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MEMORANDUM

To: Quang Nguyen, Claudia Hosch - EPA Region 6 Date: November 22, 2010

From: Tony Donigian, John Imhoff Client: EPA Region 6
AQUA TERRA Consultants

Copies: Project No.: 20610-436

Subject: Model Selection for the Illinois River TMDL in AR/OK

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EXECUTIVE SUMMARY

The Illinois River is a multi-jurisdictional tributary of the Arkansas River, approximately 160 miles long, in the states of Arkansas and Oklahoma. EPA Region 6 is funding AQUA TERRA Consultants to develop a watershed model to determine reductions in phosphorus loads needed to improve the water quality in the Illinois River Watershed (IRW). This watershed model will serve as a tool for sound technical decisions on appropriate point and nonpoint source controls to meet this objective.

In order to develop a scientifically sound modeling system to represent the entire IRW, including the land areas, the stream channels and Lake Tenkiller, models must be selected to represent each of these components. If the selected models are not already integrated within a single modeling system, the models must be linked to provide a comprehensive tool that addresses the watershed hydrology, generation of pollutants, fate/transport within the stream system, and ultimately dynamics and impacts on Lake Tenkiller.

The purpose of this technical memorandum is to describe and document the process of evaluating, selecting, and recommending the specific models for use in this TMDL effort. This report also provides the basis for the next step in this modeling study, development of the Simulation Plan. The Simulation Plan will provide details of the planned model application effort – for both watershed and waterbody models – including the calibration and validation time periods, constituents to be simulated, model scales and resolution, model performance targets, and potential scenarios to be investigated as part of the TMDL development procedure. Thus, this model selection memo should be viewed as a companion and supporting document to the Simulation Plan.

Since the prior modeling studies applied well-known, widely-used, and respected public-domain models for both the Illinois River watershed and the Lake Tenkiller, a detailed, comprehensive review of all available and relevant models was not considered necessary, nor the best use of project resources. Consequently, our approach in model selection was to review the applications and published reviews and comparisons of the HSPF and SWAT models, for the watershed, and the EFDC and AQUATOX models for the lake simulation, and then select and recommend which of these models should be used in this study.
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The model comparison and selection process resulted in the recommendation that the HSPF watershed model and the EFDC lake model be used in a linked application to provide the necessary modeling framework for performing this study.

HSPF is recommended because it provides a stronger dynamic (i.e. short time step, hourly) hydrologic and hydraulic model simulation, and an improved instream fate/transport simulation of sediment and phosphorus, linked to the soil nutrient and runoff models; this combination provides an improved capability to relate upstream watershed point and nonpoint source contributions to downstream conditions and impacts at both the AR/OK state line and to Lake Tenkiller.

EFDC is recommended because it allows a more mechanistic modeling of thermal stratification and a higher level of spatial resolution in Lake Tenkiller, both of which are essential to support water quality compliance issues in OK.

Details of the selection process are provided in the technical memo that follows.

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1.0 INTRODUCTION

1.1 BACKGROUND AND STUDY OBJECTIVES

The Illinois River is a multi-jurisdictional tributary of the Arkansas River, approximately 160 miles long, in the states of Arkansas and Oklahoma. The objective of this study is to develop a watershed model to determine reductions in phosphorus loads needed to improve the water quality in the Illinois River Watershed (IRW). This watershed model will serve as a tool for sound technical decisions on appropriate point and nonpoint source controls to meet this objective. Ultimately, the intent is development of a tool that can lead to scientifically sound TMDLs and a basin-wide water quality restoration plan.

The U.S. Environmental Protection Agency's (EPA's) Region 6 is funding this project through Work Assignments #3-36 and #4-36 -- Water Quality Modeling and TMDL Development for the Illinois River Watershed -- under EPA's BASINS contract (# EP-C-06-029) with AQUA TERRA Consultants, Mountain View, California. AQUA TERRA will conduct work for this project in conformance with the Quality Assurance (QA) program described in the BASINS Quality Management Plan (QMP) and with the procedures detailed in the Quality Assurance Project Plan (QAPP) developed for this effort (AQUA TERRA Consultants, 2010).

The Illinois River begins in the Ozark Mountains in the northwest corner of Arkansas, and flows for 50 miles west into northeastern Oklahoma (See Figure 1.1). The Arkansas portion of the Illinois River Watershed is characterized by fast growing urban areas and intensive agricultural animal production. It includes Benton, Washington and Crawford Counties and according to the US Census Bureau, the population of Benton and Washington Counties increased by 45% between 1990 and 2000. Arkansas ranked second in the nation in broiler production in 1998. Benton and Washington Counties ranked first and second respectively in the state. Other livestock production such as turkey, cattle and hogs are also all significant in this area. Upon entering Oklahoma, the river flows southwest and then south through the mountains of eastern Oklahoma for 65 miles, until it enters the reservoir Tenkiller Ferry Lake, also known as Lake Tenkiller. The lake comprises almost 13,000 acres of water and over 130 miles of shoreline, and is the central feature of one of Oklahoma's most heavily used recreational areas. The upper section of the Illinois River in Oklahoma is a designated scenic river and home to many native species of bass with spring runs of white bass. The lower section, below Tenkiller dam flows for 10 miles to the Arkansas River, and is a designated year-round trout stream, stocked with rainbow and brown trout.

Several segments of the Illinois River are currently on the State of Oklahoma's 303(d) list for Total Phosphorus (TP), while the mainstem Illinois River in Arkansas is not listed for TP. However, several tributaries to the Illinois River in Arkansas (e.g. Osage Creek, Muddy Fork, and Spring Creek) are designated as Phosphorus-impaired and included in the State's Clean Water Act 303(d) list. (See Figure 1.2)

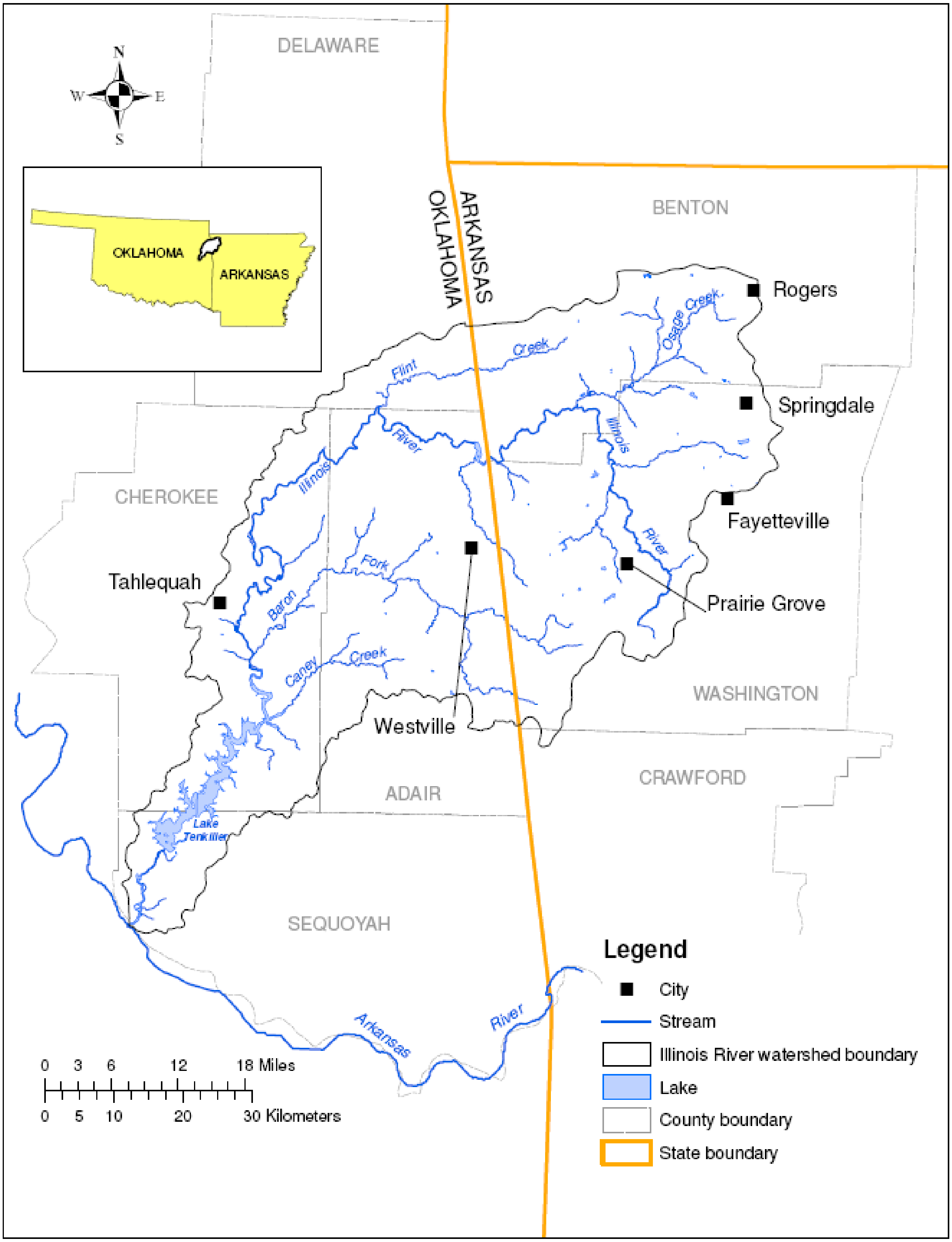


Figure 1.1 Illinois River Watershed Location Map

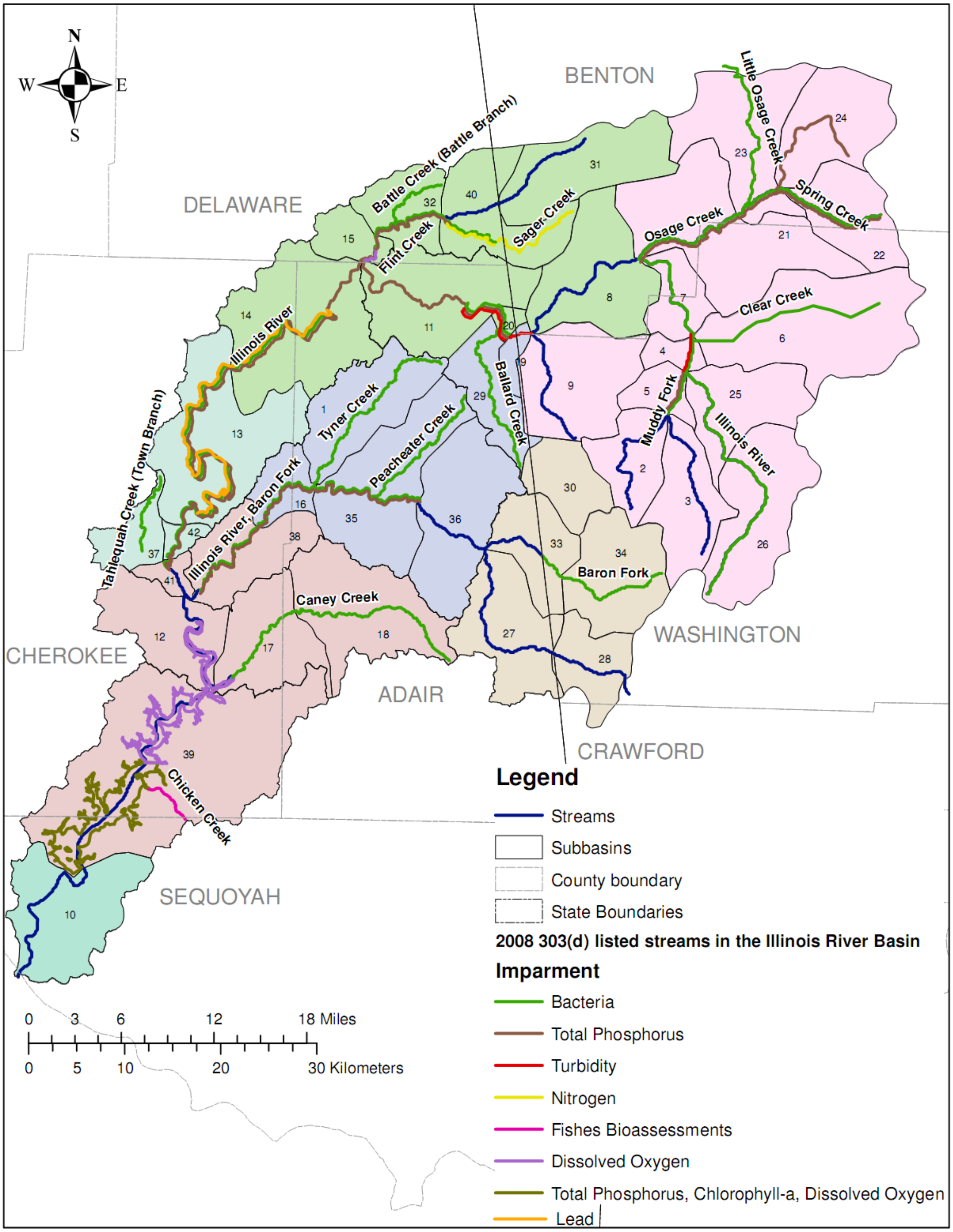


Figure 1.2 Section 303(d) Listed Impaired Segments within the Illinois River Watershed

A tremendous amount of data, reports, and information has been provided to EPA Region 6 for use in this study as a result of these initial data requests and acquisition efforts. A Draft Data Report, describing and documenting these data gathering efforts and comparing the data that has been collected to the data requirements for watershed and waterbody modeling in the IRW, was submitted for review by project stakeholders and interested parties in August 2010 (AQUA TERRA Consultants, 2010).

As shown in Figure 1.1, the Illinois River drains an extensive land area of approximately 1600 square miles in NE Oklahoma and NW Arkansas, and feeds into Lake Tenkiller prior to its confluence with the Arkansas River. In order to develop a scientifically sound modeling system to represent the entire IRW, including the land areas, the stream channels and Lake Tenkiller, models must be selected to represent each of these components. If the selected models are not already integrated within a single modeling system, the models must be linked to provide a comprehensive tool that addresses the watershed hydrology, generation of pollutants, fate/transport within the stream system, and ultimately dynamics and impacts on Lake Tenkiller.

The purpose of this technical memorandum is to describe and document the process of evaluating, selecting, and recommending the specific models for use in this TMDL effort. This report also provides the basis for the next step in this modeling study, development of the Simulation Plan. The Simulation Plan will provide details of the planned model application effort – for both watershed and waterbody models – including the calibration and validation time periods, constituents to be simulated, model scales and resolution, model performance targets, and potential scenarios to be investigated as part of the TMDL development procedure. Thus, this model selection memo should be viewed as a companion and supporting document to the Simulation Plan, which is expected to follow within four to six weeks.

1.2 PRIOR MODELING STUDIES

As is the case with any modeling and/or data assessment effort, the initial step in the IRW study was to review prior modeling studies that might identify and compile relevant data on the IRW and Lake Tenkiller, and also identify any specific issues and challenges in representing the hydrology and water quality of the IRW. This section discusses the major prior modeling efforts on the IRW and Lake Tenkiller with a focus on the specific models applied.

Over the recent past, the IRW has been the focus of at least two previous modeling efforts by Donigian et al., (2009) and Storm et al., (2006 and 2009) which focused on the entire IRW. Under WA 2-11 of EPA Contract EP-C-06-029, AQUA TERRA and Eco Modeling completed an integrated-linked watershed and ecosystem modeling effort of the Illinois River and Tenkiller Reservoir, using the US EPA HSPF watershed model and AQUATOX ecosystem model (Donigian et al., 2009). This effort was directed to nutrient criteria development and was based on a relatively limited period of available data. The watershed simulation covered a 20-year period from 1984 through 2003, but available water quality data (at that time) limited the TN calibration to the period 1990-1996 and the TP calibration from 1999-2003, with downstream stations primarily in OK. In this HSPF/AQUATOX effort, the AQUATOX calibrations were limited to the 1992-1993 using Clean Lakes Program data from Oklahoma State University (1996). As noted in the Data Report, additional data are now available through 2009 to support extended model calibration efforts in both OK and AR.

The watershed modeling effort by Storm et al. (2006) used the USDA SWAT model to represent the IRW, including specific consideration of the poultry litter applied to pasture areas, and subsequent runoff to the river system. That effort used relatively simple instream algorithms to approximate the complex instream fate and transport interactions of dissolved and particulate phosphorus. SWAT model runs were performed for the period of 1980 through 2006, including both calibration and validation; water quality calibration for TP (and dissolved P) was performed for 1990 through 2006. The ODEQ provided to EPA and AQUA TERRA the most recent modeling report submitted by Dr. Storm (Storm et al., 2009), along with the model input and data files, including GIS files used in this SWAT model setup, as these may provide valuable spatial data coverages for this effort.

There have been at least two studies of Lake Tenkiller using the US EPA HSPF watershed model for loadings and the US EPA EFDC model for hydrodynamics and water quality simulation of the lake. These include an initial study performed in support of TMDL development by EPA Region 6 and OK DEQ (US EPA and OK DEQ, 2001), with Tetra Tech contracted to perform the modeling, and a subsequent revision and refinement of that effort performed by Dynamic Solutions LLC (2006) with AQUA TERRA Consultants (2005) subcontracted to upgrade the HSPF model of the IRW. The Tenkiller lake bathymetry was refined in this effort to better represent the measured volume-elevation relationship for the lake; the bathymetry was transformed into absolute bottom elevations by tying into scanned USGS topographic maps of the adjacent land areas. Water quality calibrations were performed with available Clean Lakes Program data for 1992 and 1993, the same period as the subsequent AQUATOX application noted above. Thus, initial model setups for both EFDC and AQUATOX are available, along with the supporting calibration data, as candidate starting points for the current modeling effort of Lake Tenkiller.

Just prior to the publication of the Draft Data Report, we received a draft copy of the Illinois River Watershed Partnership (IRWP) Watershed Management Plan (IRWP, 2010). This WMP presents a watershed management strategy with the goal to “improve water quality in the Illinois River and its tributaries so that all waters meet their designated uses both now and in the future.” The report by the IRWP notes two additional watershed modeling efforts, by White (2009) and Saraswat et al (2010); the reports for which we have been attempting to obtain to investigate the model application procedures and results, along with the data and information relevant to this study. Just prior to the publication of this technical memorandum we were successful in acquiring a copy of the Saraswat report, and are in the process of reviewing that at the current time. In addition we are continuing our efforts to obtain a copy of the White report.

1.3 THIS TECHNICAL MEMORANDUM

This technical memo addresses the issue of model selection for the IRW TMDL effort based on the prior modeling studies noted and discussed above. Section 2 describes the watershed model selection effort while Section 3 addresses the lake model selection. Since the prior studies applied well-known, widely-used, and respected public-domain models for both the watershed and the lake, a detailed, comprehensive review of all available and relevant models was not considered necessary nor the best use of project resources. Consequently, our approach in model selection was to review the applications and published reviews and comparisons of the HSPF and SWAT models, for the watershed, and the EFDC and AQUATOX models for the lake simulation, and then select and recommend which of these models should be used in this study.

2.0 WATERSHED MODEL SELECTION

For those readers not familiar with the HSPF and SWAT models, brief summaries are provided in the following two sections below. These summaries are taken essentially verbatim from a recent modeling review by Borah and Bera (2003) to provide descriptions from relatively unbiased, non-developers of these models. Note that minor revisions and additions to the original descriptions are shown underlined.

2.1 OVERVIEW OF HSPF

HSPF, the Hydrological Simulation Program – Fortran (Bicknell et al., 2005; Donigian et al., 1995), first publicly released in 1980, was put together by Hydrocomp, Inc. (Johanson et al., 1980) under contract with the U.S. Environmental Protection Agency (US EPA). It is a continuous watershed simulation model that produces a time history of water quantity and quality at any point in a watershed. HSPF is an extension and reformulation of several previously developed models: the Stanford Watershed Model (SWM) (Crawford and Linsley, 1966), the Hydrologic Simulation Program (HSP) including HSP Quality (Hydrocomp, 1977), the Agricultural Runoff Management (ARM) model (Donigian and Davis, 1978), and the Nonpoint Source Runoff (NPS) model (Donigian and Crawford, 1979). HSPF uses many of the software tools developed by the U.S. Geological Survey (USGS) for providing interactive capabilities on model input, data storage, input-output analyses, and calibration. … HSPF has been incorporated as a nonpoint-source model (NPSM) into the US EPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), which was developed by Tetra Tech, Inc. (Lahlou et al., 1998), under contract with the US EPA. The main purpose of BASINS is to analyze … and develop TMDL standards and guidelines nationwide. The most recent version is BASINS4 (US EPA, 2007; Duda et al., 2003) which is based on an open-source code concept and includes a number of models as plug-in components, including HSPF and SWAT.

2.2 OVERVIEW OF SWAT

SWAT, the Soil and Water Assessment Tool (Arnold et al., 1998; Neitsch et al., 2002), was developed at the USDA-ARS Grassland, Soil, and Water Research Laboratory in Temple, Texas. It emerged mainly from SWRRB (Arnold et al., 1990) and features from CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1984), and ROTO (Arnold et al., 1995). It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment, and agricultural chemical yield in large ungauged watersheds or river basins. The model is intended for long-term yield predictions and is not capable of detailed single-event flood routing. It is an operational or conceptual model that operates on a daily time step. The model has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Although most of the applications of SWAT have been on a daily time step, recent additions to the model are the Green and Ampt (1911) infiltration equation using rainfall input at any time increment, and channel routing at an hourly time step (Arnold, 2002). Similar to HSPF, SWAT is also incorporated into the USEPA's BASINS for nonpoint-course simulations on agricultural lands, and has been recently enhanced to accommodate urban land categories.

2.3 MODEL COMPARISONS

As part of a model peer review performed for the Florida Department of Agriculture and Consumer Services, Tony Donigian was part of a panel of experts that reviewed the Watershed Assessment Model (WAM) (SWET, 2008) to determine its adequacy and functionality as a watershed-scale modeling tool for addressing water resources issues in Florida (Graham et al., 2009). As part of that effort a model comparison matrix was developed by the expert panel to demonstrate how WAM compared with other major modeling tools, including both HSPF and SWAT. The comparison matrix is shown in Table 2.1.

This matrix provides a good comparison of the watershed simulation capabilities of the two models, HSPF and SWAT, along with a side-by-side comparison with both a simpler model, WAM, and a more detailed model, MIKE SHE. Viewing HSPF and SWAT within this broader range of watershed model complexity provides an opportunity to appreciate the similarities in complexity and approach of the two models as well as the differences.

WAM is a relatively simple GIS-based planning-level tool, providing a daily simulation with land-based processes modeled by a version of the CREAMS/GLEAMS algorithms, within an empirical watershed-scale routing framework. It uses a GIS-based grid approach to represent the watershed on a consistent spatial scale, with routing attenuation factors for instream processes in place of physically-based process simulations.

MIKE SHE is at the other end of the complexity scale for watershed models. MIKE SHE (Refsgaard and Storm, 1995), based on SHE, the European Hydrological System (Abbott et al., 1986a, 1986b), is a comprehensive, distributed, and physically based numerical model simulating water, sediment, and water quality parameters in two-dimensional overland grids, one-dimensional channels, and one-dimensional unsaturated and three-dimensional saturated flow layers. It also has both continuous long-term and single-event simulation capabilities. The model was developed by a European consortium of three organizations: the U.K. Institute of Hydrology, the French consulting firm SOGREAH, and the Danish Hydraulic Institute (DHI). MIKE SHE is a proprietary model sold, licensed, and distributed by DHI, and requires extensive spatial datasets for model applications.

Table 2.2 (below) summarizes some of the key differences between HSPF and SWAT that factor into the model selection effort for the IRW TMDL. Figure 2.1 compares the watershed representation of the IRW by the HSPF and SWAT models, and shows the relative similarities in terms of spatial representation of the IRW.

Table 2.2 Comparison of Key Differences Between BASINS/HSPF and SWAT

BASINS/HSPF

- Hourly time step typical
- Multi-land use capabilities
- Strong hydrology model
- Current IL River application uses simplified processes
- Detailed soil nutrient models available
- Detailed instream routing and WQ process, including sediment-nutrient interactions
- Moderate spatial resolution with ~40 subbasins

SWAT

- Daily time step typical
- Multi-land use, but strength is agricultural
- SCS CN hydrology
- Detailed ag practices included
- IL River application includes poultry litter contributions
- Simplified instream processes
- Moderate spatial resolution with ~90 subbasins

Table 2.1 Characteristics and Capabilities of WAM and Selected Watershed Models (Adapted/Modified from Borah and Bera, 2003)

Description/ Criteria	WAM	BASINS/HSPF	MIKE SHE	SWAT
Model components/ capabilities	Runoff and water quality constituents for pervious and impervious areas modeled by choice of 3 alternative methods, with GLEAMS (default choice), EAAMOD, and special case module; routing from each grid cell for both overland and groundwater with delay factors; extensive GIS interface and uses 1 ha cells; channel routing with a modified linear reservoir approach	Runoff and water quality constituents on pervious and impervious land areas, simple and complex (process-based) WQ options, and water and constituents in stream channels and mixed reservoirs. Currently, part of the USEPA BASINS modeling system with user interface and ArcViewGIS platform.	Interception-ET, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, dual porosity, irrigation, and user interface with pre- and post-processing, GIS, and UNIRAS for graphical presentation.	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, and part of the USEPA BASINS modeling system with user interface and ArcView GIS platform.
Temporal scale	Long term; daily for field models, and sub-daily steps for channel routing.	Long term; variable constant steps (typically hourly, but can range from 5-min to daily).	Long term and storm event; variable steps depending numerical stability.	Long term; daily steps.
Watershed representation	GIS raster or grid-based representation of watershed, with rain zones, soils, land use, etc. overlain; 1-D channel and reservoirs; considers wetlands, depressions, etc.	Pervious and impervious land areas, stream channels, and mixed reservoirs; 1-D simulations.	2-D rectangular/square overland grids, 1-D channels, 1-D unsaturated and 3-D saturated flow layers.	Sub-basins grouped based on climate, hydrologic response units (lumped areas with same cover, soil, and management), ponds, groundwater, and main channel.
Rainfall excess on overland/ water balance	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.	Water budget considering interception, ET, and infiltration with empirically based areal distribution.	Interception and ET loss and vertical flow solving Richards equation using implicit numerical method.	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.
Runoff on overland	Runoff curve number generating daily runoff volume, routed over 3 days with user-defined fractions	Empirical outflow depth to detention storage relation and flow using Chezy-Manning equation.	2-D diffusive wave equations solved by an implicit finite-difference scheme.	Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.

Table 2.1 Characteristics and Capabilities of WAM and Selected Watershed Models (Adapted/Modified from Borah and Bera, 2003) (con't)

Description/ Criteria	WAM	BASINS/HSPF	MIKE SHE	SWAT
Subsurface flow	Subsurface flow from field-scale models routed over 90 days with user-defined fractions	Interflow outflow, percolation, and groundwater outflow using empirical storage and recession relations.	3-D groundwater flow equations solved using a numerical finite-difference scheme and simulated river-groundwater exchange.	Lateral subsurface flow using kinematic storage model (Sloan et al., 1983), and groundwater flow using empirical relations.
Runoff in channel	Derivative of a linear-reservoir routing approach, 1-D simulation	Routing based on 'storage' or 'kinematic-wave' methods; All inflows assumed to enter upstream end, and outflow is a depth-discharge function of reac volume or user-supplied demanc Flexible options to handle time and volume varying demands, and multiple outflow points.	Uses MIKE-11 model with optional full (St. Venant) or 1-D diffusive wave equations solved by an implicit finite-difference scheme. Both complex and simple hydrologic methods available.	Routing based on variable storage coefficient method and flow using Manning's equation adjusted for transmission losses, evaporation, diversions, and return flow.
Flow in reservoir	Same as channel, with flexible placement of weirs, gated structures, culverts and pumps	Same as channel, with flexibility to handle user-defined reservoir operations and structures.	Same as channel, with wide range of capabilities to handle hydraulic structures and operations.	Water balance and user-provided outflow (measured or targeted).
Overland sediment	Uses CREAMS/GLEAMS approach, based on USLE with channel, impoundment, and alternative overland flow paths and configurations.	Rainfall splash detachment and wash off of the detached sediment based on transport capacity as function of water storage and outflow plus scour from flow using power relation with water storage and flow.	2D overland flow model drives MIKE SHE SE (soil erosion) model.	Sediment yield based on Modified Universal Soil Loss Equation (MUSLE) expressed in terms of runoff volume, peak flow, and USLE factors.
Channel sediment	Empirical attenuation factors used to account for losses during channel travel time	Non-cohesive (sand) sediment transport using user-defined relation with flow velocity or Toffaleti or Colby method, and cohesive (silt, clay) sediment transport based on critical shear stress and settling velocity.	Hydraulic in MIKE-11 simulation drives both cohesive and non-cohesive sediment transport, including suspension, resuspension, settling.	Bagnold's stream power concept for bed degradation and sediment transport, degradation adjusted with bed erodibility and channel cover factors (for vegetation), and deposition based on particle fall velocity.
Reservoir sediment	Same as channel.	Same as channel.	Same as channel.	Outflow using simple continuity based on volumes and concentrations of inflow, outflow, and storage.

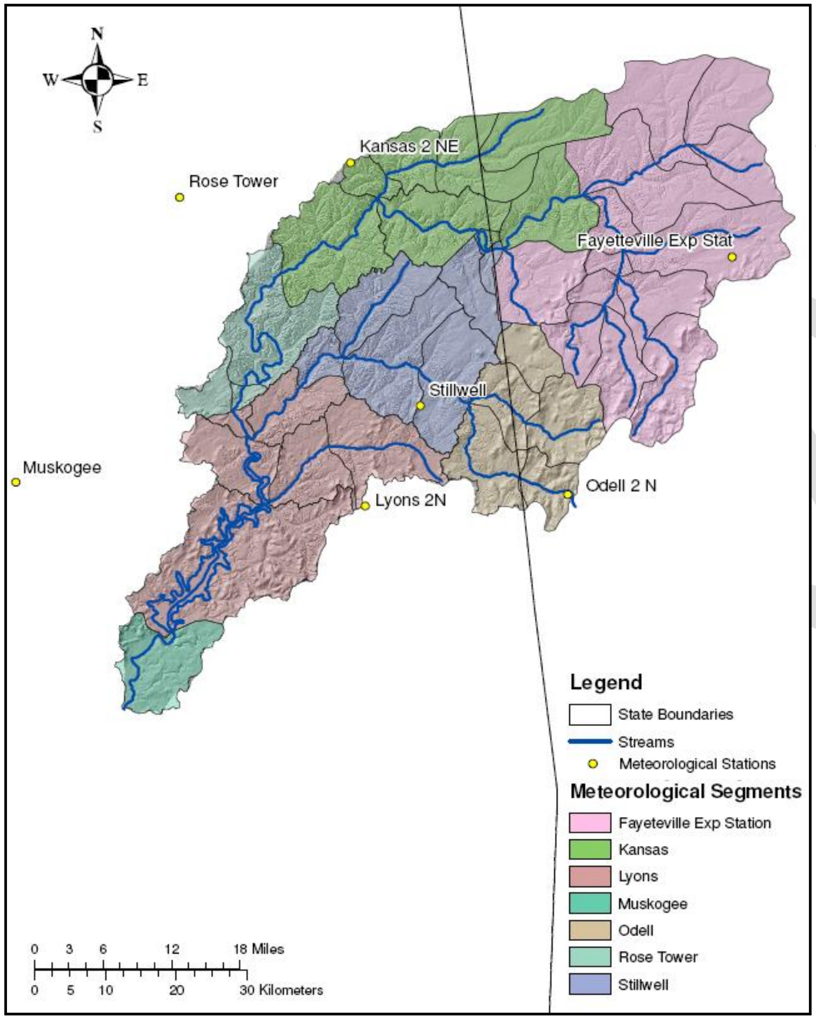
Table 2.1 Characteristics and Capabilities of WAM and Selected Watershed Models (Adapted/Modified from Borah and Bera, 2003) (con't)

Description/ Criteria	WAM	BASINS/HSPF	MIKE SHE	SWAT
Chemical simulation	Field-scale GLEAMS module can handle nutrients and pesticides, including runoff and movement through the soil to groundwater. All components of N and p cycles including crop uptake are considered.	Soil and water temperatures, dissolved oxygen, carbon dioxide, nitrate, ammonia, organic N, phosphate, organic P, pesticides in dissolved, adsorbed, and crystallized forms, and tracer chemicals chloride or bromide to calibrate solute movement through soil profiles. Detailed instream water quality simulation, including sediment transport (sand, silt, clay) with sediment-chemical interactions with both water column and bed; BOD/DO, nutrient and algal simulation (phytoplankton and multiple benthic algal species); and parent-daughter formulations for pesticides and other organic chemicals.	Dissolved conservative solutes in surface, soil, and ground waters by solving numerically the advection-dispersion equation for the respective regimes. MIKE-11 water quality capabilities used for surface water quality.	Nitrate-N based on water volume and average concentration, runoff P based on partitioning factor, daily organic N and sediment adsorbed P losses using loading functions, crop N and P use from supply and demand, and pesticides based on plant leaf-area-index, application efficiency, wash off fraction, organic carbon adsorption coefficient, and exponential decay according to half lives.
BMP evaluation	Extensive BMP capabilities in GLEAMS and other field scale modules. , EEAMOD provides capabilities for shallow water table /drained soils.	Nutrient, pesticide, and irrigation management by parameter changes, or simple BMP module with removal efficiencies.	Extensive BMP capabilities expected for the process-based land modules.	Agricultural management: tillage, irrigation, fertilization, pesticide applications, and grazing.

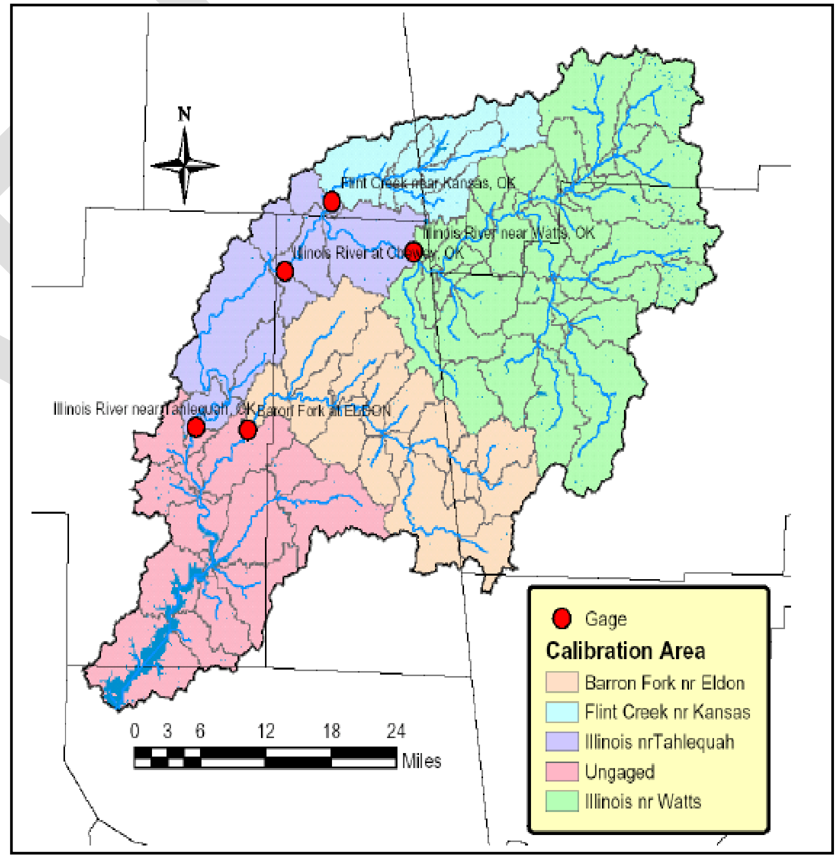
Source: Graham et al., 2008.

Figure 2.1 Illinois River Watershed Representation by the BASINS/HSPF and SWAT Models

BASINS/HSPF (Donigian et al, 2008)



SWAT Model (Storm et al, 2006)



As noted above, the prior modeling efforts by Donigian et al (2009) and Storm et al., (2009), provide sound alternatives for the watershed modeling component of this effort. However, each of these models and their applications to the Illinois River Watershed has particular strengths and weaknesses that need to be considered in this model selection process. Some of the issues related to the individual model capabilities are as follows:

- HSPF is generally recognized as providing a stronger hydrologic model than SWAT using hourly (or less) precipitation, for more accurate storm event simulations, and an energy-balance approach to snow accumulation and melt processes, although snow is not a major hydrologic component for the IRW. In addition, the hourly simulation of flows and loads is often a requirement when linking watershed models to downstream spatially explicit waterbody models (e.g. EFDC, as discussed in Section 3).

- Both models include multi-land use capabilities. HSPF's abilities to represent complex multi-land use watersheds has been a strength since its original development in 1980, whereas SWAT's capabilities for non-agricultural lands is relatively recent anduse of the model for urbanized areas is limited.

- Although HSPF has extensive capabilities to represent agriculture-dominated watersheds, the prior Illinois River application was constrained by resources and its original development effort (by ODEQ and their contractors) to only model three constitutents – Total Nitrogen (TN), Total Phosphorus (TP), and BOD5. Sediment was not included in that modeling and it is a major transport mechanism for phosphorus.

- The SWAT model application to the IRW (Storm et al., 2009) also did not model sediment fate/transport in the river system, but it provides a more detailed representation of the poultry litter sources of phosphorus and their application to pasture areas.

- Both models include detailed soil nutrient process models for simulating N and P balances and runoff components, with HSPF being slightly more detailed in the process end, and SWAT providing more detail in representing alternative agricultural management practices. However that advantage for SWAT is not a determining factor in model selection since row crops and associated rotations are a small fraction, less than 1 %, of the IRW land area.

- The instream TP fate/transport model used in the Storm et al., (2009) study was developed for that effort, and is a relatively simple representation of riverine processes for TP. It uses transfer coefficients between the bed and the water column for TP without direct modeling of sediment scour/deposition processes.

- HSPF provides a moderately complex sediment transport capability and allows direct modeling of sediment-contaminant interactions, partitioning of dissolved and particulate inorganic phosphorus, transfer between the bed and water column, and uptake/cycling of phosphorus by algae and DO/BOD processes. SWAT also includes an instream capability, but it does not appear to allow scour of nutrients from the channel bed (J. Butcher, Tetra Tech, personal communication, 8 October 2009).

- The improved HSPF instream simulation, linked with its soil nutrient runoff model, provides a better representation of upstream point and nonpoint source contributions to downstream water quality conditions and impacts, both at the AR/OK state line and at Lake Tenkiller.

- In the most recent model applications to the IRW, the SWAT model used about 90 subbasins whereas the HSPF model used about 40 subbasins. These are really comparable levels of spatial resolution, and the proposed TMDL modeling will likely include a higher level of resolution approaching 150 to 200 subbasins; either model is capable of providing this level of spatial resolution.

In summary, both the HSPF and SWAT watershed models have extensive capabilities, are widely used, well-known, and accepted by the modeling community, and have been applied to hundreds of watersheds across the US and abroad. In addition, both have been successfully used in TMDL studies in the US. Based on our review and prior knowledge of these models, and the specific needs for the IRW TMDL study, we recommend use of the HSPF model as the watershed model, for the following reasons:

a. The HSPF hydrology model with its hourly (or less) simulation will provide a better representation of the dynamic hydrology of the IRW, and is better suited for the short time step linkage with a detailed waterbody model of Lake Tenkiller.

b. The sediment transport and instream water quality capabilities of HSPF provide a better process-based representation of the fate and transport processes for nutrients, including phosphorus, along with sediment-nutrient interactions and scour/deposition impacts with the sediment bed. This is expected to provide an improved simulation of both point source and nonpoint source contributions of phosphorus both to the OK/AR state line and to Lake Tenkiller.

c. The HSPF soil nutrient models are comparable to SWAT, provide some additional level of detail for inorganic nutrients forms, and include capabilities to allow approximation of poultry litter applications to pasture lands subject to limitations of the available data.

d. The HSPF improved instream fate/transport simulation of sediment and phosphorus, linked to the soil nutrient and runoff models, will provide an improved capability to relate watershed point and nonpoint sources to downstream impacts and contributions at both the AR/OK state line and to Lake Tenkiller.

3.0 LAKE MODEL SELECTION

This section focuses on the effort related to modeling Lake Tenkiller, and specifically on the selection of the model that will be used for the modeling effort.

In writing the scope of work for this effort, EPA did not specify the specific models that were to be applied to the watershed, the Illinois River, or to Lake Tenkiller. In developing the work plan, AQUA TERRA noted the fact that two lake models had recently been applied to Lake Tenkiller:

1. Environmental Fluids Dynamic Code (and coupled water quality model) (Hamrick, 1992; 2007). There have been at least two studies of Lake Tenkiller using the US EPA HSPF watershed model for loadings and the US EPA EFDC model for hydrodynamics and water quality simulation of the lake. These include an initial study performed in support of TMDL development by EPA Region 6 and OK DEQ (US EPA and OK DEQ, 2001), with Tetra Tech contracted to perform the modeling, and a subsequent revision and refinement of that effort performed by Dynamic Solutions LLC (Craig, 2006) with AQUA TERRA Consultants (2005) subcontracted to upgrade the HSPF model of the IRW.
2. AQUATOX (USEPA, 2009). AQUA TERRA and Eco Modeling completed an integrated-linked watershed and ecosystem modeling effort of the Illinois River and Tenkiller Reservoir, using the US EPA HSPF watershed model and AQUATOX ecosystem model (Donigian et al., 2009). This effort was directed to nutrient criteria development.

Given the recent application of two respected lake models to Lake Tenkiller, AQUA TERRA suggested in the work plan that one of these two models be used for the current application thereby providing an opportunity for considerable leveraging of the information collected and the effort expended on the pre-existing applications. A preference to apply AQUATOX was expressed.

A work assignment kick-off meeting was held at EPA Region 6 headquarters in October 2009, including representatives from the Region, the State of Arkansas, the State of Oklahoma and AQUA TERRA. Two conclusions were drawn from the discussions at that meeting regarding the modeling effort for Lake Tenkiller. First, it was concluded that consideration of lake models other than EFDC and AQUATOX was not warranted. Second, a need to provide a more rigorous evaluation and comparison between EFDC and AQUATOX was expressed by more than one of the participants. The objectives of this document are to fulfill this need and to recommend a lake model for application in this study.

To date three *evaluation endpoints* that warrant consideration in selecting, developing and applying an improved lake model for Tenkiller have been identified, and a priority among the objectives has been implied. In order of perceived importance, they are as follows:

1. Dissolved oxygen. Address the Oklahoma WQS DO compliance issue: *"the Fish and Wildlife Propagation beneficial use designated for a lake or reservoir or portion thereof shall be deemed to be not supported with respect to the DO criterion if more than 50% of the water column at any given sample site has dissolved oxygen concentrations less than* 2 mg/l *due to other than naturally occurring conditions."*
2. Chlorophyll a (expressed as Carlson's Trophic State Index [TSI]). Oklahoma statutes designate a water body as "threatened by nutrients" if planktonic chlorophyll a values in the water column indicate that it has a TSI of 62 or greater. The index provides a linearization of algal biomass that can be related to the eutrophication gradient. For that reason, it is deemed more useful than a direct interpretation of chlorophyll a trends. (The most recent (2005-2006) TSI values for Tenkiller Reservoir (OWRB,

2008) classify the Illinois River Arm as eutrophic [TSI = 59], while the lower end of the lake is determined to be mesotrophic [TSI = 48].)

3. *Cylindrospermopsis*. This invasive cyanobacterium first appeared in the lake in 2001 and is characterized by rampant growth and production of a dangerous cyanotoxin.

Selection Approach: The recommendation of the most appropriate lake model for application in this study was developed using the following methodology:

1. Examine previous Lake Tenkiller modeling studies looking for kinds of conclusions achieved and identified strengths and weaknesses of each model application to the Lake Tenkiller setting and environmental issues
2. Consider/characterize stakeholder's feedback; use feedback to refine generic criteria to reflect specific needs of project
3. Consider/characterize current application objectives and relate these to traditional model selection criteria
4. Develop comparison approach
5. Review and summarize existing model reviews/characterizations and extract relevant characterization information
6. Provide conclusions and recommendation

3.1 PREVIOUS STUDIES

Previous Lake Tenkiller modeling studies were examined with an eye towards (1) the kinds of conclusions that resulted from the studies, (2) the identified strengths and weaknesses of each model application to the Lake Tenkiller setting and environmental issues.

3.1.1 EFDC STUDIES

A brief summary of the report "Water Quality Modeling Analysis in Support of TMDL Development for Tenkiller Ferry Lake and the Illinois River Watershed in Oklahoma" (US EPA Region 6 and OK DEQ. 2004) follows. The intent is to provide perspective on the kinds of conclusions that can be achieved using EFDC, and the strengths and limitations of the model that were apparent in its application to Lake Tenkiller. The study was performed within the context of establishing a preliminary TMDL. The report includes documentation of the EFDC model application to define the linkage between selected targets and the identified sources, describes the model testing to reproduce the existing condition, and evaluates lake response to load reductions.

Kinds of conclusions achieved

The 'flavor' of results that were achieved using EFDC at Lake Tenkiller is illustrated in the following statements in the report:

- "The modeled increase in total phosphorus concentrations during the summer strongly influenced the anoxic condition at the bottom of the lake."
- "It is evident that the EFDC model simulates temperature variation and lake stratification satisfactorily."
- "It is evident from model results that the anoxic volume is more than 30 percent of the lake volume during the summer seasons."

EFDC also provided a basis for conclusions that focused on compliance with a surface dissolved oxygen criteria and violations of the State standard for TSI values.

Using the Lake Tenkiller model, reduction scenarios were performed in the lake by reducing nutrient loadings to determine the nutrient load reductions required to reach the target criteria. The influence of nutrient loadings of BOD5, nitrogen, and phosphrus were studied numerically using the calibrated Lake Tenkiller model. A variety of loading sensitivity simulations were conducted to analyze the response of the lake eutrophication conditions to the nutrient allocations. The conclusion was drawn from this study that eutrophication in Lake Tenkiller is most sensitive to changes in phosphorus loadings. Phosphorus was found to be the limiting nutrient for water quality in the lake. It was determined that a 25 percent reduction in phosphorus loading was required for lake water quality to satisfy the target criteria.

Strengths of application to Tenkiller Lake

The following strengths were identified:

- EFDC simulated the DO quite well. Because DO is controlled by reaeration, sediment oxygen demand, nitrification, denitrification, decay of organic substances, photosynthesis of algae, and respiration of algae, the modelers considered the DO simulation as good indicator of model performance in terms of water quality simulation.
- Chlorophyll a plots indicated good correlation of model results with observed data.
- The EFDC results for the phosphorus agreed very well with the available data at the three stations that were used for calibration.
- The model results for organic nitrogen and 'nitrite plus nitrate' matched observations very well most of the time.
- The modelers considered the EFDC lake model to be well calibrated and representative of existing hydrodynamic and water quality processes in the lake. They judged that model testing and source response evaluation indicate that the combined watershed/lake model was suitable for allocation scenarios, analysis, and TMDL calculations.

Limitations of application to Tenkiller Lake

The following limitation was identified:

- The EFDC calibration effort for BOD5 resulted in slightly lower simulations than the observations in the stream reaches for which carbon data are available. Algal growth and dissolved oxygen levels in the lake are not limited by carbon and are therefore not very sensitive to this parameter, which limited the sensitivity of the calibration to model parameter adjustments.

3.1.2 AQUATOX STUDIES

A brief summary of the report "Tenkiller Ferry Lake Modeling Case Study – HSPF and AQUATOX" (Donigian et al., 2009) follows. The intent is to provide perspective on the kinds of conclusions that can be achieved using AQUATOX, and the strengths and limitations of the model that were apparent in its application to Lake Tenkiller. The study was performed within the context of establishing nutrient criteria for the lake. Ten scenarios were run with concurrent load reductions in TP, TN, and BOD, corresponding to a range of nonpoint source best management practices (BMPs) and point-source reductions in order to judge the feasibility of reaching water quality goals and water quality criteria.

Kinds of conclusions achieved

The ‘flavor’ of results that were achieved at Lake Tenkiller using AQUATOX is illustrated in the study’s concluding paragraph:

> AQUATOX predicts that increasing load reductions would achieve sequential improvements in water quality, based especially on chlorophyll a and the chlorophyll TSI. A 30% load reduction is predicted to achieve a measurable decrease in chlorophyll a and a change to mesotrophy at the dam. A 50% reduction is predicted to result in the chlorophyll a criterion of 10 micrograms/L being met. A 60% load reduction is predicted to achieve pre-1974 water quality in Lacustrine A. And a 90% load reduction is predicted to achieve mesotrophy in all lacustrine segments, as well as bringing the reservoir close to the Oklahoma Scenic Rivers standard of 0.037 mg/L TP.

AQUATOX also provided a basis for conclusions that focused on the impacts of modeling diagenesis and the composition of the algal community during the simulation period.

Strengths of application to Tenkiller Lake

The following strengths were identified:

- AQUATOX was set up with a full food web, including five phytoplankton groups. Although parameterized, the invasive blue-green *Cylindrospermopsis* was not simulated because it did not appear in Tenkiller until after the calibration period. Biotic parameters were adjusted only slightly from default values. The exception was that nitrogen-fixation in blue-greens was forced, giving them a competitive advantage. Uncertainty analysis suggested that blue-greens are skewed toward higher concentrations in the simulation of Lacustrine A; however, lower concentrations occur in Lacustrine C compared with observations. If there were to be additional calibration, blue-greens would be a good candidate. Biweekly data expressed as biomass of representative algal groups would be very useful for future applications to Tenkiller.
- The calibrations represent general ecosystem responses to nutrients, sediments, and detritus. While not the object of calibration, the predicted and observed nutrient concentrations are roughly comparable, generally within a factor of two.
- Chlorophyll a is a defensible endpoint for Tenkiller applications; the results generally matched observations for segments and were predicted to decrease toward the dam similar to the observed trend.
- Conversions of chlorophyll a to Carlson’s Trophic State Indices matched observed TSI values reasonably well and could be used to predict eutrophic trends.

Limitations of application to Tenkiller Lake

The following limitations were identified:

- Difficulties in matching the timing of hypoxia were experienced and may be a reflection of continued uncertainty in the flow field.
- Blue-greens were not well simulated. Likewise, overall algal composition was not as well represented as chlorophyll a.
- Water clarity, as represented by Secchi depth, was ignored in the analyses because of uncertainties in TSS loadings.
- The goal of investigating the declining effects of suspended sediments toward the dam was frustrated by the lack of observed data.

3.2 STAKEHOLDER'S FEEDBACK

Both the Oklahoma Department of Environmental Quality (ODEQ) and the Oklahoma Water Resources Board (OWRB) have provided valuable feedback relevant to the selection of the lake model that will be used for this study.

3.2.1 ODEQ

As a result of their involvement and familiarity with the previous EFDC and AQUATOX modeling studies on Tenkiller Lake, ODEQ (2010) identified the following list of issues:

1. Evaluating compliance with Oklahoma's Water Quality Standards for dissolved oxygen in lakes necessitates a detailed simulation of lake stratification. A modeling approach that determines stratification with relation to changes in the physical properties (water temperature, density as a function of air temperature, wind, and other hydrodynamic conditions) is warranted.

2. It is advantageous to use a model that enables efficient development and use of a spatial grid scheme that accommodates the simulation of individual lake sampling points and the subsequent integration of the grids to evaluate Water Quality Standard compliance.

3. Previous studies have demonstrated that nutrient loadings to the lake are dominated by short term, high flow, high load events. It is highly likely that many stakeholders in the watershed will pay special attention to the short-term impact of runoff from agricultural land to the lake and possibly the receiving streams. Therefore, dynamic, short-term response to flow and loading changes to the lake needs to be simulated.

4. Considering the intense scrutiny that various stakeholders have already given to this project, benefit can be realized by selecting and applying a lake model that has a well established track record as an effective tool for developing EPA-approved TMDLs.

5. The priority endpoints of the current modeling exercise will be compliance with water quality criteria. For instance, compliance with the chlorophyll-a criterion does not depend on any detailed analysis of the specific algal communities present. The calibration and simulation of these ecosystem interactions adds a layer of complexity that is not necessary for this study.

6. ODEQ modeling staff already have significant experience with using and reviewing EFDC lake models. This extensive experience makes it a preferred model from the product review standpoint.

3.2.2 OWRB

1. It may be advantageous to use a lake model that enables the capabilities needed to evaluate bio-manipulation as a lake management method.

2. The recent proliferation of the cyanobacterium *Cylindrospermopsis* is of concern to OWRB. It may be advantageous to use a lake model that enables simulation of this species and of its impacts up the food chain.

3.3 RELATIONSHIP OF STUDY OBJECTIVES TO TRADITIONAL MODEL SELECTION CRITERIA

In this section the current application objectives are considered in relation to traditional model model selection criteria. The goal is to focus attention on the most relevant selection criteria within the context of the current study.

According to the work plan for this study, a pivotal study objective is "development of a tool that will lead to scientifically sound TMDLs". Recently, numerous model comparisons have been developed to guide the selection of appropriate model(s) for achieving this objective (Imhoff and Yager, 1999; Fitzpatrick et al., 2001; Imhoff et al., 2003; Imhoff et al., 2004; Shoemaker et al., 2005). Water Environment Research Foundation's report entitled "Water Quality Models: A Survey and Assessment" (Fitzpatrick et al., 2001) provides a model selection framework that features the following criteria for selecting an appropriate receiving water quality model for a given application:

- Dimensionality (1-D, 2-D, 3-D)
- Time representation (Steady-state, Dynamic)
- Waterbody type (Lake, Reservoir, River, Estuary, Coastal)
- Level of analysis (Screening, Detailed/Planning)
- Source release types (Constant, Time-variable, Single, Multiple)
- Processes and state variables (BOD/DO, Eutrophication, Sediment-water, Chemical Fate, Diagenesis, Biotic)
- Resource requirements
    - Level of effort (Low, Medium, High)
    - Data requirements (Low, Medium, High)
    - Modeler/Reviewer expertise (Low, Medium, High)
- Model support
- Model availability (Public domain, Proprietary)

A number of the above selection criteria can be dismissed for this exercise of choosing between EFDC and AQUATOX for application to Lake Tenkiller:

- Time representation. Both models provide dynamic simulation.
- Waterbody Type. Both models are appropriate for modeling lakes, although the spatial resolution that is typically used in doing so differs between the two models.
- Level of analysis. Both models are detailed and appropriate for supporting planning decisions, although their strengths lie in their ability to support different types of planning decisions.
- Source release types. Both models support the representation of multiple, time-varying sources.
- Model support. Expert support is readily available for both models.
- Model availability. Both models are readily available and are public domain.

With no need to further consider the subset of traditional model selection criteria that we have dismissed above, the model selection approach can justifiably be limited to the criteria listed below. Note that the criteria have been refined and customized at this point to consider study objectives and stakeholder input. The perceived relative importance of criteria to selecting the lake model for the current study is implied by the order in which the list is presented.

1. Processes and State Variables: Ability to provide assessment of environmental processes and endpoints that are the focal point of regulatory compliance issue(s) or potential lake management decisions
    a. Dissolved oxygen concentrations, expressed with the spatial representation needed to define anoxic zones, and the temporal resolution needed to track the dynamics of the anoxic zones
    b. Chlorophyll *a* expressed Trophic State Index
    c. Proliferation of *Cylindrospermopsis* and its potential effects on the Lake Tenkiller biotic community
2. Ability to provide adequate spatial resolution to evaluate WQS compliance
3. Ability to provide adequate temporal resolution to represent critical stressor events
4. Level of model understanding and acceptance by both regulatory and regulated communities
5. Availability of previous model applications to study site and assessment of the degree to which they can be effectively leveraged to benefit the current study
6. Resource requirements
    a. Level of effort
    b. Data requirements
    c. Modeler expertise

3.4 MODEL COMPARISON APPROACH

The following model comparison approach was developed. The results of using this approach are reported in Section 5, and the conclusions are provided in Section 6.

1. Compare processes and state variables - describe model domains; relate model domains and capabilities to necessary evaluation endpoints; provide expanded comparison of processes and state variables in modeling compartment required to estimate and evaluate required endpoints.
2. Evaluate ability of models to provide adequate spatial resolution to evaluate WQS compliance.
3. Evaluate ability of models to provide adequate temporal resolution to represent critical stressor events.
4. Evaluate availability of previous model applications to study site and assessment of the degree to which they can be effectively leveraged to benefit the current study – this evaluation is provided in Section 5.X and results from review of the studies described in Section 1 of this document.
5. Evaluate level of model understanding and acceptance by both regulatory and regulated communities
6. Assess resource requirements
    a. Level of effort
    b. Data requirements
    c. Modeler expertise

3.5 MODEL COMPARISON RESULTS

The information presented in this section results from a review of existing model comparisons (Imhoff and Yager, 1999; Fitzpatrick et al., 2001; Imhoff et al., 2003; Imhoff et al., 2004; Shoemaker et al., 2005). Relevant information has been extracted from these reviews and customized to meet the need of the model selection process for the current study.

Model Domains

The modeling domains of EFDC and AQUATOX differ. On the most general level, EFDC can be characterized as a robust hydrodynamic model with strong accompanying water quality modeling capabilities. AQUATOX has its strengths and focus as a biological effects model. Hence the first, and perhaps most important mode of comparison for the two models is to more carefully describe their modeling domains.

The Environmental Fluid Dynamics Code (**EFDC**) is an advanced three-dimensional, time-variable model that provides the capability of internally linking hydrodynamic, water quality and eutrophication, sediment transport and toxic chemical transport and fate sub-models in a unique single source code framework EFDC is designed to represent a finite difference computational grid as either a simple cartesian grid or an orthogonal, curvilinear coordinate system for irregular coastlines. In the vertical domain, EFDC uses a 'sigma-stretched-grid' to represent complex bathymetry. The sediment transport model of EFDC incorporates advanced formulations for simulating settling, deposition and resuspension of cohesive and non-cohesive solids as well as sediment bed geomechanics; functional relationships of bed shear stress and bed shear strength for cohesive solids and the 'Shields' parameter for non-cohesive solids; consolidation of the sediment bed represented by a surface bed layer and multiple deep bed layers that respond to the accumulation or erosion of solids from the bed; and multiple classes of cohesive and non-cohesive solids and bedload processes. The contaminant fate model of EFDC accounts for multiple toxic chemicals and multiple classes of solids in an integrated model of hydrodynamics, sediment transport and toxic chemical fate. The eutrophication model is an advanced water quality model that directly links with the hydrodynamic model. The eutrophication model incorporates multiple functional groups of planktonic algae, dissolved oxygen, nutrient cycles of nitrogen, phosphorus and silica, organic carbon, chemical oxygen demand and total active metal as the 21 state variables of the model. Organic carbon and organic nutrients are represented as dissolved and particulate labile and refractory forms. The predictive sediment diagenesis model of Di Toro (2001) is incorporated in EFDC to internally couple the deposition of particulate organic carbon to the sediment bed with sediment-water fluxes of inorganic nutrients and dissolved oxygen. EFDC does not model secondary and tertiary biotic populations.

AQUATOX is a mechanistic and dynamic fate and effects model that simulates the significant physical, chemical, and biological processes affecting aquatic biota in streams (including runs, riffles, and pools), rivers, ponds, lakes, reservoirs, and estuaries. AQUATOX can model multiple species of periphyton, phytoplankton, macrophytes, aquatic insects, mollusks, and fish as well as nutrients, sediments, and toxic organics. AQUATOX Release 3 models the uptake of organic chemicals into a food chain or a food web. Size-class and age-class fish populations can be modeled. The AQUATOX model includes a hydraulic flow model based on HSPF formulations. AQUATOX does not include an internal hydrodynamic model. Time-dependent hydraulic data is provided externally by the modeler as input data to assign flow, velocity, surface elevation and/or depth, surface area, cross-sectional area and volume of the waterbody. AQUATOX also includes an eutrophication model that includes ammonia, nitrate, phosphate, carbon dioxide, and oxygen as state variables. The eutrophication model links to internal models of aerobic and anaerobic microbial degradation of organic sediments. A simple inorganic sediment transport model is included, again primarily based on HSPF formulations. AQUATOX computes chemical fate and equilibrium within the waterbody modeled. Chronic and acute toxicity are both simulated.

Figures 3.1 and 3.2 highlight the differences in model domain between the two models. At this level of scrutiny, both models share compartments for modeling hydrodynamics, sediment transport, chemical fate and transport, eutrophication and sediment diagenesis (although the strength of their capabilities in each of the compartments are different). In addition, AQUATOX includes modeling compartments modeling multi-level biota, risk, and toxicity. In the remainder of this section we will mine deeper into the modeling compartments that are required in order to evaluate the endpoints of potential interest for the current study using appropriate metrics, as well as necessary spatial and temporal resolution.

Modeling Compartments Requirements for Modeling Evaluation Endpoints

1. Effectively simulating dissolved oxygen concentrations, expressed with the spatial representation needed to define anoxic zones, and the temporal resolution needed to track the dynamics of the anoxic zones requires the following modeling compartments: hydrodynamics (or possibly hydraulic flow), sediment transport, eutrophication, chemical fate and transport, diagenesis.
2. Effectively simulating primary producers and expressing them first as chlorophyll a, then as TSI values, requires all the compartments listed for dissolved oxygen above.
3. Simulating Cylindrospermopsis shares the compartment requirements of the other two evaluation endpoints, but also requires a biotic compartment that represents more detailed biological processes.

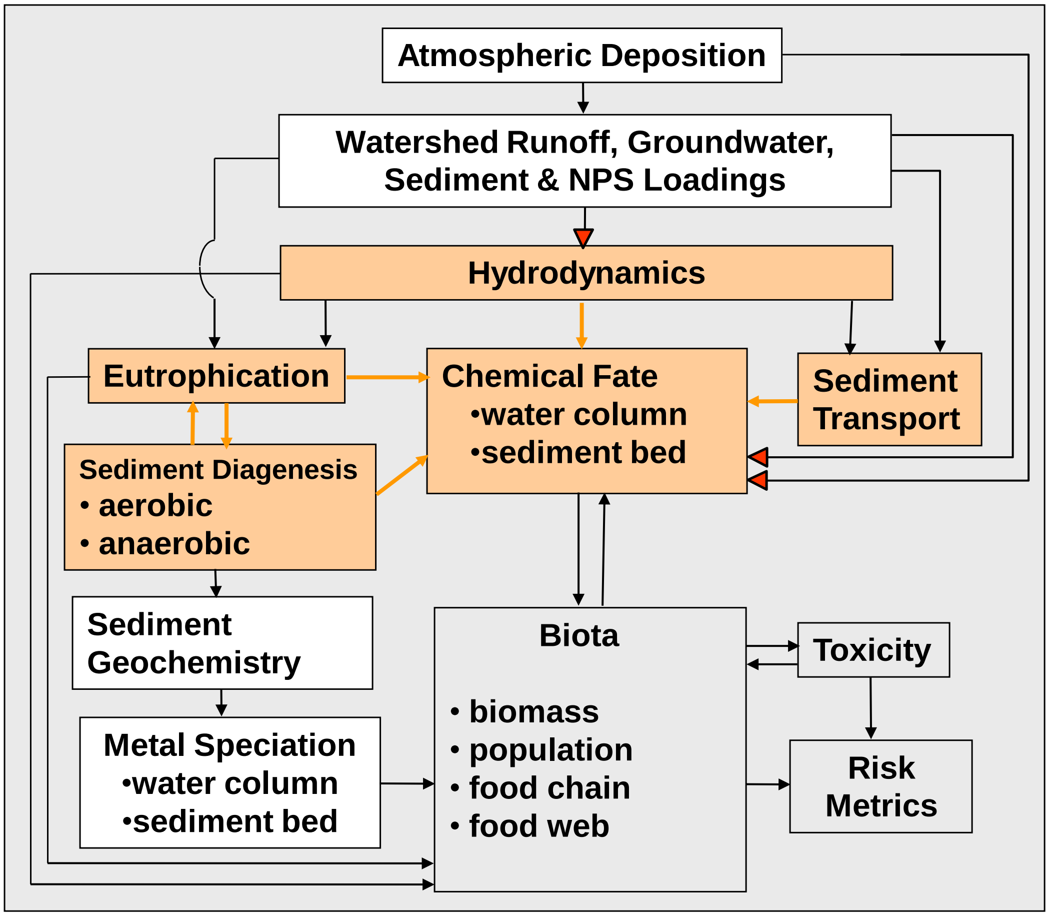
3.6 MODELING GRID

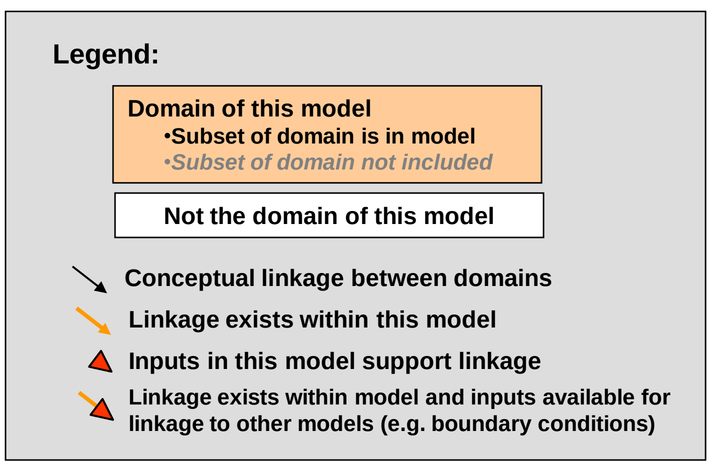
In AQUATOX, large compartments need to be set up to simulate different parts of a lake and the link between the compartments requires special model input/setup. It is not clear how many compartments AQUATOX can accommodate in one model setup. The existing AQUATOX model for Lake Tenkiller divides the lake into 9 compartments while the existing EFDC model has195 active cells. EFDC's spatial resolution is clearly more resolute, and this is an important factor both in modeling the dynamic nature of the anoxic zone and in evaluating WQS compliance.

3.2.1 HYDRODYNAMIC CAPABILITIES

A comparison of the hydrodynamic capabilities of the two models cannot be performed at the same level of detail as that which will be used for the water quality modeling capabilities (Section 5.3). AQUATOX is not a hydrodynamic model – rather it either uses an internal hydraulic flow model based on HSPF formulations or accepts and uses time-dependent hydraulic data that is provided by the modeler as input data to assign flow, velocity, surface elevation and/or depth, surface area, cross-sectional area and volume of the waterbody.

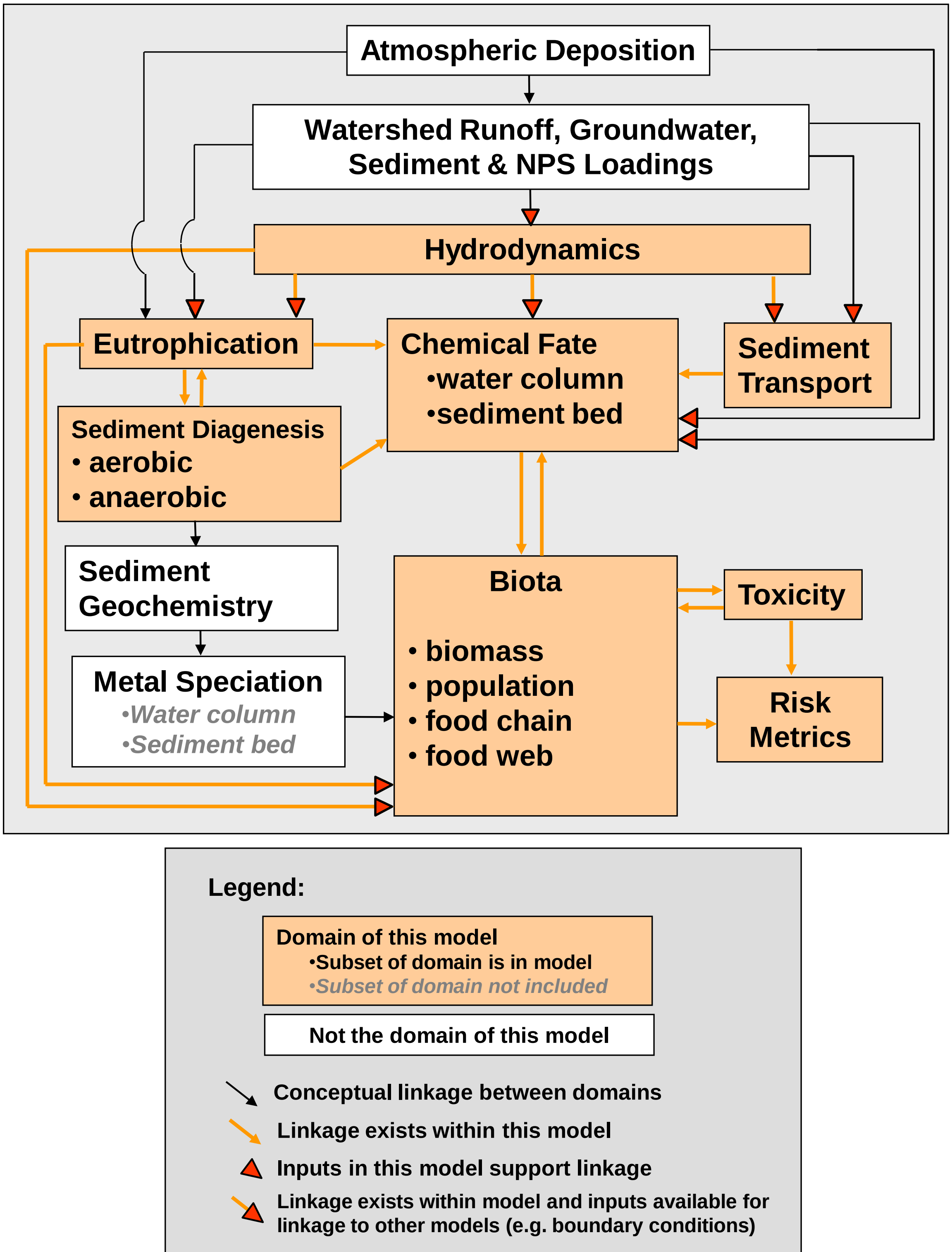
EFDC is a robust and versatile hydrodynamic model. The hydrodynamics model of EFDC accounts for all the major physical processes that govern the barotropic and baroclinic components of water motion in natural water systems. Prognostic state variables of EFDC include water temperature, salinity, water surface elevations and the 3D velocity/ flow field. Turbulent closure formulations are incorporated in the model to provide internal simulations of horizontal diffusion and vertical diffusion processes. The hydrodynamic model can be executed in two modes: (1) the results of the hydrodynamic model can be saved and used as input for the mass transport sub-models or (2) EFDC can be executed in a fully coupled mode with coupled simulations of hydrodynamics, sediment transport, toxic chemicals and eutrophication.





EFDC

Figure 3.1 Domain schematic for EFDC



AQUATOX

Figure 3.2 Domain schematic for AQUATOX Release 3

Comparison criteria typically applied for the review and evaluation of hydrodynamic models include the following features and processes:

- Spatial Dimensionality
- State Variables and Computed Variables
- Approximations and Assumptions
- Surface and Bottom Boundaries
- Vertical stratification
- Turbulence Closure
- Wetting and Drying
- Boundary Conditions and External Forcing Functions
- Computational Grid Schemes and Transformations
- Numerical Methods for Time-Dependent Solution

A discussion of each of these criteria including associated state variables is provided by Imhoff et al. (2003), and Table A-3 in the appendix of this document provides characterization of EFDC using these criteria.

3.2.1 WATER QUALITY MODELING CAPABILITIES

Models for conventional pollutant (i.e., dissolved oxygen, nutrients) fate and transport and eutrophication have been developed over the past few decades as very simplified screening level models, intermediate level models applied for water quality management planning studies, and complex, or advanced, models developed for R&D studies and applied problem settings characterized by complex physical domains and a need for a high level of scientific credibility.

Imhoff et al. (2003) provides an extensive comparison of the state variables and process formulations that are used in AQUATOX (version 2.0) and EFDC (2003 version) to model conventional pollutants. To support the current needs, the comparisons have been updated with the assistance of experts for both models.

In the appendix to this document Table A-1 presents an updated comparison of the state variables represented in each model, and Table A-2 presents an updated comparison of the kinetic processes and interactions incorporated in each model. A verbal comparison follows:

Both EFDC and AQUATOX are considered advanced conventional pollutant transport and fate models. These models are classified as advanced models for the following reasons: (1) primary producer species groups are split as multiple species groups of algae (e.g., diatoms, blue-greens, greens dinoflagellates etc), benthic algae and macrophytes in a complex aquatic food chain representation; (2) biogeochemical reactions for organic nutrients and organic carbon are split into dissolved/particulate components with the dissolved/particulate components further split as labile and refractory components as separate state variables; (3) internal processes that influence biological production and the abundance of algal biomass, such as light extinction in the water column and zooplankton predation, are represented by functional relationships coupled with internally simulated suspended solids and zooplankton abundance; and (4) mass fluxes of nutrients and dissolved oxygen across the sediment-water interface are simulated using a state-of-the-art sediment diagenesis model that is internally coupled with the deposition of particulate organic carbon to the sediment bed (Di Toro et al., 1990; Di Toro, 2000).

AQUATOX and EFDC provide a detailed representation of primary producers in natural waters. Functional groups of algae represented in these models include: diatoms, blue-greens, greens, and dinoflagellates. Benthic algae are also incorporated in AQUATOX and EFDC. Macrophytes are explicitly represented only in AQUATOX. In both of these advanced models, primary producer growth rates and productivity are simulated as non-linear relationships dependent on water temperature, the availability of light and the availability of inorganic nitrogen and phosphorus. Silica, required for diatom growth, is included as an additional inorganic nutrient in both these advanced models. Algal biomass for each functional group is allowed to settle out of the water column to the bed via user-assigned settling velocities. AQUATOX is the only advanced model designed to represent herbivorous zooplankton as a dynamic state variable in a detailed aquatic food chain. EFDC accounts for the loss of algal biomass by zooplankton grazing as an external forcing function for zooplankton biomass and/or a parameterized zooplankton grazing rate to account for algal mortality from predation. AQUATOX is the only advanced model that attempts to provide a realistic representation of the production, decomposition and transfers of organic matter and inorganic nutrients within an aquatic food web across all trophic levels in the water column (pelagic) and the sediment bed (benthic) compartments.

Both models represent the inorganic forms of nitrogen, phosphorus, silica and the organic forms of nitrogen, phosphorus and carbon. The organic nutrients and organic carbon state variables are split into dissolved/particulate forms with the dissolved and particulate components further split as labile/refractory components to account for differences in the reaction rates for decay. Decomposition thus accounts for the combined effects of slow (refractory) and fast (labile) reacting fractions of organic nutrients and organic carbon. Of the advanced models, AQUATOX is the only model that includes a mass balance of inorganic carbon to simulate carbon dioxide.

Salinity and/or chlorides are represented as state variables of the hydrodynamic model for EFDC. Salinity and/or chlorides simulated in the hydrodynamic model is directly coupled with the water quality model. AQUATOX does not include salinity/chlorides as a state variable.

Multiple classes of generalized solids are represented as state variables in the sediment transport model of EFDC. AQUATOX includes clays, silts and sands as inorganic solids state variables. Solids deposition and resuspension velocities are provided to AQUATOX by linkage with an internal sediment transport model. Total suspended solids are computed as an output variable in these models as the sum of the multiple suspended solids classes, detrital organic matter and algal biomass (as dry weight). The effects of suspended solids and algal biomass on light extinction in the water column are included in both models as functional relationships that are coupled with the internally simulated concentrations of suspended solids and algal biomass.

EFDC is the only advanced model designed to account for pathogens, such as fecal coliform bacteria, as a state variable. Bacterial mortality is simulated as a simple temperature dependent function. The dependence of mortality on the availability of light and the fraction of seawater (as salinity/chlorides) is not, however, considered in EFDC.

The kinetic reactions that influence dissolved oxygen are essentially identical in both models. Kinetic terms for dissolved oxygen include: production of oxygen from primary producer photosynthesis; uptake of oxygen from primary producer respiration; loss of oxygen via nitrification and decomposition of organic matter; the transfer of oxygen from the atmosphere to the water column via reaeration; and the loss of oxygen across the sediment-water interface via decomposition of organic matter in the sediment bed (i.e., sediment oxygen demand or SOD). Both models also include a term to account for the loss of oxygen by heterotrophic respiration of DOC. Chemical oxygen demand is incorporated in EFDC. AQUATOX includes the respiratory losses of oxygen from zooplankton and the pelagic and benthic organisms represented in all other trophic levels.

Both EFDC and AQUATOX simulate the mass fluxes of inorganic nutrients and dissolved oxygen (sediment oxygen demand or SOD) across the sediment-water interface using a state-of-the-art sediment diagenesis model that is internally coupled with the deposition of particulate organic carbon to the sediment bed.

3.7 BIOTIC MODELING CAPABILITIES

A detailed comparison of the biotic modeling capabilities of the two models cannot be performed for organisms that are higher on the food chain than primary producers. As the previous section describes, both models represent both water column and benthic algae. With its emphasis on biology, AQUATOX expands the biotic simulation to represent invertebrates, fish and aquatic plants. Populations (expressed as biomass), food chains and food webs can be defined and simulated. Accordingly, AQUATOX provides a means to address biologically-focused issues such as bio-manipulation and food chain effects (see Section 2).

Comparison criteria typically applied for the review and evaluation of biological models include the following features and processes:

- State Variables
- Bioavailability
- Biotic Processes
- Physico-chemical Processes
- Temporal Resolution
- Initial and Boundary Conditions
- Model Accuracy

A discussion of each of these criteria including associated state variables is provided by Imhoff et al. (2004), and Tables A-4 and A-5 in the appendix of this document provide characterization of AQUATOX in terms of biotic state variables and processes that are represented.

It should be noted that an additional benefit to the current study's objectives could possibly be achieved by using AQUATOX to simulate secondary and tertiary producers. There appears to be adequate evidence in support of the importance of tertiary and secondary consumers in nutrient cycling to justify incorporating the higher trophic levels of ecology models into studies of eutrophication (see Appendix B).

3.8 CONCLUSIONS AND RECOMMENDATION

3.8.1 CONCLUSIONS

Based on the evaluation described in the previous sections, we have drawn the following conclusions:

1. Of the two models, EFDC provides a more effective spatial framework and process representation scheme that will allow the mechanistic modeling of thermal stratification phenomena in Lake Tenkiller. This capability is deemed essential to one of the two most important evaluation endpoints, i.e., the identification of time-varying anoxic conditions.
2. By offering a more mechanistically based simulation of stratification, EFDC in turn offers potential advantage in representing the *physica*l modeling component of the eutrophication process.

3. Both models provide adequate *biochemical* process representation to model and evaluate chlorophyll a concentrations expressed as Carlson's Trophic State Index. EFDC has a perceived advantage in more accurately mapping observed data to its detailed grid system. AQUATOX has a potential advantage to add accuracy to the eutrophication modeling that determines the chlorophyll a estimations by enabling modeling of secondary and tertiary producers living in Lake Tenkiller. While there may be advantage to doing this, selecting and parameterizing the necessary process algorithms is still considered a research issue. We expect that credible results for simulated chlorophyll a can be achieved using EFDC's eutrophication modeling capabilities.
4. Of the two models, only AQUATOX provides the capabilities needed to evaluate bio-manipulation as a lake management method.
5. Of the two models, only AQUATOX provides the capabilities needed to simulate the cyanobacterium *Cylindrospermopsis* and of its potential effects on other biota in the Lake Tenkiller food chain.
6. The high spatial resolution that is inherent in EFDC applications (and results) offers advantages in applications that are intended to support compliance with water quality standards. The planned application for this work assignment has that objective.
7. One modeling approach that has been considered is using EFDC to simulate lake hydrodynamics and using/transforming EFDC flow results to provide the flow input for AQUATOX, which would in turn perform the water quality simulation. We suggest that the spatial resolution and the physical detail achieved by the EFDC flow simulation provides significant benefit to a water quality simulation performed <u>at the same level of spatial resolution</u> as the EFDC hydrodynamics simulation, and that it would be counter-productive to simplify and generalize this information in the process of translating it into required input to support an AQUATOX application.
8. Previous applications of both models to Lake Tenkiller provide significant opportunities for leveraging. It is our understanding that there has been a greater LOE expended on previous EFDC applications to Lake Tenkiller than there has on AQUATOX simulations, and implicitly there is a greater body of information that could be moved forward into an application to support the current work assignment. On the other hand, we expect that the LOE required for an EFDC application for this study will nonetheless be significantly greater than that required for an AQUATOX application.
9. The majority of the burden for understanding and accepting model results for Lake Tenkiller will fall on Oklahoma State agencies, and with the current study's focus on development of TMDLs and compliance with water quality standards, it is our understanding that the lead agency will be ODEQ. Consequently the fact that ODEQ is favorably experienced with both reviewing and performing EFDC applications is a valid and practical consideration in selecting between the two models.
10. Regarding resource requirements for applying the two models, the Project Team is capable of providing appropriate and effective modeler expertise to support application of both models. We believe that adequate data are available to support application of either model. The level of effort needed to apply EFDC will be greater than that required to apply AQUATOX, and EPA Region 6 has been made aware of this by the Project Team providing initial LOE estimates for an EFDC application. With adequate data and adequate modeling expertise available to support application of either model, resource requirements for applying the two models <u>are not</u> deemed a determining factor in making our recommendation. However, EPA Region 6 will of necessity need to approve a modeling approach consistent with the available funds.

3.8.2 RECOMMENDATION

Based on the conclusions presented above in Section 3.8.1, **EFDC** is recommended as the lake model for the current study.

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