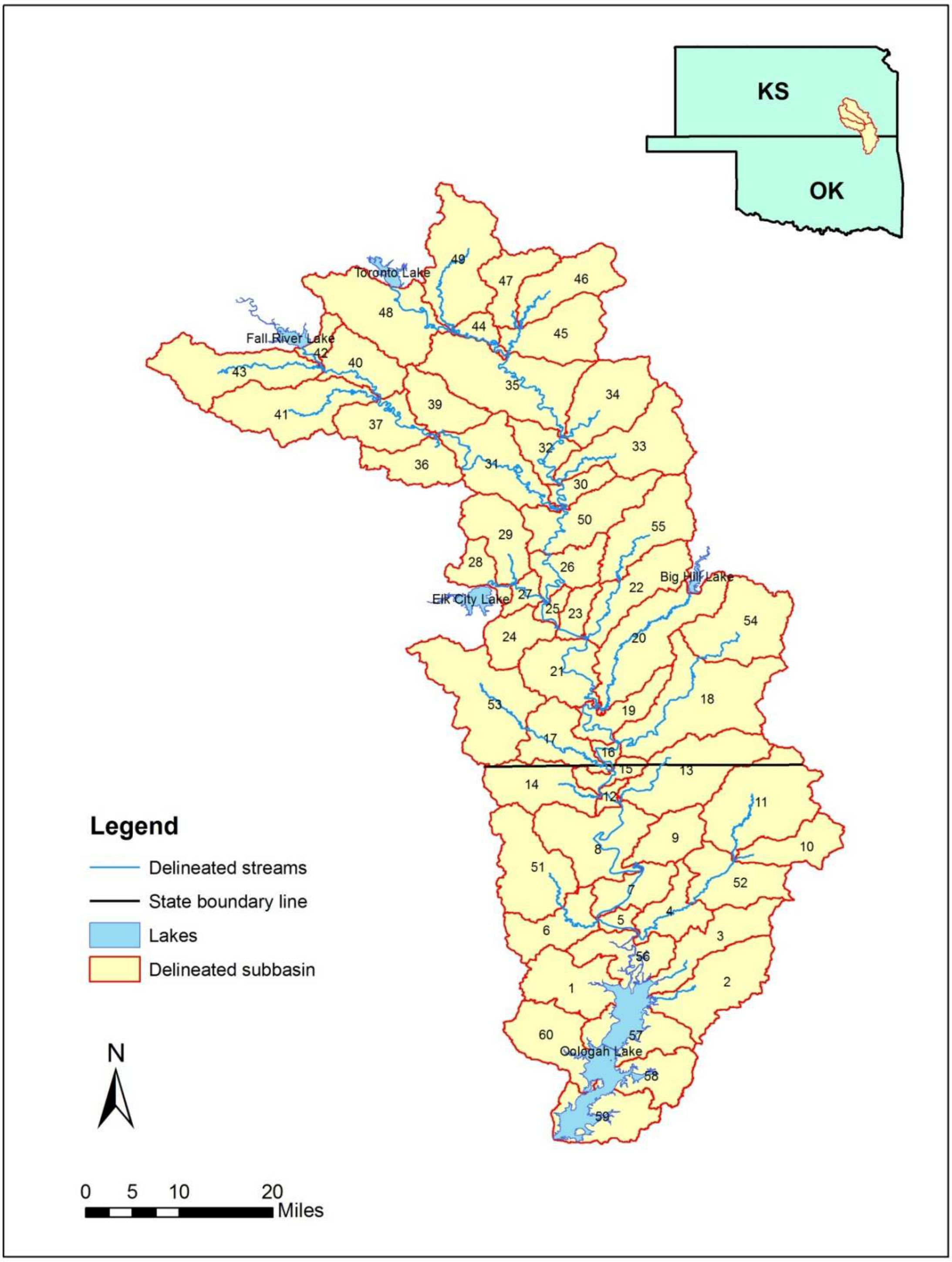

Figure 3 Model Discretization of the Fort Gibson Lake Watershed

Table 1 REACH Characteristics Developed by BASINS

Stream_ID	Length (mile)	DELT_H (feet)	Longitudinal Slope
1	0.86	10	0.002198
2	6.46	23	0.000673
3	3.45	36	0.001972
4	10.62	30	0.000534
5	4.5	10	0.000420
6	8.26	36	0.000824
7	8.82	16	0.000343
8	17.89	16	0.000169
9	0.49	23	0.008871
10	2.27	33	0.002748
11	12.49	75	0.001135
12	2.01	7	0.000658
13	9.38	108	0.002176
14	7.39	49	0.001253
15	3.71	13	0.000662
16	6.4	7.8	0.000230
17	15.41	56	0.000687
18	19.82	85	0.000811
19	10.37	26	0.000474
20	30.63	105	0.000648
21	14.72	30	0.000385
22	10.31	46	0.000843
23	2.78	10	0.000680
24	0.42	13	0.005850
25	4.73	13	0.000519
26	10.19	13	0.000241
27	4.98	13	0.000493
28	3.61	7	0.000366
29	5.15	10	0.000367
30	5.57	13	0.000441
31	29.76	52	0.000330
32	11	16	0.000275
33	10.56	33	0.000591
34	7.39	20	0.000512
35	19.08	16	0.000158
36	7.39	20	0.000512
37	15.28	7	0.000087
39	7.39	20	0.000512
40	9.69	30	0.000585
41	16.9	112	0.001253
42	4.29	46	0.002027
43	15.03	161	0.002025
44	11.37	23	0.000382
45	5.4	3	0.000105
46	9.75	49	0.000950
47	3.86	10	0.000490
48	14.1	46	0.000617
49	15.1	89	0.001114
50	8.7	10	0.000217
51	6.01	39	0.001226
52	7.7	36	0.000884
53	10.62	46	0.000819
54	6.9	30	0.000822
55	10	62	0.001172

2.4 Land Use

Since the model simulation period is from July 1, 2004 to December 31, 2007, the 2006 National Land Cover Database (NLCD) land use data were used for the development of the watershed model. The land uses were grouped into six different classes to capture the variation of watershed characteristics affecting the flow and pollutant loads. Figure 4 shows the land use distribution by the 2006 NLCD land use data. The area and percentage of each land use are given in Table 2.

Table 2 Land Use Distribution in the Verdigris River Watershed Model

Landuse	Area (acre)	Percentage
Cropland	167228	11.51%
Forest	196608	13.53%
Grassland	338889	23.33%
Pasture	659419	45.39%
Urban	83013	5.71%
Wetland	7691	0.53%
Total	1452848	100.00%

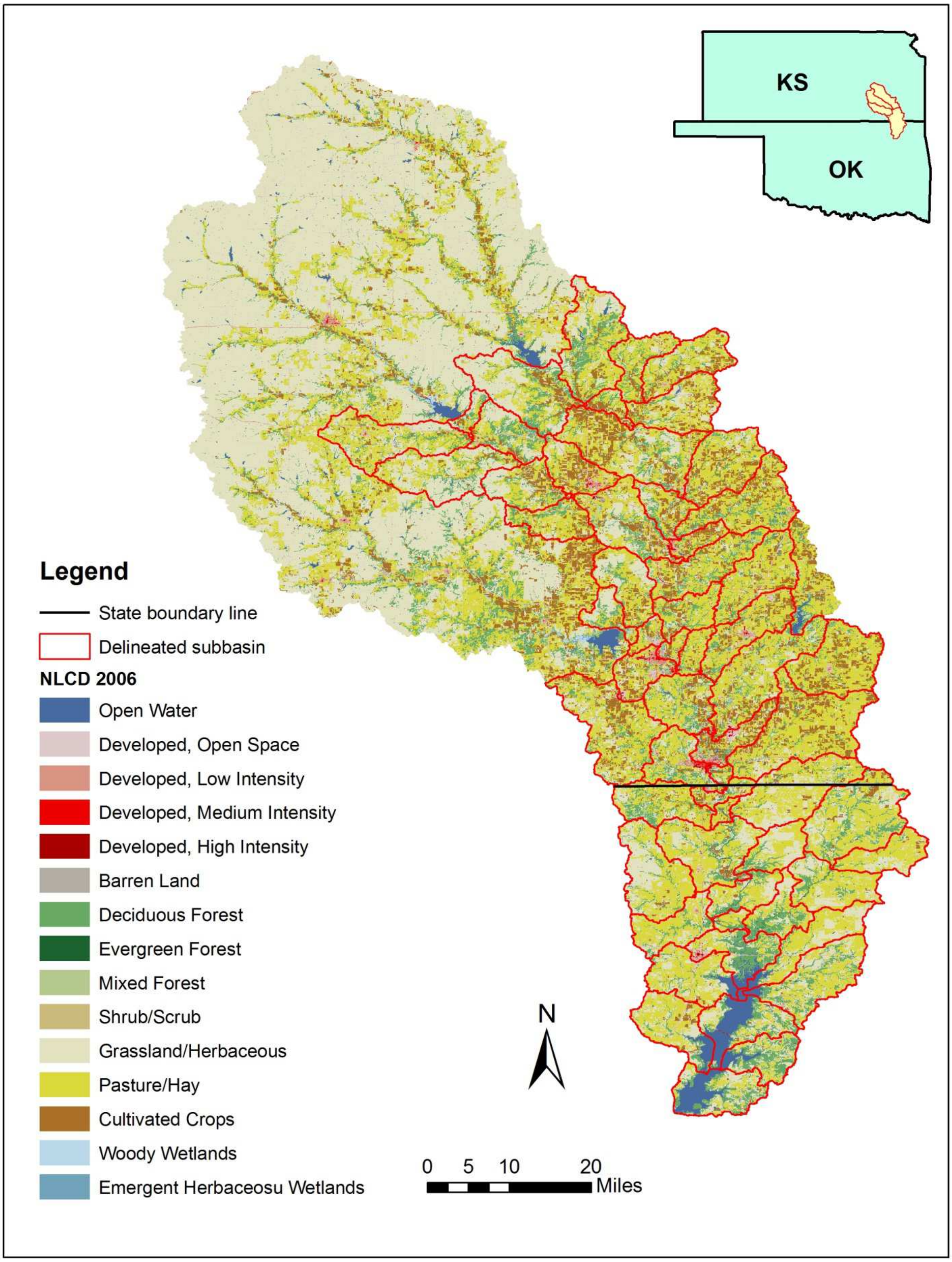

Figure 4 Landuse Distribution in the Verdigris River Watershed

2.5 Meteorological Data

Seven meteorological variables are required for hydrological and water quality simulation using HSPF. These variables are precipitation, evapotranspiration, air temperature, dew point temperature, wind speed, solar radiation, and cloud cover. HSPF uses meteorological data to generate runoff and pollutant loads. Modeled runoff and pollutant loads from point and nonpoint sources were routed through stream reaches. Representative rainfall and potential evapotranspiration (PET) are the key meteorological inputs to HSPF.

Rainfall data from two MESONET stations and five NOAA NCDC stations were used to represent the spatial variations in the Verdigris River Basin, as shown in Figures 5-6. Detailed information of these stations is given in Table 3 and 4.

Cloud cover data are available at four NOAA stations, as shown in Figure 6. Detailed information of these stations is given in Table 4. Observed solar radiation data are available at all three MESONET stations, as shown in Table 3. At NOAA stations of Chanute Martin Johnson Airport and Coffeyville Municipal Airport, solar radiation was calculated based on the cloud cover and latitude data. Daily PET data was computed in WDMUtil of BASINS using Hamon's method (Hamon, 1961). Daily PET was then desegregated to hourly values using WDMUtil.

Other meteorological data including air temperature, dew point temperature, and wind speed are available at three MESONET stations and two NOAA stations, as shown in Figure 5 and 7.

Table 3 Mesonet Meteorological Stations Used in the HSPF Model

Station ID	Station Name	County	Latitude	Longitude
COPA	Copan	Washington	36.90987	-95.88553
PRYO	Pryor	Mayes	36.36914	-95.27138
VINI	Vinita	Craig	36.77536	-95.22094

Table 4 NOAA NCDC Meteorological Stations Used in the HSPF Model

Station Name	WBAN ID	Latitude	Longitude
CLAREMORE REGIONAL AIRPORT	53940	36.294	-95.479
BARTLESVILE MUNICIPAL AIRPORT	03959	36.768	-96.026
INDEPENDENT MUNICIPAL AIRPORT	00141	37.158	-95.778
COFFEYVILLE MUNICIPAL AIRPORT	93967	37.091	-95.566
TRI-CITY AIRPORT	3998	37.328	-95.504
CHANUTE MARTIN JOHNSON AIRPORT	13981	37.67	-95.484

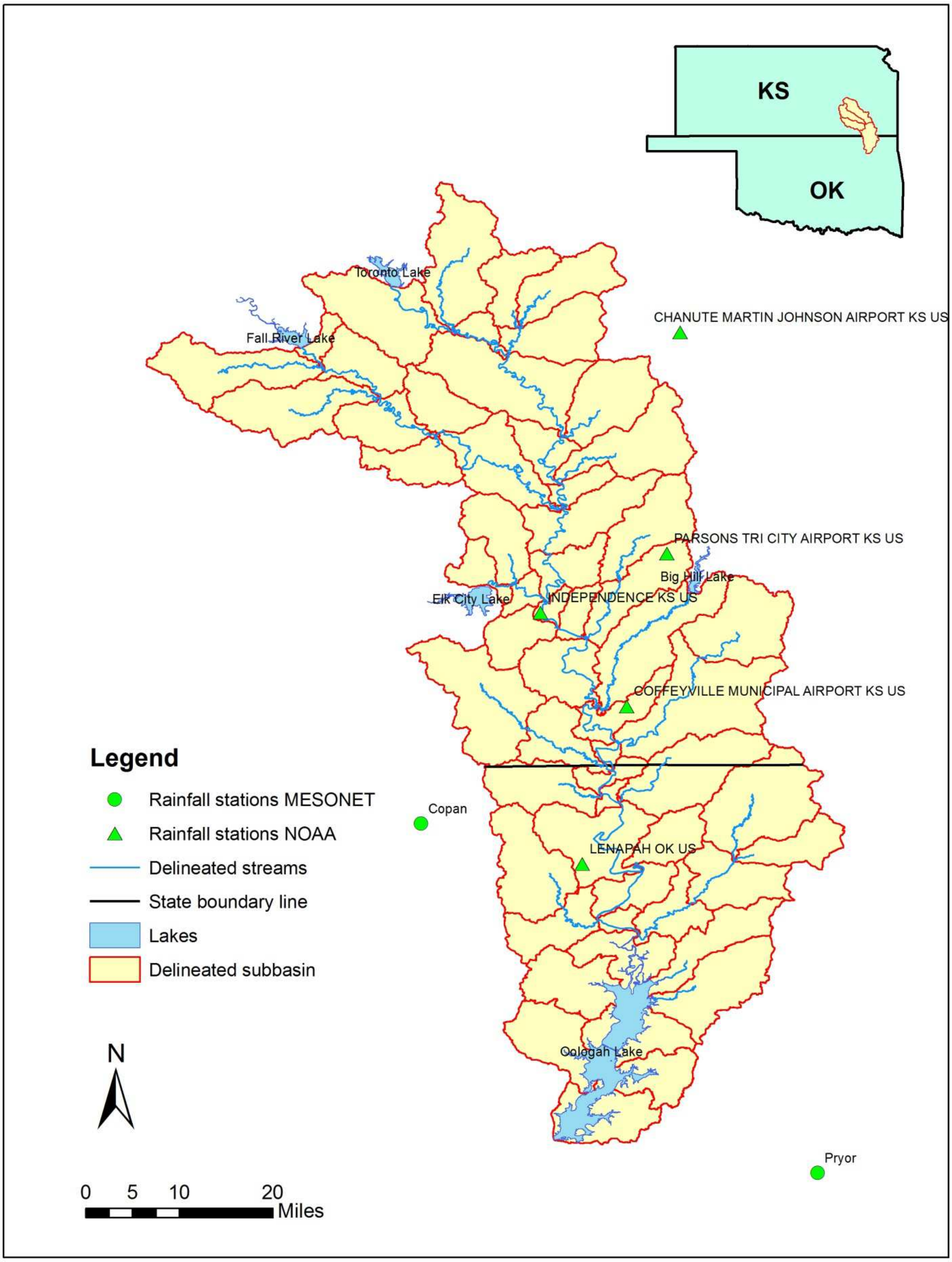

Figure 5 Locations of MESONET and NOAA Rainfall Stations

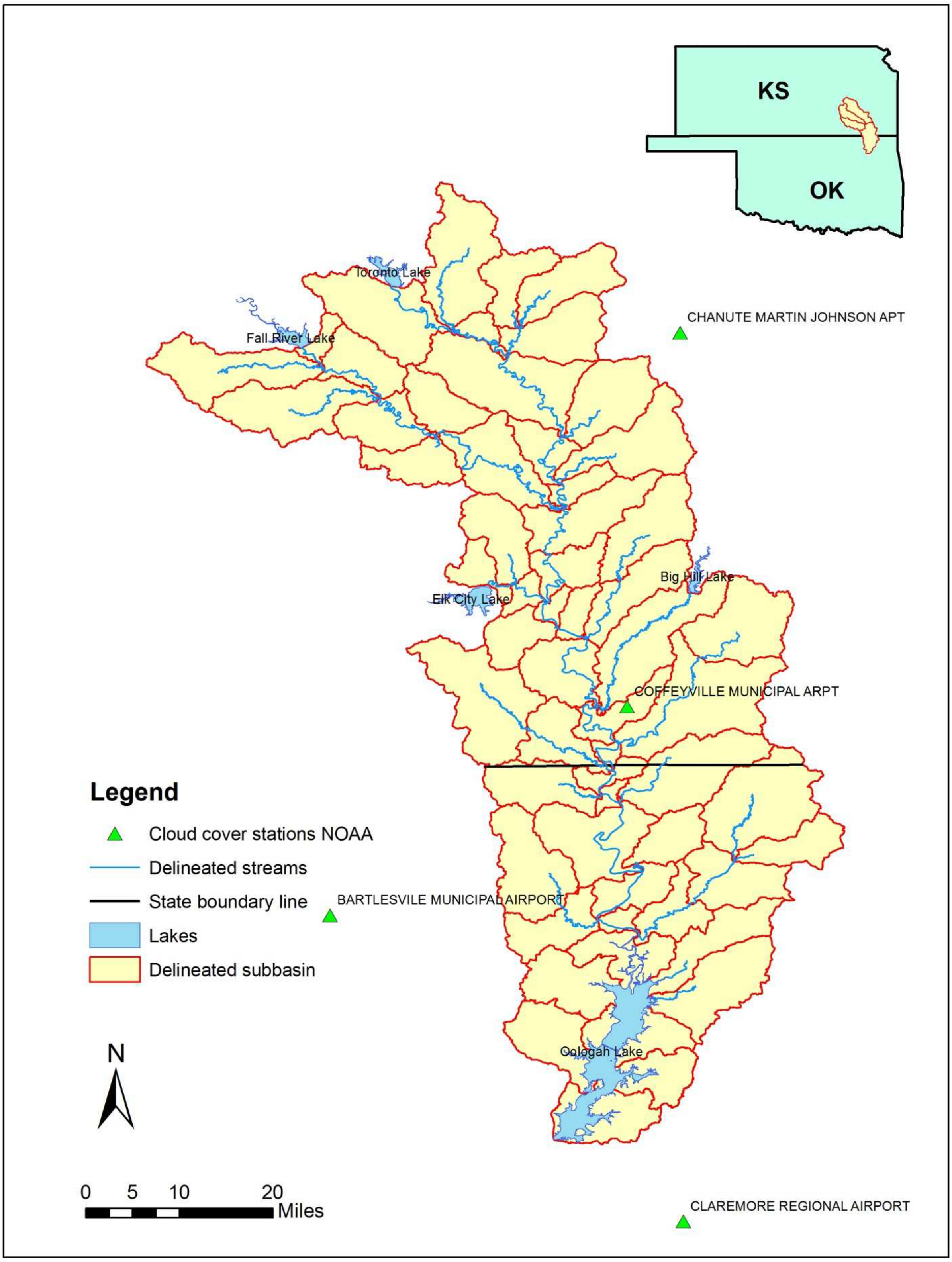

Figure 6 Locations of NOAA Cloud Cover Stations

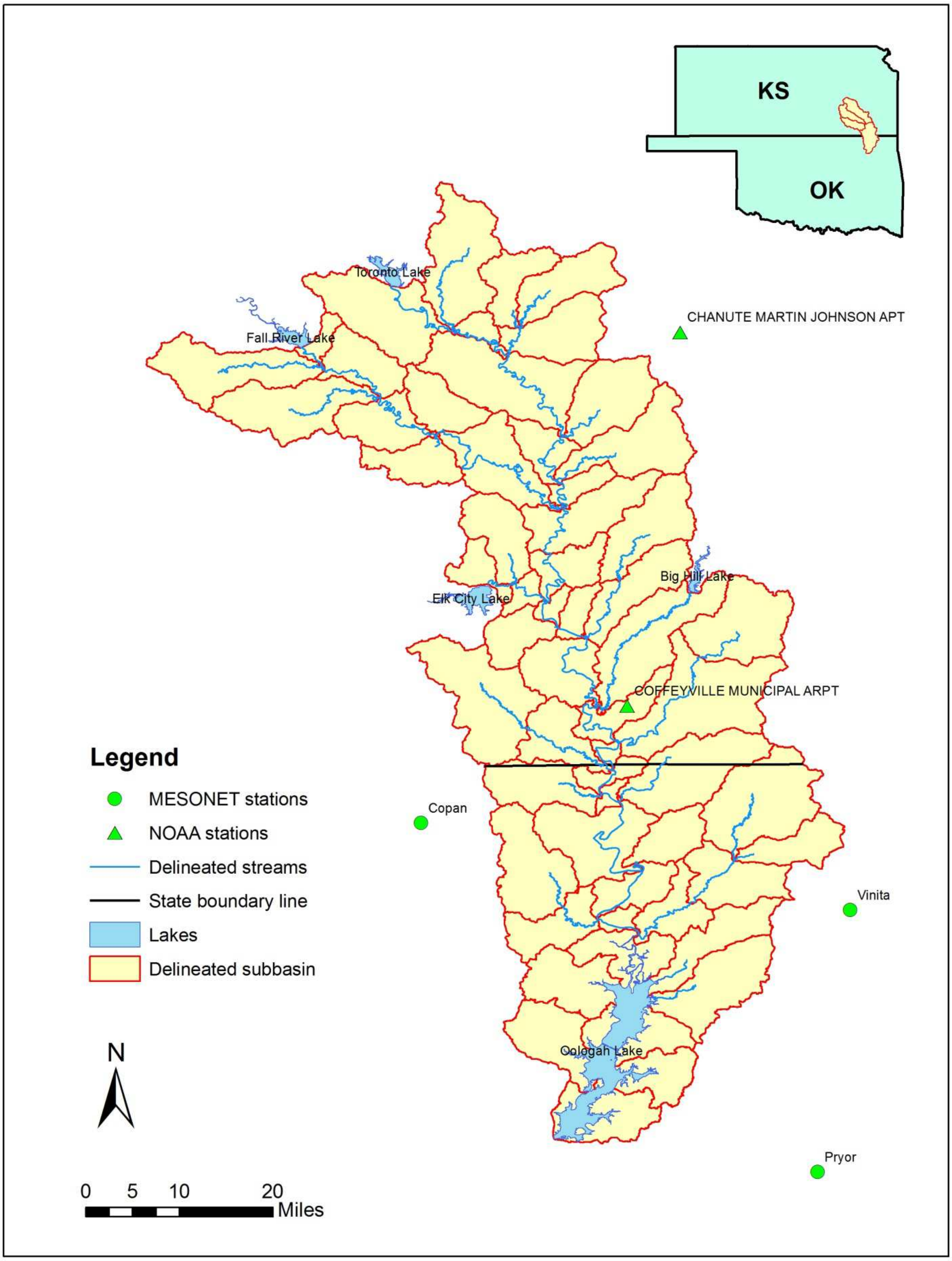

Figure 7 Locations of MESONET and NOAA Meteorological Stations

2.6 Upstream Lake Boundary Condition

Toronto Lake, Fall River Lake, Elk City Lake, and Big Hill Lake are four federally regulated reservoirs that discharge into the Verdigris River Basin, as shown in Figure 1. Flow and water quality constituent data from these four reservoirs are required to develop the upstream boundary conditions for the watershed model.

The observed data available at these four reservoirs include flow, water temperature, TSS, NH4, NO3, dissolved TKN, total TKN, dissolved orthophosphate, dissolved total phosphorus, DOC, TOC, and chlorophyll a. Dam discharge flows were measured at 1-hour intervals, which is adequate for the development of upstream boundary condition.

The water quality constituent data were collected monthly or bi-weekly by USACE. For the development of upstream boundary conditions of water temperature and DO, the monthly or bi-weekly interval is insufficient. The hourly water temperature and DO are needed to capture the diurnal change in water temperature and DO.

Hourly water temperature monitoring data by USACE at several locations in the Verdigris River are available, as shown in Figure 8. It was found that there exists a strong linear relationship between the water temperatures in the dam release and collected at the river station. For example, the determination coefficient (r^2) between the paired water temperature of Toronto Lake and Station VR-3 is 0.9827, as shown in Figure 9. Hence, the linear regression equation was used to back-calculate the hourly water temperature for the Toronto Lake.

The same approach was used to back-calculate the water temperature for the other three reservoirs: Fall River Lake, Elk City Lake, and Big Hill Lake. The strong linear correlations between the lake water temperature and the river water temperature are given in Figures 9-12.

For these four reservoirs, the hourly saturated DO concentrations can be calculated based on the hourly water temperature, assuming no salinity present in the lake water. The calculated hourly saturated DO concentrations were used as boundary conditions for these reservoirs. This is a reasonable approximation because the lake water is reaerated during the process of discharge.

The HSPF model requires ultimate BOD data to simulate DO cycle in a river. However, UASCE only collected DOC and TOC data. The approach by Hendrickson et al. (2002) was used to estimate the ultimate BOD data based on DOC and TOC data. For other missing water quality constituent data required by HSPF, the stoichiometric ratios of typical algae were used to make reasonable estimation.

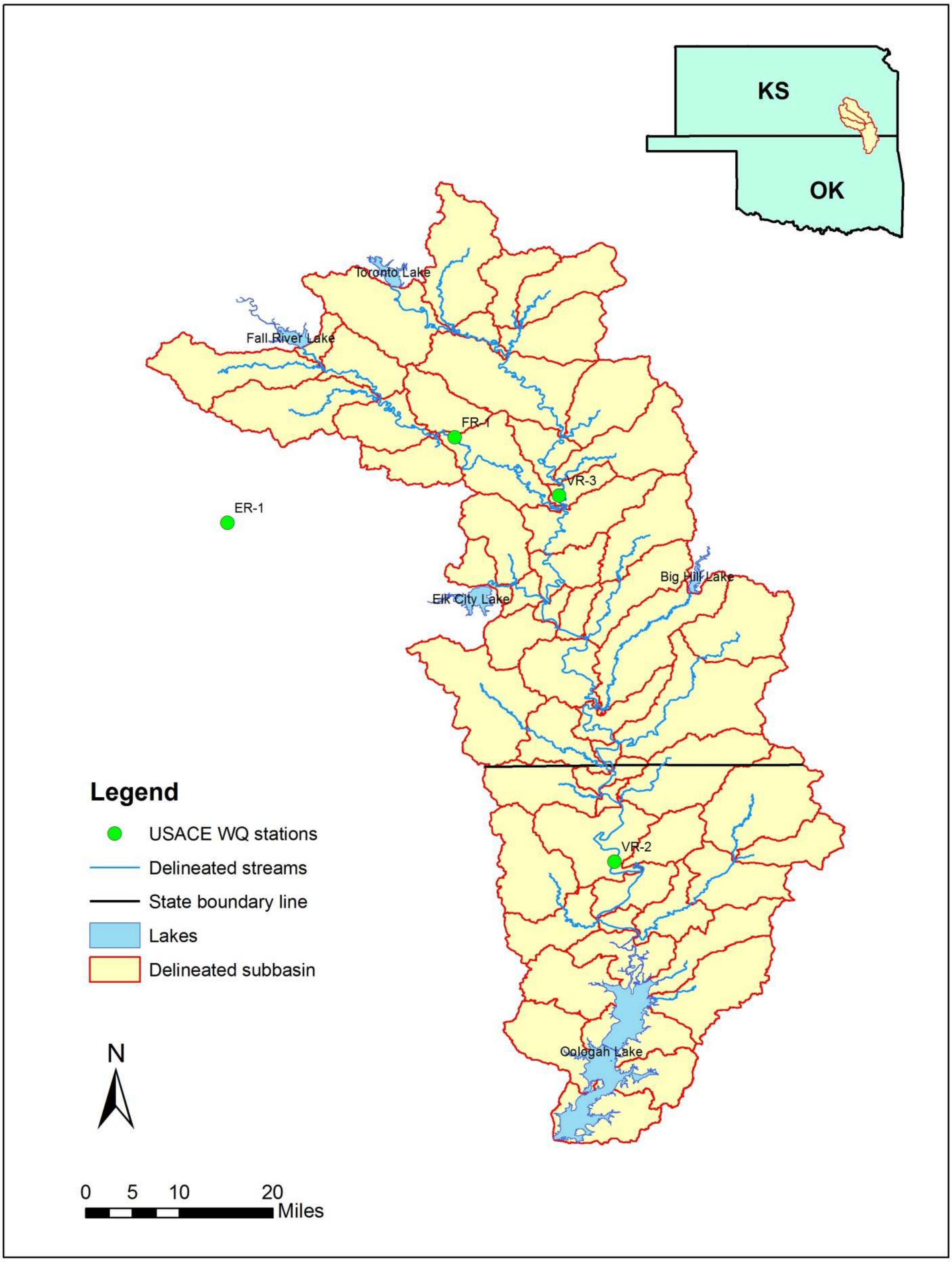

Figure 8 Locations of the USACE Water Quality Stations

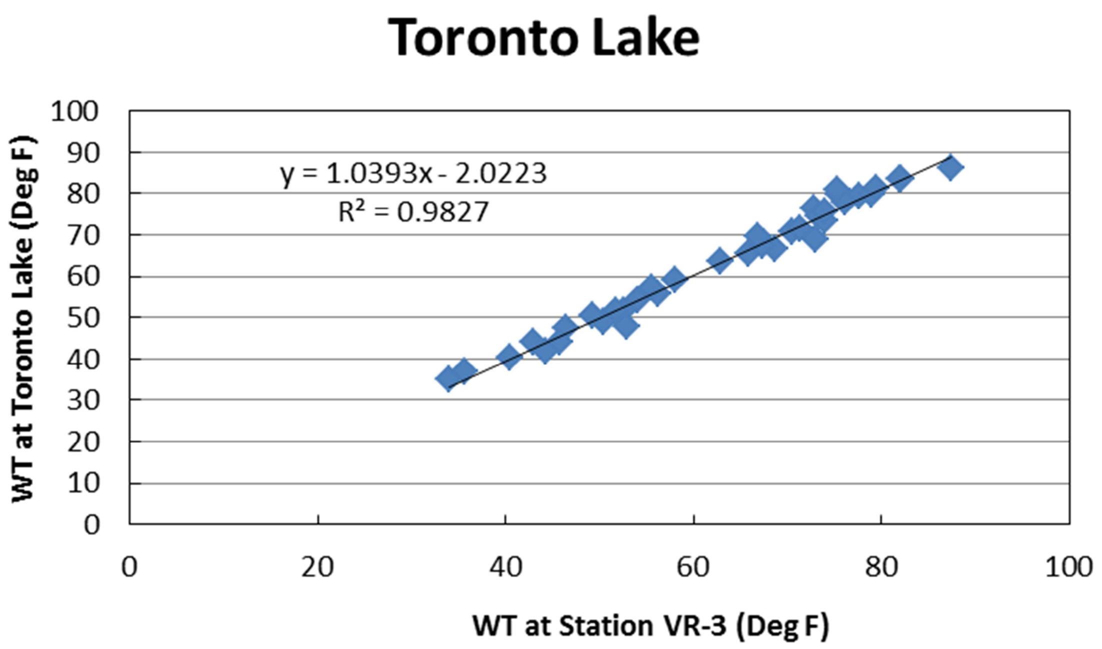

Figure 9 Linear Relationship of Water Temperature between Toronto Lake and VR-3

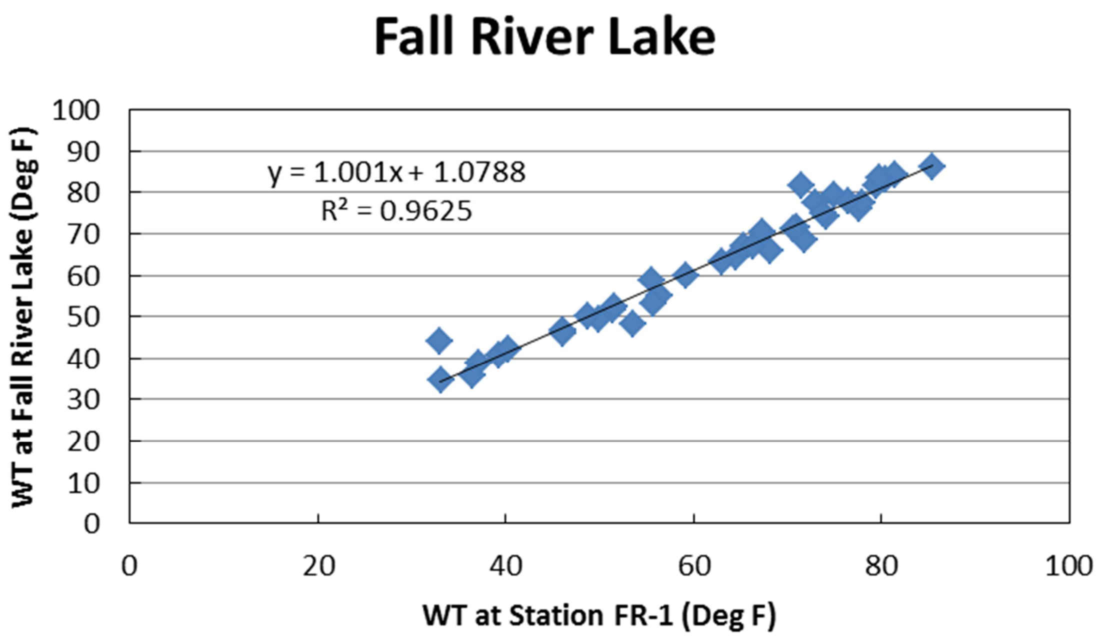

Figure 10 Linear Relationship of Water Temperature between Fall River Lake and FR-1

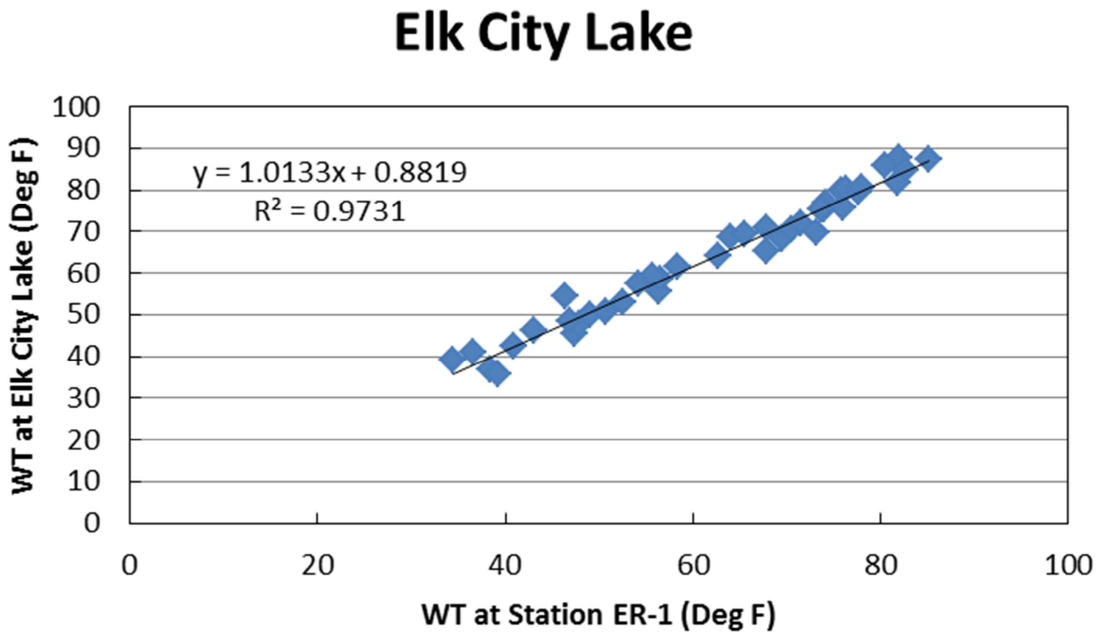

Figure 11 Linear Relationship of Water Temperature between Elk City Lake and ER-1

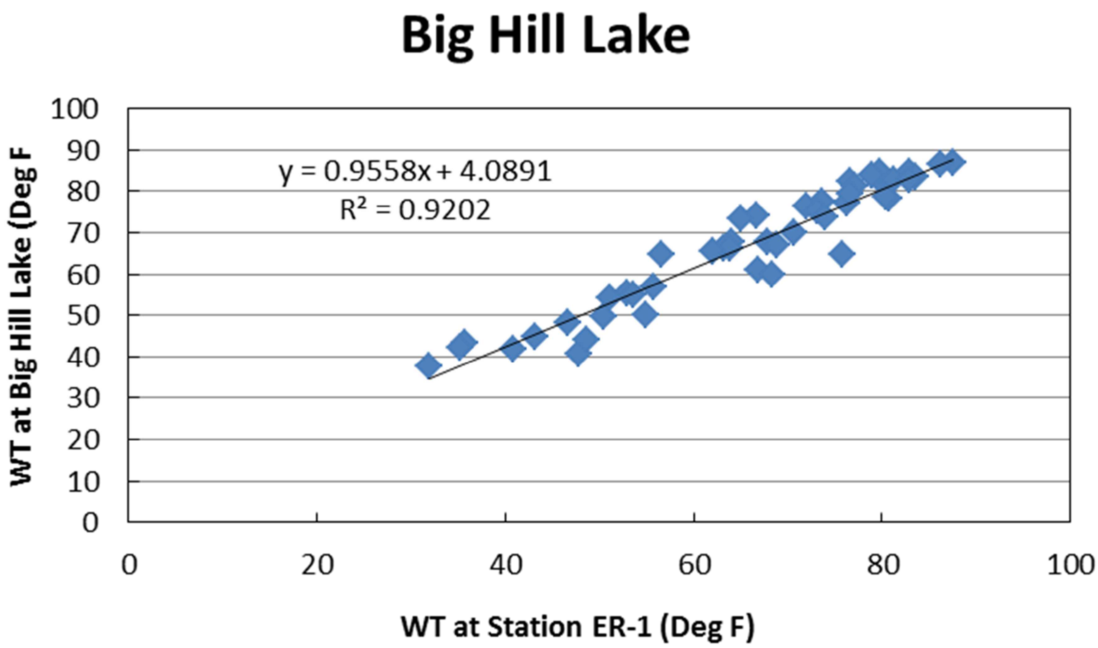

Figure 12 Linear Relationship of Water Temperature between Big Hill Lake and ER-1

2.7 Point Source Discharge

Based on the data collection report (DSLLC, 2015), there are a total of 81 permits issued to discharge flow into the Verdigris River Basin. In the list of these facilities, many permits are typically ready mix plants that do not discharge; some facilities are general permits for industrial and construction and there are no data for these facilities; some facilities are quarries or mineral extraction/processing facilities that typically do not discharge (T. Stiles, personal communication, June 8, 2015).

The NPDES facilities that discharge into the Verdigris River with monthly average discharge higher than 0.1 MGD (0.15cfs) were considered in this modeling project. For a watershed like Verdigris Basin with contributing area of 1,452,848 acres, the nutrient loadings from an NPDES facility with an average flow lower than 0.1 MGD can be negligible compared to the loadings from watershed runoff. Hence, the NPDES facilities included in the watershed model were narrowed down to seven, as shown in Figure 13 and Table 5.

Table 5 Information of the Wastewater Treatment Facilities

NPDES ID	FACILITY NAME	COUNTY	Latitude	Longitude
OK0020117	SOUTH COFFEYVILLE WWT	NOWATA	36.998639	-95.612361
KS0050733	COFFEYVILLE, CITY OF	MONTGOMERY	37.006469	-95.609672
KS0000248	COFFEYVILLE RESOURCES REFINING & MARKETING	MONTGOMERY	37.043300	-95.610800
KS0095486	INDEPENDENCE WASTEWATER PLANT	MONTGOMERY	37.228841	-95.692941
KS0094803	CHERRYVALE WASTEWATER PLANT WADE WEBBER, PUBLIC WORKS DIR.	MONTGOMERY	37.276028	-95.582556
KS0025658	NEODESHA, CITY OF	WILSON	37.432093	-95.683690
KS0045985	FREDONIA WASTE WATER TREATMENT PLANT C/O CITY HALL	WILSON	37.532704	-95.826473

Required effluent data for these NPDES facilities for model input are flow, water temperature, Dissolved Oxygen (DO), Total Suspended Solids (TSS), Total Organic Carbon (TOC), Nitrogen (TON,NH3,NO3), Phosphorus (TOP,PO4), Ultimate BOD (BODU) and Inorganic Suspended Solids (InorgSS). Discharge Monitoring Report (DMR) data were obtained from the Kansas Department of Health and Environment and Oklahoma Department of Environmental Quality. The data availability of monitored water quality parameters at each NPDES facility is given in Table 6.

If a required water quality parameter is not available then stoichiometric ratios of typical effluent concentrations were used to estimate the missing parameter from available observations according to the facility type and literature values (Metcalf & Eddy, Inc., 1991; Rozzi et al., 1999; Stoddard et al., 2002; Hyder and Bari, 2011). Daily time series of flow and all effluent parameters were assigned from either observed data or estimated data based on linear interpolation of effluent data from 1 January 2004 through 31 December 2007.

Table 6 Monitored DMR Data at the NPDES Facilities

NPDES_ID	Flow	DO	BOD5	NH3	NO2	NO3	TON	TKN	TN	TP	TSS	Temperature
OK0020117	√	√	√	√							√	
KS0000248	√		√	√		√	√			√	√	√
KS0025658			√	√							√	
KS0045985	√		√	√	√	√		√	√	√	√	
KS0050733	√	√	√	√	√	√		√	√	√	√	
KS0094803			√	√							√	
KS0095486	√	√	√	√	√	√		√	√	√	√	√

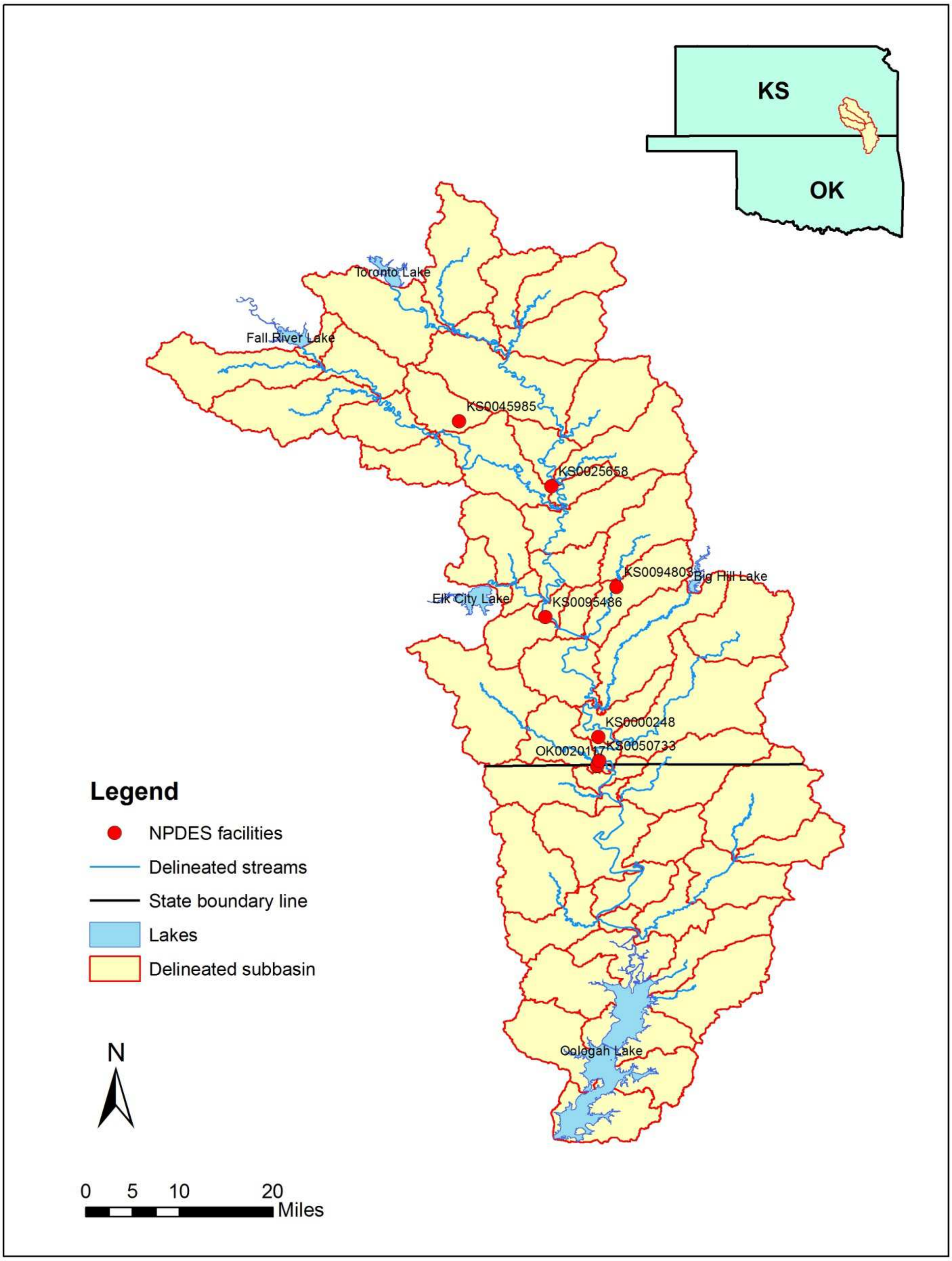

Figure 13 Locations of the Major NPDES Facilities

2.8 Water Withdrawals

Surface water is the predominant source of water for beneficial use in the Verdigris River Basin, making up over 98% of the water used (KOS, 2009). The majority of the water used is for municipal (56%), industrial (36%), and irrigation (8%).

The surface water withdrawal data were obtained by submitting the Open Records Request Form from the Kansas Department of Agriculture (http://agriculture.ks.gov/document-services/open-records-request). For the majority of the municipal and industrial water users, monthly water withdrawal data were available and only one industrial facility with WUAPERS_ID of 40450 has annual water withdrawal data (Figure 14 and Table 7). For these industrial and municipal facilities, the monthly or annual flow will be evenly distributed into daily flows.

Table 7 Information of Water Withdrawals for Industrial and Municipal Facilities

WUAPERS_ID	Name	UMW_CODE	COUNTY	LONGITUDE	LATITUDE	Data Interval
233	City of Altoona	MUN	WL	-95.66513	37.5235	Monthly
2219	City of Buffalo	MUN	WL	-95.72466	37.70876	Monthly
2768	City of Cherryvalle	MUN	MG	-95.676341	37.285685	Monthly
3018	City of Coffeyville	MUN	MG	-95.63432	37.06126	Monthly
8379	City of Independence	MUN	MG	-95.69758	37.23757	Monthly
17839	City of Thayer	MUN	NO	-95.488629	7.4819017	Monthly
19999	City of Yates Center	MUN	WO	-95.80314	37.83286	Monthly
28086	Heartland Cement Co	IND	MG	-95.67288	37.21177	Monthly
57793	Coffeyville Resources & Marketing LLC	IND	MG	-95.60744	37.05537	Monthly
58869	Hirricane Service LLC	IND	WL	-95.71430172	37.6389941	Monthly
40450		IND	WO	-95.841984	37.787805	Annual

The water withdrawals used for irrigation and recreation purposes is only available at annual intervals, as shown in Figure 15 and Table 8. Lamm et al. (2006) estimated the average (34 years, 1972-2005) monthly distribution of net irrigation requirements for four major irrigated crops at Colby, Kansas, as shown in Table 9. These four crops are corn, grain sorghum, soybean, and sunflower.

Three crops of corn, grain sorghum, and soybean, are used to develop a composite monthly distribution of irrigation requirement. The developed composite monthly distribution will be applied to all irrigation facilities to distribute the annual withdrawal to monthly withdrawal. The monthly withdrawal will be evenly distributed into daily flows.

Table 8 Information of Water Withdrawals for Irrigation and Recreation Facilities

WUAPERS_ID	UMW_CODE	COUNTY	LONGITUDE	LATITUDE	Data Interval
5758	IRR	WL	-95.84572	37.6761	Annual
11933	IRR	WL	-95.7715	37.64152	Annual
13831	IRR	WL	-95.76514	37.64267	Annual
17006	IRR	MG	-95.69001	37.26701	Annual
20363	IRR	MG	-95.62196	37.11937	Annual
21593	IRR	MG	-95.675088	37.218105	Annual
22295	IRR	MG	-95.674111	37.216686	Annual
23970	IRR	WL	-95.85814	37.67538	Annual
24314	IRR	WL	-95.81242	37.66876	Annual
36298	IRR	MG	-95.68249	37.06102	Annual
52670	IRR	WL	-95.82613	37.6584839	Annual
52994	REC	MG	-95.5257967	37.2432193	Annual

Table 9 Average Monthly Percentage of Simulated Net Irrigation Requirements for Four Major Irrigated Crops at Colby, Kansas

Crop	June	July	August	September
Corn	13.7	42.6	41.9	1.8
Grain sorghum	6	38.9	50.5	4.6
Soybean	10	43.2	40.5	6.4
Sunflower	2.3	25.5	53.2	19.1

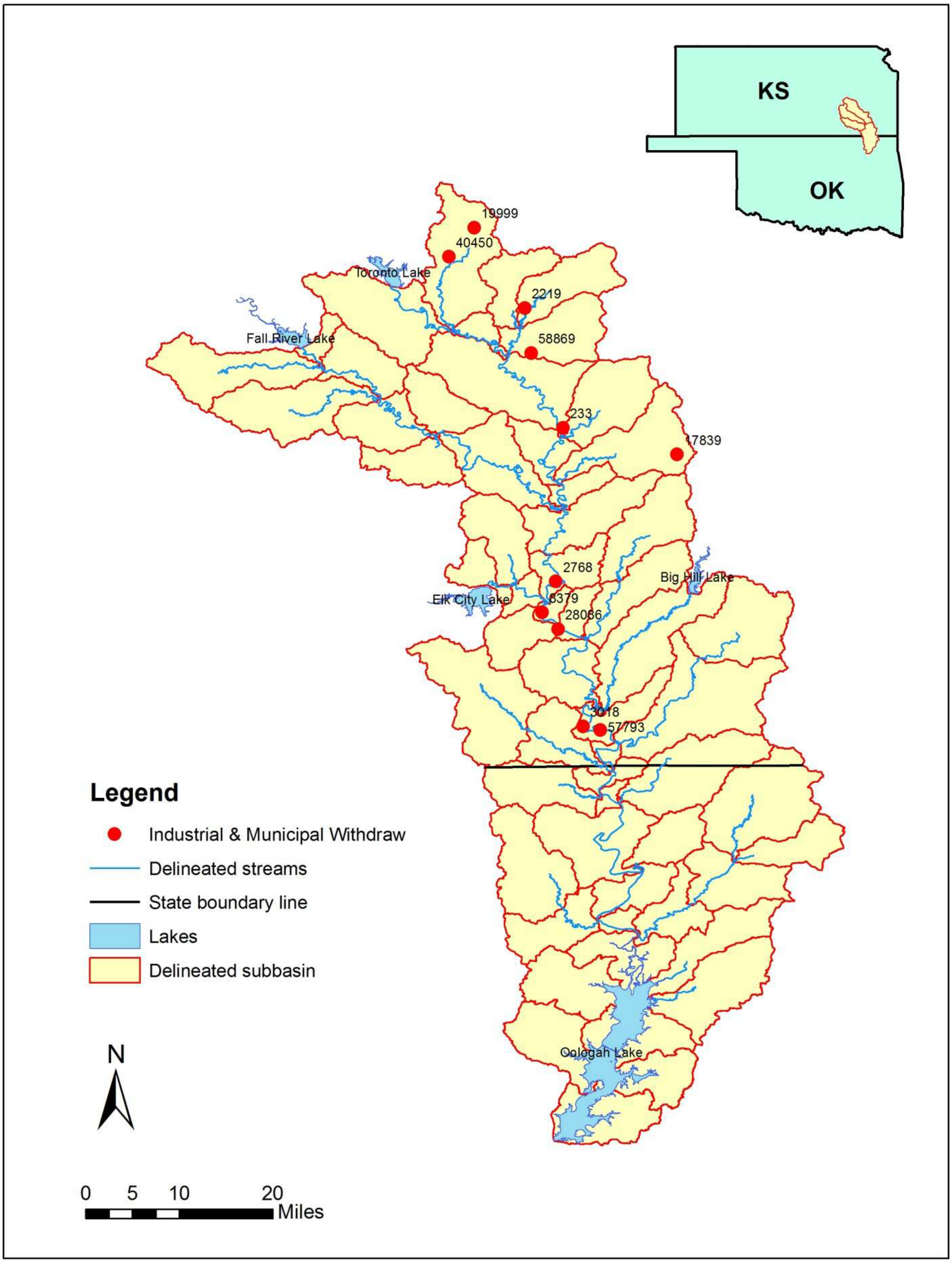

Figure 14 Locations of Water Withdrawals for Industrial and Municipal Facilities

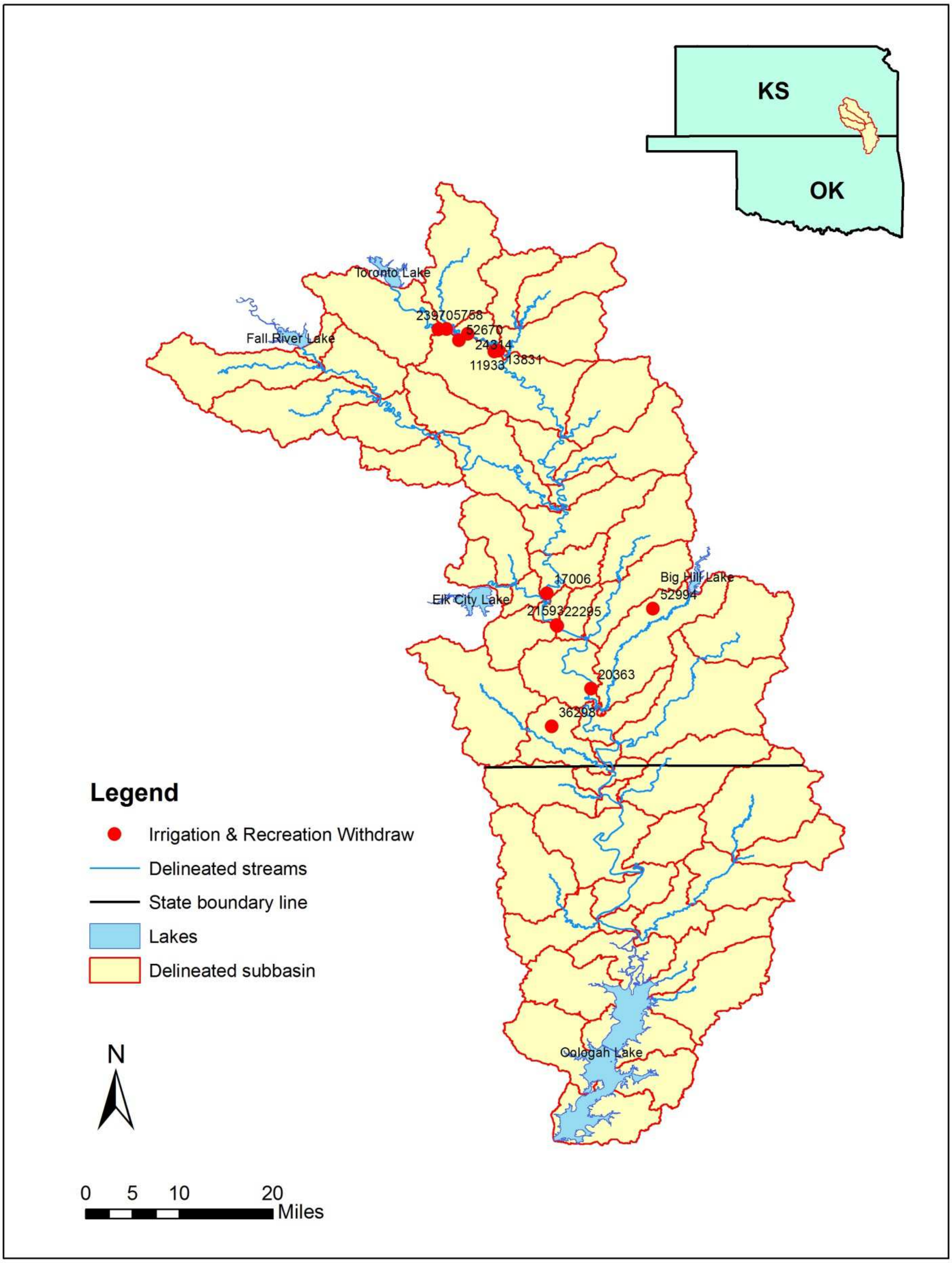

Figure 15 Locations of Water Withdrawals for Irrigation and Recreation Facilities

2.9 Initial Conditions

In a continuous simulation model it is necessary to specify the state of the system at the start of the simulation. In HSPF, initial conditions are specified by assigning values to a number of state variables. HSPF input for initial hydrologic conditions are not directly measurable quantities. Generally, the variables that determine the initial hydrologic conditions of the watershed were estimated by adjusting their values to match modeled flow with observed data. In this modeling project, a half-year spin up period was run to diminish the impact of initial conditions.

3. Observed Data for Model Calibration and Validation

3.1 Observed Data for Flow Calibration and Validation

The Verdigris River watershed HSPF model was calibrated at five USGS gage stations, as shown in Figure 16 and Table 10. These five USGS stations are located in the upper, middle, and lower part of the Verdigris River watershed modeling domain.

Table 10 Summary of USACE Discharge Data for Model Calibration and Validation

Station ID	Station Name	Latitude	Longitude
07171000	Verdigris River near Lenapah, OK	36.851111	-95.585833
07170990	Verdigris River at Coffeyville, KS	37.005278	-95.592500
07170500	Verdigris River at Independence, KS	37.223611	-95.677500
07166500	Verdigris River near Altoona, KS	37.529722	-95.674444
07169500	Fall River at Fredonia, KS	37.508333	-95.833333

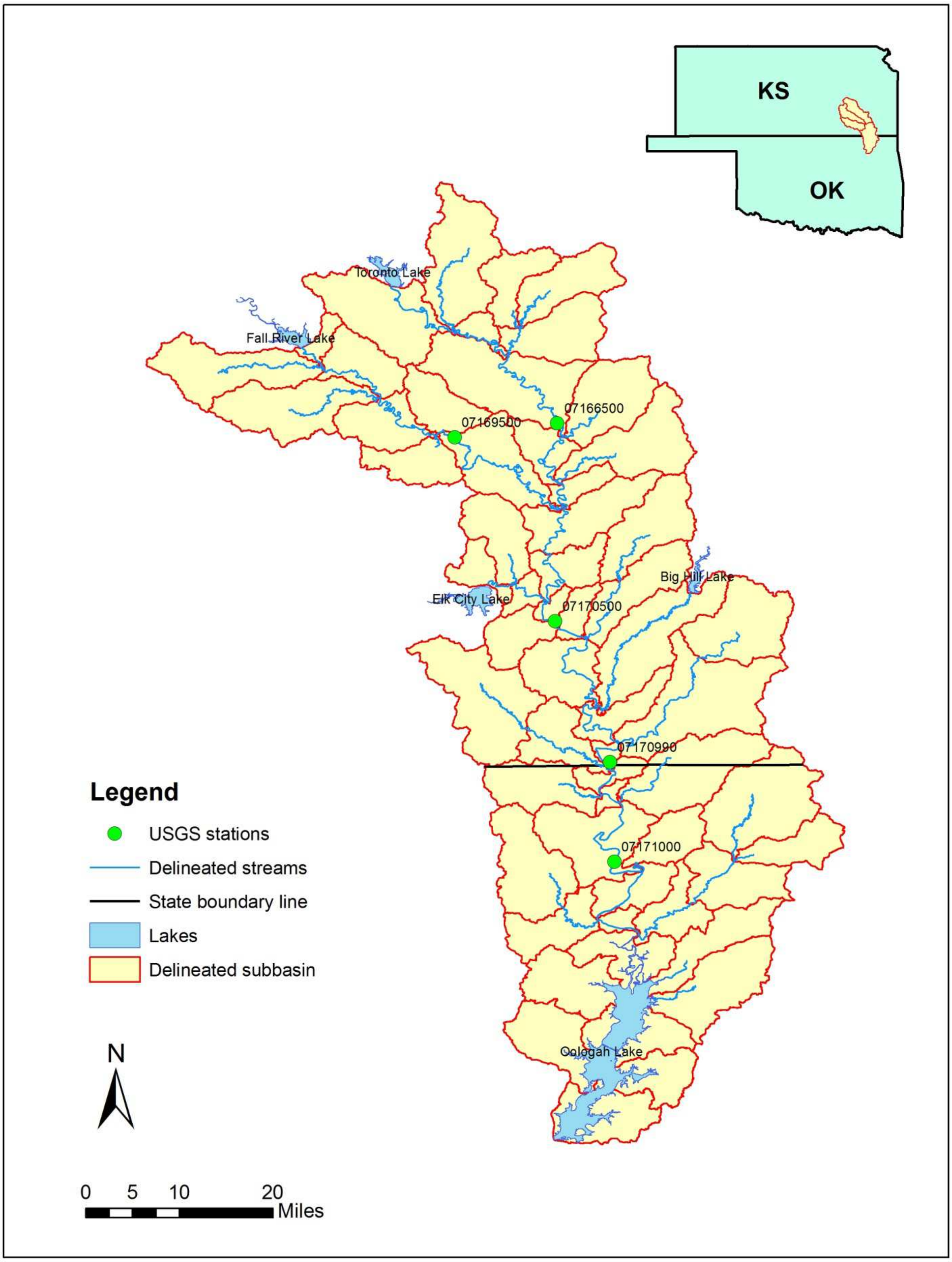

Figure 16 Locations of USGS Flow Stations for Model Calibration and Validation

3.2 Observed Data for Water Quality Calibration and Validation

The Verdigris River watershed HSPF water quality model are calibrated at one OWRB station, three USACE stations, and five EPA STORET stations, as shown in Figures 17-18 and Table 11. USACE station of VR-2 and OWRB station of 121510020010-001AT are located at the same location.

Table 11 Summary of Water Quality Data Stations for Model Calibration and Validation

Station Code	Agency	Latitude	Longitude
FR-1	USACE	37.508333	-95.833333
VR-2	USACE	36.851111	-95.585833
VR-3	USACE	37.418333	-95.671389
121510020010-001AT	OWRB	36.851216	-95.585313
SC105	EPA	37.32676	-95.68463
SC215	EPA	37.00553	-95.59228
SC561	EPA	37.52999	-95.67501
SC562	EPA	37.43219	-95.72315
SC563	EPA	37.17256	-95.65707

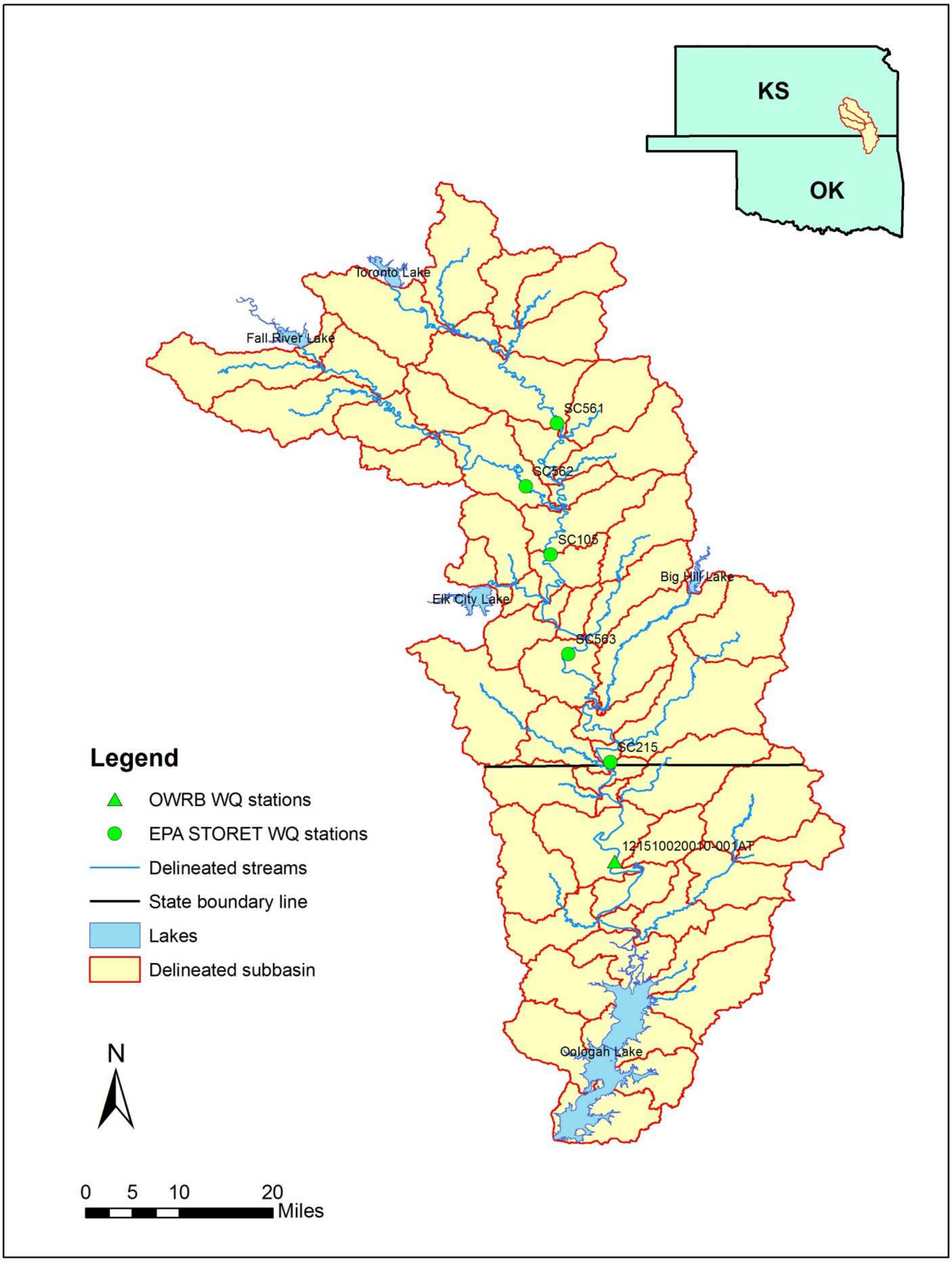

Figure 17 Locations of EPA and OWRB Stations for Model Calibration and Validation

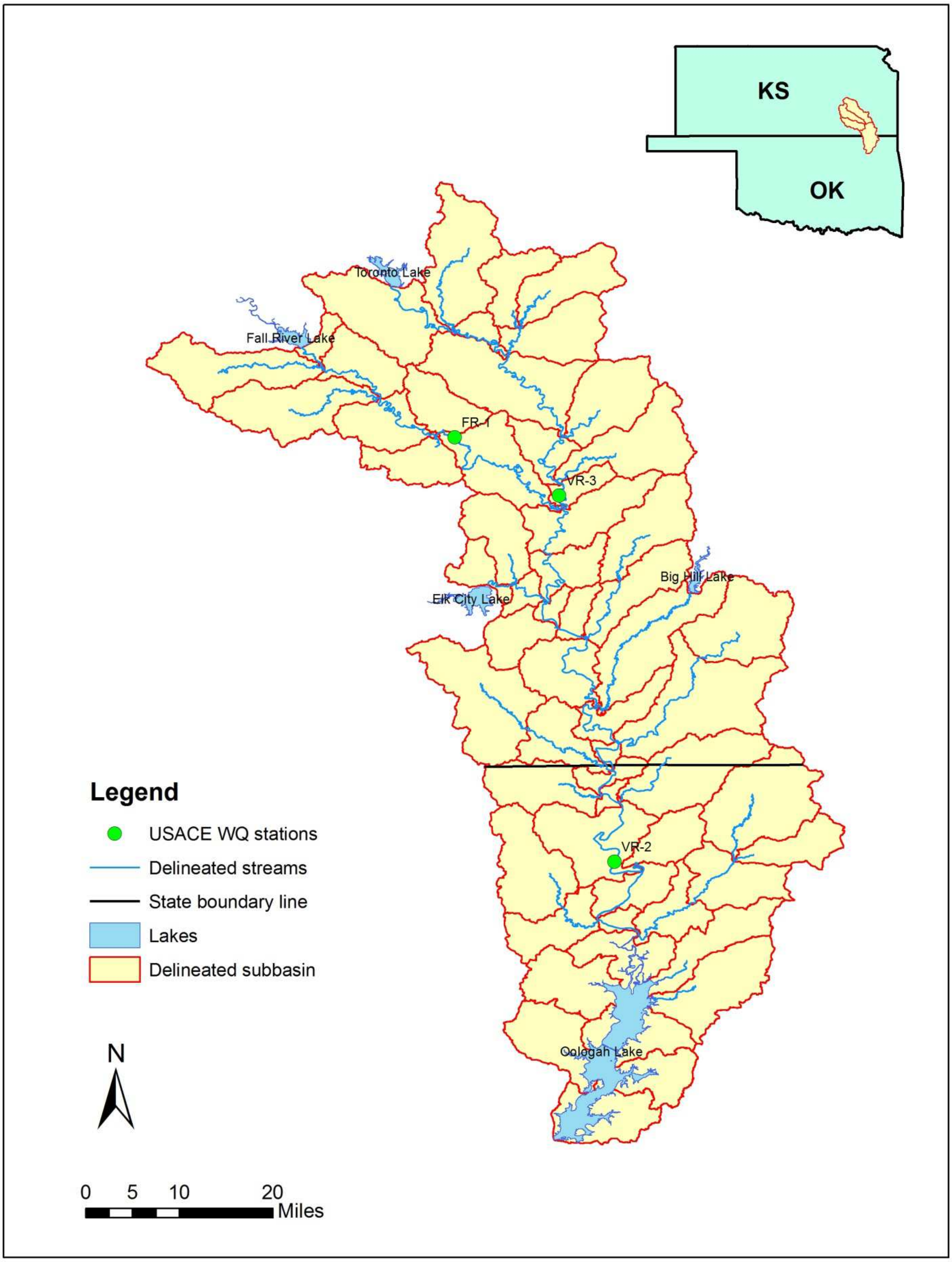

Figure 18 Locations of USACE Stations for Model Calibration and Validation

4. Model Comparison Statistics

The model performance, or model-data comparison, statistical parameters selected for the calibration and validation of the Lake Oologah watershed model are the mean percent error (MPE), correlation coefficient (R), and Nash-Sutcliffe Efficiency Coefficient (NS).

The MPE, R, and NS are calculated by

$$MPE = \frac{\sum_{i=1}^{N} \frac{(O_i - X_i)}{O_i}}{N}$$

$$R = \frac{N * \sum O_i X_i - \sum O_i * \sum X_i}{\sqrt{(N * \sum X_i^2 - \sum X_i * \sum X_i)(N * \sum O_i^2 - \sum O_i * \sum O_i)}}$$

$$NS = 1 - \frac{\sum_{i=1}^{N} (O_i - X_i)^2}{\sum_{i=1}^{N} (O_i - O_m)^2}$$

respectively.

Where:

O – the observed value;
X – the corresponding model value in space or time;
N – the number of valid data/model pairs; and
O_m – the mean of the observed data.

5. Hydrological Calibration and Validation

The developed Verdigris River watershed HSPF model was calibrated from July 1 2004 to December 31 2005 and validated from January 1 2006 to December 31 2007. The hydrological model was calibrated and validated at five USGS flow stations.

5.1 Hydrological Calibration Results

The calibration plots and duration curves for these five USGS stations are given in Figures 19-28. The calculated statistics for the daily flows for these five USGS stations are shown in Table 12. Generally, the hydrological calibration results are good with the mean percent error (MPE) ranging from 5.6% to 13.8% (Table 12). The calculated Nash-Sutcliffe Efficiency Coefficient (NS) are all higher than 0.6 except at USGS station 07166500. The calculated statistics for the monthly flows for these five USGS stations are shown in Table 13.

The streams are flashy, characterized by flooding during storm events, followed by low flows during dry weather (KWO, 1999). At the most-downstream USGS station of 07171000, the lowest daily flow is lower than 30 cfs, which is very low for such a large watershed of the Verdigris River Basin. By checking the flow duration curves, it was found the model reasonably well simulated the high flow and low flows. However, when flows are lower than 50 cfs, it was difficult for the model to replicate the observed data.

Table 12 Calculated Statistics for Daily Flows (cfs) during Calibration Period

Calibration Station	Observed Average	Simulated Average	Sample Size	MPE	R	NSE
USGS 07169500	884	869	549	1.73	0.85	0.69
USGS 07166500	1106	953	549	13.84	0.71	0.3
USGS 07170500	2581	2494	549	3.37	0.88	0.73
USGS 07170990	2930	2678	549	8.58	0.89	0.7
USGS 07171000	2990	2823	549	5.6	0.89	0.73

Table 13 Calculated Statistics for Monthly Flows (cfs) during Calibration Period

Calibration Station	Observed Average	Simulated Average	Sample Size	MPE	R	NSE
USGS 07169500	26974	26507	18	1.73	0.98	0.96
USGS 07166500	33744	29074	18	13.84	0.99	0.93
USGS 07170500	78722	76069	18	3.37	0.99	0.98
USGS 07170990	89356	81690	18	8.58	0.99	0.96
USGS 07171000	91200	86093	18	5.6	0.99	0.97

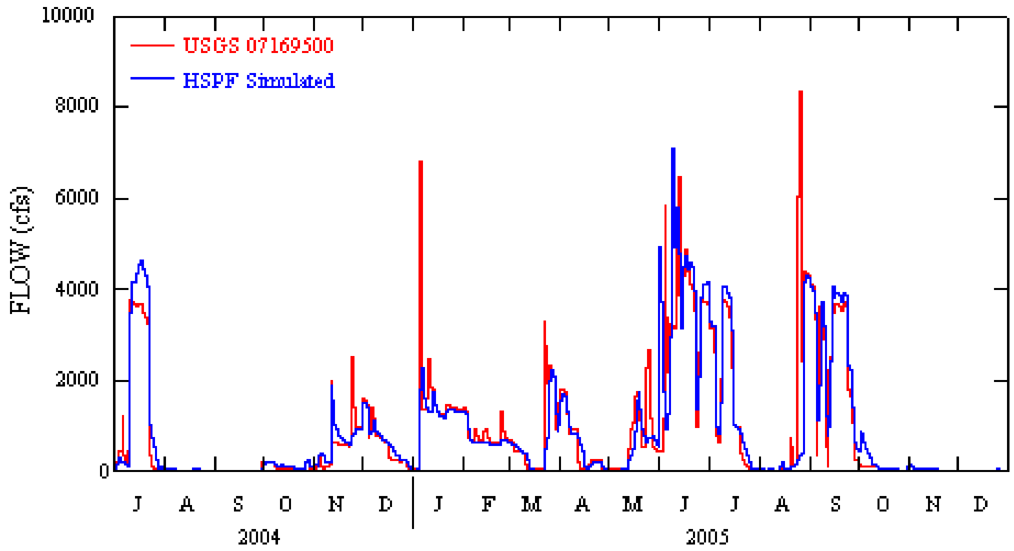

Figure 19 Flow Calibration Plot at USGS 07169500

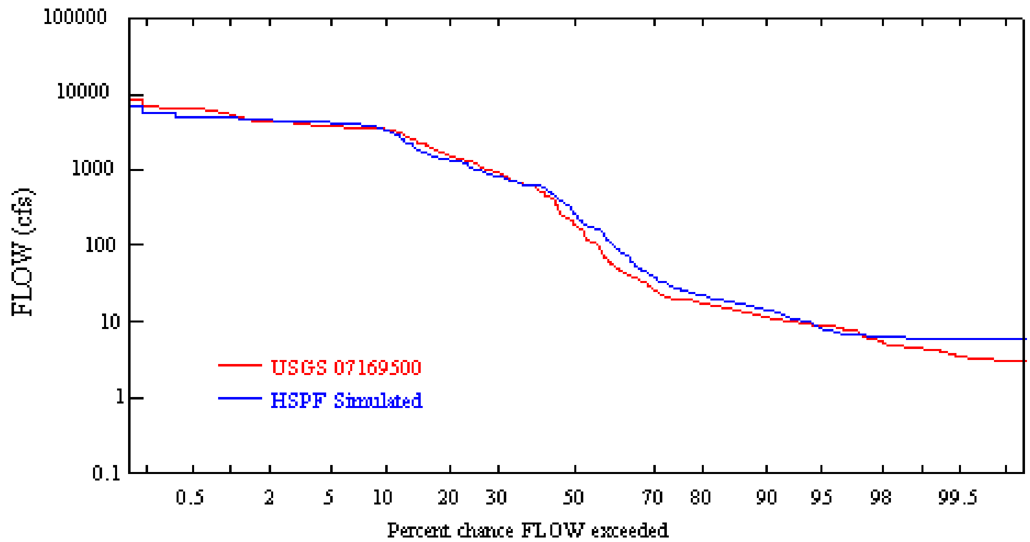

Figure 20 Flow Duration Curve during Calibration Period at USGS 07169500

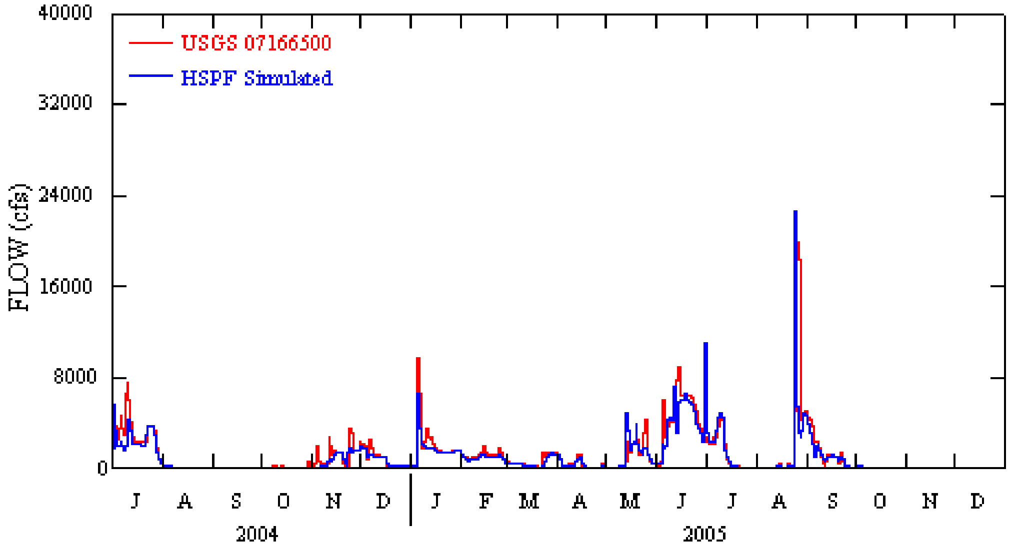

Figure 21 Flow Calibration Plot at USGS 07166500

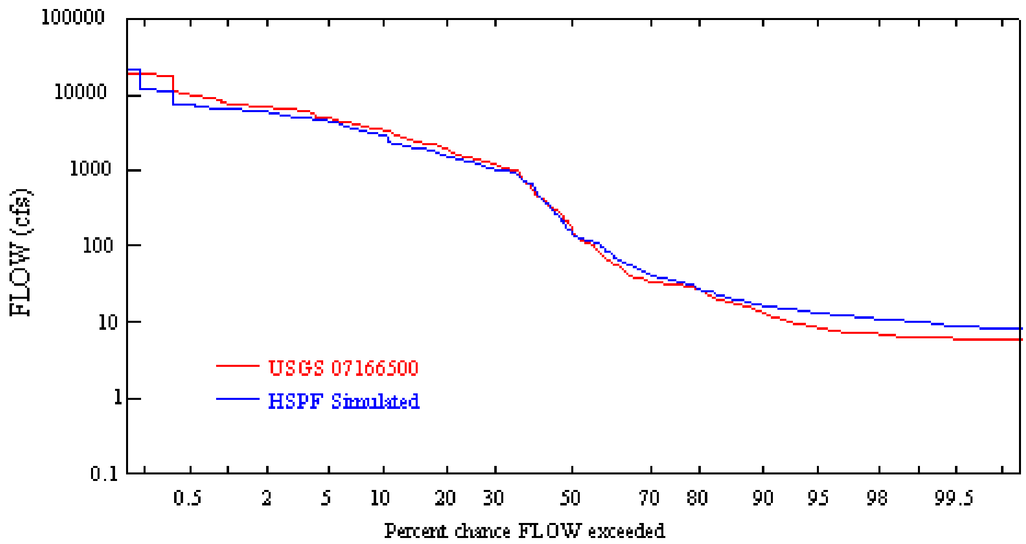

Figure 22 Flow Duration Curve during Calibration Period at USGS 07166500

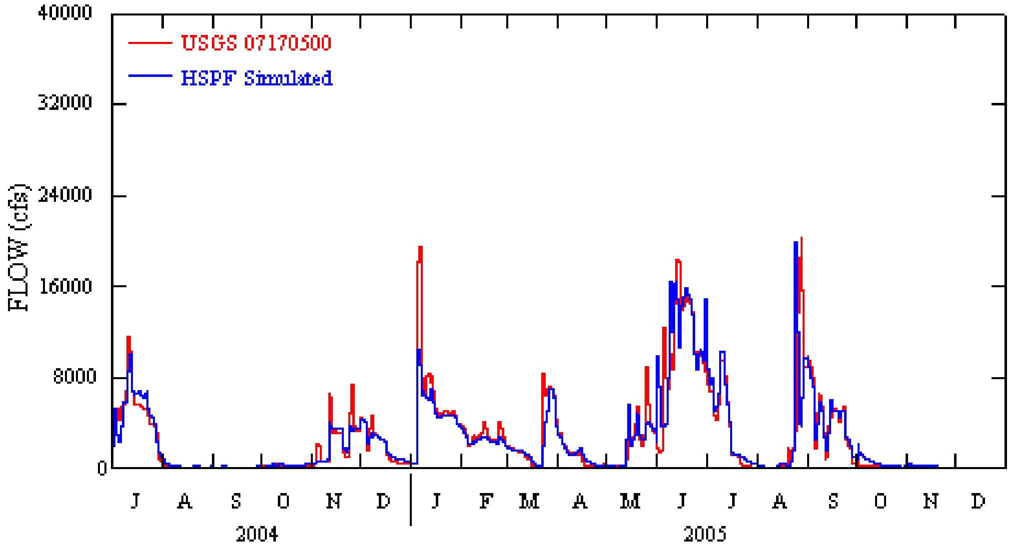

Figure 23 Flow Calibration Plot at USGS 07170500

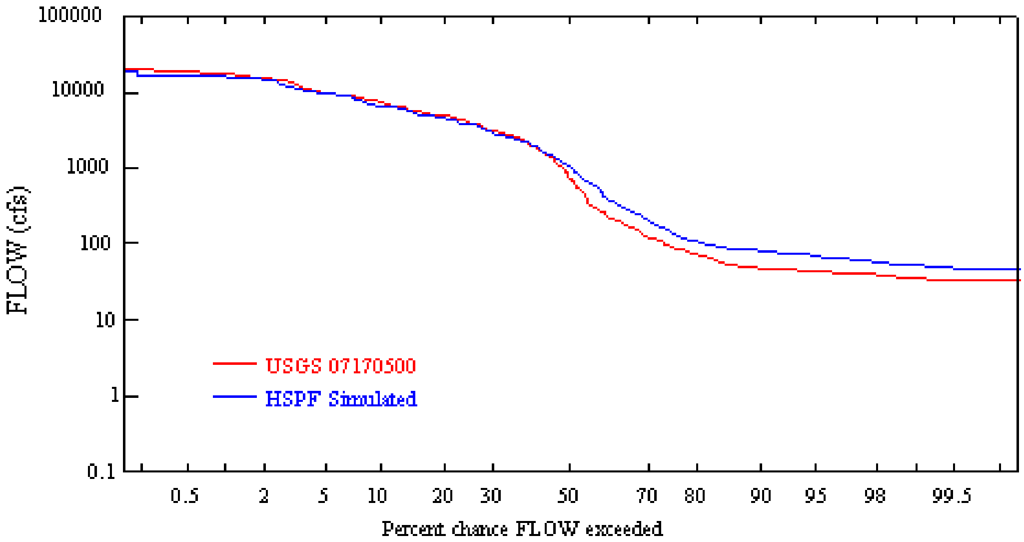

Figure 24 Flow Duration Curve during Calibration Period at USGS 07170500

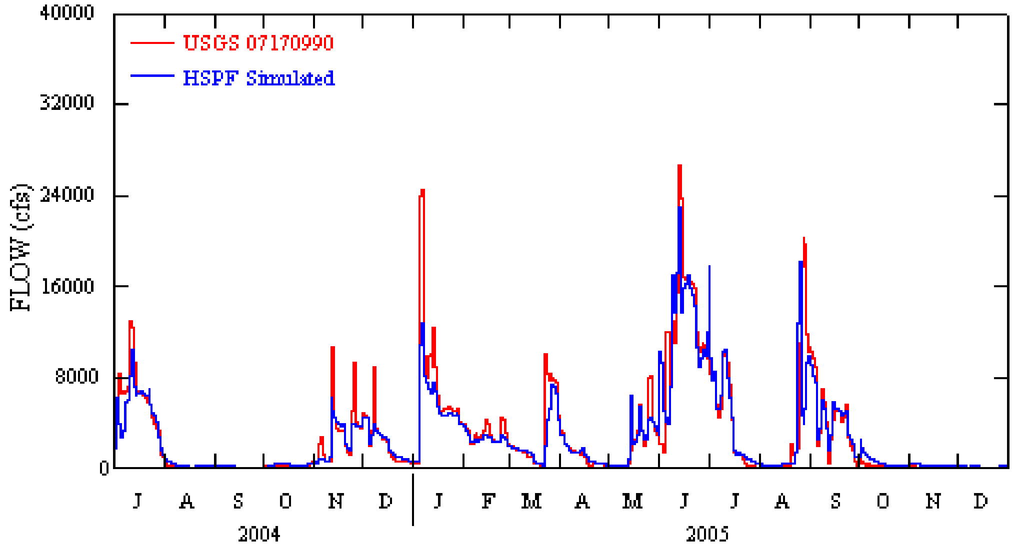

Figure 25 Flow Calibration Plot at USGS 07170990

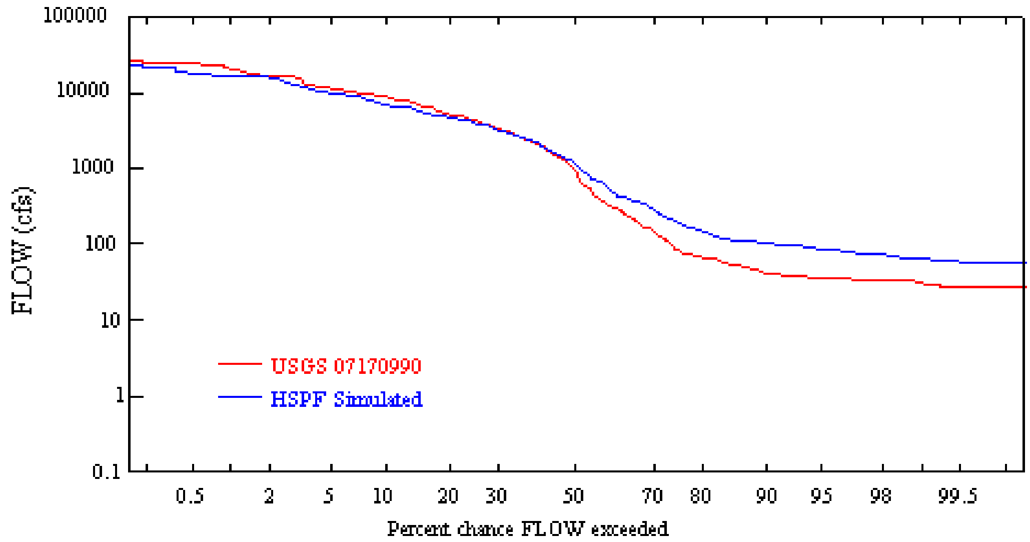

Figure 26 Flow Duration Curve during Calibration Period at USGS 07170990

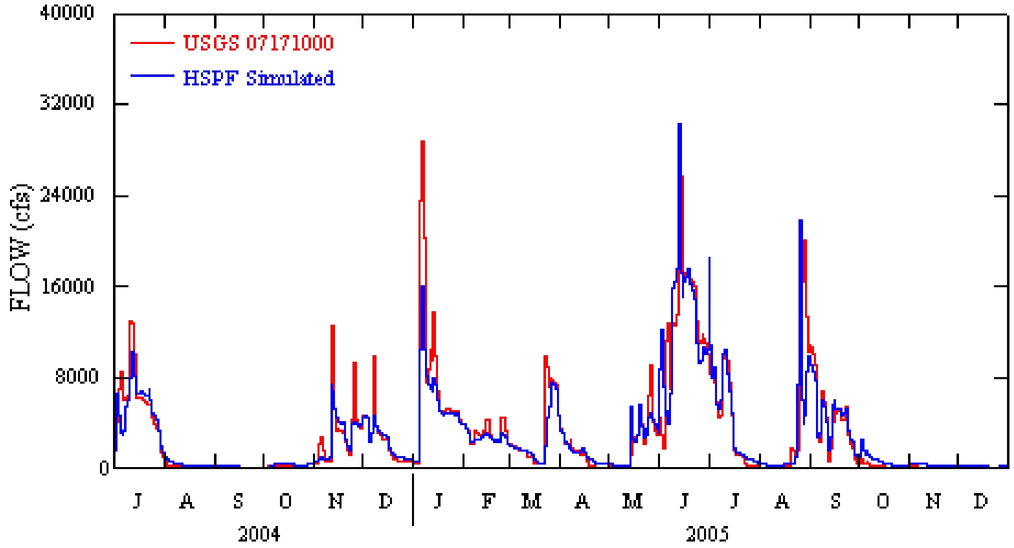

Figure 27 Flow Calibration Plot at USGS 07171000

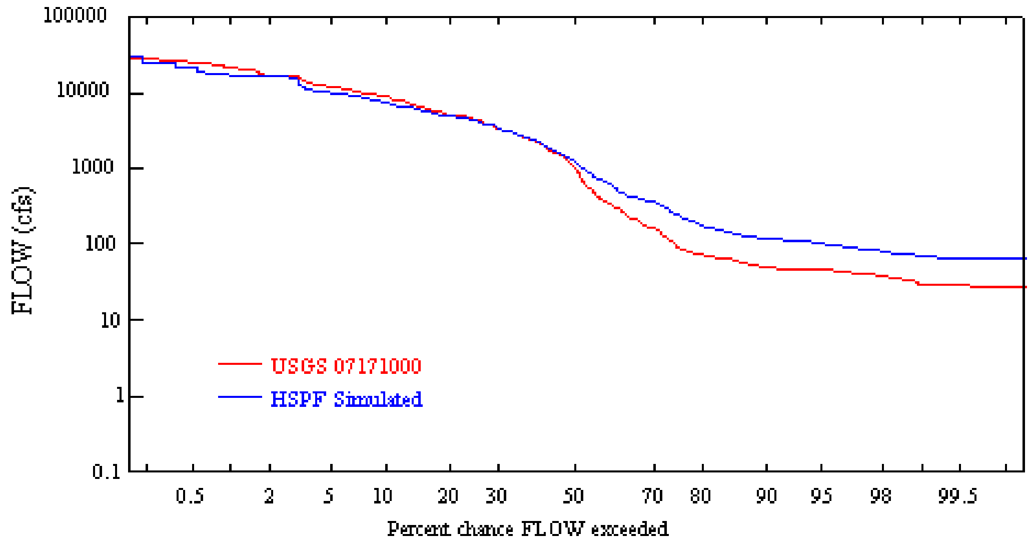

Figure 28 Flow Duration Curve during Calibration Period at USGS 07170990

5.2 Hydrological Validation Results

The watershed HSPF hydrological model was validated from January 1 2006 to December 31 2007. The validation plots and duration curves for these five USGS stations are given in Figures 29-38. The calculated statistics for the daily flows for these five USGS stations are shown in Table 14. Generally, the hydrological validation results are good with the mean percent error (MPE) ranging from -0.86% to 11.07% (Table 14). The calculated statistics for the monthly flows for these five USGS stations are shown in Table 15.

Table 14 Calculated Statistics for Daily Flows (cfs) during Validation Period

Validation Station	Observed Average	Simulated Average	Sample Size	MPE	R	NSE
USGS 07169500	670	605	730	9.68	0.9	0.21
USGS 07166500	623	629	730	-0.86	0.92	0.78
USGS 07170500	2243	2142	730	4.48	0.88	0.48
USGS 07170990	2727	2425	730	11.07	0.8	0.29
USGS 07171000	2910	2671	730	8.21	0.78	0.41

Table 15 Calculated Statistics for Monthly Flows during Validation Period

Validation Station	Observed Average	Simulated Average	Sample Size	MPE	R	NSE
USGS 07169500	20367	18396	24	9.68	0.97	0.8
USGS 07166500	18956	19119	24	-0.86	0.99	0.97
USGS 07170500	68218	65161	24	4.48	0.97	0.87
USGS 07170990	82955	73772	24	11.07	0.96	0.77
USGS 07171000	88508	81242	24	8.21	0.96	0.82

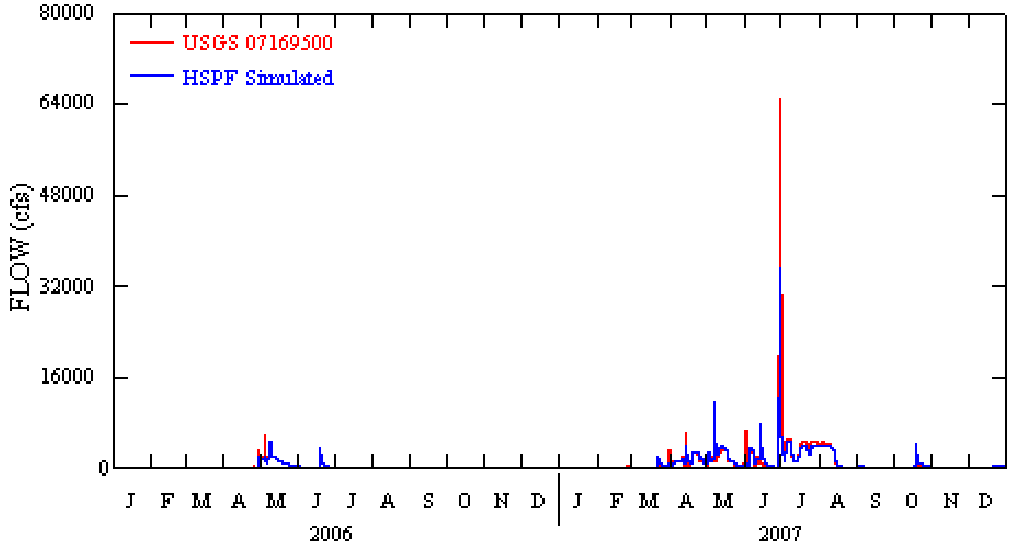

Figure 29 Flow Validation Plot at USGS 07169500

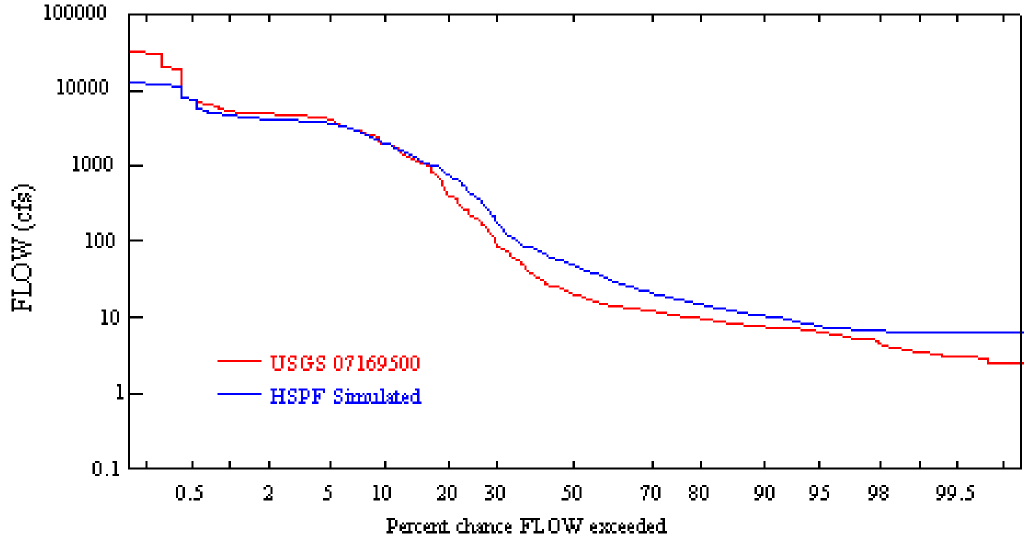

Figure 30 Flow Duration Curve during Validation Period at USGS 07169500

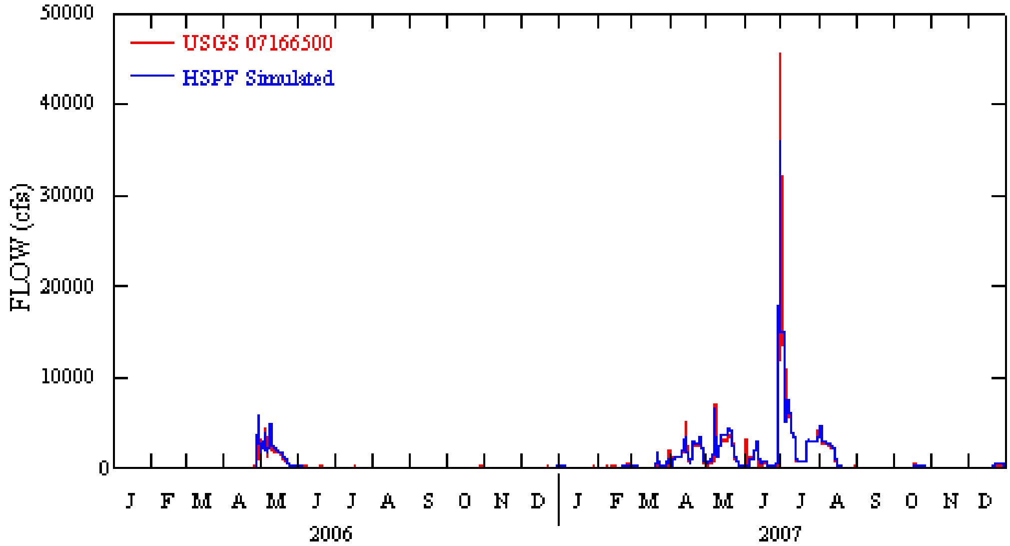

Figure 31 Flow Validation Plot at USGS 07166500

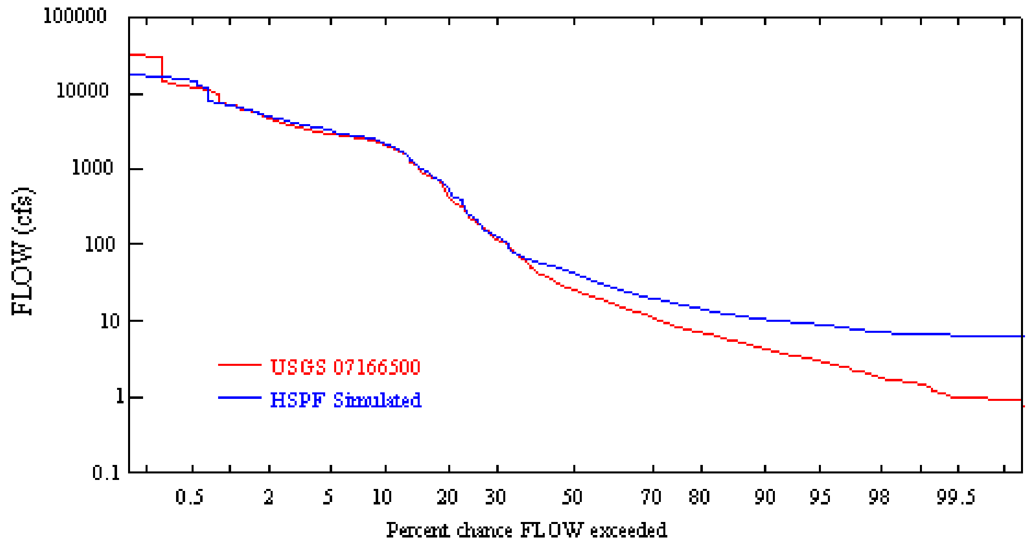

Figure 32 Flow Duration Curve during Validation Period at USGS 07166500

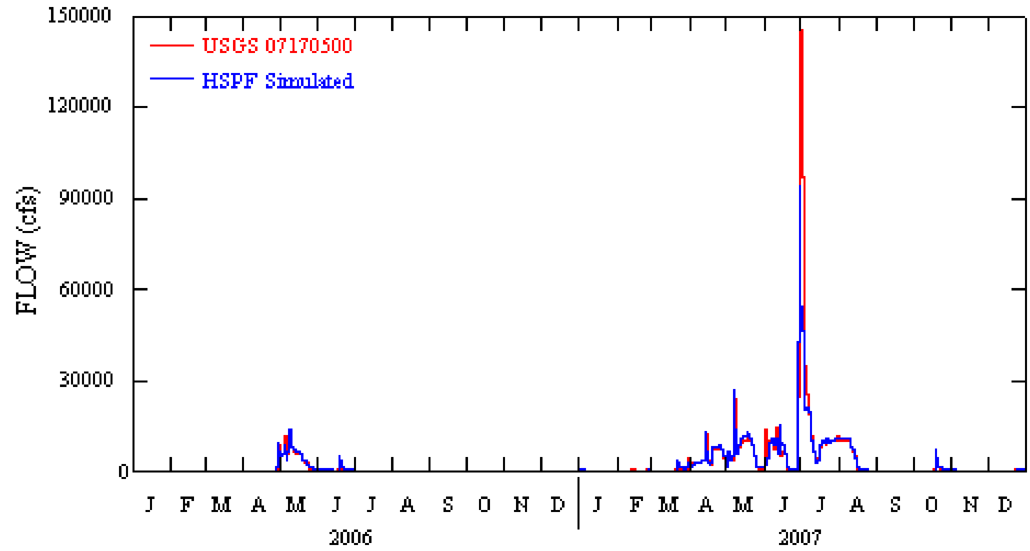

Figure 33 Flow Validation Plot at USGS 07170500

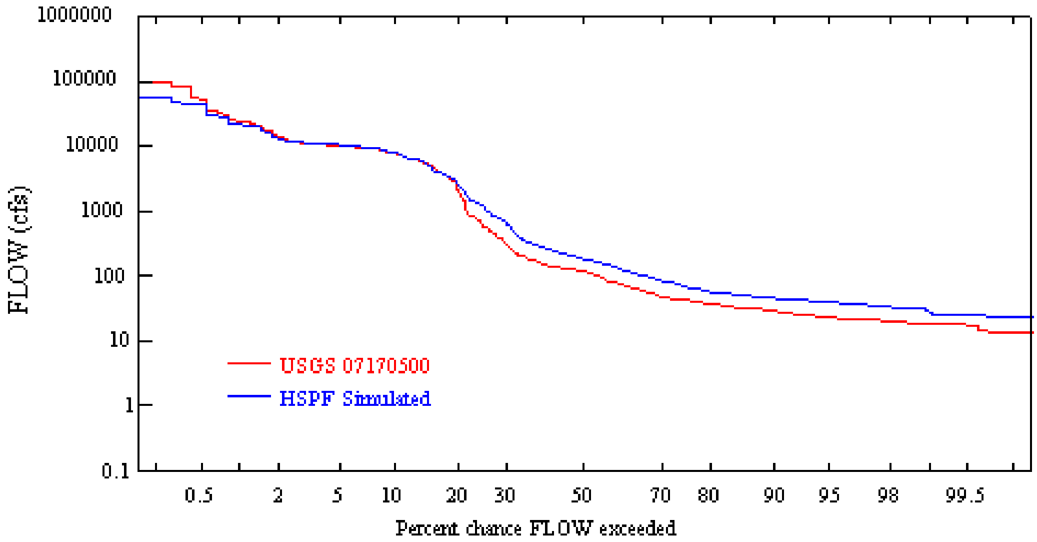

Figure 34 Flow Duration Curve during Validation Period at USGS 07170500

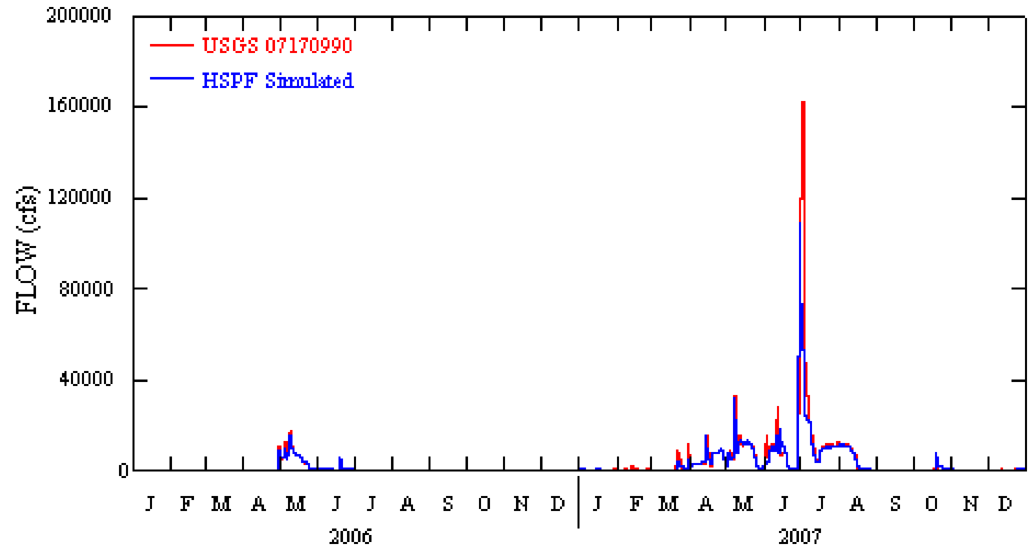

Figure 35 Flow Validation Plot at USGS 07170990

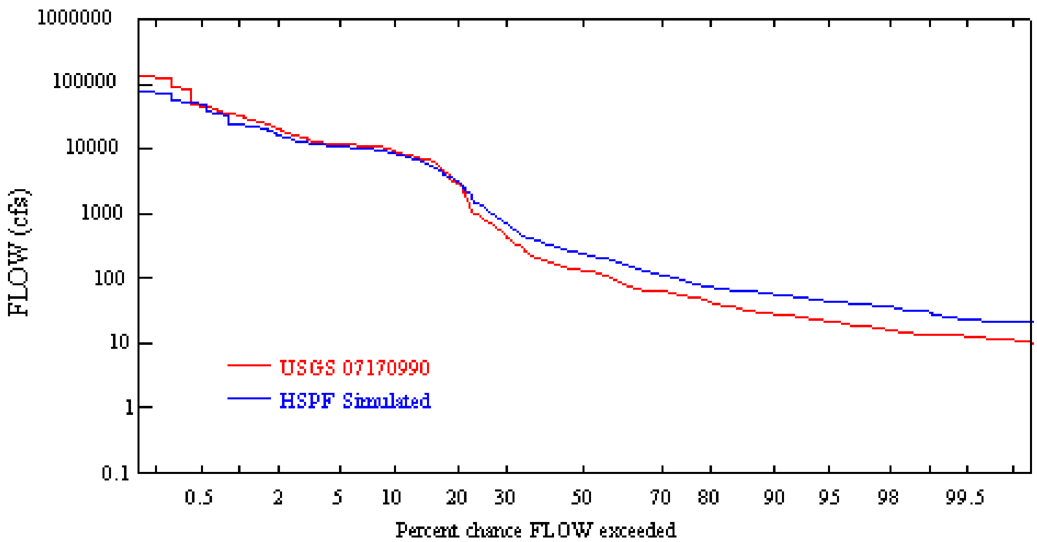

Figure 36 Flow Duration Curve during Validation Period at USGS 07170990

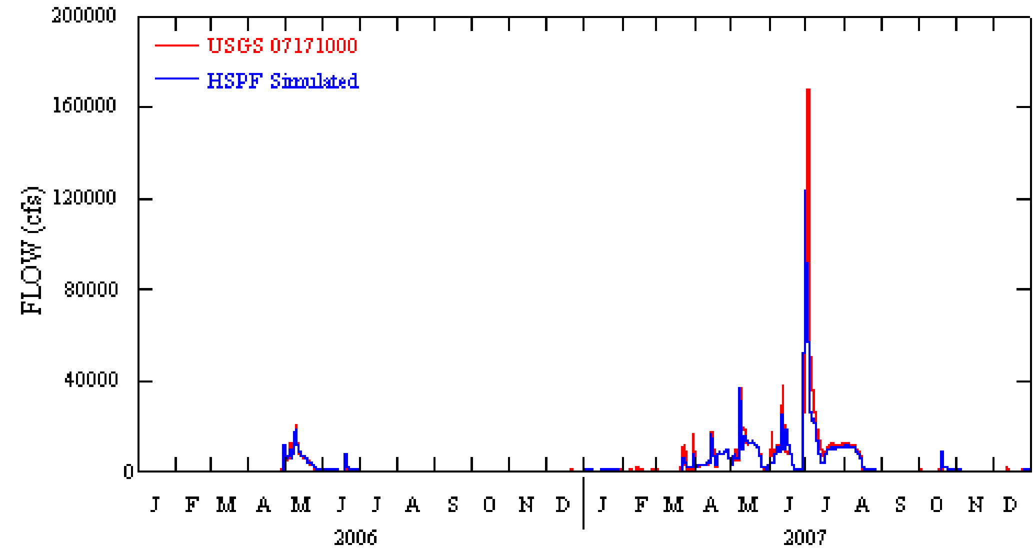

Figure 37 Flow Validation Plot at USGS 07171000

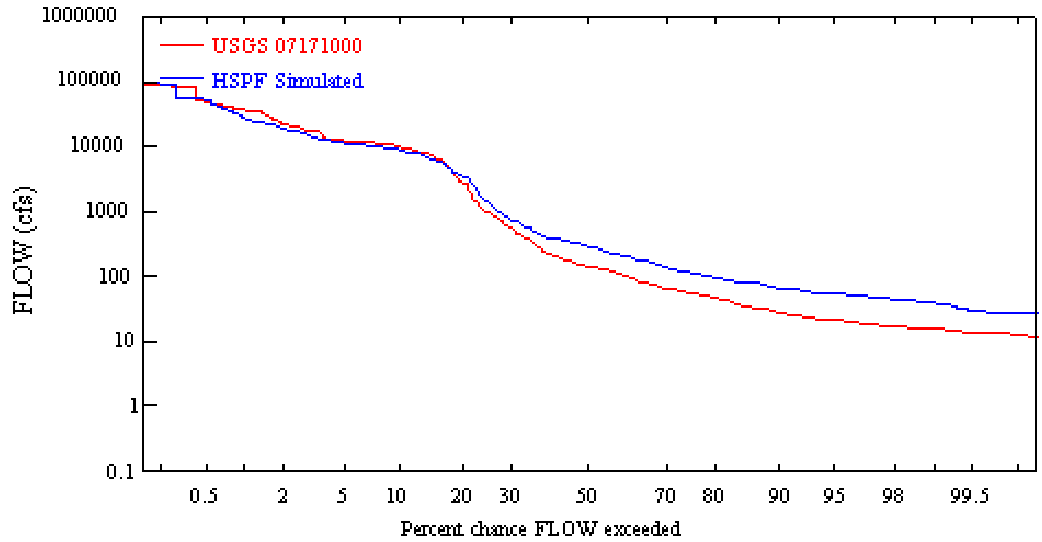

Figure 38 Flow Duration Curve during Validation Period at USGS 07170990

The overall model performance for flow calibration and validation is good. However, the Verdigris watershed model over-predicted the low flows, 50^{th} percentile or higher, as shown in these flow duration curves (Figures 22-38), for both calibration and validation periods. The discrepancy could be attributed to some unaccounted water losses like withdrawal and direct flow leakage due to the existence of Karst geology. Generally speaking, the majority of nutrient loadings from watershed are contributed by large storm-events; therefore slight over-prediction of the low flow events would not have much impact on the total nutrient loadings from the Verdigris watershed.

6. Water Temperature Calibration and Validation

There are water temperature data at a total of nine stations from USACE, EPA STORET, and OWRB available for model calibration and validation. The calibration and validation plots of water temperature at these nine stations are given in Figure 39-56. The calculated statistics for model calibration and validation are shown in Table 16 and 17.

The simulated water temperature generally reflects the seasonal trend of the observed temperature as shown in Figures 39-56. The model performance for water temperature simulation is very good as indicated by the calculated statistics (Table 16 and 17). The mean percent error (MPE) ranged from -3.51% to 2.45% during calibration period and ranged from -4.57% to 5.24% during the calibration period (Table 16 and 17). The calculated Nash-Sutcliffe Efficiency Coefficient (NS) are all higher than 0.86 at all stations for both calibration and validation periods.

Table 16 Calculated Statistics for Water Temperature (F) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE	R	NSE
USACE FR-1	12241	60.38	61.55	-1.94	0.97	0.94
EPA SC562	8	62.83	63.48	-1.04	0.95	0.9
EPA SC561	8	63.73	63.74	-0.02	0.95	0.91
USACE VR-3	12961	60.98	62.85	-3.07	0.96	0.91
EPA SC105	8	62.83	65.04	-3.51	0.94	0.86
EPA SC563	9	65	63.41	2.45	0.98	0.95
EPA SC215	9	66	65.74	0.39	0.98	0.97
USACE VR-2	13171	62.89	63.00	-0.17	0.96	0.92
OWRB	14	65.3	65.27	0.04	0.96	0.92

Table 17 Calculated Statistics for Water Temperature (F) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE	R	NSE
USACE FR-1	17179	60.39	60.95	-0.93	0.97	0.92
EPA SC562	12	61.55	60.02	2.48	0.97	0.92
EPA SC561	12	62	59.98	3.26	0.99	0.94
USACE VR-3	17389	60.36	63.12	-4.57	0.96	0.89
EPA SC105	12	62	62.25	-0.41	0.98	0.96
EPA SC563	12	67.1	63.58	5.24	0.97	0.87
EPA SC215	12	68.15	66.13	2.97	0.96	0.9
USACE VR-2	16984	62.37	61.93	0.71	0.95	0.9
OWRB	18	65.92	67.10	-1.79	0.97	0.93

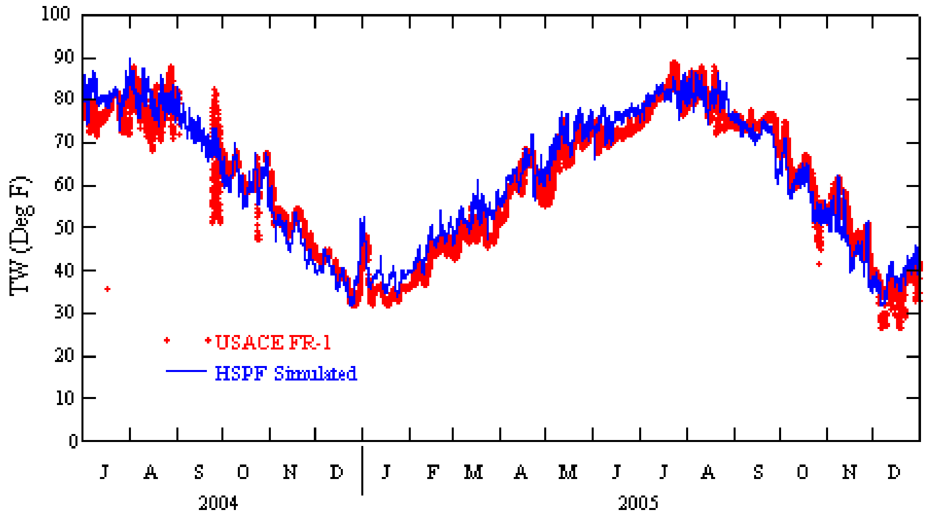

Figure 39 Water Temperature Calibration Plot at USACE FR-1

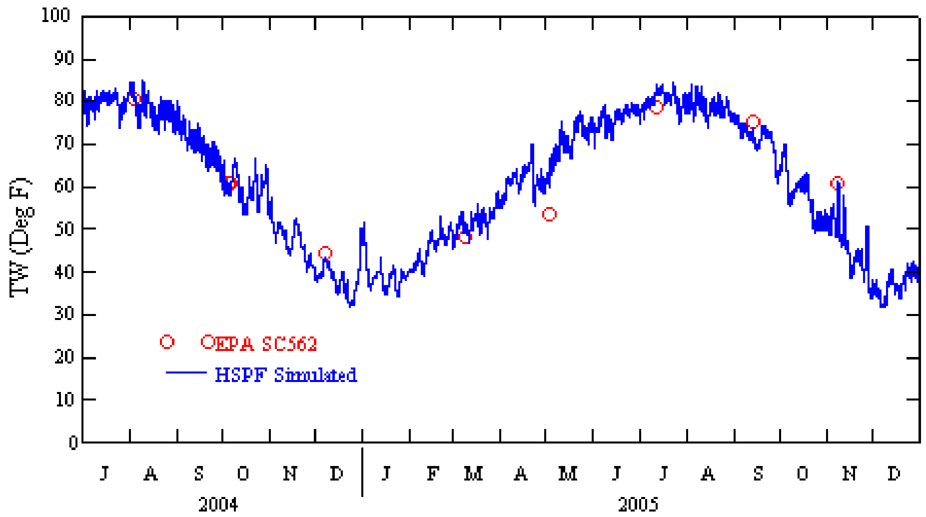

Figure 40 Water Temperature Calibration Plot at EPA SC562

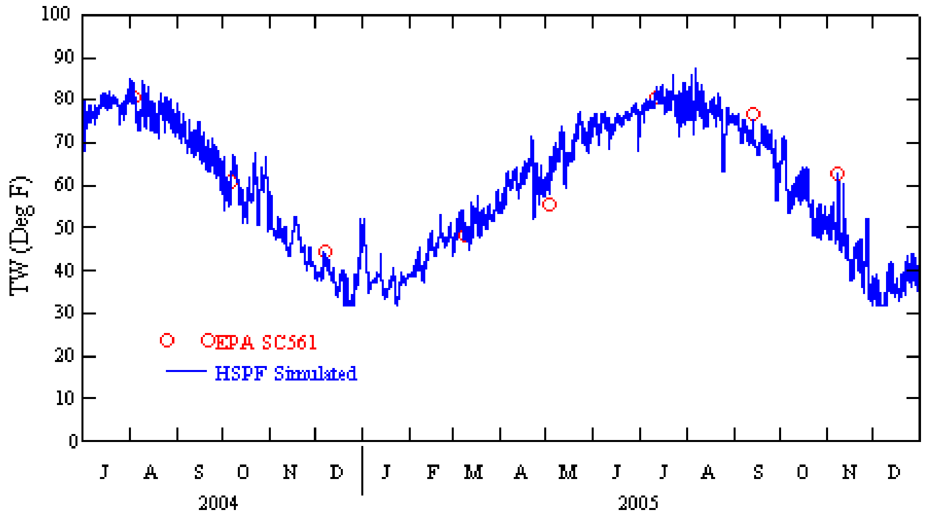

Figure 41 Water Temperature Calibration Plot at EPA SC561

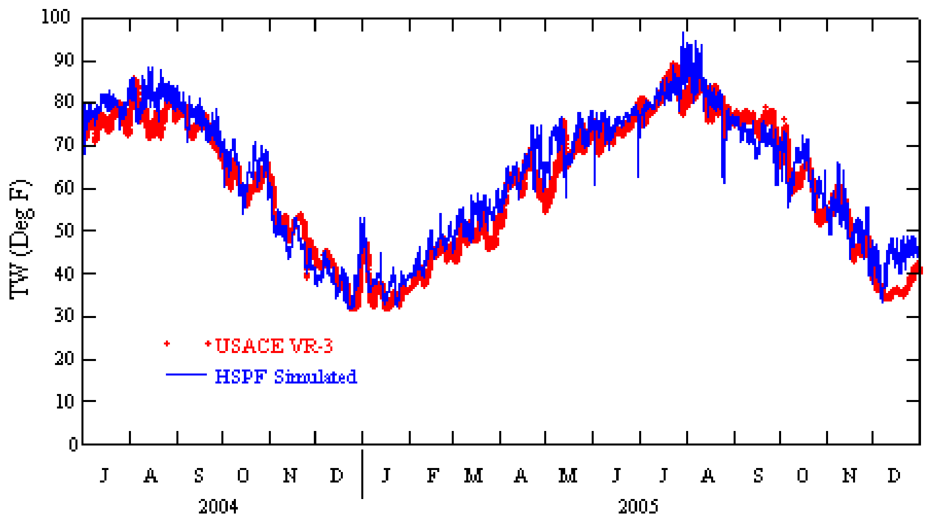

Figure 42 Water Temperature Calibration Plot at USACE VR-3

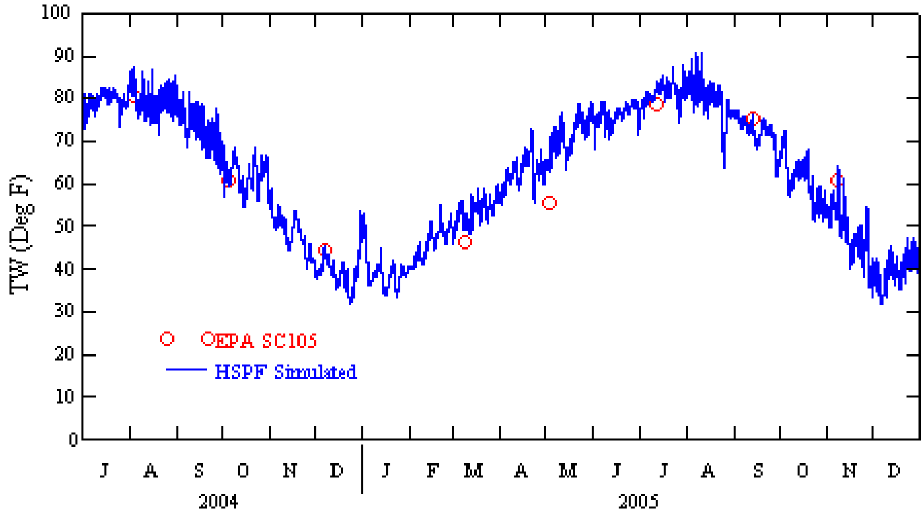

Figure 43 Water Temperature Calibration Plot at EPA SC105

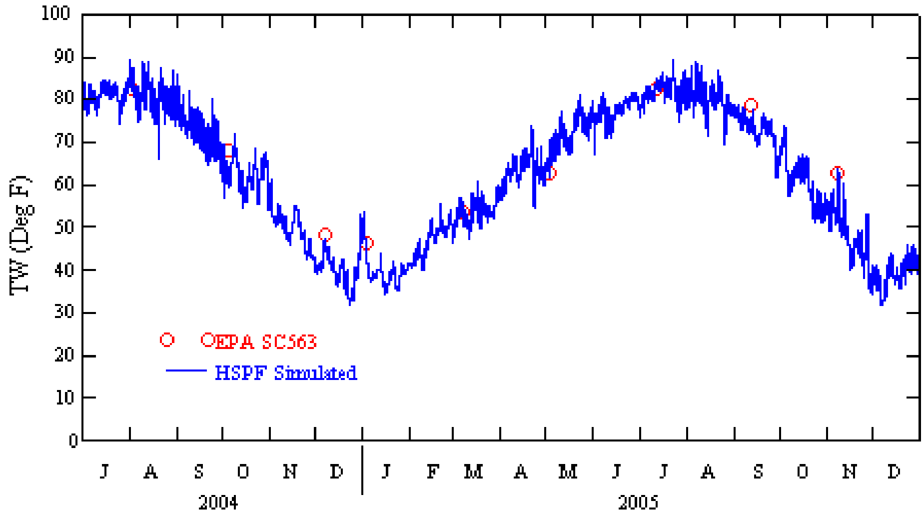

Figure 44 Water Temperature Calibration Plot at EPA SC563

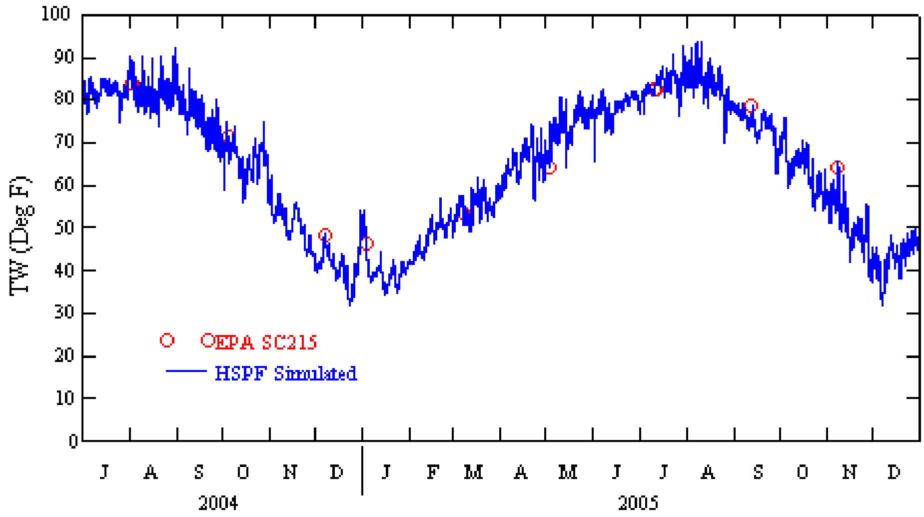

Figure 45 Water Temperature Calibration Plot at EPA SC215

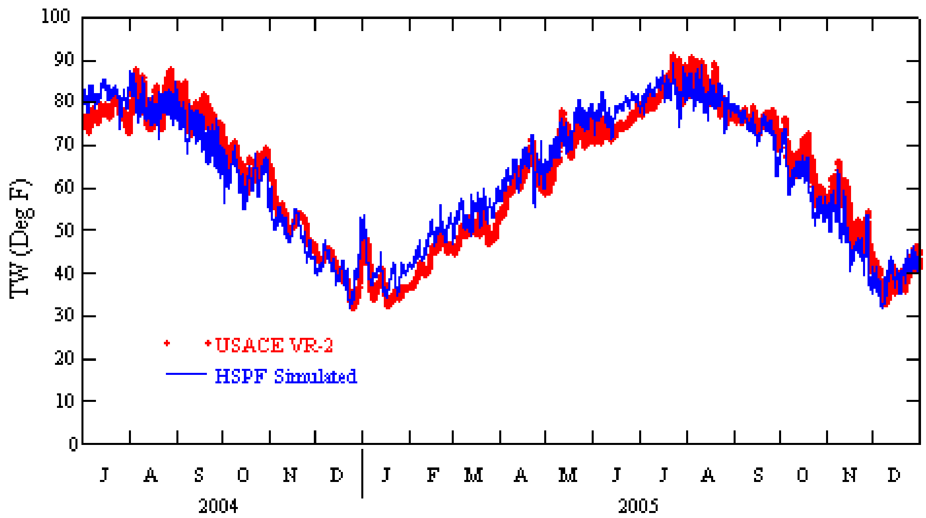

Figure 46 Water Temperature Calibration Plot at USACE VR-2

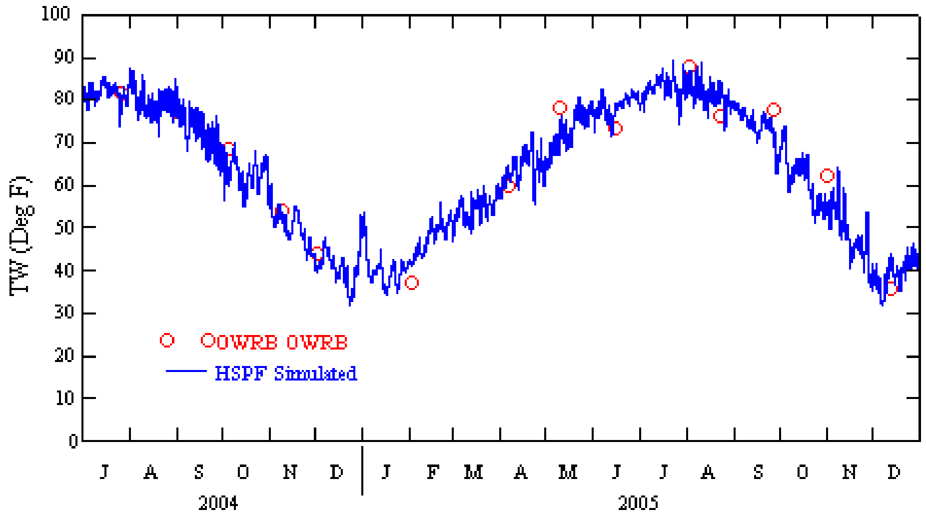

Figure 47 Water Temperature Calibration Plot at OWRB Station

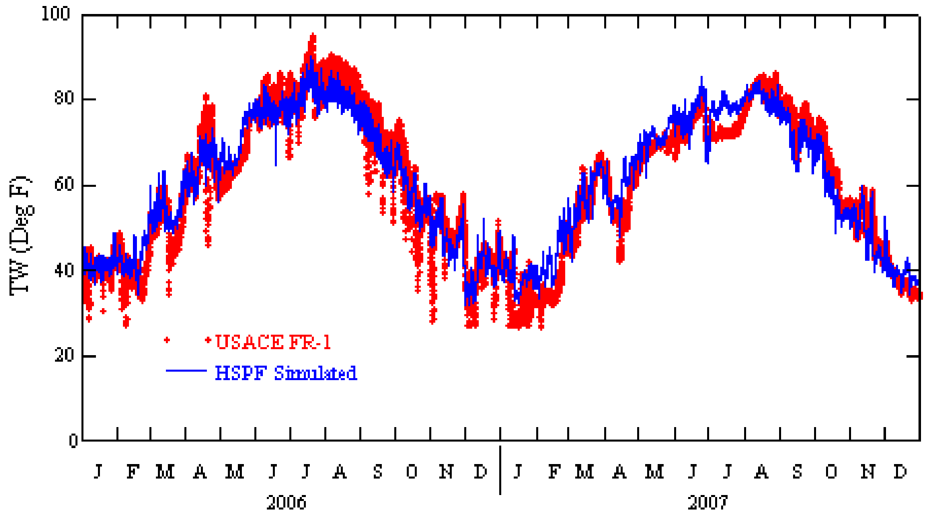

Figure 48 Water Temperature Validation Plot at USACE FR-1

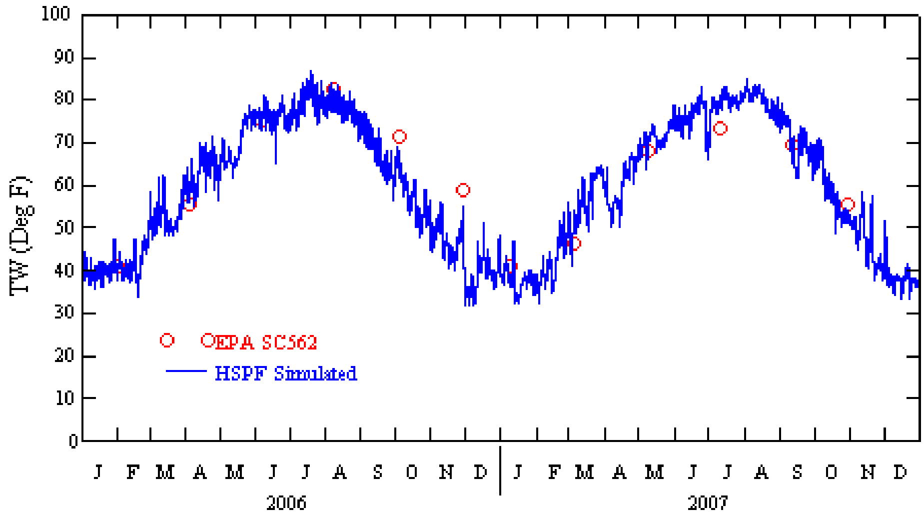

Figure 49 Water Temperature Validation Plot at EPA SC562

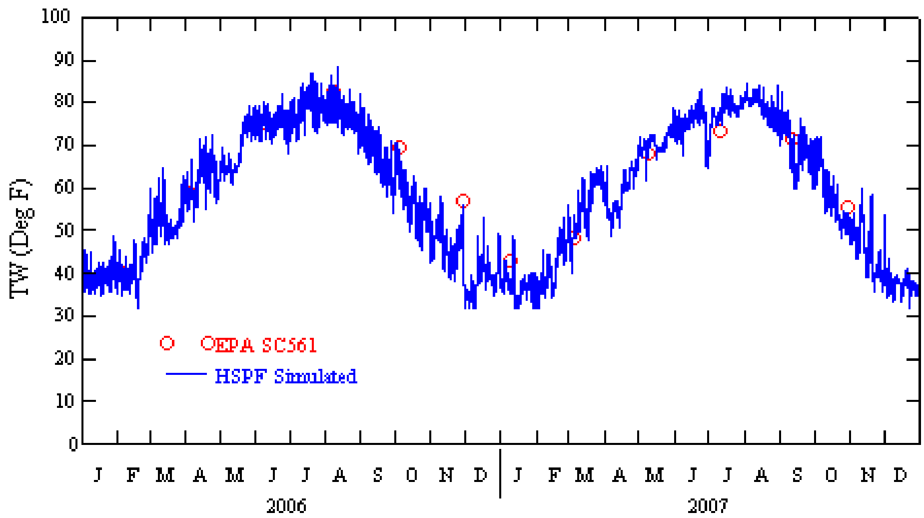

Figure 50 Water Temperature Validation Plot at EPA SC561

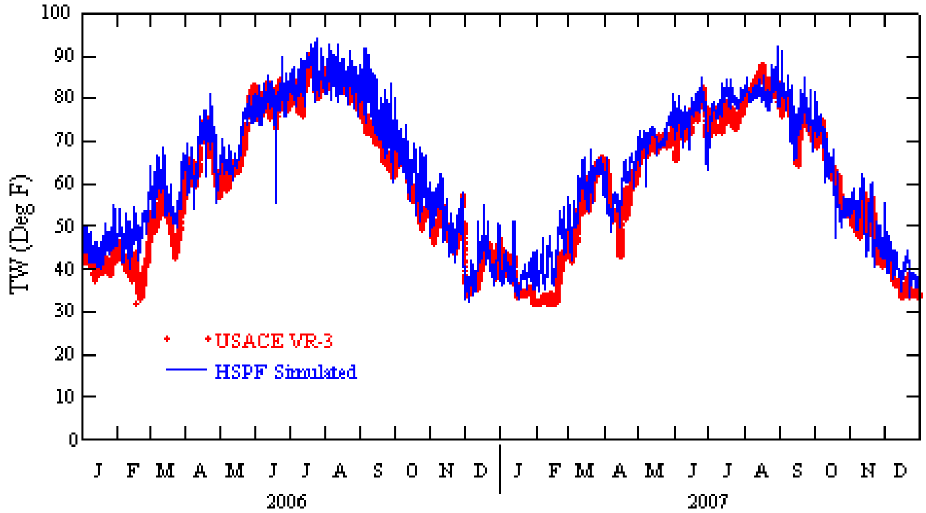

Figure 51 Water Temperature Validation Plot at USACE VR-3

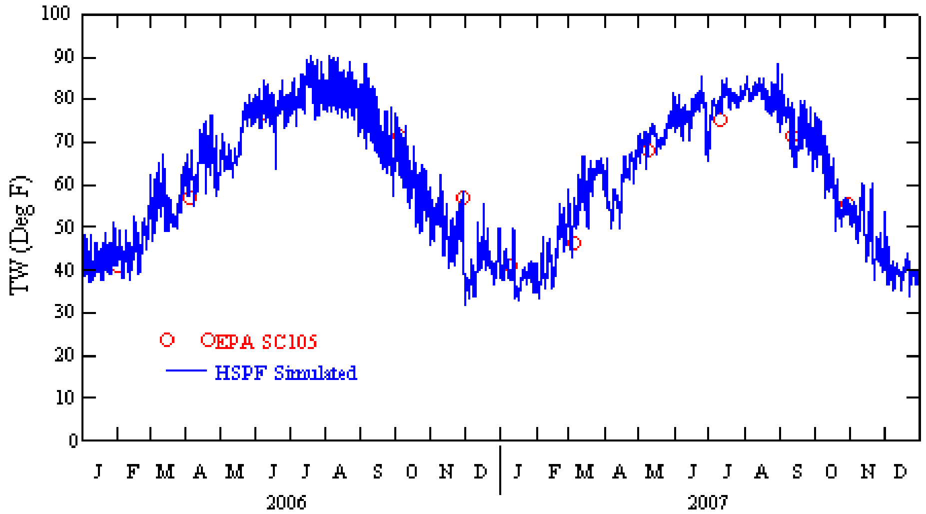

Figure 52 Water Temperature Validation Plot at EPA SC105

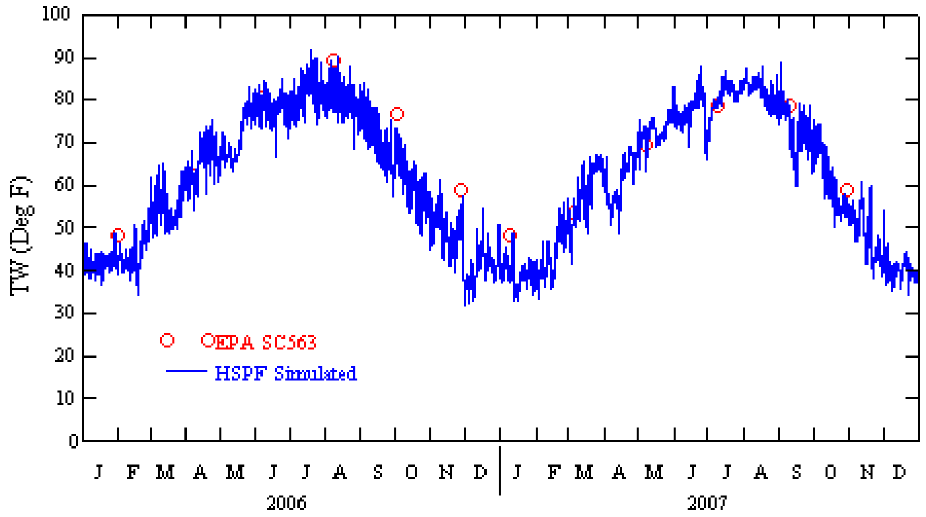

Figure 53 Water Temperature Validation Plot at EPA SC563

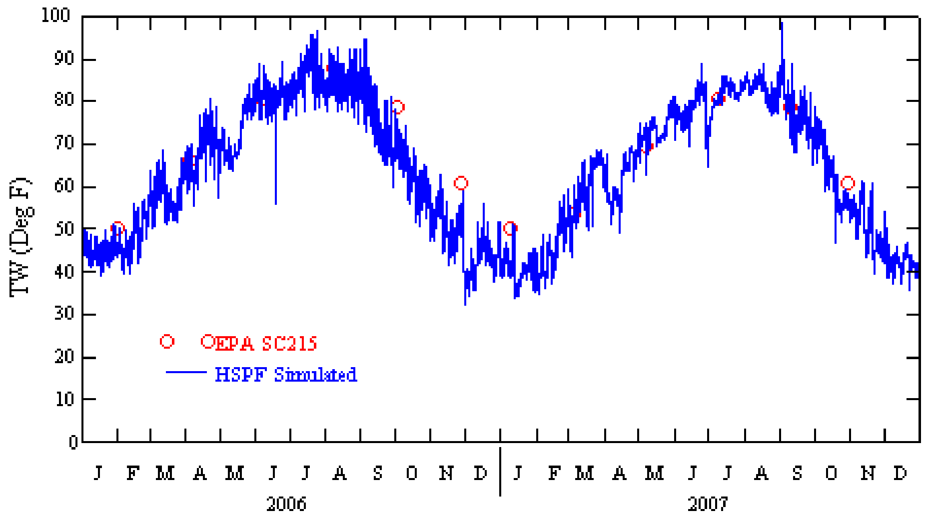

Figure 54 Water Temperature Validation Plot at EPA SC215

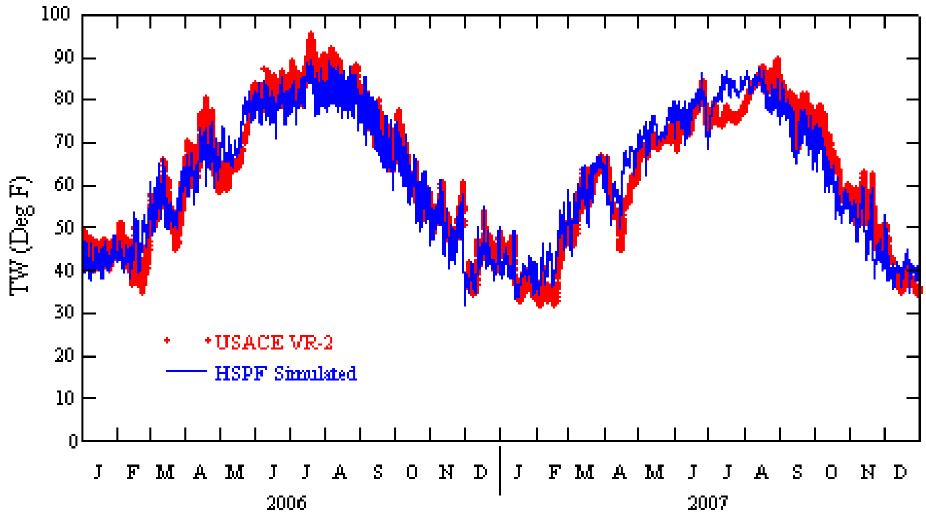

Figure 55 Water Temperature Validation Plot at USACE VR-2

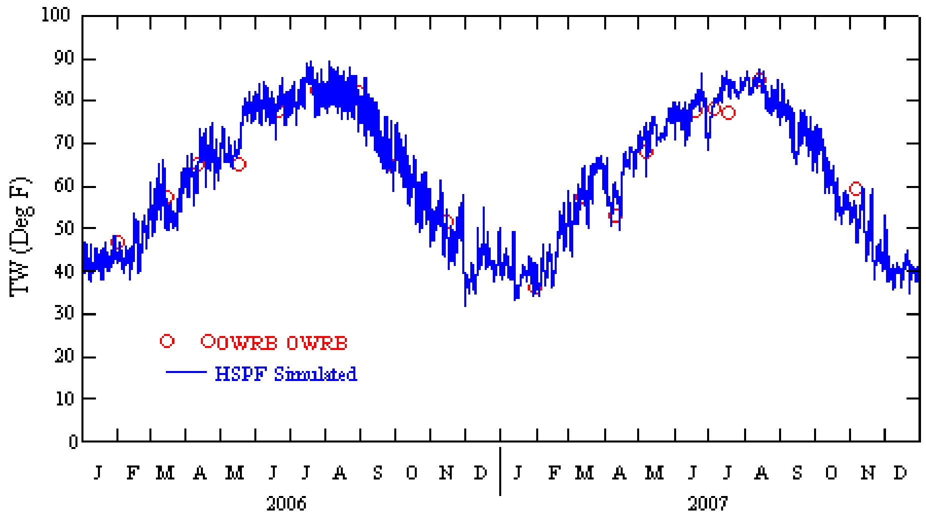

Figure 56 Water Temperature Validation Plot at OWRB Station

7. Water Quality Calibration and Validation

The overall water quality calibration and validation include two major processes. First, the pollutant loadings from the overland are calibrated to reasonable values. Second, the in-stream parameters are adjusted to match the observed concentrations.

For the Verdigris River watershed model, the NO3, NH4, TPO4, and BOD loadings from the overland are simulated using the PQUAL/IQUAL modules of HSPF. Parameters NO3 and NH4 are associated with overland flow and TPO4 and BOD are associated with sediment. The calibrated average annual pollutant loadings from all landuses of the Verdigris River HSPF model are given in Table 18.

Table 18 Average Annual Water Quality Constituents Loadings from all Landuses

Parameters	Impervious Urban	Wetland	Urban	Forest	Cropland	Grassland	Pasture
Sediment (ton/year)	0.12	0.02	0.19	0.06	1.12	0.32	0.45
NO3 (lb/year)	1.39	0.54	2.91	1.23	7.82	2.53	2.41
NH3 (lb/year)	0.46	0.07	0.63	0.25	0.71	0.49	0.45
TPO4 (lb/year)	0.24	0.01	0.17	0.05	0.87	0.44	0.72
BOD (lb/year)	9.31	1.06	6.38	1.74	26.72	6.68	13.94
TN (lb/year)	2.81	0.71	4.20	1.66	11.28	3.70	4.29
TP (lb/year)	0.33	0.02	0.23	0.06	1.13	0.50	0.85

For all water quality parameters, only sample size, the mean observed, the mean simulated, and the mean percent error (MPE) were calculated for model performance evaluation.

7.1 TSS Calibration and Validation

The calibration and validation plots of total suspended solids (TSS) at these observation stations are given in Figure 57-72. The TSS data are not available at the OWRB station of 121510020010-001AT. The calculated statistics for model calibration and validation are shown in Table 19 and 20.

The overal model performance of TSS for both calibration and validaation periods is fairly good with all the calculated mean percent error (MPE) values within the range of -100% and +100% except at station USACE FR-1 during the calibration period (Table 19-20).

Table 19 Calculated Statistics for TSS (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	16	59.0	26.7	54.7
EPA SC562	8	38.4	27.0	29.7
EPA SC561	8	31.9	33.3	-4.6
USACE VR-3	16	53.8	33.0	38.6
EPA SC105	8	42.1	29.7	29.6
EPA SC563	9	26.2	25.8	1.5
EPA SC215	9	40.9	23.7	42.0
USACE VR-2	16	86.5	54.8	36.6

Table 20 Calculated Statistics for TSS (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	24	63.3	182.8	-189.0
EPA SC562	12	45.7	71.6	-56.7
EPA SC561	12	35.0	47.9	-36.8
USACE VR-3	24	66.3	86.2	-30.0
EPA SC105	12	42.0	73.8	-75.7
EPA SC563	12	70.0	89.8	-28.3
EPA SC215	12	72.4	94.2	-30.1
USACE VR-2	21	97.0	91.0	6.2

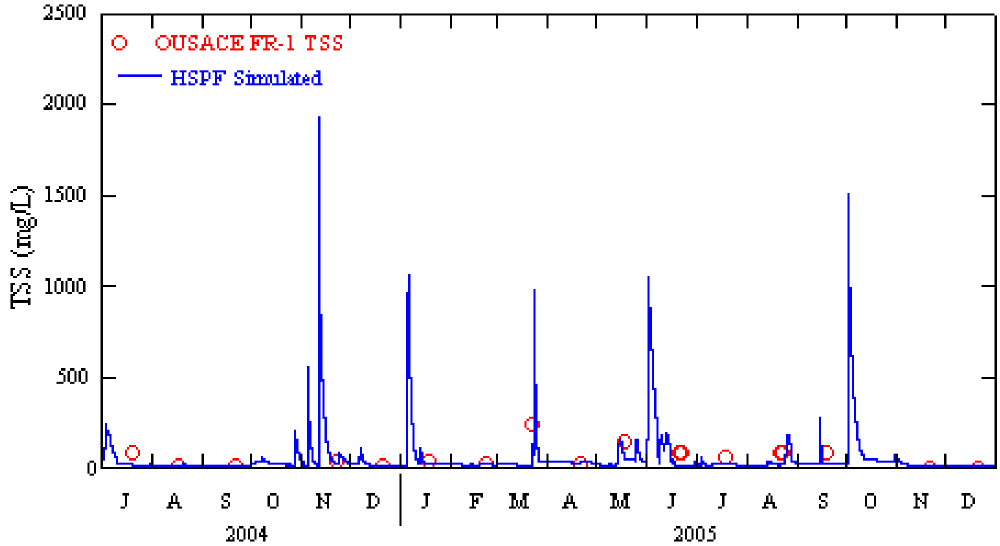

Figure 57 TSS Calibration Plot at USACE FR-1

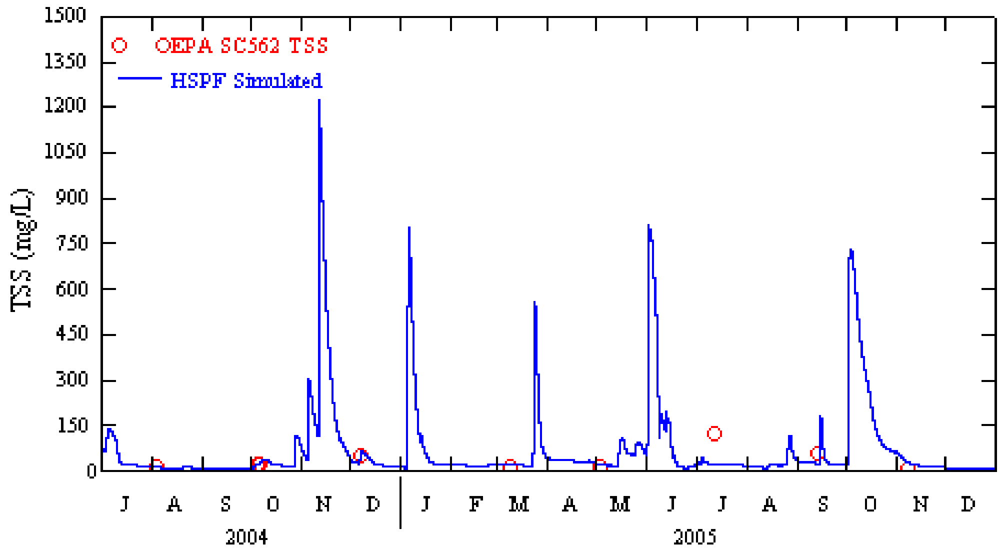

Figure 58 TSS Calibration Plot at EPA SC562

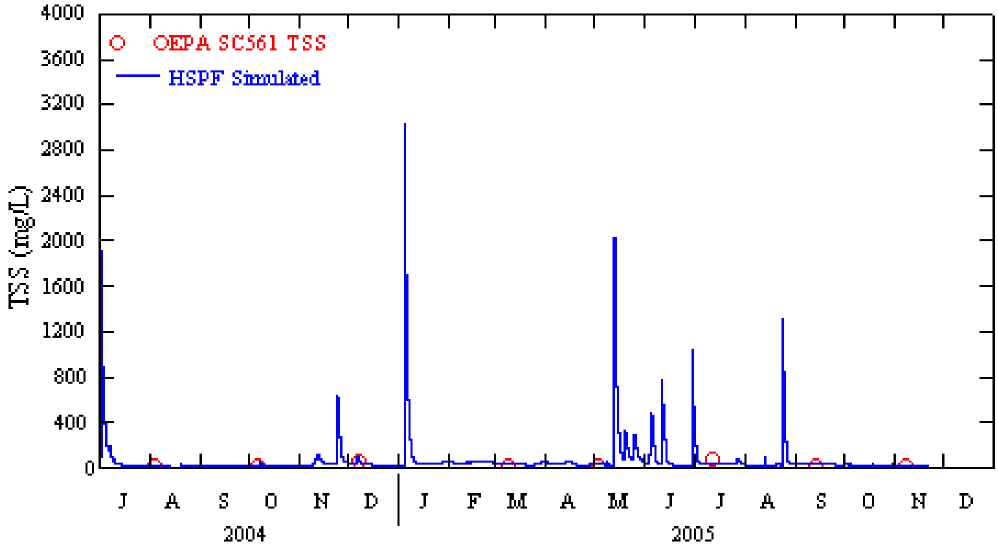

Figure 59 TSS Calibration Plot at EPA SC561

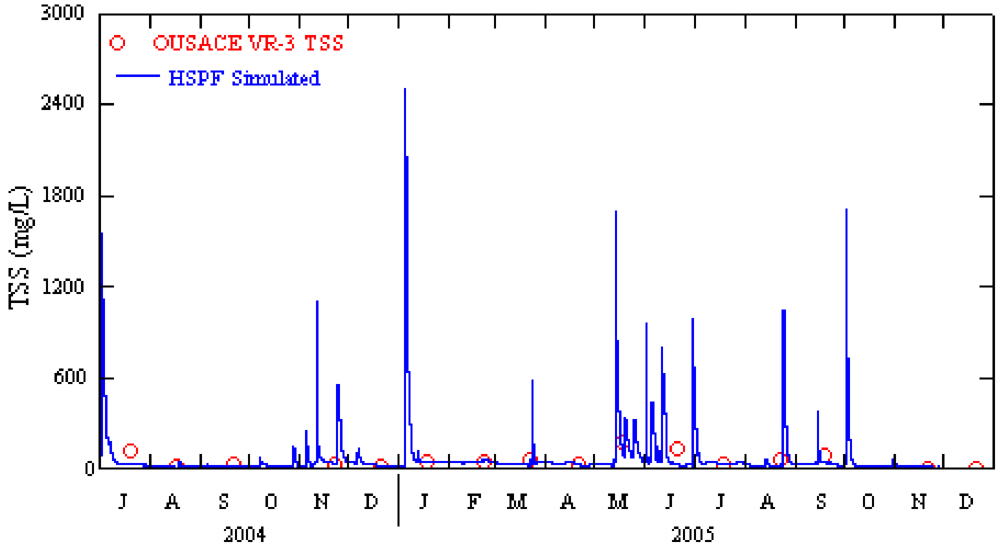

Figure 60 TSS Calibration Plot at USACE VR-3

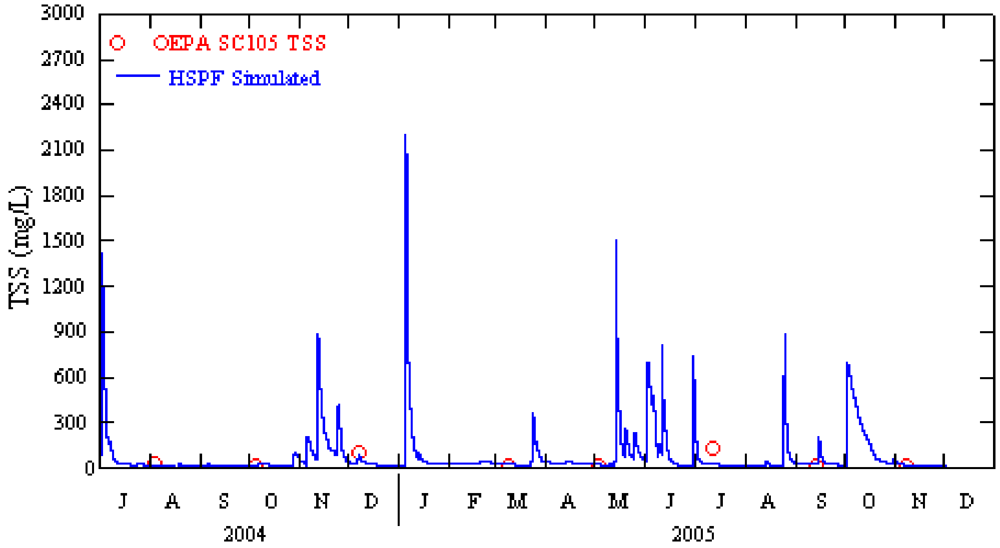

Figure 61 TSS Calibration Plot at EPA SC105

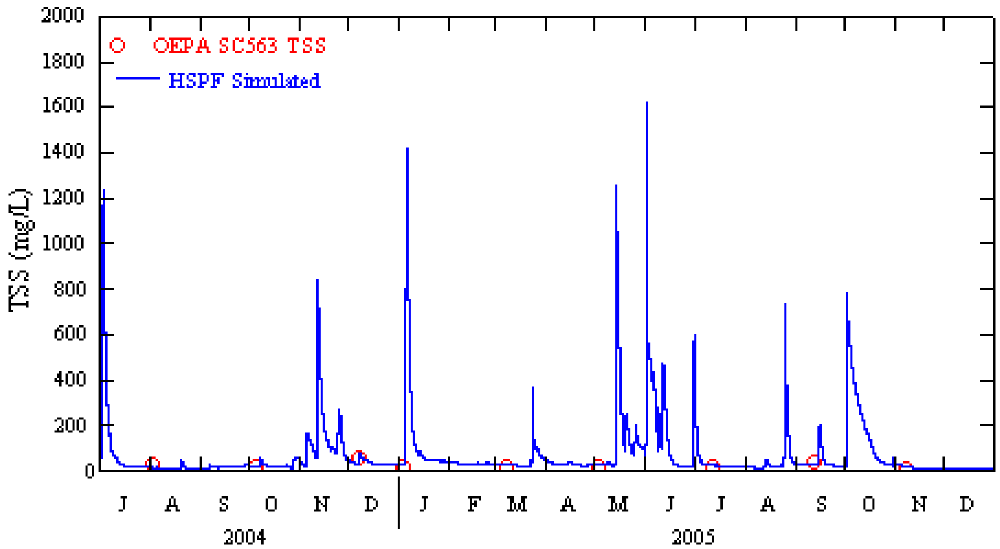

Figure 62 TSS Calibration Plot at EPA SC563

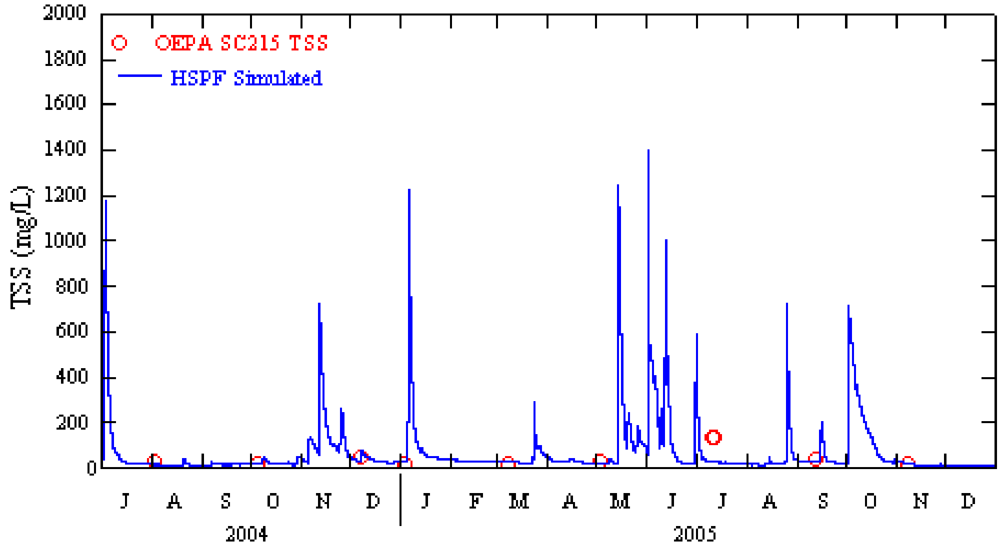

Figure 63 TSS Calibration Plot at EPA SC215

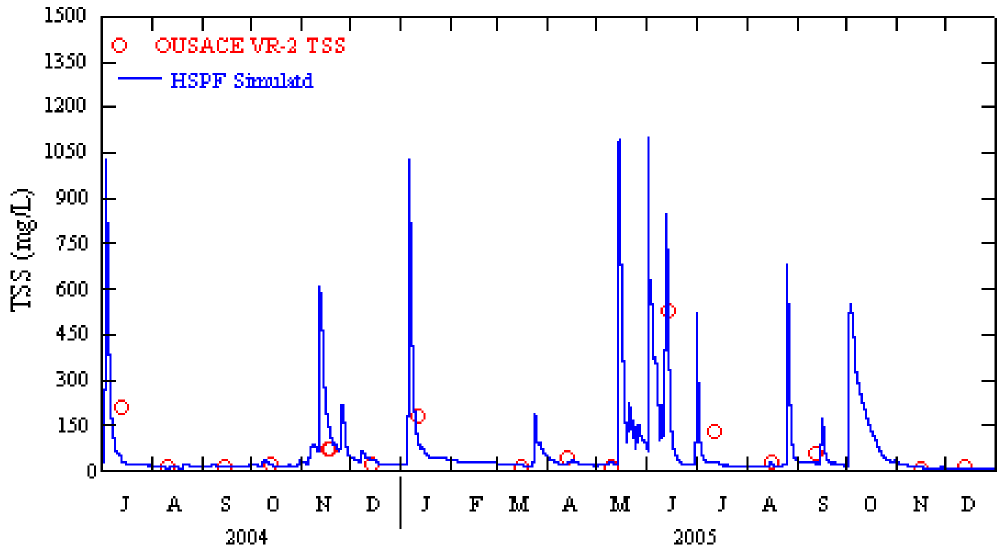

Figure 64 TSS Calibration Plot at USACE VR-2

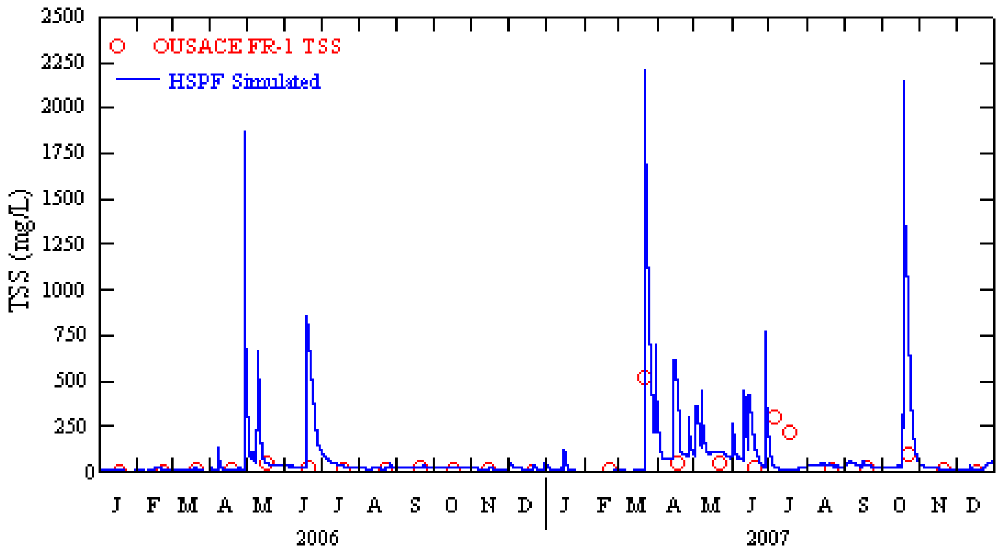

Figure 65 TSS Validation Plot at USACE FR-1

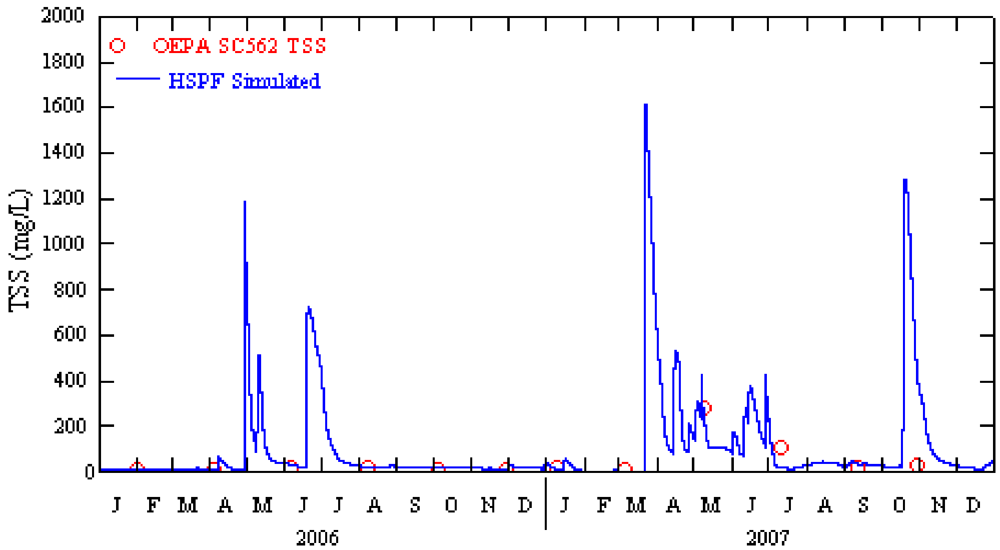

Figure 66 TSS Validation Plot at EPA SC562

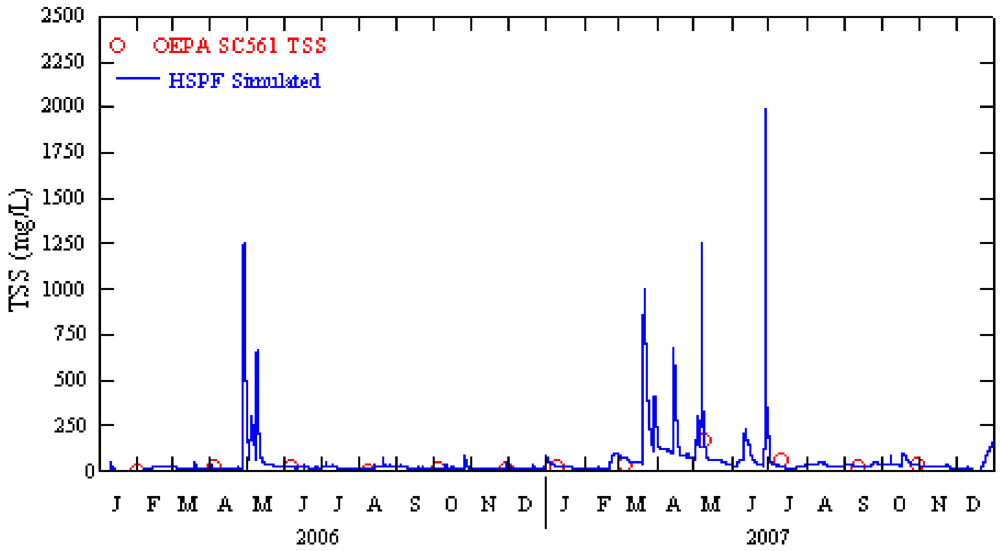

Figure 67 TSS Validation Plot at EPA SC561

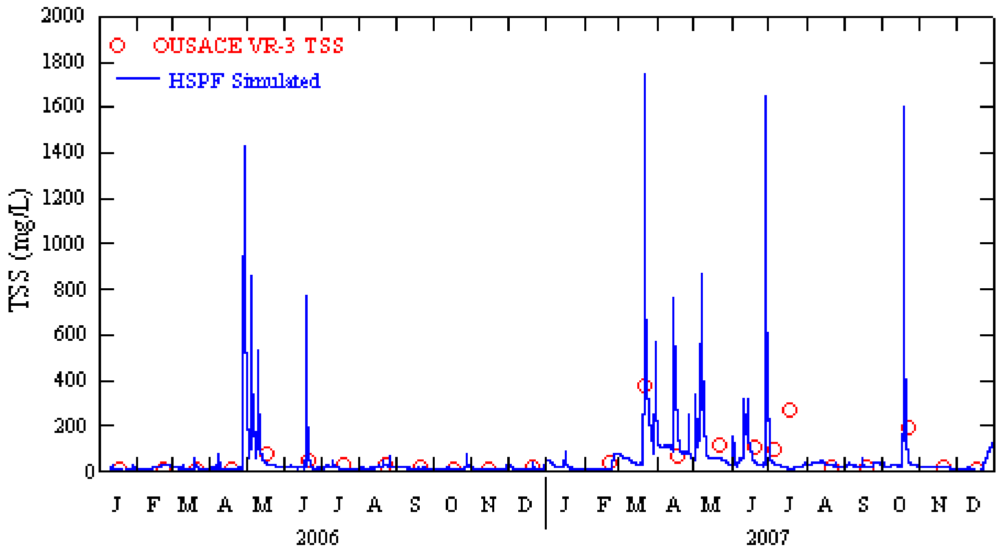

Figure 68 TSS Validation Plot at USACE VR-3

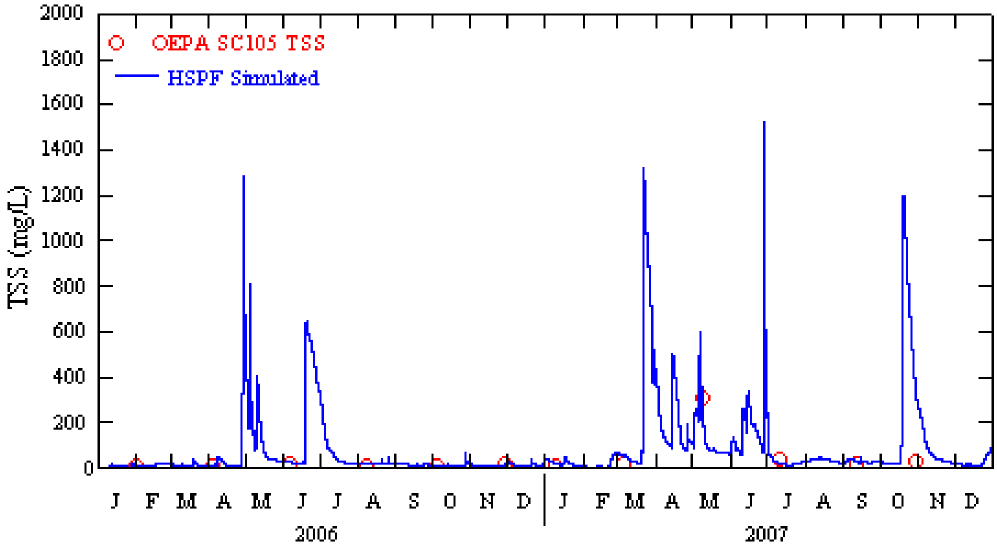

Figure 69 TSS Validation Plot at EPA SC105

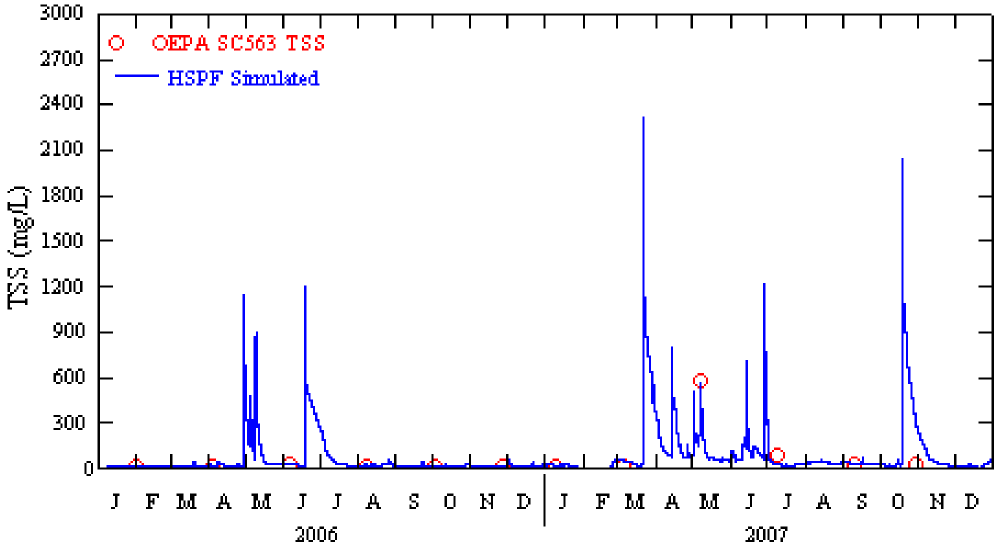

Figure 70 TSS Validation Plot at EPA SC563

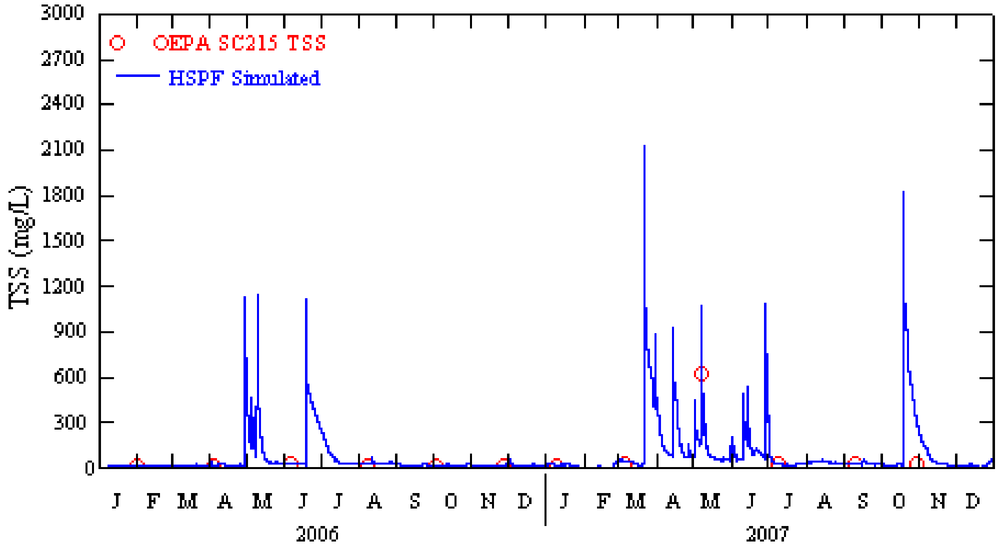

Figure 71 TSS Validation Plot at EPA SC215

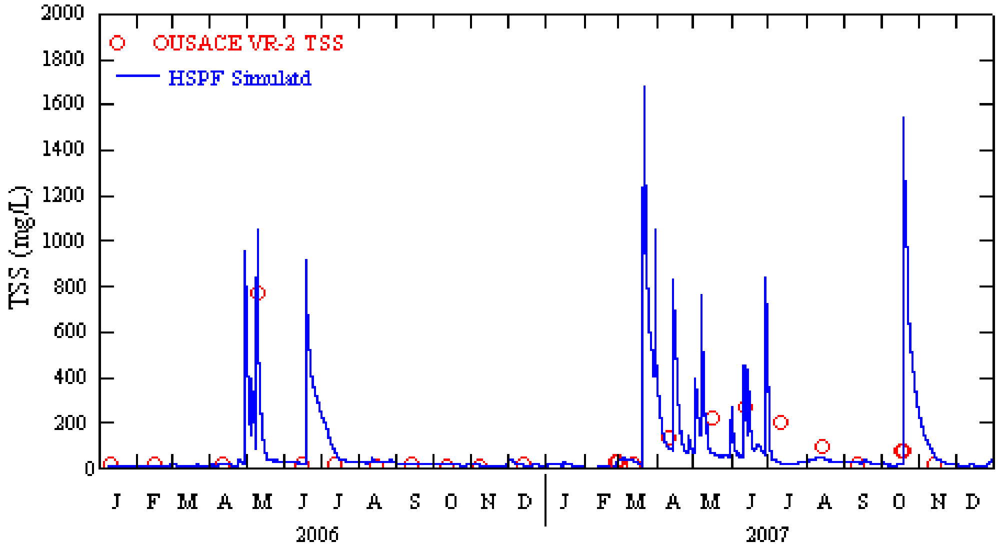

Figure 72 TSS Validation Plot at USACE VR-2

7.2 Dissolved Oxygen Calibration and Validation

The calibration and validation plots of dissolved oxygen (DO) at these observation stations are given in Figure 73-84. The calculated statistics for model calibration and validation are shown in Table 21 and 22.

The general model performance for DO at both calibraton and validation periods is good. The simulated DO followed the trends of the observed DO data (Figures 73-84). The calculated mean percent error (MPE) values are within the range of -10% to +10% except at EPA station SC215 and SC561, in which the absolute values of the calculated MPE are slightly higher than 10% (10.31% and -11.19%) for the validation period.

Table 21 Calculated Statistics for DO (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
EPA SC562	8	8.55	8.6	-0.68
EPA SC561	8	8.28	8.7	-5.12
EPA SC105	8	8.58	8.1	5.87
EPA SC563	9	9.34	8.5	9.18
EPA SC215	9	8.83	8.7	1.20
OWRB	14	9.12	8.6	6.16

Table 22 Table Calculated Statistics for DO (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
EPA SC562	12	8.53	8.5	0.03
EPA SC561	12	8.27	9.2	-11.19
EPA SC105	12	8.44	8.8	-4.32
EPA SC563	12	9.23	8.9	3.35
EPA SC215	12	10.12	9.1	10.31
OWRB	18	8.48	8.7	-2.64

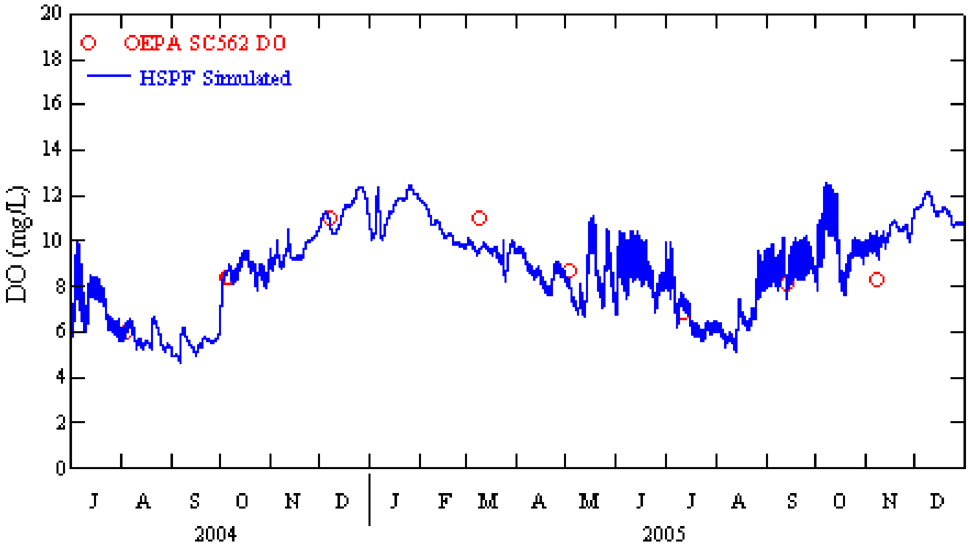

Figure 73 DO Calibration Plot at EPA SC562

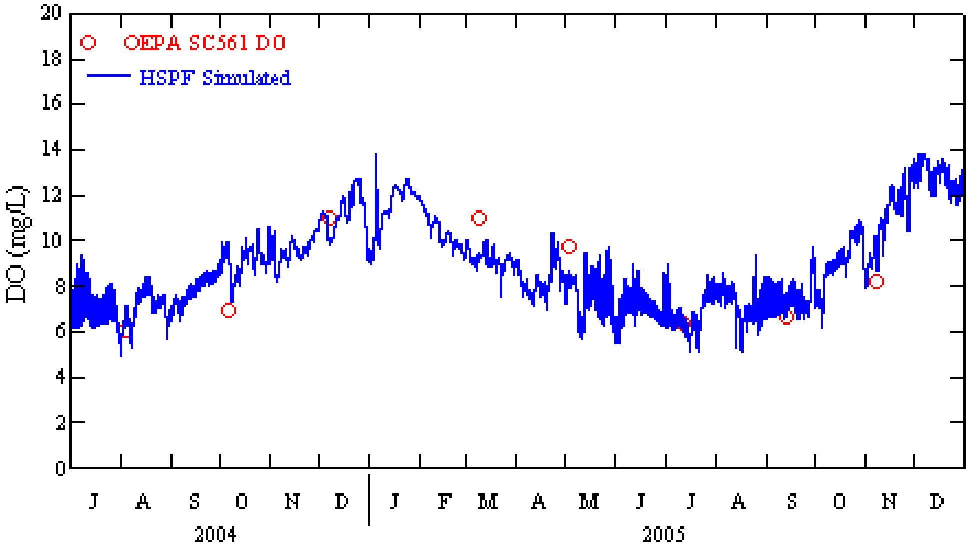

Figure 74 DO Calibration Plot at EPA SC561

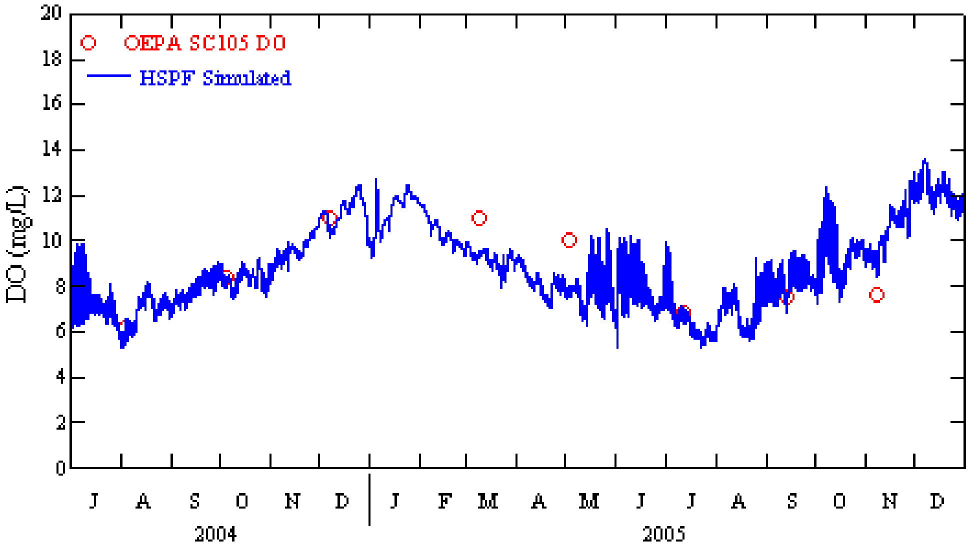

Figure 75 DO Calibration Plot at EPA SC105

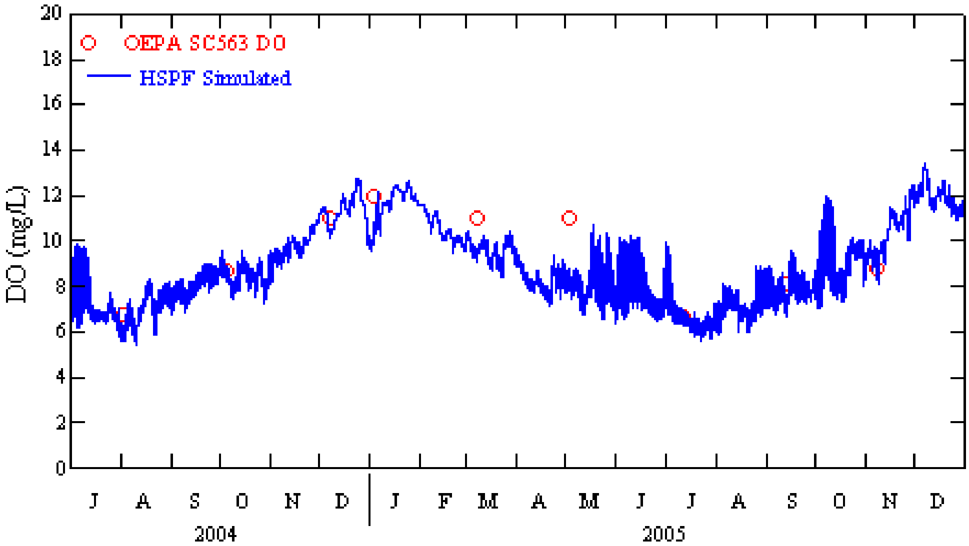

Figure 76 DO Calibration Plot at EPA SC563

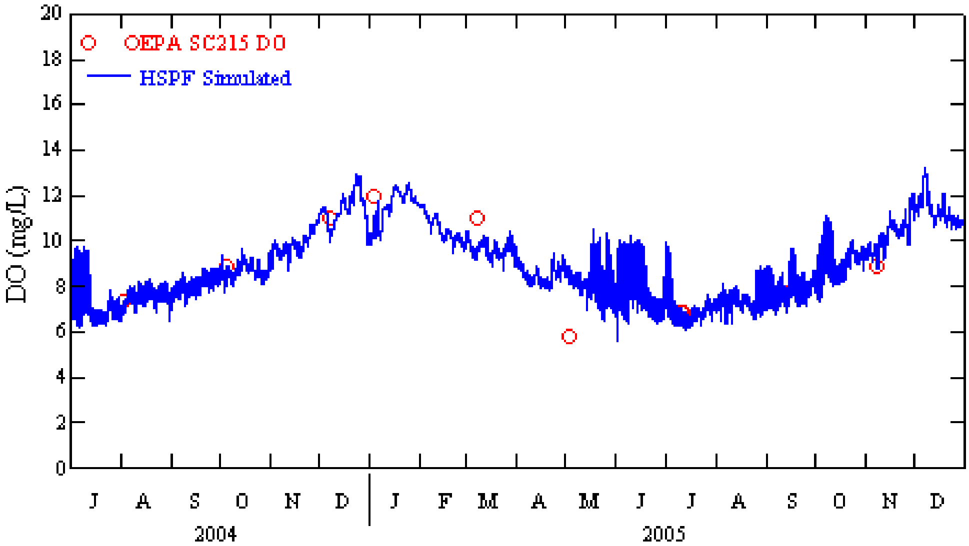

Figure 77 DO Calibration Plot at EPA SC215

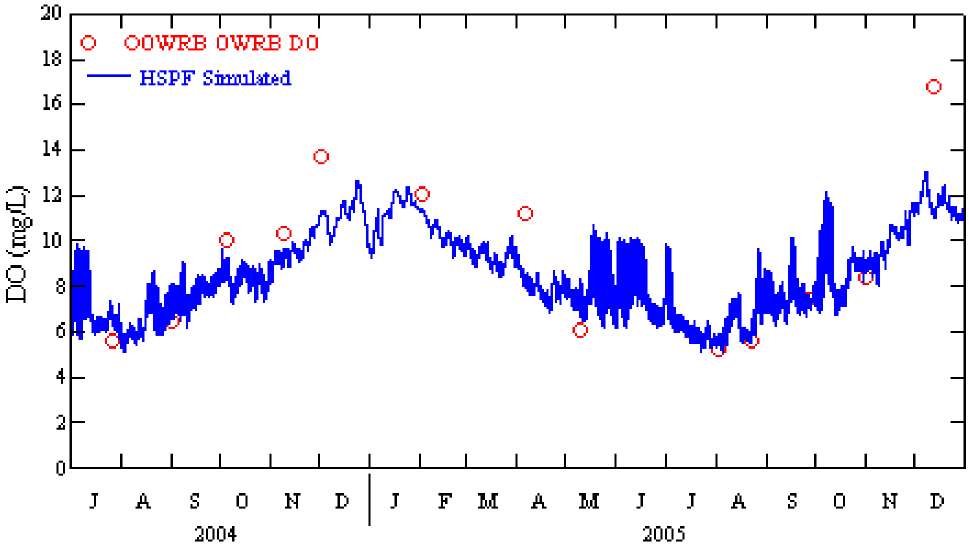

Figure 78 DO Calibration Plot at OWRB Station

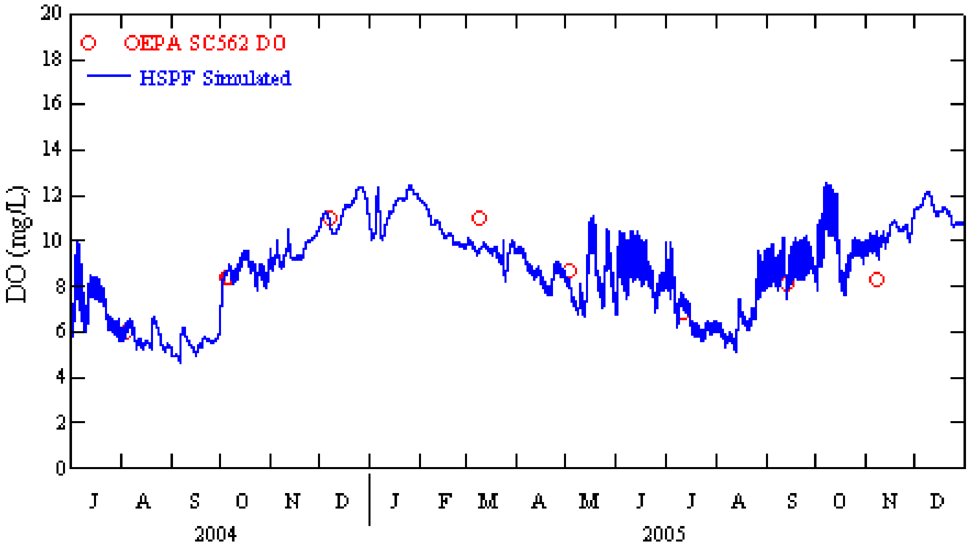

Figure 79 DO Validation Plot at EPA SC562

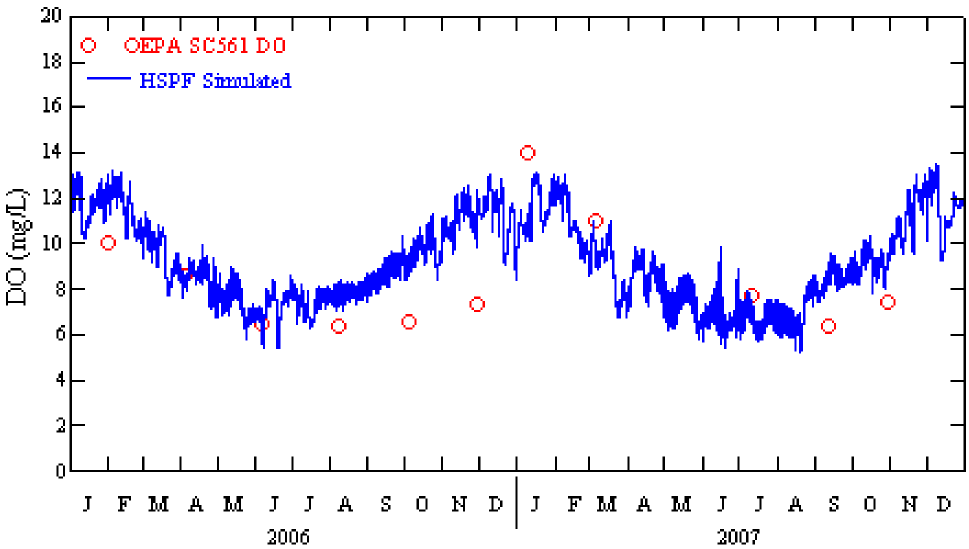

Figure 80 DO Validation Plot at EPA SC561

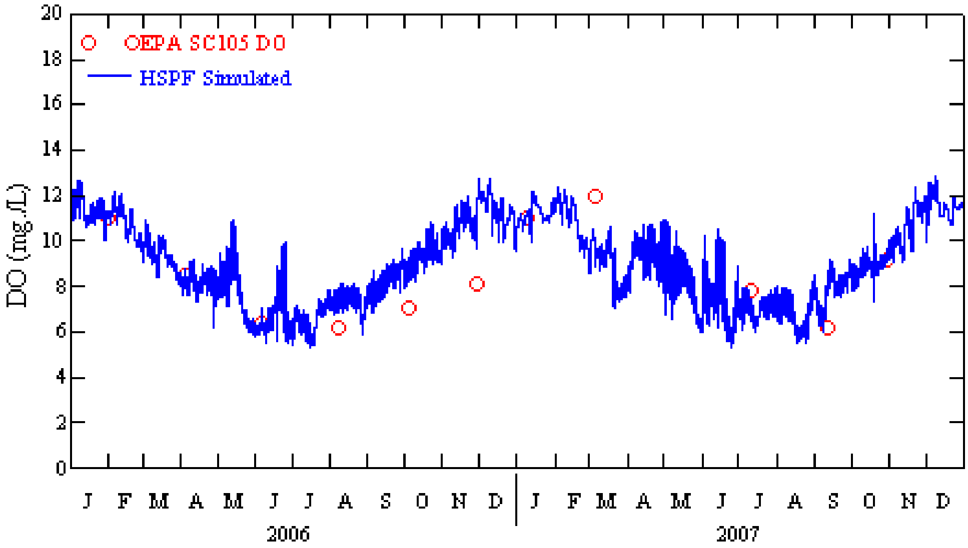

Figure 81 DO Validation Plot at EPA SC105

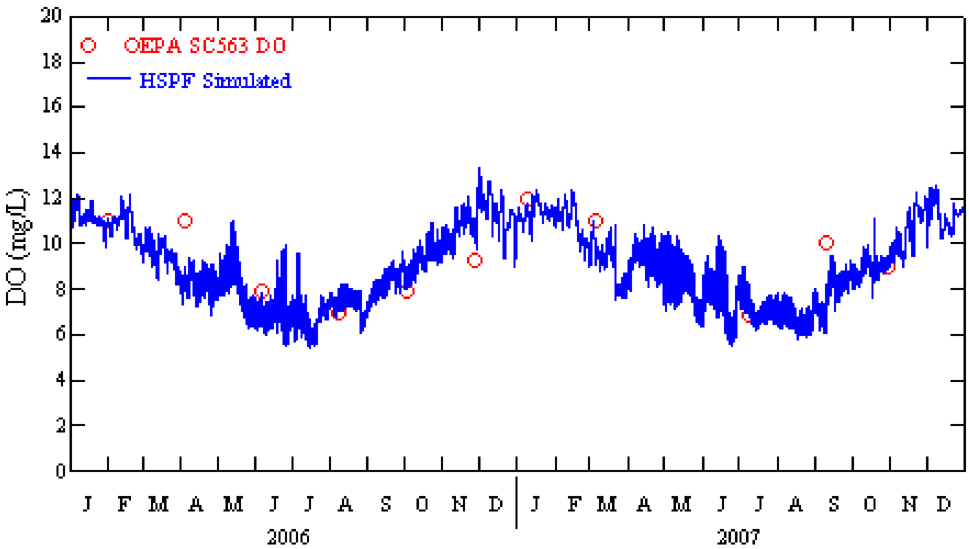

Figure 82 DO Validation Plot at EPA SC563

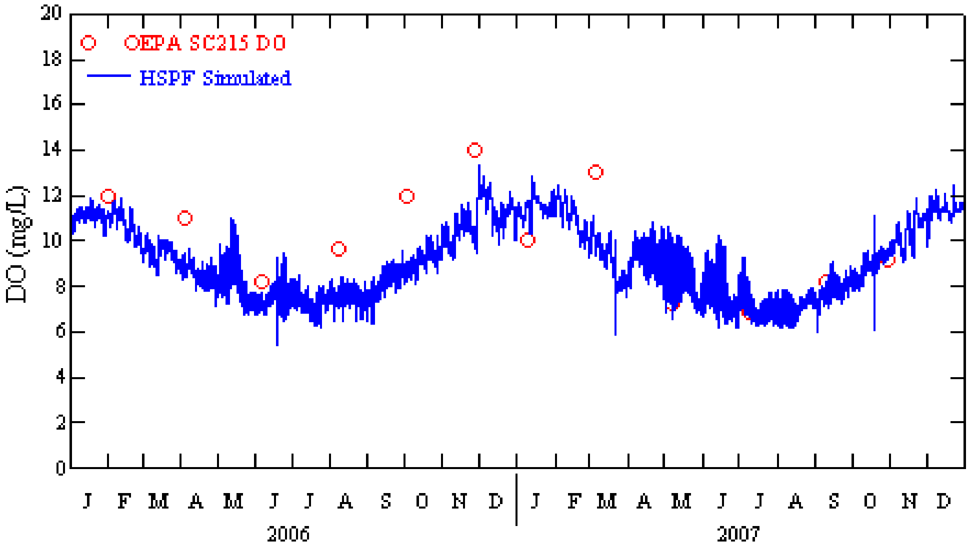

Figure 83 DO Validation Plot at EPA SC215

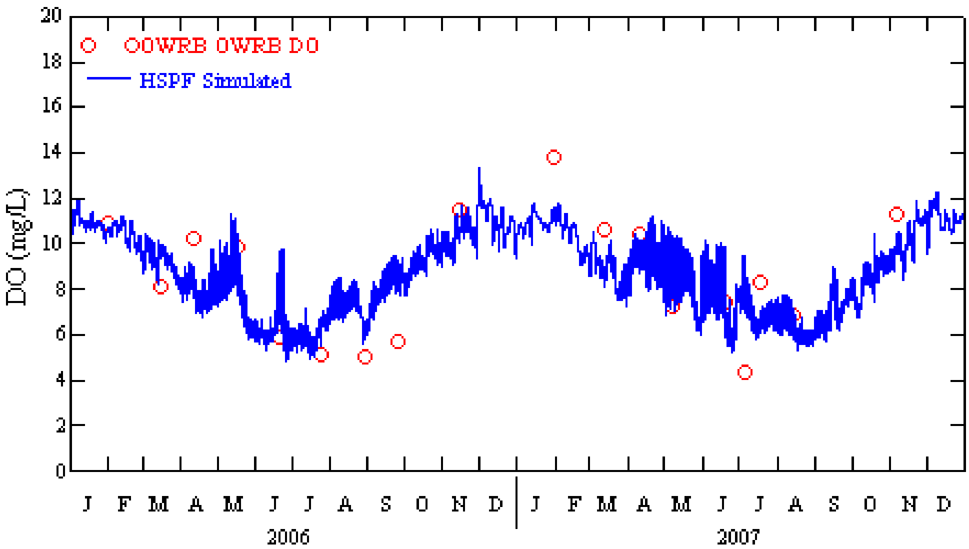

Figure 84 DO Validation Plot at OWRB Station

7.3 Nitrogen Calibration and Validation

The calibration and validation plots of nitrogen (NH4, NO3, and TN) at these observation stations are given in Figures 85-128. The calculated statistics for model calibration and validation are shown in Tables 23-28.

The NH4 observation data are available at three USACE stations and OWRB station (Table 23 and 24). The sample sizes for both calibration and validation periods for these stations are small, ranging from 3 ton 7. The calculated mean percent error (MPE) values are all within the range of -100% to +100% at all stations for both calibration and validation periods (Table 23 and 24).

The NO3 observation data are available at all these nine stations (Table 25 and 26). The sample sizes range from 1 to 20. The model performance of NO3 is slightly better for the calibration period that the validation period. During calibration period, the calculated MPE values at all stations are within the range of -100% to +100% except station SC105, while the MPE values at two observation stations are lower than -100% during validation period (Table 25 and 26).

The TN observation data are available at all these nine stations (Table 27 and 28). The model performance of TN is fairly good with all the calculated MPE values within the range of -100% to +100%. The TN model performance at the validation period is better than at the calibration period. The calculated MPE values at the validation period are all within the range of -25% to +25% (Table 27 and 28). Especially, the TN model performance is very good at station EPA SC215 with the calculated MPE vale of -0.02%.

Table 23 Calculated Statistics for NH4 (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	6	0.13	0.06	52.65
USACE VR-3	3	0.08	0.05	36.98
USACE VR-2	4	0.06	0.02	74.25
OWRB	4	0.09	0.01	88.28

Table 24 Calculated Statistics for NH4 (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	7	0.29	0.09	69.45
USACE VR-3	3	0.21	0.17	20.01
USACE VR-2	3	0.09	0.12	-30.47
OWRB	7	0.12	0.06	48.19

Table 25 Calculated Statistics for NO3 (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	14	0.44	0.22	49.57
EPA SC562	1	0.16	0.00	97.78
EPA SC561	3	0.13	0.24	-87.41
USACE VR-3	14	0.24	0.20	16.65
EPA SC105	3	0.18	0.38	-110.19
EPA SC563	4	0.24	0.24	-0.12
EPA SC215	5	0.22	0.21	6.20
USACE VR-2	11	0.23	0.17	28.16
OWRB	10	0.33	0.23	29.78

Table 26 Calculated Statistics for NO3 (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	20	0.61	0.62	-1.33
EPA SC562	6	0.25	0.65	-159.84
EPA SC561	5	0.51	0.82	-61.33
USACE VR-3	15	0.66	0.45	31.33
EPA SC105	6	0.40	0.70	-74.23
EPA SC563	8	0.30	0.68	-127.63
EPA SC215	9	0.46	0.71	-53.56
USACE VR-2	11	0.49	0.55	-11.58
OWRB	13	0.46	0.67	-45.43

Table 27 Calculated Statistics for TN (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	16	0.99	0.75	24.52
EPA SC562	8	0.39	0.72	-85.74
EPA SC561	8	0.47	0.83	-75.74
USACE VR-3	15	0.94	0.92	2.03
EPA SC105	8	0.48	0.78	-62.72
EPA SC563	9	0.52	0.83	-59.42
EPA SC215	9	0.60	0.89	-48.21
USACE VR-2	16	0.87	0.94	-7.50
OWRB	14	0.89	0.97	-9.12

Table 28 Calculated Statistics for TN (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	24	1.37	1.26	8.05
EPA SC562	12	0.74	0.92	-23.83
EPA SC561	12	0.85	1.00	-17.24
USACE VR-3	24	1.37	1.07	22.08
EPA SC105	12	0.88	1.06	-20.15
EPA SC563	12	1.06	1.19	-11.93
EPA SC215	12	1.33	1.35	-1.84
USACE VR-2	20	1.33	1.25	6.00
OWRB	11	1.24	1.43	-19.52

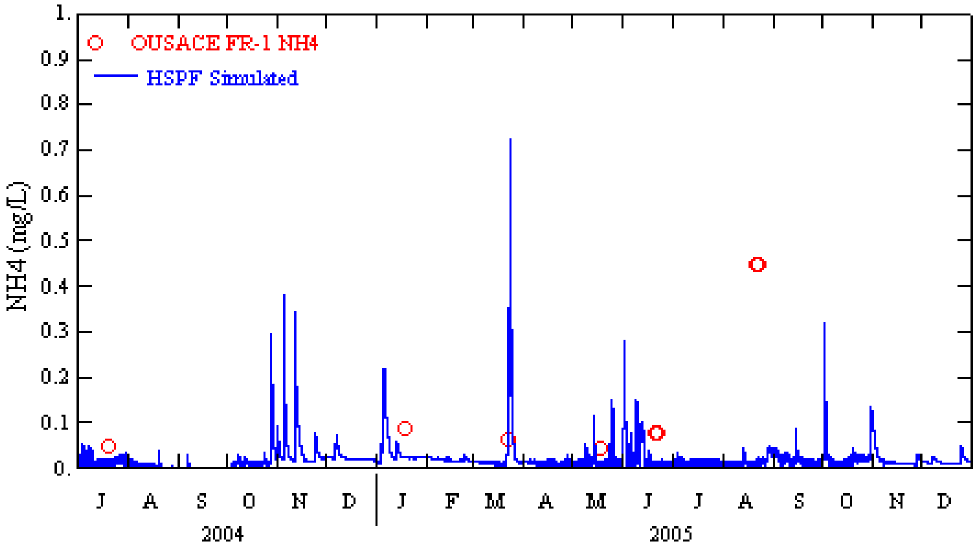

Figure 85 NH4 Calibration Plot at USACE FR-1

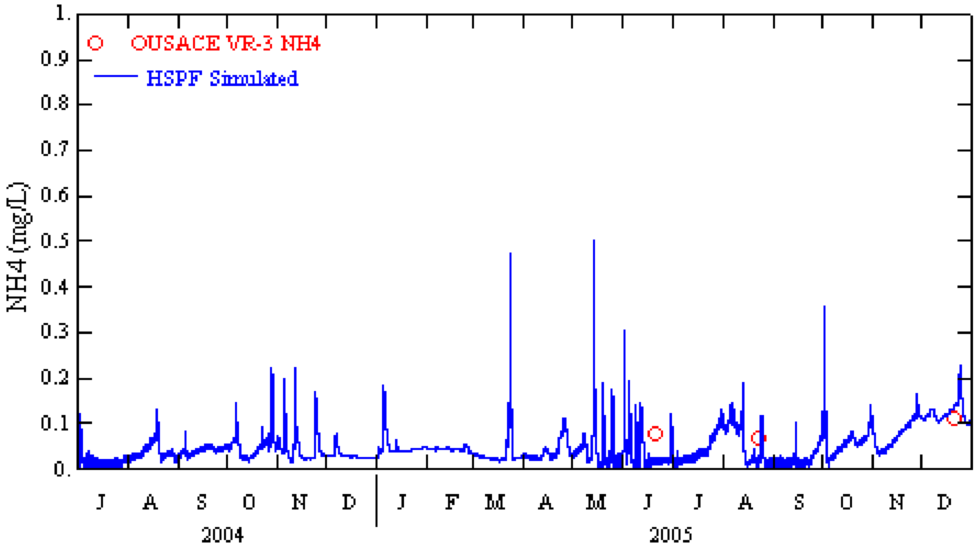

Figure 86 NH4 Calibration Plot at USACE VR-3

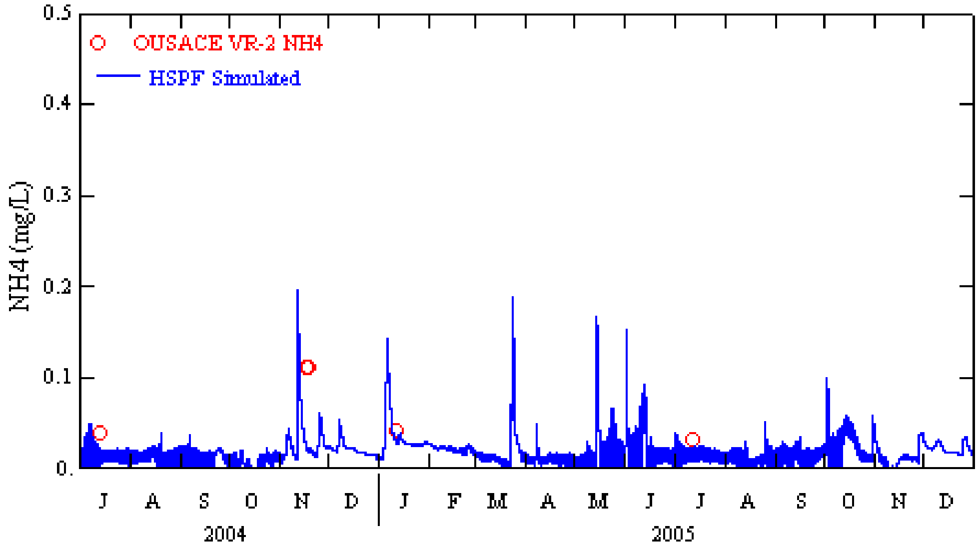

Figure 87 NH4 Calibration Plot at USACE VR-2

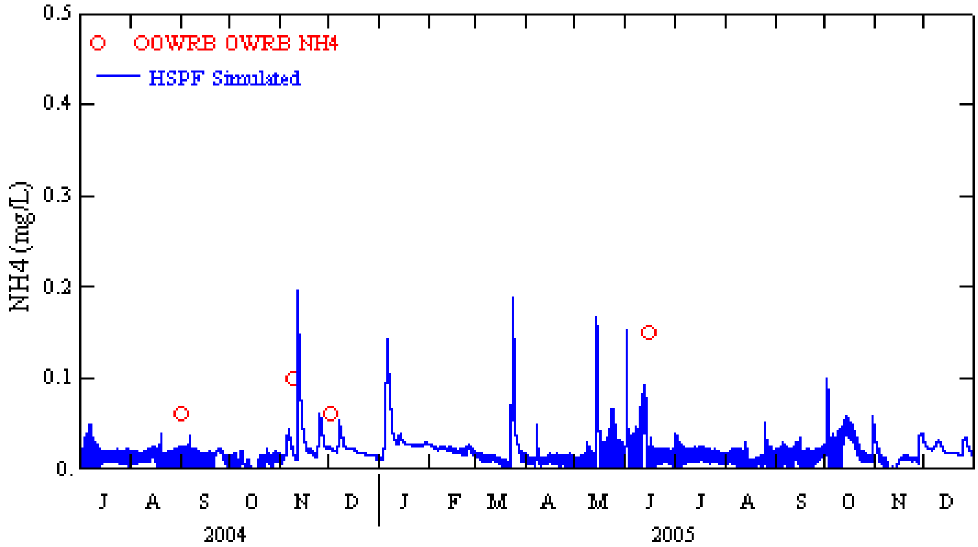

Figure 88 NH4 Calibration Plot at OWRB Station

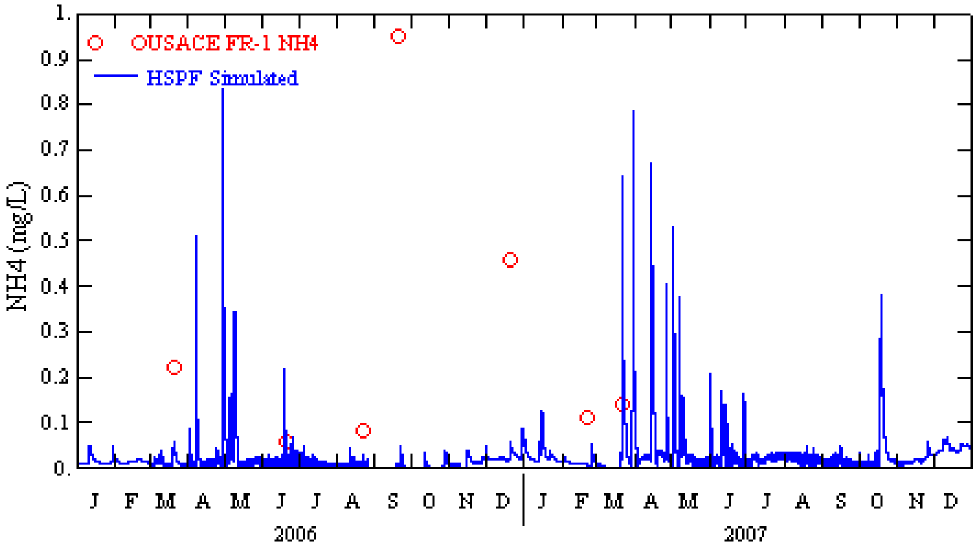

Figure 89 NH4 Validation Plot at USACE FR-1

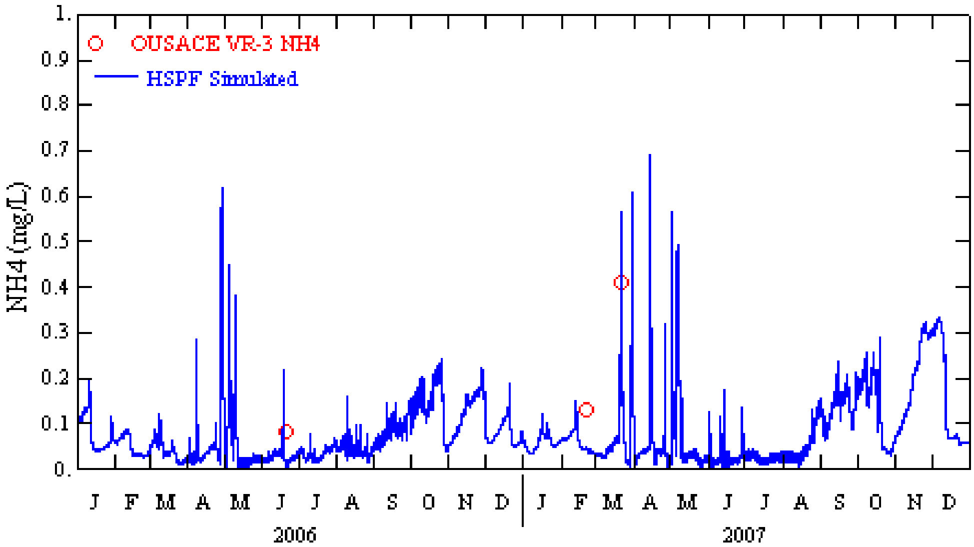

Figure 90 NH4 Validation Plot at USACE VR-3

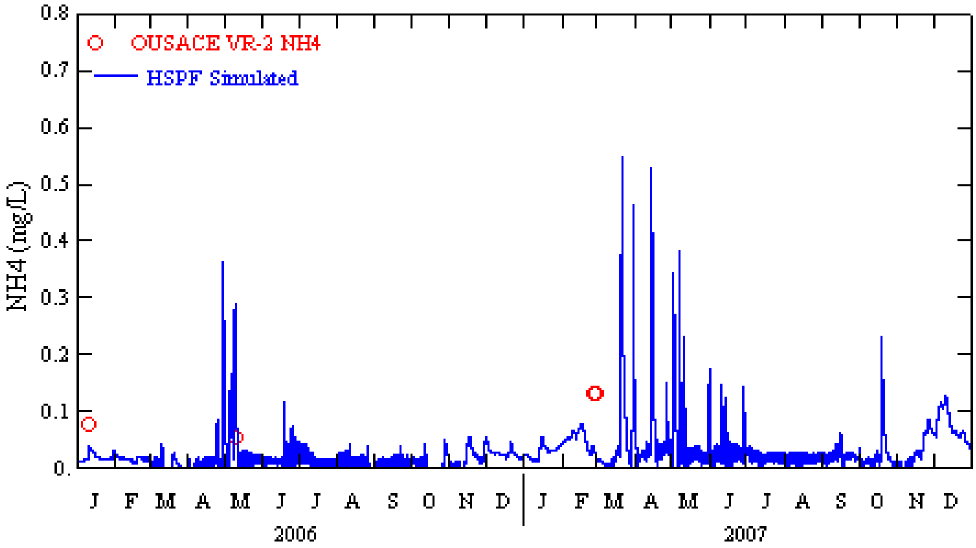

Figure 91 NH4 Validation Plot at USACE VR-2

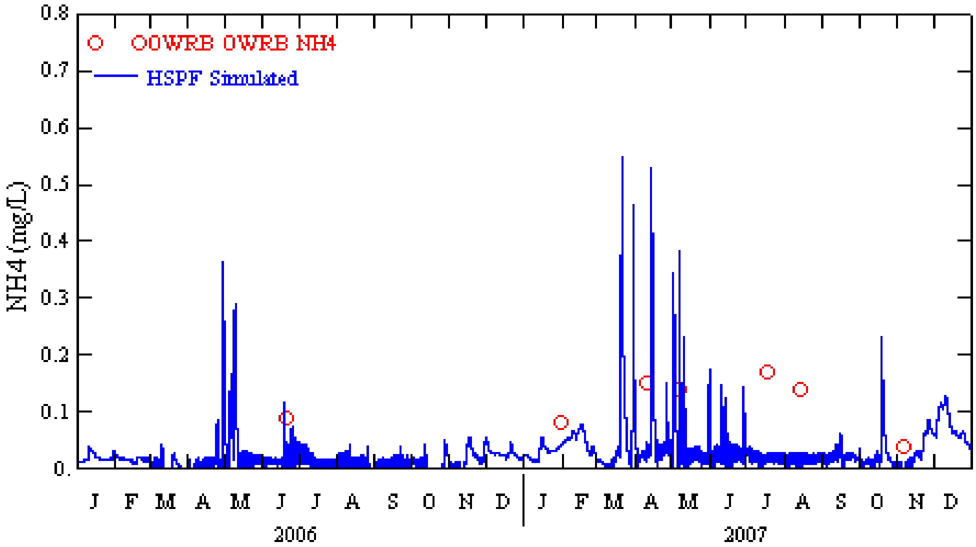

Figure 92 NH4 Validation Plot at OWRB Station

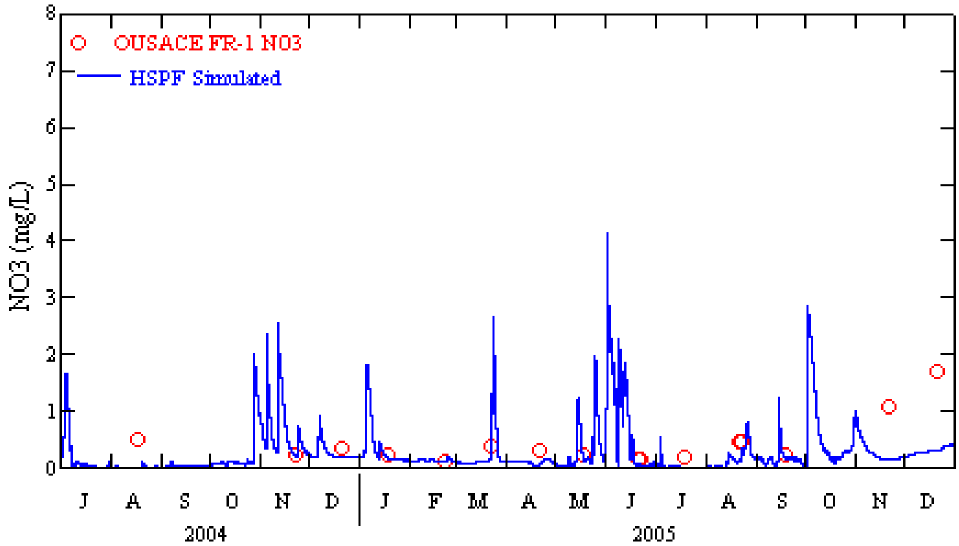

Figure 93 NO3 Calibration Plot at USACE FR-1

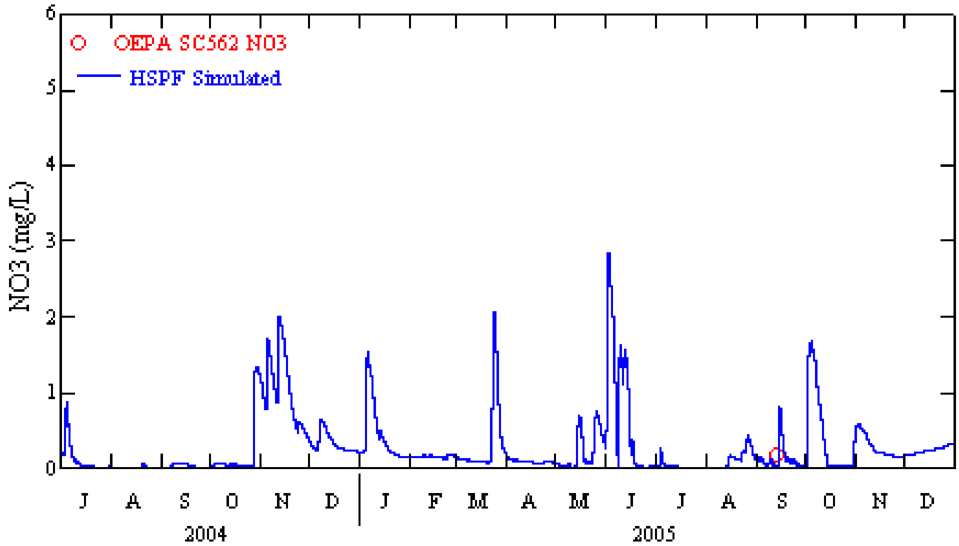

Figure 94 NO3 Calibration Plot at EPA SC562

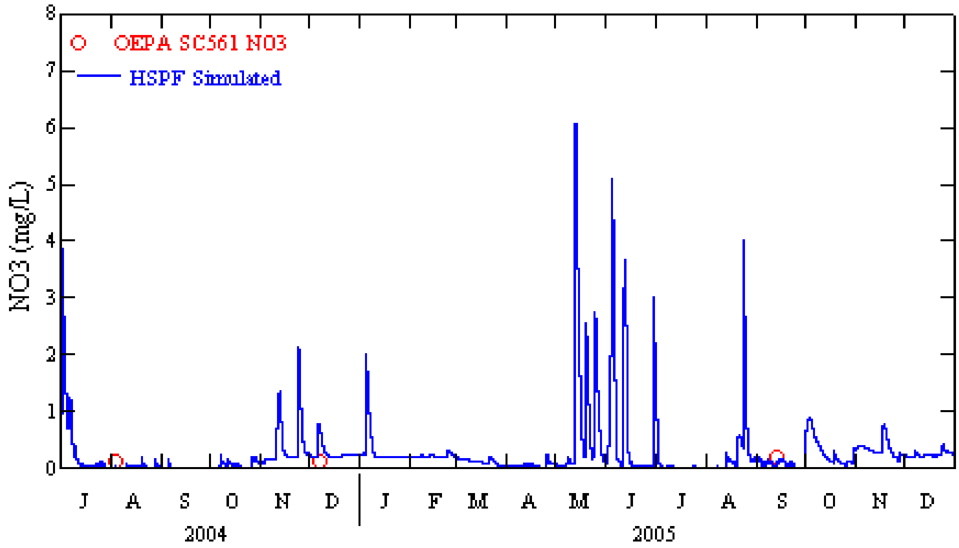

Figure 95 NO3 Calibration Plot at EPA SC561

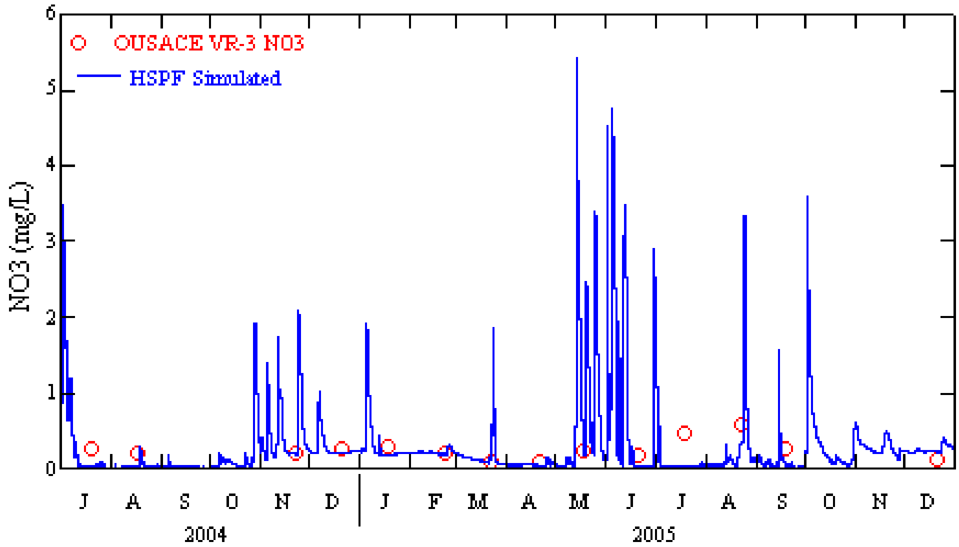

Figure 96 NO3 Calibration Plot at USACE VR-3

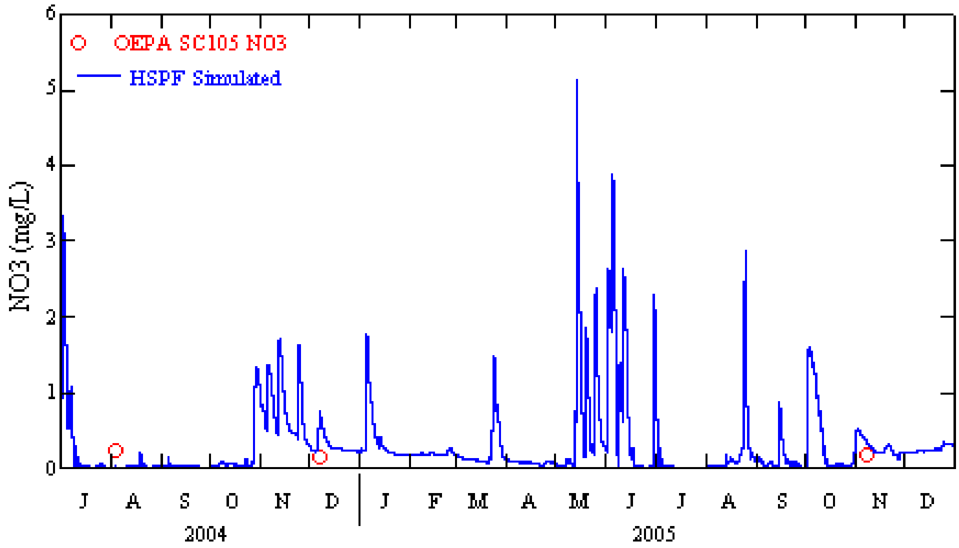

Figure 97 NO3 Calibration Plot at EPA SC105

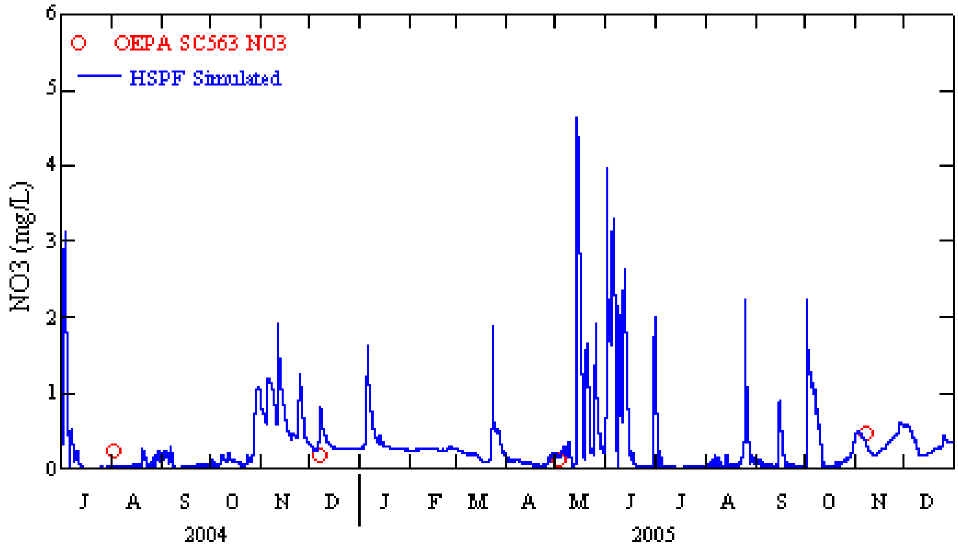

Figure 98 NO3 Calibration Plot at EPA SC563

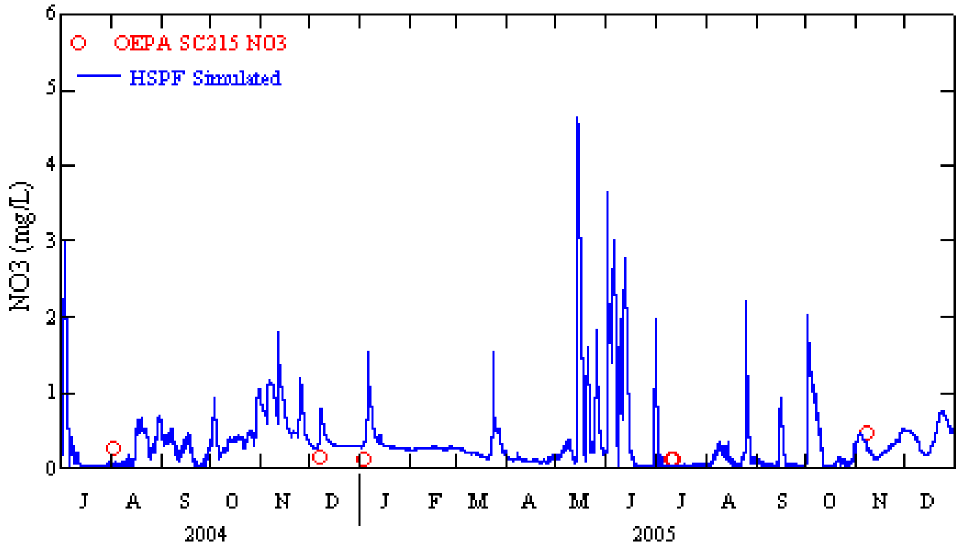

Figure 99 NO3 Calibration Plot at EPA SC215

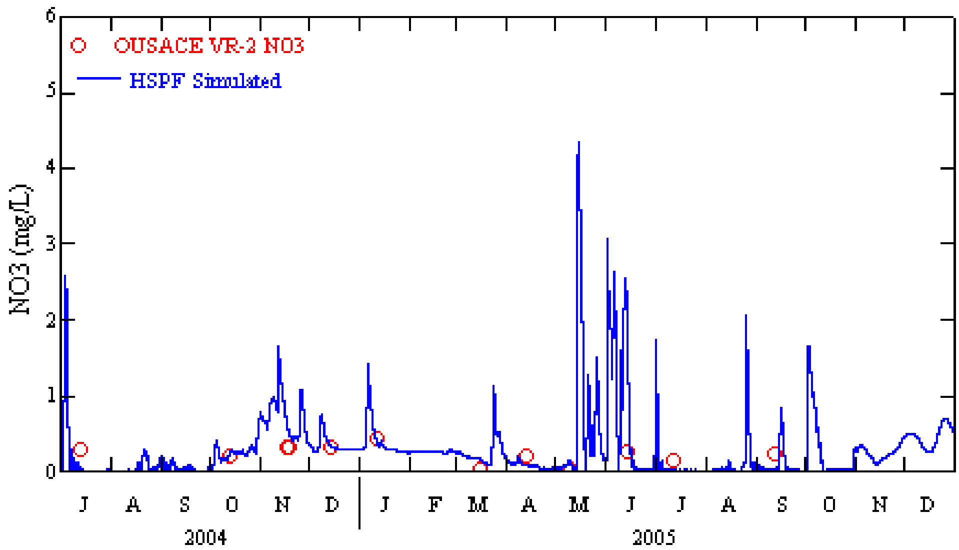

Figure 100 NO3 Calibration Plot at USACE VR-2

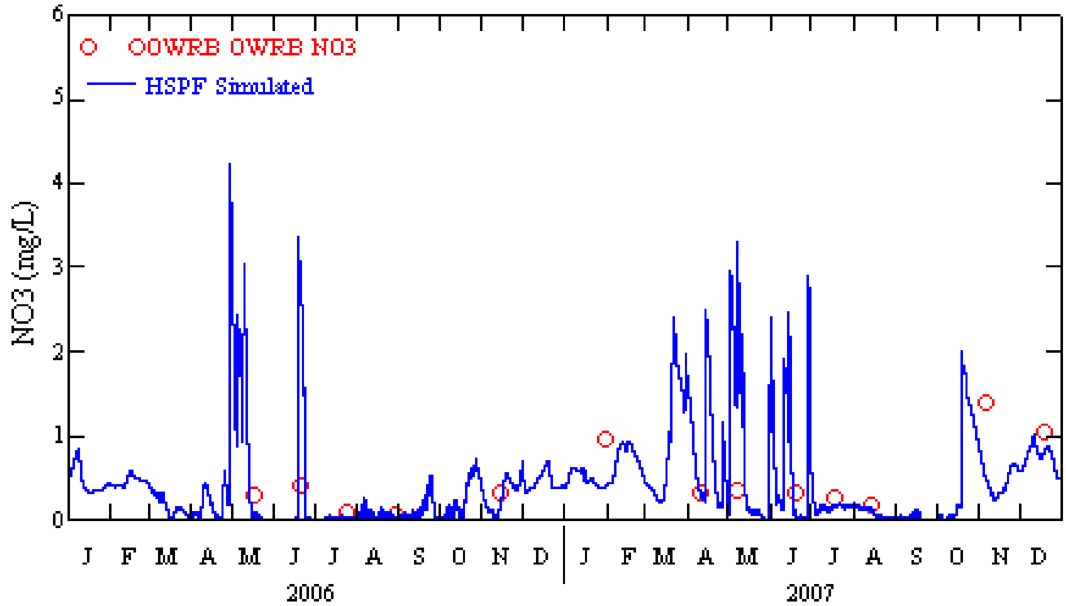

Figure 101 NO3 Calibration Plot at OWRB Station

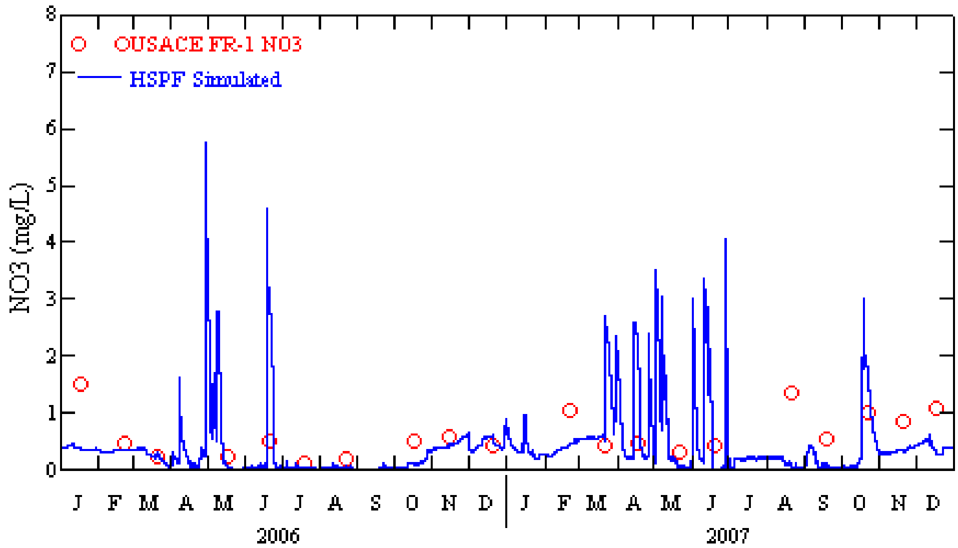

Figure 102 NO3 Validation Plot at USACE FR-1

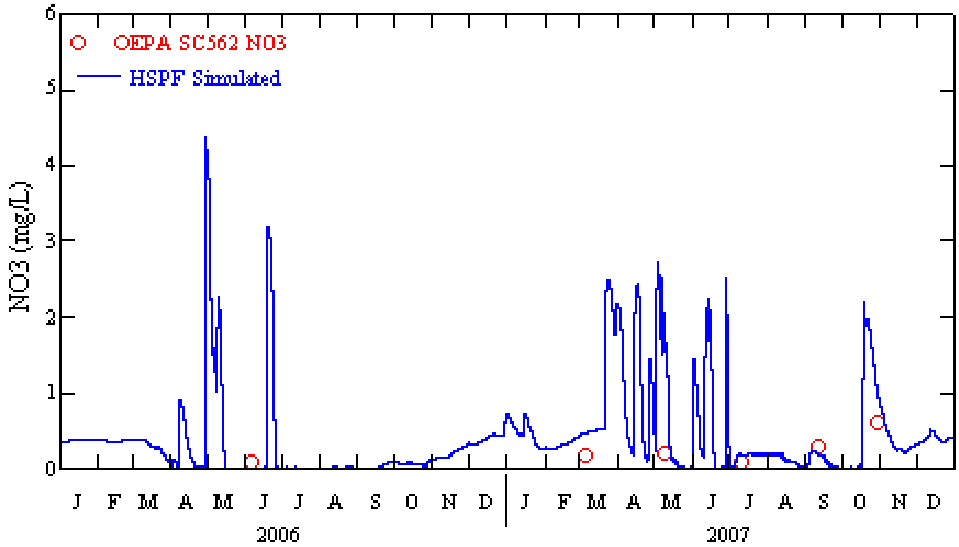

Figure 103 NO3 Validation Plot at EPA SC562

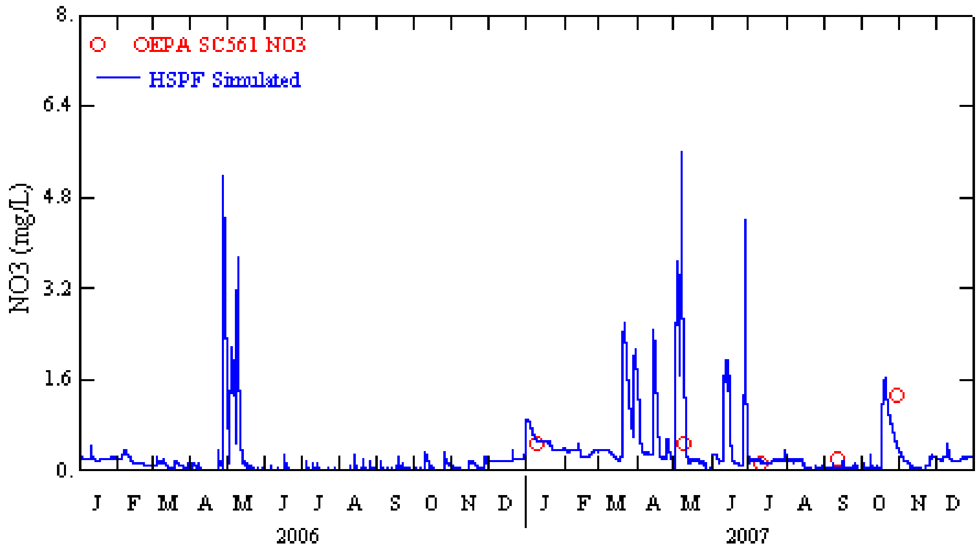

Figure 104 NO3 Validation Plot at EPA SC561

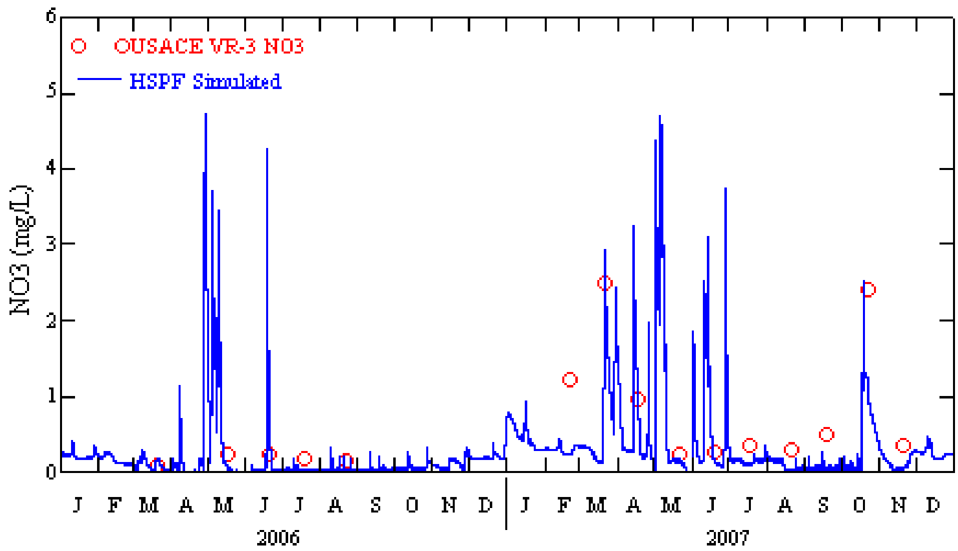

Figure 105 NO3 Validation Plot at USACE VR-3

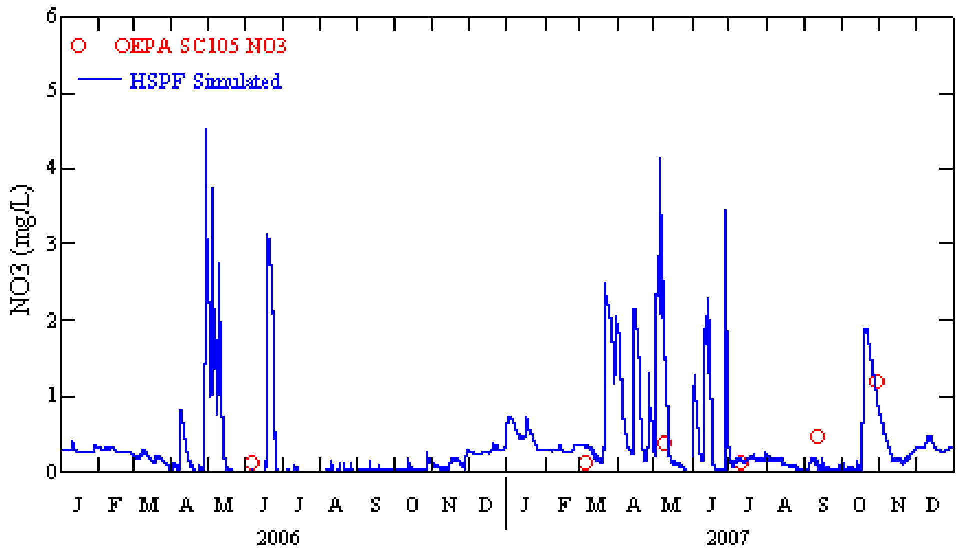

Figure 106 NO3 Validation Plot at EPA SC105

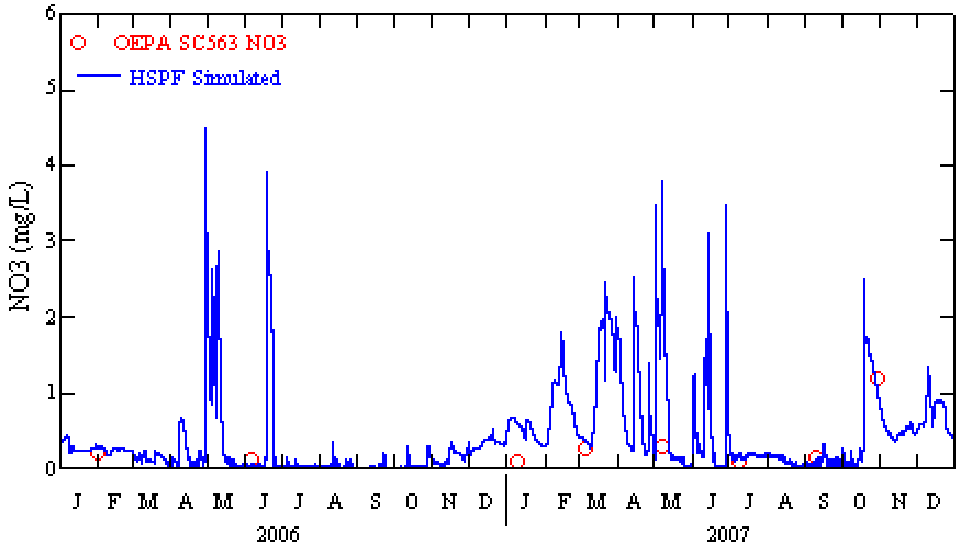

Figure 107 NO3 Validation Plot at EPA SC563

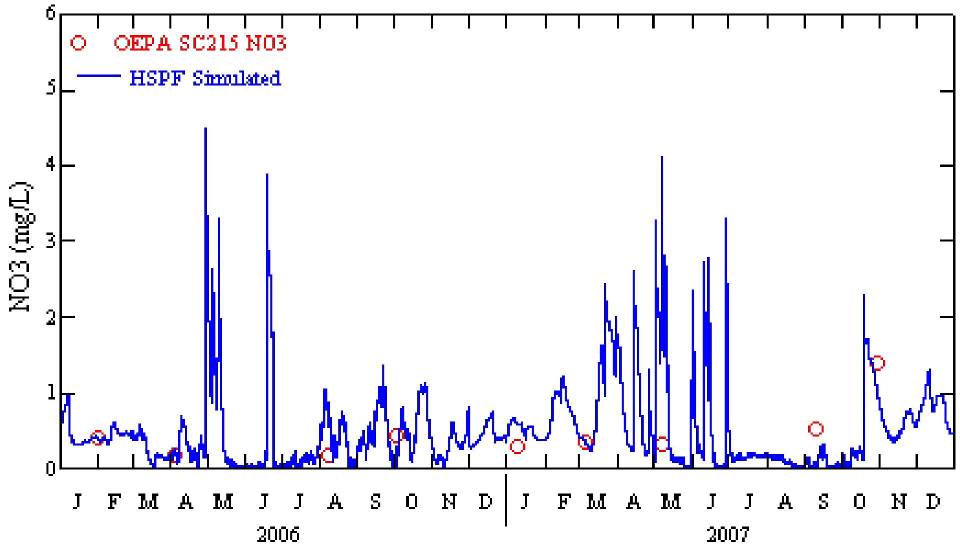

Figure 108 NO3 Validation Plot at EPA SC215

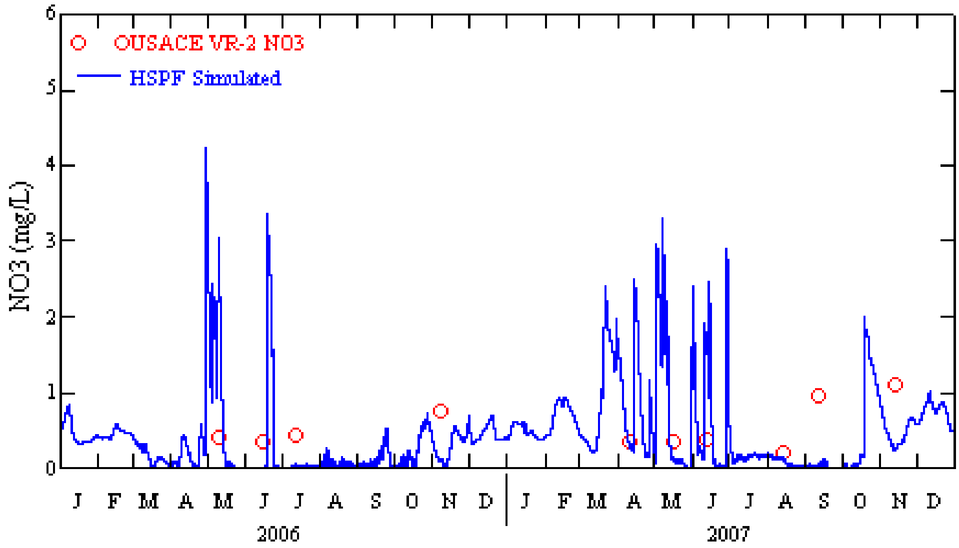

Figure 109 NO3 Validation Plot at USACE VR-2

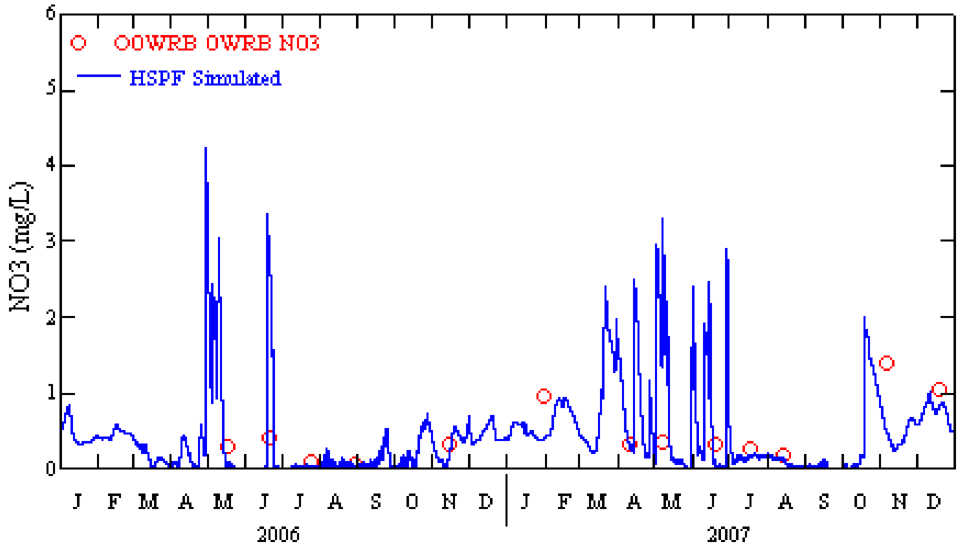

Figure 110 NO3 Validation Plot at OWRB Station

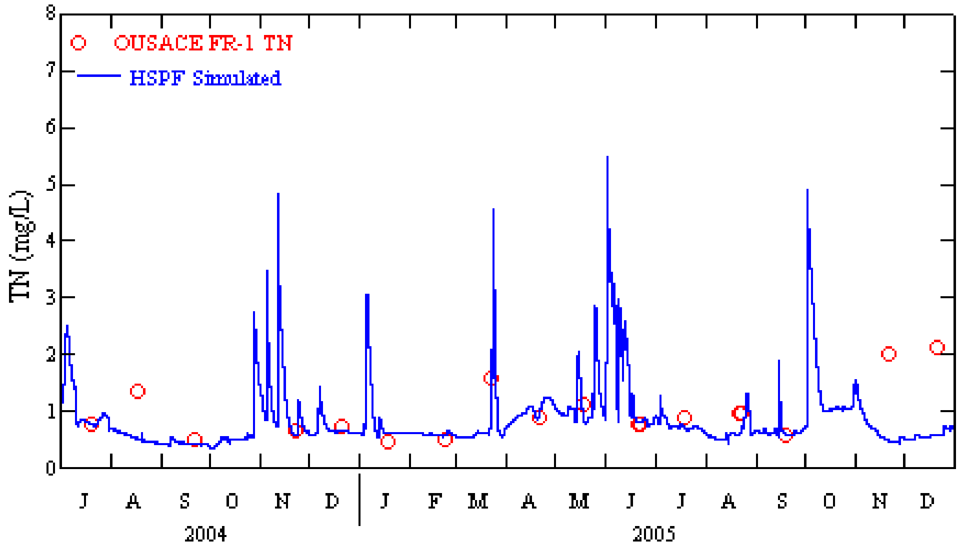

Figure 111 TN Calibration Plot at USACE FR-1

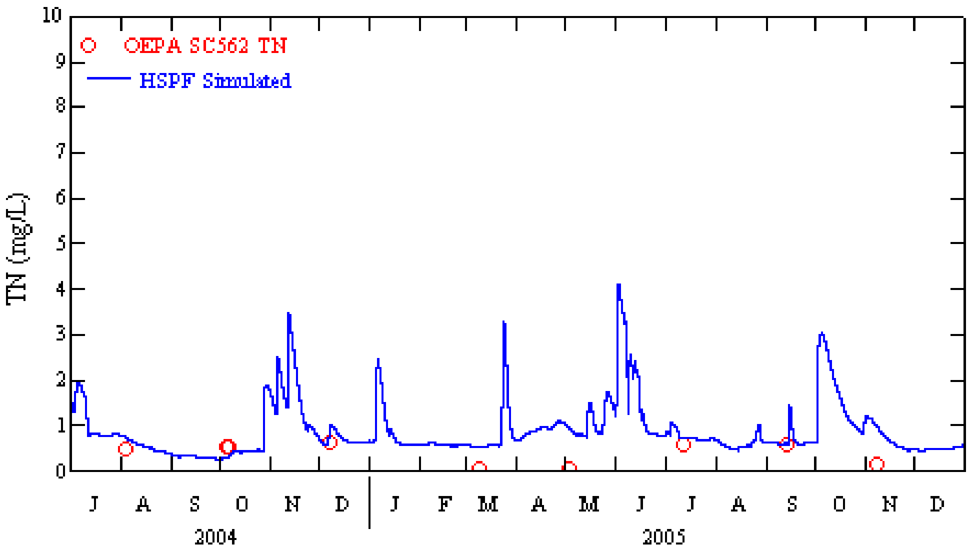

Figure 112 TN Calibration Plot at EPA SC562

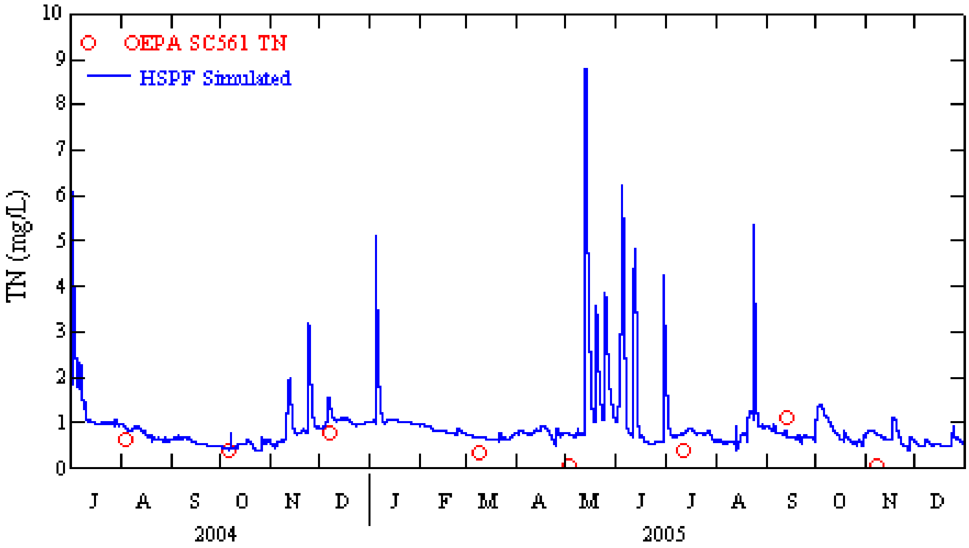

Figure 113 TN Calibration Plot at EPA SC561

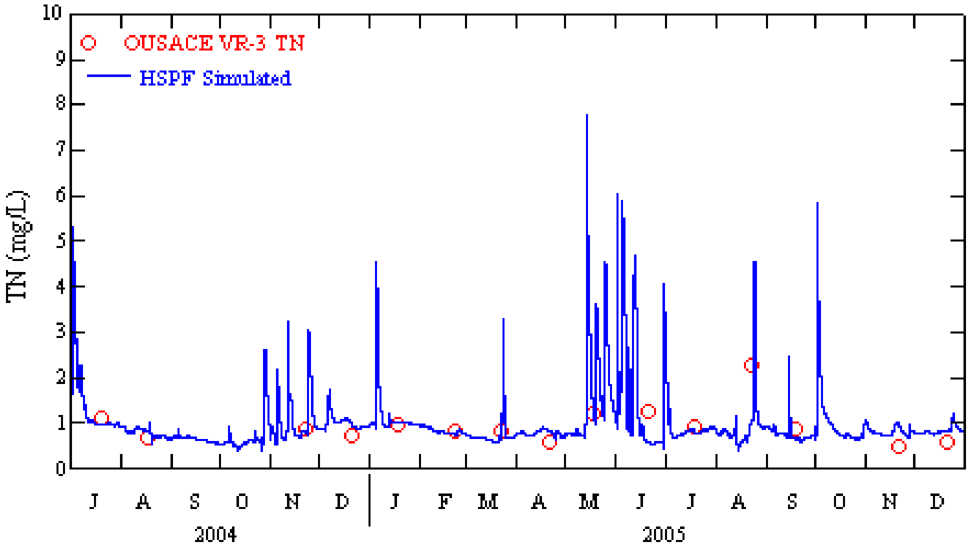

Figure 114 TN Calibration Plot at USACE VR-3

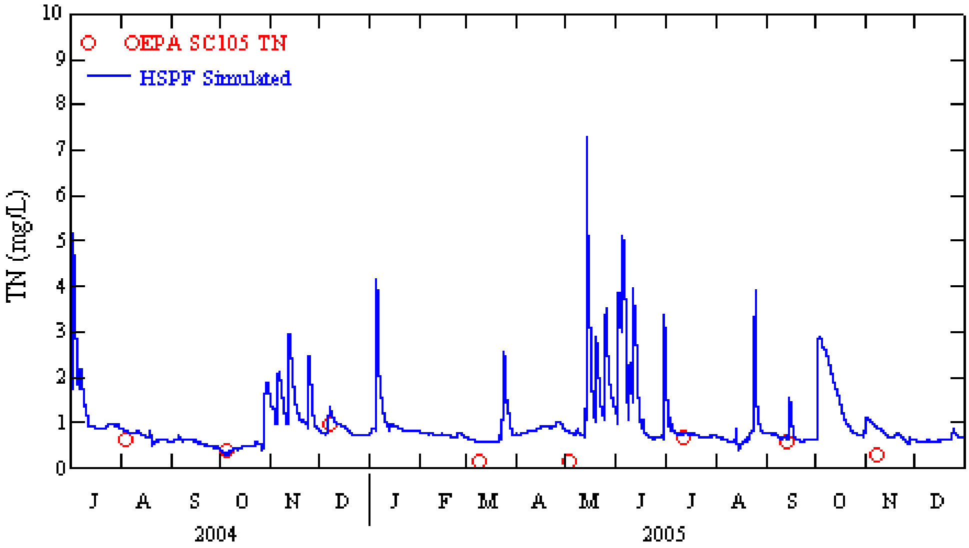

Figure 115 TN Calibration Plot at EPA SC105

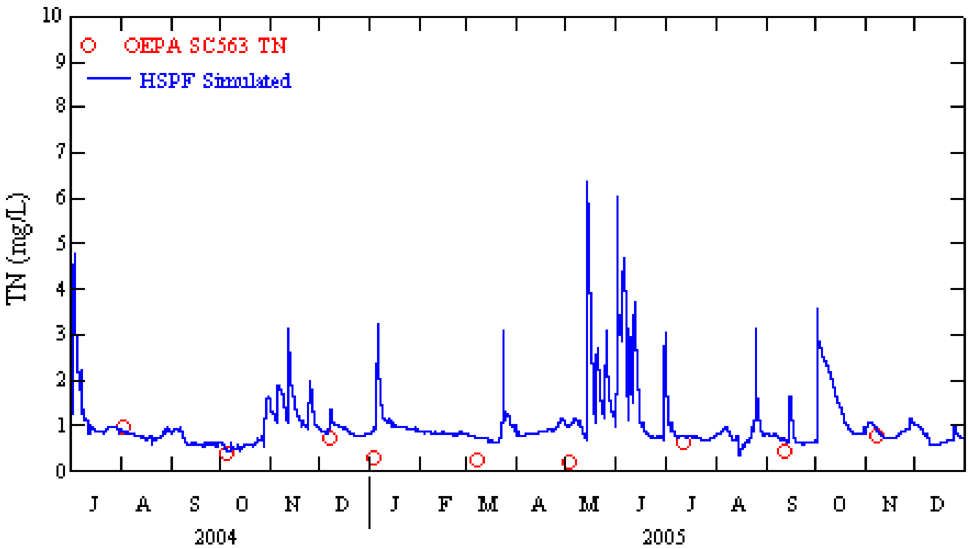

Figure 116 TN Calibration Plot at EPA SC563

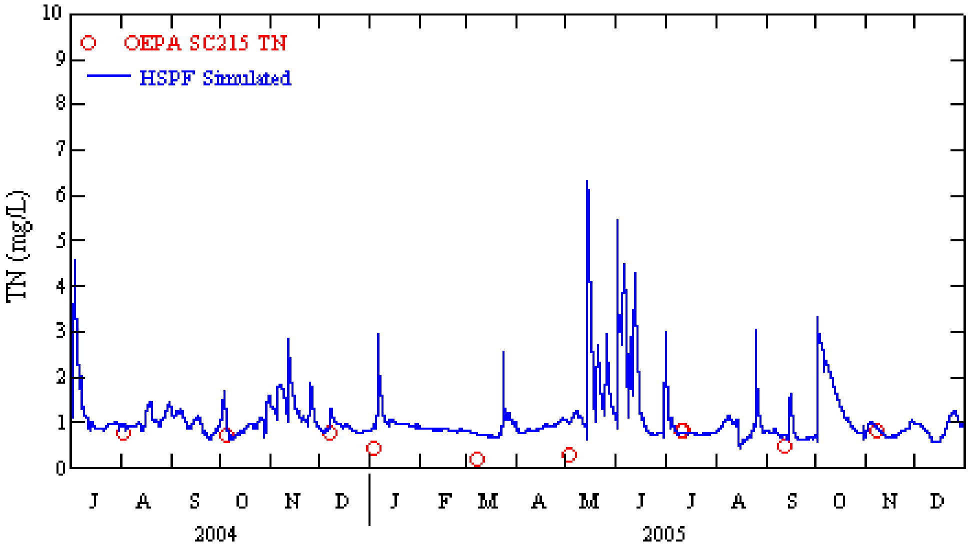

Figure 117 TN Calibration Plot at EPA SC215

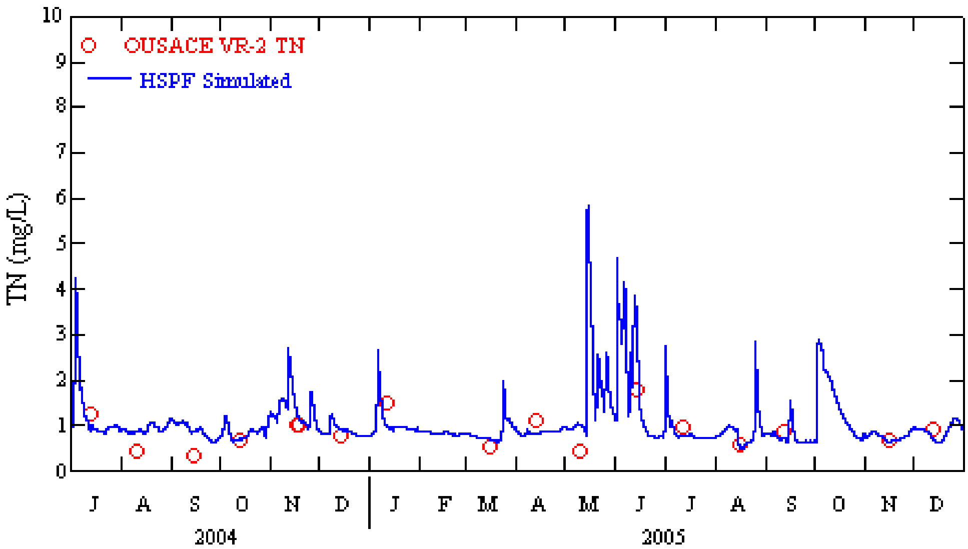

Figure 118 TN Calibration Plot at USACE VR-2

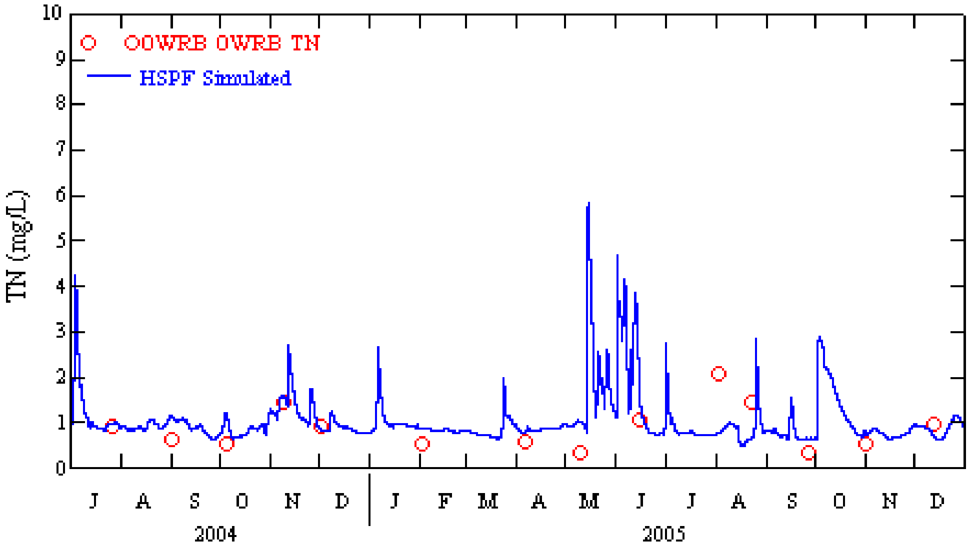

Figure 119 TN Calibration Plot at OWRB Station

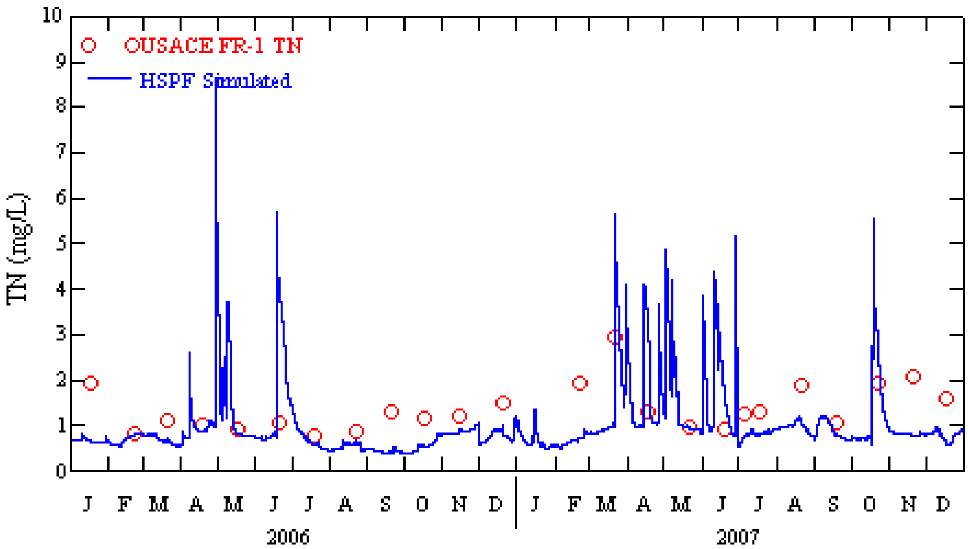

Figure 120 TN Validation Plot at USACE FR-1

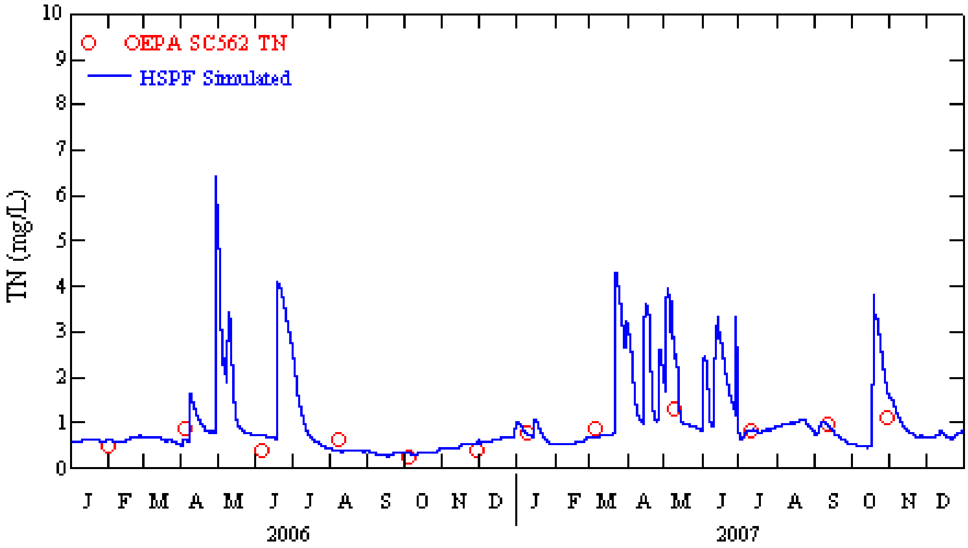

Figure 121 TN Validation Plot at EPA SC562

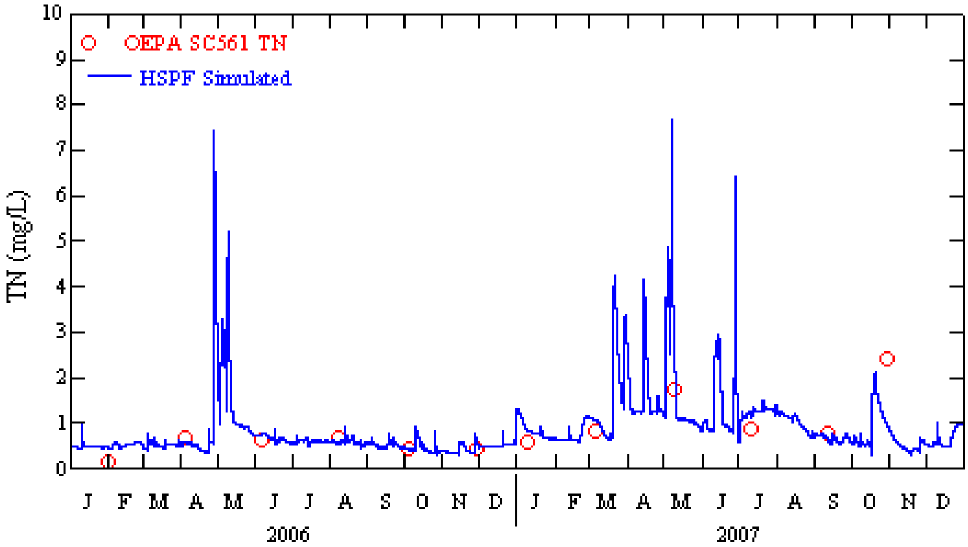

Figure 122 TN Validation Plot at EPA SC561

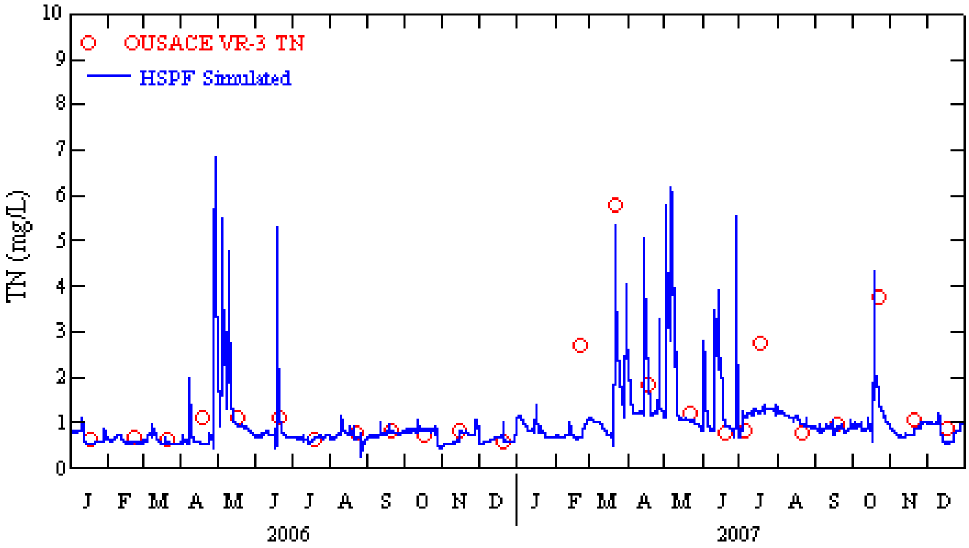

Figure 123 TN Validation Plot at USACE VR-3

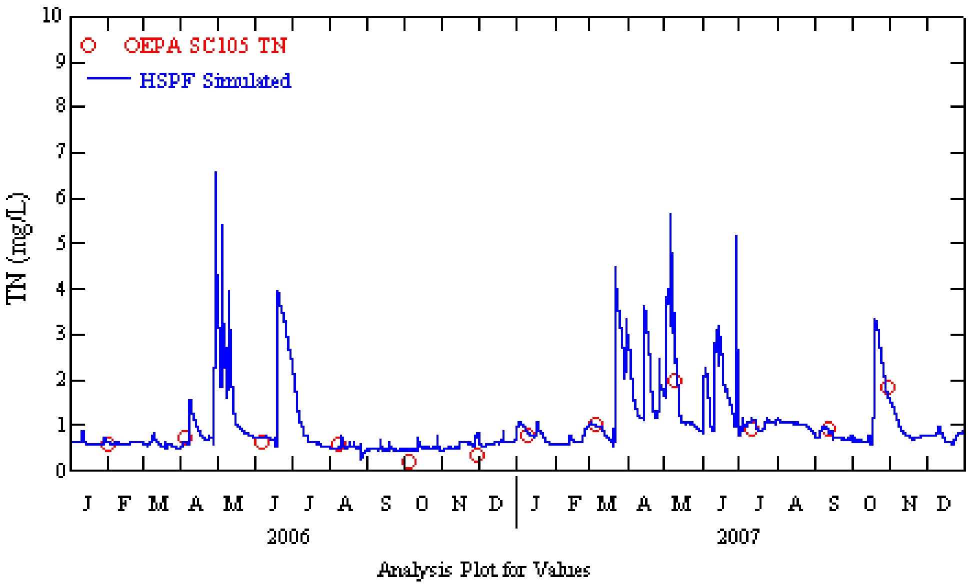

Figure 124 TN Validation Plot at EPA SC105

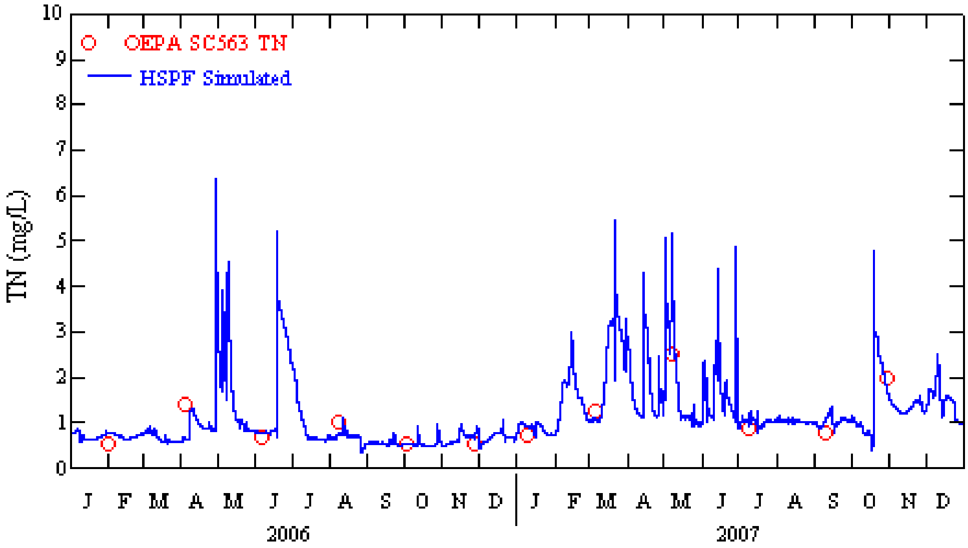

Figure 125 TN Validation Plot at EPA SC563

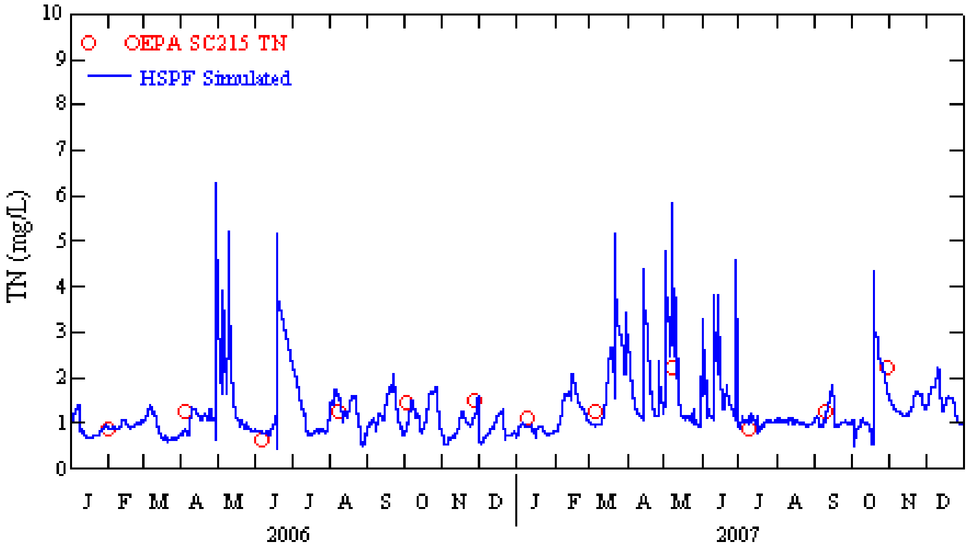

Figure 126 TN Validation Plot at EPA SC215

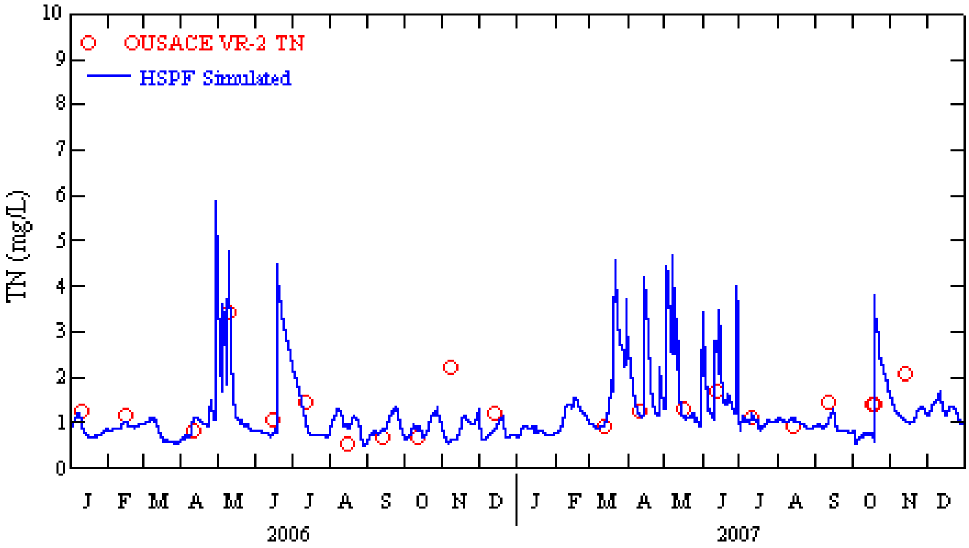

Figure 127 TN Validation Plot at USACE VR-2

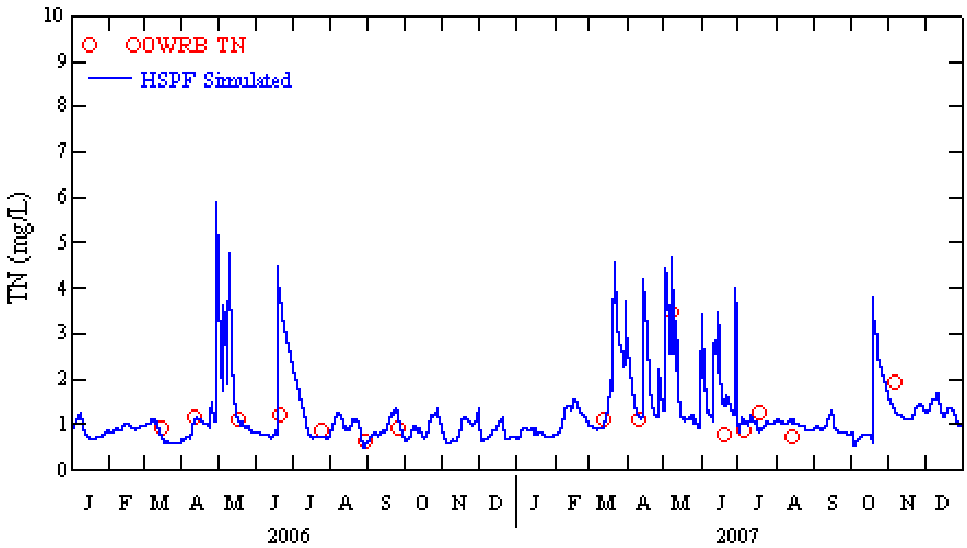

Figure 128 TN Validation Plot at OWRB Station

7.4 Phosphorus Calibration and Validation

The calibration and validation plots of phosphorus (TPO4 and TP) at these observation stations are given in Figures 129-154. The calculated statistics for model calibration and validation are shown in Tables 29-32.

The model performance of ortho-phosphate (TPO4) is fairly good with the calculated mean percent error (MPE) values either within the range of -50% to +50% or very close to +50% (Table 29 and 30).

The model performance of total phosphorus (TP) is fairly good with all the calculated mean percent error (MPE) values within the range of -50% to +50% except at EPA station SC561 in which, the calculated MPE value is -60.44% at calibration period (Table 29 and 30). The TP model performance is better at validation period than the calibration period. During validation period, the calculated mean percent error (MPE) values are all within the range of -25% to +25% except at EPA station SC562 (Figure 29 and 30).

Table 29 Calculated Statistics for TPO4 (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	16	0.050	0.026	48.73
USACE VR-3	16	0.030	0.022	25.52
USACE VR-2	15	0.030	0.029	2.23
OWRB	14	0.060	0.029	51.29

Table 30 Calculated Statistics for TPO4 (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	24	0.070	0.072	-2.44
USACE VR-3	22	0.050	0.047	6.55
USACE VR-2	19	0.040	0.060	-49.34
OWRB	18	0.100	0.070	29.78

Table 31 Calculated Statistics for TP (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	23	0.13	0.07	45.68
EPA SC562	8	0.06	0.07	-24.80
EPA SC561	7	0.05	0.08	-60.44
USACE VR-3	16	0.14	0.09	35.78
EPA SC105	8	0.08	0.08	0.32
EPA SC563	9	0.08	0.08	-4.37
EPA SC215	9	0.12	0.11	11.18
USACE VR-2	16	0.20	0.11	46.95
OWRB	14	0.13	0.10	22.00

Table 32 Calculated Statistics for TP (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	24	0.18	0.19	-7.14
EPA SC562	12	0.08	0.11	-33.49
EPA SC561	12	0.11	0.09	22.33
USACE VR-3	24	0.16	0.13	19.93
EPA SC105	12	0.12	0.11	6.91
EPA SC563	12	0.14	0.14	-3.09
EPA SC215	12	0.20	0.15	24.46
USACE VR-2	21	0.17	0.16	4.05
OWRB	20	0.16	0.16	-1.44

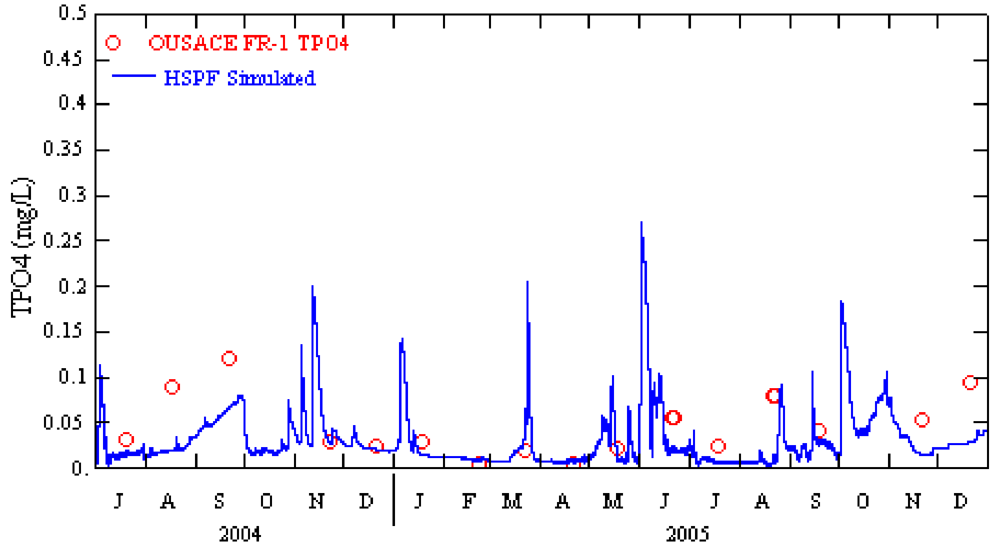

Figure 129 TPO4 Calibration Plot at USACE FR-1

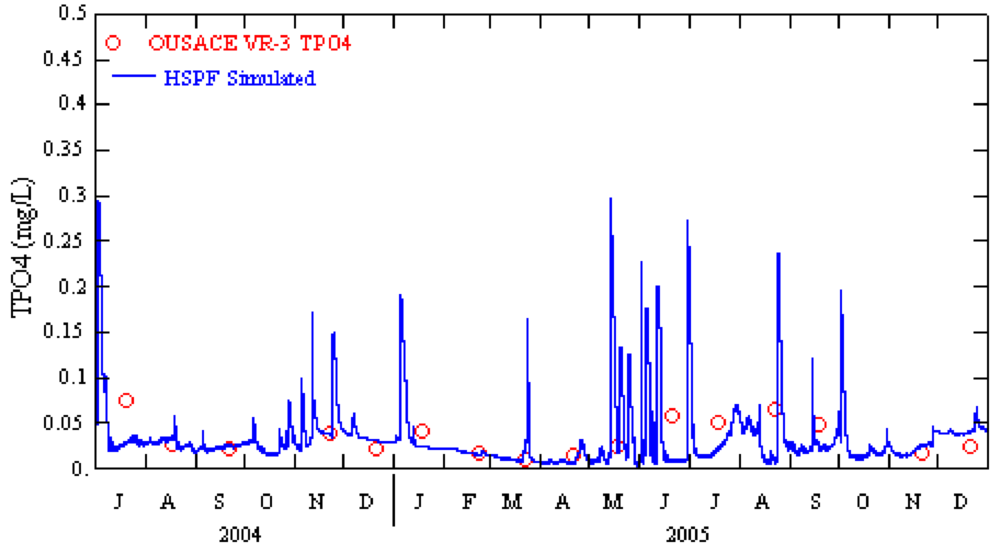

Figure 130 TPO4 Calibration Plot at USACE VR-3

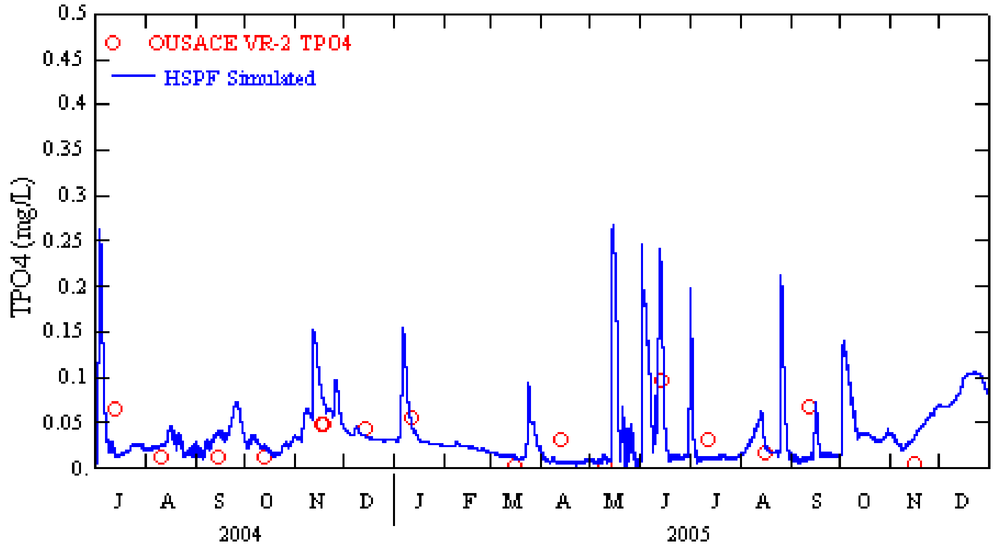

Figure 131 TPO4 Calibration Plot at USACE VR-2

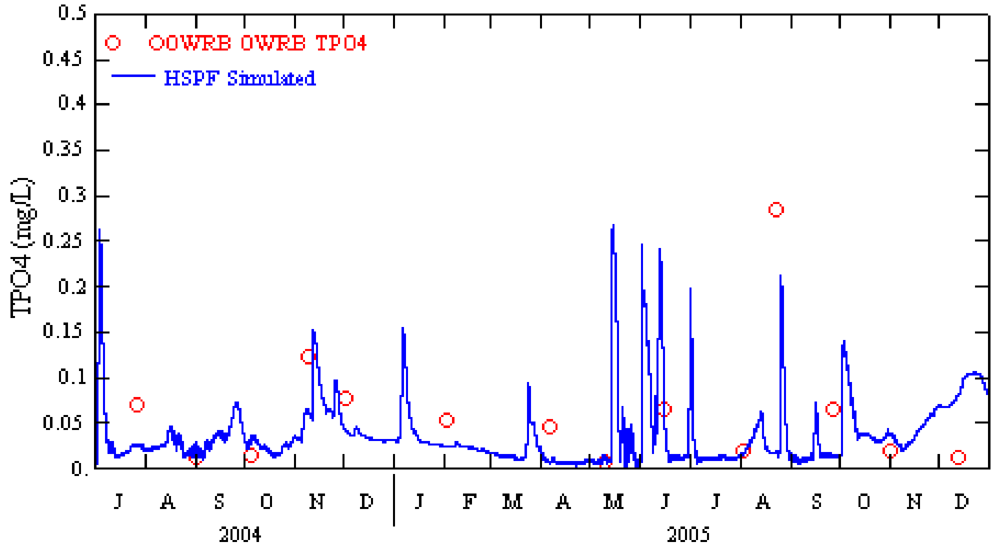

Figure 132 TPO4 Calibration Plot at OWRB Station

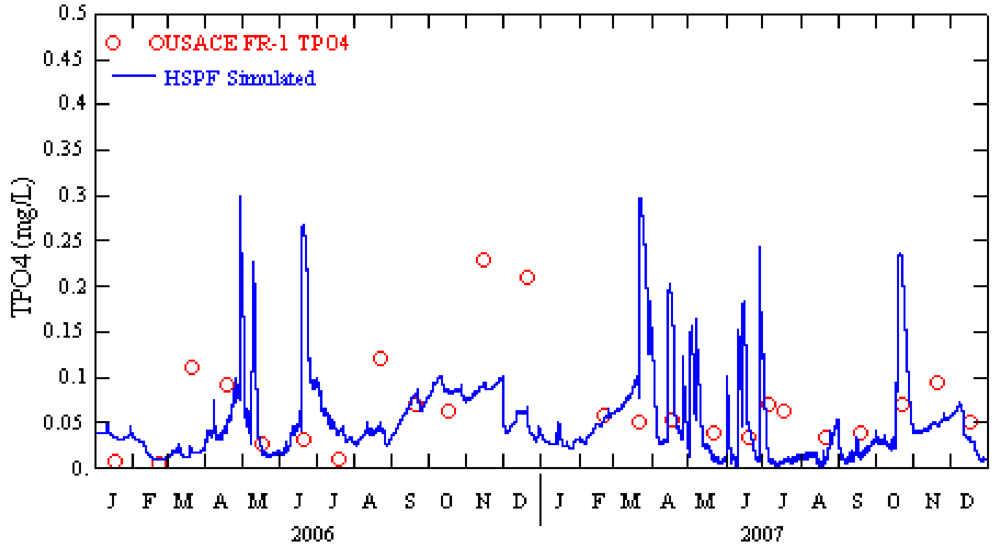

Figure 133 TPO4 Validation Plot at USACE FR-1

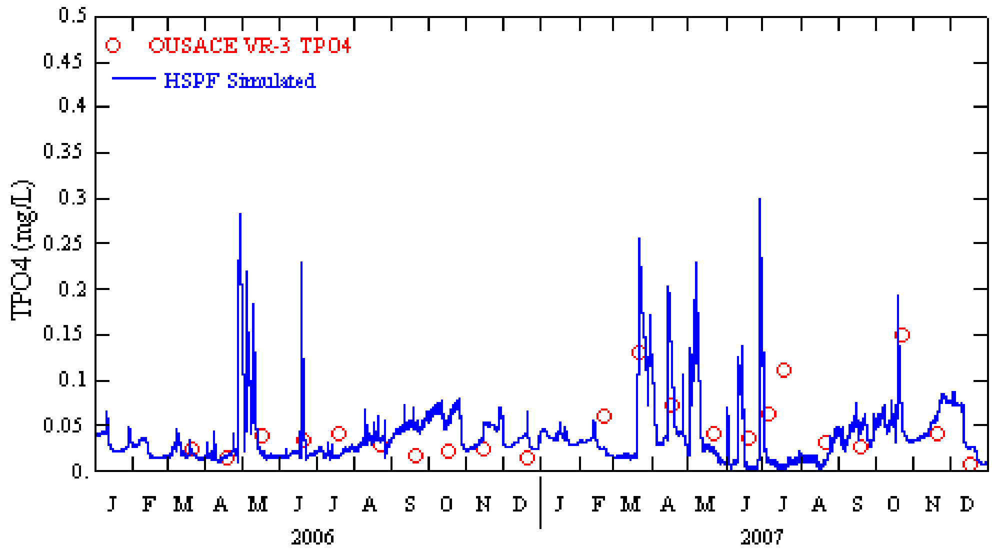

Figure 134 TPO4 Validation Plot at USACE VR-3

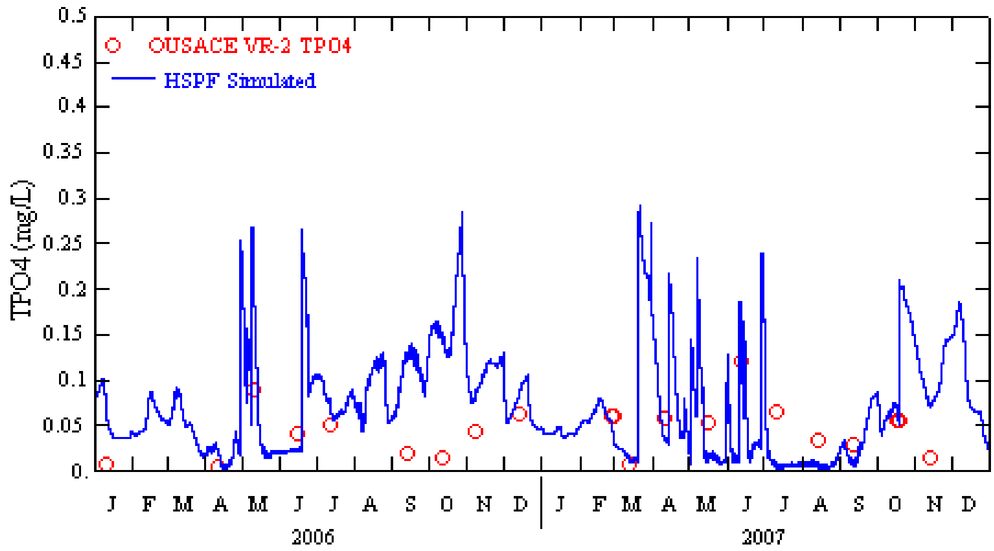

Figure 135 TPO4 Validation Plot at USACE VR-2

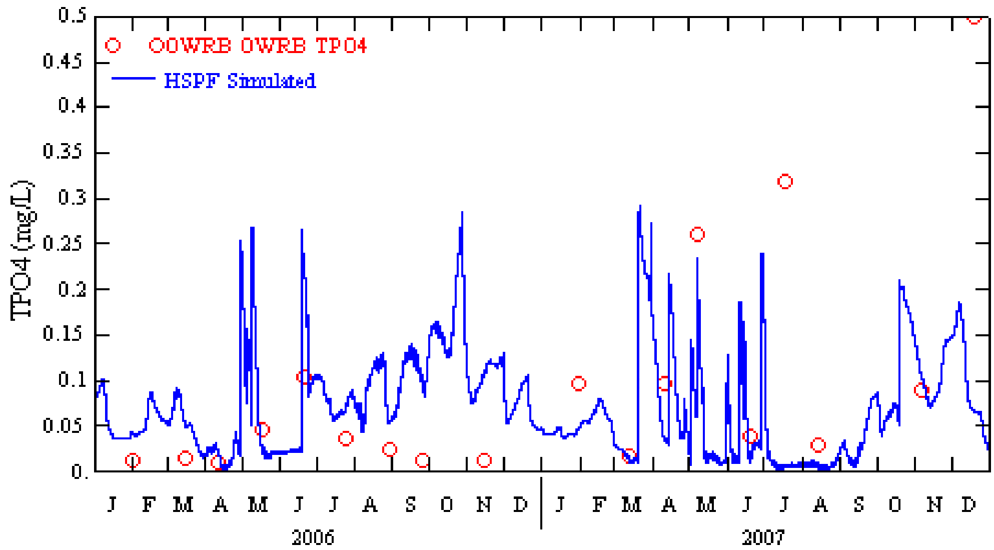

Figure 136 TPO4 Validation Plot at OWRB Station

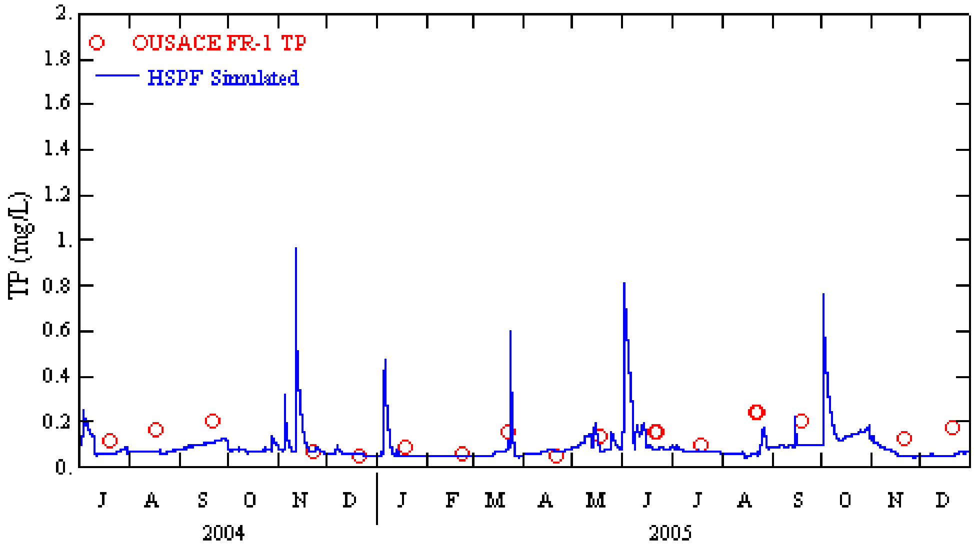

Figure 137 TP Calibration Plot at USACE FR-1

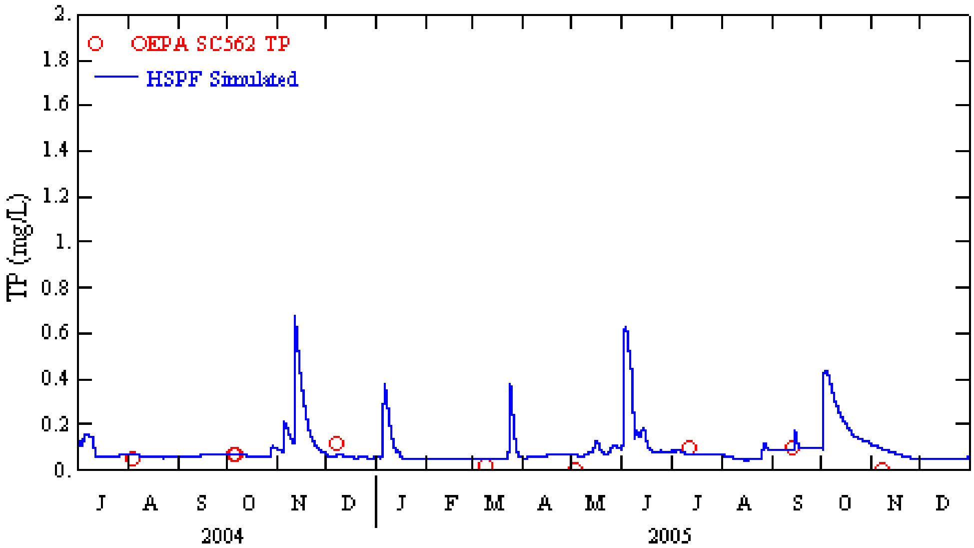

Figure 138 TP Calibration Plot at EPA SC562

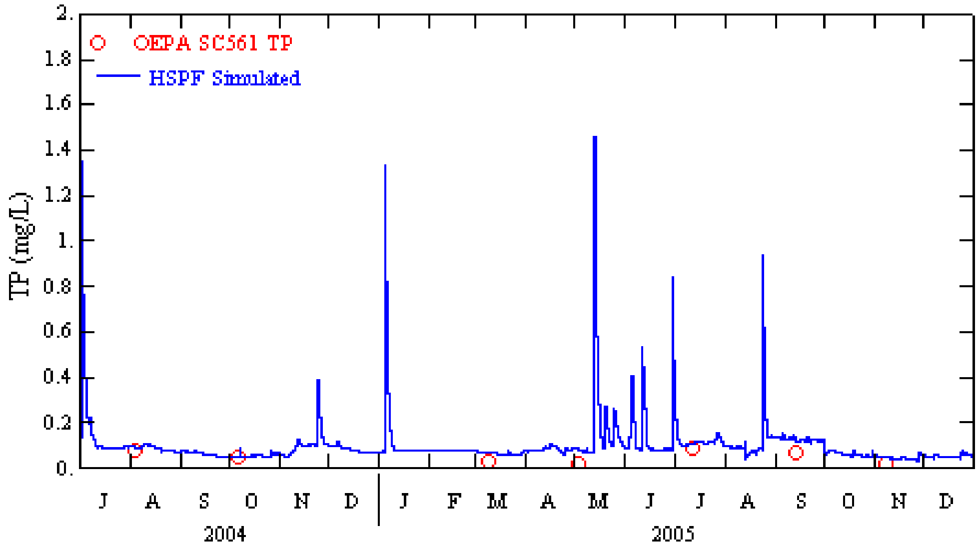

Figure 139 TP Calibration Plot at EPA SC561

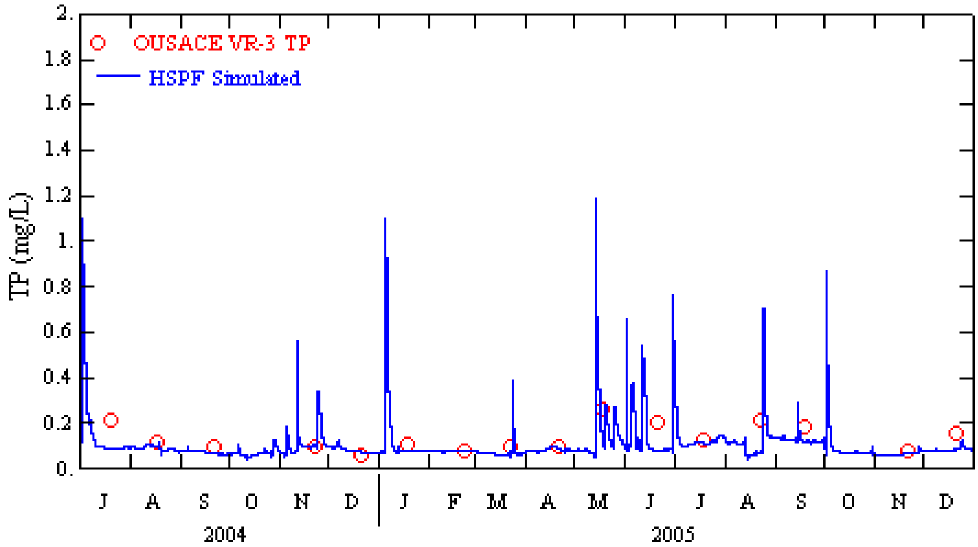

Figure 140 TP Calibration Plot at USACE VR-3

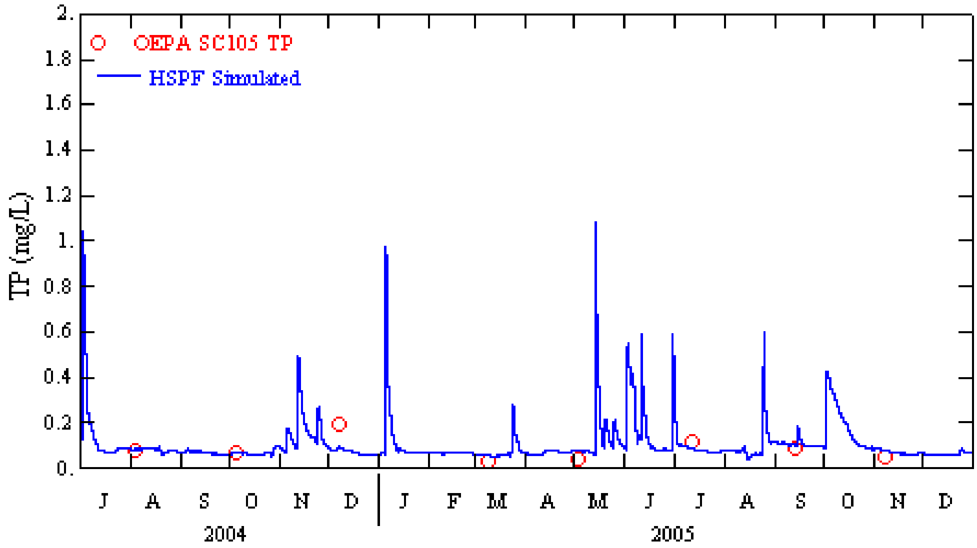

Figure 141 TP Calibration Plot at EPA SC105

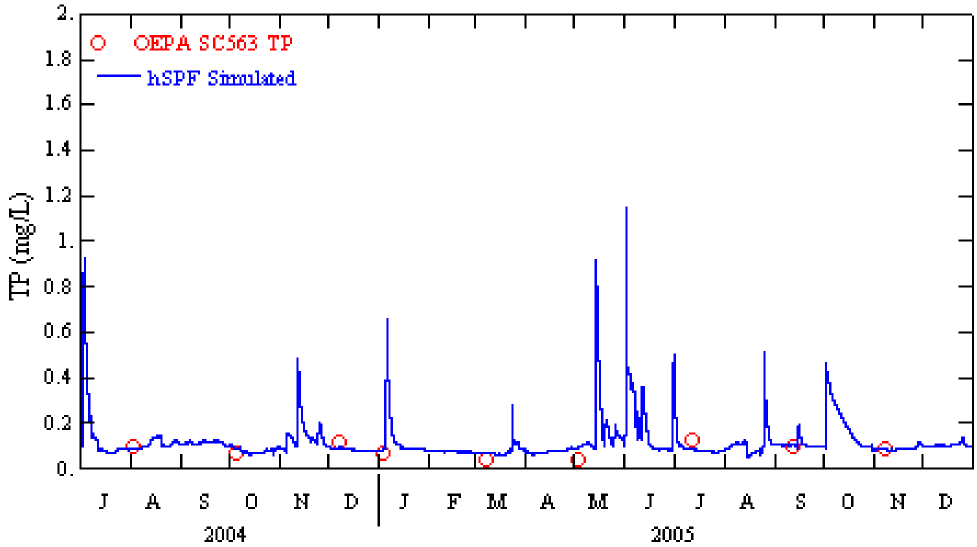

Figure 142 TP Calibration Plot at EPA SC563

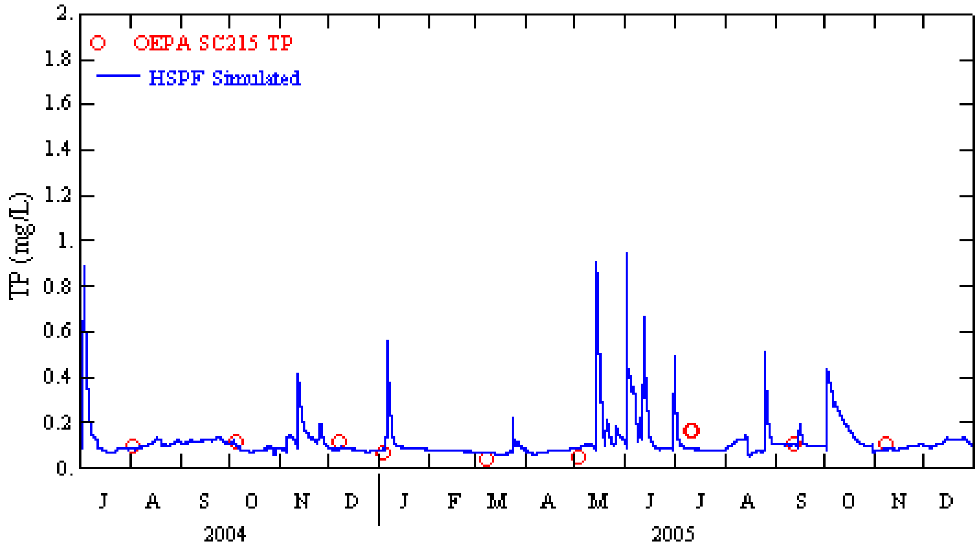

Figure 143 TP Calibration Plot at EPA SC215

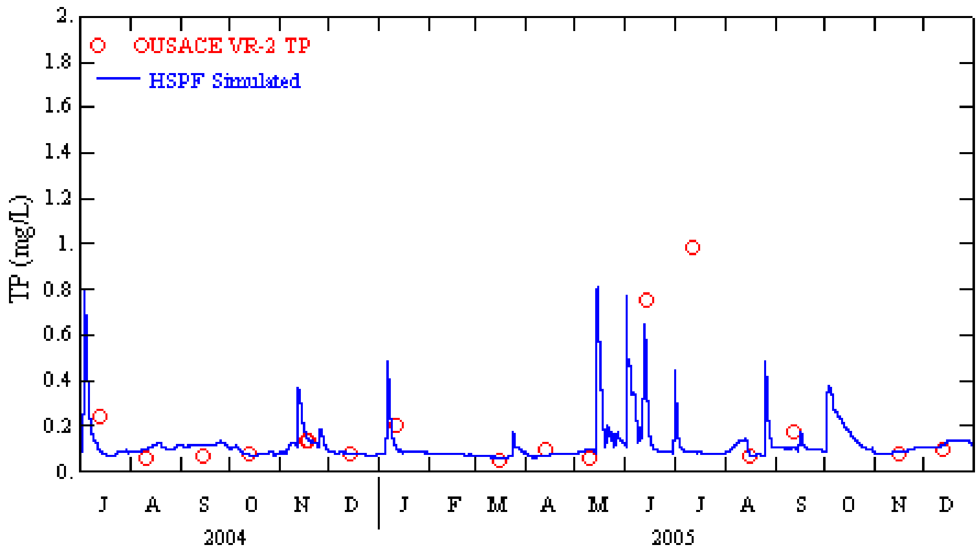

Figure 144 TP Calibration Plot at USACE VR-2

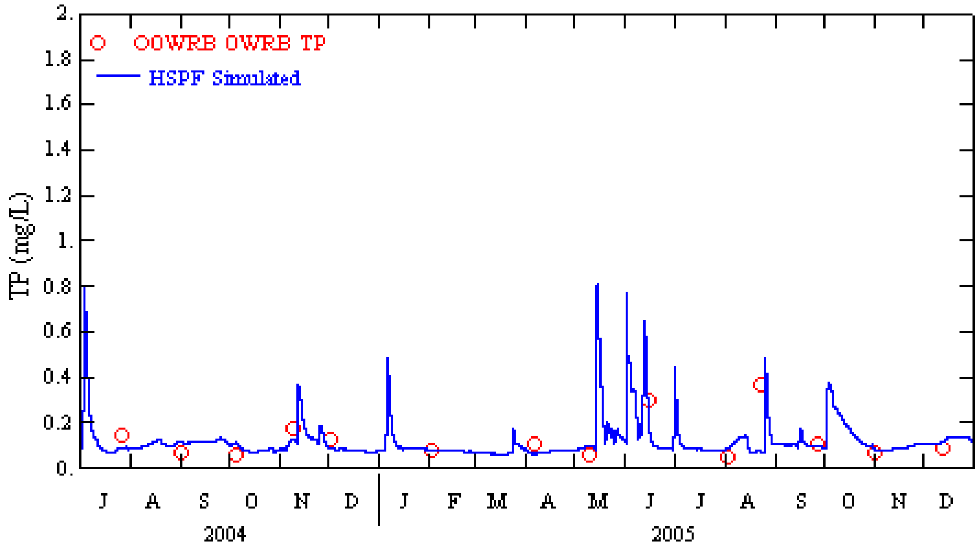

Figure 145 TP Calibration Plot at OWRB Station

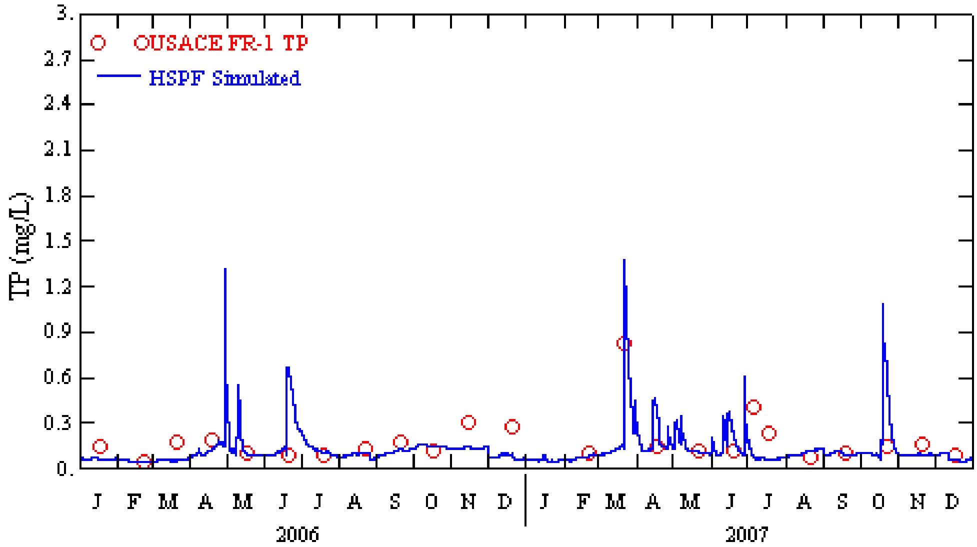

Figure 146 TP Validation Plot at USACE FR-1

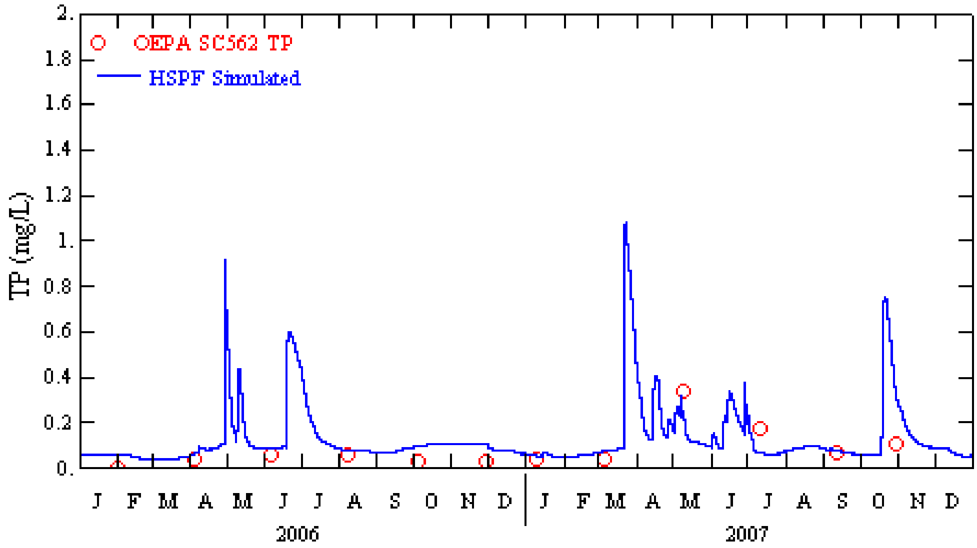

Figure 147 TP Validation Plot at EPA SC562

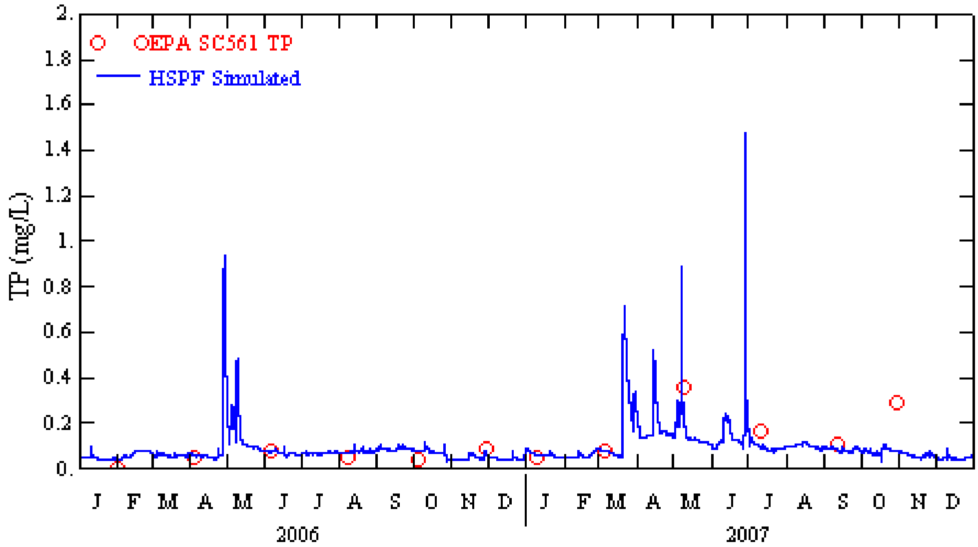

Figure 148 TP Validation Plot at EPA SC561

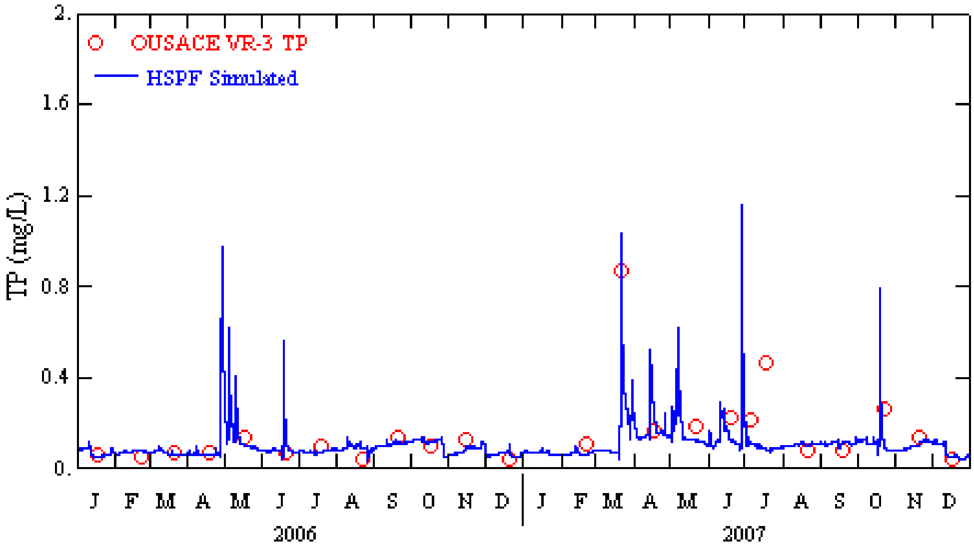

Figure 149 TP Validation Plot at USACE VR-3

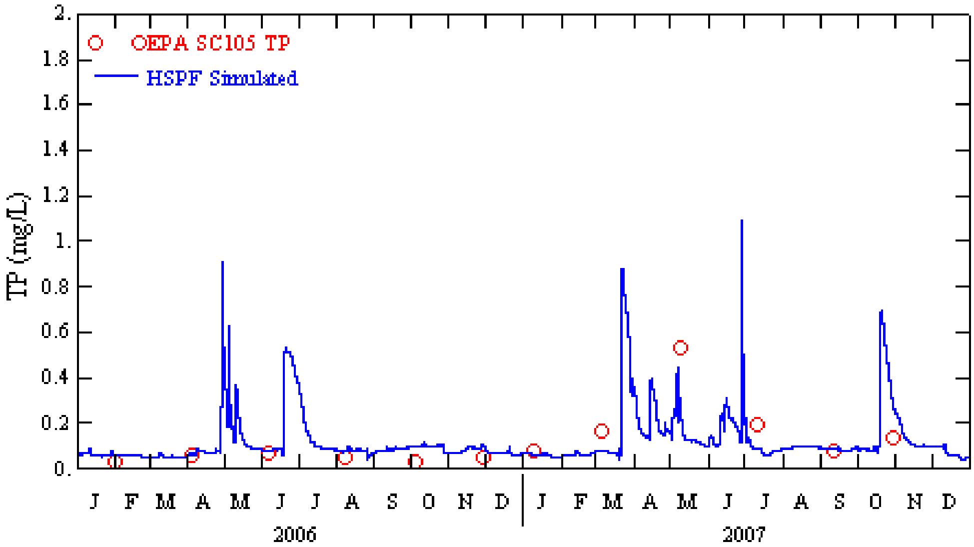

Figure 150 TP Validation Plot at EPA SC105

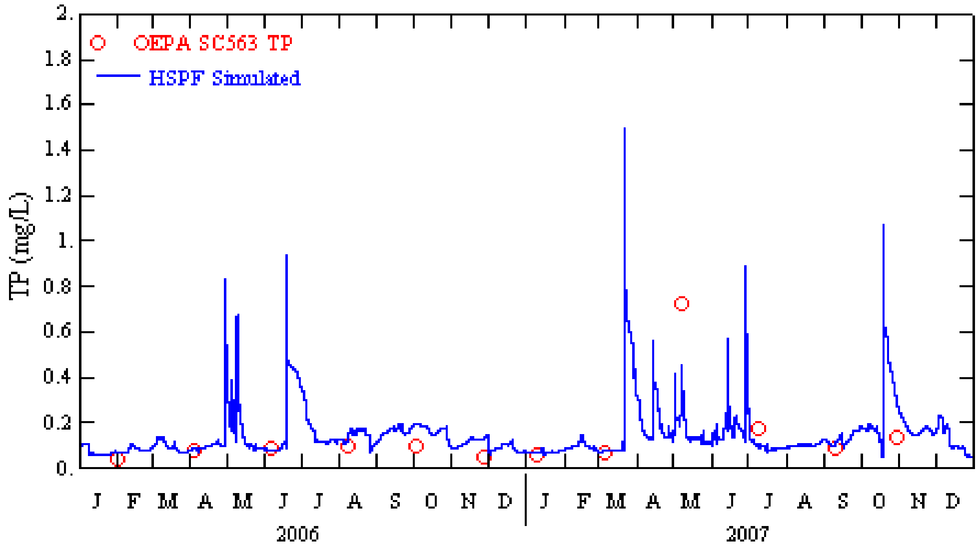

Figure 151 TP Validation Plot at EPA SC563

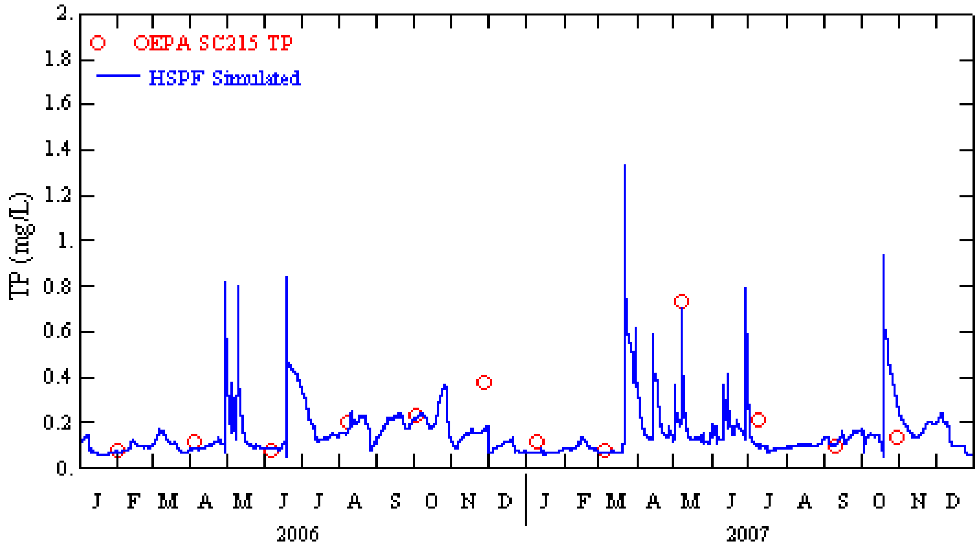

Figure 152 TP Validation Plot at EPA SC215

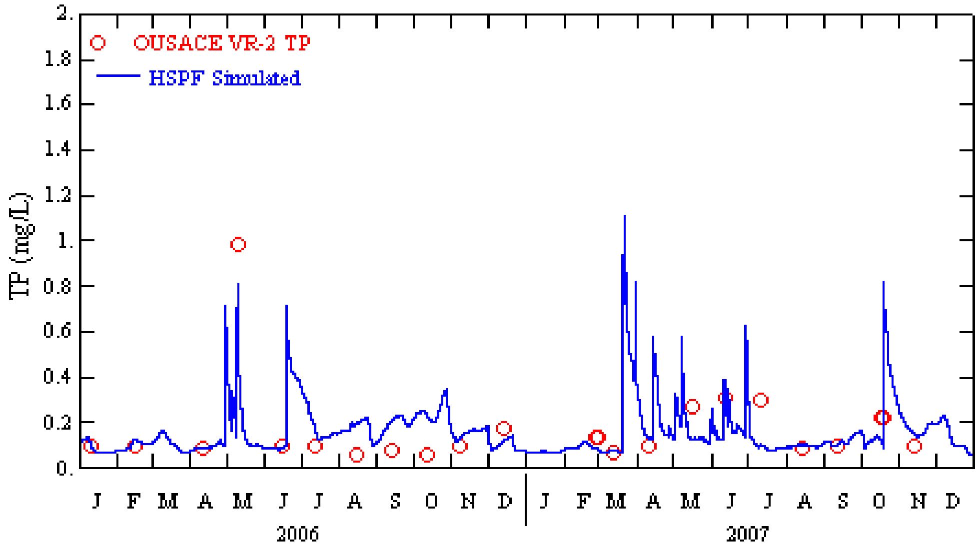

Figure 153 TP Validation Plot at USACE VR-2

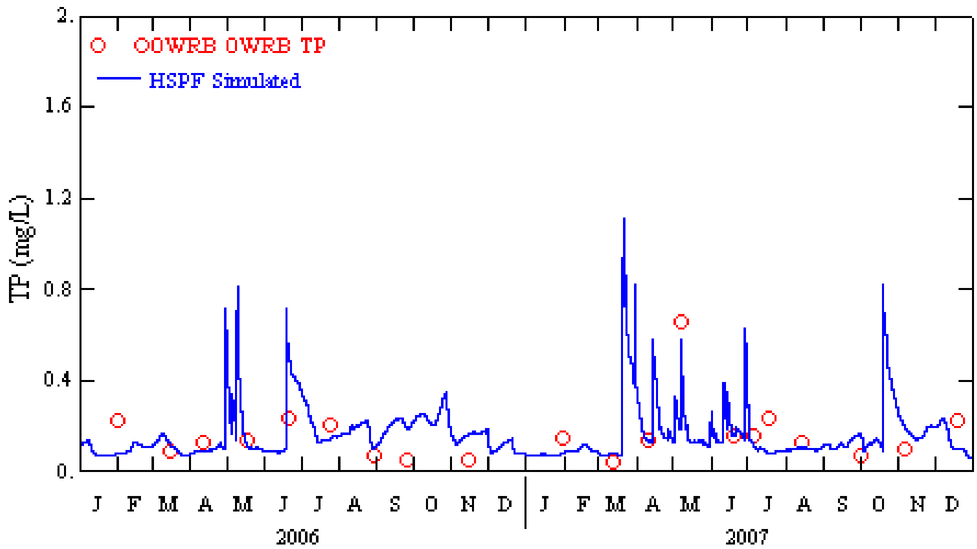

Figure 154 TP Validation Plot at OWRB Station

7.5 TOC Calibration and Validation

The calibration and validation plots of TOC at these observation stations are given in Figures 155-170. The calculated statistics for model calibration and validation are shown in Tables 33-34.

The TOC model performance for both calibraton and validaiton period is fairly good with the calculated men percent error (MPE) values all within the range of -50% to +50% (Table 33 and 34). The model performance is better at calibration period with all the calculated MPE values within the range of -25% to +25%.

Table 33 Calculated Statistics for TOC (mg/l) during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	14	3.80	3.97	-4.50
EPA SC562	8	5.24	4.20	19.77
EPA SC561	8	6.03	4.56	24.39
USACE VR-3	14	4.33	4.94	-14.01
EPA SC105	8	5.38	4.53	15.75
EPA SC563	9	6.23	4.77	23.40
EPA SC215	9	6.60	5.00	24.18
USACE VR-2	16	4.58	5.04	-10.07

Table 34 Calculated Statistics for TOC (mg/l) during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	24	4.40	4.98	-13.09
EPA SC562	12	5.10	3.46	32.08
EPA SC561	12	6.26	3.65	41.75
USACE VR-3	24	5.53	4.74	14.32
EPA SC105	12	5.53	4.01	27.43
EPA SC563	12	5.47	4.99	8.84
EPA SC215	12	6.36	5.45	14.25
USACE VR-2	21	5.43	5.71	-5.16

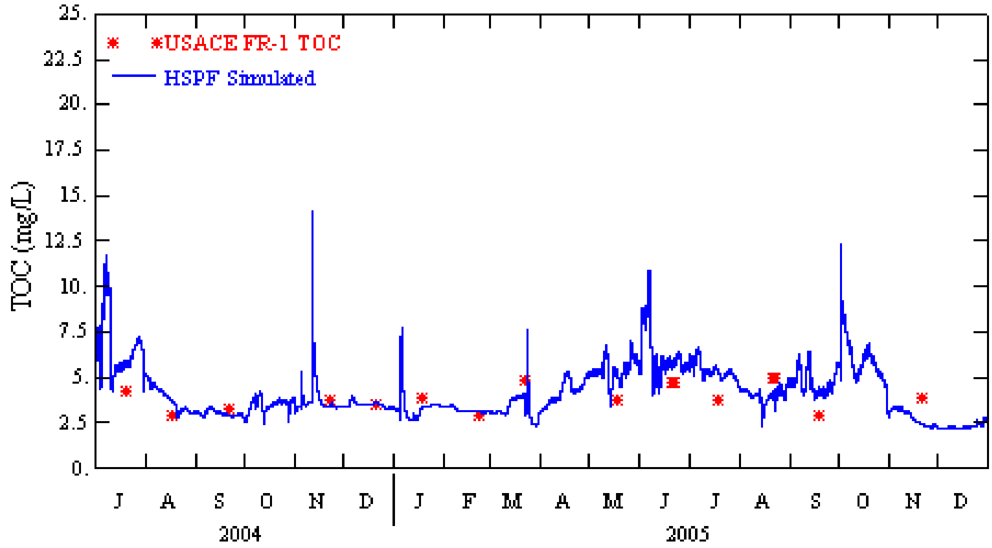

Figure 155 TOC Calibration Plot at USACE FR-1

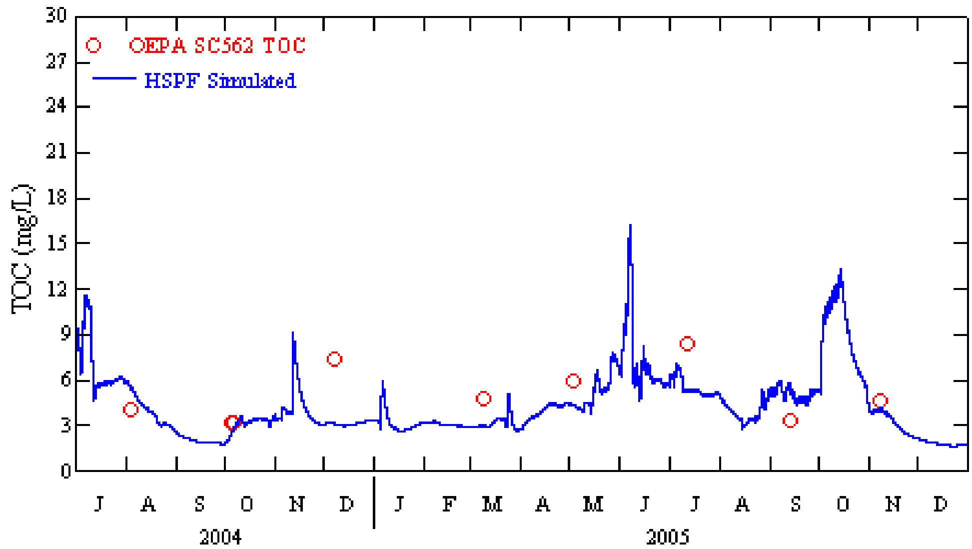

Figure 156 TOC Calibration Plot at EPA SC562

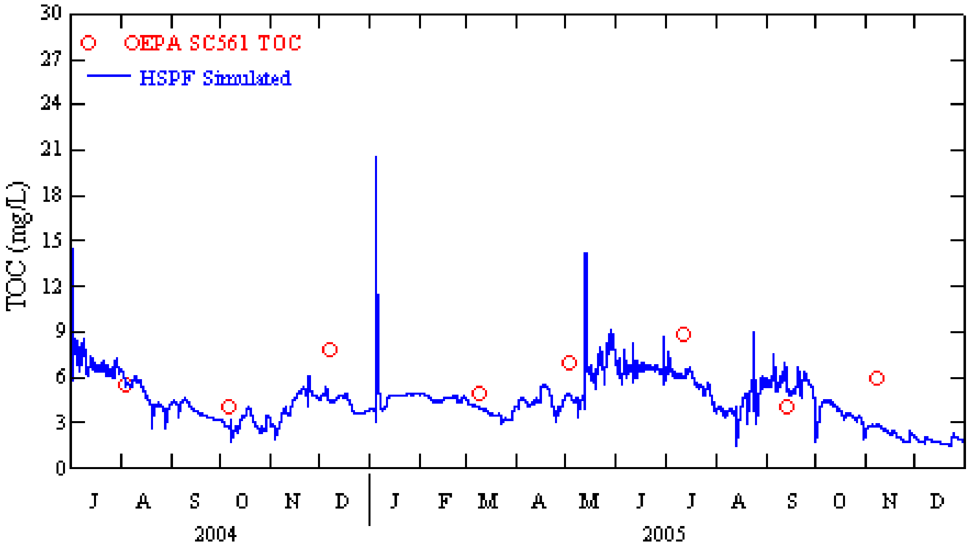

Figure 157 TOC Calibration Plot at EPA SC561

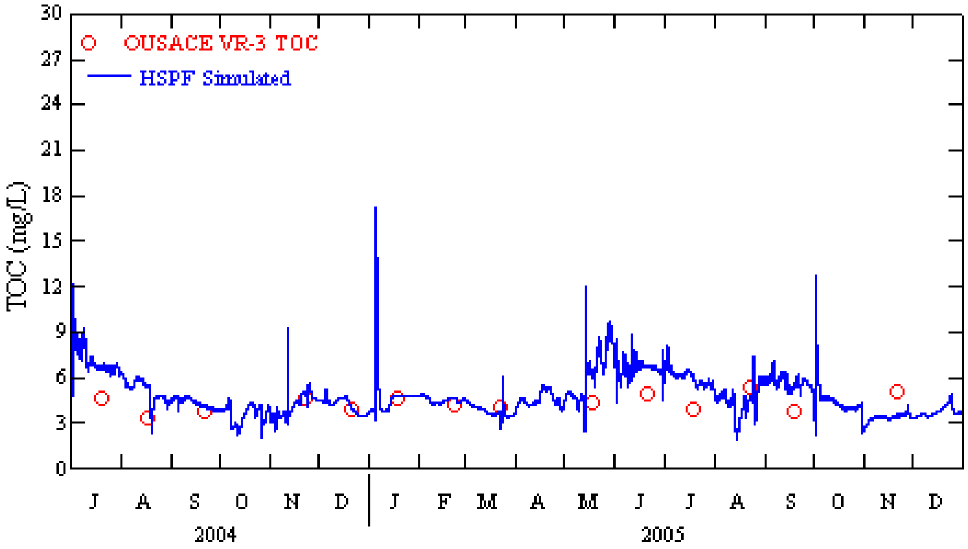

Figure 158 TOC Calibration Plot at USACE VR-3

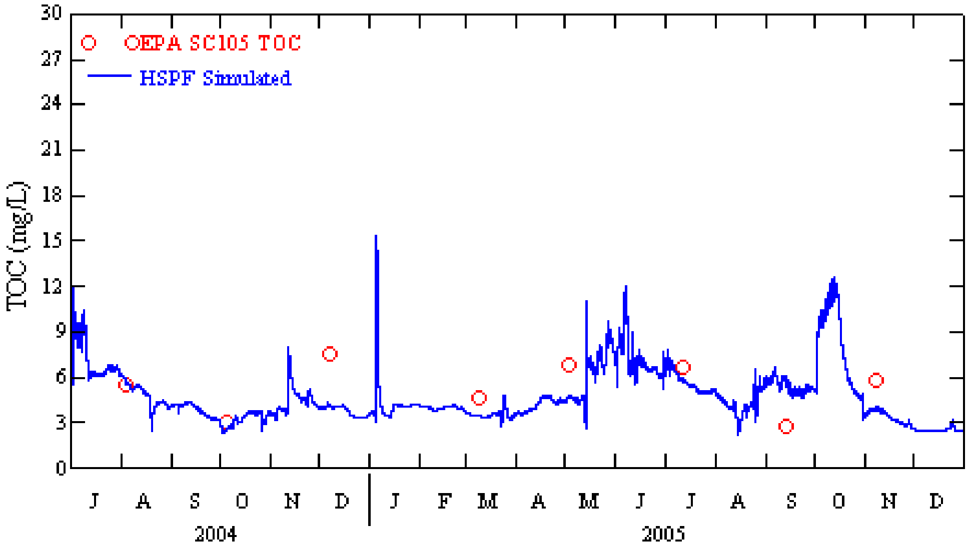

Figure 159 TOC Calibration Plot at EPA SC105

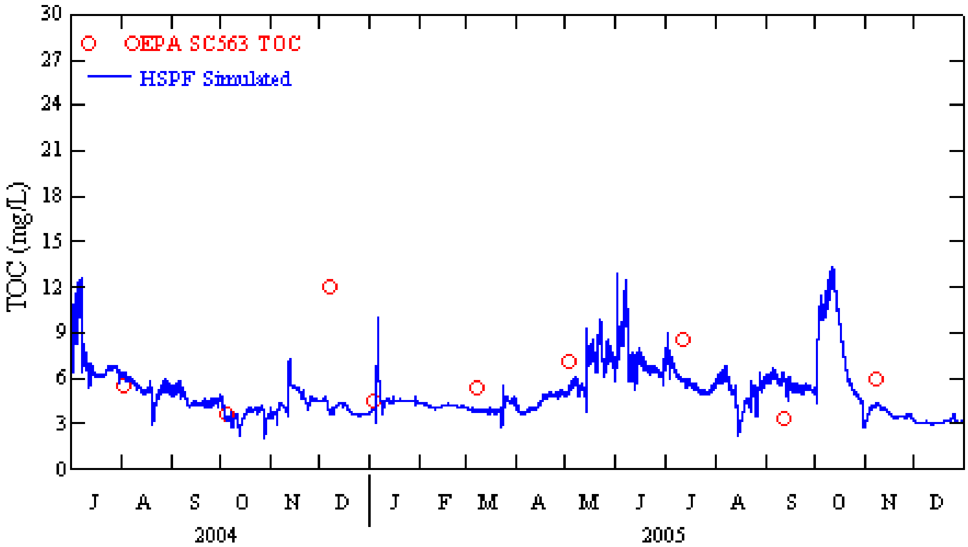

Figure 160 TOC Calibration Plot at EPA SC563

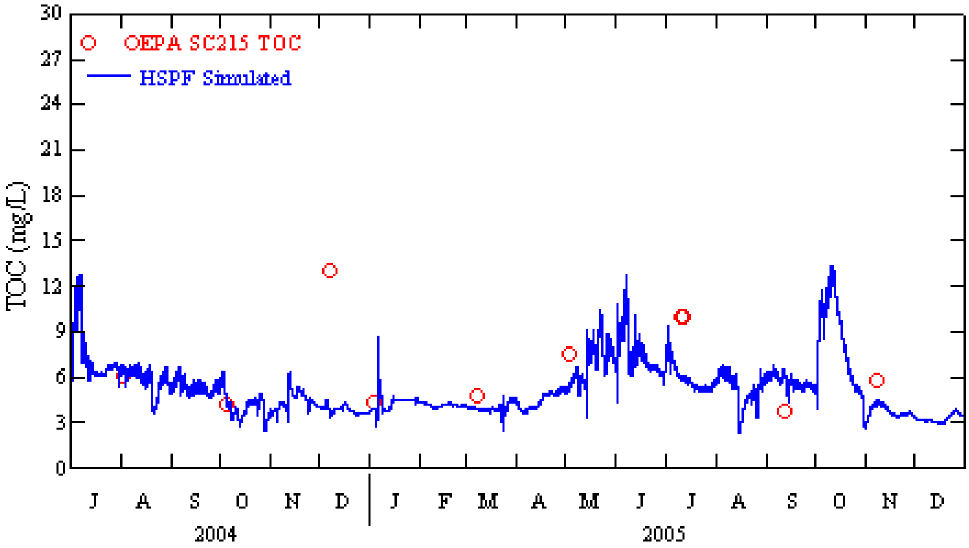

Figure 161 TOC Calibration Plot at EPA SC215

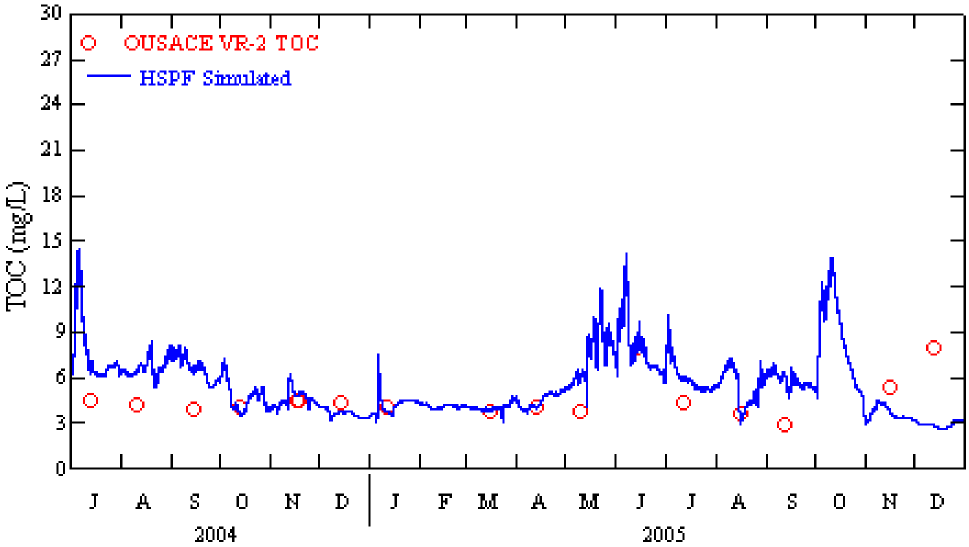

Figure 162 TOC Calibration Plot at USACE VR-2

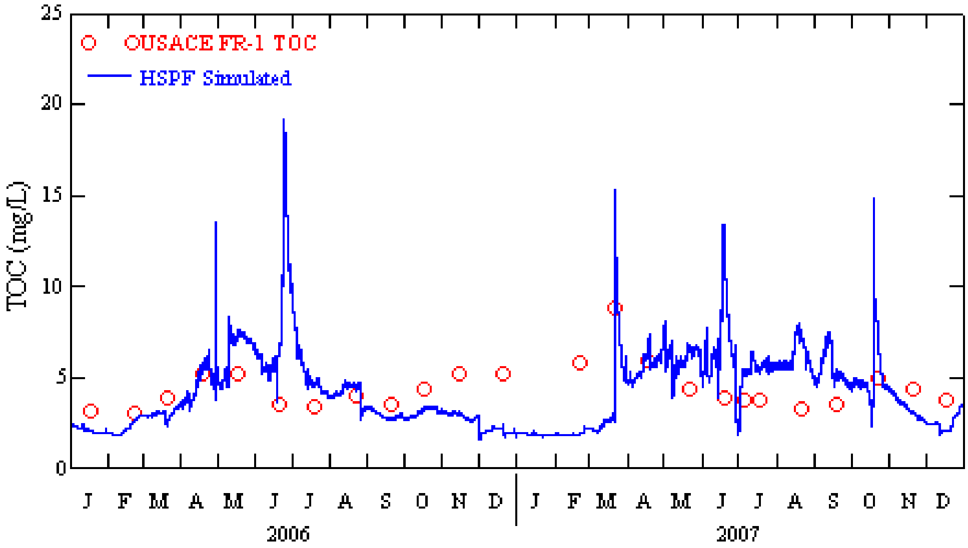

Figure 163 TOC Validation Plot at USACE FR-1

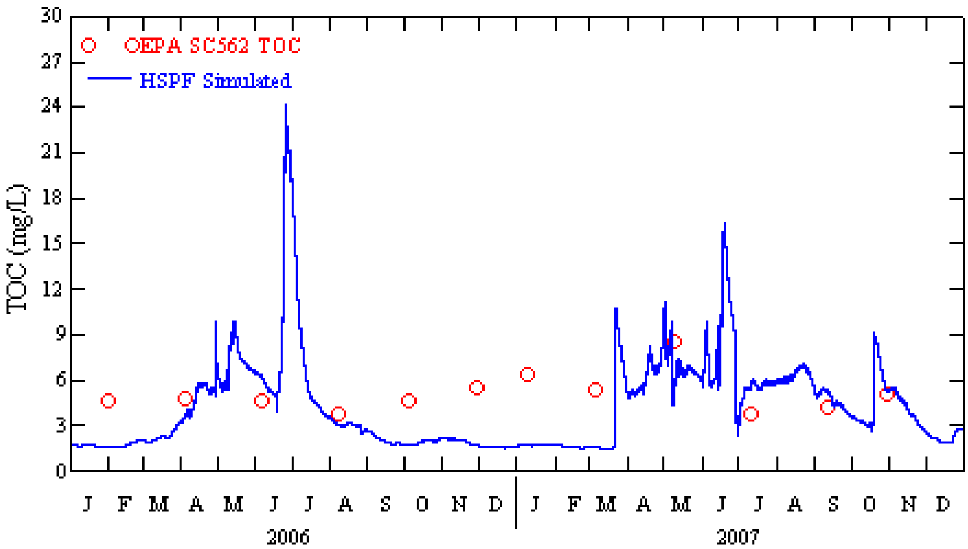

Figure 164 TOC Validation Plot at EPA SC562

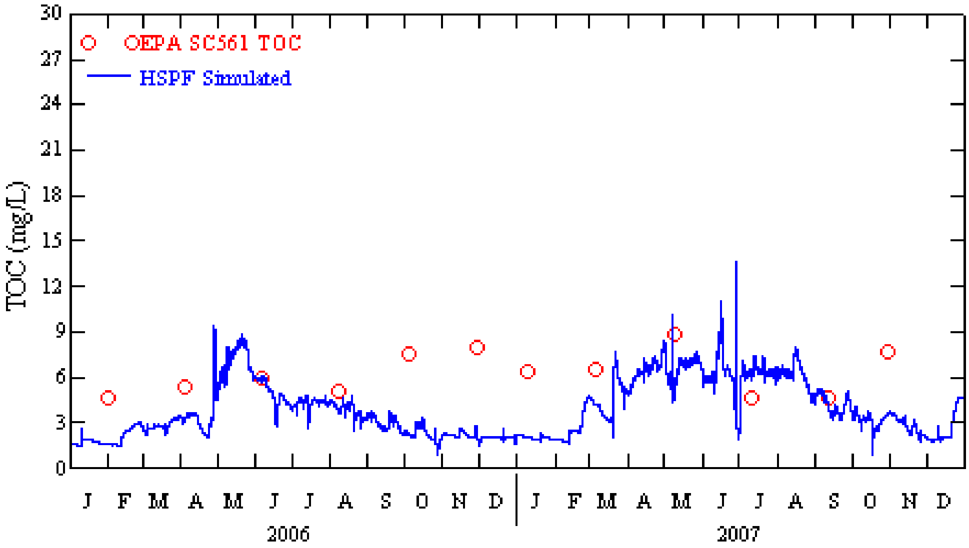

Figure 165 TOC Validation Plot at EPA SC561

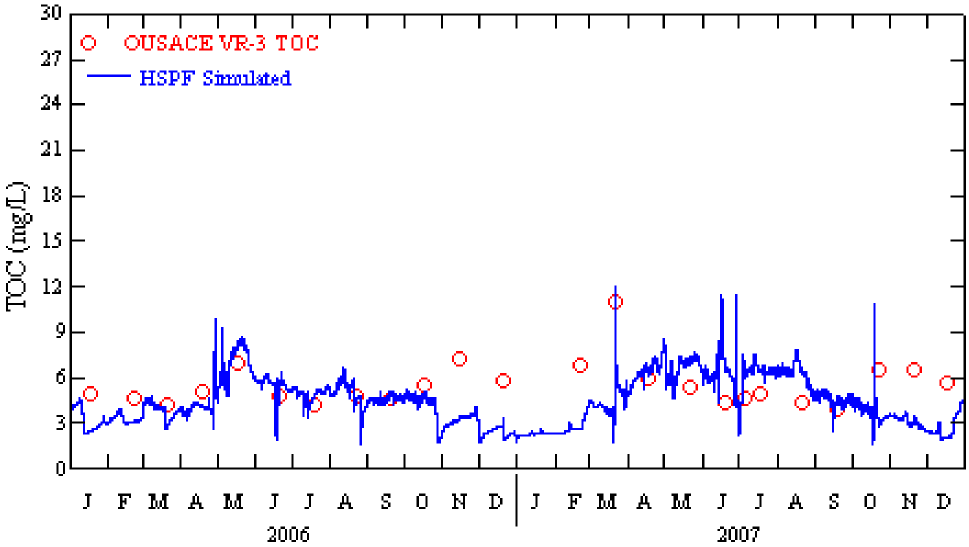

Figure 166 TOC Validation Plot at USACE VR-3

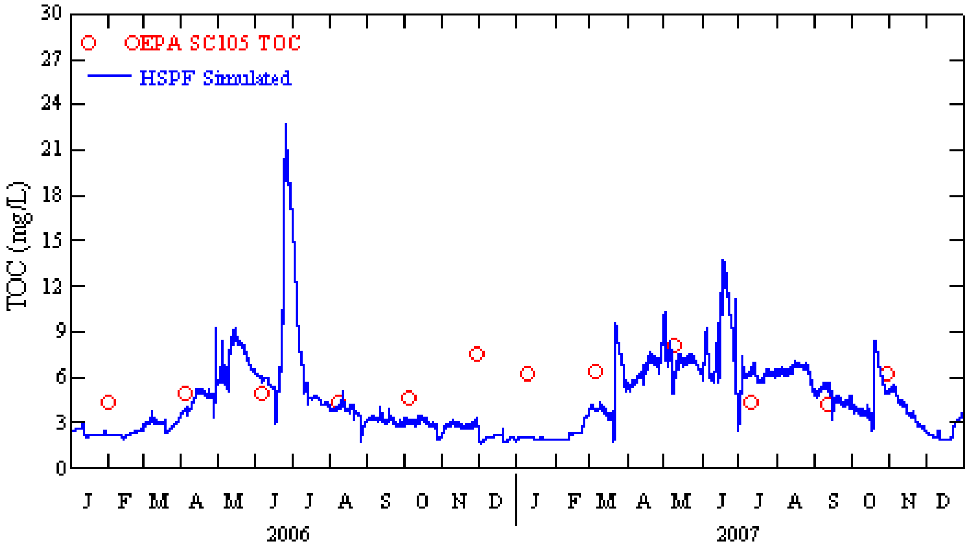

Figure 167 TOC Validation Plot at EPA SC105

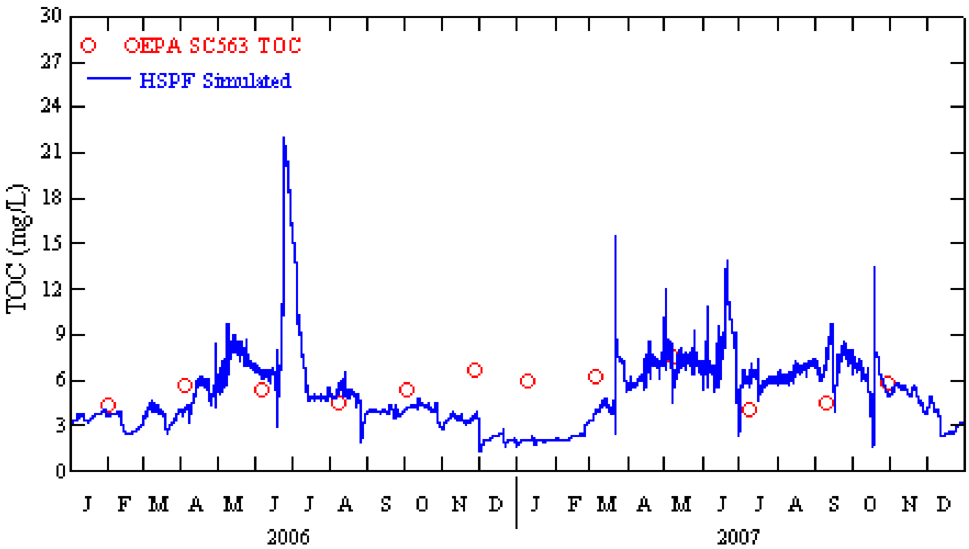

Figure 168 TOC Validation Plot at EPA SC563

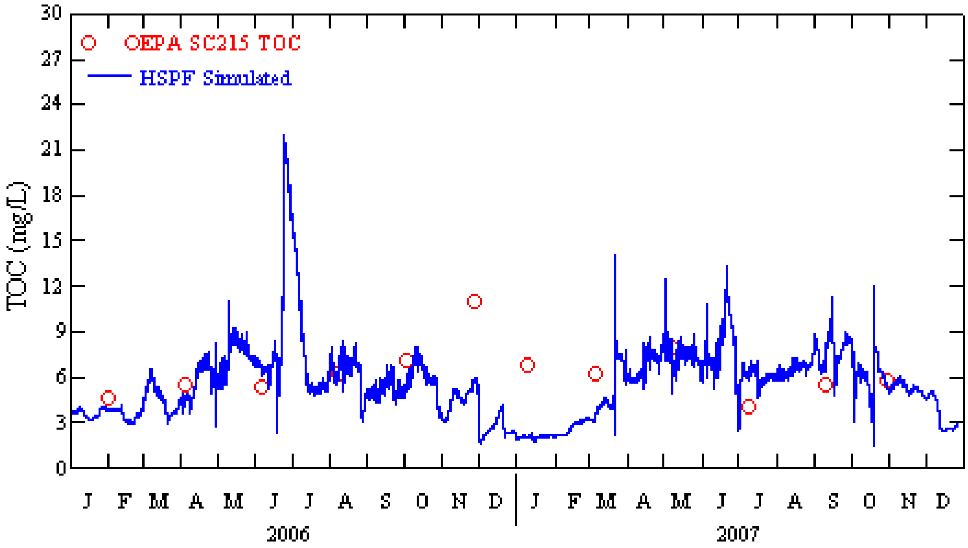

Figure 169 TOC Validation Plot at EPA SC215

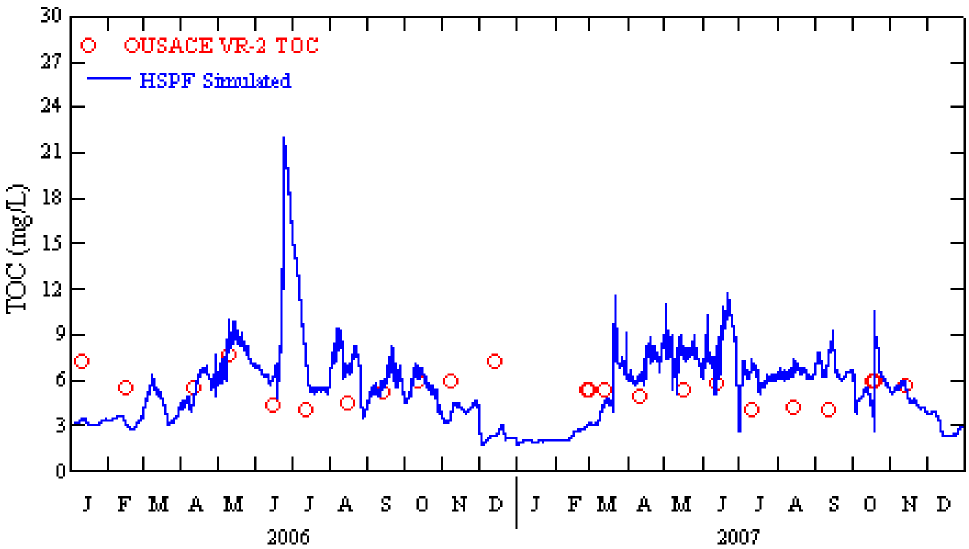

Figure 170 TOC Validation Plot at USACE VR-2

7.6 Chlorophyll a Calibration and Validation

The calibration and validation plots of chlorophyll a at these observation stations are given in Figures 171-178. The calculated statistics for model calibration and validation are shown in Tables 35-36.

The chlorophyll a observation data are not available for all the EPA STORET stations. The chlorophyll a model performance is fairly good for both calibration and validation periods with all the calculated mean percent error (MPE) values within the range of -100% to +100%.

Table 35 Calculated Statistics for Chlorophyll (ug/l) a during Calibration Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	15	9.52	5.25	44.83
USACE VR-3	15	6.74	6.42	4.72
USACE VR-2	15	15.00	9.12	39.18
OWRB	11	5.61	9.67	-72.33

Table 36 Calculated Statistics for Chlorophyll (ug/l) a during Validation Period

Station	Sample Size	Observed Average	Simulated Average	MPE
USACE FR-1	23	9.71	5.56	42.74
USACE VR-3	23	6.13	3.51	42.66
USACE VR-2	21	12.52	8.69	30.61
OWRB	15	26.13	9.24	64.64

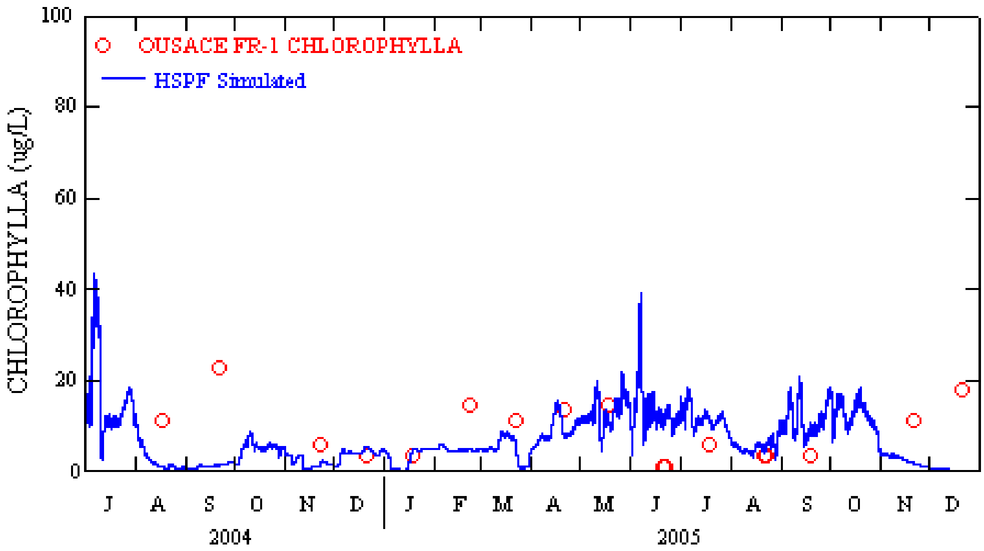

Figure 171 CHLOROPHYLL A Calibration Plot at USACE FR-1

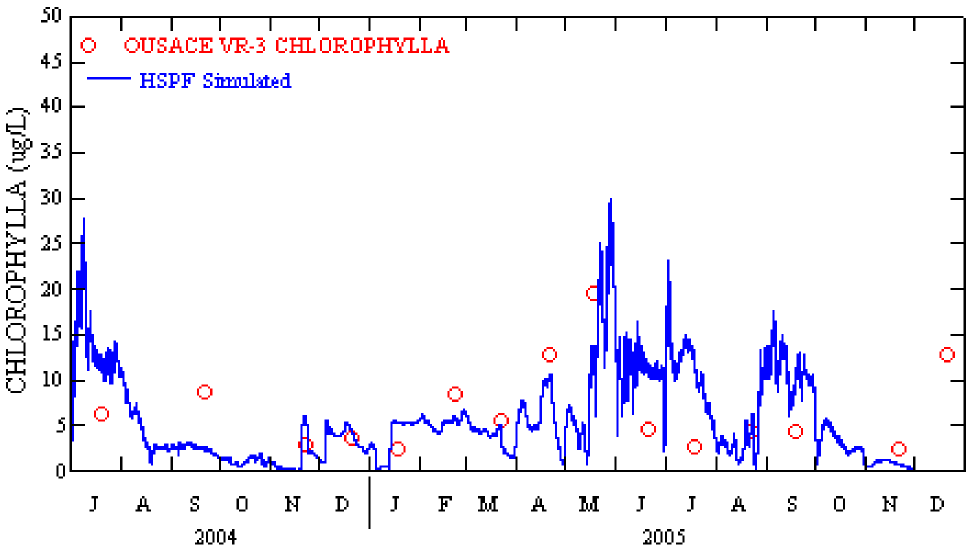

Figure 172 CHLOROPHYLL A Calibration Plot at USACE VR-3

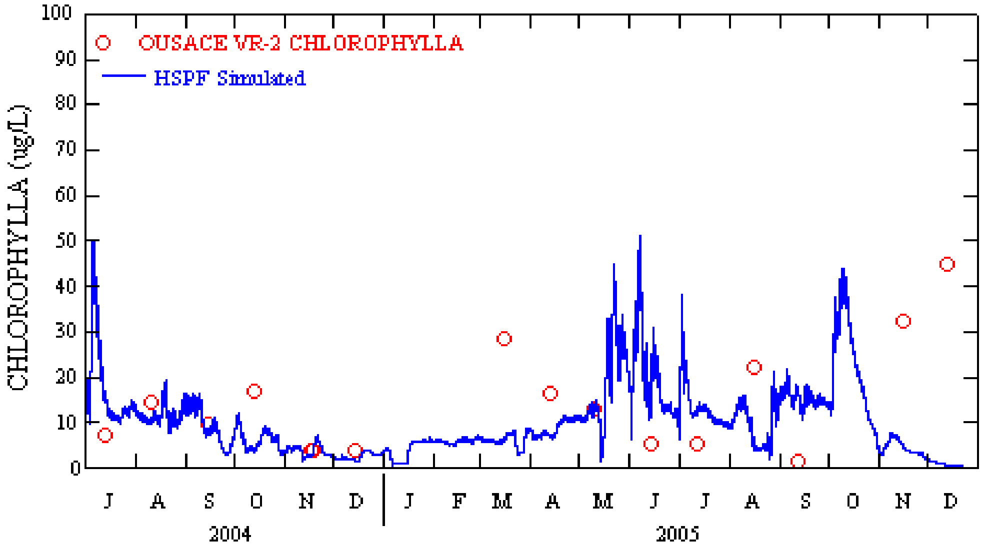

Figure 173 CHLOROPHYLL A Calibration Plot at USACE VR-2

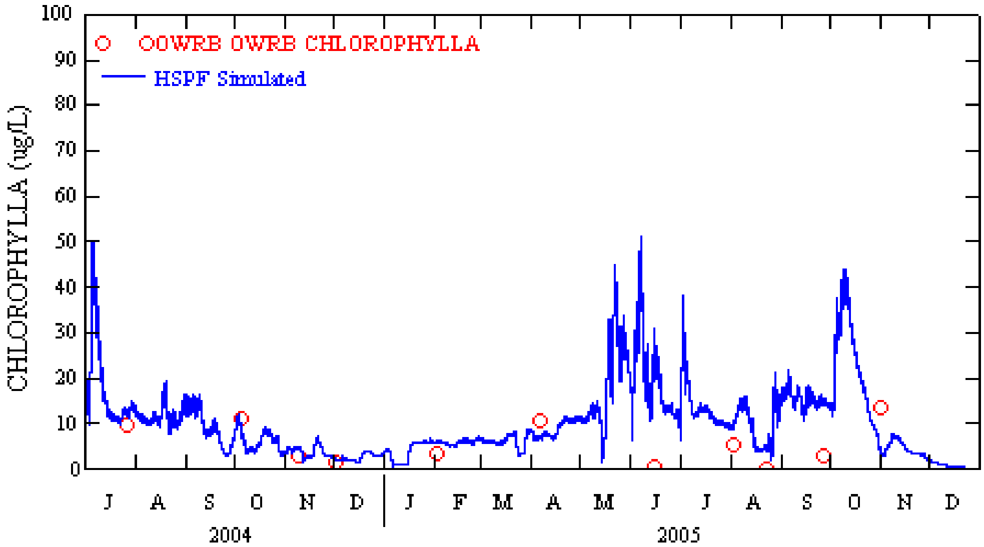

Figure 174 CHLOROPHYLL A Calibration Plot at OWRB Station

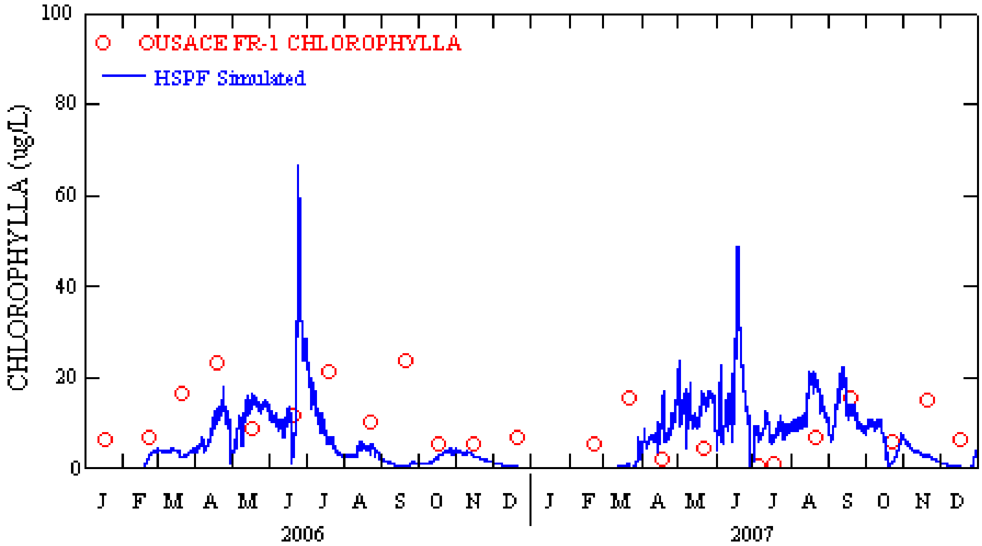

Figure 175 CHLOROPHYLL A Validation Plot at USACE FR-1

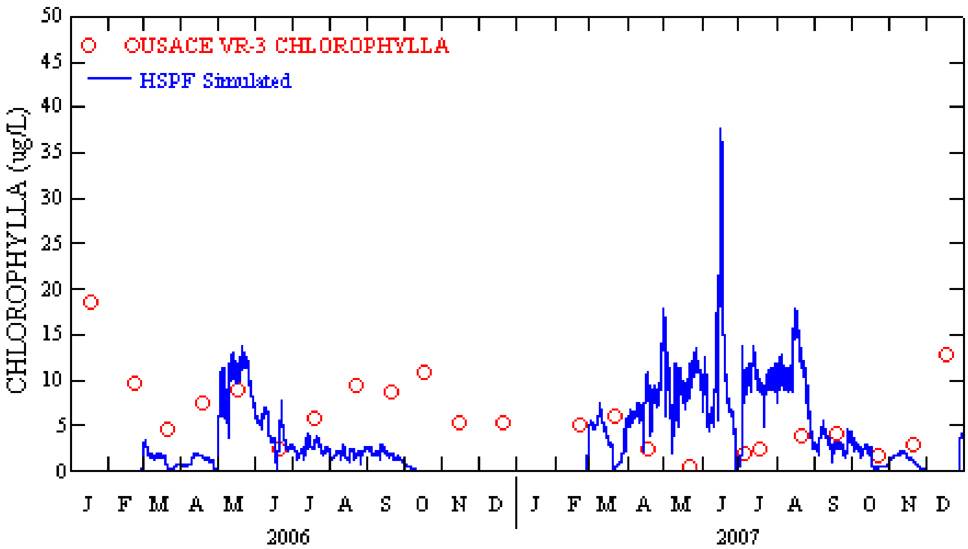

Figure 176 CHLOROPHYLL A Validation Plot at USACE VR-3

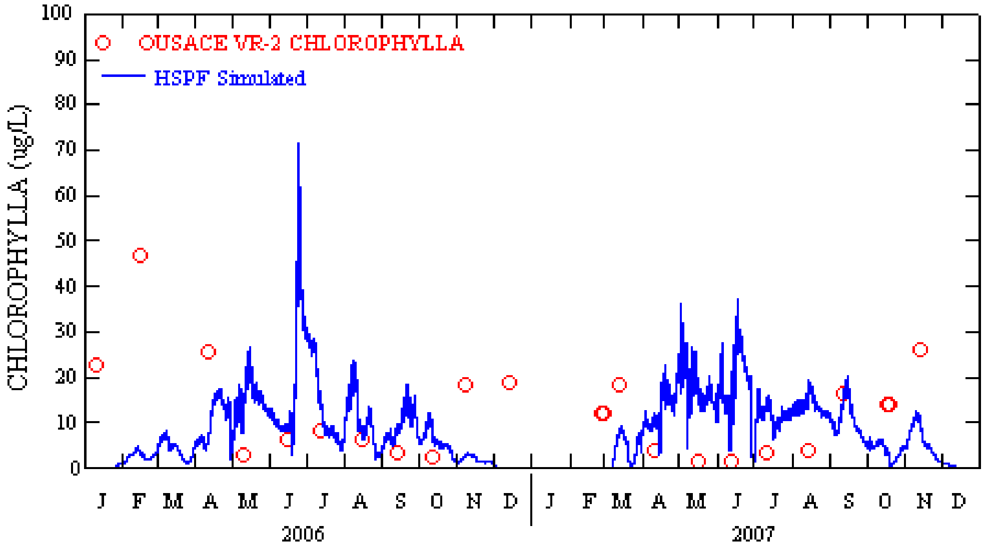

Figure 177 CHLOROPHYLL A Validation Plot at USACE VR-2

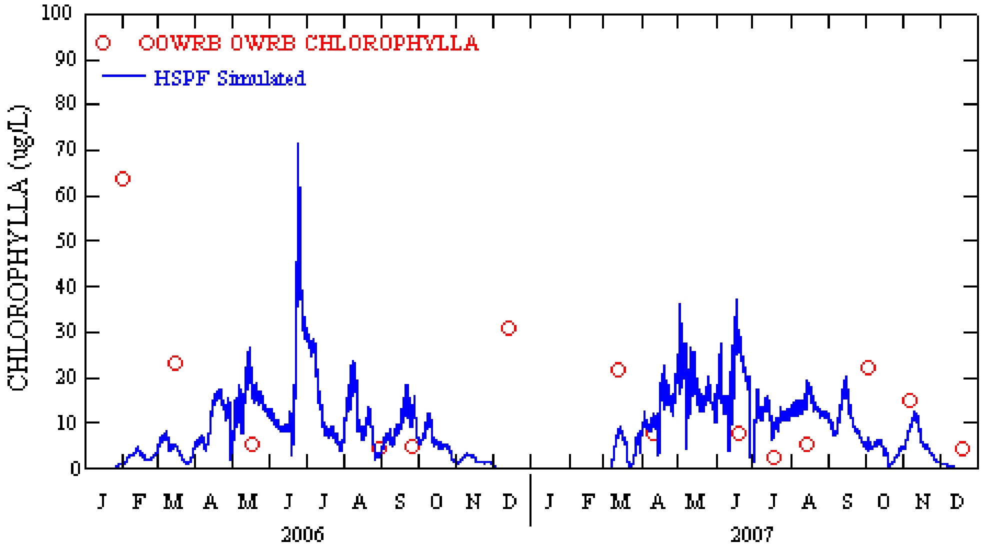

Figure 178 CHLOROPHYLL A Validation Plot at OWRB Station

8. SUMMARY

The purpose of this modeling effort is to calibrate and validate a watershed hydrology and water quality model for the Verdigris River Basin in support of the DO and turbidity TMDL development in Lake Oologah.

The watershed model simulation period is from January 1 2004 to December 31 2007 with half-year spin up period to diminish the impact of initial conditions. The watershed model was calibrated during July 1 2004 to December 31 2005 and validated during January 1 2006 to December 31 2007.

The flow and water quality constituent loadings from the four federal reservoirs served as the upstream boundary conditions of the watershed model. The watershed model also took into account the water withdrawals from industrial, municipal, irrigation, and recreation facilities. The flow and pollutant loadings from the industrial and municipal NPDES facilities were also accounted for by the watershed model.

The Verdigris River hydrologic model was calibrated and validated at 5 USGS stations. The hydrologic calibration performance is good with the mean percent error (MPE) values ranging from 5.6% to 13.8%. The hydrologic model simulated reasonably well both high and low flows.

There are water temperature data at a total of nine stations from USACE, EPA STORET, and OWRB available for model calibration and validation. The model performance for water temperature simulation is very good as indicated by the lower values of MPE and high values of Nash-Sutcliffe Efficiency Coefficient (NS).

The general model performance for DO at both calibraton and validation periods is good. The simulated DO followed the trends of the observed DO data. The calculated mean percent error (MPE) values are either within the range of -10% to +10% or very close to +10%. The overall model performance of TSS is fairly good with the majority of calculated mean percent error (MPE) values within the range of -100% and +100%.

The overall model performance for NH4, NO3, TN, TPO4, TP, TOC, and chlorophyll a is fairly good with the majority of calculated MPE values within the range of -100% and +100%. The model performance of TN and TP is better at the validation period with the majority of calculated MPE values within the range of -25% to +25%.

9. REFERENCES

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jobes, T.H., and Donigian, A.S. 2001. Hydrological Simulation Program Fortran (HSPF) User's Manual for Release 12. U.S. EPA National Research Laboratory. Athens, GA.

City of Tulsa, 2006. Tulsa Comprehensive Water System Study. Available online at http://www.planitulsa.org/files/Searchable-070910%20pdf.pdf

Donigian, A.S., Imhoff, J.C., Kittle, J.L. 1999. HSPFParm-An Interactive Database of HPSF Model Parameters. Version 1.0. EPA-823-R-99-004, USEPA, Washington, DC.

Duda, P.B., Kittle, J.L., Gray, M.H., Hummel, P.R., and Dusenbury, R.A. 2002. WinHSPF - An Interactive Windows Interface to HSPF: User's Manual. U.S. EPA Office of Water, Washington D.C.

Dynamic Solutions, LLC, 2015. Three-Dimensional Hydrodynamic and Water Quality Model of Lake Oologah, Oklahoma Task 2 Data Collection, Inventory, and Processing for Watershed and Lake Models. Report submitted to Oklahoma Department of Environmental Quality. June 26, 2015.

US Environmental Protection Agency. 2013. Environmental Fluid Dynamics Code (EFDC). Available online at http://www.epa.gov/athens/wwqtsc/html/efdc.html

Hamon, W.R. 1961. Estimating Potential Evapotranspiration Journal of the. HYDRAULICS DIVISION. Proceedings of the American Society of Civil Engineers. 87: 107-120.

Hendrickson, J., Trahan, N., Stecker, E., Ouyang, Y. 2002. TMDL & PLRG Modeling of the Lower St. Johns River Technical Report Series Volume 1: Calculation of the External Load. Online Available at http://www.academia.edu/1438337/TMDL_and_PLRG_Modeling_of_the_Lower_St._Johns_River_Technical_Report_Series_Volume_1_Calculation_of_the_External_Load

Hyder, S. and A. Bari. (2011). Characterization and study of correlations among major pollution parameters in textile wastewater. Mehran University Research Journal of Engineering and Technology, 30(4): 577-582.

Kansas Water Office (KWO). 2009. Verdigris River Basin. Online available at http://www.kwo.org/Water%20Plan/KWP2009/Rpt_VER_Entire_Basin_Section_KWP_2009.pdf

Lamm, F.R., Stone, L.R., and O'Brien, D.M. 2006. Crop Production in Western Kansas as Related to Irrigation Capacity, American Society of Agricultural and Biological Engineers Meeting Presentation. Paper Number : 062208. Portland, Oregon. July 9-12 2006.

Metcalf & Eddy, Inc. (1991). Wastewater Engineering, Treatment, Disposal and Reuse, 3rd Edition. Irwin/ McGraw Hill, 1334 pp.

Oklahoma Department of Wildlife Conservation. 2008. Oologah Lake Management Plan. Available online at http://www.wildlifedepartment.com/fishing/Oologah2008.pdf

Rozzi, A, F. Malpei, L. Bonomo and R. Bianchi (1999). Textile wastewater reuse in northern Italy (COMO) , Water Science and Technology, Vol 39 No 5 pp 121–128, IWA Publishing

Stoddard, A., J. B. Harcum, J.R. Pagenkopf, J. Simpson and R.K. Bastian .2002. Municipal wastewater treatment: evaluating improvements in national water quality. John Wiley & Sons, Inc., New York, NY.