# Final

# Oologah Lake TMDL Report

**Prepared for:**

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| | |
|---|---|
| 3-D | Three-dimensional |
| ADCP | Acoustic Doppler Continuous Profiler |
| ARRA | American Recovery and Reinvestment Act of 2009 |
| BMP | Best management practices |
| CBOD | Carbonaceous Biochemical oxygen demand |
| BUMP | Beneficial Uses Monitoring Program |
| CAFO | Concentrated Animal Feeding Operation |
| CASTNET | Clean Air Status and Trends Network |
| CFR | Code of Federal Regulations |
| cfs | cubic feet per second |
| Chl-a | Chlorophyll-a |
| COD | Chemical Oxygen Demand |
| COE | United States Army Corps of Engineers |
| COMCD | Central Oklahoma Master Conservancy District |
| CPP | Continuing Planning Process |
| CST | Central Standard Time Zone |
| CV | Coefficient of Variation |
| CWA | Clean Water Act |
| DEQ | Oklahoma Department of Environmental Quality |
| DIN | Dissolved inorganic nitrogen (DIN=nitrate + ammonia) |
| DMR | Discharge Monitoring Report |
| DO | Dissolved Oxygen |
| DOC | Dissolved Organic Carbon |
| DON | Dissolved Organic Nitrogen |
| DOP | Dissolved Organic Phosphorus |
| DSLLC | Dynamic Solutions, LLC |
| EFDC | Environmental Fluid Dynamics Code |
| EPA | Environmental Protection Agency |

| | |
|---|---|
| FWP | Fish & Wildlife Propagation |
| HSPF | Hydrologic Simulation Program FORTRAN |
| HUC | Hydrologic Unit Code |
| GIS | Geographic Information System |
| GUI | Graphical user interface |
| KDHE | Kansas Department of Health and Environment |
| Kg | Kilograms |
| LA | Load Allocation |
| lb | pound |
| LTA | Long term average load |
| mg/L | milligrams per liter |
| MDL | Maximum Daily Load |
| MOS | Margin of Safety |
| MPE | Mean Percent Error |
| MS4 | Municipal separate storm sewer system |
| MSGP | Multi-Sector General Permits |
| MSL | Mean Sea Level |
| NADP | National Atmospheric Deposition Program |
| NAD83 | North American Datum of 1983 |
| NAVD88 | North American Vertical Datum of 1988 |
| NCDC | National Climatic Data Center (NOAA) |
| NED | National Elevation Dataset |
| NGVD29 | National Geodetic Vertical Datum of 1929 |
| NH4 | Ammonium-N |
| NHD | National Hydrography Dataset |
| NLCD | National Land Cover Database |
| NLW | Nutrient Limited Watershed |
| NO2 | Nitrite-N |
| NO3 | Nitrate-N |
| NO23 | Nitrite-N + Nitrate-N |
| NOAA | National Oceanic Atmospheric Administration |
| NPDES | National Pollutant Discharge Elimination System |
| NPS | Nonpoint Source |
| N-S | Nash-Sutcliffe Coefficient |
| NTU | Nephelometric Turbidity Units |
| O.S. | Oklahoma Statutes |
| OAC | Oklahoma Administrative Code |
| OCC | Oklahoma Conservation Commission |
| ODAFF | Oklahoma Department of Agriculture, Food, and Forestry |
| OKWBID | Oklahoma Waterbody Identification Number |
| OWRB | Oklahoma Water Resources Board |
| PFO | Poultry Feeding Operation |
| POC | Particulate Organic Carbon |
| PON | Particulate Organic Nitrogen |

| | |
|---|---|
| POP | Particulate Organic Phosphorus |
| RMS | Root Mean Square |
| RMSE | Root Mean Square Error |
| $r^2$ | Correlation Coefficient |
| SIC | Standard Industrial Classification |
| SOD | Sediment Oxygen Demand |
| SSO | Sanitary Sewer Overflow |
| SWP3 | Storm Water Pollution Prevention Plan |
| SWS | Sensitive Water Supply |
| TKN | Total Kjeldahl Nitrogen |
| TMDL | Total Maximum Daily Load |
| TN | Total Nitrogen |
| TOC | Total Organic Carbon |
| TON | Total Organic Nitrogen |
| TOP | Total Organic Phosphorus |
| TP | Total Phosphorus |
| TPO4 | Total Phosphate |
| TSI | Trophic State Index |
| TSS | Total Suspended Solids |
| USDA | United States Dept. Agriculture |
| USGS | United States Geological Survey |
| UTM | Universal Transverse Mercator (map projection) |
| WLA | Wasteload Allocation |
| WQM | Water Quality Monitoring |
| WQMP | Water Quality Management Plan |
| WQS | Water Quality Standard |
| WWAC | Warm Water Aquatic Community |
| WWTP | Wastewater Treatment Plant |

# EXECUTIVE SUMMARY

Oologah Lake 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 contributing areas in both Kansas and Oklahoma (USACE, Tulsa District) (Figure 1). The Oologah Lake dam [-95.679 Longitude (W), 36.4225 Latitude (N)] 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, after some project delays, the project was completed in 1974. 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 29,460 acres, the mean depth is 18.7 feet, and the storage volume is 457,160 acre-ft.

The City of Tulsa obtains approximately 40-50% of its water supply needs from Oologah Lake. 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 (US Army Corps of Engineers Tulsa District and City of Tulsa, 2012).

The Water Body ID (WBID) for Oologah 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). The Oklahoma 303(d) List of Impaired Waters for 2012 identifies impairments of Oologah Lake because of dissolved oxygen (DO) and turbidity based on data collected by OWRB in 2012.

This report documents the data and assessment methods used to establish total maximum daily loads (TMDL) for Oologah Lake (OK121510010020-00). Data assessment and TMDL calculations are conducted in accordance with requirements of Section 303(d) of the federal Clean Water Act (CWA), Water Quality Planning and Management Regulations (40 CFR Part 130), United States Environmental Protection Agency (USEPA) guidance, and Oklahoma Department of Environmental Quality (DEQ) guidance and procedures. DEQ is required to submit all TMDLs to the USEPA for review and approval. Once the USEPA approves a TMDL, the waterbody may then be moved to Category 4 of a state's Integrated Water Quality Monitoring and Assessment Report, where it remains until compliance with water quality standards (WQS) is achieved (USEPA, 2003).

The purpose of this TMDL report is to establish waste load allocations (WLA) and load allocations (LA) determined to be necessary for reducing turbidity and maintaining sufficient dissolved oxygen levels in Oologah Lake to attain water quality targets to restore impaired Fish & Wildlife Propagation (FWP) beneficial uses for the Verdigris River Watershed. TMDLs determine the pollutant loading that a waterbody, such as Oologah Lake, can assimilate without exceeding water quality standards. TMDLs also establish the pollutant load allocation necessary to meet the water quality standards established for a waterbody based on the relationship between pollutant sources and water quality conditions in the waterbody. A TMDL consists of a waste load allocation (WLA) component, load allocation (LA) component, and a margin of safety (MOS). The WLA is the fraction of the total pollutant load apportioned to point sources, and includes municipal and industrial wastewater treatment facilities and urban storm water discharges regulated as point sources by Section 402 of the Clean Water Act under the National Pollutant Discharge Elimination System (NPDES). The LA is the fraction of the total pollutant load apportioned to nonpoint or distributed sources. The MOS is a percentage of the TMDL set aside to account for the lack of knowledge associated with natural processes in aquatic systems, assumptions of the watershed-lake model, and data limitations.

This report does not identify specific control actions (regulatory controls) or management measures (voluntary best management practices) necessary to reduce point and nonpoint source pollutant loading from the watershed. Watershed-specific control actions and management measures will be identified, selected, and implemented under a separate process involving stakeholders who live and work in the watershed, along with local, state, and federal government agencies.

Problem Identification and Water Quality Targets. Designated uses of Oologah Lake are hydropower production, flood control, public and private water supply, agriculture, primary body contact recreation, and fish and wildlife propagation. As of the 2010 census, the Verdigris River basin population is estimated at 59,358 persons. Oologah Lake serves as a public water supply for several municipalities and rural towns located in the watershed. The lake is also an important recreational resource for the area with excellent fishing, swimming, camping, picnicking, boating, hunting, and sailing.

The 2012 Integrated Report and 303(d) list is used as the basis for identifying dissolved oxygen and turbidity as the water quality constituents responsible for impairments for FWP for a Warm Water Aquatic Community (WWAC) in Oologah Lake. Oologah Lake is designated as a Category 5a lake on the 2012 Oklahoma 303(d) list with a Priority 1 ranking. Category 5 defines a waterbody where, since water quality standards are not attained, the waterbody is impaired or threatened for one or more designated uses by pollutant(s), and the water body requires a TMDL. As shown in the 2012 Integrated Report, Oologah Lake is not supporting its designated uses for Fish & Wildlife Propagation for a Warm Water Aquatic Community because of dissolved oxygen and turbidity (OKWBID: OK121510010020-00). High levels of turbidity can have deleterious effects on raw water quality, such as taste and odor complaints and treatment costs of drinking water. Low levels of dissolved oxygen below the thermocline reflect decay of organic matter in the sediment bed and restricted transfer of dissolved oxygen from the surface layer because of summer thermal stratification.

The water quality targets established for Oologah Lake, based on statistics of the most recent 10 years of record used for the 2012 303(d) listing, are defined as 25 NTUs for turbidity. The recently revised Oklahoma water quality standards for dissolved oxygen for Oologah Lake are specified in relation to (a) spring and summer stratified conditions for the surface layer (epilimnion) and the anoxic volume of the lake within the hypolimnion and (b) non-stratified conditions for the surface layer (OWRB, 2014a). Within the surface layer (epilimnion) during the early period of thermal stratification in spring, 10% or less of the dissolved oxygen samples shall be no less than 6 mg/L from April 1 to June 15. During the summer period of stratification from June 16-October 15, 10% or less of the dissolved oxygen samples shall be no less than 5 mg/L. During the remainder of the year (October 16 to March 31) 10% or less of the dissolved oxygen samples shall be no less than 5 mg/L for the months when the lake is non-stratified. DO criteria for a Warm Water Aquatic Community lake are also defined on the basis of the anoxic volume of the lake that is less than a target cutoff level of DO. During the period of thermal stratification, the lake is fully supporting if 50% or less of the lake volume is less than the target cutoff of 2 mg/L. Where water column DO data, rather than volumetric DO data, were used to determine impairment of the lake, the lake is considered to be fully supporting if 70% or less of the water column of sampling sites are less than the target cutoff of 2 mg/L.

Pollutant Source Assessment. Water quality constituents that relate to impairments of Oologah Lake include suspended sediment, chlorophyll-a, phosphorus, nitrogen, and total organic carbon (TOC). The seven (7) NPDES wastewater facilities listed in Table 3-1 and Table 3-19 are all included as point source wastewater discharges to tributary reach sub-basins of the HSPF watershed model. Wastewater pollutant loading contributed by NPDES permitted discharges within the Verdigris River watershed is therefore represented as point source inputs to tributary reach catchments of the HSPF watershed model. The combined contributions of point source loading of NPDES wastewater discharges and nonpoint source runoff over a catchment are accounted for by flow and pollutant loading simulated at the downstream outlets of each tributary reach sub-basin of the HSPF watershed model. As there are no point source NPDES wastewater facilities that discharge directly into Oologah Lake the share of point source NPDES loading to Oologah Lake is zero because the NPDES wastewater loading to tributaries of the watershed model is incorporated as part of the Annual HSPF percentage share of pollutant loading shown in Table ES- 1. Existing watershed runoff from the HSPF model accounts for the largest share (94.5%) of nitrogen sources while benthic release from the lake bed (4.46%) contribute much smaller shares. For phosphorus loading, watershed runoff (86.67%) accounts for over half of the existing loading while benthic release from the lake bed contributes 13.29% of the phosphorus inputs to the lake.

Table ES- 1 Relative Contribution of Existing Nonpoint Source and Point Source Loading of Pollutants Delivered to Oologah Lake (EFDC Model Validation, Jan-Dec 2007)

| **Model Validation: 2007 WQ Parameter/Source Percentage** | | **Annual HSPF %** | **Annual AtmDep %** | **Annual SedFlux %** | **Annual PS:NPDES %** | **Annual Total %** |
|---|---|---|---|---|---|---|
| Total Nitrogen | TN | 94.50% | 1.04% | 4.46% | 0.00% | 100.00% |
| Total Phosphorus | TP | 86.67% | 0.04% | 13.28% | 0.00% | 100.00% |
| Total Organic Carbon | TOC | 100.00% | 0.00% | 0.00% | 0.00% | 100.00% |
| Total Suspended Solids | TSS | 100.00% | 0.00% | 0.00% | 0.00% | 100.00% |

Watershed and Lake Model. A mass balance-based surface water model framework was developed to establish the cause-effect linkage between external pollutant loading from the Verdigris River watershed and hydrodynamic and water quality conditions in Lake Oologah. The watershed (HSPF) and lake (EFDC) models are dynamic models that represent time-variable conditions as a continuous simulation. HSPF is a public-domain lumped parameter watershed model that represents runoff, streamflow and loading of sediment, nutrients and organic matter within a watershed network of catchments. EFDC is a public-domain 3-dimensional model that includes hydrodynamics, sediment transport, and biogeochemical processes for water quality and eutrophication. The HSPF-EFDC model framework for Oologah Lake has been successfully applied for numerous TMDL studies including applications in Oklahoma for Tenkiller Ferry Lake, Lake Thunderbird and Ft. Gibson Lake.

Flow and pollutant loading from the watershed was simulated for a calibration and validation period from January 2005 to December 2007 with the HSPF model. The EFDC lake model, developed with data collected during the two-year period from January 2006 through December 2007, was calibrated to 2006 observations and then validated to data collected in 2007. Watershed model results, atmospheric deposition data and the results of the EFDC sediment flux model were used to estimate the relative contributions of existing point and nonpoint sources of pollutant loading presented in Table ES- 1. Model performance statistics for the calibration and validation periods, computed from a comparison of paired observed/simulated data, demonstrated that the watershed and lake model results were either better than, or close to, the target criteria specified for the model framework.

EFDC is designed to link external flow and point/nonpoint source loading with hydrodynamics, seasonal stratification, eutrophication and internal coupling of organic matter deposition to the sediment bed with decomposition processes in the bed that, in turn, produce benthic fluxes of nutrients and sediment oxygen demand across the sediment-water interface. The EFDC model of Oologah Lake accounts for the cause-effect interactions of external loading with water clarity, nutrient cycling, algal production, organic matter deposition, decay in the sediment bed, and internally generated benthic fluxes of nutrients and sediment oxygen demand. These are critical capabilities of the EFDC model because Oologah Lake, like many reservoirs in Oklahoma, is characterized by seasonal thermal stratification, hypoxia and internal benthic loading of nutrients that is triggered, in part, by low dissolved oxygen conditions in the hypolimnion.

Multiple load reduction scenario lake model runs were performed with the calibrated and validated model to determine if water quality targets for turbidity and dissolved oxygen could be attained with uniform watershed load reductions. Based on spin-up analysis of the 40% removal scenario, model results indicated that compliance with water quality criteria for dissolved oxygen and turbidity could be achieved within a reasonable time frame. The watershed-lake model based on HSPF and EFDC thus provides DEQ with a scientifically defensible surface water model framework to support determination of TMDLs and development of water quality management plans for Oologah Lake.

TMDL, Waste Load Allocation, Load Allocation and Margin of Safety. The linked watershed (HSPF) and lake (EFDC) model framework was used to calculate average annual Total Suspended Solids (TSS), TOC, Total Nitrogen and Total Phosphorus loads (kg/yr), that, if achieved, should meet the water quality targets established for turbidity and dissolved oxygen. For reporting purposes, the final TMDLs, according to EPA (2007) guidelines, are expressed as daily loads (kg/day).

Seasonal variation was accounted for in the TMDL determination for Oologah Lake in two ways: (1) water quality standards, and (2) the time period represented by the watershed and lake models. Oklahoma's water quality standards for dissolved oxygen for lakes are developed on a seasonal basis to be protective of fish and wildlife propagation for a warm water aquatic community at all life stages, including spawning. Within the surface layer, dissolved oxygen standards specify that DO levels shall be no less than 6 mg/L from April 1 to June 15 to be protective of early life stages and no less than 5 mg/L for the remainder of the year during summer stratified conditions (June 16 to October 15) and winter well-mixed conditions (October 16 through March 31). Under summer stratified conditions in Oologah Lake, the hypoxic volume of the lake, defined by a DO target of 2 mg/L, is not to be greater than 50% of the lake volume. Where water column DO data, rather than volumetric DO data, were used to determine impairment of the lake, the lake is considered to be fully supporting if 70% or less of the water column of sampling sites are less than the target cutoff of 2 mg/L. Seasonality was also accounted for in the TMDL analysis by developing the models using two years of streamflow and water quality data collected as part of routine water quality monitoring programs conducted by OWRB and the USACE. The watershed and lake models were developed with hourly to sub-hourly time steps over two years of simulation (2006-2007) with meteorological data representative of the dry and wet hydrologic conditions in the watershed that characterized much of eastern Oklahoma during 2006-2007.

EPA guidance about the Margin of Safety (MOS) for development of TMDLs states that: *A margin of safety expressed as unallocated assimilative capacity or conservative analytical assumptions used in establishing the TMDL; e.g., derivation of numeric targets, modeling assumptions, or effectiveness of proposed management actions which ensures attainment and maintenance of water quality standards for the allocated pollutant [40 CFR 130.33(b)(7)].* EPA guidance identifies two approaches for defining the MOS. In the first approach, an explicit MOS quantifies an allocation amount separate from other load and wasteload allocations. In the second approach, an implicit MOS is not specifically quantified but consists of conservative assumptions used in the TMDL analysis. *http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/TMDL-ch3.cfm*

The TMDL determined for Oologah Lake applies an implicit Margin of Safety (MOS) based on a conservative assumption for derivation of more stringent numeric water quality targets for turbidity, and dissolved oxygen. Adoption of a 10% MOS as a conservative assumption for the derivation of more stringent water quality targets for turbidity and the anoxic percentage of the water column will ensure an adequate implicit MOS for the determination of load allocations (LA) for Oologah Lake. Turbidity, a measure of water clarity, is caused by scattering and adsorption of light by suspended particles in the water column. Turbidity, however, cannot be expressed as a mass load. Total suspended solids (TSS) are therefore modeled and evaluated as a surrogate water quality constituent for turbidity using a site-specific relationship derived from paired TSS and turbidity measurements in Oologah Lake. The TMDL for TSS, TOC, TN and TP, determined from the lake model response to watershed load reductions, is based on 40% reduction of the existing watershed runoff loads estimated with the HSPF model (Table ES-2).

The statistical methodology, documented in EPA (2007) "*Options for Expressing Daily Loads in TMDLs*", for computing the maximum daily load (MDL) limit is based on a long-term average load (LTA), temporal variability of the pollutant loading dataset expressed by the coefficient of variation (CV), the

Z-score statistic (1.645) for 95% probability of occurrence and the assumption that flow and pollutant loading from the watershed can be described as a lognormal distribution. The waste load allocation (WLA) and the load allocation (LA) are computed from the MDL and the percentage splits of the total existing PS and NPS load accounted for by NPS watershed runoff (Table ES-3). As there are no direct NPDES point source discharges of wastewater into Oologah Lake, the percentage split of the WLA for the PS load is zero and the percentage split of the LA for the NPS load is 100%.

Table ES-2 Existing Long Term Loading, Load Reduction Rate and Reduced Long Term Loading for Oologah Lake

| Water Quality Constituent Oologah Lake | LTA, Existing Annual kg/yr | Load Reduction % | LTA, Reduced Annual kg/yr | LTA, Reduced Daily kg/day |
|---|---|---|---|---|
| Total Nitrogen (TN) | 8,160,833 | 40% | 4,896,500 | 13,415 |
| Total Phosphorus (TP) | 1,214,873 | 40% | 728,924 | 1,997 |
| Total Organic Carbon (TOC) | 33,328,891 | 40% | 19,997,335 | 54,787 |
| Suspended Solids (TSS) | 1,842,230,207 | 40% | 1,105,338,124 | 3,028,324 |

Table ES-3 TMDL for Oologah Lake: WLA and LA for Watershed

| Water Quality Constituent Oologah Lake | LTA Reduced Daily kg/day | Load CV n=363 | Z-Score for 95% Probability | MDL Load kg/day | WLA PS % | LA NPS % | MOS |
|---|---|---|---|---|---|---|---|
| Total Nitrogen (TN) | 13,415 | 5.362 | 1.645 | 50,906 | 0% | 100% | Implicit |
| Total Phosphorus (TP) | 1,997 | 6.432 | 1.645 | 7,407 | 0% | 100% | Implicit |
| Total Org-Carbon (TOC) | 54,787 | 5.415 | 1.645 | 207,688 | 0% | 100% | Implicit |
| Suspended Solids (TSS) | 3,028,324 | 41.188 | 1.645 | 6,524,666 | 0% | 100% | Implicit |
| LTA- Long Term Avg Load | | | | | | | |
| CV- Coefficient of Variation | | | | | | | |

* Implicit Margin of Safety (MOS) based on conservative assumptions for derivation of more stringent numeric water quality targets for turbidity and dissolved oxygen.

Public Participation A public notice was sent to local newspapers, to stakeholders in the Study Area affected by these draft TMDLs, and to stakeholders who requested copies of all TMDL public notices. The public notice, draft TMDL report, and draft 208 Factsheet were posted at the following DEQ website: https://www.deq.ok.gov/water-quality-division/watershed-planning/tmdl/.

The public had 45 days (November 14, 2023 to December 29, 2023) to review the draft TMDL report and make written comments. No public comments were made and there were no requests for a public meeting.

The DO and Turbidity TMDL report for Oologah Lake was finalized and submitted to EPA for final approval.

# 1. Introduction

## 1.1 Clean Water Act and TMDL Program

Section 303(d) of the federal Clean Water Act (CWA) and U.S. Environmental Protection Agency (USEPA) Water Quality Planning and Management Regulations (40 Code of Federal Regulations [CFR] Part 130) require states to develop Total Maximum Daily Loads (TMDL) for waterbodies not meeting designated uses where technology-based controls are in place. TMDLs establish the allowable loadings of pollutants or other quantifiable parameters for a waterbody based on the relationship between pollution sources and in-stream water quality conditions, so States can implement water quality-based controls to reduce pollution from point and nonpoint sources and restore and maintain water quality (USEPA, 1991a).

This report documents the data and assessment used to establish TMDLs for turbidity and dissolved oxygen for Oologah Lake reservoir in Rogers County, northeastern Oklahoma at the downstream end of the Middle Verdigris River Basin (HUC8 11070103). High levels of turbidity reflect sediment loading from the watershed and low levels of dissolved oxygen, particularly at depths deeper than the seasonal thermocline, reflect the effects of decomposition of organic matter below the thermocline and within the sediment bed and restricted mixing of dissolved oxygen from the surface layer of the lake to the lower layer of the lake during conditions of summer stratification.

The purpose of this TMDL report is to establish sediment, organic matter and nutrient load allocations necessary for improving turbidity and dissolved oxygen levels in the lake as the first step toward restoring water quality in this lake. TMDLs determine the pollutant loading a waterbody can assimilate without exceeding applicable water quality standards (WQS). TMDLs also establish the allocation of pollutant loads necessary to meet the WQS established for a waterbody based on the cause-effect relationship between pollutant sources and water quality conditions in the waterbody. A TMDL consists of three components: (1) wasteload allocation (WLA), (2) load allocation (LA), and (3) margin of safety (MOS). The WLA is the fraction of the total pollutant load apportioned to point sources. Point sources include municipal and industrial wastewater facilities and urban storm water discharges regulated under the CWA NPDES. The LA is the fraction of the total pollutant load apportioned to nonpoint sources (NPS). The MOS is a percentage of the TMDL set aside to account for the lack of knowledge associated with natural process in aquatic systems, surface water model assumptions, and data limitations.

Data assessment and TMDL calculations are conducted in accordance with requirements of Section 303(d) of the CWA, Water Quality Planning and Management Regulations (40 CFR Part 130), USEPA guidance, and Oklahoma Department of Environmental Quality (DEQ) guidance and procedures. DEQ is required to submit all TMDLs to USEPA for review and approval. Once the USEPA approves a TMDL, then the waterbody may be moved to Category 4a of a State's Integrated Water Quality Monitoring and Assessment Report, where it remains until compliance with water quality standards (WQS) is achieved (USEPA, 2003).

This report does not stipulate specific control actions (regulatory controls) or management measures (voluntary best management practices) necessary to reduce nutrients within the lake watershed.

Watershed-specific control actions and management measures will be identified, selected, and implemented under a separate process involving stakeholders who live and work in the watersheds, along with local, state, and federal government agencies.

Oologah Lake is on Oklahoma's 2014 303(d) list for impaired beneficial uses of Fish and Wildlife Propagation for Warm Water Aquatic Community life. Causes of impairment have been identified as low dissolved oxygen and high turbidity (OKWBID OK121510010020-00) (ODEQ, 2014).

Figure 1-1 shows a location map of Oologah Lake and the contributing sub-watersheds of the drainage basin to the lake. The map displays the locations of stream water quality monitoring (WQM) stations in the watershed, and lake water quality monitoring stations used for this TMDL determination. Water quality data obtained from the lake stations over the past 10 years were used as the basis for placement of Oologah Lake on the Oklahoma 303(d) list.

## 1.2 Watershed and Oologah Lake Description

Oologah Lake, a 29,460-acre reservoir in Rogers County in northeastern Oklahoma, is located about 2 miles southeast of Oologah and about 27 miles northeast of Tulsa in Tulsa County. 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. Normal pool elevation is 638 feet and the surface area of the lake is 29,460 acres, the mean depth is 18.7 feet, and the storage volume is 457,160 acre-ft (Table 1-1).

Designated uses of Oologah Lake include flood control, public and private water supply, navigation, recreation, and fish and wildlife propagation. As of the 2010 census, the Verdigris River basin population is estimated at 59,358. Oologah Lake serves as a public water supply source for the City of Tulsa, 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).

Table 1-1 Physical Characteristics of Oologah Lake

| | | |
|---|---|---|
| Drainage Area | sq-miles | 4,339 |
| Surface Area @ Normal Pool Elevation* | acres | 29,460 |
| Normal Conservation Pool Elevation | ft, NGVD29 | 638.0 |
| Conservation Pool Storage Volume | acre-ft | 457,160 |
| Surface Area @ Flood Pool Elevation | acres | 56,800 |
| Flood Pool Elevation | ft, NGVD | 661.0 |
| Flood Control Pool Storage Volume | acre-ft | 1,405,389 |
| Average Depth | ft | 18.7 |
| Maximum Depth | ft | 18.78 |
| Shoreline | miles | 180.0 |

* Elevation: vertical datum, NGVD29
*Data Sources: OWRB & USACE*
*OWRB- http://tulsaaudubon.org/guides/oologah-lake-map-owrb.pdf*
*USACE- http://www.swt-wc.usace.army.mil/OOLO.lakepage.html*

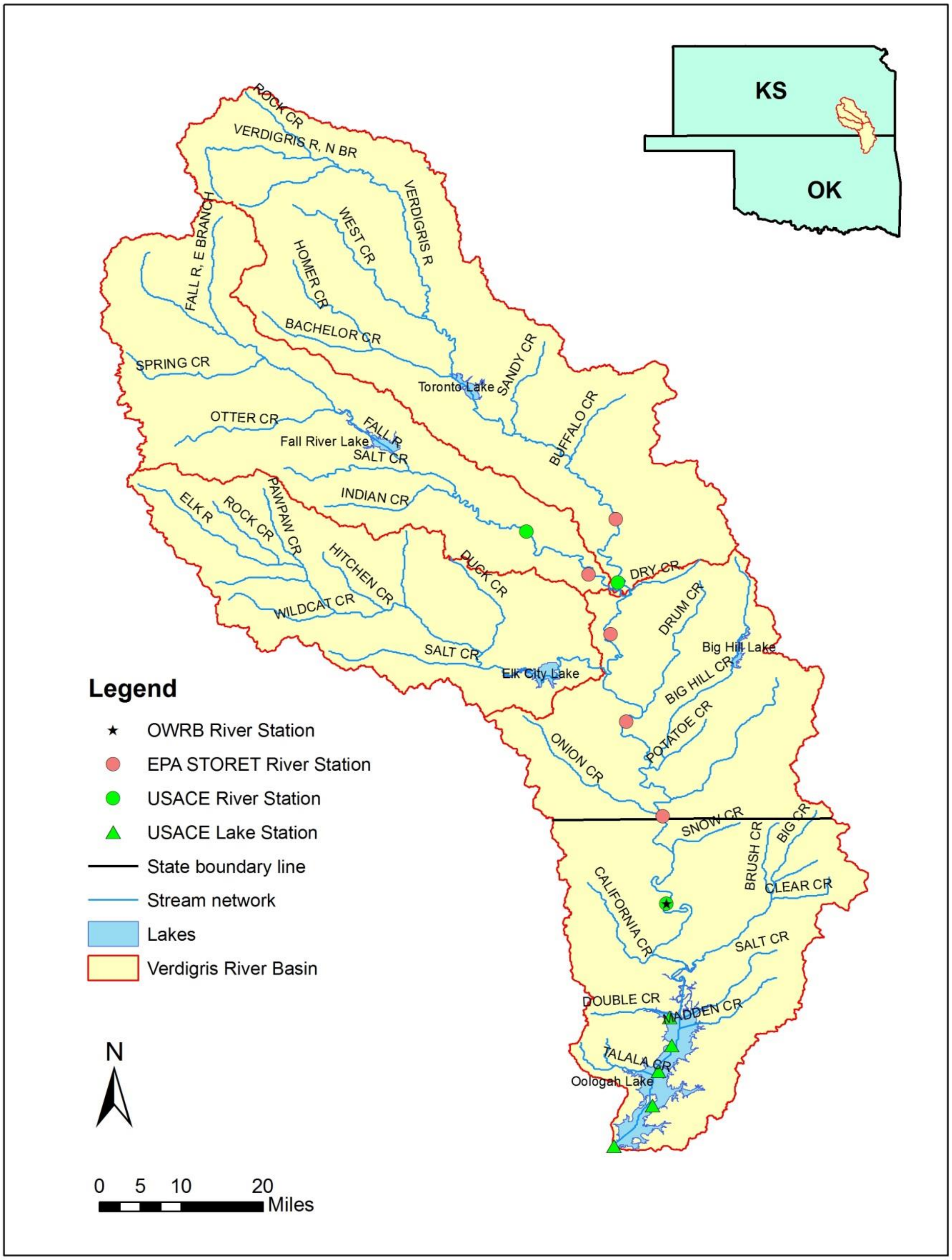


Figure 1-1 Oologah Lake and Contributing Watershed

The total Verdigris River basin is about 2,737,822 acres as shown in Figure 1-1. The portion of the Verdigris River basin that is included in the HSPF watershed model is presented in Figure 1-2 with the exclusion of the contributing areas of 1,246,672 acres attributed to 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. As shown in both Figure 1-1 and Figure 1-2, most of the watershed contributing area is located in the state of Kansas with 492,804 acres of the contributing area in Oklahoma.

The watershed is generally characterized as being in the Osage Cuestas Ecoregion with a physiography of cuestas and gentle undulating plains dissected by perennial and intermittent streams (Woods et al., 2005). Silty and clayey residuum and colluvium with alternating layers of Pennsylvanian sandstone, limestone, and shale characterize area geology. Glacial drift is fairly abundant in the extreme northern part of this ecoregion. Soils in the western part of the basin were developed from the underlying limestones and shales and in most parts of the watershed the soils are relatively shallow, making them best suited for native pastures. In the eastern part of the basin, soils are generally sandy residual soils which are low in fertility and quite erosive. These soils occur on undulating to hilly topography and are relatively shallow. In general, this area is more suitable for grazing than for cultivation.

Table 1-2 summarizes the percentages and acres of land use categories for the contributing watershed of the Verdigris River basin used for the watershed model. Land use and land cover data were derived from the 2006 National Land Cover Database (NLCD) database. The most common land use category in the study area is Pasture with 45.4% of the watershed area. In addition to Cropland land use (11.5%) and Forest land use (13.5%), about quarter of the basin is classified as Grassland with 23.3% of the watershed area. Urban developed land use categories account for only 5.7% of the watershed area and Wetland accounts for 0.5%. Land use distribution within the watershed is shown in Figure 1-3.

Table 1-2 Land Use Characteristics of the Verdigris River Watershed

| Land Use | Area (acres) | Percentage |
|---|---|---|
| Cropland | 16,7228 | 11.5% |
| Forest | 196,608 | 13.5% |
| Grassland | 338,889 | 23.3% |
| Pasture | 659,419 | 45.4% |
| Urban | 83,013 | 5.7% |
| Wetland | 7,691 | 0.5% |
| Total | 1,452,848 | 100.0% |

Annual precipitation in the basin varies from approximately 34 inches in the west to almost 40 inches in the southeast corner. Approximately 70 percent of this precipitation falls between April and September. Between 11 and 18 inches of snow falls in an average year. Average air temperature varies from 34 $^{o}$F in the winter to 79 $^{o}$F in the summer.

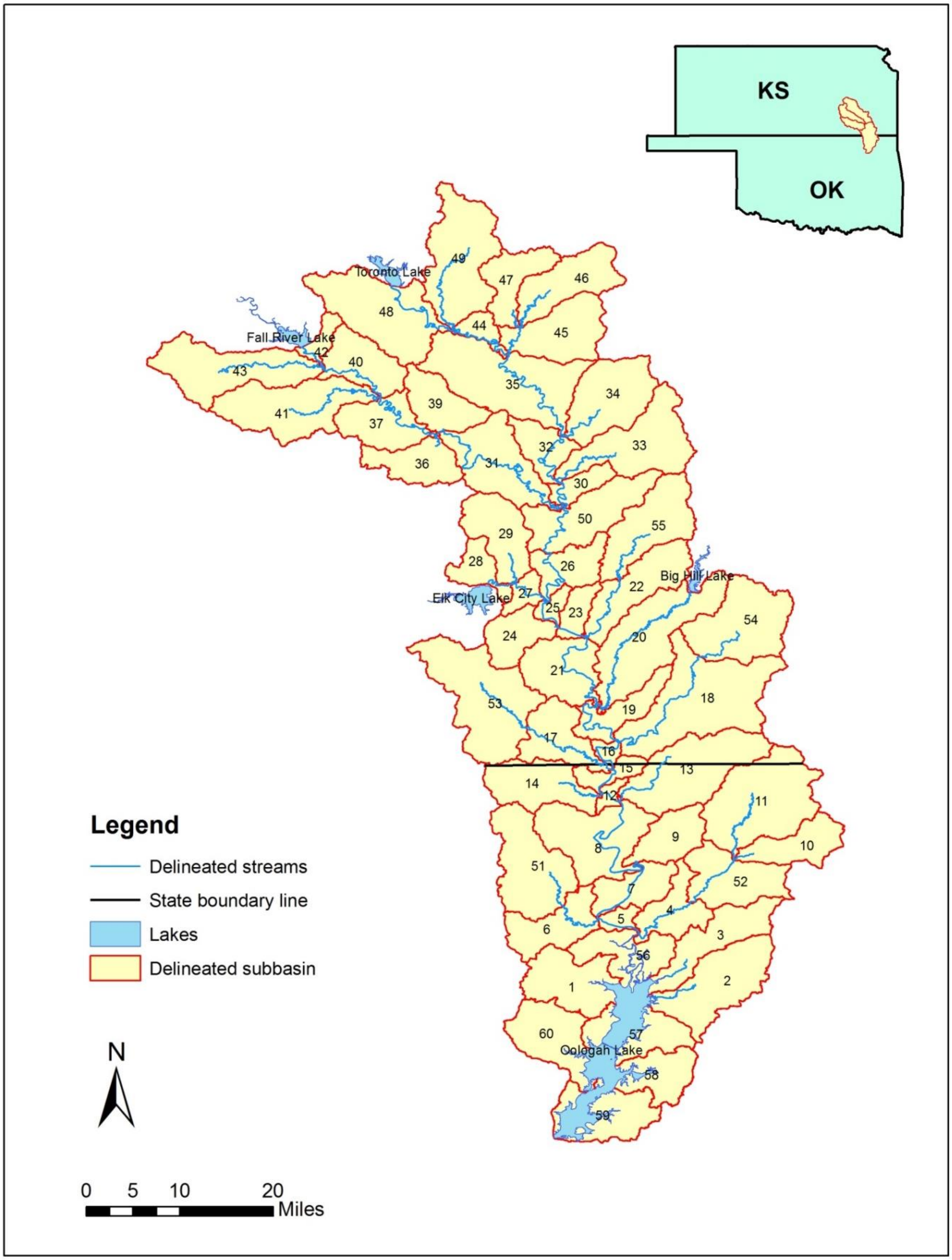


Figure 1-2 Modeled Oologah Lake Watershed and Its Discretization.

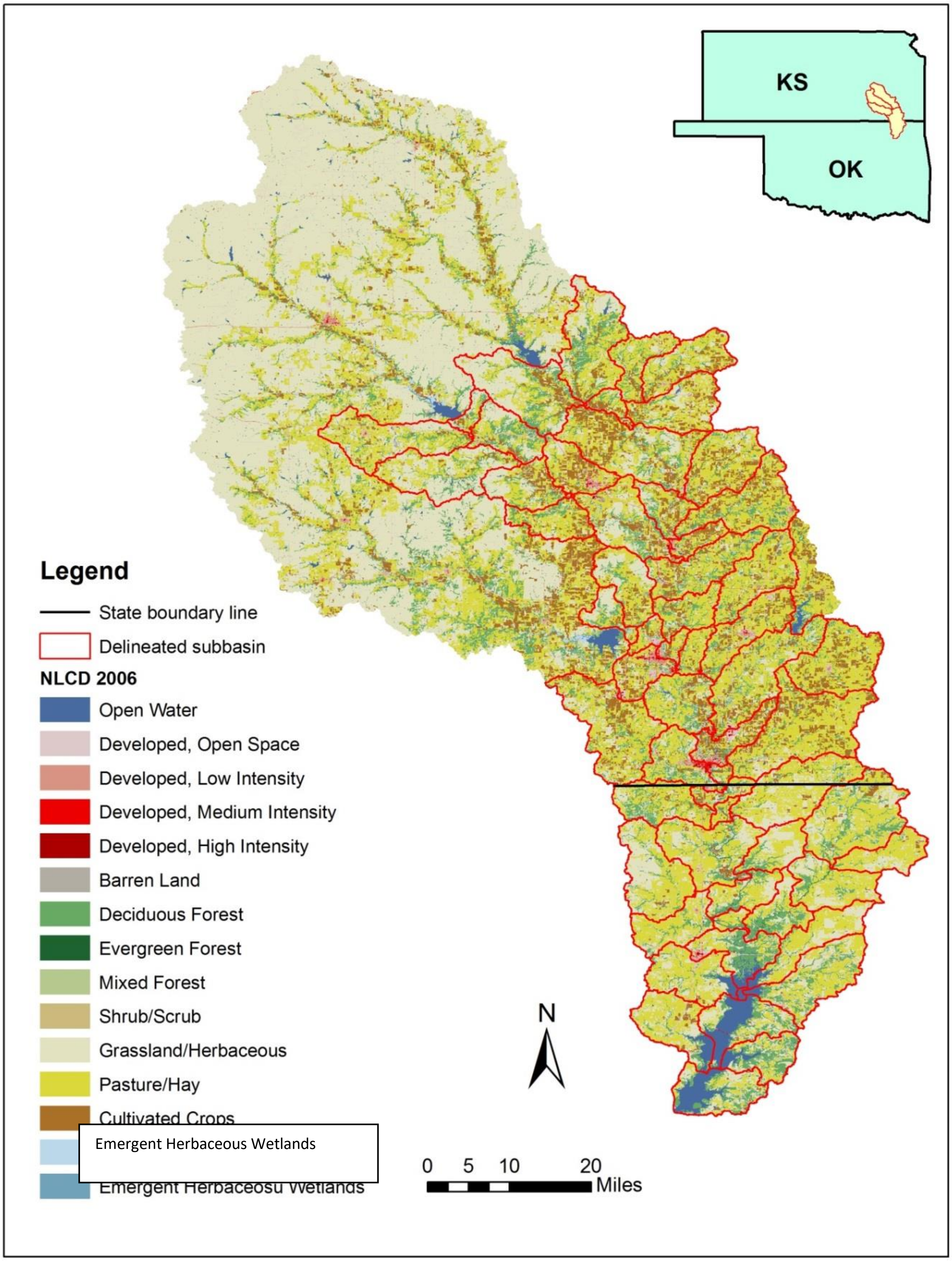


Figure 1-3 Landuse Distribution in the Verdigris River Watershed

Based on 2010 census data (US Census Bureau, 2011), the population within this watershed is estimated as 59,358 based on an overlay of the watershed boundary and census tract data. Figure 1-4 presents population density of the census tract areas located within the watershed boundary. As can be seen, the highest population density of 489-3,437 persons per square mile corresponds to the municipal areas. The lowest population density (4-26 persons per square mile) is characteristic of rural areas of the watershed. The unpopulated low-density areas correspond to the dominant land use categories of grassland, agriculture pasture, and forest, as shown in Figure 1-3.

Table 1-3 presents population data for Elk, Greenwood, Labette, Montgomery, Neosho, Wilson, Woodson, Craig, Nowata, and Roger counties that are located within the watershed. The table presents the total population of each county and the population of each county located within the watershed based on compilation of census tract data as shown in Figure 1-4.

Table 1-3 County Population within the Verdigris River Watershed

| County | State | Population Total | Population in Watershed |
|---|---|---|---|
| Elk | KS | 3,001 | 389 |
| Greenwood | KS | 6,666 | 369 |
| Labette | KS | 21,776 | 2,416 |
| Montgomery | KS | 34,254 | 30,538 |
| Neosho | KS | 16,046 | 384 |
| Wilson | KS | 9,474 | 9,087 |
| Woodson | KS | 3,240 | 414 |
| Craig | OK | 15,158 | 1,632 |
| Nowata | OK | 10,528 | 9,596 |
| Rogers | OK | 85,654 | 4,531 |
| Total | | 205,797 | 59,358 |
| *Data Source: 2010 US Census* | | | |

Based on 2010 census tract data and a GIS map of municipalities in the watershed (Figure 1-5) estimates of the population served by public sewers (54.8%) and those with septic tanks that are not served by public sewers (45.2%) in 2010 are presented in Table 1-4.

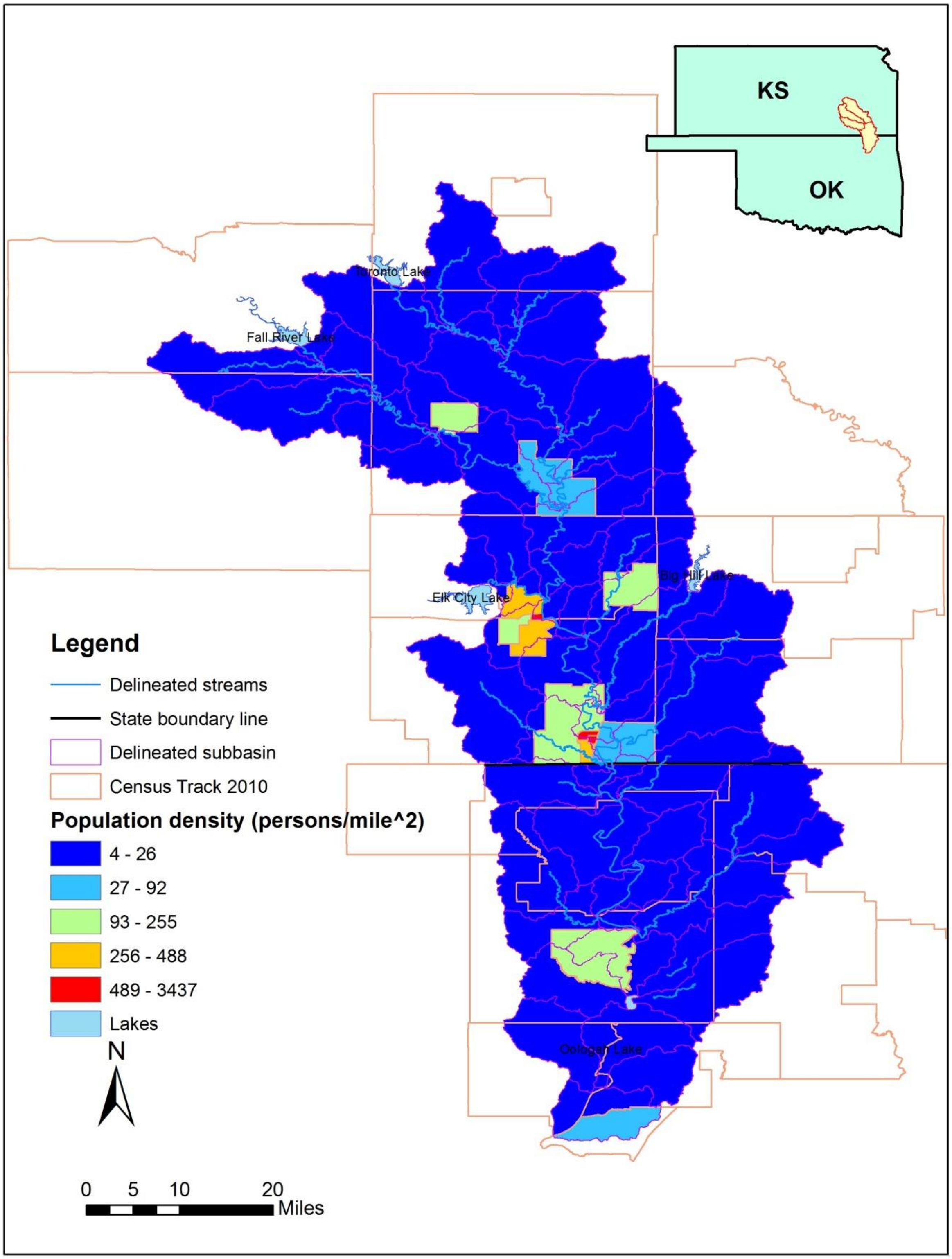


Figure 1-4 Population Density (persons per square mile) based on 2010 Census Tracts within the Counties of the Oologah Lake Watershed

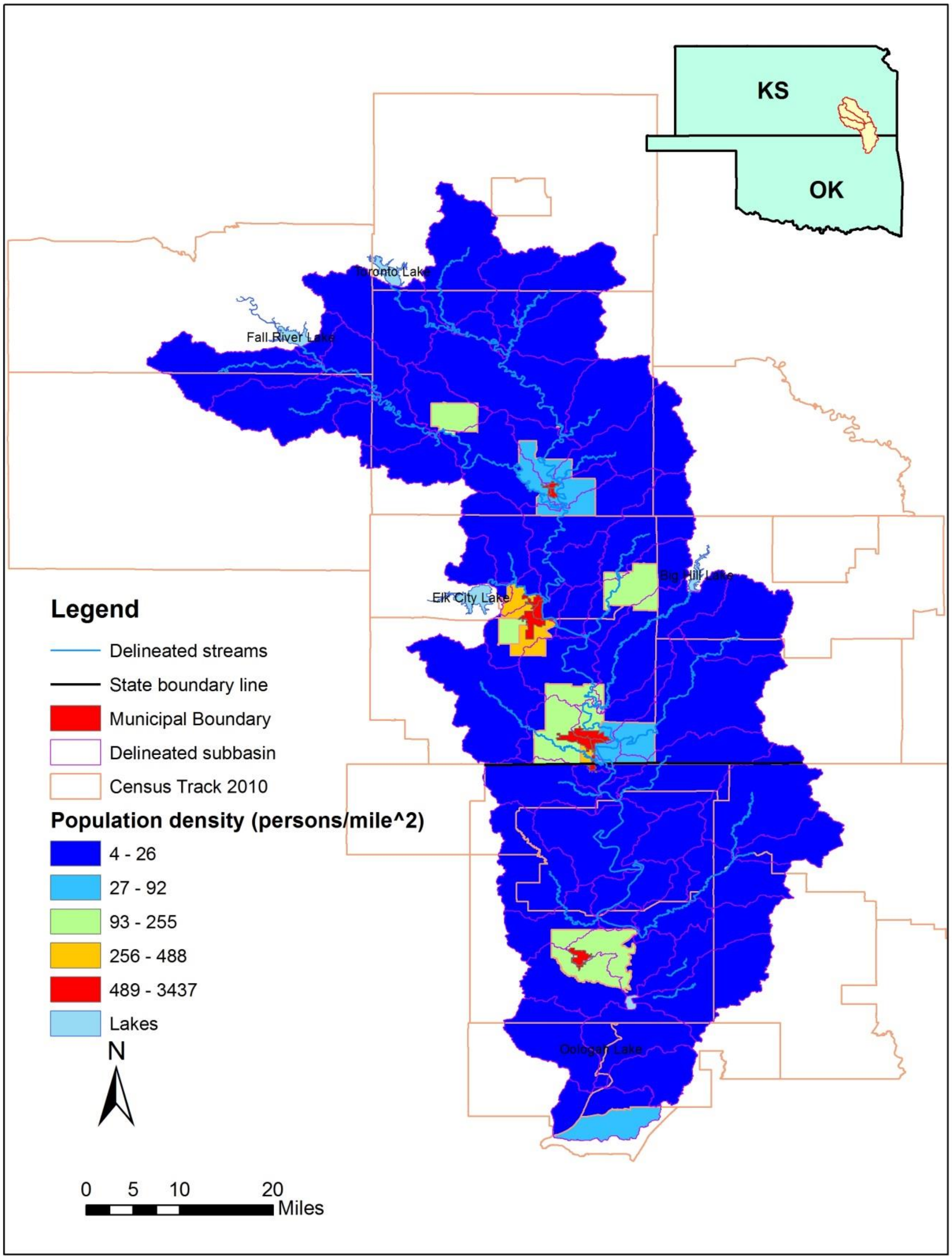


Figure 1-5 Municipal Boundaries within the Oologah Lake Watershed

Table 1-4 2010 Population Served by Public Sewer Systems in the Oologah Lake Watershed

| 2010 | Population Total | Percent of Total |
|---|---|---|
| Public Sewer | 32,528 | 54.8% |
| Septic Tank, Unsewered | 26,830 | 45.2% |
| Total | 59,358 | 100% |
| Data Source: 2000 US House Census Data | | |

## 1.3 Streamflow Characteristics

The magnitudes of annual, seasonal and daily variability of streamflow in the watershed provide essential data to characterize water and pollutant load inflows to a receiving waterbody for a water quality management study such as this TMDL assessment of Oologah Lake. Major inflow to the lake is via the Verdigris River with streamflow measured at the USGS gage 07171000 near Lenapah, OK.

Based on 30 years of hourly flow records from 1988-2017 at the Lenapah gage, long-term average flow in the Verdigris River is 2,800 cfs. During this period of record, minimum flow recorded was 0 cfs in 1989 and maximum flow was 192,000 cfs in 2007. Monthly average flow ranges from a high of 3,932 – 5,987 cfs during April through June and a low of 1,334 – 1,438 cfs from December through February.

During the year selected for lake model validation (2007), annual flow of 4,394 cfs was higher than the long-term annual average flow of 2,945 cfs and was the fourth highest annual flow recorded from 1988 to 2017. Evaluation of annual rainfall data and annual streamflow data indicates that the 2007 data set used for development of the watershed-lake model and analysis of pollutant loads for the TMDL determination represent wet hydrologic conditions for the watershed.

Flow estimates for rivers/creeks/streams and overland runoff entering the lake were simulated with the calibrated HSPF watershed model. The watershed model developed for the Oologah Lake study is summarized in Section 3.2 of this report. A technical report for the watershed model is presented in Appendix B of this report.

# 2. Problem Identification and Water Quality Targets

## 2.1 Oklahoma Water Quality Standards/Criteria

Chapters 45 and 46 of Title 785 of the Oklahoma Administrative Code (OAC) contain Oklahoma's WQS and implementation procedures, respectively. The Oklahoma Water Resources Board (OWRB) has statutory authority and responsibility concerning establishment of state water quality standards, as provided under 82 Oklahoma Statute [O.S.], §1085.30. This statute authorizes the OWRB to promulgate rules …*which establish classifications of uses of waters of the state, criteria to maintain and protect such classifications, and other standards or policies pertaining to the quality of such waters*. [O.S. 82:1085:30(A)]. Beneficial uses are designated for all waters of the state. Such uses are protected through restrictions imposed by the anti-degradation policy statement, narrative water quality criteria, and numerical criteria (OWRB, 2016). An excerpt of the Oklahoma WQS (Chapter 45, Title 785) summarizing the State of Oklahoma Anti-degradation Policy is provided in Appendix D. Table 2-1, excerpted from the 2014 Integrated Report, lists beneficial uses designated for Oologah Lake (ODEQ, 2014). Beneficial uses include:

- AES – Aesthetics
- AG – Agriculture
- NAV - Navigation
- WWAC – Warm Water Aquatic Community, Fish and Wildlife Propagation
- PBCR – Primary Body Contact Recreation
- PPWS – Public & Private Water Supply

Table 2-1 2014 Integrated Report – Oklahoma §303(d) List of Impaired Waters (Category 5a) for Oologah Lake

| Waterbody Name | Waterbody ID | AES | AG | NAV | WWAC | FISH | PBCR | PPWS |
|---|---|---|---|---|---|---|---|---|
| Oologah Lake | OK121510010020_00 | F | F | F | N | I | F | I |

F – Fully supporting; I=Insufficient Information; N – Not supporting; X – Not assessed
Source: 2010 Integrated Report, ODEQ 2010

The 2014 Integrated Report and 303(d) list is used as the basis for identifying dissolved oxygen and turbidity as the water quality constituents responsible for impairments for Fish & Wildlife Propagation (FWP) for a Warm Water Aquatic Community (WWAC) in Oologah Lake. Table 2-2 summarizes the impairment status from the 2014 Integrated Report for the Waterbody ID of Oologah Lake. Oologah Lake is designated as a Category 5a lake. Category 5 defines a waterbody where, since the water quality standard is not attained, the waterbody is impaired or threatened for one or more designated uses by a pollutant(s), and the water body requires a TMDL. This category constitutes the Section 303(d) list of waters impaired or threatened by a pollutant(s) for which one or more TMDL(s) are needed. Sub-Category 5a means that a TMDL is underway or will be scheduled. The TMDLs established in this report, which are a necessary step in the process of restoring water quality, address water quality issues related to nonattainment of the public and private water supply and warm water aquatic community beneficial uses.

Table 2-2 2014 Integrated Report – Oklahoma 303(d) List for Oologah Lake

| Waterbody Name | Waterbody ID | Size (acres) | TMDL Date | Priority | Turbidity | DO |
|---|---|---|---|---|---|---|
| Oologah Lake | OK121510010020_00 | 29,460 | 2012 | 1 | ● | ● |

## Turbidity Standards for Lakes

The following excerpt from the Oklahoma WQS [OAC 785:45-5-12(f)(7)] stipulates the turbidity numeric criterion to maintain and protect "Warm Water Aquatic Community" beneficial uses (OWRB, 2016).

*(A) Turbidity from other than natural sources shall be restricted to not exceed the following numerical limits:*

*i. Cool Water Aquatic Community/Trout Fisheries: 10 NTUs;*

*ii. Lakes: 25 NTU; and*

*iii. Other surface waters: 50 NTUs.*

*(B) In waters where background turbidity exceeds these values, turbidity from point sources will be restricted to not exceed ambient levels.*

*(C) Numerical criteria listed in (A) of this paragraph apply only to seasonal base flow conditions.*

*(D) Elevated turbidity levels may be expected during, and for several days after, a runoff event*

The abbreviated excerpt below from Chapter 46: 785:46-15-5, stipulates how water quality data will be assessed to determine support of fish and wildlife propagation as well as how the water quality target for TMDLs will be defined for turbidity.

*Assessment of Fish and Wildlife Propagation support*

*(a) Scope. The provisions of this Section shall be used to determine whether the beneficial use of Fish and Wildlife Propagation or any subcategory thereof designated in OAC 785:45 for a waterbody is supported.*

*(e) Turbidity. The criteria for turbidity stated in 785:45-5-12(f)(7) shall constitute the screening levels for turbidity. The tests for use support shall follow the default protocol in 785:46-15-4(b).*

***785:46-15-4. Default protocols***

*(b) Short term average numerical parameters.*

*(1) Short term average numerical parameters are based upon exposure periods of less than seven days. Short term average parameters to which this Section applies include, but are not limited to, sample standards and turbidity.*

*(2) A beneficial use shall be deemed to be fully supported for a given parameter whose criterion is based upon a short-term average if 10% or less of the samples for that parameter exceed the applicable screening level prescribed in this Subchapter.*

*(3) A beneficial use shall be deemed to be fully supported but threatened if the use is supported currently but the appropriate state environmental agency determines that available data indicate that during the next five years the use may become not supported due to anticipated sources or adverse trends of pollution not prevented or controlled. If data from the preceding two-year period indicate a trend away from impairment, the appropriate agency shall remove the threatened status.*

*(4) A beneficial use shall be deemed to be not supported for a given parameter whose criterion is based upon a short-term average if at least 10% of the samples for that parameter exceed the applicable screening level prescribed in this Subchapter.*

Turbidity is a measure of water clarity and is caused by suspended particles in the water column. Turbidity, however, cannot be expressed as a mass load. Total suspended solids (TSS) are therefore modeled and evaluated as a surrogate for turbidity using a site-specific relationship derived from paired TSS and turbidity measurements.

**Dissolved Oxygen Standards for Lakes**

Oklahoma water quality standards for dissolved oxygen are found in the Oklahoma Administrative Code (OAC), Title 785, Chapter 45 (OAC785:45) (2016). Compliance with the standards for dissolved oxygen is specified in relation to the surface layer of a waterbody for early life stages between April 1 and June 15 and other life stages in summer conditions between June 16 and October 15 and winter conditions between October 16 and March 31 and whole lake water column.

Table 2-3 summarizes the water quality standards for dissolved oxygen within the surface layer of a waterbody.

Table 2-3 Dissolved Oxygen Criteria to Protect Fish and Wildlife Propagation and All Subcategories Thereof. Source: OWRB (2016)

**Dissolved Oxygen Criteria to Protect Fish and Wildlife Propagation and All Subcategories Thereof [1]**

| SUBCATEGORY OF FISH AND WILDLIFE PROPAGATION (FISHERY CLASS) | DATES APPLICABLE | DO CRITERIA[4] (MINIMUM) (mg/L) | SEASONAL TEMPERATURE (°C) |
|---|---|---|---|
| **Habitat Limited Aquatic Community** | | | |
| Early Life Stages | 4/1 - 6/15 | 4.0 | 25[3] |
| Other Life Stages | | | |
| Summer Conditions | 6/16 - 10/15 | 3.0 | 32 |
| Winter Conditions | 10/16 - 3/31 | 3.0 | 18 |
| **Warm Water Aquatic Community[5]** | | | |
| Early Life Stages | 4/1 - 6/15 | 6.0[2] | 25[3] |
| Other Life Stages | | | |
| Summer Conditions | 6/16 - 10/15 | 5.0[2] | 32 |
| Winter Conditions | 10/16 - 3/31 | 5.0 | 18 |
| **Cool Water Aquatic Community & Trout** | | | |
| Early Life Stages | 3/1 - 5/31 | 7.0[2] | 22 |
| Other Life Stages | | | |
| Summer Conditions | 6/1 - 10/15 | 6.0[2] | 29 |
| Winter Conditions | 10/16 - 2/28 | 6.0 | 18 |

1 For use in calculation of the allowable load.
2 Because of natural diurnal dissolved oxygen fluctuation, a 1.0 mg/l dissolved oxygen concentration deficit shall be allowed for not more than eight (8) hours during any twenty-four (24) hour period.
3 Discharge limits necessary to meet summer conditions will apply from June 1 of each year. However, where discharge limits based on Early Life Stage (spring) conditions are more restrictive, those limits may be extended to July 1.
4 DO shall not exhibit concentrations less than the criteria magnitudes expressed above in greater than 10% of the samples as assessed across all life stages and seasons.
5 For Lakes, the warm water aquatic community dissolved oxygen criteria expressed above are applicable to the surface waters.

In addition to water quality standards for dissolved oxygen within the surface layer, the Oklahoma water quality standards for dissolved oxygen also specify criteria based on the percent volume of the lake or percent of the water column (OAC785:45, 2016).

*For lakes, no more than 50% of the water volume shall exhibit a DO concentration less than 2.0 mg/L. If no volumetric data is available, then no more than 70% of the water column at any given sample site shall exhibit a DO concentration less than 2.0 mg/L. If a lake specific study including historical analysis demonstrates that a different percent volume or percent water column than described above is protective of the WWAC use, then that lake specific result takes precedence.*

## 2.2 Overview of Water Quality Problems and Issues

Based on an assessment of water quality monitoring data for the 2014 Integrated Report, Oklahoma DEQ has determined that Oologah Lake is not supporting its designated uses for Fish and Wildlife Propagation for a Warm Water Aquatic Community because of high levels of turbidity and low dissolved oxygen. Within the 4,339 square mile drainage basin, external sources of nutrient and TSS loading related to low dissolved oxygen and turbidity problems in Oologah Lake include loading from the Verdigris River basin and the outflows from the four federal reservoirs: Toronto Lake, Fall River Lake, Elk City Lake, and Big Hill Lake in Kansas State. In addition to the major inflow from the Verdigris River, nutrient loading to Oologah Lake is also contributed by local land use driven loading from several small tributaries and direct overland runoff. A TMDL assessment for Oologah Lake is required by the CWA to determine appropriate load reductions for these external sources that could be implemented to achieve compliance with water quality standards for the lake.

Table 2-4 summarizes the site designation names, station numbers and geographic locations of the water quality monitoring stations maintained by OWRB and the USACE Tulsa District in Oologah Lake. Figure 2-1 shows the locations of the OWRB and USACE stations in the lake.

Table 2-4 OWRB and USACE Water Quality Monitoring Stations
for Oologah Lake (WBID OK121510010020-00)

| Station_ID | Agency | Longitude (W) | Latitude (N) |
|---|---|---|---|
| 121510010020-01 | OWRB | -95.676092 | 36.422569 |
| 121510010020-02 | OWRB | -95.656497 | 36.436083 |
| 121510010020-03 | OWRB | -95.599028 | 36.455378 |
| 121510010020-04 | OWRB | -95.596817 | 36.493028 |
| 121510010020-05 | OWRB | -95.606822 | 36.537147 |
| 121510010020-06 | OWRB | -95.587617 | 36.573406 |
| 121510010020-07 | OWRB | -95.565636 | 36.603967 |
| OOL_1 | USACE | -95.677917 | 36.422333 |
| OOL_2 | USACE | -95.610233 | 36.493650 |
| OOL_3 | USACE | -95.599417 | 36.554933 |
| OOL_4 | USACE | -95.575833 | 36.599883 |
| OOL_5 | USACE | -95.579333 | 36.649633 |

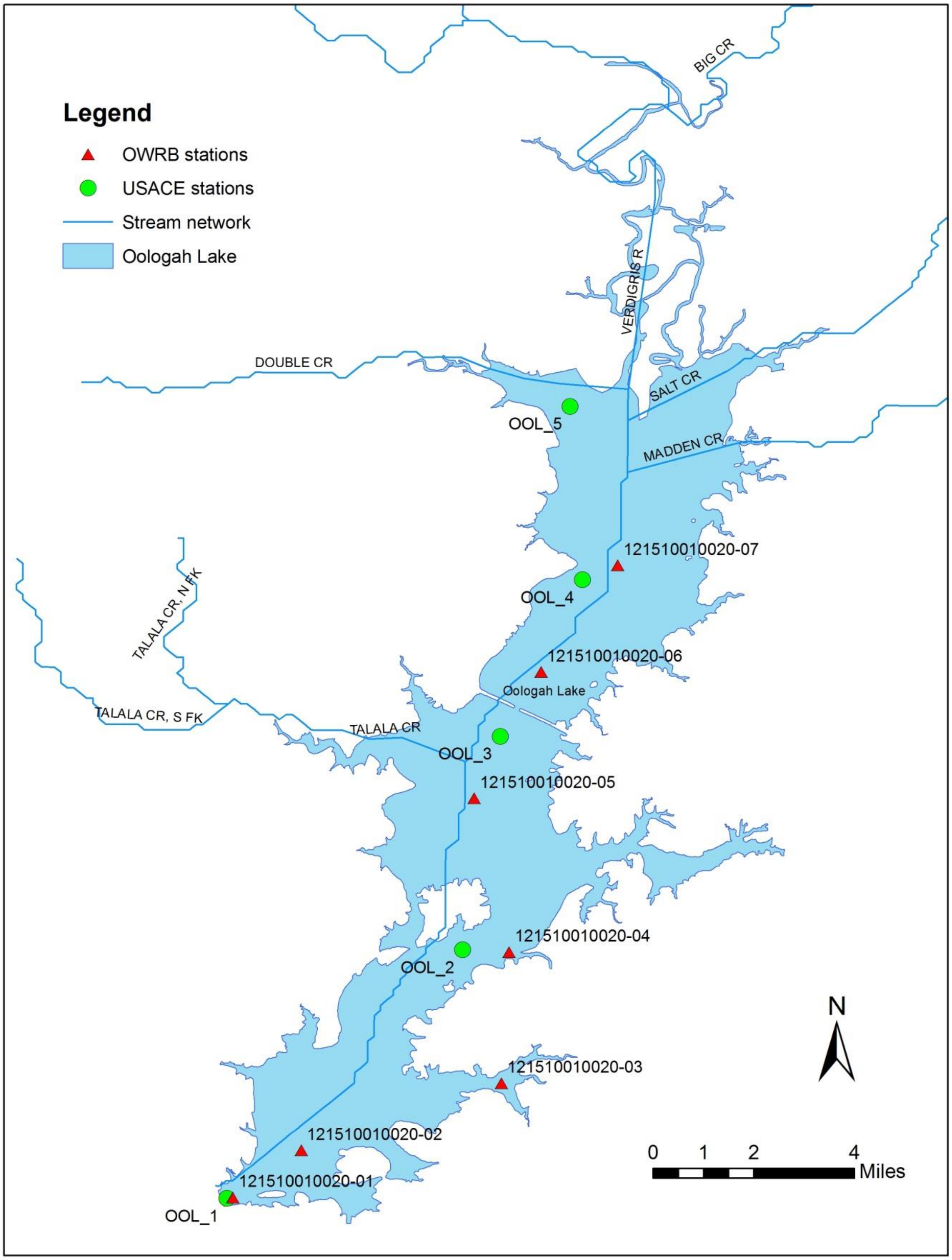


Figure 2-1 OWRB BUMP and USACE Water Quality Monitoring Stations for Oologah Lake

## 2.3 Water Quality Observations and Targets for Turbidity and Dissolved Oxygen

Water quality targets adopted for the Oologah Lake TMDL study for turbidity and dissolved oxygen are as follows:

- Turbidity: no more than 10% of surface layer turbidity samples greater than 25 NTU based on long-term record of most recent 10 years
- Dissolved Oxygen for early life stages from April 1 to June 15: Within the surface/epilimnion layer for protection of fish and wildlife propagation in warm water aquatic community DO no less than 6 mg/L.
- Dissolved Oxygen for other life stages in summer conditions June 16 to October 15: Within the surface/epilimnion layer for protection of fish and wildlife propagation in warm water aquatic community DO no less than 5 mg/L.
- Dissolved Oxygen for other life stages in winter conditions October 16 to March 31: Within the surface/epilimnion layer for protection of fish and wildlife propagation in warm water aquatic community DO no less than 5 mg/L.
- Dissolved Oxygen: Anoxic volume of the lake, defined by a DO target level of 2 mg/L, shall not exceed 50% of the lake volume based on volumetric data or 70% of the water column at any given sample site.

As stipulated in the Implementation Procedures for Oklahoma Water Quality Standards [785:46-15-3c], the most recent 10 years of water quality data are to be used as the basis for assessment of the water quality conditions and beneficial use support for a waterbody (OWRB, 2014a). Oologah Lake was listed as impaired in the 2014 Integrated Report based on an analysis of 10 years of records for turbidity and DO data collected by OWRB from October 2004 through May 2014.

OWRB provided data files used for analysis of the lake water quality data to support impairment determinations for the 2014 Integrated Report and 303(d) list. Inspection of the data sets showed that data were available from the Oologah Lake OWRB BUMP surveys for the period from October 2004 through May 2014. Data were also available from the USACE Tulsa District for October 2002 through April 2009. The dates presented in Table 2-5, Table 2-6 and Table 2-7 show the date ranges of the available water quality data used by OWRB for the 2014 Integrated Report and 303(d) list.

Summary statistics presented in Table 2-5 through Table 2-7 are based on data collected by OWRB from 2004 to 2014 and by USACE from 2002 to 2009. These data were used by OWRB for evaluation of the impairments of Oologah Lake. Time series of turbidity, shown in Figure 2-2, are the data collected at the USACE and OWRB monitoring sites listed in Table 2-5.

Figure 2-3 presents surface to bottom water column data for dissolved oxygen for the OWRB and USACE monitoring sites located near the dam. Data plotted in Figure 2-2 and Figure 2-3 show both OWRB and USACE data. Data, other than that available from OWRB BUMP surveys, is presented to provide Oklahoma DEQ, EPA Region 6, and Stakeholders with more information about observed turbidity and dissolved oxygen over the 10-year period used for assessment. A listing of the water quality data sets collected by the USACE Tulsa District in 2006-2007 that was used to support development of the watershed and lake models for this TMDL are presented in Appendix I.

The number of data points shown in Table 2-5 for the OWRB and USACE turbidity datasets is 81 and 911, respectively. Figure 2-2 shows both OWRB and USACE surface layer turbidity data, in order to provide Stakeholders with more information about observed turbidity over the 10-year period.

Table 2-5 Summary Statistics for USACE and OWRB Observed Surface Layer Turbidity (in NTUs) in Oologah Lake

| | USACE | OWRB | WQ Target |
|---|---|---|---|
| Count | 911 | 81 | |
| Start Date | 10/22/2002 | 10/18/2004 | |
| End Date | 4/15/2009 | 5/19/2014 | |
| Min | 0.1 | 6 | |
| 10th %ile | 5.4 | 9 | |
| 25th %ile | 8.8 | 12 | |
| Mean | 31.0 | 27.4 | |
| 50th %ile | 19.3 | 18 | |
| 75th %ile | 39.5 | 34 | |
| 90th %ile | 67.6 | 56 | 25 |
| Max | 599.8 | 111 | |

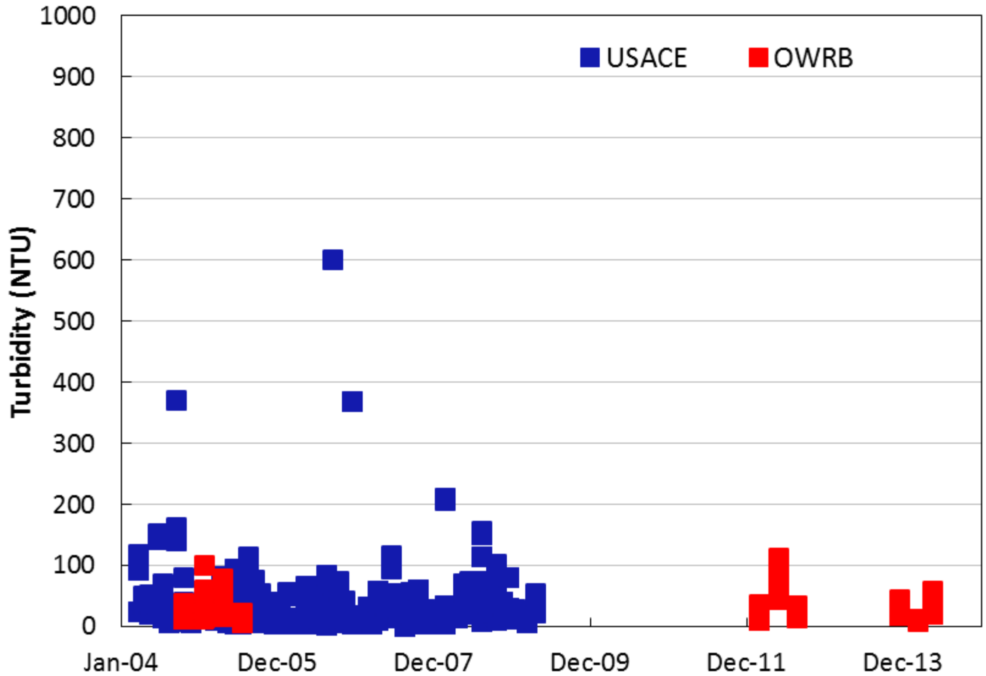


Figure 2-2  Observed Surface Layer Turbidity in Oologah Lake

As can be seen in the data presented in Table 2-5, the 90th percentile for observed turbidity in Oologah Lake exceeds the water quality criteria target of 25 NTU.  The observed data used by OWRB for the 2014 303(d) list documents that water quality conditions in Oologah Lake did not support the Warm Water Aquatic Community use for Fish and Wildlife Propagation because of impairments relating to turbidity and dissolved oxygen.

Based on an assessment of water column dissolved oxygen data for the 2014 303(d) list, OWRB has determined that Oologah Lake is not fully supporting its beneficial uses for Fish and Wildlife Propagation because of the anoxic percentage of the water column of dissolved oxygen during summer conditions. As shown in

Table 2-6, vertical profiles of dissolved oxygen collected at the OWRB station near the dam (121510010020-01) showed that more than 70% of the water column was less than the 2 mg/L target for anoxia within the hypolimnion for one sampling survey (Aug-5-2008) during the period from 2003-2008.

The Code of Federal Regulations [40 CFR §130.7(c)(1)] states that, "*TMDLs shall be established at levels necessary to attain and maintain the applicable narrative and numerical water quality standards*." The water quality targets established for Oologah Lake must demonstrate compliance with the numeric criteria prescribed for Fish and Wildlife Propagation, Warm Water Aquatic Community and NLW lakes in the Oklahoma WQS.

Water quality variables that relate to impairments of Oologah Lake for turbidity (water clarity) include suspended sediment, detrital particulate organic carbon, color (dissolved organic carbon) and algae biomass as chlorophyll-a. Water quality constituents that relate to impairments for dissolved oxygen include algae biomass, TOC, CBOD, and ammonia nitrogen.

Although the water quality criteria for water clarity is based on turbidity, Total Suspended Solids (TSS) is commonly used as a surrogate indicator of water clarity for development of the mass balance-based loading analysis required for the TMDL determination. A site-specific relationship based on paired measurements collected in Oologah Lake must be developed therefore to transform modeled TSS data to modeled turbidity to be able to compare the effect of sediment loading of TSS from the watershed on compliance with the water quality criteria for turbidity in the lake. The methodology used to develop the TSS-turbidity relationship is summarized in Section 4 of this report.

Table 2-6 Water Column Observations of Dissolved Oxygen at OWRB and USACE Stations Near the Dam in Oologah Lake

| **Date** | **Water Column < 2 mg/l** |
|---|---|
| Target--> | <70% |
| USACE Station | OOL-1 |
| 6/24/2003 | 0.0% |
| 7/15/2003 | 2.7% |
| 7/15/2003 | 52.4% |
| 7/29/2003 | 32.4% |
| 8/12/2003 | 45.3% |
| 8/26/2003 | 66.2% |
| 7/13/2004 | 0.0% |
| 8/10/2004 | 3.1% |
| 7/12/2005 | 0.0% |
| 7/12/2005 | 22.2% |
| 8/16/2005 | 20.5% |
| 6/15/2006 | 50.5% |
| 7/11/2006 | 41.0% |
| 8/15/2006 | 23.7% |
| 6/12/2007 | 0.0% |
| 7/10/2007 | 35.0% |
| 8/14/2007 | 30.8% |
| 6/11/2008 | 0.0% |
| 7/8/2008 | 6.5% |
| 8/12/2008 | 0.0% |
| OWRB Station | 121510010020-01 |
| 7/21/2003 | 48.8% |
| 7/18/2005 | 56.6% |
| 8/5/2008 | 86.6% |

Table 2-7 Observations of Dissolved Oxygen at OWRB and USACE Stations

| Date | Early stages (4/1-6/15) | Other stages (6/16-3/31) |
|---|---|---|
| Target--> | > 6.0 mg/l | > 5.0 mg/l |
| USACE Stations | | |
| 2003 | 6.6 | 5.9 |
| 2004 | 7.1 | 6.9 |
| 2005 | 6.4 | 6.4 |
| 2006 | 6.7 | 6.4 |
| 2007 | 4.9 | 6.2 |
| 2008 | 6.8 | 6.0 |
| OWRB Stations | | |
| 2003 | 7.1 | 5.8 |
| 2004 | | 9.6 |
| 2007 | | 10.4 |
| 2008 | 7.0 | 6.5 |

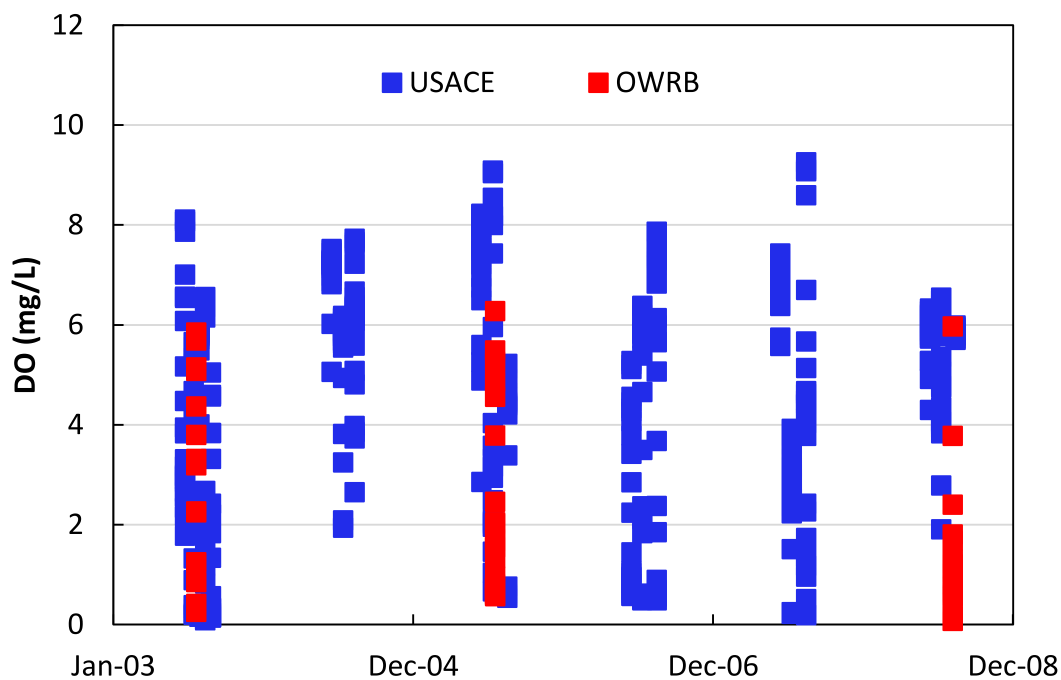


Figure 2-3 Water Column Observations of Dissolved Oxygen at OWRB and USACE Stations near the Dam in Oologah Lake

# 3. Pollutant Source Assessment

This section includes an assessment of the known and suspected sources of nutrients, organic matter and sediments contributing to the turbidity and dissolved oxygen impairments of Oologah Lake. Pollutant sources identified are categorized and quantified to the extent that reliable information is available. Generally, sediment and nutrient loadings causing impairment of lakes originate from point or nonpoint sources of pollution. Point source discharges are regulated under permits through the NPDES program, which includes stormwater discharges covered by Municipal Separate Storm Sewer System (MS4) permits. Nonpoint sources are diffuse sources that typically cannot be identified as entering a waterbody through a discrete conveyance, such as a pipe, at a single location. Nonpoint sources may originate from rainfall runoff and landscape dependent characteristics and processes that contribute sediment, organic matter and nutrient loads from runoff to surface waters. For the TMDLs presented in this report, all sources of pollutant loading not regulated under the NPDES permit system are considered nonpoint sources.

Under 40 CFR, §122.2, a point source is described as an identifiable, confined, and discrete conveyance from which pollutants are, or may be, discharged to surface waters. NPDES permitted facilities classified as point sources that may contribute sediment, organic matter and nutrient loading include:

- NPDES Municipal wastewater treatment plant (WWTP) discharges;
- NPDES Industrial WWTP discharges;
- Municipal No-discharge WWTPs;
- NPDES Municipal separate storm sewer system (MS4) discharges;
- Sanitary Sewer Overflows (SSO)
- NPDES Construction Site stormwater discharges;
- NPDES Multi-Sector General Permits (MSGP) stormwater discharges; and
- NPDES Concentrated Animal Feeding Operation (CAFO)
- NPDES Poultry Feeding Operation (PFO)

All of the above listed types of permitted facilities are present in the Oologah Lake study area. Facilities under multi-sector general permits (MSGP), and NPDES permitted construction sites, which are regulated under the EPA NPDES Program, can all contribute sediment loading to the lake. Within the Oologah Lake watershed there are a number of construction site permits and multi-sector general permits that have been issued and will be addressed in Section 3.1.3 and 3.1.4 of this report. 40 CFR §130.2(h) requires that NPDES-regulated stormwater discharges must be addressed by the wasteload allocation (WLA) component of a TMDL assessment.

## 3.1 Assessment of Point Sources

### *3.1.1 NPDES Municipal and Industrial Wastewater Dischargers*

All NPDES-permitted municipal and industrial wastewater facilities located within the Verdigris River watershed are listed in Appendix A of this TMDL report. Point source wastewater facilities are identified by EPA as either major or minor NPDES permitted dischargers based on effluent flow rate or other factors. All of the municipal and industrial wastewater discharge facilities listed in Table 3-1 discharge effluent to tributaries of the Verdigris River basin. Six (6) of the NPDES point source dischargers are municipal wastewater treatment facilities (SIC code=4952) and one (1) NPDES discharge (KS0000248: Coffeyville Resources Refining & Marketing) is a petroleum refining facility (SIC code=2911). The South Coffeyville Public Works Authority (PWA) (OK0020117) is a municipal wastewater treatment facility located in Oklahoma and the other five (5) wastewater treatment plants are located in Kansas within the Verdigris River basin watershed. There are no municipal or industrial NPDES permitted facilities that discharge directly into Oologah Lake. Any wastewater pollutant loading contributed by NPDES point source discharges is accounted for in the watershed-lake model framework as point source inputs to tributary reach catchments of the HSPF watershed model as shown in Table 3-1. NPDES facilities listed in Table 3-1 were selected for input to the HSPF watershed model if the effluent flow rate was larger than 0.1 MGD. Figure 3-1 shows the locations of the NPDES wastewater point sources included in the watershed model. Effluent flow rate and effluent concentration data used to assign input point source discharge data for the NPDES wastewater facilities to the HSPF watershed model are presented in Appendix H of this TMDL report.

Table 3-1 NPDES Wastewater Treatment Point Source Dischargers to Oologah Lake Watershed

| NPDES ID | FACILITY NAME | Receiving Water | Latitude (N) | Longitude (W) | Design flow (MGD) |
|---|---|---|---|---|---|
| OK0020117 | SOUTH COFFEYVILLE PWA (SIC=4952) | Lower Onion Creek | 36.998639 | -95.61236 | 0.15 |
| KS0050733 | COFFEYVILLE, CITY OF(SIC=4952) | Lower Onion Creek | 37.006469 | -95.60967 | 5 |
| KS0000248 | COFFEYVILLE RESOURCES REFINING & MARKETING (SIC=2911) | Claymore Creek | 37.043300 | -95.61080 | 2.2 |
| KS0095486 | INDEPENDENCE WASTEWATER PLANT(SIC=4952) | Choteau Creek | 37.228841 | -95.69294 | 3.0 |
| KS0094803 | CHERRYVALE WASTEWATER PLANT WADE WEBBER, PUBLIC WORKS DIR. (SIC=4952) | Drum Creek | 37.276028 | -95.58256 | 0.3 |
| KS0025658 | NEODESHA, CITY OF(SIC=4952) | Washington Branch | 37.432093 | -95.68369 | 0.5 |
| KS0045985 | FREDONIA WASTE WATER TREATMENT PLANT C/O CITY HALL(SIC=4952) | Salt Creek | 37.532704 | -95.82647 | 0.47 |

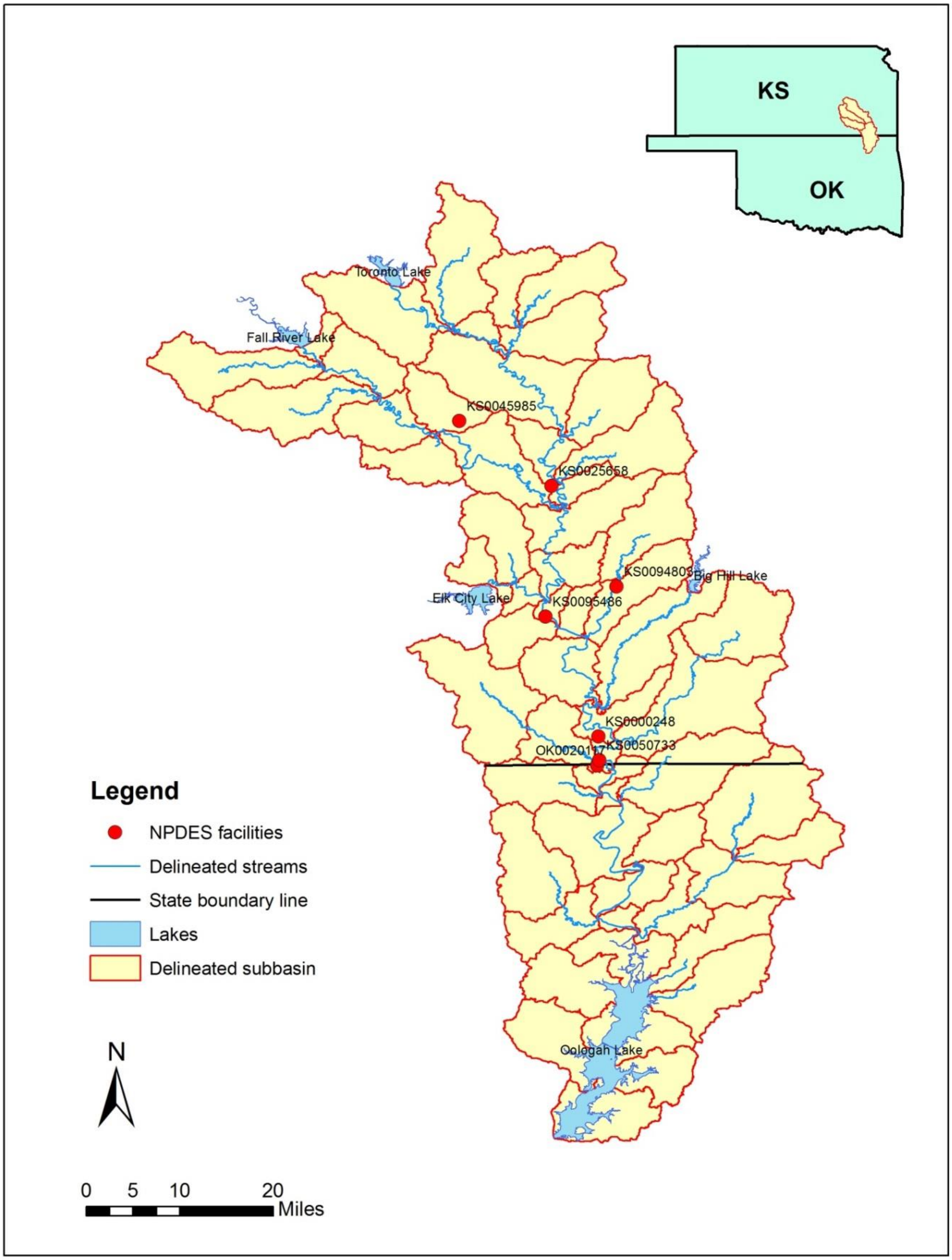


Figure 3-1 NPDES Wastewater Dischargers to Oologah Lake Watershed

### 3.1.2 Municipal No-Discharge Wastewater Plants

No-discharge wastewater facilities do not discharge effluent to streams of the watershed or directly to Oologah Lake. Seven no-discharge wastewater facilities in the Kansas portion of the Verdigris River watershed are identified in Table 3-2 and shown on the map in Figure 3-2. For the purposes of this TMDL study, no-discharge facilities are not considered as source of flow, sediment, organic matter or nutrient loading to either Oologah Lake or streams of the watershed.

It is possible, however, that the wastewater collection system associated with no-discharge facilities could be a source of pollutant loading to streams, or that discharges may occur during large rainfall events that exceed the storage capacity of the no-discharge wastewater system. These types of unauthorized wastewater discharges, typically reported as sanitary sewer overflows (SSOs) or bypass overflows, are listed in Appendix F and are discussed in Section 3.1.4 of this TMDL report.

Table 3-2 NPDES No-Discharge Wastewater Facilities in Oologah Lake Watershed

| FAC_NAME | NPDES_N | DESIGN_F | COUNTY | LAT (N) | LON (W) |
|---|---|---|---|---|---|
| WESTMINSTER WOODS | KSJ00015 | 0 | Wilson | 37.6425 | -95.93463 |
| FALL RIVER | KSJ00064 | | Elk | 37.5446 | -96.06243 |
| CANDLEROCK | KSJ00053 | 0 | Wilson | 37.5193 | -95.78675 |
| PARK WEST PROPERTIES | KSJ00016 | 0 | Montgomery | 37.2150 | -95.75352 |
| SPORTSMAN INN MOTEL | KSJ00053 | 0 | Wilson | 37.4353 | -95.65044 |
| USD #387 ALTOONA- | KSJ00024 | 0.006 | Wilson | 37.6687 | -95.65258 |
| KDWP&T - ELK CITY | KSJ00024 | 0.0006 | Montgomery | 37.2831 | -95.79796 |

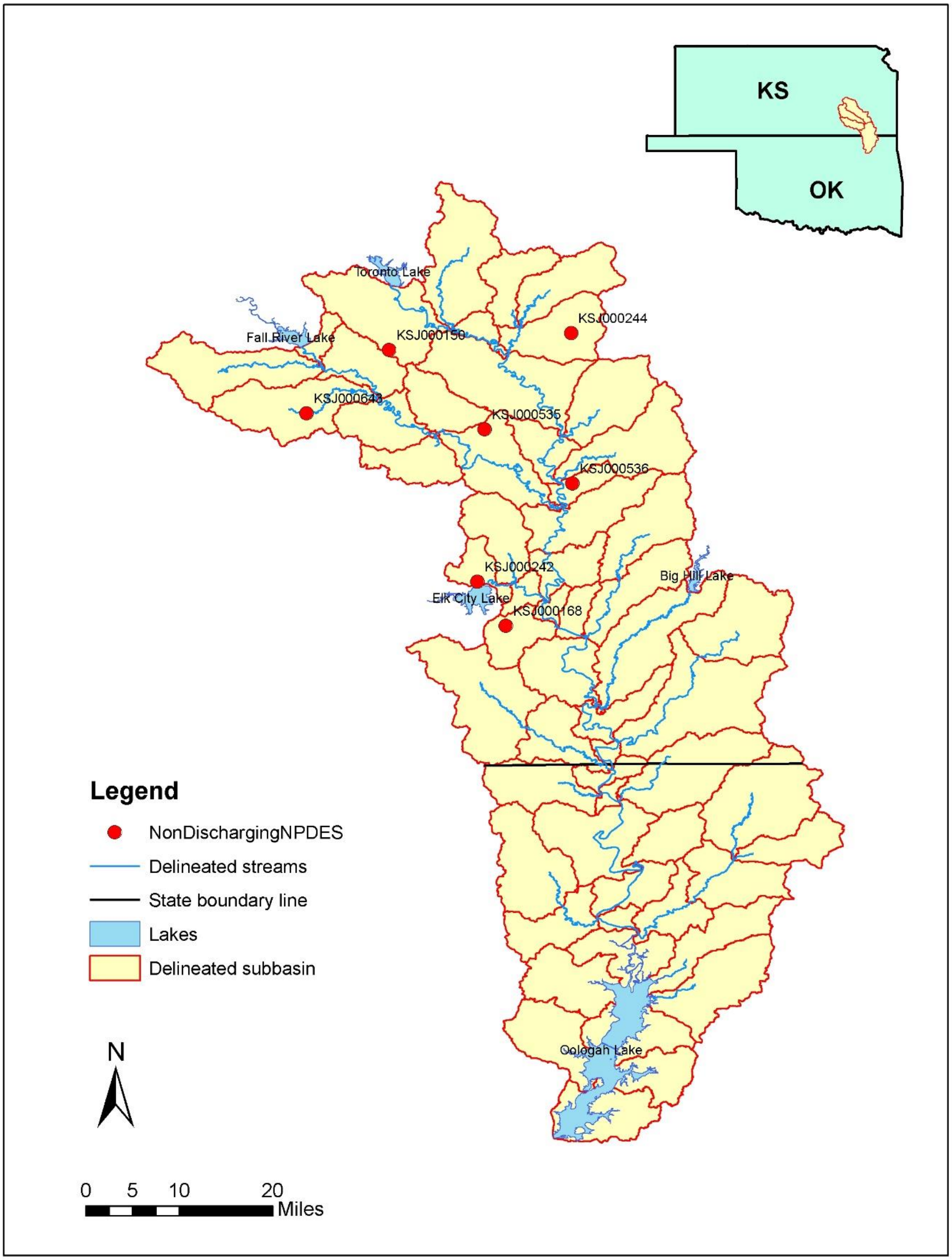


Figure 3-2 Location of NPDES No-Discharge WWTP Facilities in Oologah Lake Watershed

### *3.1.3 NPDES Municipal Separate Storm Sewer System (MS4)*

In 1990 the EPA developed rules establishing Phase I of the NPDES Stormwater Program, designed to prevent pollutants from either being washed off by stormwater runoff into municipal separate storm sewer systems (MS4s) or dumped directly into the stormwater system and then discharged into local receiving water bodies (USEPA, 2005). Phase I of the program required operators of medium and large MS4s, defined as facilities serving urban populations of 100,000 or greater, to implement a stormwater management program as a means to control polluted urban runoff discharges to surface waters. Approved stormwater management programs for medium and large MS4s are required to address a variety of water quality-related issues, including roadway runoff management, municipal-owned operations, and hazardous waste treatment. There are no Phase I MS4 permits within the Verdigris River watershed.

Phase II of the rule extends coverage of the NPDES stormwater program to certain smaller urban areas with stormwater systems. Small MS4s are defined as any MS4 that is not defined as a medium or large MS4 covered by Phase I of the NPDES Stormwater Program. Phase II requires operators of regulated small MS4s to obtain NPDES permits and develop stormwater management programs. Small MS4 stormwater programs are designed to reduce discharges of pollutants to the "maximum extent practicable," protect water quality, and satisfy appropriate water quality requirements of the CWA. Small MS4 stormwater programs must address the following minimum control measures:

- Public Education and Outreach;
- Public Participation/Involvement;
- Illicit Discharge Detection and Elimination;
- Construction Site Runoff Control;
- Post- Construction Runoff Control; and
- Pollution Prevention and Good Housekeeping.

The small MS4 General Permit for communities in Oklahoma became effective on February 8, 2005. DEQ provides information on the current status of the MS4 program on the agency website (http://www.deq.state.ok.us/WQDnew/stormwater/ms4/). There are no pollutant contributions from Phase II MS4 permits in the Oklahoma portion of the Middle Verdigris River basin in Rogers, Nowata, and Washington counties. In Kansas, the City of Coffeyville has been issued a Phase II MS4 Stormwater Program permit by the Kansas Department of Health and Environment (KDHE) (Table 3-3 and Figure 3-3).

As there are no numeric load limits associated with the Coffeyville MS4 permit, any pollutant loading from the City of Coffeyville is included as urban runoff within the sub-watershed defined for the HSPF model that includes the City of Coffeyville. As the stormwater loading contributed by Coffeyville is included as nonpoint source urban runoff in the HSPF watershed model, the Coffeyville MS4 permit is not included as a point source Waste Load Allocation (WLA) for purposes of this TMDL study. The urban stormwater contribution of flow and pollutant loading from Coffeyville is included in the compilation of total nonpoint source loading for the HSPF model domain and will be accounted for by the Load Allocation (LA) estimated for the Oologah Lake TMDL.

Table 3-3 Phase II MS4 Stormwater Facility in Oologah Lake Watershed

| FAC_NAME | NPDES_NO | NPDES_TYPE | COUNTY | LATITUDE (N) | LONGITUDE (W) |
|---|---|---|---|---|---|
| COFFEYVILLE, CITY OF, KANSAS | KSR440002 | STORMWATER | Montgomery | 37.037388 | -95.616865 |

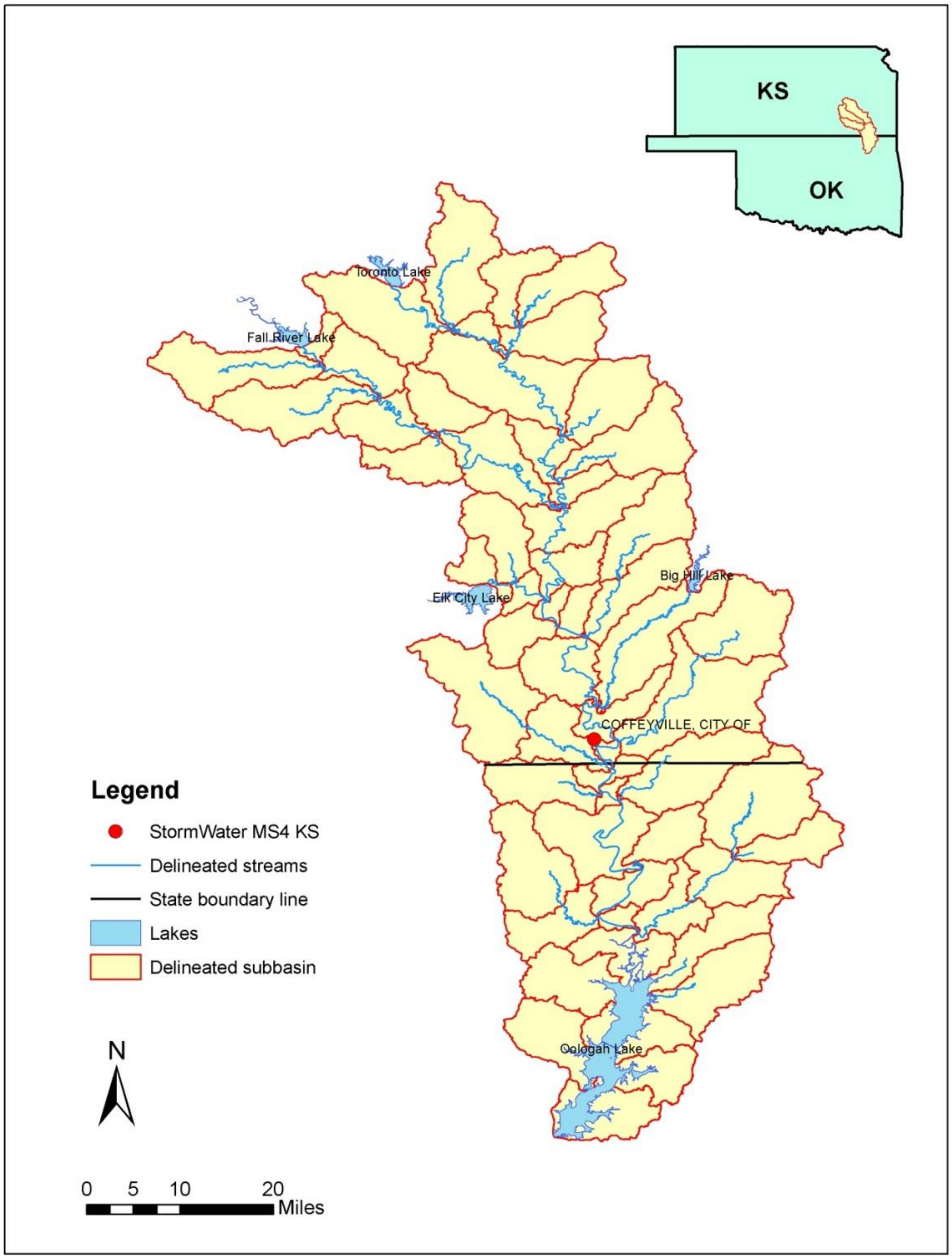


Figure 3-3 Location of Phase II MS4 Stormwater Facility in Oologah Lake Watershed

### 3.1.4 Sanitary Sewer Overflow (SSO)

Sanitary sewer overflows (SSO) from wastewater collection systems of discharging WWTP facilities, although infrequent, can be a major source of pollutant loading to streams. SSOs have existed since the introduction of separate sanitary sewers, and most are caused by blockage of sewer pipes by grease, tree roots, and other debris that clog sewer lines, by sewer line breaks and leaks, cross connections with storm sewers, and inflow and infiltration of groundwater into sanitary sewers. SSOs are NPDES permit violations that must be addressed by the responsible NPDES permit holder.

The reporting of SSOs has been strongly encouraged by EPA, primarily through enforcement and monetary fines. While not all sewer overflows are reported, DEQ maintains a database on reported SSOs. At the City of Delaware, there were 13 overflow events reported during the years from 1993 to 2013 that spilled more than 1,000 gallons with a maximum bypass volume of 600,000 gallons. At the City of Nowata, there were 7 overflows reported during the years from 1992 to 2017 that spilled more than 1,000 gallons with a maximum bypass volume of 48,000 gallons. At the City of South Coffeyville, there were 3 overflows reported during the years from 1992 to 2008 that spilled more than 1,000 gallons with a maximum bypass volume of 6,030,000 gallons. Table 3-4 summarizes the SSO bypass occurrences in the municipalities of Delaware, Nowata, and South Coffeyville. A list of SSO bypass events for these cities is presented in Appendix F.

Table 3-4 Summary of Sanitary Sewer Overflow (SSO) Bypass (> 1000 gallons) Occurrences in the Oologah Lake Watershed

| City Name | Bypass Volume (gallons) | Number Events | Date Range | | Max. Bypass Volume (gallons) |
|---|---|---|---|---|---|
| | | | From | To | |
| Delaware, S21502 | 1,903,550 | 13 | 4/7/1993 | 5/30/2013 | 600,000 |
| Nowata, S21503 | 70,348 | 7 | 7/15/1992 | 4/27/2017 | 48,000 |
| South Coffeyville, S21501 | 11,730,000 | 3 | 7/14/1992 | 1/4/2008 | 6,030,000 |

### 3.1.5 NPDES Construction Site Permits

The Oklahoma Department of Environmental Quality (DEQ) has issued the "General Permit OKR10 for Stormwater Discharges from Construction Activities within the State of Oklahoma". Permit authorizations are required for construction activities that disturb more than one acre or less than one acre if the construction activity is part of a larger common plan of development that totals at least one acre. This includes the installation, or relocation, of water or sewer lines that have the potential to disturb more than one acre. Construction activities that are on Indian Country Lands or are at oil and gas exploration and production related industry and pipeline operations that are under the jurisdiction of the Oklahoma Corporation Commission are regulated by the US Environmental Protection Agency.

A permit authorization to discharge storm water from activity at a construction site must be obtained prior to the commencement of any soil disturbing activities. The owner/operator must also develop and implement a Storm Water Pollution Prevention Plan (SWP3) for the construction site. The SWP3 shall provide information that pertains to the site description, storm water controls, maintenance, inspections and non-storm water discharges. Permit authorizations are terminated at the completion of the project or when there is a change of owner/operator for the entire project. Permit termination means that all of the temporary sediment control measures have been removed and that the site has had 70 percent vegetative cover established. The locations, and year, of the six-construction site permits within the Oologah Lake watershed are shown in Figure 3-4. Table 3-5 summarizes the information available for the construction site permits issued from 2012 (n=3), 2013 (n=2), and 2014 (n=1) where the issue date of the permit was available.

Table 3-5 Construction Site Permits Issued in the Oologah Lake Watershed

| Permit # | Permittee | Facility Name | County | Date Issued |
|---|---|---|---|---|
| OKR1020686 | RWD No 3 Rogers County | Tacora Water Treatment Plant Improvement Project | Rogers | 9/28/2012 |
| OKR1020692 | Becco Contractors Inc. | ODOT JP 23129 04 | Nowata | 11/5/2012 |
| OKR1020860 | Oklahoma Conservation Commission | Bacon-251 AML Project | Rogers | 10/19/2012 |
| OKR1022590 | C Gawf Construction Inc. | ODOT JP 25524 05 | Rogers | 9/18/2013 |
| OKR1022931 | Cherokee Nation Entertainment | South Coffeyville Casino | Nowata | 12/20/2013 |
| OKR1023313 | Belk Bridge Inc. | ODOT JP 27818 04 | Nowata | 5/8/2014 |

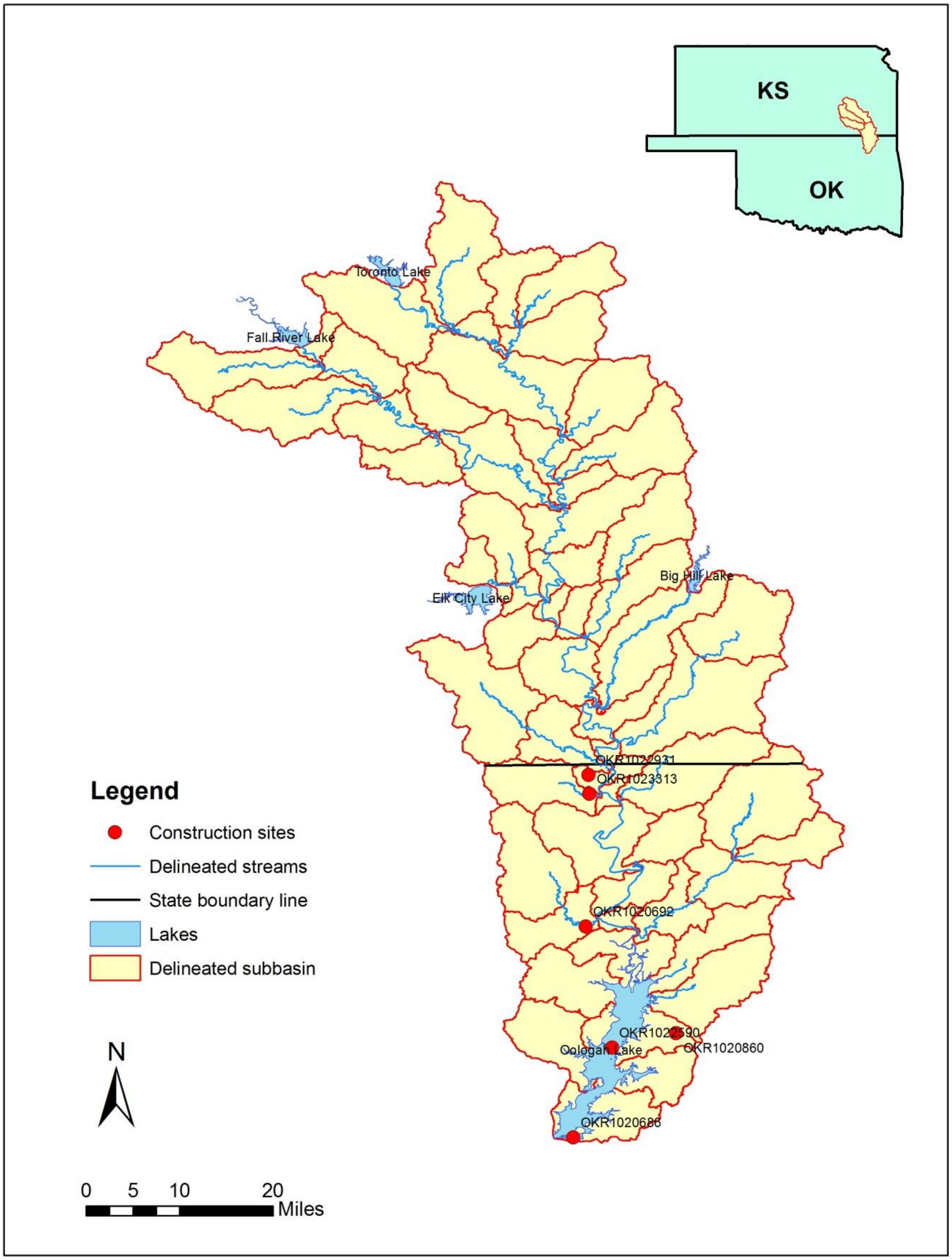


Figure 3-4 Construction Site Permits in Oologah Lake Watershed

### 3.1.6 NPDES Multi-Sector General Permits (MSGP) for Industrial Sites

NPDES permit authorizations are required for stormwater discharges from 9 sectors of SIC-coded industrial activities listed in the OKR05 Multi-Sector General Permit (DEQ, 2012). Industrial activities that are on Indian Country Lands or are at oil and gas exploration and production related industry and pipeline operations that are under the jurisdiction of the Oklahoma Corporation Commission are regulated by the US Environmental Protection Agency.

An NPDES permit authorization to discharge storm water from an industrial activity must be obtained prior to the start of any operations. The owner/operator permit holder must also develop and implement a Storm Water Pollution Prevention Plan (SWP3) for the industrial facility maintained at the site. The SWP3 provides information that pertains to the site description, storm water controls, maintenance, inspections and non-storm water discharges. Permit authorizations are terminated when operations have ceased and there no longer are discharges of storm water associated with industrial activity from the facility. Table 3-6, organized by facility name and the permit identification numbers, lists the MSGP industrial site permits issued in the Oologah Lake watershed. The locations of the industrial site MSGP permits are shown in Figure 3-5.

Table 3-6 Industrial Site MSGP Permits Issued in Oologah Lake Watershed

| Permit # | Permittee | Facility Name | County | Date Issued |
|---|---|---|---|---|
| OKR050275 | Jensen International, Inc. | Jencast Division of Jensen International, Inc. | Nowata | 10/27/2011 |
| OKR050642 | Industrial Piping Specialists, Inc. | Industrial Piping Specialists, Inc. | Tulsa | 10/17/2011 |
| OKR051197 | Collins Auto Salvage | Collins Auto Salvage | Nowata | 9/19/2011 |
| OKR051554 | John Lakey's Salvage | John Lakey's Salvage | Nowata | 10/25/2011 |
| OKR052103 | Mahle Industrial Filtration USA Inc. | Mahle Industrial Filtration USA Inc. | Nowata | 10/28/2011 |
| OKR052110 | Peerless Materials Co | Lenapah Quarry | Nowata | 11/29/2011 |
| OKR052314 | APAC Central Inc. | Nowata Quarry | Nowata | 12/15/2011 |
| OKR052655 | Southern Industries Inc. | Southern Industries Inc. | Nowata | 11/6/2013 |
| OKR052730 | APAC Central Inc. | Claremore Quarry | Rogers | 4/7/2014 |

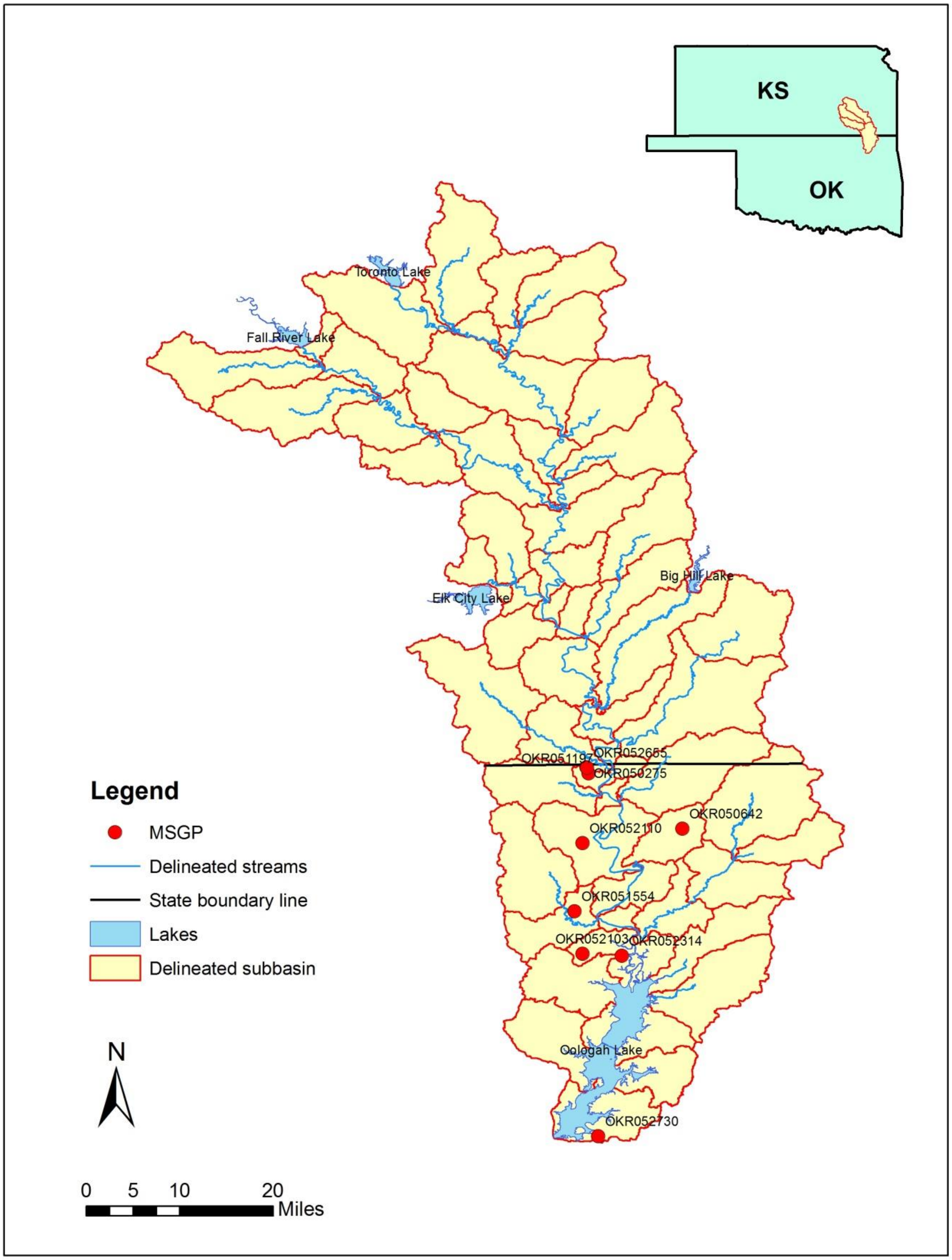


Figure 3-5 Multi-Sector General Permits (MSGP) Issued in the Oologah Lake Watershed for Industrial Sites

### 3.1.7 NPDES Concentrated Animal Feedlot Operations (CAFO) and Poultry Feeding Operations (PFO)

There are no Concentrated Animal Feeding Operations (CAFO) in the Oklahoma portion of the Oologah Lake watershed. In Kansas, however, there are numerous CAFOs as identified in Table 3-7. In Oklahoma, there are a number of Poultry Feeding Operations (PFOs) located in the Oologah Lake watershed. The PFOs are identified in Table 3-8 and mapped in Figure 3-6. There are no PFOs in the Kansas portion of the Oologah Lake watershed.

In Oklahoma, the Agricultural Environmental Management Services (AEMS) of the Oklahoma Department of Agriculture, Food and Forestry (ODAFF) was created to help develop, coordinate, and oversee environmental policies and programs aimed at protecting the Oklahoma environment from pollutants associated with agricultural animals and their waste.

Table 3-7 Concentrated Animal Feeding Operations (CAFO) in Oologah Lake watershed

| Permit Number | County | Record Type | Status | Federal Permit | HUC 12 Number | HUC 12 Name |
|---|---|---|---|---|---|---|
| A-VEGW-MA03 | Greenwood | Certification | Inactive | no | 110701020301 | Salt Creek |
| A-VEGW-B005 | Greenwood | Permit | Active | no | 110701010401 | Carlisle Br - V. River |
| A-VEWO-BA01 | Woodson | Certification | Active | no | 1107010104052 | West Buffalo Creek |
| 1363 | Wilson | Registration | Active | no | 110701020302 | Shawnee Creek - Fall River |
| A-VEEK-K001 | Elk | Renewal | Active | no | 110701020303 | Indian Creek |
| A-VEWL-S019 | Wilson | Renewal | Active | no | 110701020306 | Coon Creek - Fall River |
| A-VEWL-MA01 | Wilson | Certification | Active | no | 110701010502 | Leonards Lake – B Cedar Cr |
| A-VEWL-MA02 | Wilson | Certification | Inactive | no | 110701040504 | Thayer City Lake - Chetopa Creek |
| A-VEWL-S003 | Wilson | Permit | Active | no | 110701040504 | Thayer City Lake - Chetopa Creek |
| A-VEWL-M006 | WIlson | Application | Active | no | 110701040504 | Thayer City Lake - Chetopa Creek |
| A-VEWL-S022 | Montgomery | Permit | Inactive | no | 110701040308 | Sycamore Creek |
| A-VEMG-S041 | Montgomery | Permit | Active | no | 110701040308 | Sycamore Creek |
| A-VEMG-S042 | Montgomery | Permit | Active | no | 110701040308 | Sycamore Creek |
| A-VEMG-S044 | Montgomery | Permit | Active | no | 110701040308 | Sycamore Creek |
| A-VEMG-S040 | Montgomery | permit | Active | no | 110701040308 | Sycamore Creek |
| A-VEMG-H002 | Montgomery | Permit | Active | Yes - KS0087114 | 110701040308 | Sycamore Creek |
| A-VEMG-H009 | Montgomery | Permit | Active | Yes - KS0085448 | 110701040308 | Sycamore Creek |
| A-VEMG-T001 | Montgomery | Permit | Active | no | 110701040308 | Sycamore Creek |
| A-VEMG-S027 | Montgomery | Permit | Inactive | no | 110701040308 | Sycamore Creek |
| A-VEMG-S017 | Montgomery | Permit | Inactive | no | 110701030103 | Choteau Creek - V. River |
| A-NENO-M003 | Neosho | Registration | Active | no | 110701030104 | Headwaters - Drum Creek |
| A-VELB-MA01 | LaBette | Certification | Inactive | no | 110701030108 | Middle Big Hill Creek |
| A-VEMG-B001 | Montgomery | Renewal | Active | no | 110701030109 | Rock Creek - V. River |
| A-NELB-MA08 | LaBette | Certification | Inactive | no | 110701030202 | Upper Pumpkin Creek |
| A-VEMG-S021 | Montgomery | Permit | Inactive | no | 110701030109 | Coal Creek - V. River |
| A-VEMG-S010 | Montgomery | Permit | Active | no | 110701030109 | Coal Creek - V. River |
| A-VEMG-BA01 | Montgomery | Certification | Active | no | 110701030109 | Coal Creek - V. River |
| A-VEMG-MA09 | Montgomery | Certification | Active | no | 110701030109 | Coal Creek - V. River |

| Permit Number | County | Record Type | Status | Federal Permit | HUC 12 Number | HUC 12 Name |
|---|---|---|---|---|---|---|
| A-NELB-SA01 | LaBette | Certification | Inactive | no | 110701030203 | Middle Pumpkin Creek |
| A-VEMG-SA01 | Montgomery | Certification | Inactive | no | 110701030205 | Upper Onion Creek |
| 1337 | Montgomery | Registration | Active | no | 110701030205 | Upper Onion Creek |
| A-VEMG-BA02 | Montgomery | Certification | Active | no | 110701030205 | Upper Onion Creek |
| A-VEMG-MA08 | Montgomery | Registration | Active | no | 11070030206 | Middle Onion Creek |
| A-VEMG-M008 | Montgomery | Renewal | Inactive | no | 110701030207 | Lower Onion Creek |
| A-VEMG-MA06 | Montgomery | Certification | Active | no | 110701030207 | Lower Pumpkin Creek |
| A-VELB-MA02 | LaBette | Certification | Inactive | no | 110701030302 | Headwaters - Snow Creek |
| A-VELB-S001 | LaBette | Permit | Inactive | no | 110701030302 | Headwaters - Snow Creek |

Table 3-8 Poultry Feeding Operations in Oologah Lake watershed

| POULTRY ID | INTEGRATOR | TYPE | TOTAL # OF BIRDS | # HOUSES | COUNTY |
|---|---|---|---|---|---|
| 1015 | SIMMONS FOODS | Broilers | 480,000 | 3 | Rogers |
| 1354 | SIMMONS FOODS | Broilers | 120,000 | 1 | Craig |
| 1703 | SIMMONS FOODS | Broilers | 180,000 | 1 | Rogers |

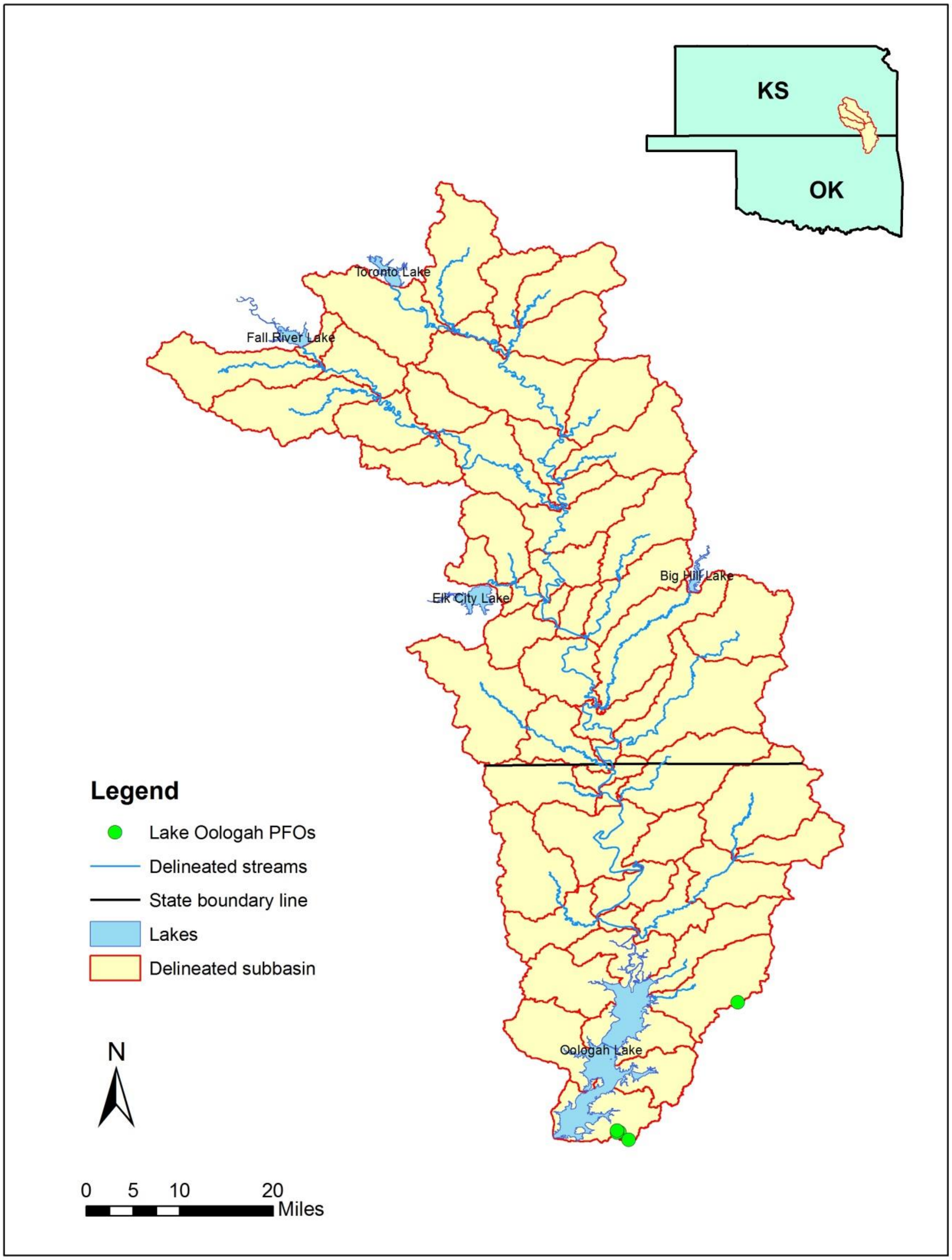


Figure 3-6 Poultry Feeding Operations (PFOs) in the Oologah Lake Watershed

### 3.1.8 Atmospheric Deposition of Nutrients

In many coastal and inland watersheds, atmospheric deposition of nitrogen, derived primarily from burning fossil fuels, can account for a significant fraction of the total nitrogen loading to a waterbody. Atmospheric deposition, for example, accounts for 10-40% of nitrogen loading to estuaries along the East coast of the USA and eastern Gulf of Mexico (Paerl et al., 2002) and 25-28% in Chesapeake Bay (USEPA, 2010). In watersheds characterized by agricultural land uses, such as the Oologah Lake watershed, farmers apply large quantities of nitrogen fertilizer to the soil. EPA estimates that 0.5 million metric tons of ammonia were emitted to the atmosphere from fertilizer applications in 1997. More than three times as much ammonia was emitted from livestock waste (manure and urine) in feedlots. Nationwide, fertilizer applications and livestock waste account for almost 80% of ammonia emissions to the atmosphere (http://nadp.sws.uiuc.edu/lib/brochures/nitrogen.pdf). Atmospheric deposition of nitrogen is therefore a potentially significant component of nutrient loading to a waterbody.

Atmospheric deposition is considered to be an uncontrollable source term for the Oologah Lake TMDL determination. Nevertheless, lake water quality models that simulate the nutrient balance of the lake must account for all uncontrollable and controllable sources of both nitrogen and phosphorus. Atmospheric deposition of nitrogen and phosphorus to a waterbody is contributed by both dry and wet deposition. Dry deposition is defined as a mass flux rate (as $g/m^2$-day) for a constituent that settles as dust or is deposited on a dry surface during a period of no precipitation. The mass flux of a constituent from wet deposition is defined by the concentration of the constituent in rainfall and the rate of precipitation. For Oologah Lake, wet and dry deposition data were estimated as the average of annual data from 2006-2007 for ammonia and nitrate from the National Atmospheric Deposition Program (NADP) for Station AR27 (Fayetteville, AR) and the Clean Air Status and Trends Network (CASTNET). Data were not available from the CASTNET or NADP sites for deposition of phosphorus. Dry deposition for phosphorus was estimated using the CASTNET and NADP data for nitrogen with annual average N/P ratios for atmospheric deposition of N and P reported for 6 sites located in Iowa (Anderson and Downing, 2006). Annual average wet phosphorus concentration was estimated in proportion to the Dry/Wet ratio for phosphate deposition fluxes reported by Anderson and Downing (2006). Appendix C details the data sources and parameter values used to assign atmospheric deposition of nitrogen and phosphorus for the EFDC lake model.

### 3.1.9 Watershed Loading of Nutrients and Sediment

Watershed loading results from precipitation and hydrologic runoff processes over drainage area catchments that are dependent on characteristic properties of the landscape such as topography, land use, soil types and physical processes such as infiltration and erosion. Flow and pollutants, derived from watershed runoff, are transported through a network of streams and rivers with discharge into the lake at downstream outlets of the streams. As the watershed loading of nutrients usually is a significant component of the overall nutrient loading to a waterbody, loading from the watershed to the lake is considered as a controllable source term for a TMDL determination.

Streamflow, nonpoint source runoff, and pollutant loading to Oologah Lake are provided as time series output from a watershed model for input to the lake model. Simulated flow and watershed pollutant loading are dependent on land use characteristics, soils, topography and hydrologic inputs, including point source dicharges from NPDES wastewater facilities to tributaries, for each sub-watershed catchment of the watershed model domain. Natural background conditions are not represented as an explicit component of watershed loading to Oologah Lake. All flow and pollutant loading data assigned for input to the lake model are derived from the watershed model.

Runoff and pollutant loading of nutrients and sediments from the Verdigris River basin into Oologah Lake is simulated using a public domain and peer reviewed watershed model, Hydrologic Simulation Program-FORTRAN (HSPF). An overview description of the HSPF watershed model and the application for the Oologah Lake TMDL study is presented in Section 3.2 of this report. A more complete description of the HSPF watershed model is given in Appendix B of this TMDL report.

### *3.1.10 Internal Lake Loading from Benthic Nutrient Release*

In addition to the external loading of nutrients from watershed runoff and atmospheric deposition into the lake, decomposition processes in the sediment bed can also contribute a significant internal load of nutrients to the overall nutrient loading to the lake and contribute to eutrophication of the lake. Particulate organic matter in the water column and sediment bed of Oologah Lake is derived from both external wastewater sources and watershed runoff and internal biological production of organic matter. Particulate organic matter settles out of the water column, accumulates within the sediment bed, and undergoes decomposition processes. During the period of thermal stratification, decay processes within the sediment bed deplete dissolved oxygen below the thermocline and release inorganic nutrients from the sediment bed back into the water column. The release of ammonia and phosphate from the bed to the water column, in particular, is controlled, in part, by bottom water dissolved oxygen levels with the largest internal release rates occurring during summer anoxic conditions. This internal source of nutrients is considered to be an uncontrollable source term for the TMDL determination in this study. Nevertheless, just like atmospheric deposition of nutrients, lake water quality models that simulate the nutrient balance of the lake must account for this internal source of nutrients as a contributing factor for eutrophication and the mass balance of nutrients.

Site-specific measurements of nutrient release from the sediment bed under aerobic and anoxic conditions in Oologah Lake are not available. Benthic nutrient release data are available, however, from some lakes and reservoirs in the region such as Lake Wister (Haggard and Scott, 2011); Lake Frances (Haggard and Soerens, 2006); Lake Eucha (Haggard et al., 2005) in Oklahoma; Beaver Lake in Arkansas (Sen et al., 2007; Hamdan et al., 2010), Acton Lake in Ohio (Nowlin et al., 2005) and a group of 17 lakes and reservoirs in the Central Plains (Dzialowski and Carter, 2011). Benthic phosphate release rates, characteristic of eutrophic lakes and reservoirs, can also be estimated for Oologah Lake using an empirical methodology developed by Nurnberg (1984). Measured data collected by Dzialowski and Carter (2011) were used to confirm model results simulated by the internally coupled sediment diagenesis sub-model of the EFDC lake model that was developed for Oologah Lake.

## 3.2 HSPF Watershed Model

### *3.2.1 Overview of HSPF model*

The Hydrological Simulation Program FORTRAN (HSPF) is a public domain model supported by EPA and the USGS (https://www.epa.gov/exposure-assessment-models/hspf). HSPF is a lumped parameter watershed runoff model that simulates watershed hydrology and non-point source pollutant loadings for organic matter, nutrients, sediments, bacteria and toxic chemicals within a watershed network of delineated sub-basins. The internal stream reach model in HSPF routes flow and water quality constituents through a network of tributary reaches and overland runoff catchments for each sub-basin of a watershed (Bicknell et al., 2001). The HSPF hydrologic sub-model provides for simulation of water balances in each sub-basin based on precipitation, evaporation, water withdrawals, irrigation, diversions, NPDES wastewater discharges, infiltration, and active and deep groundwater reservoirs. Empirical model parameters are assigned for each sub-basin land use through model calibration to simulate the water balance and pollutant loading from a sub-basin. HSPF is designed as a time variable model with results generated on an hourly or daily basis. Hundreds of applications of HSPF over the past three decades have included short-term storm events and/or continuous simulations over annual and decadal cycles. BMP alternatives designed to reduce pollutant loads to receiving waters can be represented in HSPF by adjustments of land use-based yield coefficients for a pollutant. Windows-based user-friendly GUI software tools such as WinHSPF (Duda et al., 2001), GenScn (Kittle et al., 1998) and HSPFParm (Donigian et al., 1999) have been developed to facilitate pre- and post-processing tasks for HSPF.

Time series results for streamflow and pollutant loads generated by the HSPF watershed model have been linked for input to numerous hydrodynamic (e.g., EFDC, CH3D) and water quality model (e.g., EFDC, CE-QUAL-ICM, WASP) receiving water modeling applications over the past decade and this approach is adopted for the Oologah Lake TMDL study. Output results generated by the HSPF watershed model of the Verdigris River basin provide flow and pollutant loading as time series data to Oologah Lake as input data to the EFDC lake model. As shown in the EFDC lake model report (Appendix C: Table 2), loading to the lake is defined by overland runoff catchments and tributary reach sub-basins. As described in Section 3.1.1 of this TMDL report, there are no point source NPDES wastewater facilities that discharge directly into Oologah Lake.

### *3.2.2 Model Setup and Data Sources*

The HSPF model was initially setup using EPA's BASINS watershed modeling platform. The sub-watershed boundaries were delineated based on USGS's National Elevation Dataset and EPA's River Reach File Version 1 (RF1) stream network. Data sets collected in 2005-2007 were identified for calibration of the watershed-lake model because this period covers normal, dry and wet conditions. Although the most recent data available for land use is the 2011 NLCD database, the 2011 data set is not consistent with the choice of 2005-2007 as the time period for development and calibration of the watershed model. The 2006 NLCD data are used for watershed model setup because it provides the best representation of the effect of watershed runoff on land uses and land cover that, in turn, impacted water quality conditions in watershed streams during 2005-2007. Flow data were monitored by USGS at five stations in the upper, middle, and lower part of the Verdigris River watershed modeling domain as shown in Figure 3-7. Water quality data were available for comparison to the watershed model results at one OWRB station, three USACE stations and five EPA STORET stations as shown in Figure 3-8 and Figure 3-9, respectively.

Rainfall data from two MESONET stations and five NOAA NCDC stations, as shown in Figure 3-10, are used to represent spatial variability of precipitation in the watershed. Detailed information for these stations is given in Table 3-9 and Table 3-10.

Cloud cover data are available at four NOAA stations as shown in Figure 3-11. Detailed information for these stations is given in Table 3-10. Observed solar radiation data are available at all three MOSONET station in Table 3-9. 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 were computed in WDMUtil of BASINS using Hamon's method (Hamon, 1961). Daily PET was then disaggregated 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 3-12.

Table 3-9 Meteorological Stations Used in the HSPF Model

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

Table 3-10 NOAA NCDC Meteorological Stations Used in the HSPF Model

| Station Name | WBAN ID | Latitude (N) | 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 |

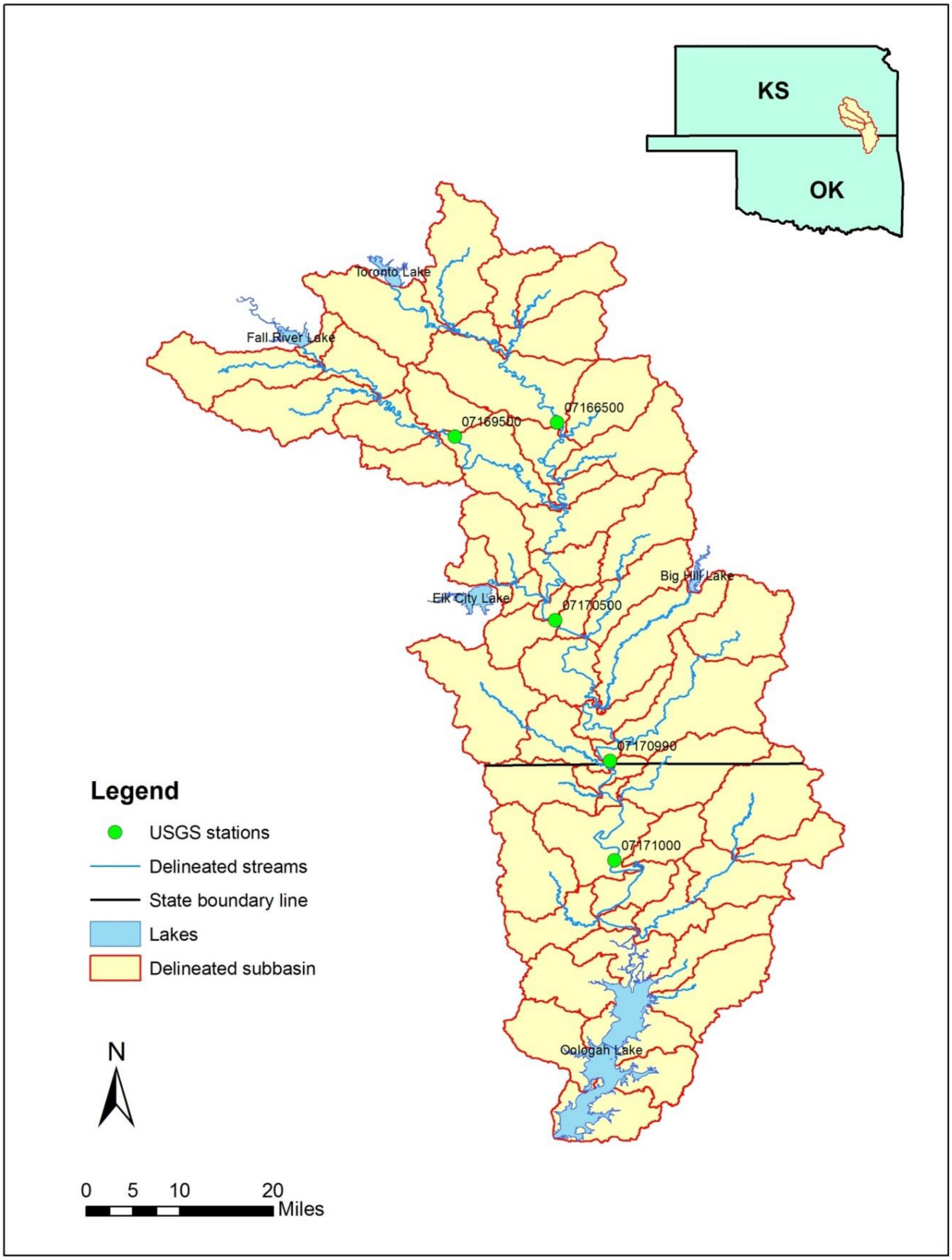


Figure 3-7 Locations of USGS Flow Stations in the Oologah Lake Watershed

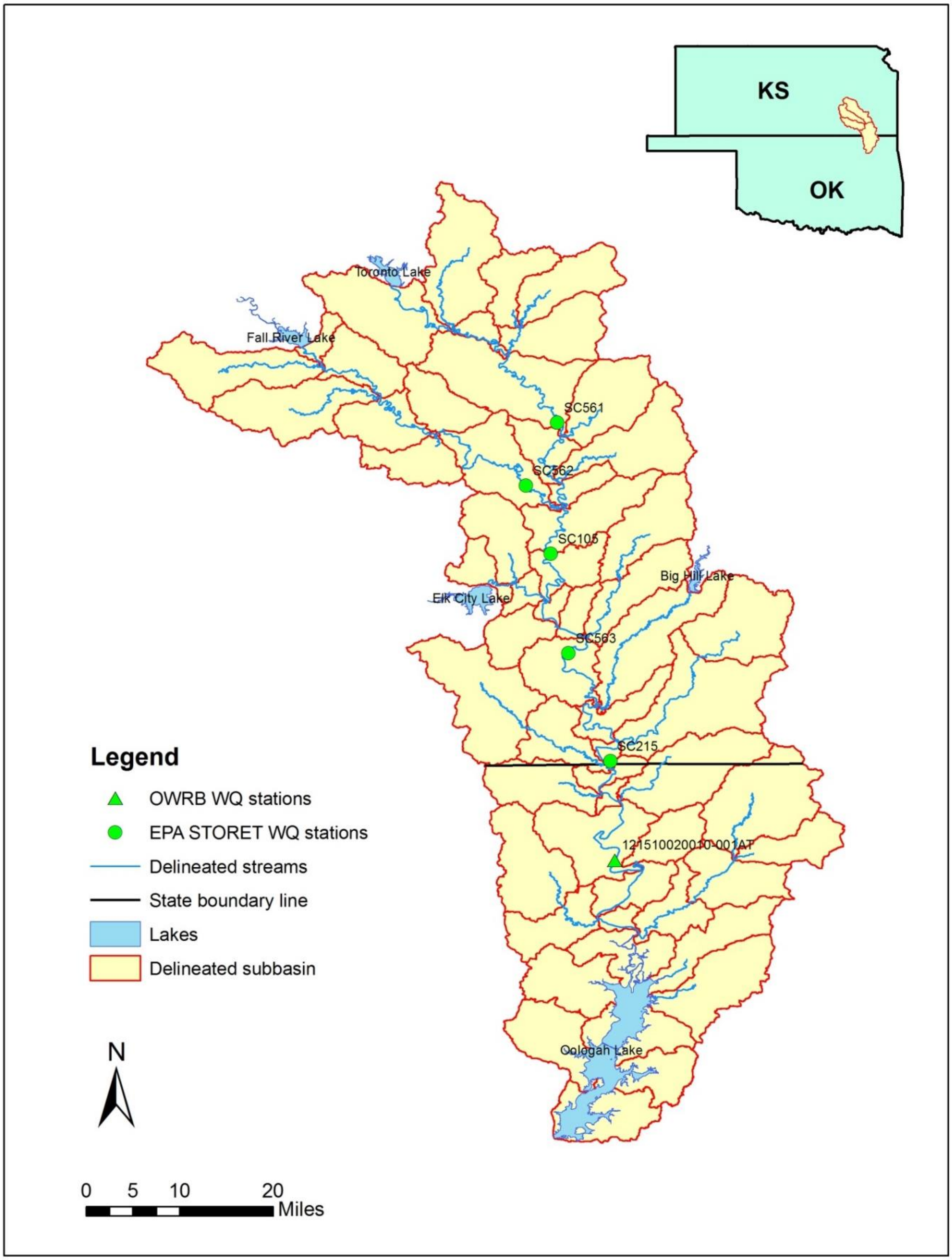


Figure 3-8 Locations of EPA and OWRB Water Quality Stations for Watershed Model Simulation

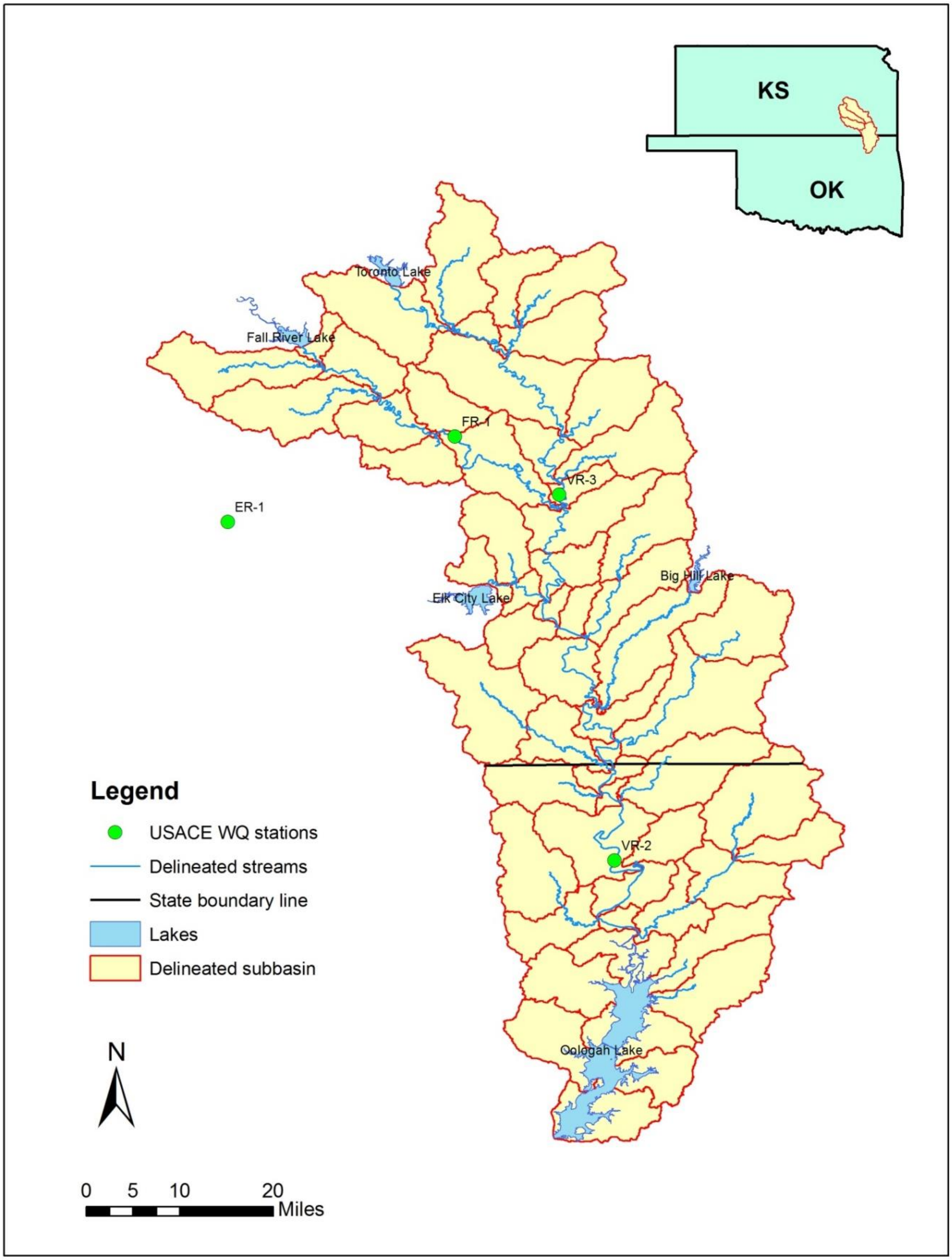


Figure 3-9 Locations of USACE Water Quality Stations for Watershed Model Simulation

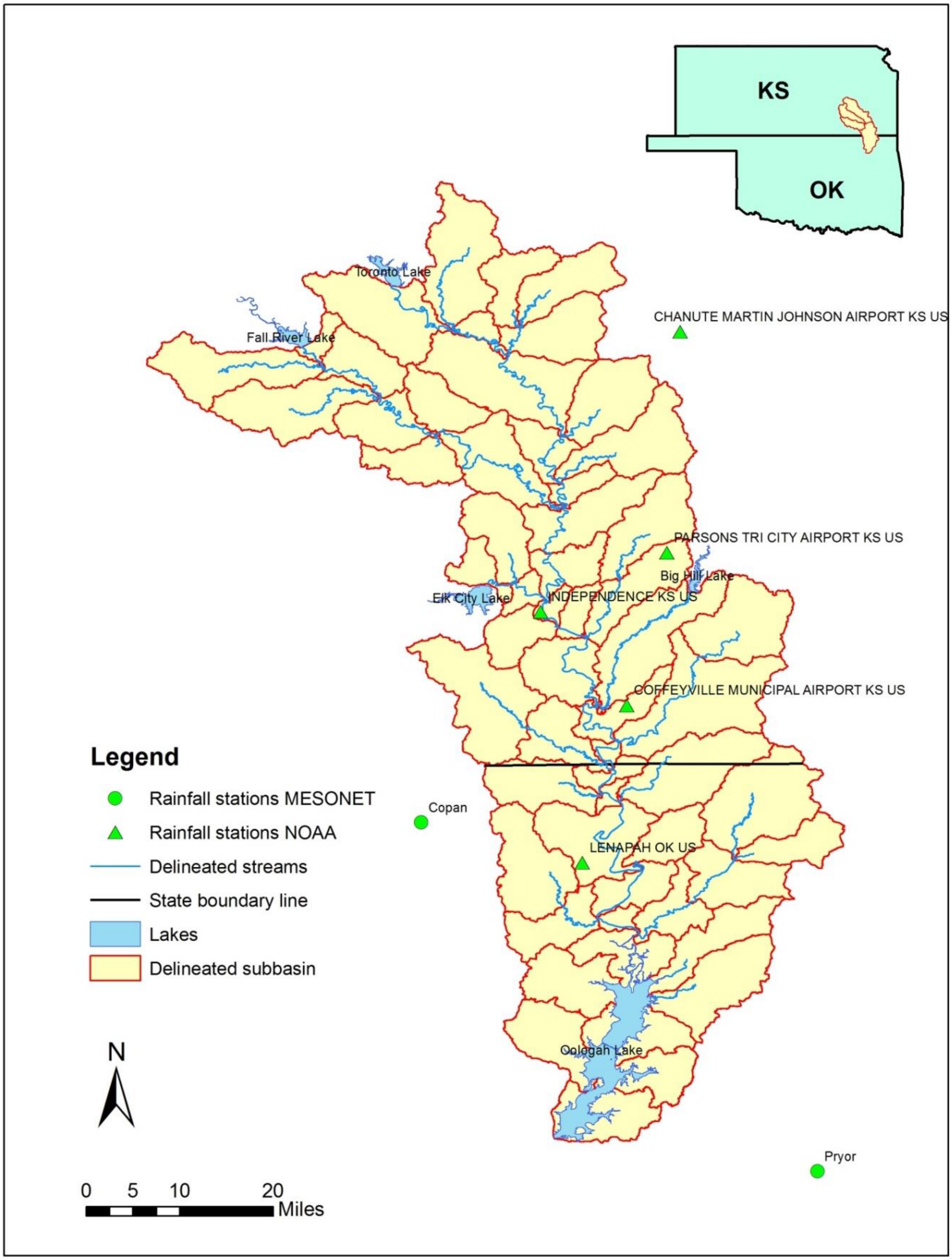


Figure 3-10 Locations of MESONET and NOAA Rainfall Stations in Oologah Lake Watershed

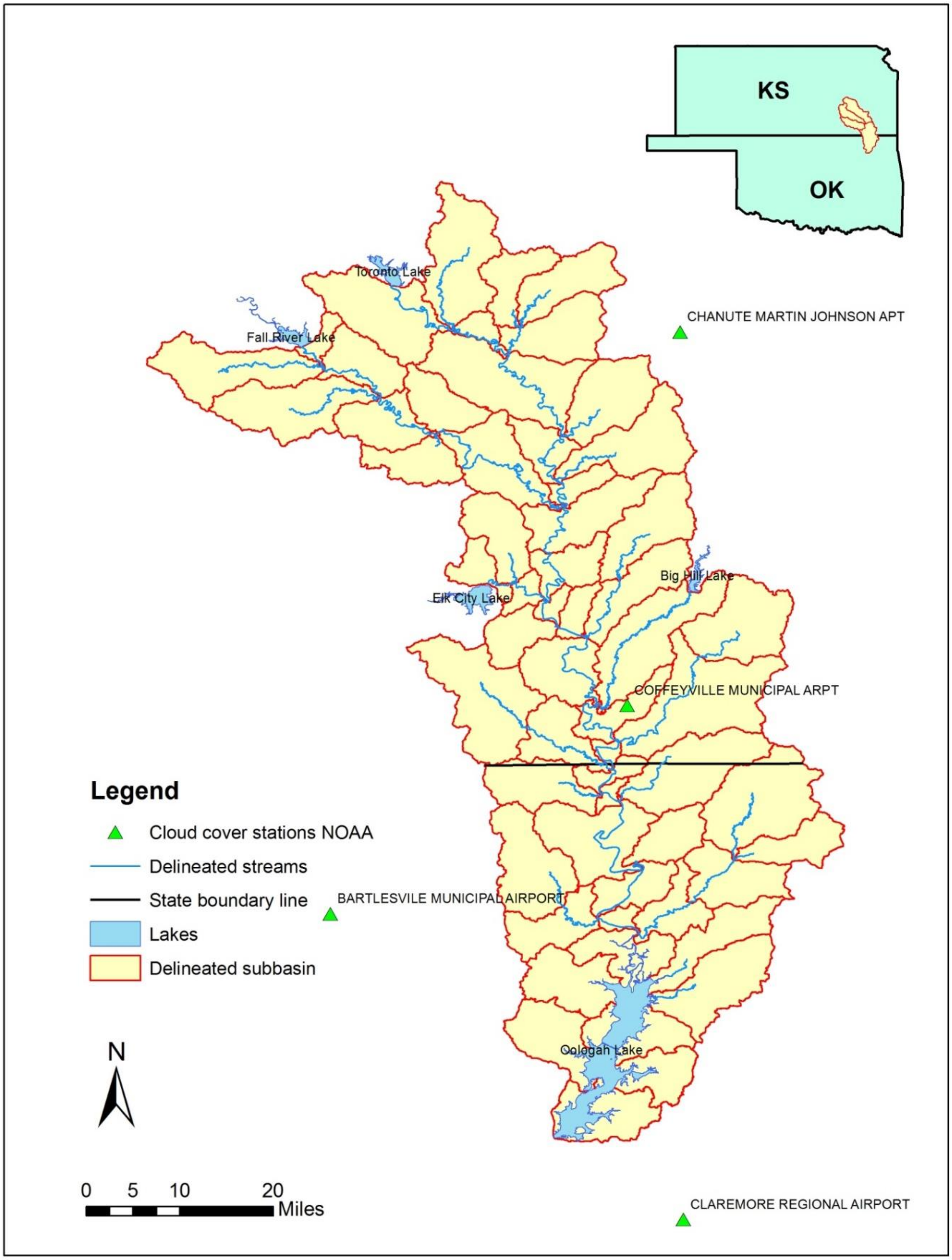


Figure 3-11 Locations of NOAA Cloud Cover Stations in Oologah Lake Watershed

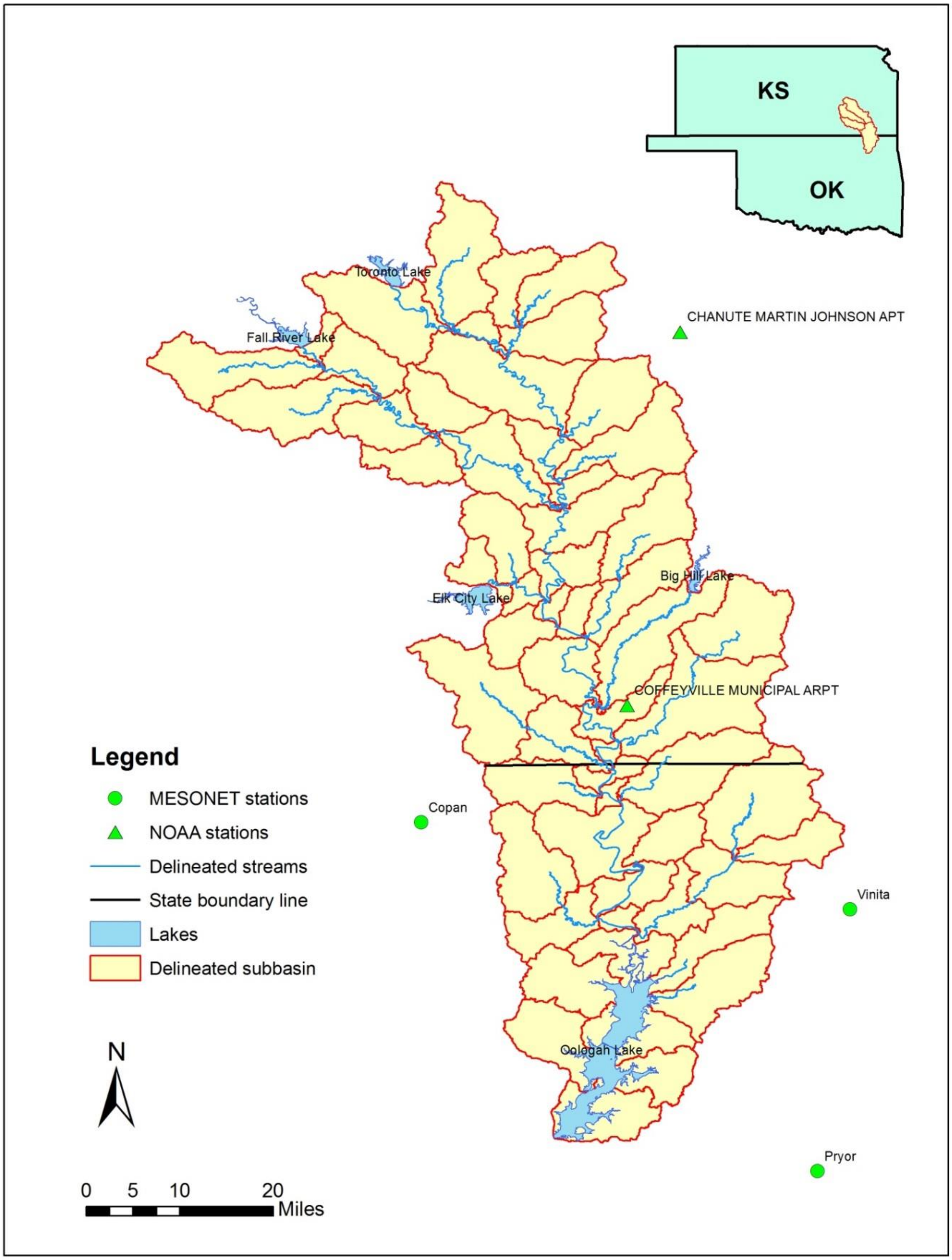


Figure 3-12 Locations of MESONET and NOAA Meteorological Stations in Oologah Lake Watershed

EPA's National Pollutant Discharge Elimination System (NPDES) identifies a total of 81 major and minor wastewater facilities (point sources) that discharge into the Verdigris River Basin. Inspection of the list of these facilities in Kansas shows that many permits are typically ready mix plants that do not discharge wastewater; some facilities are general permits for industrial activities and construction without any data for these facilities; and some facilities are quarries or mineral extraction/processing facilities that typically do not discharge wastewater to surface waters (Tom Stiles, KDHE, personal communication, June 8, 2015).

Seven NPDES permitted facilities, as shown in Figure 3-13 and Table 3-11, with a monthly average effluent discharge greater than 0.1 MGD (0.15 cfs) were considered as point source discharges of wastewater for input to the HSPF watershed model. Six (6) of the NPDES point source dischargers are municipal wastewater treatment facilities (SIC code=4952) and one (1) industrial NPDES discharge (KS0000248: Coffeyville Resources Refining & Marketing) is a petroleum refining facility (SIC code=2911). The South Coffeyville Public Works Authority (PWA) (OK0020117) is a municipal wastewater treatment facility located in Oklahoma and permitted by the state of Oklahoma. The other six (6) wastewater treatment plants are located in Kansas and are permitted by the state of Kansas. The stream reach receiving effluent from each NPDES point source facility was identified using either EPA's Permit Compliance System (PCS) or GIS-based geographic locations of a facility.

Table 3-11 NPDES Wastewater Treatment Facilities Included in Watershed Model

| NPDES ID | FACILITY NAME | Receiving Water | Latitude (N) | Longitude (W) | Design flow (MGD) |
|---|---|---|---|---|---|
| OK0020117 | SOUTH COFFEYVILLE PWA (SIC=4952) | Lower Onion Creek | 36.998639 | -95.61236 | 0.15 |
| KS0050733 | COFFEYVILLE, CITY OF (SIC=4952) | Lower Onion Creek | 37.006469 | -95.60967 | 5 |
| KS0000248 | COFFEYVILLE RESOURCES REFINING & MARKETING (SIC=2911) | Claymore Creek | 37.043300 | -95.61080 | 2.2 |
| KS0095486 | INDEPENDENCE WASTEWATER PLANT(SIC=4952) | Choteau Creek | 37.228841 | -95.69294 | 3.0 |
| KS0094803 | CHERRYVALE WASTEWATER PLANT (SIC=4952) | Drum Creek | 37.276028 | -95.58256 | 0.3 |
| KS0025658 | NEODESHA, CITY OF (SIC=4952) | Washington Branch | 37.432093 | -95.68369 | 0.5 |
| KS0045985 | FREDONIA WASTE WATER TREATMENT PLANT (SIC=4952) | Salt Creek | 37.532704 | -95.82647 | 0.47 |

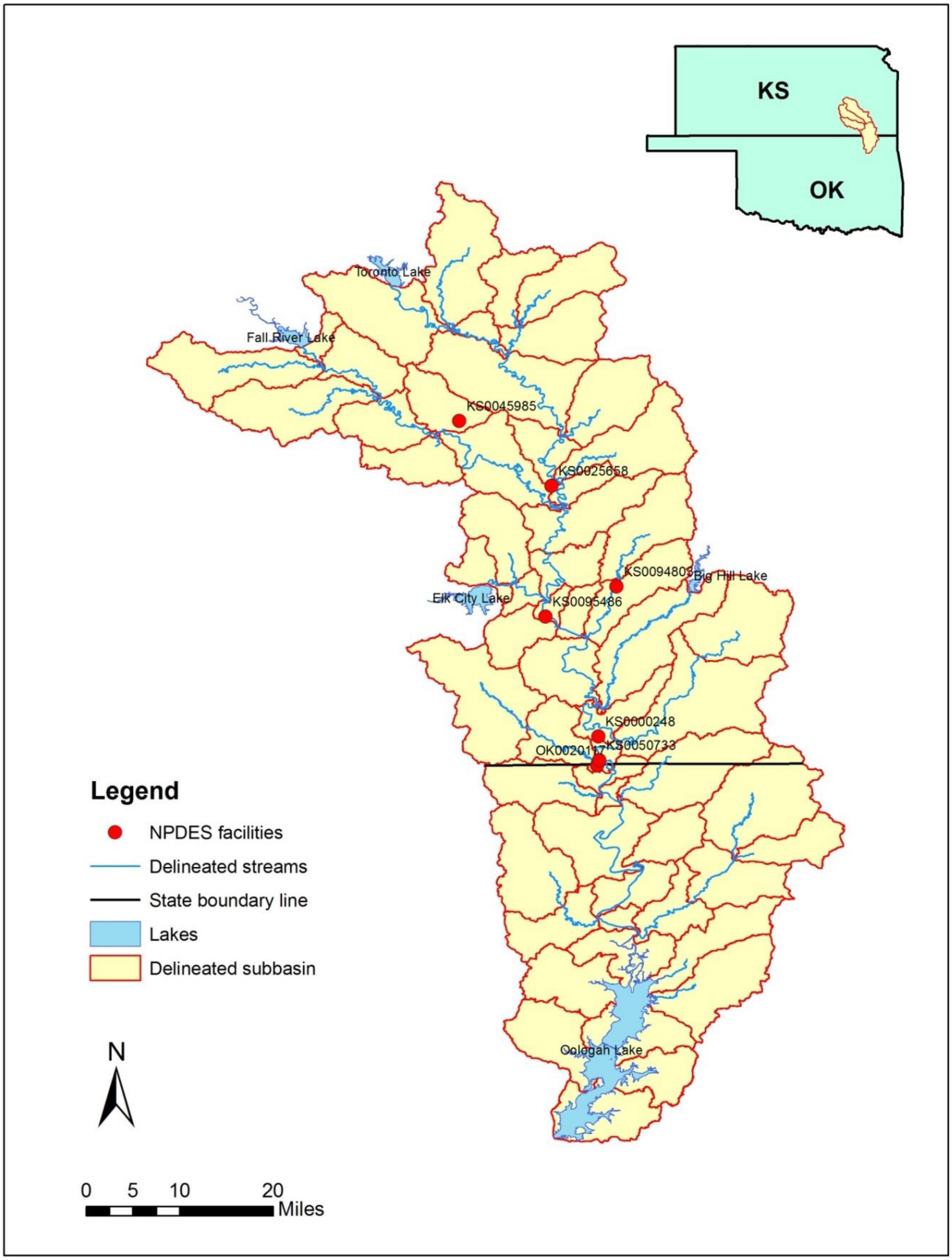


Figure 3-13 Locations of the Major NPDES Facilities in Oologah Lake Watershed

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%) purposes.

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 3-14 and Table 3-12). For these industrial and municipal facilities, the monthly or annual flow records were evenly distributed to derive daily flow data.

Table 3-12 Information of Water Withdrawals for Industrial and Municipal Facilities

| WUAPERS _ID | Name | UMW _CODE | COUNTY | LONGITUDE (W) | LATITUDE (N) | 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 Cherryvale | MUN | MG | -95.67634 | 37.28569 | 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 | -95.48863 | 7.481902 | 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 | Hurricane Service LLC | IND | WL | -95.71430 | 37.63899 | Monthly |
| 40450 | Unknown name | IND | WO | -95.84198 | 37.78781 | Annual |

The water withdrawal data used for irrigation and recreation purposes were only available at annual intervals, as shown in Figure 3-15 and Table 3-13. 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 3-14. These four crops are corn, grain sorghum, soybean, and sunflower. Three crops (corn, grain sorghum, and soybeans), were used to develop a composite monthly distribution of irrigation requirements for water withdrawals. The developed composite monthly distribution was applied to all irrigation facilities to distribute the annual withdrawal to monthly withdrawals. The monthly withdrawal data was then evenly distributed to derive daily flows.

Detailed water withdrawal records summarized in Table 3-12, Table 3-13, and Table 3-14 are presented in Appendix E “Water Withdrawals in the Verdigris River Basin”.

Although water withdrawal records are available for the Kansas portion of the Verdigris River watershed, similar surface water withdrawal records for the Verdigris River and tributaries were not readily available for the Oklahoma sub-basins of the watershed. In addition, the City of Tulsa, municipalities of Collinsville, Chelsea, and Claremore and some Rogers County Rural Water Districts withdraw water from Oologah Lake as their raw water source. Oklahoma water supply withdrawal records were, therefore, not available for either the Oklahoma portion of the HSPF watershed model or the EFDC model of Oologah Lake.

The water withdrawal records listed in Appendix E are used as input data to the HSPF watershed model for calibration and validation of streamflow at USGS gage stations located within the Kansas and Oklahoma portions of the Verdigris River basin. Although water withdrawal data from the Verdigris River or tributaries were not available for input to the HSPF model for the Oklahoma sub-basins, any water withdrawals actually occurring within the Oklahoma sub-basins would account for only a minor component of the overall hydrologic balance of streamflow modeled over the total contributing drainage area of 3,584 square miles to the USGS gage 07171000 on the Verdigris River at Lenapah, Oklahoma. The impact of the missing Oklahoma water withdrawal records on calibration and validation of streamflow at the Lenapah gage would be very small.

Table 3-13 Information of Water Withdrawals for Irrigation and Recreation Facilities

| WUAPERS_ID | UMW_CODE | COUNTY | LONGITUDE (W) | LATITUDE (N) | 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 3-14 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 |

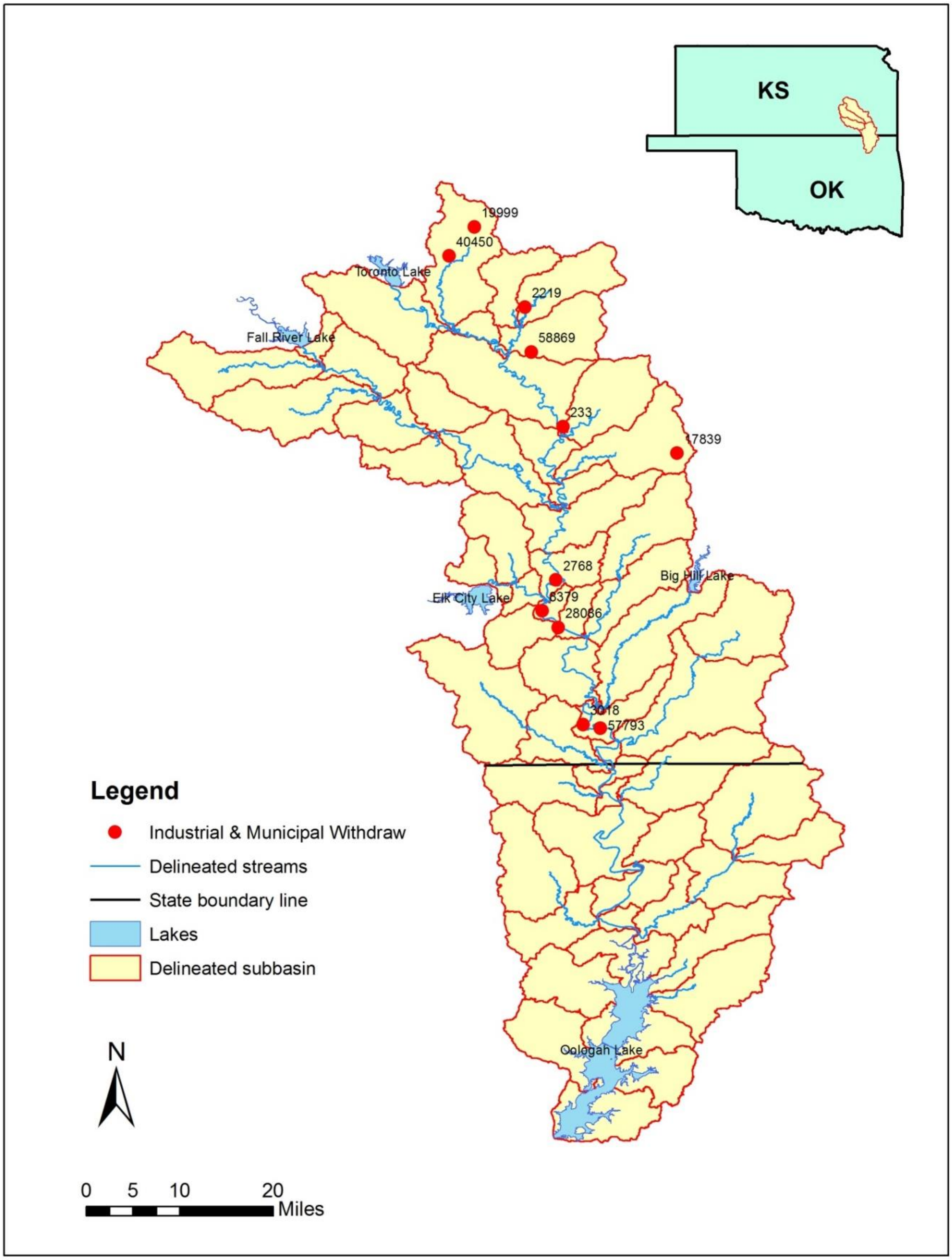


Figure 3-14 Locations of Water Withdrawals for Industrial and Municipal Facilities in Oologah Lake Watershed

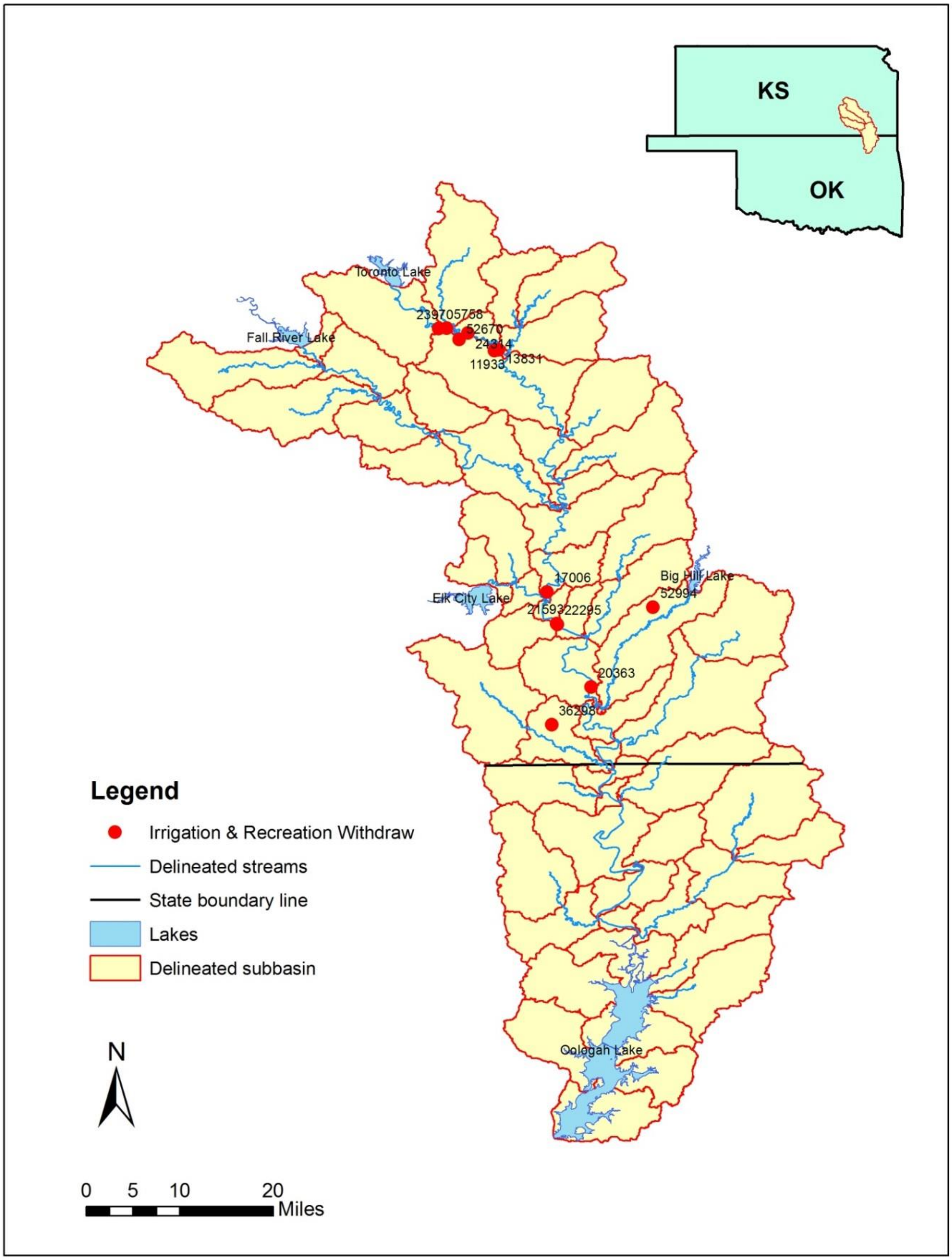


Figure 3-15 Locations of Water Withdrawals for Irrigation and Recreation Facilities in Oologah Lake Watershed

Flow discharge and water quality constituent data from Toronto Lake, Fall River Lake, Elk City Lake, and Big Hill Lake federal reservoirs were needed to define upstream boundary conditions as input to the HSPF watershed model. The observed water quality data available at these four reservoirs included flow, water temperature, dissolved oxygen, TSS, NH4, NO3, dissolved TKN, total TKN, dissolved orthophosphate, dissolved total phosphorus, organic carbon (DOC, TOC), and chlorophyll-a.

Hourly discharge flows recorded at the dam were adequate for the development of upstream flow boundary conditions from each reservoir. However, monthly or bi-weekly water temperature and dissolved oxygen data collected by the USACE in the reservoirs were not adequate for the development of HSPF upstream boundary conditions as the lower frequency data did not capture the higher-frequency variability in water temperature and dissolved oxygen.

As discussed in Section 2.6 of Appendix B of this TMDL report, strong correlation relationships were found for each of the four reservoirs between monthly or bi-weekly water temperature measured in the dam releases and the hourly water temperature recorded at the downstream USACE river stations VR-3, FR-1 and ER-1 (locations shown in Figure 3-9). The correlation relationships for each reservoir were used to calculate and assign hourly water temperature data as upstream boundary data for the dam releases. Hourly dissolved oxygen concentrations for each dam release were then calculated and assigned for model input as upstream boundary data based on the calculated hourly water temperature and the corresponding freshwater saturation level of dissolved oxygen for each dam release. This methodology for estimating hourly saturated dissolved oxygen concentration as the upstream boundary release from each reservoir provides a reasonable approximation for oxygen loading to the river because water discharged from the reservoirs is reaerated during release at the dams.

The HSPF model requires ultimate biochemical oxygen demand (BOD) data to simulate dissolved oxygen processes in a river. However, the USACE only collected organic carbon (DOC, TOC) data. The approach adopted by Hendrickson et al. (2002) was used to estimate the ultimate BOD data based on DOC and TOC data measured by the USACE. Where other water quality constituent data required by HSPF was not available, data gaps were filled in based on stoichiometric ratios for sediment, organic carbon and nutrients of riverine organic matter (Meybeck, 1982; Middelburg et al., 2004) to derive reasonable estimates of missing water quality data.

### *3.2.3 Model domain and discretization for sub-watershed representation*

The Verdigris River watershed was delineated into 60 sub-watersheds (see Figure 1-2) based on the USGS National Elevation Dataset. HSPF sub-watersheds are defined by two types of catchments: (1) sub-watershed areas that are defined by a single tributary reach flow and pollutant loading; and (2) sub-watershed areas that do not include a delineated stream reach and flow and pollutant loading are defined as a uniform distribution of overland runoff flow and pollutant loading over the catchment. The 60 sub-watersheds of the Verdigris River basin include catchments defined by delineated tributaries and catchments defined by overland runoff. Table 3-15 provides the stream reach characteristics developed by BASINS for the catchments defined only by tributary reaches used in the HSPF model. The overland runoff sub-watersheds [56, 57, 58, 59, 60 and 1] shown in the Verdigris River basin map (Figure 1-2) are not defined by stream reaches and are, therefore, not listed in the table of stream reaches. The overland runoff sub-watersheds are adjacent to Oologah Lake, and discharge flow and pollutant loading directly into the EFDC lake model.

Table 3-15 BASINS REACH Characteristics

| Stream_ID | Length (mile) | Δ Elev* (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 |

| Stream_ID | Length (mile) | Δ Elev* (feet) | Longitudinal Slope |
|---|---|---|---|
| 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 |

* Δ Elev is the drop in stream bed elevation from the upstream to downstream end of a reach

### *3.2.4 Observed Flow and Water Quality Data for Model Calibration*

For the Oologah Lake watershed model, flow was calibrated to five USGS gage stations as shown in Figure 3-7 and Table 3-16. Observed water quality data including temperature, DO, nitrate, ammonia, total nitrogen, orthophosphate and total phosphorus are available at one OWRB station, five EPA STORET stations and three USACE stations as shown in Figure 3-8 and Figure 3-9 and Table 3-17.

Table 3-16 Summary of USACE Flow Stations for Model Calibration and Validation

| Station ID | Station Name | Latitude (N) | Longitude (W) |
|---|---|---|---|
| 0717100 | Verdigris River near Lenapah, OK | 36.85111 | -95.585833 |
| 0717099 | Verdigris River at Coffeyville, KS | 37.00527 | -95.592500 |
| 0717050 | Verdigris River at Independence, | 37.22361 | -95.677500 |
| 0716650 | Verdigris River near Altoona, KS | 37.52972 | -95.674444 |
| 0716950 | Fall River at Fredonia, KS | 37.50833 | -95.833333 |

Table 3-17 Summary of Water Quality Stations for Model Calibration and Validation

| Station Code | Agency | Latitude (N) | Longitude (W) |
|---|---|---|---|
| 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 |

### *3.2.5 HSPF Model Calibration*

Computer water quality models are simplified representation of the physical world. In addition, observed data from monitoring have inherent errors from the sample collection process, equipment used, and lab analysis procedures. As a result, models, even after calibration, do not produce results that match exactly with observed data. To judge if a model performs as designed and simulates pollutant loads with a reasonable accuracy, graphic comparison and statistical analyses are performed to evaluate model performance.

In the Oologah Lake TMDL study, observed stream discharge and water quality parameters for water temperature, DO and nutrients were plotted on the same graphs with simulated time series. Visual inspections were made to compare the observed and simulated data. Three statistics, percent difference of average values (MPE, % error), correlation coefficient ($r^2$), and Nash-Sutcliffe coefficient (N-S), were calculated to quantify how well the HSPF model matched the observed data sets.

Section 5 of Appendix B “Watershed Model Calibration and Validation Report” describes model performance statistics and presents time series plots of model results and observed data sets for all stations for flow, water temperature and water quality constituents. Model performance statistics, compiled from tables given in Appendix B, are presented in Table 3-18 for the following HSPF state variables for Verdigris River stations nearest to the inflow to Oologah Lake:

- Flow (USGS 07171000 at Lenapah)
- Water temperature (USACE VR-2)
- Dissolved oxygen and nutrients (OWRB 121510020010-001AT)

Model performance statistics given in the table are based on data compiled for the two-year period model validation period from Jan 2006 through Dec 2007. Model performance statistics for flow and water temperature include sample size (N), mean observed and mean simulated values, mean percent error (MPE), correlation coefficient ($R^2$), and Nash-Sutcliffe efficiency coefficient (N-S). Model performance statistics for dissolved oxygen and nutrients include sample size (N), mean observed and mean simulated values, and mean percent error (MPE). The equations used to compute HSPF model performance statistics are presented in Section 4 of Appendix B.

As shown in Table 3-18, the large number of observations available for watershed model-observed data comparison and calculation of model performance statistics for flow and water temperature for the two-year model validation period are based on automated hourly measurements. The number of observations, therefore, for daily averaged flow (n=730) and hourly water temperature (n=16,984) is very large. The number of observations available for water quality constituents, however, is based on much lower frequency grab sampling at monthly or bi-monthly intervals.

The interpretation of the goodness-of-fit evaluation of model performance based on the Nash-Sutcliffe efficiency coefficient is strongly dependent on the sample size or the number (N) of model-data paired records and the confidence level (e.g., 95%) desired for the performance statistic. Liu et al. (2018) show that if N is greater than 200 then the computed N-S value provides a robust metric as a goodness-of-fit criteria to judge model performance. As the number of observations available from monthly or bi-monthly water quality monitoring is limited (N <25), there are insufficient observed data records to support reliable watershed model performance estimates based on correlation or Nash Sutcliffe Efficiency. These two statistics, although used for assessment of model performance for flow and water temperature are, therefore, not presented in Table 3-18 for dissolved oxygen and nutrients.

Watershed and lake model performance is evaluated using a "weight of evidence" approach that includes qualitative visual inspection of time series plots of model results compared to observed data sets and quantitative evaluation of model-data performance statistics. Although correlation coefficients and Nash-Sutcliffe coefficients were not determined for dissolved oxygen and nutrients because of the limited availability of observations, model performance is evaluated for Mean Percent Error (MPE) as shown in Table 3-18. MPE, shown to be less than 5% for dissolved oxygen and less than 50% for nutrients, demonstrates acceptable agreement between HSPF watershed model results and observations (Donigian, 2000).

The "weight of evidence" approach recognizes that, as an approximation of flow and water quality in the Verdigris River and tributaries of the watershed, perfect agreement between observed data and watershed model results is not expected and is not specified as a performance measure for success of HSPF model calibration and validation. The combination of the quantitative assessment of Mean Percent Error statistics and the qualitative visual comparison of HSPF model results to observed data demonstrate that the HSPF watershed model provides a technically credible representation of the pollutant loading of water quality constituents from the Verdigris River watershed into Oologah Lake. Time series plots showing a comparison of observed data to HSPF model results for flow, water temperature and nutrients are presented in Figure 3-16 through Figure 3-23. A complete set of model-data plots for the HSPF watershed model are presented in Appendix B.

Table 3-18 - HSPF Watershed Model Performance Statistics for Flow, Water Temperature, Dissolved Oxygen and Nutrients for Model Validation Period (January 2006-December 2007)

| Station | State Variable | Sample (N) | Mean Observed | Mean Simulated | MPE | $R^2$ | N-S |
|---|---|---|---|---|---|---|---|
| USGS 07171000 | Daily Flow (cfs) | 730 | 2910 | 2671 | 8.21 | 0.78 | 0.41 |
| USACE VR-2 | WTemp (°F) | 16,984 | 62.37 | 61.93 | 0.71 | 0.95 | 0.9 |
| OWRB | DO (mg/L) | 18 | 8.48 | 8.7 | -2.64 | | |
| OWRB | NH4 (mg N/L) | 7 | 0.12 | 0.06 | 48.19 | | |
| OWRB | NO3 (mg N/L) | 13 | 0.46 | 0.67 | -45.43 | | |
| OWRB | TN (mg N/L) | 15 | 1.24 | 1.48 | -19.52 | | |
| OWRB | TPO4 (mg P/L) | 18 | 0.100 | 0.070 | 29.780 | | |
| OWRB | TP (mg P/L) | 20 | 0.16 | 0.16 | -1.44 | | |

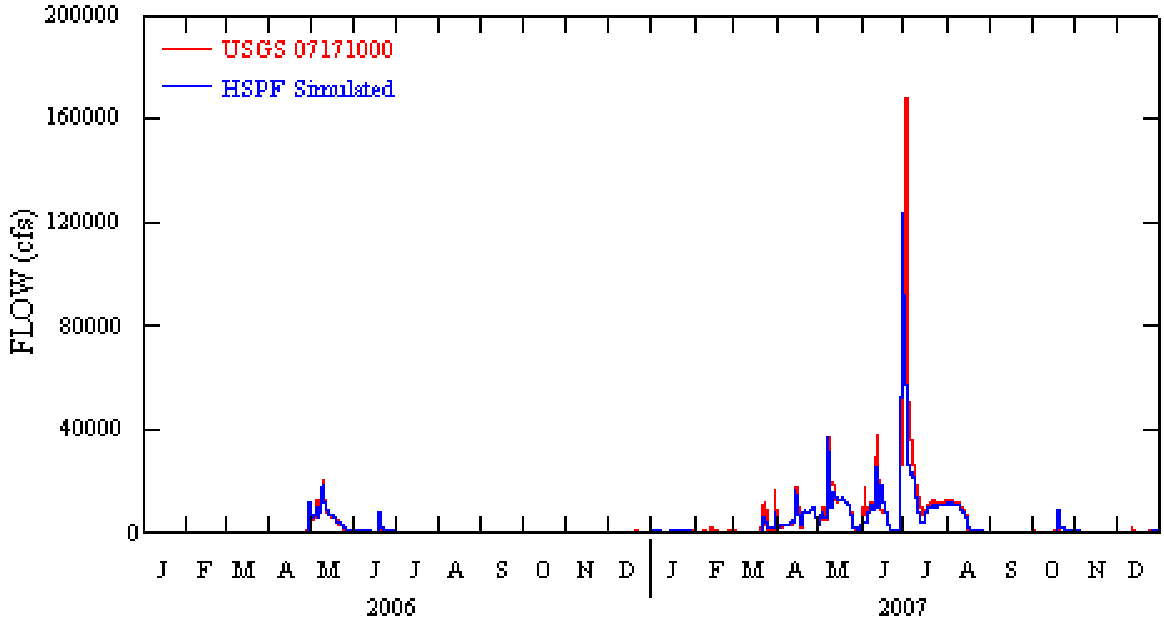


Figure 3-16 Flow Validation at USGS 07171000 Station

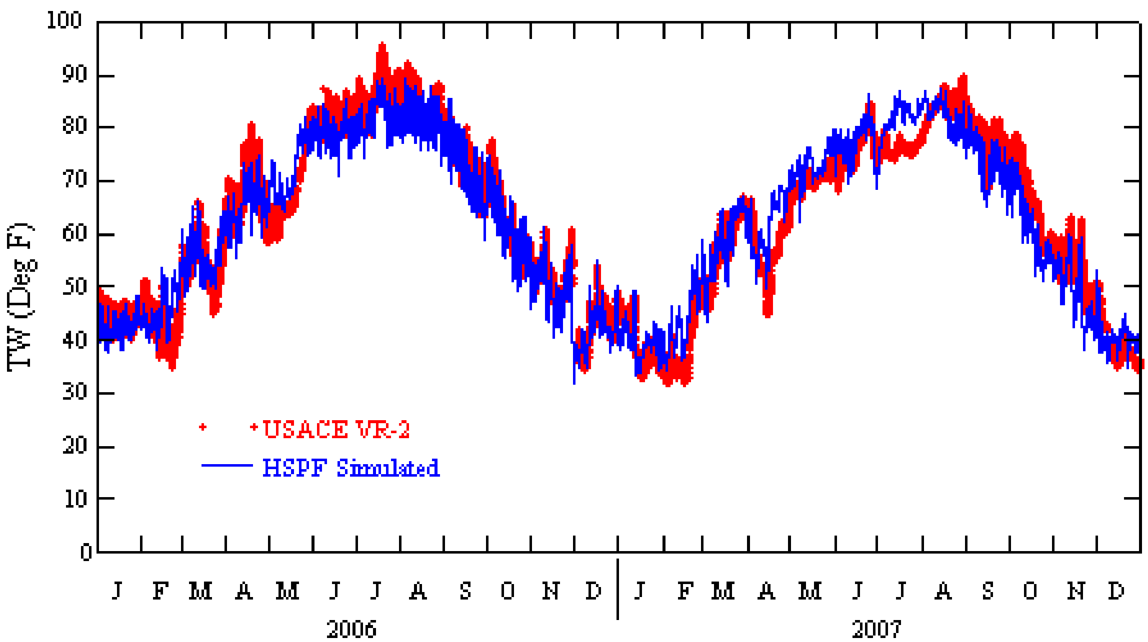


Figure 3-17 Water Temperature Validation at USACE VR-2 station

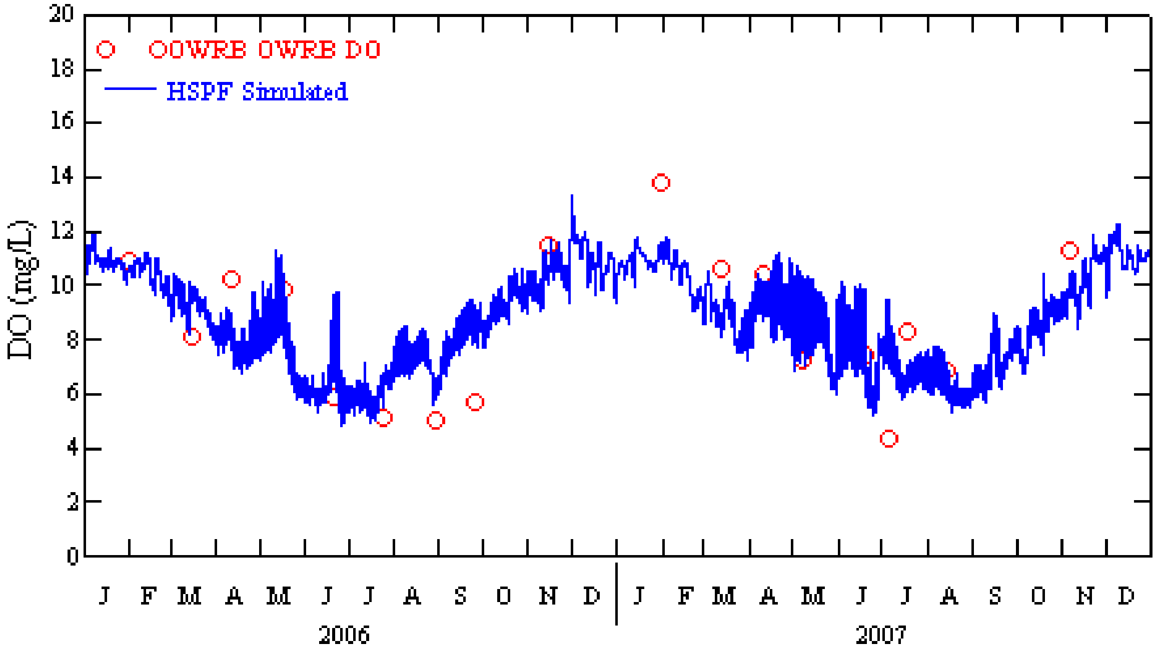


Figure 3-18 DO Validation at OWRB station 121510020010-001AT

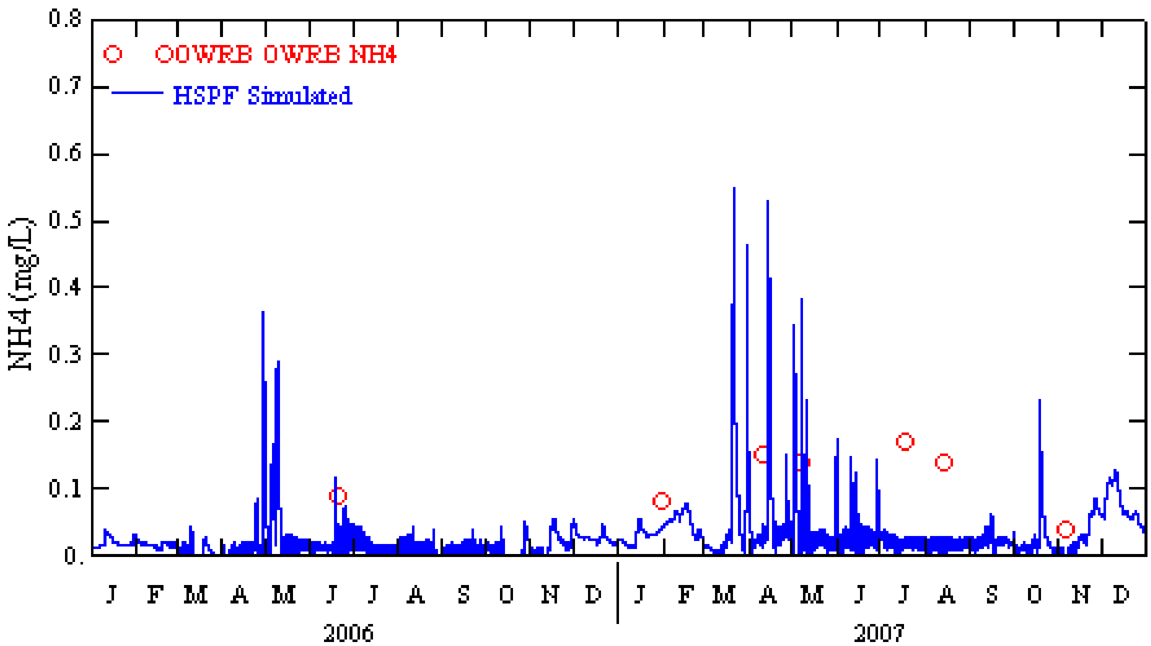


Figure 3-19 NH4 Validation at OWRB Station 121510020010-001AT

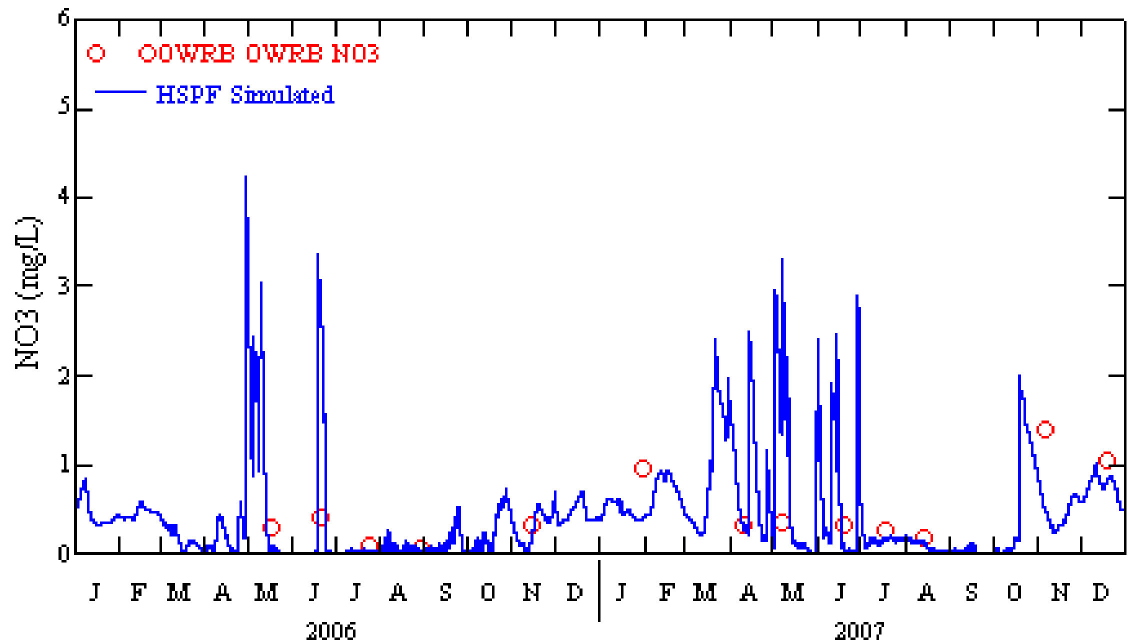


Figure 3-20 Nitrate Validation at OWRB Station 121510020010-001AT

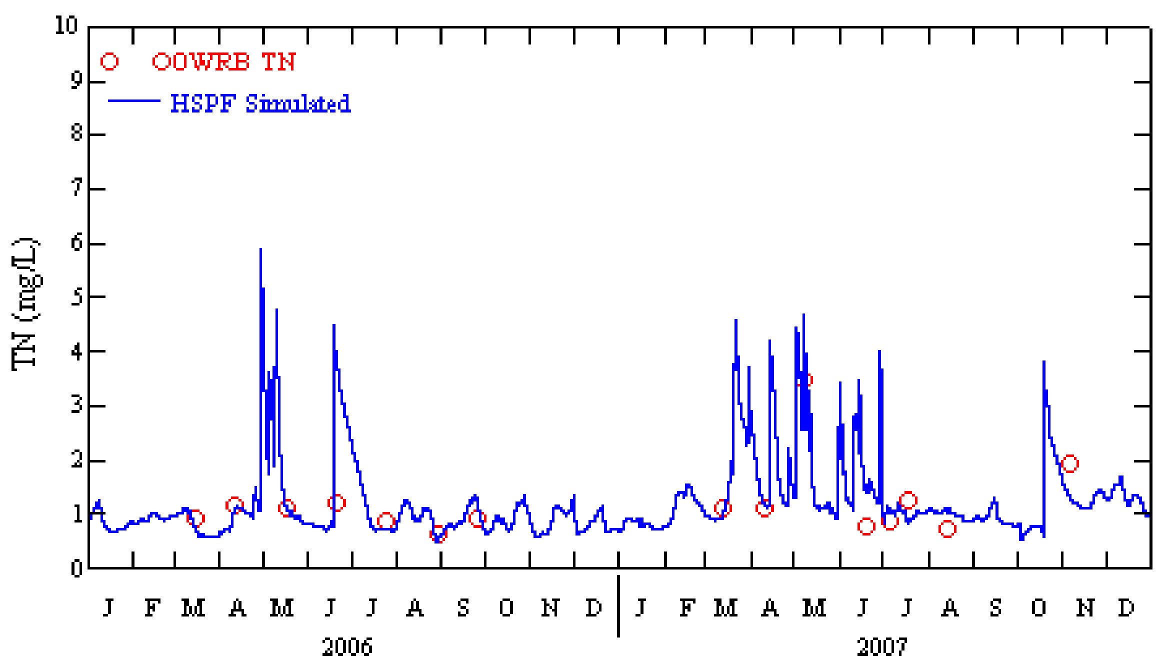


Figure 3-21 Total Nitrogen Validation at OWRB Station 121510020010-001AT

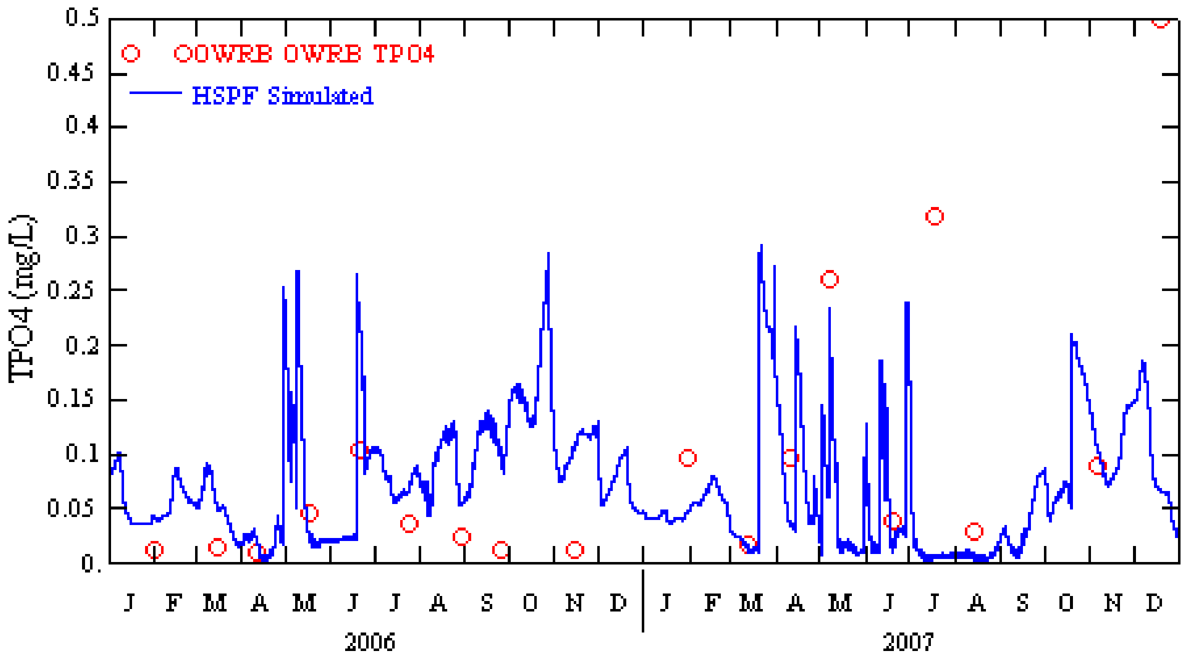


Figure 3-22 Total Orthophosphate Validation at OWRB Station 121510020010-001AT

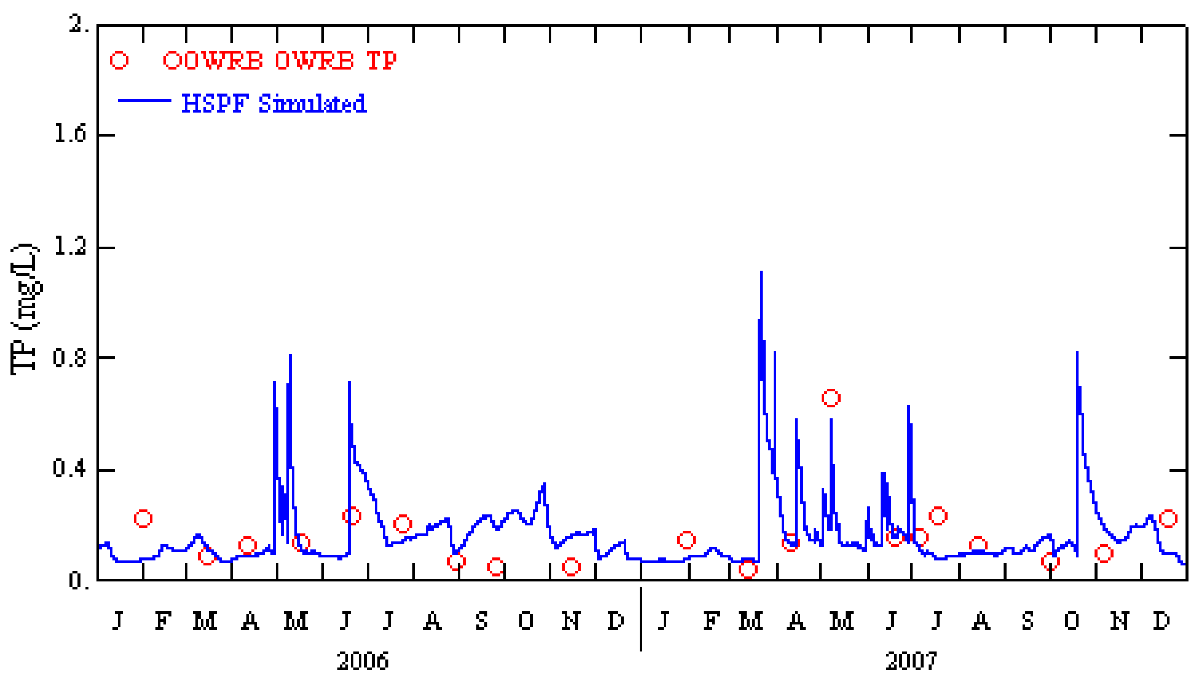


Figure 3-23 Total Phosphorus Validation at OWRB Station 121510020010-001AT

### *3.2.6 HSPF Loads for TSS, TN, TP and CBOD for Existing Calibration Conditions*

The HSPF model framework consists of a network of sub-watersheds that generate flow and pollutant loading from runoff over the land uses of sub-watersheds defined within a larger watershed domain for a project. Some, but not all, sub-watersheds are defined by an in-stream reach where flow and pollutant loads simulated as land use dependent runoff are input and routed through a tributary reach that is defined by length, volume, surface area, depth and hydraulic residence time. A sub-watershed that is defined by a tributary reach generates flow and water quality concentrations at a specific downstream outlet location of the sub-watershed. Any wastewater pollutant loading contributed by NPDES point source discharges to a tributary reach is accounted for in the HSPF watershed - EFDC lake model framework as external point source inputs to tributary reaches of the HSPF watershed model. The output of a sub-watershed tributary reach can, therefore, include both NPS runoff over the catchment and NPDES point source loading if a NPDES permitted facility discharges to the tributary (see Table 3-1). A sub-watershed that does not include a tributary reach generates water volume and loads as distributed overland runoff over the entire sub-watershed. By aggregating wastewater discharge loading and pollutant loading from all the tributary reach sub-watersheds and NPS overland sub-watersheds without a tributary, the annual pollutant PS and NPS load budget estimated by the HSPF model for the entire watershed model domain for 2007 is presented in Table 3-19. Design flow and annual average pollutant loading rates for 2007 from NPDES wastewater dischargers shown in Table 3-19 are summarized in Table 6 of Appendix B (Oologah Lake Watershed Model) of this TMDL report. The pollutant load budget shows that point source wastewater discharge loading accounts for only 2% or less of the sediment, CBOD and nutrient loading within the watershed and 90-92% of pollutant loading is contributed by tributary reaches with the Verdigris River accounting for the largest share of tributary loads. The area normalized sub-watershed pollutant loadings for 2007 are mapped in Figure 3-24 through Figure 3-27.

Table 3-19 HSPF Model Watershed Load Budget for 2007 for the Verdigris River Watershed (lbs/year)

| | **PS & NPS Load as lbs/year (2007)** | | | |
|---|---|---|---|---|
| **Source** | **Sediment** | **CBOD** | **TN** | **TP** |
| PS Loading from WWTP | 1.5189E+05 | 6.2697E+05 | 1.8677E+05 | 2.8362E+04 |
| NPS Tributary loading | 2.1098E+09 | 2.7473E+07 | 1.1413E+07 | 1.6416E+06 |
| NPS Distributed Runoff | 1.8500E+08 | 2.1000E+06 | 9.1200E+05 | 1.4800E+05 |
| Total NPS | 2.2948E+09 | 2.9573E+07 | 1.2325E+07 | 1.7896E+06 |
| Total (PS + NPS) | 2.2950E+09 | 3.0200E+07 | 1.2512E+07 | 1.8180E+06 |
| | **PS & NPS Load as % Share of Total (PS + NPS)** | | | |
| **Source** | **Sediment** | **CBOD** | **TN** | **TP** |
| PS Loading from WWTP | 0.01% | 2.08% | 1.49% | 1.56% |
| NPS loading from tributary | 91.93% | 90.97% | 91.22% | 90.30% |
| NPS loading from distributed runoff | 8.06% | 6.95% | 7.29% | 8.14% |
| Total NPS | 99.99% | 97.92% | 98.51% | 98.44% |
| Total (PS + NPS) | 100.00% | 100.00% | 100.00% | 100.00% |

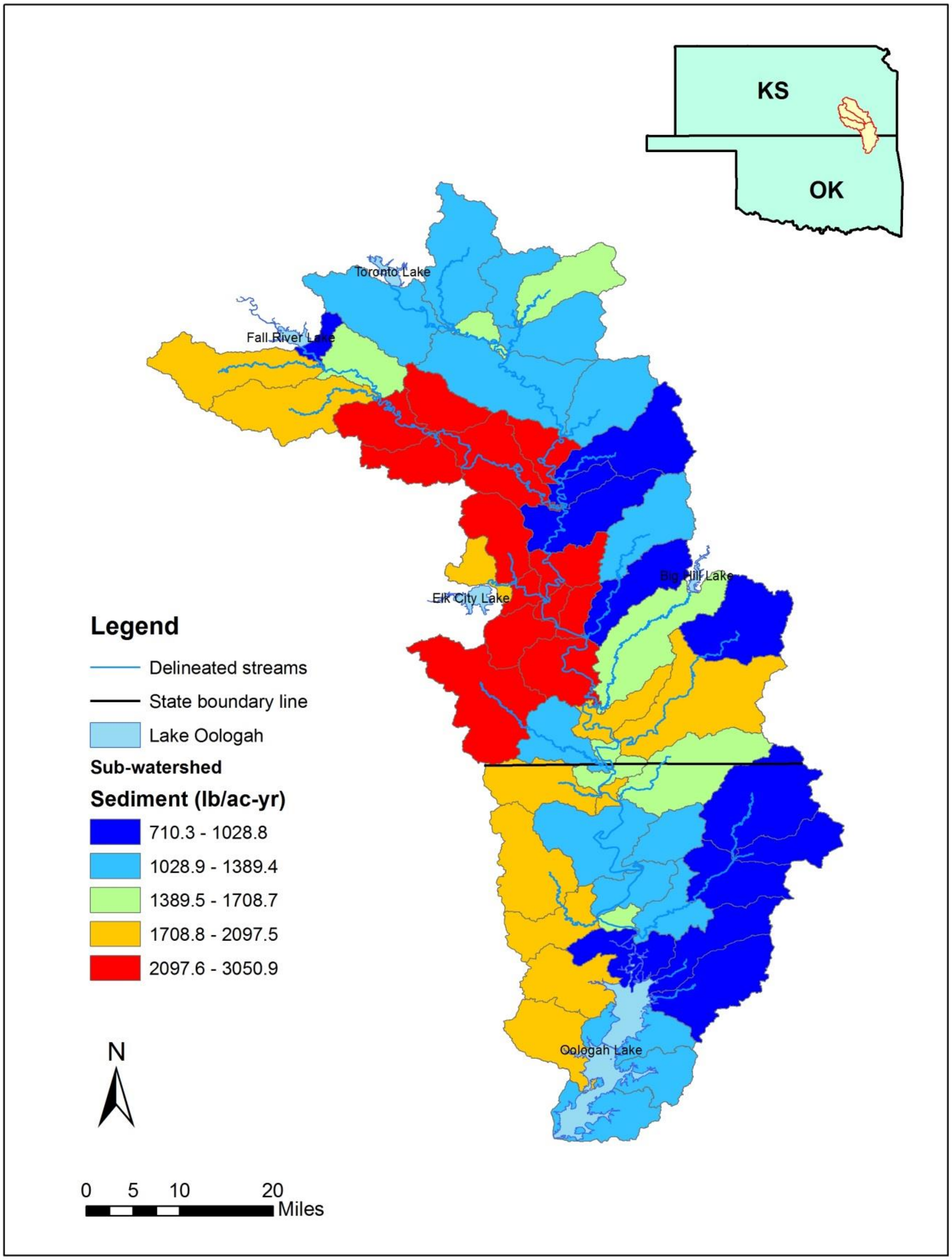


Figure 3-24 Sub-watershed sediment loadings by HSPF Model (lbs/acre-yr)

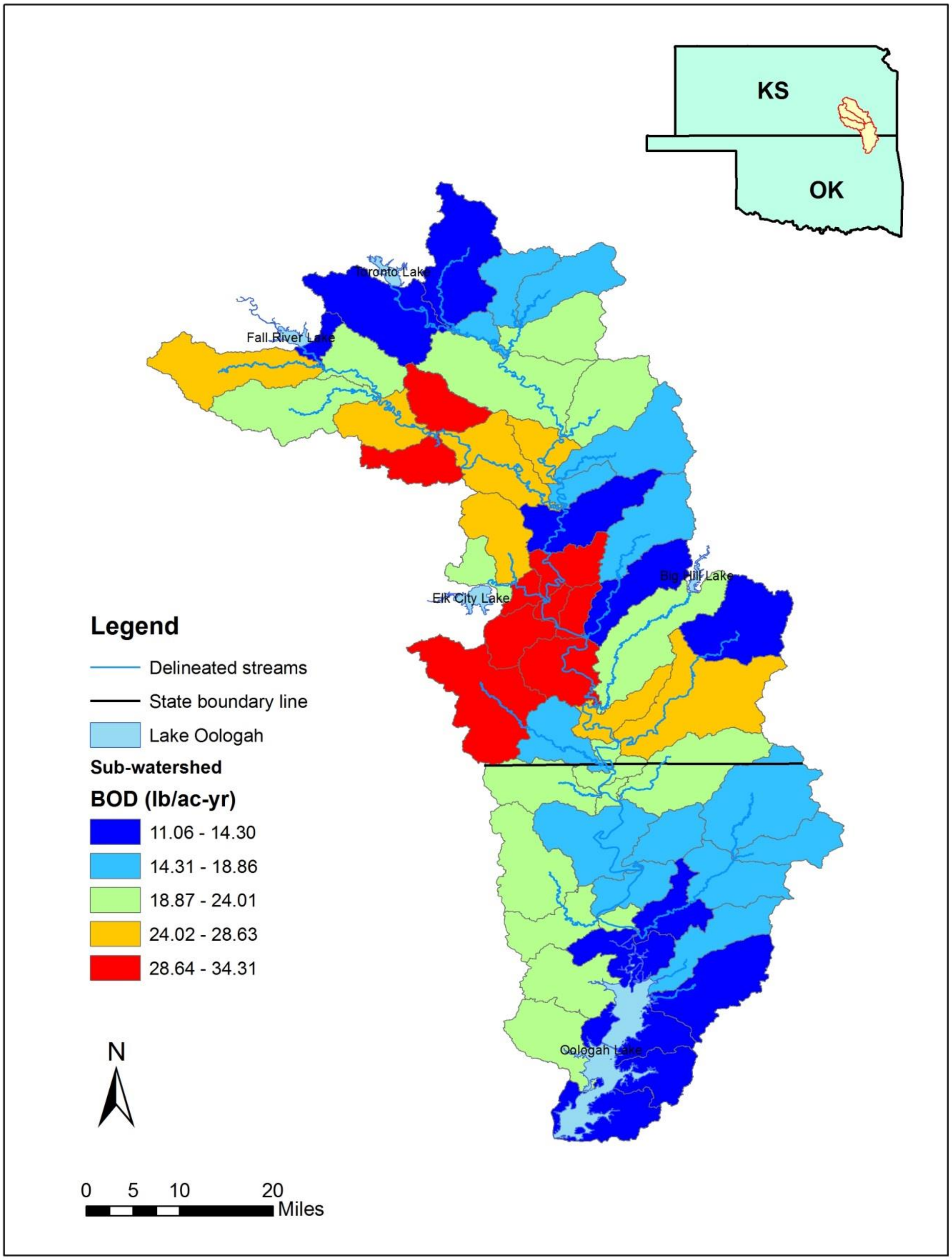


Figure 3-25 Sub-watershed CBOD loadings by HSPF Model (lbs/acre-yr)

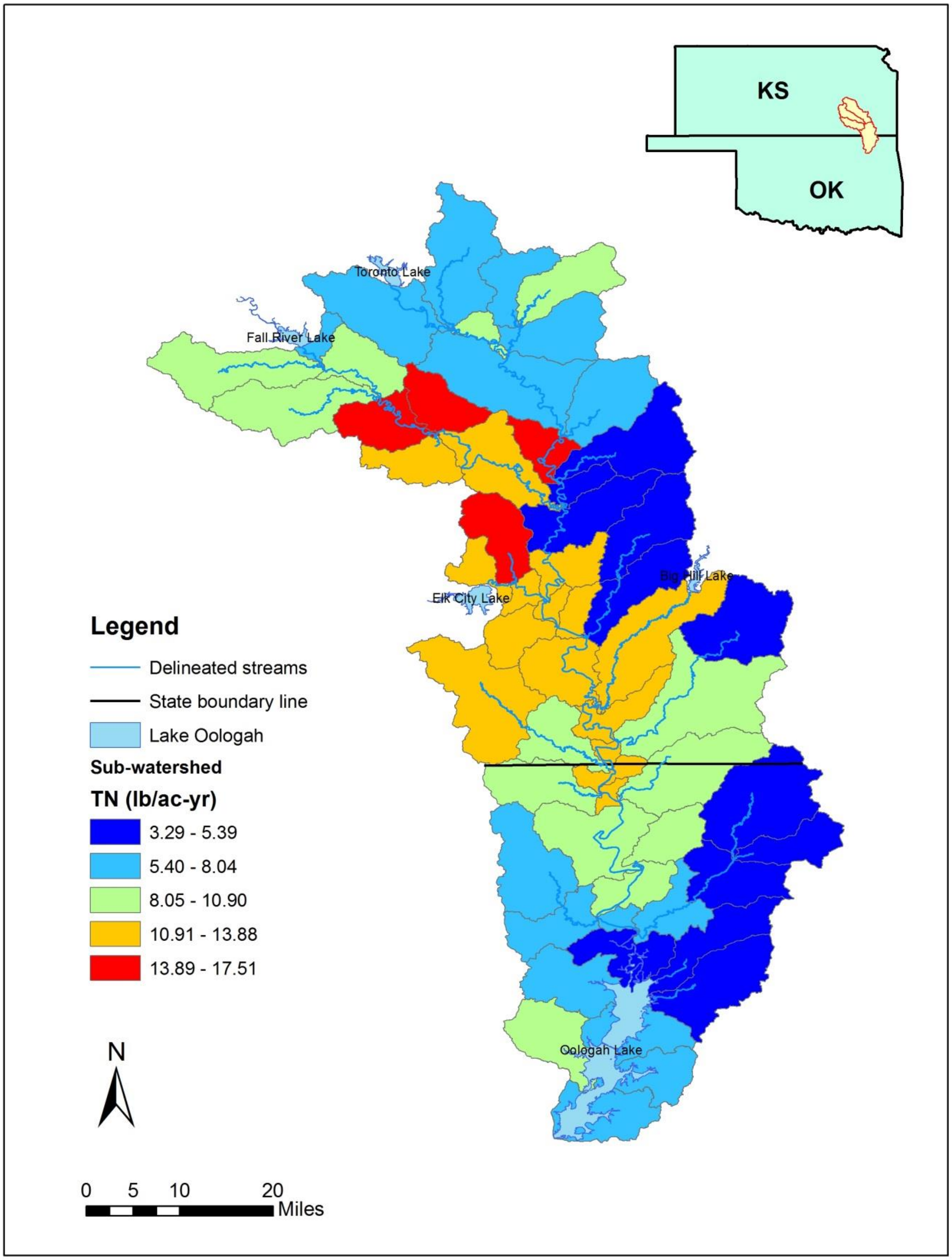


Figure 3-26 Sub-watershed TN loadings by HSPF Model (lbs/acre-yr)

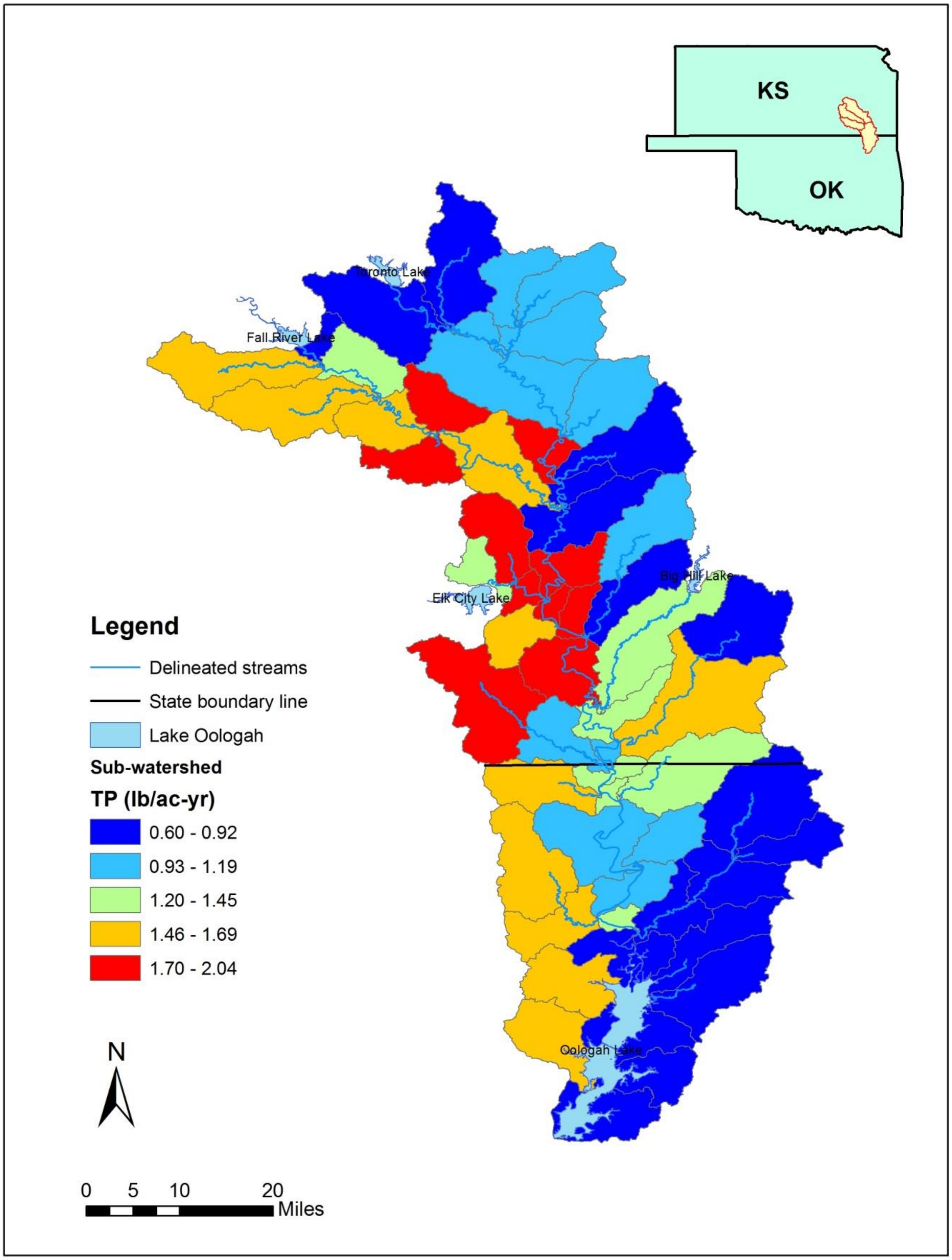


Figure 3-27 Sub-watershed TP loadings by HSPF Model (lbs/acre-yr)

# 4. Lake Model and Watershed-Lake Model Linkage

The objective of a TMDL study is to estimate allowable pollutant loads expected to achieve compliance with water quality criteria. The allowable load is then allocated among the known pollutant sources in the watershed so that appropriate control measures can be implemented to reduce pollutant loading. To determine the effect of watershed management measures on in-lake water quality, it is necessary to establish a cause-effect linkage between the external loading of sediments, nutrients and organic matter from the watershed and the waterbody response in terms of lake water quality conditions for sediments, nutrients, organic matter, dissolved oxygen and chlorophyll-*a*. This section describes an overview of the water quality modeling analysis of the EFDC linkage between water quality conditions in Oologah Lake and HSPF watershed flow and pollutant loading. Appendix C of this TMDL report presents a description of the EFDC model, setup of the model, data sources, and model results for existing conditions and analysis of the effects of watershed load reductions on lake water quality.

## 4.1 EFDC Model Description

EFDC is an advanced surface water modeling package for simulating three-dimensional (3-D) circulation, salinity, water temperature, sediment transport and biogeochemical processes in surface waters including rivers, lakes, reservoirs, estuaries, and coastal systems. The EFDC model has been supported by EPA over the past decade as a public domain, peer reviewed model to support surface water quality investigations including numerous TMDL evaluations (Ji, 2017). EFDC directly couples the hydrodynamic model (Hamrick, 1992, 1996) with sediment transport (Tetra Tech, 2002), water quality (Park et al., 2000; Hamrick, 2007) and sediment diagenesis models (Di Toro, 2001). EFDC state variables include suspended solids, dissolved oxygen, nutrients (N, P), organic carbon, algae, sediment bed organic carbon and nutrients and benthic fluxes of nutrients and dissolved oxygen. The EFDC model is time variable with model results output at user-assigned hourly time intervals. The EFDC model requires input data to characterize lake geometry (shoreline, depth, surface area, and volume), time varying watershed inputs of flow and pollutant loads, time varying water supply withdrawals and release flows, and kinetic coefficients to describe water quality interactions such as nutrient uptake by algae. Observed water quality data collected at lake monitoring sites are used for calibration and validation of the model results to observations. Model setup, data input, and post-processing of model results is facilitated with the EFDC_Explorer graphical user interface (Craig, 2012).

## 4.2 Data Sources and EFDC Model Setup

<u>Data Sources</u>. Data sources used for development of the lake model included lake water quality monitoring by OWRB and the USACE Tulsa District; lake level, releases and storage volume monitoring by the USACE Tulsa District; and meteorological data from NOAA NCDC and Oklahoma MESONET stations in the vicinity of the watershed. The bathymetry data of Oologah Lake were obtained from the Oologah Lake Watershed Assessment Study (USACE and City of Tulsa, 2012). OWRB collected water quality data only one time (November 7, 2007) at seven sites (Sites 1 through 7) during the model calibration and validation period. As a result, the limited OWRB data were not used for model-data comparison. Data collected by the USACE Tulsa District, including chlorophyll-a, nutrients, total

suspended sediment, water temperature, turbidity, organic carbon, and dissolved oxygen in 2006-2007, were used to support model-data comparisons for development of the EFDC model for Oologah Lake. Tables of observed water quality data used for EFDC lake model development are presented in Appendix I of this report.

EFDC Model Domain. The EFDC model allows for the physical representation of the lake with a horizontal mesh of curvilinear grid or Cartesian grid cells to account for the shoreline, embayments, and bathymetry, particularly the deeper parts of the lake (Figure 4-1). The computational grid developed to map the geometry of Oologah Lake consisted of 888 horizontal cells. Depth of the water column was represented with 5 sigma vertical layers to account for the effects of seasonal stratification. The shoreline of the lake is defined by the normal pool elevation of 638.00 feet, NGVD29. Bottom elevation of the lake model was interpolated to each grid cell using the high-resolution bathymetry data collected by the USACE (Figure 4-1).

Boundary Conditions. The EFDC lake model requires specification of external boundary data to describe: (1) flow and pollutant loading from watershed tributaries and distributed runoff; (2) flow releases at the dam; (3) withdrawals from water supply intakes; (4) wind forcing, evaporation, precipitation, and other meteorological forcing; and (5) atmospheric deposition of nutrients.

As described in Section 3, flow and pollutant loading from the watershed was provided by the HSPF model as time series inflow data for tributaries and overland runoff discharged into the lake. As shown in the EFDC lake model report (Appendix C: Table 2), tributary reach inflows to the lake included the Verdigris River, Big Creek, Salt Creek, Double Creek, Madden Creek and Talala Creek. No point source NPDES wastewater facilities discharge directly into Oologah Lake. Stoichiometric transformations of HSPF water quality results as input to state variables needed for the EFDC lake model are described in Appendix C of this report.

Water supply withdrawal data for Oologah Lake were not readily available. A flow balance analysis was estimated using all inflow data including all HSPF simulated watershed flows, rainfall and all outflows including evaporation and flow releases at the dam. A flow balance was computed to implicitly account for water supply withdrawals to ensure that the EFDC model simulation of lake stage would be in good agreement with observed lake stage records. The methodology used to estimate the flow balance ensures that the simulated lake stage accurately represents water surface elevation, depth, surface area and volume of the lake for the model calibration and validation periods. This approach is an accepted practice for developing hydrodynamic models of a reservoir as a flow balance estimate is needed to account for measurement errors and unknown inflows and outflows that control the accuracy of the simulation of lake stage at the dam.

The EFDC model requires time series data to describe the effect of meteorological forcing and winds on lake circulation processes. Cloud cover data were obtained from the NOAA station at Claremore Regional Airport. Other meteorological data and wind speed and direction data were obtained from the Oklahoma MESONET database at Station Pryor. Meteorological data needed for the model includes wind, air temperature, air pressure, relative humidity, precipitation, evaporation, cloud cover and solar radiation.

The EFDC model requires specification of wet and dry atmospheric deposition of nitrogen and phosphorus over the entire surface area of the lake. Atmospheric deposition of nutrients is represented using the same constant loading rate for both model calibration and validation to existing conditions (2006-2007) and model evaluations of watershed load reduction scenarios. Since atmospheric deposition is uncontrollable on the local watershed scale, there is no load allocation for atmospheric deposition of nutrients for the TMDL. For Oologah Lake, wet and dry deposition data for nitrogen, presented in Appendix C, was estimated as the average of annual data from 2006-2007 for ammonia and nitrate from the National Atmospheric Deposition Program (NADP) for Station AR27 (Fayetteville, AR) and the Clean Air Status and Trends Network (CASTNET) Station CHE185 (Cherokee Nation). Wet deposition input of ammonia and nitrate is based on a constant concentration in rainfall and the time series of precipitation assigned for 2006-2007 input conditions. As data were not available from the CASTNET or NADP sites for deposition of phosphate, dry deposition for phosphate was estimated using the CASTNET and NADP data for nitrogen with annual average N/P ratios for atmospheric deposition of N and P reported for 6 sites located in Iowa (Anderson and Downing, 2006). Annual average wet phosphate concentration was estimated in proportion to the Dry/Wet ratio for phosphate deposition fluxes reported by Anderson and Downing (2006).

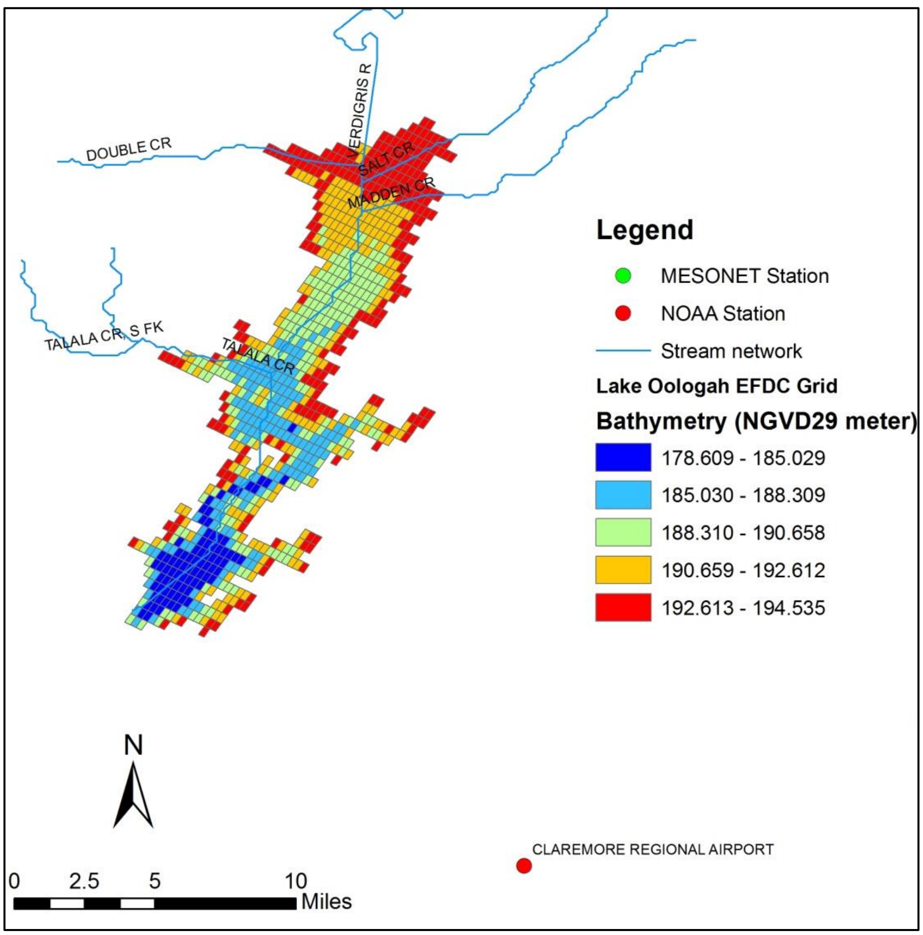


Figure 4-1 Oologah Lake Computational Grid and Bottom Elevation

Initial Conditions. As a time-varying model, EFDC requires the specification of initial distributions of all the model state variables at the beginning of the model simulation period in January 2006. The spatial distribution of initial conditions for the model is based on simulated conditions at the end of the 1-year model simulation run. Restart conditions, written for all state variables of the model at the end of a preliminary model run for 2005, were used to assign a simulated set of initial conditions for January 2006 that accounted for spatial variability of conditions in the water column and sediment bed.

## 4.3 EFDC Model Calibration and Validation to Existing Conditions

The EFDC lake model was setup for a 2-year period from January 1, 2006 through December 31, 2007. Model results were calibrated and validated against observed data collected at 4 water quality monitoring sites shown in Figure 4-2. Station OOL_5 was not selected for model calibration and validation because water quality data collected at this station, which is located near the upstream boundary at the north end of the lake, would be controlled by upstream boundary inflow from the Verdigris River and would not be representative of water quality conditions in the upper portion of Oologah Lake. Model results were calibrated to observations for water level, water temperature, TSS, nitrogen, phosphorus, dissolved oxygen, and algae biomass (chlorophyll-a). The model-data performance statistics selected for calibration of the hydrodynamic and water quality model are the Root Mean Square Error (RMSE) and the Relative RMS Error. The Relative RMS error, computed as the ratio of the RMSE to the observed range of each water quality constituent, is expressed as a percentage. The Relative RMS Error thus provides a straightforward performance measure statistic to evaluate agreement between model results and observations in comparison to model performance targets. This section provides a brief description of the EFDC lake model calibration and validation results. More details on the procedure used for EFDC model development and the results obtained for EFDC model calibration and validation are given in Appendix C of this report.

Turbidity and TSS. Water clarity is an issue for impairment of Fish & Wildlife Propagation for the Warm Water Aquatic Community within Oologah Lake and turbidity is the water quality parameter used to determine if the lake fully supports designated uses. Oklahoma water quality criteria states that no more than 10% of samples collected over the most recent 10-year period shall be greater than 25 NTU. Turbidity is a measure of the optical properties of water that causes light to be scattered and absorbed by particles in the water sample. Turbidity, as measured with a Nepholometer and reported with units of Nephelometric Turbidity Units (NTUs), however, accounts only for the scattering of light. Since turbidity is not a mass-based concentration, a surrogate indicator of water quality must be used to develop a TMDL that addresses compliance with water quality criteria for turbidity. Total Suspended Solids (TSS) is a common water quality measurement that can be used as a surrogate indicator for turbidity. Although turbidity and TSS measure very different properties of water samples, both measurements do provide information about water clarity. TSS vs. turbidity relationships can therefore be developed and applied for TMDL determinations. The TSS vs. turbidity relationship must, however, be developed using a site-specific paired data set since inconsistencies and interferences in the relationship can result from site-specific properties of a water sample including water color, size, shape and refractive index of sediment particles, the organic and inorganic composition of sediment particles, and the inconsistency of instruments used for the turbidity measurement itself (Thackston and Palermo, 2000; Bash, Berman and Bolton, 2001).

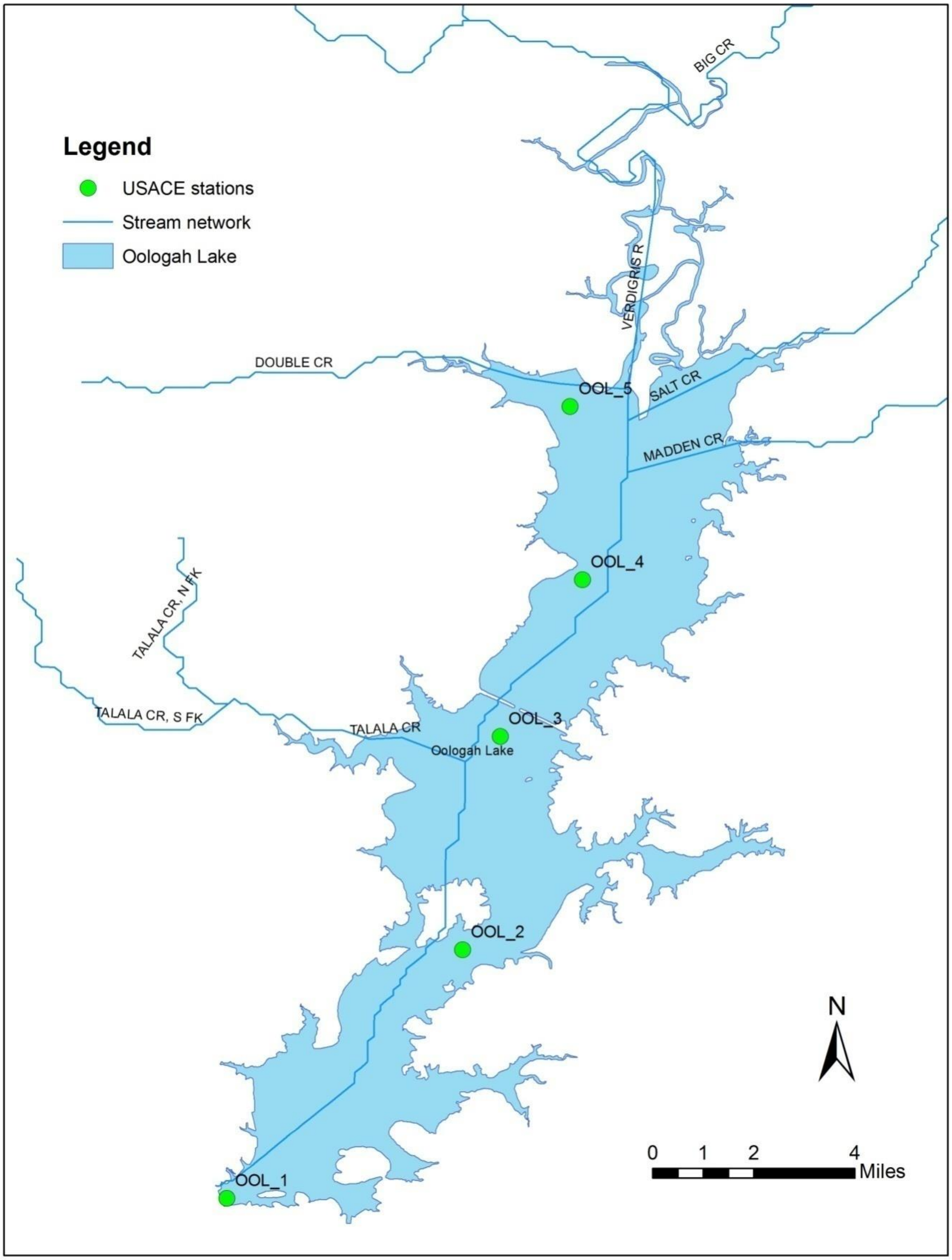


Figure 4-2 Location of USACE Stations for Lake Model Calibration and Validation

For the Oologah Lake study, paired TSS and turbidity measurements from USACE lake stations in the lake were used to develop a linear regression relationship as shown in Figure 4-3. Based on the correlation coefficient ($r^2$ =0.78, n=116), the relationship was considered acceptable to apply a site-specific correlation to compute simulated turbidity from modeled TSS for Oologah Lake.

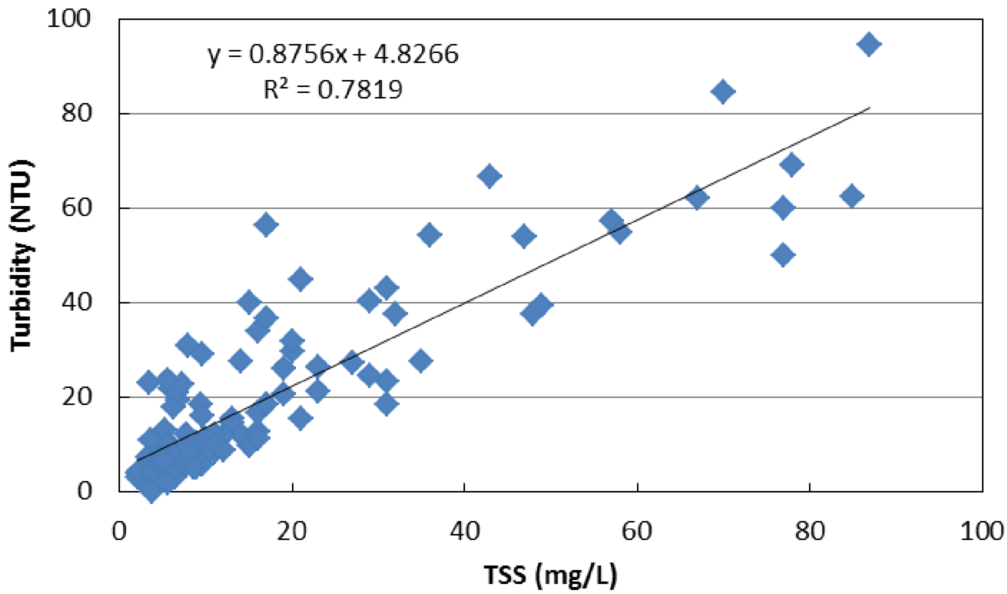


Figure 4-3 Correlation between Turbidity and TSS in Oologah Lake

The TSS vs. turbidity relationship developed for Oologah Lake was used to transform EFDC model results of TSS to turbidity for comparison to the water quality criteria for turbidity of 25 NTU. The model performance statistic for TSS for the surface layer of USACE stations OOL-1, OOL-2, OOL-3 and OOL-4 in Oologah Lake was very good with a Relative RMS Error of 64.1%, 87.0%, 47.0% and 53.7%, respectively, which was better than the performance target of 100% defined for TSS.

Summary statistics computed from OWRB and USACE turbidity data collected from 2004 to 2014 and from 2002 to 2009, respectively, indicated that the 90$^{th}$ percentile values for observed turbidity exceeds the water quality target of 25 NTU as shown in Table 2-5. As can be seen in Figure 2-2, turbidity values greater than 25 NTU observed by OWRB and USACE were recorded for all the years when turbidity data were collected.

<u>Dissolved Oxygen</u>. Proposed Oklahoma water quality standards for dissolved oxygen (OWRB, 2014a) for Oologah Lake are specified as follows: 1) Surface DO shall not exhibit concentrations less than 6 mg/L in greater than 10% of the samples at early life stages (April 1 to June 15); 2) Surface DO shall not exhibit concentrations less than 5 mg/L in greater than 10% of the samples at other life stages including summer conditions (June 16 to October 15) and winter condition (October 16 to March 31); 3) Anoxic volume of the lake, defined by a DO target level of 2 mg/L, shall not exceed 50% of the lake volume based on volumetric data or 70% of the water column at any given sample site.

Model results for dissolved oxygen at sites in the lake show good agreement with the observed seasonal trend of both surface layer dissolved oxygen and bottom layer depletion of dissolved oxygen during stratified summer conditions. In the bottom layer, observed anoxic conditions during the summer months are controlled by the onset and erosion of lake stratification and decomposition of organic matter in the hypolimnion and the sediment bed. The model performance statistics for dissolved oxygen were good with a Relative RMS Error of 12.9% for the surface layer and 14.7% for the bottom layer at the forebay station OOL-1. At all the validation stations, the performance for the surface and bottom layer results met the model performance target of 20% defined for the Relative RMS Error for dissolved oxygen.

Based on an assessment of water column dissolved oxygen data for the OWRB and USACE monitoring stations near the dam (121510010020-01 and OOL-1), OWRB determined that Oologah Lake was not fully supporting its beneficial uses for Fish and Wildlife Propagation for a Warm Water Aquatic Community because dissolved oxygen data at this site showed that more than 70% of the water column was less than the 2 mg/L target for anoxia within the hypolimnion. As discussed in Section 2, vertical profiles of dissolved oxygen near the dam showed that more than 70% of the water column was less than the 2 mg/L target for anoxia within the hypolimnion for 1 of the sampling surveys from 2003-2008. The observed data used by OWRB for the 2010 303(d) list documents that the Warm Water Aquatic Community use for Fish and Wildlife Propagation was not attained because of depletion of dissolved oxygen in the hypolimnion of the deep waters of the lake near the dam.

Model results for dissolved oxygen are post-processed for selected sampling sites to derive time series data sets to compute the percentage of the water column defined as anoxic based on the cutoff target DO of 2 mg/L. Figure 4-4 shows model validation results for the percentage of the water column <2 mg/L. As can be seen, the model results are in good agreement with the observed data for the USACE Station OOL-1 near the dam. With a maximum of 80% of the water column <2 mg/L, model validation results show violations of the 70% target for the water column in late July and August. In the transition zone (OOL-2, OOL-3, and OOL-4), the maximum anoxic percentage of the water column are all lower than 70%.

Benthic Flux of Phosphate and Sediment Oxygen Demand. Model results for the validation year of 2007 are analyzed to evaluate benthic flux rates of phosphate and sediment oxygen demand (SOD) simulated with the sediment diagenesis model. These coupled water column-sediment bed processes provide a critical link with the lake model results obtained for nutrients, dissolved oxygen, and chlorophyll-a. As observed benthic flux measurements of phosphate and SOD are not available for Oologah Lake, modeled benthic fluxes for phosphate and SOD are extracted for the stratified period defined for other life stages (June 16 to October 15) for sites in the lacustrine (OOL_1 and OOL_2) and transition (OOL_3 and OOL_4) zones. Simulated benthic fluxes are then compared to literature data from other lakes and reservoirs to assess how well the sediment flux model reproduces typical measured benthic flux rates. The mean modeled benthic flux rate for phosphate (4.1 mg P/m$^2$-day), with a range of 1.2 - 10.7 mg P/m$^2$-day, is consistent with the observed range of anoxic phosphate fluxes reported by Dzialowski and Carter (2011) for mesotrophic (1.7 -7.4 mg P/m$^2$-day) and eutrophic (2.6 - 18.5 mg P/m$^2$-day) reservoirs in the Central Plains. The mean modeled SOD rate (1.1 g/m$^2$-day), with a range of 0.5 - 1.9 g/m$^2$-day, is also consistent with the observed range of SOD rates measured in Wister Lake in Oklahoma (0.24 - 0.54 g $O_2/m^2$-day) (Haggard and Scott, 2011) and mesotrophic and eutrophic reservoirs in Texas and Oklahoma (1.7 - 4.1 g $O_2/m^2$-day) (Veenstra and Nolen, 1991).

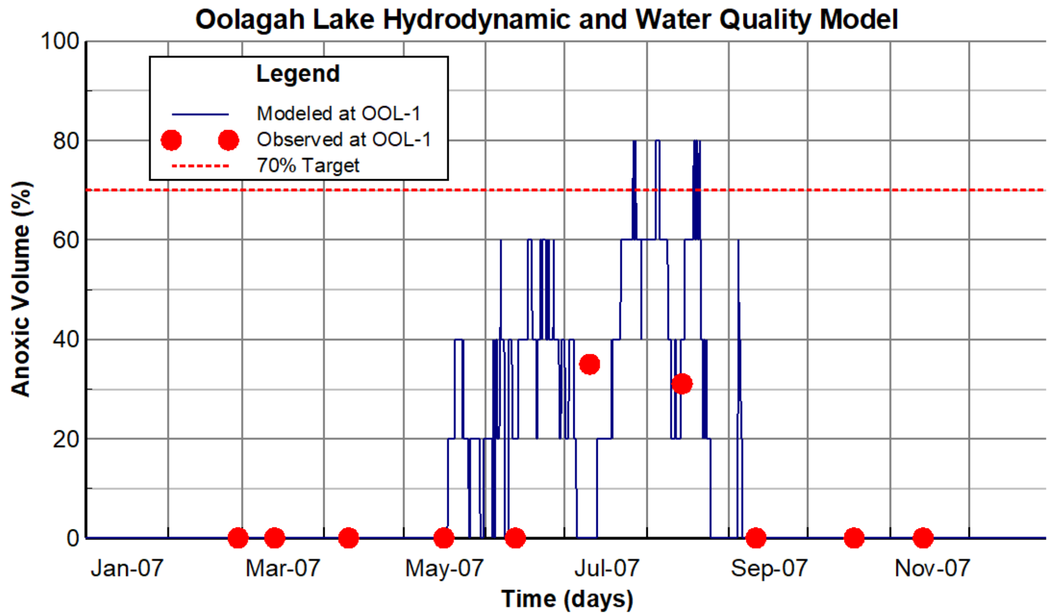


Figure 4-4 Model Validation for the Anoxic Water Column at USACE Station OOL_1 Near the Dam.

Model-Data Performance. The Relative RMS Error performance of the lake model, defined as composite statistics derived from pooled model-observed data pairs for 2006-2007 for stations compiled in Appendix C, are consistent with model performance targets recommended for surface water models (Donigian, 2000). As presented in Appendix C, the model performance targets for dissolved oxygen (20%), water temperature (20%), TSS (100%), nutrients (50%) and chlorophyll (100%) are all attained with the model results for these state variables either better than, or close to, the target criteria for model performance.

Given the lack of a general consensus for defining quantitative model performance criteria, the inherent errors in input and observed data, and the approximate nature of model formulations, *absolute* criteria for model acceptance or rejection are not appropriate for studies such as the development of the model for Oologah Lake. The Relative RMS Errors are used as targets for performance evaluation of the calibration and validation of the lake model, but not as rigid absolute criteria for rejection or acceptance of model results. The "weight of evidence" approach used in this study recognizes that, as an approximation of a waterbody, perfect agreement between observed data and model results is not expected and is not specified as performance criteria for defining the success of model calibration. Model performance statistics are used as guidelines to supplement the visual evaluation of model-data plots for model calibration. The "weight of evidence" approach used for this study thus acknowledges the approximate nature of the model and the inherent uncertainty in both input data and observed data.

## 4.4 Pollutant Loads for Existing Model Validation (2007)

Using data developed for validation of the HSPF watershed model and the EFDC lake model to 2007 conditions, mass loads for sediment and nutrients are compiled to identify the relative magnitude of the external and internal sources of pollutant loading to the lake. External sources include watershed tributary and overland runoff inputs from the HSPF model; NPDES permitted wastewater dischargers; and wet and dry atmospheric deposition. Internal sources to the lake include the benthic fluxes of inorganic nutrients across the sediment-water interface of the lake. Loading rates (as kg/day) are compiled in Table 4-1 for the 363-day simulation period from January to December 2007.

The seven (7) NPDES wastewater facilities listed in Table 3-1 are all included as point source wastewater discharges to tributary reach sub-basins of the HSPF watershed model. Table 3-19 and Table 6 in Appendix B present the design flow and annual average pollutant loading rates assigned for each of the seven (7) NPDES point source dischargers that are accounted for as inputs to tributaries of the watershed model. Any wastewater pollutant loading contributed by NPDES permitted discharges within the Verdigris River watershed is therefore represented as point source inputs to tributary reach catchments of the HSPF watershed model. The combined contributions of point source loading of NPDES wastewater discharges and nonpoint source runoff over a catchment are accounted for by flow and pollutant loading simulated at the downstream outlets of each tributary reach sub-basin of the HSPF watershed model. As there are no point source NPDES wastewater facilities that discharge directly into Oologah Lake the share of point source NPDES loading to the lake is zero because the NPDES wastewater loading to tributaries of the watershed model are incorporated as part of the Annual HSPF share of pollutant loading shown in Table 4-1 and Table 4-2.

Table 4-1 presents a summary of nutrient, organic carbon and sediment loads for the existing 2007 validation conditions for HSPF loads that represent watershed runoff plus point source NPDES loading to tributary reach sub-watersheds of the HSPF model. The table presents a summary, and comparison, of sources from the HSPF model, atmospheric deposition and internal benthic flux loading rates for the existing 2007 validation conditions. Table 4-2 presents the percentage contributions from the HSPF model, atmospheric deposition and benthic flux loading to the total loads. As described above, it is important to understand that the contribution of pollutant loading from the NPDES point source wastewater dischargers listed in Table 3-1 is included as part of the total nonpoint source load contribution from the HSPF watershed model. As shown in Table 4-2, the internal benthic flux of total phosphorus accounts for 13.28% of the total phosphorus loading to the lake on an annual basis while external loading of phosphorus from the watershed accounts for 86.67%. The load budget for total nitrogen is dominated by loading from the HSPF watershed model (94.50%) with 4.46% of the load derived from the internal benthic flux of nitrogen. Atmospheric deposition of both phosphorus and nitrogen accounts for only minor contributions to the total loading to the lake.

Table 4-1 Annual Loading of Existing Nonpoint Source and Point Source Loading of Pollutants Delivered to Oologah Lake for EFDC Model Validation (Jan-Dec 2007)

| **Model Validation: 2007 WQ Parameter Load Units** | | **Annual HSPF kg/day** | **Annual AtmDep kg/day** | **Annual SedFlux kg/day** | **Annual PS:NPDES kg/day** | **Annual Total kg/day** |
|---|---|---|---|---|---|---|
| Total Nitrogen | TN | 2.03E+04 | 2.23E+02 | 9.59E+02 | 0 | 2.15E+04 |
| Total Phosphorus | TP | 3.06E+03 | 1.47E+00 | 4.69E+02 | 0 | 3.53E+03 |
| Total Organic Carbon | TOC | 7.16E+04 | 0 | 0 | 0 | 7.16E+04 |
| Total Suspended Solids | TSS | 2.40E+06 | 0 | 0 | 0 | 2.40E+06 |

Table 4-2 Relative Contribution of Existing Nonpoint Source and Point Source Loading of Pollutants Delivered to Oologah Lake for EFDC Model Validation (Jan-Dec 2007)

| **Model Validation: 2007 WQ Parameter Percentage** | | **Annual HSPF %** | **Annual AtmDep %** | **Annual SedFlux %** | **Annual PS:NPDES %** | **Annual Total %** |
|---|---|---|---|---|---|---|
| Total Nitrogen | TN | 94.50% | 1.04% | 4.46% | 0.00% | 100.00% |
| Total Phosphorus | TP | 86.67% | 0.04% | 13.28% | 0.00% | 100.00% |
| Total Organic Carbon | TOC | 100.00% | 0.00% | 0.00% | 0.00% | 100.00% |
| Total Suspended Solids | TSS | 100.00% | 0.00% | 0.00% | 0.00% | 100.00% |

## 4.5 Water Quality Response to Modeled Load Reduction Scenarios

The validated lake model was used to evaluate the water quality response to reductions in watershed loading of sediment and nutrients. Load reduction scenario “spin-up” simulation runs were performed to determine if water quality targets for turbidity and dissolved oxygen could be attained with watershed-based load reductions of 30%, 40%, 45%, and 50%. Based on an evaluation of the load reduction scenario results the 40% removal alternative was selected to describe the long-term water quality response of the lake to changes in watershed loads. The 40% removal scenario was used to simulate 8 years of sequential “spin-up” runs to evaluate the long-term response of water quality conditions in the lake to the 40% removal change in external loads from the watershed. For the set of spin-up runs, watershed flow and reduced pollutant loading from the HSPF model were repeated for each of the 8 spin-up years. The results derived from the 8 years of spin-up simulations did not, therefore, account for any projected, or future, conditions of hydrologic variability within the watershed.

The 40% pollutant removal scenario identified for the TMDL for Oologah Lake is based on a simple uniform reduction of all sediment, BOD, TOC, TN and TP loads contributed by all tributaries and distributed runoff from the watershed to represent the reduction of external pollutant loads to Oologah Lake. The methodology applied for developing the load reduction scenarios did not attempt to represent changes in external watershed loading based on implementation of specific BMPs or point source waste load allocations within the Oologah Lake watershed.

Results of the spin-up model runs for the 40% removal scenario are presented to show long-term trends in turbidity, dissolved oxygen, benthic phosphate flux, and sediment oxygen demand. The spin-up results are also used to evaluate long-term changes in the relative contribution of internal phosphate loading from the sediment bed to external phosphate loads from the watershed and atmospheric deposition.

Turbidity. As discussed in Section 2 of this report, the Oklahoma water quality standard for turbidity is as follows:

- *Turbidity*: no more than 10% of turbidity samples greater than 25 NTUs based on compilation of historical records of the most recent 10 years

Table 4-3 summarizes annual statistics for surface layer turbidity for (a) the validated model results and the results generated with (b) eight years of spin-up runs for the 40% removal scenario, respectively. Summary statistics are computed from model results extracted for 4 USACE sites located in Oologah Lake. Statistics are computed for the annual simulation period from January 2007 to December 2007. The turbidity statistics are computed as the average of the surface layer model results for the USACE sites as shown in Figure 4-2.

Table 4-3 Summary Statistics for Surface Layer Turbidity: Observations (2007), Model Validation and 8 Years Spin-Up of the 40% Removal Scenario. Target for Turbidity is 25 NTU for 90$^{th}$ Percentile Statistic Based on Annual Data.

| **TURBIDITY (NTU), OOLOGAH LAKE** | **ANNUAL** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **OOL-1, OOL-2, OOL-3, OOL-4** | **N_OBS** | **MEAN** | **MIN** | **10Pct** | **25Pct** | **50Pct** | **75Pct** | **90Pct** | **MAX** |
| OBS DATA | 46 | 16.52 | 0.10 | 4.35 | 6.03 | 11.60 | 23.15 | 32.50 | 56.20 |
| VALIDATION 2007 | 8715 | 13.42 | 0.00 | 5.29 | 6.03 | 8.23 | 13.29 | 25.66 | 310.07 |
| YR0 | 8715 | 12.70 | 0.00 | 5.23 | 5.92 | 7.96 | 12.64 | 23.92 | 268.81 |
| YR2 | 8715 | 12.68 | 0.00 | 5.23 | 5.91 | 7.95 | 12.73 | 23.93 | 281.94 |
| YR4 | 8715 | 12.66 | 0.00 | 5.23 | 5.91 | 7.97 | 12.71 | 23.80 | 248.57 |
| YR6 | 8715 | 12.72 | 0.00 | 5.23 | 5.89 | 7.95 | 12.64 | 23.88 | 285.25 |
| YR8 | 8715 | 12.71 | 0.00 | 5.23 | 5.90 | 7.97 | 12.68 | 23.91 | 279.01 |

For the model validation year of 2007, the 90$^{th}$ percentile of observed turbidity (32.50 NTU) and simulated turbidity (25.66 NTU) presented in Table 4-3 for Oologah Lake showed violation of the water quality target of 25 NTU. Figure 4-5 presents the simulated long-term trend of the 90$^{th}$ percentile of annual turbidity based on 8 years of simulated spin-up results. The load reduction scenario results in ~7% decrease of the 90$^{th}$ percentile of annual turbidity (from 25.66 to 23.91 NTU) in the lake.

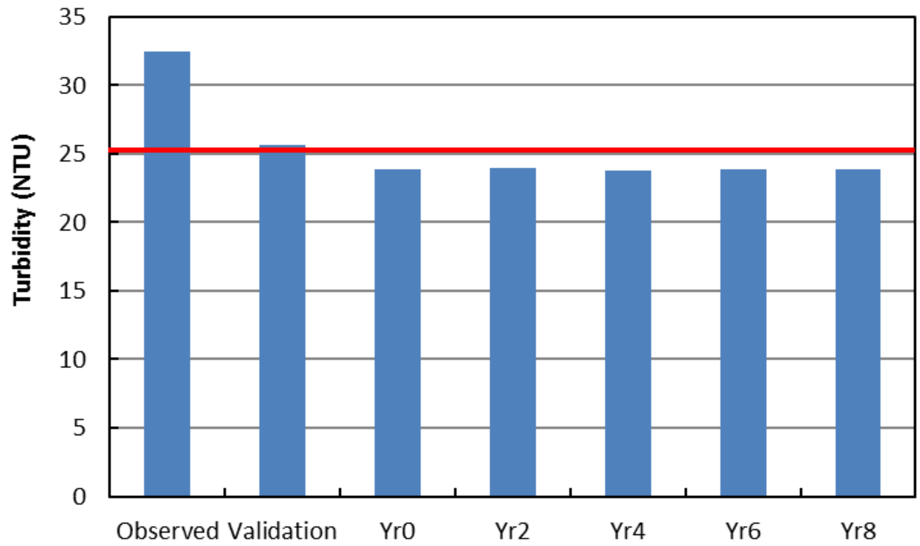


Figure 4-5 Turbidity, 90th Percentile: Observations (2007), Model Validation and 8 Years Spin-Up of the 40% Removal Scenario.

The internal loading of phosphate to the lake, controlled by hypoxic bottom water oxygen conditions, occurs during the summer stratified period from June through October. The sediment phosphate release rate showed a slight decreasing trend over the spin-up years. As can be seen in Figure 4-6, average benthic phosphate fluxes for stations OOL-1, OOL-2, OOL-3, and OOL-4 decrease from 4.19 mg P/m$^2$-day for the existing validation conditions to 4.09 mg P/m$^2$-day after 8 years of model spin-up. The maximum benthic phosphate flux rate also decreases from 10.64 mg P/m$^2$-day to 9.11 mg P/m$^2$-day.

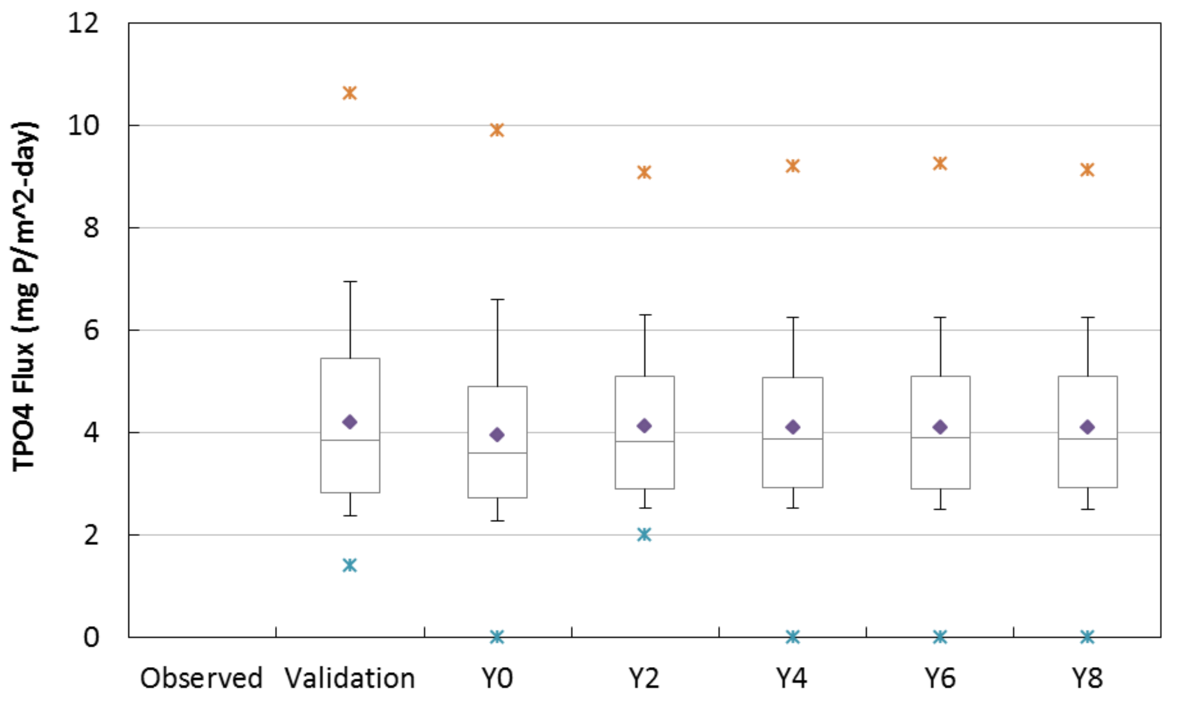


Figure 4-6 Sediment Flux of Phosphate (mg P/m$^2$-day), Spin-Up Model Results for 40% Removal, Summer Seasonal Average from June 16 to October 15 of OOL-1, OOL-2, OOL-3, and OOL-4.

The spin-up simulation analysis of the coupled water column-sediment bed response to the 40% reduction in watershed and wastewater loading of sediment and nutrients indicates that compliance with the water quality criteria for turbidity of 25 NTU can be attained within a reasonable time frame. **It is important to emphasize that the model spin-up results are not a prediction of the number of years required for lake recovery because of the idealized spin-up conditions of a precisely maintained watershed and wastewater discharge load reduction level and repeated climatic and hydrologic conditions of 2007.** The model results, do, however, provide technically credible evidence that future conditions can be in compliance with water quality targets for turbidity within a reasonable time frame if watershed loads are reduced as recommended and the reduction is sustained.

Dissolved Oxygen. The recently revised Oklahoma water quality standards for dissolved oxygen (OWRB, 2016) for Oologah Lake are specified as follows: 1) Surface DO shall not exhibit concentrations less than 6 mg/L in greater than 10% of the samples at early life stages (April 1 to June 15); 2). Surface DO shall not exhibit concentrations less than 5 mg/L in greater than 10% of the samples at other life stages including summer conditions (June 16 to October 15) and winter condition (October 16 to March 31); 3) Anoxic volume of the lake, defined by a DO target level of 2 mg/L, shall not exceed 50% of the lake volume based on volumetric data or 70% of the water column at any given sample site. Each criterion was checked to see whether the spin-up runs meet the TMDL DO targets or not.

Early life stages (April 1 to June 15), 10th percentile value for surface DO is used for comparison to the water quality target of 6 mg/L since the water quality criteria state that no more than 10% of the samples are allowed to be lower than 6 mg/L.

Table 4-4 summarizes annual statistics for surface dissolved oxygen for (a) the validated model results and the results generated with (b) eight years of spin-up runs for the 40% removal scenario, respectively. Summary statistics are computed from model results extracted for four USACE sites located within Oologah Lake. Statistics are computed for the simulation period from April 1 2007 to June 15 2007. The dissolved oxygen statistics are computed as the average of the model results for the USACE sites as shown in Figure 4-2.

For the model validation year of 2007, the 10$^{th}$ percentile of observed surface dissolved oxygen was 5.19 mg/L, indicating a violation of the water quality standard of 6 mg/L. However, it must be pointed out that the sample size (n=14) is too small to generate meaningful statistics. The sample size for the EFDC results for dissolved oxygen is 1,828 (4-hour interval), which is much more robust to represent the overall condition of the early life stages. The average of the 10$^{th}$ percentile of observed surface dissolved oxygen at these four USACE stations during the early life stages for the validation model was 7.32 mg/L, indicating compliance with the water quality standard. For the spin-up years, the average of the 10$^{th}$ percentile of observed surface dissolved oxygen seemed to be relatively constant around 7.7 mg/L, as shown in Table 4-4 and Figure 4-7.

Table 4-4 Summary Statistics for Dissolved Oxygen, Surface: Observations (2007), Model Validation and 8 Years Spin-Up of the 40% Removal Scenario. Early Life Stage (April 1- June 15) for Oologah Lake.

| **DO (mg/L), OOLOGAH LAKE** | **ANNUAL** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **OOL-1, OOL-2, OOL-3, OOL-4** | **N_OBS** | **MEAN** | **MIN** | **10Pct** | **25Pct** | **50Pct** | **75Pct** | **90Pct** | **MAX** |
| OBS DATA | 14 | 7.07 | 4.16 | 5.19 | 6.08 | 6.79 | 8.66 | 9.27 | 9.56 |
| VALIDATION | 1,828 | 9.44 | 3.40 | 7.32 | 8.41 | 9.21 | 10.37 | 11.80 | 16.39 |
| YR0 | 1,828 | 9.40 | 4.14 | 7.66 | 8.52 | 9.26 | 10.18 | 11.09 | 16.23 |
| YR2 | 1,828 | 9.45 | 4.31 | 7.68 | 8.54 | 9.34 | 10.24 | 11.16 | 16.16 |
| YR4 | 1,828 | 9.44 | 4.32 | 7.68 | 8.55 | 9.33 | 10.25 | 11.09 | 16.37 |
| YR6 | 1,828 | 9.45 | 4.31 | 7.67 | 8.54 | 9.35 | 10.23 | 11.11 | 16.29 |
| YR8 | 1,828 | 9.44 | 4.29 | 7.71 | 8.53 | 9.33 | 10.25 | 11.10 | 16.03 |

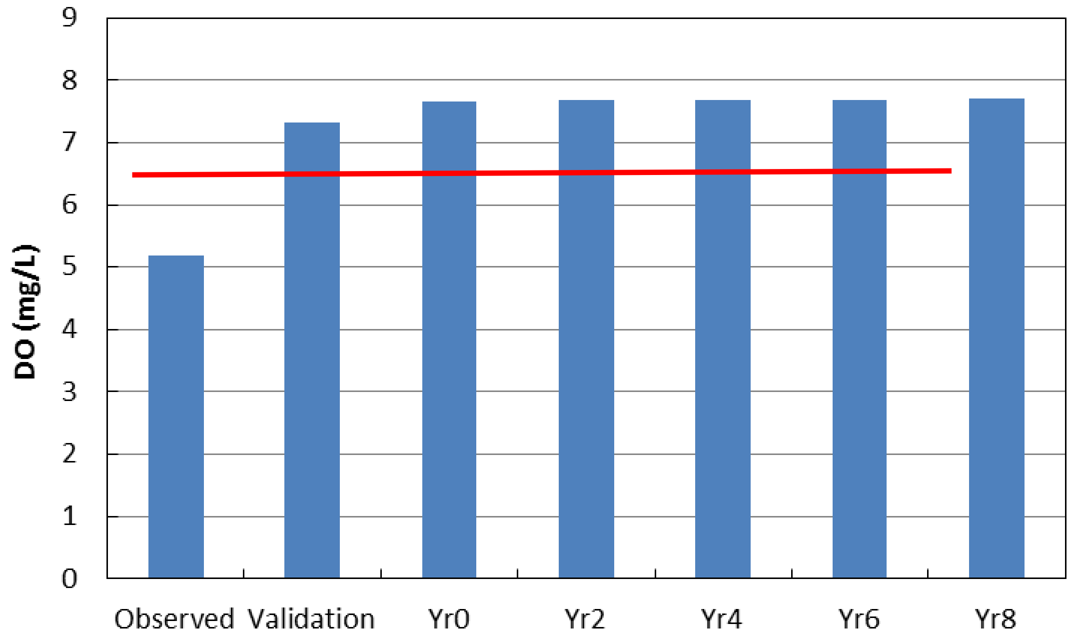


Figure 4-7 Dissolved Oxygen, Surface, 10th percentile: Observations (2007), Model Validation and 8 Years Spin-Up of the 40% Removal Scenario. Early Life Stage (April 1- June 15) for Oologah Lake.

Other life stages including summer conditions (June 16 to October 15) and winter condition (October 16 to March 31). The 10th percentile value for surface DO is used for comparison to the water quality target of 5 mg/L since the water quality criteria states that no more than 10% of the samples are allowed to be lower than 5 mg/L.

Table 4-5 summarizes annual statistics for surface dissolved oxygen for (a) the validated model results and the results generated with (b) eight years of spin-up runs for the 40% removal scenario, respectively. Summary statistics are computed from model results extracted for 4 USACE sites located in Oologah Lake. Statistics are computed for the simulation period of other life stages (summer and winter conditions). The dissolved oxygen statistics are computed as the average of the model results for the USACE sites as shown in Figure 4-2.

For the model validation year of 2007, the 10th percentile of observed surface dissolved oxygen was 9.45 mg/L, indicating compliance with the water quality standard at other life stages even though the sample size (n=33) is small. The validation model and spin-up runs also confirmed compliance for the water quality standard for dissolved oxygen at other life stages.

Table 4-5 Summary Statistics for Dissolved Oxygen: Surface Observations (2007), Model Validation and 8 Years Spin-Up of the 40% Removal Scenario. Other Life Stages (summer and winter conditions) for Oologah Lake.

| DO (mg/L), OOLOGAH LAKE | ANNUAL | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| OOL-1, OOL-2, OOL-3, OOL-4 | N_OBS | MEAN | MIN | 10Pct | 25Pct | 50Pct | 75Pct | 90Pct | MAX |
| OBS DATA | 33 | 9.45 | 3.87 | 6.28 | 7.77 | 9.53 | 11.14 | 12.40 | 13.18 |
| VALIDATION | 6,892 | 9.50 | 2.75 | 6.59 | 7.53 | 9.36 | 11.83 | 12.84 | 13.40 |
| YR0 | 6,892 | 9.60 | 3.60 | 6.92 | 7.68 | 9.49 | 11.80 | 12.79 | 13.83 |
| YR2 | 6,892 | 9.58 | 3.63 | 6.93 | 7.69 | 9.48 | 11.88 | 12.69 | 13.89 |
| YR4 | 6,892 | 9.58 | 3.63 | 6.93 | 7.69 | 9.49 | 11.87 | 12.69 | 13.87 |
| YR6 | 6,892 | 9.58 | 3.63 | 6.92 | 7.69 | 9.50 | 11.87 | 12.69 | 13.84 |
| YR8 | 6,892 | 9.58 | 3.63 | 6.93 | 7.68 | 9.48 | 11.87 | 12.69 | 13.69 |

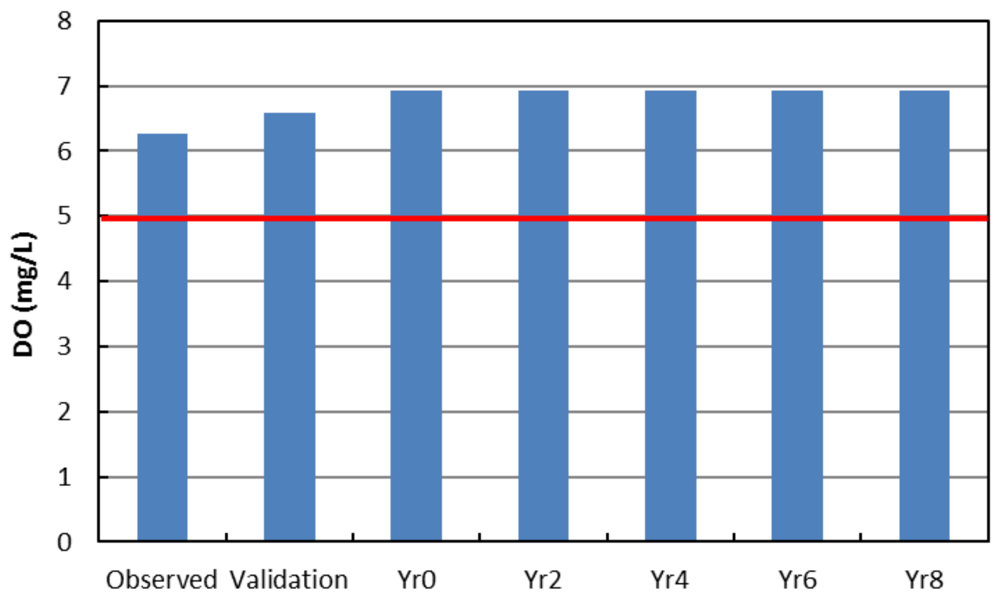


Figure 4-8 Dissolved Oxygen, Surface: 10$^{th}$ percentile Observations (2007), Model Validation and 8 Years Spin-Up of the 40% Removal Scenario. Other Life Stages (summer and winter conditions) for Oologah Lake.

Anoxic Water Column. Anoxic volume of the lake, defined by a DO target level of 2 mg/L, shall not exceed 50% of the lake volume based on volumetric data or 70% of the water column at any given sample site. The revised water quality criteria for dissolved oxygen require that, on a volumetric basis, 50% or less of the whole lake volume must be lower than a 2 mg/L cutoff concentration for DO. The revised criteria also indicate that no more than 70% of the DO measurements in a water column profile at a sampling site can be less than 2 mg/L (OWRB, 2014a).

Time series of the model results for the anoxic water column are extracted for the USACE site at the dam (OOL-1). As can be seen in Figure 4-4 for model validation, the model results for the percentage of the water column <2 mg/L are in good agreement with observations near the dam at the USACE Station OOL-1. Although observed data are not available for confirmation, the model results indicate that a maximum of 80% of the water column is <2 mg/L in late July and August.

If spin-up of the load reduction scenario succeeds in decreasing the peak anoxic percentage of the water column to less than 70% then compliance with the criteria for water column dissolved oxygen at a sampling site will be attained. Figure 4-9 presents time series results for model validation and spin-up of the 40% removal scenario for every other year. As can be seen by comparison of the model validation results to the spin-up results after 8 years, the peak anoxic percentage in late July and August is seen to decrease from 80% for the existing conditions to less than 70% for the 40% removal scenario after Y0.

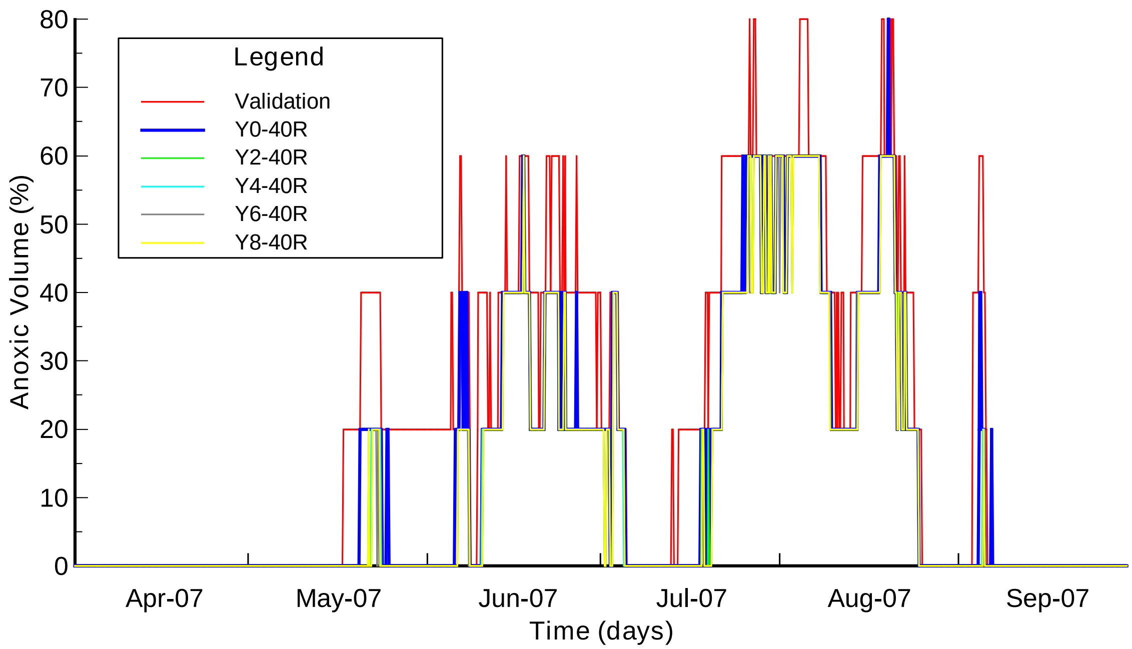


Figure 4-9 Time Series of Anoxic Water Column for Selected Spin-up Years of the 40% Removal Scenario. Model validation results are shown as blue line. Percentage of anoxic water column is based on extraction of grid cell model results for USACE Station OOL-1 near the dam. DO cutoff target is 2 mg/L.

Sediment Oxygen Demand (SOD). The sediment oxygen demand rate showed a decreasing trend over the spin-up years. As shown in Figure 4-10, average SOD based on model results for OOL-1, OOL-2, OOL-3, and OOL-4 decreases from 1.1 g $O_2/m^2$-day for the existing validation conditions to 1.0 g $O_2/m^2$-day after 8 years of model spin-up. The maximum SOD rate also decreases from 1.91 g $O_2/m^2$-day to 1.79 mg g $O_2/m^2$-day.

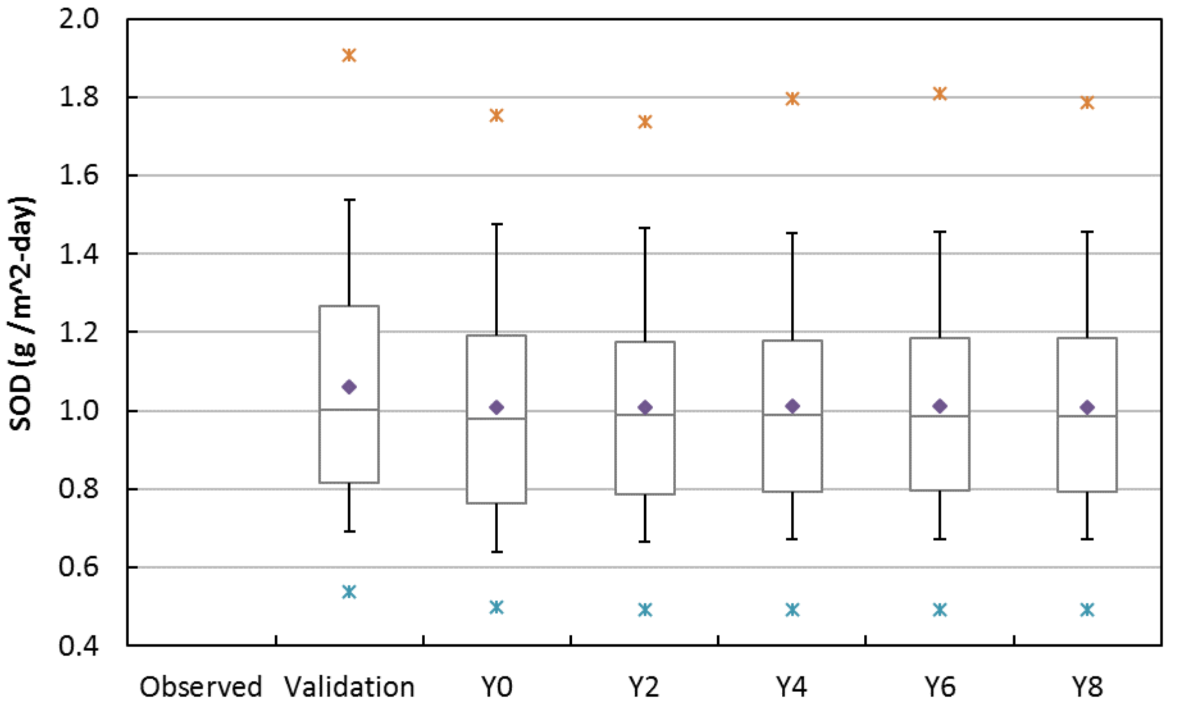


Figure 4-10 Sediment Oxygen Demand (g $O_2$/$m^2$-day). Spin-Up Model Results for 40% Removal, Summer Seasonal Average from June 16 to October 15 of OOL-1, OOL-2, OOL-3, and OOL-4.

As demonstrated with the analysis of model results for the spin-up years, the 40% reduction of nutrients and sediment loads determined for the TMDL is expected to result in compliance with Oklahoma water quality criteria for surface layer dissolved oxygen at both early and other life stages. The 40% reduction scenario also results in improvement of the anoxic conditions at the deep-water site OOL-1 near the dam with the peak anoxic percentage of the water column shown to be less than the 70% target.

## 4.6 Pollutant Loads for 40% Removal Scenario

As described above in Section 4.5, pollutant loads from the watershed model into Oologah Lake were systematically reduced until water quality targets for the lake were shown to be in compliance. The water quality targets for the load reduction analysis are the conservative assumptions adopted for the more stringent water quality standards for turbidity and dissolved oxygen. A water quality target for nutrients is not explicitly specified for the TMDL analysis because targets are only designated for the water quality constituents that are directly linked to impairments.

The 40% load reduction determined for the load allocation analysis was assigned a uniform reduction of 40% for the nonpoint loading from HSPF watershed inflows to the lake. The 40% load reductions for TN, TP, TOC and TSS are determined from existing conditions loads (2007) as follows:

- The reduction for watershed loading is computed from the existing HSPF model watershed loading to the lake x (1-40% Reduction).
- No point source NPDES wastewater loads discharge to Oologah Lake.
- There is no reduction assigned for the sediment flux of nutrients since this is an internal response to external reductions for watershed loading to the lake. The decreased load shown for sediment flux loading is computed internally in the EFDC lake model as the modeled response of the sediment bed for nutrient flux to the 40% reduction in external watershed source loading.
- There is no reduction for atmospheric deposition of nutrients since this is considered to be an uncontrollable source.

Table 4-6 presents a summary of the January 2007-December 2007 loads for the 40% removal scenario for HSPF watershed loads and internal benthic flux loading rates and the external sources for atmospheric deposition and PS (NPDES).

Table 4-7 presents the percentage contributions of the HSPF watershed model, atmospheric deposition, benthic flux and PS (NPDES) loading to the total load for the 40% removal scenario.

As shown in Table 4-6 and Table 4-7, the TP contribution percentage from the internal sediment flux (21.21%) is much higher than the TN contribution percentage from the internal sediment flux (8.52%). In addition, the TP contribution percentage from the internal sediment flux (21.21%) is significantly lower than the TP contribution from watershed loading (78.72%). The nutrient contributions from atmospheric deposition are minor compared with the other sources.

Table 4-6 Annual Loading of Nonpoint Source and Point Source Loading of Pollutants Delivered to Oologah Lake for 40% Removal Scenario.

| **Model Validation: 2007**<br>**WQ Parameter/Source**<br>**Load Units** | | **Annual**<br>**HSPF**<br>**kg/day** | **Annual**<br>**AtmDep**<br>**kg/day** | **Annual**<br>**SedFlux**<br>**kg/day** | **Annual**<br>**PS:NPDES**<br>**kg/day** | **Annual**<br>**Total**<br>**kg/day** |
|---|---|---|---|---|---|---|
| Total Nitrogen | TN | 1.17E+04 | 2.23E+02 | 1.11E+03 | 0 | 1.30E+04 |
| Total Phosphorus | TP | 1.77E+03 | 1.47E+00 | 4.77E+02 | 0 | 2.25E+03 |
| Total Organic Carbon | TOC | 4.14E+04 | 0 | 0 | 0 | 4.14E+04 |
| Total Suspended Solids | TSS | 1.44E+06 | 0 | 0 | 0 | 1.44E+06 |

Table 4-7 Percentage Contribution of Annual Loading of Nonpoint Source and Point Source Loading of Pollutants Delivered to Oologah Lake for 40% Removal Scenario.

| **Model Validation: 2007**<br>**WQ Parameter**<br>**Percentage** | | **Annual**<br>**HSPF**<br>**%** | **Annual**<br>**AtmDep**<br>**%** | **Annual**<br>**SedFlux**<br>**%** | **Annual**<br>**PS:NPDES**<br>**%** | **Annual**<br>**Total**<br>**%** |
|---|---|---|---|---|---|---|
| Total Nitrogen | TN | 89.77% | 1.71% | 8.52% | 0.00% | 100.00% |
| Total Phosphorus | TP | 78.72% | 0.07% | 21.21% | 0.00% | 100.00% |
| Total Organic Carbon | TOC | 100.00% | 0.00% | 0.00% | 0.00% | 100.00% |
| Total Suspended Solids | TSS | 100.00% | 0.00% | 0.00% | 0.00% | 100.00% |

## 4.7 Summary of Watershed-Lake Model

A mass balance-based surface water model framework was developed to establish the cause-effect linkage between external pollutant loading from the Verdigris River watershed and hydrodynamic and water quality conditions in Lake Oologah. The watershed (HSPF) and lake (EFDC) models are dynamic models that represent time-variable conditions as a continuous simulation. HSPF is a public-domain lumped parameter watershed model that represents runoff, streamflow and loading of sediment, nutrients and organic matter within a watershed network of catchments. EFDC is a public-domain 3-dimensional model that includes hydrodynamics, sediment transport, and biogeochemical processes for water quality and eutrophication. The HSPF-EFDC model framework for Oologah Lake has been successfully applied for numerous TMDL studies including applications in Oklahoma for Tenkiller Ferry Lake, Lake Thunderbird and Ft. Gibson Lake.

Flow and pollutant loading from the watershed was simulated for a calibration and validation period from January 2005 to December 2007 with the HSPF model. The EFDC lake model, developed with data collected during the two-year period from January 2006 through December 2007, was calibrated to 2006 observations and then validated to data collected in 2007. Watershed model results, atmospheric deposition data and the results of the EFDC sediment flux model were used to estimate the contributions of existing point and nonpoint sources of pollutant loading presented in Table 4-1 and Table 4-2. Model performance statistics for the calibration and validation periods, computed from a comparison of paired observed/simulated data, demonstrated that the watershed and lake model results were either better than, or close to, the target criteria specified for the model framework.

EFDC is designed to link external flow and point/nonpoint source loading with hydrodynamics, seasonal stratification, eutrophication and internal coupling of organic matter deposition to the sediment bed with decomposition processes in the bed that, in turn, produce benthic fluxes of nutrients and sediment oxygen demand across the sediment-water interface. The EFDC model of Oologah Lake accounts for the cause-effect interactions of external loading with water clarity, nutrient cycling, algal production, organic matter deposition, decay in the sediment bed, and internally generated benthic fluxes of nutrients and sediment oxygen demand. These are critical capabilities of the EFDC model because Oologah Lake, like many reservoirs in Oklahoma, is characterized by seasonal thermal stratification, hypoxia and internal benthic loading of nutrients that is triggered, in part, by low dissolved oxygen conditions in the hypolimnion.

The calibrated and validated lake model was used to evaluate the water quality response to reductions in watershed nonpoint source loading of sediment, TOC and nutrients. Load reduction scenario model runs were performed to determine if water quality targets for turbidity and dissolved oxygen could be attained with point and nonpoint source load reductions based on 40% removal of loading for sediment and nutrients. Based on a long-term spin-up analysis of the watershed-lake model over an 8-year period, the 40% removal scenario model results indicated that compliance with water quality criteria for dissolved oxygen and turbidity could be achieved.

It is important to note, however, that the spin-up results for the 40% removal scenario should not be taken as absolute projections of future water quality conditions in the lake with certainty as to some future calendar date. The model results reflect the idealized spin-up conditions of a precisely maintained watershed load reduction level and repeated climatic conditions of the hydrologic conditions of 2007. The model, does however, show that water quality improvements can be achieved in Oologah Lake to support the desired beneficial uses if watershed loading can be controlled and sustained to a level based on a uniform 40% reduction of the existing pollutant loading conditions. Attainment of water quality standards will occur, however, only over a period of time and only after full implementation of NPDES point source controls and BMPs considered necessary to achieve an overall 40% removal of sediment, organic matter and nutrients from the Verdigris River watershed.

The model results suggest that compliance with water quality criteria for turbidity and dissolved oxygen can be achieved with an overall 40% removal of sediments and nutrients from Verdigris River watershed loading to Oologah Lake within a reasonable time frame. The model thus supports the development of TMDLs for sediment, organic carbon, total nitrogen and total phosphorus to achieve compliance with water quality standards for turbidity and dissolved oxygen. The calibrated and validated watershed-lake model based on HSPF and EFDC thus provides DEQ with a scientifically defensible surface water model framework to support determination of TMDLs and development of water quality management plans for Oologah Lake.

# 5. TMDLs and Load Allocations

The linked watershed (HSPF) and lake (EFDC) models were used to calculate average annual sediment, TOC, nitrogen and phosphorus loads (as kg/yr), that, if achieved, should meet the water quality targets established for turbidity, and dissolved oxygen. For reporting purposes, the final Wasteload Allocations and Load Allocations for the TMDLs, according to EPA guidelines (Grumbles, 2006), are expressed for Oologah Lake as daily maximum loads (as kg/day).

## 5.1 Wasteload Allocation (WLA)

As required by EPA, Waste Load Allocations for a TMDL are determined for NPDES permitted municipal and industrial wastewater facilities that discharge directly into an impaired waterbody.

### *5.1.1 NPDES Municipal and Industrial Wastewater Facilities*

As described in Section 3.1.1 of this TMDL report, all of the NPDES municipal and industrial facilities listed in Table 3-1 discharge wastewater to tributaries of the Verdigris River basin that are represented by sub-basin reaches in the HSPF watershed model. There are no NPDES wastewater facilities that discharge directly into Oologah Lake. The contributions of pollutant loading from the NPDES point source dischargers listed in Table 3-1 are included as a component of the total nonpoint source load contribution from the HSPF watershed model as shown in Table 3-19. The reduction of the pollutant load accounted for by the NPDES wastewater facilities is, therefore, included as a component of the 40% reduction of nonpoint source pollutant loading derived from the HSPF watershed model. The NPDES point source wastewater contribution from the wastewater facilities included in the HSPF model domain will, therefore, be accounted for by the Load Allocation (LA) determined for Oologah Lake. The Waste Load Allocation (WLA) for Oologah Lake will be zero.

### *5.1.2 Municipal No-Discharge Wastewater Plants*

No-discharge WWTP facilities do not discharge wastewater effluent to either streams of the watershed or directly to Oologah Lake. For the purposes of this TMDL study, no-discharge facilities are not considered a source of sediment, organic matter or nutrient loading to the streams of the watershed or Oologah Lake. The three no-discharge facilities in the Oologah Lake watershed are all located in the Kansas portion of the Oologah Lake watershed model domain.

It is possible, however, that the wastewater collection system associated with no-discharge facilities could be a source of pollutant loading to streams, or that discharges may occur during large rainfall events that exceed the storage capacity of the wastewater system. These types of unauthorized wastewater discharges, typically reported as sanitary sewer overflows (SSOs) or bypass overflows, are discussed below in Section 5.1.4.

### *5.1.3 NPDES Municipal Separate Storm Sewer System (MS4)*

There are no pollutant contributions from Phase II MS4 permits in the Oklahoma portion of the Middle Verdigris River basin in Rogers, Nowata, and Washington counties. In Kansas, the City of Coffeyville has been issued a Phase II MS4 Stormwater Program permit issued by the Kansas Department of Health and Environment (KDHE). Pollutant loading from the City of Coffeyville MS4 within the Oologah Lake watershed is included as urban runoff within the sub-watershed defined for the HSPF watershed model. The MS4 permit for the City of Coffeyville will, therefore, not be included as a WLA for this TMDL study. The MS4 contribution from the City of Coffeyville in the HSPF model domain will be accounted for by the Load Allocation (LA) estimated for the Oologah Lake watershed.

### *5.1.4 Sanitary Sewer Overflow (SSO)*

As discussed in Section 3, three no-discharge facilities are located within the Oologah Lake watershed study area. Pollutant loads from bypass overflows are not considered in the waste load allocation of point sources for the TMDL determination because any mitigation of bypass overflows is considered to be an enforcement action rather than a load allocation since bypass overflows are not allowed.

### *5.1.5 NPDES Construction Site Permits*

NPDES permit authorizations are required for stormwater discharges from construction activities that disturb more than one acre or less than one acre if the construction activity is part of a larger common plan of development that totals at least one acre. As discussed in Section 3.1.3 of this report, a total of 6 construction site permits have been issued within the Oologah Lake watershed from 2007-2012. Sediment and nutrient loading from construction site permit activities will be accounted for as part of the overall LA determined for the watershed.

### *5.1.6 NPDES Multi-Sector General Permits (MSGP) for Industrial Sites*

NPDES permit authorizations are required for stormwater discharges from industrial activities listed in the OKR05 General Permit (DEQ, 2011). Within the Oologah Lake watershed, 9 MSGP permits have been issued as identified in Table 3-6. The MSGP permits will be accounted for in this TMDL as part of the overall LA determined for the watershed.

### *5.1.7 NPDES Concentrated Animal (CAFO's) and Poultry Feeding Operations (PFO's)*

There are no Concentrated Animal Feeding Operations (CAFO) in the Oklahoma area of the Oologah Lake watershed. There are, however, a number of Poultry Feeding Operations (PFO's) located in Oklahoma in Rogers and Craig Counties (see Figure 3-6). Sediment and nutrient loading from PFO activities in the agricultural land uses of the watershed will be accounted for as part of the overall LA determined for the watershed.

## 5.2 Load Allocation (LA)

### *5.2.1 Nonpoint Sources and Natural Background Conditions*

EPA regulations require that a TMDL include LAs, which identify the portion of the loading capacity for an impaired waterbody attributed to existing and future nonpoint sources and to natural background conditions. Load allocations may range from reasonably accurate estimates to gross allotments (40

CFR §130.2(g)) and where possible, load allocations should be described separately for nonpoint sources and natural background conditions.

EPA TMDL guidance on natural background conditions states: "*The TMDL submittal must include a description of the point and nonpoint sources of the pollutant of concern, including the magnitude and location of the sources. Where it is possible to separate natural background from nonpoint sources, a description of the natural background must be provided, including the magnitude and location of the source(s). Such information is necessary for EPA's review of the load and wasteload allocations that are required by regulation.*"

As described in Section 3.2.1 of this TMDL report, streamflow, watershed runoff and pollutant loading to Oologah Lake are provided for input to the EFDC lake model as time series output from the HSPF watershed model. Simulated flow and pollutant loading from the watershed are dependent on land use characteristics, soils, topography, and hydrologic inputs for each sub-watershed of the watershed model domain. In addition to hydrologic inputs, NPDES point source wastewater facilities can be represented as point source inputs to specified tributary reach sub-basins of the watershed model domain. As all external pollutant loading from the Verdigris River watershed to Oologah Lake is represented by the results provided as output from the HSPF watershed model, natural background conditions are not represented as an explicit component of nonpoint source loading to Oologah Lake. All flow and pollutant loading data assigned for input to the EFDC lake model are derived from the results provided by the HSPF watershed model.

The Load Allocation for the TMDL for Oologah Lake will be based on the 40% reduction of watershed loads for sediment and nutrients derived from the HSPF watershed model loads developed for the existing conditions of 2007. The load allocation assigned for the watershed will be proportional to the HSPF watershed model's contribution to total external loading estimated for the 2007 model validation conditions (see Section 4.4).

## 5.3 Seasonal Variability

Federal regulations [40 CFR §130.7(c)(1)] require that TMDLs account for seasonal variability in watershed hydrologic conditions and pollutant loading. Seasonal variation was accounted for in the TMDL determination for Oologah Lake in two ways: (1) water quality standards, and (2) the time period represented by the watershed and lake models. As described in Section 2, Oklahoma's water quality standards for dissolved oxygen (recently revised by OWRB, 2016) for lakes are developed on a seasonal basis to be protective of fish and wildlife propagation for a warm water aquatic community at all life stages, including spawning. Within the surface layer, dissolved oxygen standards specify that the $10^{th}$ percentile of DO levels shall be no less than 6 mg/L from April 1 to June 15 to be protective of early life stages. For the summer months from June 16 through October 15, the $10^{th}$ percentile of surface DO shall be no less than 5 mg/L. For the fall-winter period from October 16-March 31, the $10^{th}$ percentile DO shall be no less than 5 mg/L. In addition to criteria for the surface layer DO, the hypoxic volume of the lake, defined by a DO target of no less than 2 mg/L, is not to be greater than 50% of the lake volume on a volumetric basis or no greater than 70% of the water column at any given sample site.

Seasonality was also accounted for in the TMDL analysis by developing the models based on two years of water quality data collected in 2006-2007 as part of routine monitoring efforts initiated by the USACE in 2003 for Oologah Lake. As discussed in Section 1.3, flow and water quality data collected during 2006-2007 for this TMDL study is considered to be representative of dry and wet hydrologic conditions. The watershed (HSPF) and lake (EFDC) models developed to support this TMDL study are both time variable models with results reported at hourly and daily intervals for the two-year study period from January 2006 through December 2007. The watershed and lake models thus included both hydrologic and limnological conditions over two full annual cycles of the four seasons.

## 5.4 Margin of Safety (MOS)

Federal regulations [40 CFR §130.7(c)(1)] require that TMDLs include a Margin of Safety (MOS). The MOS is a conservative measure incorporated into the TMDL determination that accounts for uncertainty and the lack of knowledge associated with calculating the allowable pollutant loading to ensure WQSs are attained. EPA guidance about the Margin of Safety for development of TMDLs states that: *A margin of safety expressed as unallocated assimilative capacity or conservative analytical assumptions used in establishing the TMDL; e.g., derivation of numeric targets, modeling assumptions, or effectiveness of proposed management actions which ensures attainment and maintenance of water quality standards for the allocated pollutant [40 CFR 130.33(b)(7)].*

EPA guidance allows for use of either implicit or explicit expressions of the MOS, or both. When conservative assumptions are used for development of the TMDL, or conservative factors or assumptions are used in the TMDL analysis, the MOS is implicit. When a specific percentage of the TMDL is set aside to account for the lack of knowledge, then the MOS is considered explicit and the MOS quantifies an allocation amount separate from other load (LA) and wasteload (WLA) allocations.

Although the MOS is intended to account for variability of the pollutant loading data used for model input and the reliability of the model framework used to determine loading capacity to attain water quality targets, the approach used to determine the MOS in almost all TMDL studies is most often subjective without any consideration of methods available to quantify model uncertainty. Nunoo et al. (2020) documented that 84% of EPA-approved TMDL assessments reported that the explicit MOS values assigned for TMDL studies were not based on any methodology for uncertainty analysis. The authors of this study also concluded that a 10% explicit MOS of the estimated waterbody loading capacity was most often used across all states and territories.

Regardless of whether a TMDL is based on an explicit MOS or an implicit MOS, the following steps are required for calculation of Maximum Daily Loads (MDLs):

- Confirm time series distribution of input flow and pollutant loading data as either a normal or lognormal distribution and compute existing long-term average (LTA) pollutant loading and variability of existing LTA pollutant loading (mean, variance, coefficient of variation);
- Assign water quality targets for attainment of beneficial uses for waterbody;
- Perform a series of iterative model runs to determine required percentage reduction (% R) of existing LTA loading expected to achieve compliance with water quality targets;

- Select Confidence Interval (e.g., 95% CI) and corresponding one-sided Z-score (e.g., 1.645) for calculation of MDL based on required reduction (% R) of long-term average loading (LTA);
- Calculate MDL from normal or lognormal equations given in EPA (2007) that are based on the well-known "bell-shaped" normal distribution curve;

Following the implicit Margin of Safety approach adopted for the EPA-approved Lake Thunderbird TMDL (DSLLC, 2013), the TMDL determined for Oologah Lake also accounts for an implicit MOS based on conservative assumptions for derivation of more stringent numeric water quality targets for turbidity and dissolved oxygen. Water quality targets were easily adjusted by decreasing the values used to evaluate compliance for model loading scenarios by a factor of 0.9 so that the implicit MOS is based on a 10% strengthening of the water quality target. Using a 10% MOS for turbidity the water quality target for Oologah Lake is made more stringent by decreasing the target from 25 NTUs to 22.5 NTUs. Under the revised criteria for the anoxic portion of the water column, OWRB (2014) determined that no more than 70% of the water column for a sampling site shall be less than the cutoff DO concentration of 2 mg/L. Using a 10% MOS for the revised anoxic water column criteria, a stricter implicit MOS is incorporated in the TMDL analysis with a more stringent target based on no more than 63% of the water column <2 mg/L.

The benefit of the implicit approach adopted for incorporating a MOS in the TMDL determination for Oologah Lake is the simplicity of the method. It is easy to adjust the Oklahoma water quality targets by 10% and to perform the series of model runs to determine the MDL loading capacity to attain compliance with more stringent water quality targets for turbidity and dissolved oxygen. The implicit approach is quantitative in that the more stringent water quality targets are clearly understood and defined by the adopted MOS (e.g., 10%). Although the explicit MOS approach may appear to be rigorous, the explicit MOS approach applied in 84% of EPA-approved TMDL studies nationwide has been shown to be subjective and that these studies most often adopted 10% for the explicit MOS (Nunoo et al., 2020). The only downside to the implicit approach adopted for the Oologah Lake TMDL study is that a portion of the loading capacity is not able to be quantified as an unallocated load as is reported with the explicit MOS approach.

Adoption of an implicit 10% MOS approach based on more stringent water quality targets for turbidity and dissolved oxygen is expected to ensure an adequate MOS for determination of load (LA) and waste load allocations (WLA) for the water quality constituents that control dissolved oxygen and turbidity in Oologah Lake.

## 5.5 Future Growth

Future growth in the Verdigris River watershed may include changes in land use from rural and agricultural uses to accommodate new residential areas and increases in municipal wastewater discharges to accommodate population growth. As pollutant loading changes due to future growth were not explicitly considered in developing the TMDLs for Oologah Lake, more efficient removal strategies may need to be adopted for NPDES permit limits to reduce point source loading from urban stormwater and municipal and industrial wastewater discharges and more efficient BMPs may need to be implemented to maintain compliance with the Load Allocations determined for the Lake Oologhah TMDL.

## 5.6 TMDL Calculations

A TMDL is expressed as the sum of all WLAs (point source loads), LAs (nonpoint source loads), and an appropriate Margin of Safety (MOS). This definition can be expressed by the following equation:

$$TMDL = \Sigma\, WLA + \Sigma\, LA + MOS$$

Load reduction scenario simulations were run using the linked watershed (HSPF) and lake (EFDC) models to calculate annual average suspended solids, TOC, phosphorus and nitrogen loads (in kg/yr) that, if achieved, should improve dissolved oxygen concentrations and decrease turbidity to meet the water quality targets for Oologah Lake. Given that mass transport, assimilation, and dynamics of suspended solids, TOC, and nutrients vary both temporally and spatially, pollutant loading to Oologah Lake from a practical perspective must be managed on a long-term basis with loads expressed typically as pounds or kilograms per year. However, a court decision (*Friends of the Earth, Inc. v. EPA, et al.,* often referred to as the Anacostia Decision) states that TMDLs must include a daily load expression (Grumbles, 2006). It is important to recognize that the dissolved oxygen and turbidity response to sediment and nutrient loading in Oologah Lake is affected by many factors such as: internal lake nutrient loading, hypolimnetic oxygen depletion, water residence time, wind action, resuspension, and the interaction between light penetration, nutrients, suspended solids and algal response. As such, it is important to note that expressing this TMDL on a daily basis does not imply that a daily response to a daily load from the watershed is practical from an implementation perspective.

Three documents available from EPA provide a statistical basis for the determination of a daily loading rate from an annual loading rate. "*Options for Expressing Daily Loads in TMDLs"* was published by EPA (2007) in response to the Anacostia Decision discussed above. The statistical basis for the calculation of a daily loading rate from an annual load was previously documented by EPA (1991b) in *"Technical Support Document for Water Quality-Based Toxics Control"* and EPA (1984) in "*Technical Guidance Manual for Performing Wasteload Allocations, Book VII: Permit Averaging Periods*". These documents provide the statistical methods for determining a maximum daily limit based on the existing long-term average, the required load reduction needed to attain compliance with water quality targets and temporal variability of the pollutant load time series dataset.

The methodology for the MDL is based on calculations of the (a) long-term average load (LTA) of untransformed pollutant loading data calculated with data derived from NPDES wastewater dischargers and the watershed (HSPF) model; and (b) an estimation of the statistical variability of the time series for untransformed loading data based on calculations of the mean ($\mu$), standard deviation ($\sigma$), variance ($\sigma^2$) and the coefficient of variation (CV). The CV, a measure of variability of the loading data, is computed as the ratio of the standard deviation ($\sigma$) to the mean ($\mu$). Based on the long-term average annual loading rate (LTA) required to attain compliance with water quality standards, the maximum daily load (MDL) is determined to represent the allowable upper limit of loading data that is consistent with the long-term average load (LTA) determined by the TMDL study. The allowable upper limit takes into account temporal variability of the PS and NPS loading data, the desired confidence interval of the upper bound for the MDL determination and the assumption that loading data can be described with a lognormal distribution. Figure 5-1 shows the conceptual relationship between the Long-Term Average (LTA) load, the required removal and determination of the MDL.

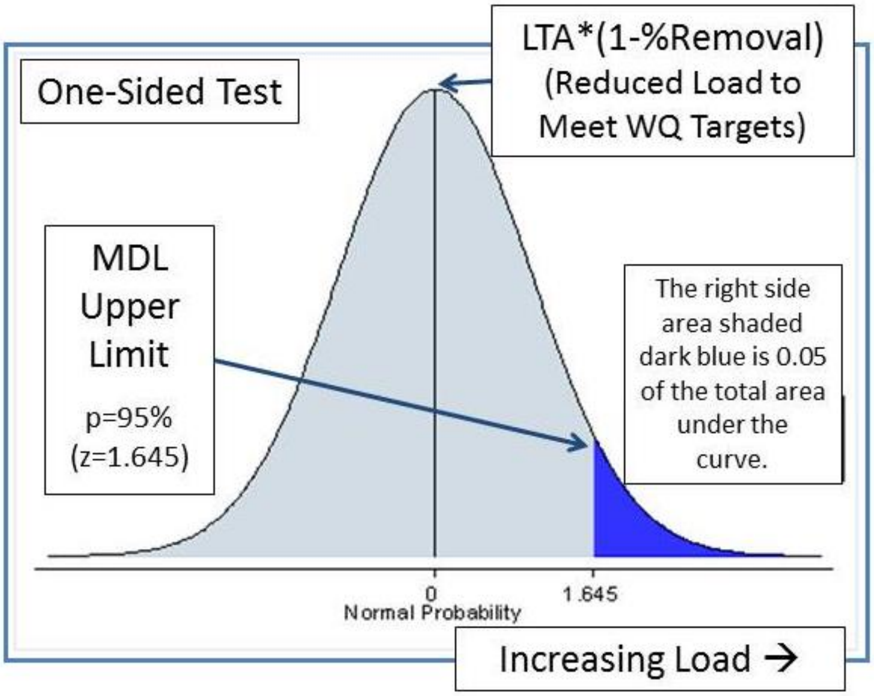


Figure 5-1- Conceptual Representation of Maximum Daily Load Methodology

Appendix D of EPA (1991b) and Section 2 of EPA (1984) present the rationale and derivation of the equations based on the lognormal distribution used to determine the maximum daily load. The MDL is computed from the LTA and the probability-based statistics of the lognormally distributed pollutant loading data by the following equations as:

$$MDL = LTA * \exp(z_p * \sigma_{\ln(x)} - 0.5 * \sigma^2_{\ln(x)})$$

$$E_x = \exp(\mu_{\ln(x)} + 0.5 * \sigma^2_{\ln(x)})$$

$$LTA = (1 - \%R) * E_x$$

$$\sigma^2_{\ln(x)} = \ln(CV_x^2 + 1)$$

$$\sigma_{\ln(x)} = \sqrt{\ln(CV_x^2 + 1)}$$

$$CV_x = \frac{s_x}{\mu_x}$$

Where:

MDL = Maximum daily load limit
$E_x$ = Expected average value of existing daily load computed from log transformed load data

%R = Required reduction percentage for load scenario (%) to meet water quality targets
LTA = Long-term average daily load based on required reduction scenario
$z_p$ = Z-score for probability for upper percentile limit of standard normal distribution
$\sigma_{\ln(x)}$ = Standard deviation computed from log transformed daily load data
$\sigma^2_{\ln(x)}$ = Variance computed from log transformed daily load data
$CV_x$ = Coefficient of variation based on untransformed daily load data
$s_x$ = standard deviation of untransformed daily load data
$\mu_x$ = mean of untransformed daily load data

The equations used for calculating the Maximum Daily Load (MDL) from the Long-Term Average (LTA) daily load are based on the assumption that streamflow, water quality, wastewater effluent and watershed loading data are lognormally distributed. It is well documented in numerous studies that a two-parameter lognormal distribution defined by the mean and variance of the log transformed data set provides a very useful approximation to the probabilistic distribution of streamflow (Nash, 1994; Limbrunner et al., 2000; Vogel et al., 2005). In addition, Van Buren et al., (1997) and Di Toro (1984) determined that water quality analyses based on an assumption of the lognormal probability distribution for effluent, streamflow and water quality concentration are quite realistic for wastewater facilities and many streams and rivers, including waterbodies investigated in the United States.

Although it is well documented, data are presented to show that the assumption of a lognormal distribution for NPS loading data holds true for Oologah Lake. It is noted that no wastewater point sources directly discharge into the lake. Total Phosphorus (TP) loading data derived from watershed runoff is used as an example to demonstrate that (a) natural log transformed TP data follows a normal distribution and (b) a lognormal distribution for loading data are an appropriate assumption for TMDL determinations for Oologah Lake. As shown in Figure 5-2, a typical bell-shaped curve is produced from the log transformed TP load data, indicating a normal distribution of the transformed data set. The probability plot for the log transformed time series of TP data are presented as the natural log of the TP load against the Z-score statistic computed from the percentile ranking of the TP load data (Figure 5-3). The log transformed TP loading data shows an approximate linear relationship ($r^2$=0.94) with the Z-score statistic confirming the assumption of a lognormal distribution. As flow is common to all loads derived from watershed runoff, TSS, TN and TOC loading data also display similar lognormal distributions.

Time series derived from the sum of all the daily loads contributed by Verdigris River and each tributary and distributed runoff catchment of the HSPF watershed model were used to compute the mean, standard deviation and the coefficient of variation (CV) of the loads for suspended solids, TN, TP and TOC. The variability of the loading data simulated by the HSPF model was determined using the CV's computed from the daily time series (N=363) of the total load accounted for in 2007 by Verdigris River and tributary and distributed runoff loads from the watershed model. Loads from all sources were summed to compute long-term averages of the total mass loading over a 363-day period from January 1 to December 29, 2007. For the Oologah Lake TMDL calculations, a 95% probability level of occurrence was used and the corresponding one-sided Z-score statistic was assigned a value of Z=1.645.

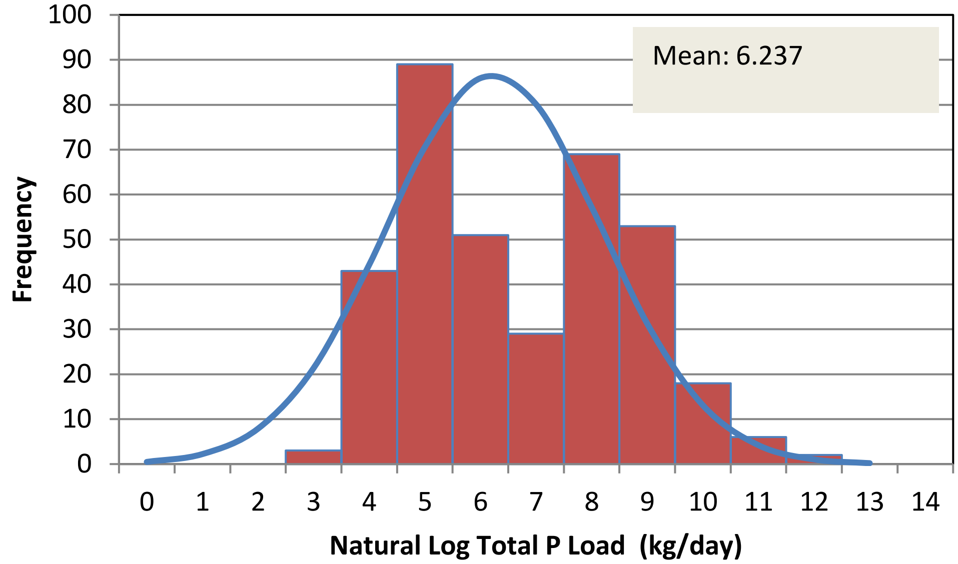


Figure 5-2 Density Distribution of the Log Transformed Total Phosphorus Existing Watershed Loading Data to Oologah Lake

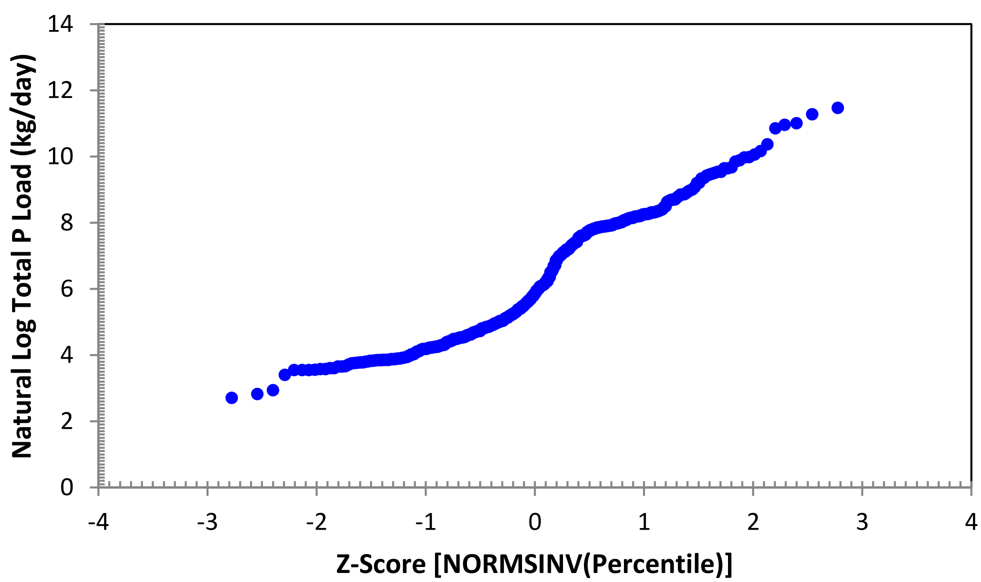


Figure 5-3 Probability Plot of Log Transformed Total Phosphorus Existing Load to Oologah Lake ($R^2$ = 0.9448)

The LA for TN, TP, TOC and Suspended Solids, determined from the lake model response to load reductions, is based on 40% reduction of the existing 2007 watershed loads estimated with the HSPF model. Load reductions are needed because the criteria for the turbidity in the lake are not in compliance under the existing loading conditions. Critical conditions for dissolved oxygen at the sampling site near the dam are also not satisfied under the existing loading conditions.

Table 5-1 and Table 5-2 present the total loading rates to Lake Oologah as the Long-Term Average (LTA) load for the existing conditions and for the projected 40% removal management scenario. The LTA load and the coefficient of variation (CV) of the time series external load data is used to compute the MDL for TN, TP, TOC, and TSS as presented in Table 5-2. Statistics for the loads and the lognormal parameter values for the Maximum Daily Load calculations for TN, TP, TOC and TSS are presented in Table 5-3, Table 5-4, Table 5-5 and Table 5-6. The Maximum Daily load values derived for TN, TP, TOC and TSS are presented in Table 5-7.

As described in Section 3.1.1 of this TMDL report, there are no NPDES point source wastewater facilities that directly discharge into Oologah Lake. All of the NPDES facilities listed in Table 3-1 discharge into tributaries included in the HSPF watershed model domain. The combined contributions of point source loading of NPDES wastewater discharges to tributaries and nonpoint source runoff over a sub-basin are accounted for by flow and pollutant loading simulated at the downstream outlet of each tributary reach sub-basin in the HSPF model domain. A pollutant load budget of PS and NPS contributions for the existing conditions of 2007 represented in the HSPF model is presented in Table 3-19. As the WLA for Oologah Lake is zero, 100% share of the MDL for TN, TP, TOC, and TSS is attributed to nonpoint source loading from the watershed (as the LA) as presented in Table 5-7.

Table 5-1 Long Term Average (LTA) Load for TN, TP, TOC, and TSS: Existing Conditions and 40% Removal in Oologah Lake

| Water Quality Constituent Oologah Lake | LTA, Existing Annual kg/yr | Load Reduction % | LTA, Reduced Annual kg/yr | LTA, Reduced Daily kg/day |
|---|---|---|---|---|
| Total Nitrogen (TN) | 8,160,833 | 40% | 4,896,500 | 13,415 |
| Total Phosphorus (TP) | 1,214,873 | 40% | 728,924 | 1,997 |
| Total Organic Carbon (TOC) | 33,328,891 | 40% | 19,997,335 | 54,787 |
| Suspended Solids (TSS) | 1,842,230,207 | 40% | 1,105,338,124 | 3,028,324 |

Table 5-2 Maximum Daily Load (MDL) for TN, TP, TOC and TSS to Meet Water Quality Targets for Turbidity and Dissolved Oxygen in Oologah Lake

| Water Quality Constituent Oologah Lake | LTA, Reduced Daily kg/day | Load CV n=363 | Z-Score for 95% Probability | MDL (TMDL) Load kg/day |
|---|---|---|---|---|
| Total Nitrogen (TN) | 13,415 | 5.362 | 1.645 | 50,906 |
| Total Phosphorus (TP) | 1,997 | 6.432 | 1.645 | 7,407 |
| Total Organic Carbon (TOC) | 54,787 | 5.415 | 1.645 | 207,688 |
| Suspended Solids (TSS) | 3,028,324 | 41.188 | 1.645 | 6,524,666 |
| LTA- Long Term Average Load | CV- Coefficient of Variation | | | |

Table 5-3 Lognormal Parameters and Estimation of Maximum Daily Load for Total Nitrogen for Watershed Loading to Oologah Lake in 2007

| | | | |
|---|---|---|---|
| Watershed Load to Oologah Lake in 2007<br>Lognormal Distribution<br>Total-Nitrogen (TN) | | | |
| Watershed Load Parameters, Log Transformed | | | |
| Ln (X, kg/day) | | Arithmetic (X, kg/day) | |
| N= | 363 | | |
| μ= | 8.318479 | E(X)= | 22,358 |
| Var= | 3.39296 | V(X)= | 1.437E+10 |
| Std_Dev= | 1.841999 | s(X)= | 119,892 |
| Coeff_Var= | 0.221435 | CV(X)= | 5.362266666 |
| Min= | 5.148727 | Min(X)= | 172 |
| Max= | 13.09 | Max(X)= | 484,076 |
| | | 1-sided, a= | 0.05 |
| | | Probability,p= | 0.95 |
| | | R^2= | 0.9632 |
| | | Z(p)= | 1.645 |
| Maximum Daily Load Parameters | | | |
| Upper Limit | | X(p)= | 84,844 |
| Variability Factor | | VF(p)=X(p)/E(X) | 3.794710774 |
| Existing Average | | E(x)= | 22,358 |
| % Removal | | %R= | 40% |
| Long Term Average | | LTA= E(X)*(1-%R) | 13,415 |
| Max Daily Load | | MDL= LTA*VF(p) | 50,906 |

Table 5-4 Lognormal Parameters and Estimation of Maximum Daily Load for Total Phosphorus for Watershed Loading to Oologah Lake in 2007

| Watershed Load to Oologah Lake in 2007<br>Lognormal Distribution<br>Total-Phosphorus (TP) | | | |
|---|---|---|---|
| Watershed Load Parameters, Log Transformed | | | |
| Ln (X, kg/day) | | Arithmetic (X, kg/day) | |
| N= | 363 | | |
| μ= | 6.237054 | E(X)= | 3,328 |
| Var= | 3.746398 | V(X)= | 4.583E+08 |
| Std_Dev= | 1.935561 | s(X)= | 21,408 |
| Coeff_Var= | 0.310333 | CV(X)= | 6.431810566 |
| Min= | 2.707417 | Min(X)= | 15 |
| Max= | 11.46848 | Max(X)= | 95,653 |
| | | 1-sided, a= | 0.05 |
| | | Probability,p= | 0.95 |
| | | R^2= | 0.9448 |
| | | Z(p)= | 1.645 |
| Maximum Daily Load Parameters | | | |
| Upper Limit | | X(p)= | 12,346 |
| Variability Factor | | VF(p)=X(p)/E(X) | 3.709138161 |
| Existing Average | | E(x)= | 3,328 |
| % Removal | | %R= | 40% |
| Long Term Average | | LTA= E(X)*(1-%R) | 1,997 |
| Max Daily Load | | MDL= LTA*VF(p) | 7,407 |

Table 5-5 Lognormal Parameters and Estimation of Maximum Daily Load for Total Organic Carbon for Watershed Loading to Oologah Lake in 2007

| | | | |
|---|---|---|---|
| Watershed Load to Oologah Lake in 2007<br>Lognormal Distribution<br>Total-Organic-Carbon (TOC) | | | |
| Watershed Load Parameters, Log Transformed | | | |
| Ln (X, kg/day) | | Arithmetic (X, kg/day) | |
| N= | 363 | | |
| μ= | 9.716033 | E(X)= | 91,312 |
| Var= | 3.412009 | V(X)= | 2.445E+11 |
| Std_Dev= | 1.847163 | s(X)= | 494,488 |
| Coeff_Var= | 0.190115 | CV(X)= | 5.415359804 |
| Min= | 6.624595 | Min(X)= | 753 |
| Max= | 13.91232 | Max(X)= | 1,101,651 |
| | | 1-sided, a= | 0.05 |
| | | Probability,p= | 0.95 |
| | | R^2= | 0.9472 |
| | | Z(p)= | 1.645 |
| Maximum Daily Load Parameters | | | |
| Upper Limit | | X(p)= | 346,146 |
| Variability Factor | | VF(p)=X(p)/E(X) | 3.790802181 |
| Existing Average | | E(x)= | 91,312 |
| % Removal | | %R= | 40% |
| Long Term Average | | LTA= E(X)*(1-%R) | 54,787 |
| Max Daily Load | | MDL= LTA*VF(p) | 207,688 |

Table 5-6 Lognormal Parameters and Estimation of Maximum Daily Load for Suspended Solids for Watershed Loading to Oologah Lake in 2007

| | | | |
|---|---|---|---|
| Watershed Load to Oologah Lake in 2007<br>Lognormal Distribution<br>Total Suspended Solids (TSS) | | | |
| Watershed Load Parameters, Log Transformed | | | |
| Ln (X, kg/day) | | Arithmetic (X, kg/day) | |
| N= | 363 | | |
| μ= | 11.7159 | E(X)= | 5,047,206 |
| Var= | 7.436881 | V(X)= | 4.322E+16 |
| Std_Dev= | 2.727065 | s(X)= | 207,884,132 |
| Coeff_Var= | 0.232766 | CV(X)= | 41.18796214 |
| Min= | 7.357178 | Min(X)= | 1,567 |
| Max= | 18.50224 | Max(X)= | 108,497,245 |
| | | 1-sided, a= | 0.05 |
| | | Probability,p= | 0.95 |
| | | R^2= | 0.9479 |
| | | Z(p)= | 1.645 |
| Maximum Daily Load Parameters | | | |
| Upper Limit | | X(p)= | 10,874,444 |
| Variability Factor | | VF(p)=X(p)/E(X) | 2.154547222 |
| Existing Average | | E(x)= | 5,047,206 |
| % Removal | | %R= | 40% |
| Long Term Average | | LTA= E(X)*(1-%R) | 3,028,324 |
| Max Daily Load | | MDL= LTA*VF(p) | 6,524,666 |

Table 5-7 Maximum Daily Load (MDL), Waste Load Allocation (WLA) and Load Allocation (LA) for TN, TP, TOC and TSS for Oologah Lake

| Water Quality Constituent Oologah Lake | WLA + LA (PS + NPS) % | WLA (PS) % | LA (NPS) % | |
|---|---|---|---|---|
| Total Nitrogen (TN) | 100% | 0% | 100% | |
| Total Phosphorus (TP) | 100% | 0% | 100% | |
| Total Organic Carbon (TOC) | 100% | 0% | 100% | |
| Suspended Solids (TSS) | 100% | 0% | 100% | |
| | | | | |
| Water Quality Constituent Oologah Lake | MDL (TMDL) Load kg/day | WLA (PS) kg/day | LA (NPS) kg/day | MOS kg/day |
| Total Nitrogen (TN) | 50,906 | 0 | 50,906 | Implicit |
| Total Phosphorus (TP) | 7,407 | 0 | 7,407 | Implicit |
| Total Organic Carbon (TOC) | 207,688 | 0 | 207,688 | Implicit |
| Suspended Solids (TSS) | 6,524,666 | 0 | 6,524,666 | Implicit |

## 5.7 Strengths and Weaknesses of Watershed-Lake Modeling Approach

Strengths. A mass balance-based surface water model framework was developed to establish the cause-effect linkage between external pollutant loading from the Verdigris River watershed and hydrodynamic and water quality conditions in Lake Oologah. The watershed (HSPF) and lake (EFDC) models are dynamic models that represent time-variable conditions as continuous simulations. HSPF is a public-domain lumped parameter watershed model that represents runoff, streamflow and loading of water quality constituents including sediment, nutrients and organic matter within a watershed network of catchments. EFDC is a public-domain 3-dimensional model that includes hydrodynamics, sediment transport and biogeochemical processes for water quality and eutrophication. EFDC is unique among advanced surface water models because the hydrodynamic model is internally coupled within a single source code to the sediment transport and water quality/eutrophication modules. The HSPF-EFDC model framework for Oologah Lake has been successfully applied for numerous TMDL studies including applications in Oklahoma for Tenkiller Ferry Lake, Lake Thunderbird and Ft. Gibson Lake.

EFDC is designed to link external flow and point/nonpoint source loading with hydrodynamics, seasonal stratification, eutrophication and internal coupling of organic matter deposition to the sediment bed with decomposition processes in the bed that, in turn, produce benthic fluxes of nutrients and sediment oxygen demand across the sediment-water interface. The EFDC model of Oologah Lake accounts for the cause-effect interactions of external loading with water clarity, nutrient cycling, algal production, organic matter deposition, decay in the sediment bed, and internally generated benthic fluxes of nutrients and sediment oxygen demand. These are critical capabilities of the EFDC model because Oologah Lake, like many reservoirs in Oklahoma, is characterized by seasonal thermal stratification, hypoxia and internal benthic loading of nutrients that is triggered, in part, by low dissolved oxygen conditions in the hypolimnion.

Model performance statistics for the calibration and validation periods, computed from a comparison of paired observed/simulated data, demonstrated that the watershed and lake model results were either better than, or close to, the target criteria specified for the model framework. Maximum Daily Loads (MDL) computed for the TMDL determinations are based on 95% confidence interval statistics of lognormal distributions of pollutant loading based on 40% removal of existing watershed loads. The watershed-lake model of HSPF and EFDC thus provides DEQ with a scientifically defensible surface water model framework to support determination of TMDLs and development of water quality management plans for Oologah Lake.

Weaknesses. As a lumped parameter watershed model, HSPF is not based on a physical representation of the landscape (i.e., 3-dimensional grid) based on topography, land uses, soil and upper/lower zones for groundwater. HSPF, instead, represents a watershed as a network of delineated catchments characterized by similar topography, soil type and land uses. Surface and subsurface hydrologic processes within catchments are then described by empirical formulations that are often considered to be overparameterized with numerous coefficients required for calibration and validation of HSPF mass balance-based hydrologic, stream routing and pollutant loading processes (Borah et al., 2019).

Watershed and lake model performance is evaluated to determine the endpoints for model calibration using a “weight of evidence” approach that has been adopted for many surface water modeling studies. The “weight of evidence” approach for evaluation of model vs. observed data includes visual inspection of model-data plots and calculation of model performance statistics. The “weight of evidence” approach recognizes that, as an approximation of a waterbody, perfect agreement between observed data and model results is not expected and is not specified as a performance criterion for success of model calibration. Model performance statistics, although determined in this study to be better than, or close to, target criteria for the watershed and lake models, have been used only as targets, but not as rigid criteria for rejection or acceptance of watershed or lake model results. The “weight of evidence” approach thus acknowledges that no surface water model is perfect, that all models are approximations of physical and biogeochemical processes in a watershed or lake and that there is inherent uncertainty in both input data and observed data used to develop the models.

In a deep waterbody where there are steep horizontal changes in bathymetry, such as the deep area near the dam in Lake Oologah, the EFDC model’s “sigma” vertical layer coordinate system can result in vertical water temperature and circulation errors. As discussed in Appendix C of this TMDL report, the “sigma” coordinate system shows good agreement at the deep station near the dam between observed and simulated water temperature within the upper part of the water column. In areas of a waterbody characterized by steep horizontal gradients in bathymetry, however, such as the deep water near the dam in Oologah Lake, the “sigma” vertical coordinate system is known to produce poor model-data agreement for vertical water temperature within the lower layer under stratified conditions (Shi et al., 2020). As shown in Appendix C, summer model results for the station near the dam under-predict observed water temperature in the lower layers. The under-prediction of lower layer and bottom water temperature for the station near the dam, the discrepancy in stratification and under-prediction of bottom dissolved oxygen are all caused by artificial vertical mixing that is induced by a horizontal pressure gradient error from the “sigma” bottom-following coordinate system used to represent 5 vertical layers throughout all shallow and deep areas of Oologah Lake. After development of the Oologah Lake model was completed, newer versions of EFDC successfully addressed the numerical error problem with the “sigma” coordinate scheme by developing a new Sigma-Zed (SGZ) scheme to specify a spatially variable number of vertical layers to represent shallow (fewer layers) and deep (more layers) areas of a waterbody. Application of the new Sigma-Zed scheme in the final EFDC model of Tenkiller Ferry Lake was shown to significantly improve model-data agreement for vertical profiles of water temperature and dissolved oxygen compared to preliminary results based on the “sigma” coordinate system (DSLLC, 2018).

TMDL guidance from EPA (2002) includes the requirement that “*TMDLs must take into account critical conditions for stream flow, loading, and water quality parameters as part of the analysis of loading capacity”*. Zhang and Padmanabhan (2019) note that consistent methodologies for defining critical conditions are typically not used for TMDL studies and that there is no guarantee that critical, or worst-case, conditions will either (a) occur or (b) be accurately simulated during a hydrologic period selected for development of a continuous time-variable model. A potential weakness of the approach used for the Oologah Lake watershed-lake model could be that the selection of representative dry, average and wet years in 2005-2007 might not have fully satisfied the very rigorous worst-case combination of pollutant loading and streamflow that causes violations of water quality standards (Zhang and Padmanabhan, 2019).

The EFDC lake model was applied to simulate eight (8) years of sequential “spin-up” runs to evaluate the long-term response of water quality conditions in the lake to a simple uniform 40% removal change in external loading from the watershed. As new sediment bed conditions in Oologah Lake need to equilibrate in response to the 40% removal scenario for external loading, watershed flow and reduced pollutant loading data generated by the HSPF model for 2007 were repeated for each spin-up year. Model results derived from the spin-up runs did not, therefore, attempt to account for any hydrologic variability of projected, or future, conditions within the Verdigris River watershed nor did the methodology attempt to represent implementation of either site-specific BMPs or reductions from NPDES point source dischargers to tributaries of the Verdigris River watershed. The 40% removal spin-up scenario results, therefore, should not be taken as absolute projections of future water quality conditions and attainment with water quality targets in Oologah Lake by some future calendar date. The lake model results demonstrate expected compliance with water quality targets as a response to idealized spin-up conditions of the precisely maintained watershed flow and simple load reduction scenario derived from repeating hydrologic conditions of 2007.

## 5.8 TMDL Implementation

Both Oklahoma DEQ and the Kansas Department of Health and Environment (KDHE) will collaborate with a host of other state agencies and local governments working within the boundaries of each state and local regulations to target available funding and technical assistance to support implementation of pollution controls and management measures. Various water quality management programs and funding sources will be used so that the pollutant reductions, as required by the TMDLs presented in this report can be achieved and water quality can be restored to maintain designated uses. DEQ’s Continuing Planning Process (CPP), required by the CWA §303(e)(3) and 40 CFR 130.5, summarizes

Oklahoma's commitments and programs aimed at restoring and protecting water quality throughout the State (ODEQ, 2012). The CPP can be accessed from DEQ's website at http://www.deq.state.ok.us/wqdnew/305b_303d/Final%20CPP.pdf. Table 5-8 provides a partial list of the state partner agencies that Oklahoma DEQ will collaborate with to address point and nonpoint source reduction goals established by the TMDLs determined for Oologah Lake.

Table 5-8 Partial List of Oklahoma Water Quality Management Agencies

| Agency | Web Link |
|---|---|
| Oklahoma Conservation Commission | http://www.ok.gov/conservation/Agency_Divisions/Water_Quality_Division |
| Oklahoma Department of Wildlife Conservation | http://www.wildlifedepartment.com/wildlifemgmt.htm |
| Oklahoma Department of Agriculture, Food, and Forestry | http://www.ag.ok.gov/aems |
| Oklahoma Water Resources Board | http://www.owrb.state.ok.us/quality/index.php |

### 5.8.1 *Point sources*

As authorized by Section 402 of the CWA, the DEQ has delegation of the NPDES Program in Oklahoma, except for certain jurisdictional areas related to agriculture (retained by State Department of Agriculture), and the oil and gas industry (retained by Oklahoma Corporation Commission), for which the EPA has retained permitting authority. The NPDES Program in Oklahoma, in accordance with an agreement between DEQ and EPA relating to administration and enforcement of the delegated NPDES Program, is implemented via the Oklahoma Pollutant Discharge Elimination System (OPDES) Act [Title 252, Chapter 606 (http://www.deq.state.ok.us/rules/611.pdf)].

As shown in Section 3 of this report, NPDES point source wastewater discharges and land use-dependent nonpoint source watershed runoff are the main sources of controllable pollutants to Oologah Lake. With the exception of the South Coffeyville wastewater treatment plant that is located in Oklahoma near the state border with Kansas, all of the NPDES wastewater discharges within the Oologah Lake study area are located in Kansas within the Verdigris River basin (see Table 3-1). Under Section 402 of the CWA, the Kansas Department of Health and Environment (KDHE) has been delegated the responsibility and authority to regulate point source wastewater discharges to Kansas waterways under the NPDES Permit Program. There are no pollutant contributions from Phase II MS4 permits in the Oklahoma portion of the Middle Verdigris River basin in Rogers, Nowata, and Washington counties. In Kansas, the City of Coffeyville has a Phase II MS4 Stormwater Program permit issued by KDHE. Stormwater best management practices (BMPs) and the requirements for different types of NPDES permits are presented in Appendix J of this report.

Although this TMDL does not specify a WLA for construction stormwater activities, permittees are required to meet the conditions of the Stormwater Construction General Permit (OKR10) issued by the DEQ and properly select, install and maintain all BMPs required under the permit, including applicable additional BMPs required in Appendix J, and meet local construction stormwater requirements if they are more restrictive. After EPA approval of this TMDL, specific stormwater construction permit requirements pertaining to this TMDL will be included as site-specific requirements in authorizations issued under permit OKR10 by the DEQ for construction activities located in the Oklahoma portion of the Oologah Lake watershed. Appendix J outlines the requirements for stormwater construction site permits.

This TMDL does not specify a WLA for industrial stormwater. However, industrial stormwater permittees in Oklahoma are required to meet the conditions of the industrial stormwater general permit (the Multi-Sector General Permit [MSGP, OKR05]) and properly select, install and maintain all BMPs required by the permit, including applicable additional BMPs required in Appendix J, for sediment and nutrient control. Existing permittees within the sectors specified in Appendix J located in the Oologah Lake watershed must update their Stormwater Pollution Prevention Plan (SWP3) to comply with the requirements in this TMDL within 12 months of EPA approval of the TMDL. Future MSGP permits proposed within the Oologah Lake watershed will be evaluated on a case-by-case basis for additional requirements if it is determined that sediment and nutrients are potential pollutants in the stormwater discharge. Appendix J outlines the requirements for MSGP permits.

### *5.8.2 Nonpoint Sources*

Nonpoint source pollution in Oklahoma is managed by the Oklahoma Conservation Commission (OCC) where OCC works with state partners such as Oklahoma Department of Environmental Quality (DEQ) and the Oklahoma Department of Agriculture, Food, and Forestry (ODAFF) to address water quality management issues. In Kansas, nonpoint source pollution is managed by the Kansas Department of Health and Environment (KDHE) Watershed Management Program in coordination with the State Conservation Commission Nonpoint Source Control Program and other State agencies such as the Kansas Water Office and Kansas Department of Agriculture, Division of Conservation (KDHE, 2019a). Oklahoma (OCC) and Kansas (KDHE) both also collaborate with federal agency partners to implement programs under EPA's Section 319 Nonpoint Source Program and the USDA's Natural Resources Conservation Service (NRCS) to address nonpoint source related water quality issues similar to those seen in the Verdigris River basin of the Oologah Lake watershed.

As described in Section 1.2, the majority of the watershed land use is agricultural and rural and consequently, pollution associated with runoff from these areas are nonpoint sources in nature. Measures to control and reduce land use-dependent loading should be considered by the counties, local municipalities and, when appropriate, in cooperation with the state agencies for Oklahoma (OCC) and Kansas (KDHE Watershed Management Program). The primary mechanisms used for management of nonpoint source pollution are incentive-based programs that support the installation of BMPs and public education and outreach. Appendix J of this report of this report includes overview descriptions of different types of BMPs that can be used to mitigate nonpoint source related water quality issues in the Verdigris River basin and Oologah Lake watershed.

### *5.8.3 Reasonable Assurances*

EPA guidance about Reasonable Assurance for development of TMDLs states that: A discussion of your reasonable assurances, as defined at 40 CFR § 130.2(p), that wasteload allocations and load allocations will be implemented (http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/TMDL-ch3.cfm).

Reasonable assurance is required by the EPA guidance for a TMDL to be approvable only when a waterbody is impaired by both point and nonpoint sources and where a point source is given a less stringent wasteload allocation based on an assumption that NPS load reductions will occur. In such a case, "reasonable assurance" that the NPS load reductions will actually occur must be demonstrated.

In this TMDL report for Oologah Lake, six (6) of the NPDES point source dischargers are municipal wastewater treatment facilities (SIC code=4952) and one (1) NPDES facility (KS0000248: Coffeyville Resources Refining & Marketing) is a petroleum refining facility (SIC code=2911). The South Coffeyville Public Works Authority (PWA) (OK0020117) is a municipal wastewater treatment facility located in Oklahoma and the other five (5) wastewater treatment plants are located in Kansas within the Verdigris River basin watershed (see Figure 3-1). As shown in the map and Table 3-1, all seven (7) NPDES facilities discharge to tributaries within the Verdigris basin. The water quality impact of NPDES point source loading is, therefore, incorporated as a source term in the tributary loading provided by output of the HSPF watershed model as external boundary condition inputs to the Oologah Lake EFDC model.

Table 3-19 presents a summary of tributary reach catchment loading (NPS runoff + NPDES PS) and overland runoff loading represented in the watershed model. All HSPF-generated nonpoint source loads discharged directly into Oologah Lake from the Verdigris River, Big Creek, Salt Creek, Double Creek, Madden Creek and Talala Creek and overland runoff catchments are assigned the same uniform percentage reduction for watershed loading that is expected to attain compliance with the water quality targets specified for Oologah Lake. As shown in Table 3-19, the NPDES wastewater discharger contribution is very small as the NPDES PS loads account for no more than 2% of the total PS and NPS loads represented in the watershed model.

The Upper Verdigris River basin (HUC8: 11070101 and 11070102) is entirely within the State of Kansas while the Middle Verdigris River basin (HUC8: 11070103 and 11070104) includes drainage in both Kansas and Oklahoma. Of the total drainage area upstream of the dam at Oologah Lake (4,339 square miles), approximately 77% of the watershed is in Kansas while the remaining 23% of the watershed is within Oklahoma (USACE Tulsa District, 2001). As watershed loading from Oklahoma and Kansas both contribute to water quality conditions in Oologah Lake, an interstate project, such as the Oologah Lake TMDL, requires coordination between the States of Oklahoma and Kansas and EPA Regions 6 and 7 to provide reasonable assurance that nonpoint source programs in the Verdigris River watershed can meet the Load Allocation targets developed for the Oologah Lake TMDL.

Nonpoint source pollution in Oklahoma is managed by the Oklahoma Conservation Commission (OCC) in conjunction with Oklahoma DEQ and other state partners such as Oklahoma Department of Agriculture, Food, and Forestry (ODAFF) (OWRB, 2014b). In Kansas, nonpoint source pollution management issues are managed by KDHE Watershed Management Program (KDHE, 2019a) in conjunction with State agencies such as the Kansas Water Office and Kansas Department of Agriculture, Division of Conservation to implement programs such as Source Water Assessment for water supplies, the Kansas Watershed Restoration and Protection Strategy (KS-WRAPS) Program and streambank restoration projects. Over the past decade, Kansas has also maintained interstate coordination efforts with Oklahoma to address water quality issues specifically for Grand Lake and Oologah Lake water supply reservoirs (KDHE, 2019a). Oklahoma and Kansas both coordinate with Stakeholders in the watershed and their federal partners through EPA's Section 319 Nonpoint Source Program and the National Water Quality Initiative with EPA and USDA's Natural Resources Conservation Service (NRCS) to design and implement programs to develop strategies to help nonpoint sources meet the load reduction goals contained in this report.

Pollutant loading sources downstream of the outlets of the four Federal reservoirs (Elk City Lake, Big Hill Lake, Fall River Lake, and Toronto Lake,) represented in the HSPF watershed model, are dominated by contributions from drainage in the State of Kansas. "Reasonable assurance", therefore, that the Load Allocation for Oologah Lake will be achieved is largely dependent on the success of NPDES point source controls and nonpoint source watershed management control strategies that have been, or will be, implemented within the Upper and Middle Verdigris River basins downstream of the four Federal reservoirs. Waste Load Allocations (WLA) and Load Allocations (LA) incorporated in EPA-approved TMDLs for the Verdigris River basin in Oklahoma and Kansas can be accessed at https://www.deq.ok.gov/water-quality-division/watershed-planning/tmdl/completed-tmdls/ and https://maps.kdhe.state.ks.us/kstmdl/. In addition to the NPDES Permit Program for point sources and nonpoint source management efforts (OWRB, 2014b; KDHE, 2019a) , both Oklahoma (OWRB, 2014b) and Kansas (KDHE, 2019b) maintain dedicated water quality monitoring programs to track groundwater, river and lake water quality conditions including evaluation of compliance with water quality standards for biennial reporting as required by Section 303(d) of the CWA.

# 6. Public Participation

This report was preliminary reviewed by EPA. After EPA reviewed this draft TMDL report, DEQ was given approval to submit this Report for Public Notice. The public notice was sent to local newspapers, to stakeholders in the Study Area affected by these draft TMDLs, and to stakeholders who requested all copies of TMDL public notices. The public notice was also posted at the DEQ website: http://www.deq.state.ok.us/wqdnew/index.htm.

The public comment period lasted 45 days from November 14, 2023 to December 29, 2023. No public comments were made and there were no requests for a public meeting.

After EPA's final approval, the TMDLs and 208 Factsheet were adopted into the WQMP.

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