DATA MANAGEMENT PLAN AND DESCRIPTION OF MODELING PROCESS AND MODEL FILES

for

The Upper Neuse River Basin Association Falls Lake and Watershed Modeling

Prepared for:

The Upper Neuse River Basin Association

P.O. Box 270

Butner, NC 27509

Plan Prepared by:

Systech Water Resources

1200 Mount Diablo Blvd.,
Suite 102
Walnut Creek, CA 94596

Brown and Caldwell

5430 Wade Park Blvd.
Suite 200
Raleigh, NC 27607

Dynamic Solutions LLC

6421 Deane Hill Dr.
Suite 1
Knoxville, TN 37919

Table of Contents

List of Figures

List of Tables

List of Abbreviations

BMP	Best Management Practice
C	Carbon
Ca	Calcium
CASTNET	Clean Air Status and Trends Network
Cl	Chloride
DEM	Digital Elevation Model
DOC	Dissolved Organic Carbon
DWR	Division of Water Resources
EFDC	Environmental Fluid Dynamics Code
ft	Feet
GIS	Geographic Information System
K	Potassium
Mg	Magnesium
MRS	Modeling and Regulatory Support
MRSW	Modeling and Regulatory Support Workgroup
MSL	Mean Sea Level
N	Nitrogen
Na	Sodium
NADP	EPA's National Atmospheric Deposition Program
NAVD88	North American Vertical Datum of 1988
NCDC	NOAA's National Climatic Data Center
NH4 or NH4-N	Ammonium
NO3 or NO3-N	Nitrate
Org-N	Organic Nitrogen
P	Phosphorous
PO4 or PO4-P	Phosphate
POC	Particulate Organic Carbon
ppt	Parts per Thousand
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
R	R Programming Language
RE	Relative Error
RMSE	Root Mean Square Error
SO4	Sulfate
TDS	Total Dissolved Solids

TN	Total Nitrogen
TOC	Total Organic Carbon
TON	Total Organic Nitrogen
TOP	Total Organic Phosphorous
TP	Total Phosphorous
TSS	Total Suspended Solids
UNRBA	Upper Neuse River Basin Association
USACE	United States Army Corps of Engineers
UTM	Universal Transverse Mercator
WARMF	Watershed Analysis Risk Management Framework

Section 1: Introduction and Purpose

The Upper Neuse River Basin Association (UNRBA) has developed a Modeling Quality Assurance Project Plan (QAPP) for the UNRBA Modeling and Regulatory Support (MRS) Project. The MRS Project includes updating, revising, and improving the existing lake and watershed models developed previously for Falls Lake. The lake is drained by 771 square miles of the Upper Neuse River Basin (HUC8: 03020201) and extends 22 miles (at normal conservation pool elevation) from the lake arm at the confluence of the Eno and Flat Rivers to the Falls Lake dam (Figure 1). Major tributaries to the reservoir include the Eno River, Flat River, Little River, and Knap of Reeds, Ellerbe, Ledge, Lick, Beaverdam and New Light Creeks.

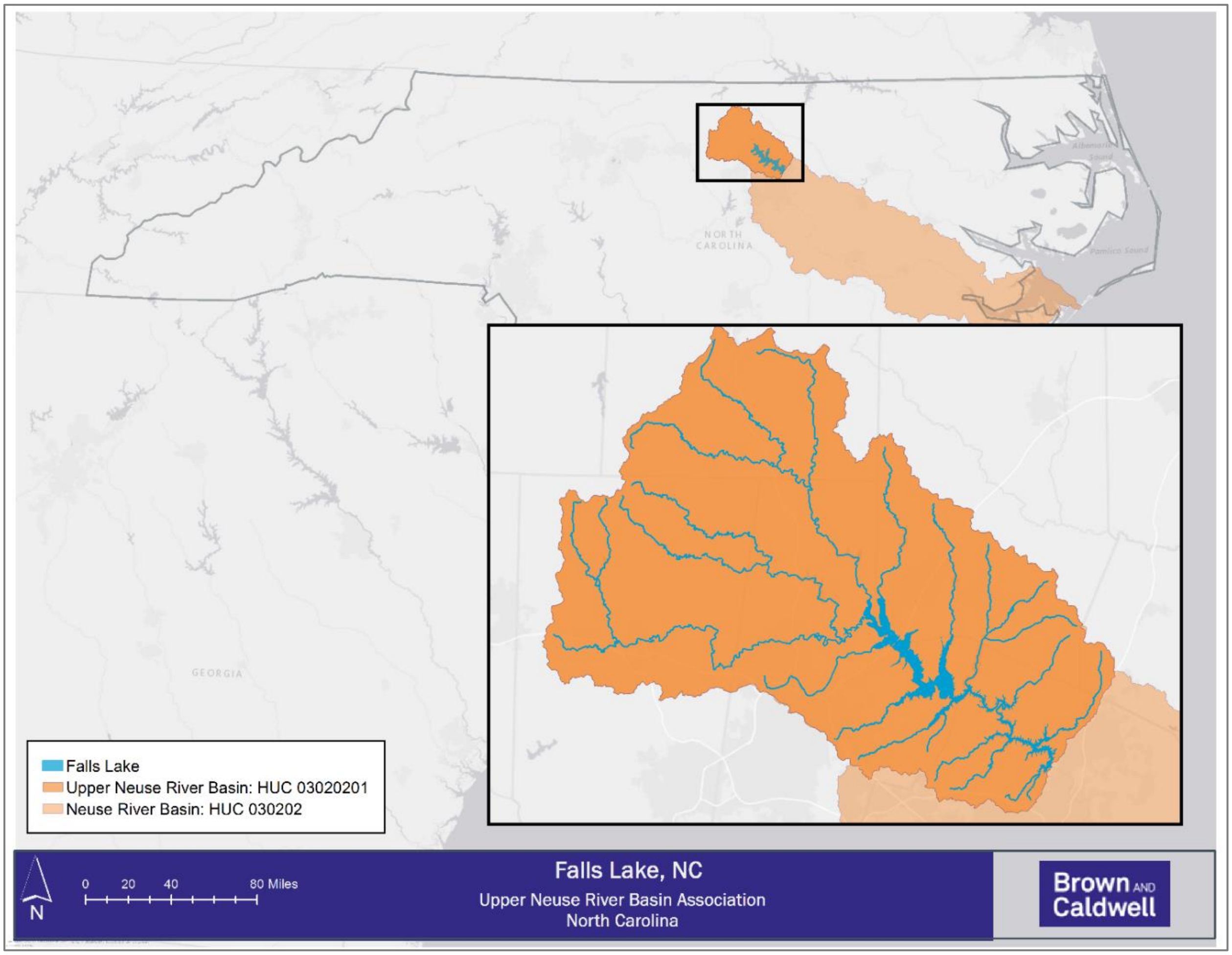


Figure 1. Falls Lake and Watershed Drainage

The updated lake and watershed models will support the reexamination of the current Nutrient Management Strategy, with specific reference to Stage II of the Falls Lake Rules (NCAC 15A 02B.0275(5)). Four models are currently under development to support the reexamination:

- The Watershed Analysis Risk Management Framework (WARMF) model has been selected to simulate watershed hydrology, runoff and loading of sediment, nutrients and organic matter to Falls Lake.
- The lake module in WARMF (one dimensional with vertical stratification) will be developed for Falls Lake and several larger impoundments in the watershed.

- The Environmental Fluid Dynamics Code (EFDC) model has been selected to simulate 3-dimensional hydrodynamics, sediment transport, water quality, eutrophication, and sediment diagenesis processes in Falls Lake.
- A statistical lake model will be developed to supplement the three mechanistic models listed above. It will also be used to evaluate uncertainty and link water quality to designated uses for the lake as established through North Carolina's water quality standards.

The Modeling QAPP was drafted during the first year of the UNRBA MRS Project in FY2017. The QAPP was finalized during the second year of the project (FY2018) and approved by the NC Division of Water Resources (DWR) on March 1, 2018. The QAPP guides the development and application of the models to support the reexamination and was developed with input from the UNRBA Modeling and Regulatory Support Workgroup (MRSW). During development of the Modeling QAPP, the MRSW requested development of a Data Management Plan to describe the management and quality assurance procedures for model input and output data. This document serves as the Data Management Plan for the MRS Project. As this document provides additional detail on data management, no formal approval by DWR is required. The existing, approved QAPP for the modeling effort stands as the agency's approval of the modeling effort under the Falls Lake reexamination component of the rules. This document will be distributed to DWR and other interested parties as part of the stakeholder engagement of the MRS project.

Section 2: Overview of Input Data Management

The UNRBA MRS Project requires data from a variety of sources, each with its own preferred formats and data structures. This diversity means that any data received may need to be reformatted, transformed, , or combined to create model input files and calibration datasets. Unfortunately, each step of this process has the potential to introduce errors or inadvertent omissions while also decreasing transparency.

Clear documentation of data provenance—the data origins and processes by which they arrived in their current state—is an essential component of the UNRBA's modeling framework. To fully document data provenance, the modeling team has adopted a process that meets the following three criteria. First, original data files must be preserved exactly as received. Second, any changes to the data received (from the original file) must be clearly documented, justified, and available for review. And third, all changes must be reproducible—that is, additional copies of the output file should be able to be regenerated from the original data source as needed.

To achieve these goals, all data files received will be given read-only permissions and archived in their original state upon receipt. If the original file does not contain all necessary original metadata, a text file describing the file's origins will be created to include the source organization, contact details, date received, period covered by the file, and other pertinent information as appropriate.

2.1 Discrete Data

For each discrete data file, an automated and reproduceable R-project script will read the original file, perform all necessary transformations, and save the transformed data as needed for modeling. The R programming language (R Core Team 2017) can read from, and write to, many file formats, including text files, databases, Microsoft Excel files, shape files, and geodatabases. The transformation R scripts will be designed to automatically produce html log files ("R notebooks") which contain the R-code along with clear, human-readable documentations of each change and its justification. The R notebook file will serve as a complete record of the data provenance (origin and manipulations) and can be used to re-generate model input files from the original data files as needed.

In addition to keeping track of data provenance, the approach described above provides an opportunity to embed both tabular and graphical summaries within the html R notebooks which can provide visual verifications of the data. Any questions about data quality arising from the visualization can be flagged within the R notebook, investigated, and any conclusions or changes to the data can be clearly recorded and justified.

For the discrete data used as model boundary conditions, initial conditions, calibration and validation for the lake hydrodynamic and water quality model, the original data without any data manipulation will be provided to the lake hydrodynamic and water quality modeling team. For quality control, source of the data, any unit conversion, any data formatting, transformation and gap filling, coordinate system re-projection if needed will be documented in a designated project log book with date and author. Any datasets or data points that are believed to be unreliable and are not used for model boundary and initial conditions, calibration and validation will be documented as well in the log book with date and author.

2.2 Spatial Data

ArcGIS is the Geographic Information System (GIS) platform that will be used to display and analyze spatial data. Common spatial data formats include raster datasets (e.g., gridded data such as land cover datasets), vector datasets (e.g., shapefiles such as stream networks), and point datasets (e.g., sampling locations and onsite wastewater treatment systems).

ArcGIS contains a comprehensive collection of spatial analysis tools for modeling various situations. The management of digital data demands the use of QA/QC parameters throughout the project to maintain data integrity. With the increased dissemination of digital data, this aspect of GIS management is most important. The quality of digital data can be ensured with management focused in three fundamental areas. The initial project management component is the first phase. Maintenance of QA/QC procedures throughout the project is the second phase, followed by final quality assurance checks prior to data delivery.

Managing a GIS project can be difficult without a QA/QC protocol. Since there can be subtasks, multiple workers, and various forms of output, the margin for error can be quite large. From conception to data delivery, a project should pass through a series of checks which are established control measures. The range of acceptable values sought by the control measures are quality assurance parameters. Project progress is directly proportional to the level of confidence in the data.

To produce high-quality map products and perform accurate data analysis, the source database must be of high quality and well maintained. ArcGIS includes Data Reviewer which is the QC tool for ArcGIS data. ArcGIS Data Reviewer allows the management of quality control and data analysis. Data Reviewer provides a complete system for automating and simplifying data quality control, which can quickly improve the integrity of the data.

ArcGIS Data Reviewer consists of a series of tools that support both automated and visual analysis of data. Data Reviewer can be used to detect anomalies with features, attributes, and relationships in databases. Data checks contain the analysis rules and can be scheduled to run automatically or run as necessary. Results of the analysis are logged in a Reviewer session, which is used to manage the life cycle of the analysis. Depending on the type of analysis being performed, the anomaly can be corrected as part of database maintenance or investigated further. The ArcGIS data analysis consists of:

- **Spatial checks**: Spatial checks analyze the spatial relationships of features.
- **Attribute checks**: Attribute checks analyze the attribute values of features and tables. This can be simple field validation like a geodatabase domain or with more complex attribute dependencies.
- **Feature integrity checks**: Feature integrity checks analyze the properties of features. Feature integrity checks ensure that the collection rules are followed for each feature class.

- **Metadata checks**: Metadata checks analyze the metadata information of the feature datasets and feature classes. Metadata can contain critical information about the source used to collect the derived data which can significantly impact the reliability of the data.
- **Managed data reviews**: Managed review of data is essential to complete data analysis. Whether reviewing the data through automated checks or visually, it is essential to examine the integrity of the entire database.

Section 3: WARMF Model Data Processing and Management

WARMF is a stand-alone watershed and lake modeling software package which can be applied to any watershed. The WARMF model framework simulates the chemical and physical processes in a watershed and its surface water network of streams and lakes. A WARMF application is divided into catchments, river segments, and reservoir segments through which water and its chemical constituents are routed. Water volume balance, heat balance, and mass balance of each chemical constituent are maintained in each model element. WARMF includes its own graphical user interface through which the user can access the model's inputs and outputs and a separate simulation engine executable file.

3.1 Overview of Files

WARMF is provided as a set of install files which includes the program files for the software and the application files for a particular application such as the Falls Lake watershed. There are three directories into which files are installed: the computer system directory (often c:\windows\system), the WARMF directory (c:\WARMF by default), and the project subdirectory (c:\WARMF\Falls_Lake). Table 1 lists the files installed with WARMF and the application files that will be developed for the Falls Lake watershed and lake.

Table 1. WARMF Files

Directory	Files Installed
System	owl52f.dll, ss32d25.dll, bds52f.dll, bw322000c.dll, bw320007.cdll, bw320009.dll, bwcc32.dll, cw3230.dll, edt32d30.dll, olch2d32.dll
WARMF Program	Graphical user interface files: warmf.exe, stavshp.dll, stdialog.dll, stedit.dll, stmap.dll, ststream.dll, stutils.dll Simulation engine: model.exe Default coefficient files: untitled.coe, untitled.con User's Guide: WARMF Users Guide.pdf Technical Documentation: WARMFTechDoc.pdf WARMFSetupWithBASINS_v6_2.pdf WARMFSetupWithBASINS4_v6_2.pdf Coefficient File Key.pdf
Falls Lake Application	Project files: *.WSM, *.WSH, *.CON Model coefficient files: *.COE Time series data files: *.MET, *.AIR, *.PTS, *.FLO, *.ORH, *.OLH, *.ORC, *.OLC Output files: *.CAT, *.RIV, *.LAK, *.PSM, *.QWQ

3.2 Input Files

The data used to create a WARMF application comes from a variety of sources and formats. WARMF model data needs can be divided into three categories: spatial data, time series input data, and time series data used to calibrate the model.

Table 2 shows spatial data which provide key inputs to WARMF for the Falls Lake watershed. These parameters do not vary over the course of a simulation. Digital elevation model (DEM) data encompassing the watershed is processed in GIS software to determine the slope and aspect of each grid cell. The stream locations are then fixed within the DEM grid. The flow paths through the DEM are calculated by determining the direction of maximum slope between each grid cell and its eight neighbors. From this it can be determined which grid cells are in the contributing watershed of each river segment. Those contributing grid cells are then grouped as catchment areas for each stream segment. The slopes of each cell within each catchment area are averaged to determine the catchment slope. A vector sum is calculated for the aspect of each grid cell to determine the net catchment aspect. The slope and aspect attributes are stored with the attribute table of the catchment boundaries shapefile and imported into WARMF. River segment lengths and upstream and downstream bed elevations are calculated from the digital elevation model and stored as attributes with the river shapefile. The tributary connections from catchments to river segments and between river segments are saved with the river shapefile attribute table, which is then imported into WARMF. Reservoir boundaries are imported into WARMF but attributes of the reservoirs are entered manually within WARMF.

Table 2. Spatial Data Sources

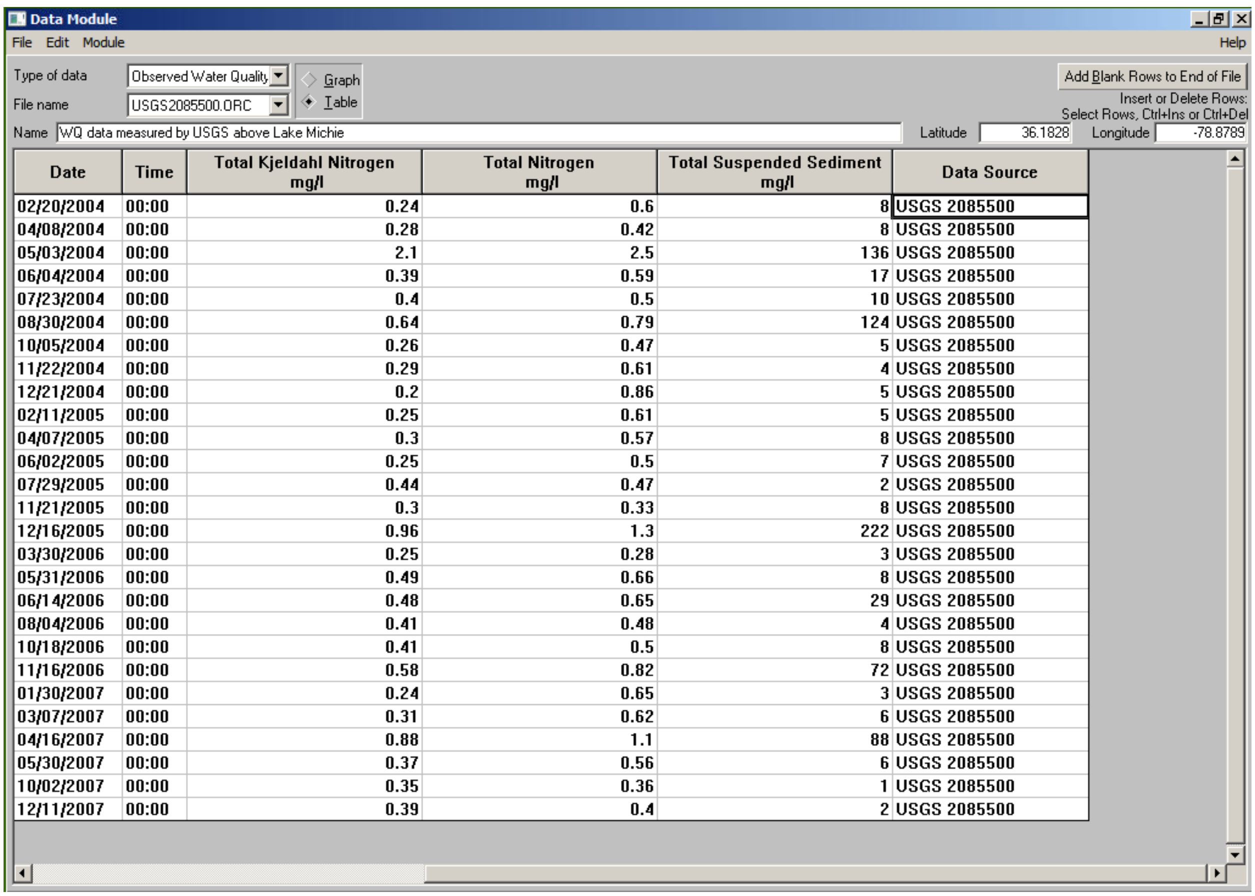
Data Type	Application in WARMF
Topography (Digital Elevation Model)	GIS calculations determine catchment delineation, shape, slope, and aspect as well as river slope, length, and bed elevations
Stream & Lake Locations	Used to place surface waters on the WARMF model grid and determine physical properties such as length and area
Land Use / Land Cover	GIS data is overlaid with catchment boundaries to determine the percentage of each land use in each catchment
Soils	Used to estimate soil horizon thickness, thickness, and hydraulic conductivity in catchments
Onsite Wastewater Systems	GIS data of onsite wastewater systems is overlain with catchment boundaries to estimate the population served by onsite wastewater systems in each catchment
Fertilizer Use	Estimated fertilizer use is entered for each month of the year for each land use. This can vary spatially but limited data often requires an assumption of uniform practices within each land use across the watershed.
Best Management Practices	WARMF accepts inputs of BMPs such as buffer strips, detention ponds, street sweeping, and cattle fencing. This information may be available in GIS format or for individual sites.

Time series inputs required to drive WARMF model simulations are listed in Table 3. Table 4 shows the time series data which are not necessary to run the model but are used to evaluate the model calibration (i.e., these times series are compared to model output to test the accuracy of the model). All these files are in text format so they can be viewed and edited from within the WARMF graphical user interface or from a text editor. The modeling team accepts the data in its native format and formats it for input to the WARMF model. The primary method used to format the data will rely on the R statistical package as described above. R allows the user to track each step in the formatting process and provides assurances and quality checks that the raw data was transformed and formatted accurately. Each line of the WARMF time series files contains a data source column which indicates the original source of the data. The modeling team will archive the original raw data, the R processing code, and processed model input file.

Table 3. Time Series Model Input Data	
Type of Data	**Data Source**
Meteorology	Data from national, state, and local sources is compiled and stored in WARMF meteorology (*.MET) text files for each site. Each catchment and reservoir has a .MET file assigned to it with rainfall and temperature adjustment factors.
Rain Chemistry	Data from national, state, and local sources is compiled and stored in WARMF air & rain chemistry (*.AIR) text files for each site. Each catchment and reservoir has a .AIR file assigned to it.
Air Chemistry	Data from national, state, and local sources is compiled and stored in WARMF air & rain chemistry (*.AIR) text files for each site. Each catchment and reservoir has a .AIR file assigned to it.
Point Sources	Data from national, state, and local sources is compiled and stored in WARMF point source (*.PTS) text files for each discharger. Each point source is assigned to the surface water segment or land catchment to which they discharge.
Reservoir Releases & Diversions	Data for controlled flows is compiled from national, state, and local sources and stored in WARMF managed flow (*.FLO) text files for each site. Each managed flow file is assigned to the water body in the model from which the water is withdrawn.

Table 4. Time Series Model Calibration Data	
Observed Hydrology	Data for measured stream flow, stream depth, reservoir surface elevation, reservoir volume, and reservoir spill is compiled from national, state, and local sources into WARMF observed river hydrology (*.ORH) and observed reservoir hydrology (*.OLH) text files. Each file is assigned to the water body in WARMF corresponding to where data was collected.
Observed Water Quality	Data for measured stream and reservoir water quality is compiled from national, state, and local sources into WARMF observed river chemistry (*.ORC) and observed reservoir chemistry (*.OLC) text files. Each file is assigned to the water body segment in WARMF corresponding to where data was collected.

The WARMF Data Module is used to find errors in the original data and ensure faithful processing into the WARMF data format. This module can be viewed in table view (Figure 2) or graphical view (Figure 3). It provides an additional quality assurance step in the development of the model. In graphical view, WARMF can display each parameter by site. Figure 3 shows an example observed river chemistry (.ORC) file made by processing US Geological Survey measured water quality data. It is the same data shown in Figure 2, but in graphical form. The user can click on each parameter for a graphical display. Outliers can be identified from the graph and checked against the original data to ensure proper data processing. If the original data were found to be in error, the erroneous data point can be removed from the WARMF database in the Data Module. Any omissions of data and data filling will be documented in the modeling team notes. The Data Module also shows average and standard deviation of plotted data which can be compared against statistics for the original data to ensure the data processing was done correctly. The Data Module is used to populate, edit, and display all WARMF time series data files: meteorology (*.MET), air & rain chemistry (*.AIR), point sources (*.PTS), and managed flows (*.FLO).



Date	Time	Total Kjeldahl Nitrogen mg/l	Total Nitrogen mg/l	Total Suspended Sediment mg/l	Data Source
02/20/2004	00:00	0.24	0.6	8	USGS 2085500
04/08/2004	00:00	0.28	0.42	8	USGS 2085500
05/03/2004	00:00	2.1	2.5	136	USGS 2085500
06/04/2004	00:00	0.39	0.59	17	USGS 2085500
07/23/2004	00:00	0.4	0.5	10	USGS 2085500
08/30/2004	00:00	0.64	0.79	124	USGS 2085500
10/05/2004	00:00	0.26	0.47	5	USGS 2085500
11/22/2004	00:00	0.29	0.61	4	USGS 2085500
12/21/2004	00:00	0.2	0.86	5	USGS 2085500
02/11/2005	00:00	0.25	0.61	5	USGS 2085500
04/07/2005	00:00	0.3	0.57	8	USGS 2085500
06/02/2005	00:00	0.25	0.5	7	USGS 2085500
07/29/2005	00:00	0.44	0.47	2	USGS 2085500
11/21/2005	00:00	0.3	0.33	8	USGS 2085500
12/16/2005	00:00	0.96	1.3	222	USGS 2085500
03/30/2006	00:00	0.25	0.28	3	USGS 2085500
05/31/2006	00:00	0.49	0.66	8	USGS 2085500
06/14/2006	00:00	0.48	0.65	29	USGS 2085500
08/04/2006	00:00	0.41	0.48	4	USGS 2085500
10/18/2006	00:00	0.41	0.5	8	USGS 2085500
11/16/2006	00:00	0.58	0.82	72	USGS 2085500
01/30/2007	00:00	0.24	0.65	3	USGS 2085500
03/07/2007	00:00	0.31	0.62	6	USGS 2085500
04/16/2007	00:00	0.88	1.1	88	USGS 2085500
05/30/2007	00:00	0.37	0.56	6	USGS 2085500
10/02/2007	00:00	0.35	0.36	1	USGS 2085500
12/11/2007	00:00	0.39	0.4	2	USGS 2085500

Figure 2. WARMF Data Module (Table View)

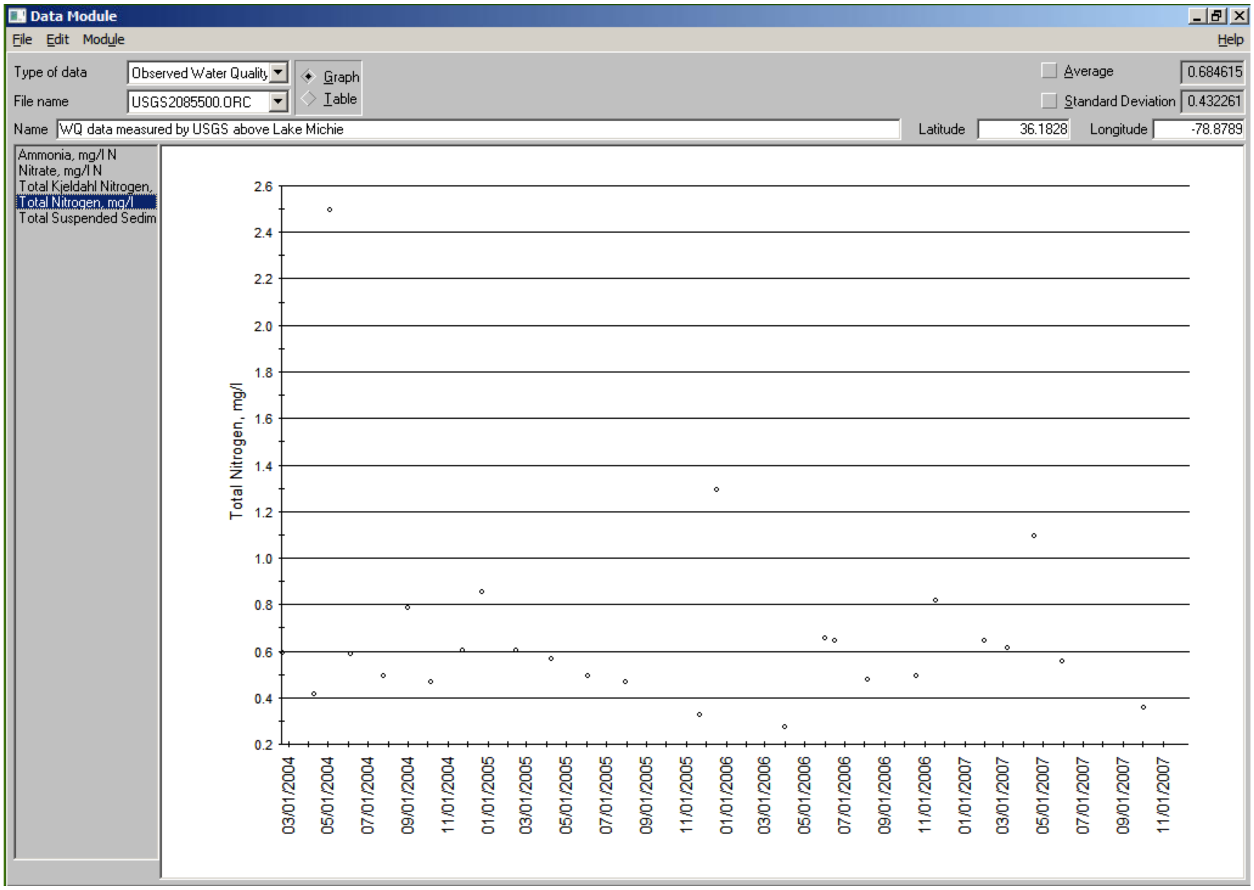


Figure 3. WARMF Data Module (Graph View)

3.3 Output Files

WARMF simulations are run on a daily or shorter time step. Classic output from WARMF provides the simulated values at each time step for each parameter in each catchment, river segment, and reservoir segment for which output is turned on. To maximize simulation speed and minimize the size of output files, they are saved in a binary format. The WARMF graphical user interface reads the output files and displays them graphically for comparison to observed data (Figure 4). In the figure, simulation results are shown in blue and observed data in black. It also can export the data to text files. The binary format for catchment (*.CAT), river (*.RIV), and reservoir (*.LAK) output files is available from the modeling team on request for those who wish to write their own utility program to read and process the WARMF time series output files. WARMF also generates two additional output files used for viewing post-processed output in the graphical user interface. These are the loading output file (*.PSM) and diversion output file (*.QWQ). All output files have the same base name of the model scenario they have in common. For example, if a scenario were called Falls_Lake1, the model coefficient file would be Falls_Lake1.COE and the outputs generated by running a simulation with those coefficients would be Falls_Lake1.CAT, Falls_Lake1.RIV, Falls_Lake1.LAK, Falls_Lake1.PSM, and Falls_Lake1.QWQ.

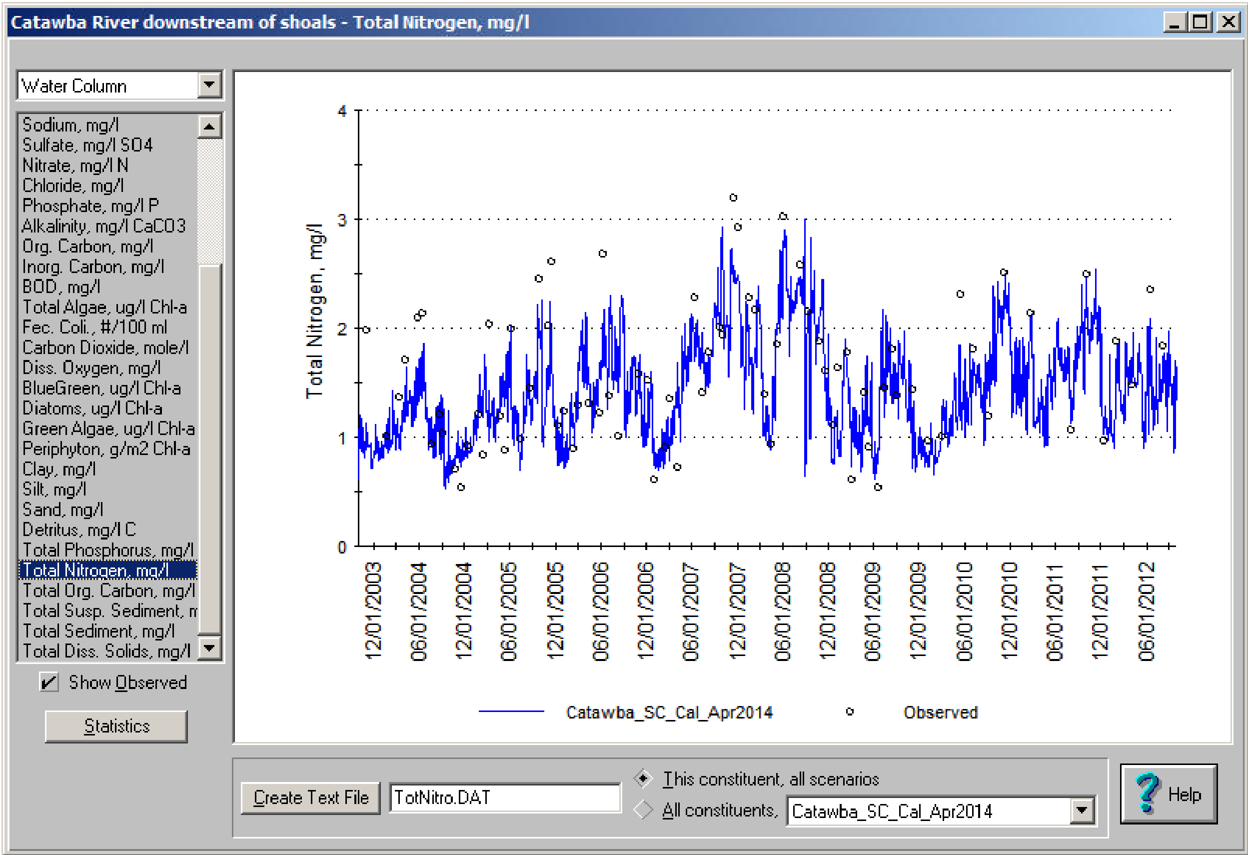


Figure 4. Example River Time Series Output

3.4 Model Calibration

Model calibration is the adjustment of model parameters which are not precisely known to minimize model error. Simulated historical hydrologic and water quality parameters are compared against measured data to determine model error. The calibration process is described in the WARMF User's Guide (Sheeder and Herr 2017) and in Herr and Chen (2012). The WARMF technical documentation describes how each of the model's parameters are used in a watershed simulation (Systech Water Resources 2017).

WARMF comes with the default set of simulated parameters shown in Table 5. The model architecture is flexible so it can simulate additional parameters as needed for an application. Calibration is performed for each parameter in a specific order. Hydrologic calibration is performed first because all water quality parameters depend on hydrology. The primary hydrologic parameters calibrated are flow in rivers and water surface elevation in reservoirs. Temperature is calibrated next because all chemical reactions are dependent upon temperature, and then hydrology calibration is rechecked and refined as needed because evaporation is dependent upon temperature. Suspended sediment is calibrated before ionic constituents because many of the ions adsorb to sediment particles. Conservative ions (Ca, Mg, K, Na, SO4, Cl) are then calibrated, followed by nutrients, phytoplankton, periphyton, and finally dissolved oxygen.

Table 5. Default Parameters Simulated by WARMF	
Type of Parameter	**Specific Parameters**
Hydrology	Flow, depth, water surface elevation, volume, spill, velocity, snow water depth, precipitation, irrigation, evapotranspiration, evaporation
Ionic constituents	pH, NH_4, Ca, Mg, K, Na, SO_4, NO_3, Cl, PO_4, inorganic carbon, alkalinity
Other water quality constituents	Temperature, organic carbon, silica, fecal coniform, biochemical oxygen demand, dissolved oxygen, phytoplankton (3 types), periphyton, detritus, clay, silt, sand
Composite parameters (calculated from ionic and other water quality constituents)	Total phosphorus, total Kjeldahl nitrogen, total nitrogen, total organic carbon, total phytoplankton, total dissolved solids, total suspended sediment

Following standard laboratory notebook procedures, detailed records of each step taken to calibrate the WARMF model for Falls Lake and the watershed will be tracked in internal modeling logbook(s) that will be maintained by the modeling team for the Falls Lake project. The modeling logbook (electronic or hardcopy) will record dates, staff name, rationale and actions taken for assignment of a model coefficient/parameter, model run-ID, input and output filenames, outcome of model run, comments and significant findings. The purpose of maintaining a detailed modeling logbook is to provide the data and information needed for another person to be able to follow the steps taken and files created to develop and calibrate the WARMF model. A QA/QC checklist developed by the modeling team will be used to ensure adherence to the UNRBA Modeling Quality Assurance Project Plan available at (https://www.unrba.org/reexamination).

3.5 Long-term Archival and Distribution of Model Files

All files necessary to run the model and to replicate scenarios presented in model reports will be archived as complete packages and provided to the UNRBA for long-term storage and distribution. In addition, Brown and Caldwell will maintain all model files for a minimum of five years following project completion.

Section 4: EFDC Model Data Processing and Management

EFDC is a mass balance-based model that represents the water quality response of a lake to external loading derived from watershed tributaries, overland runoff, and atmospheric deposition. EFDC includes an internally coupled sediment diagenesis model to link external loading of nutrients with eutrophication processes, organic matter deposition and internal loading of nutrients and oxygen consumption across the sediment-water interface of the lake. Data needed for development of the EFDC lake model include the types of data and information presented in Table 6.

4.1 Model Setup

4.1.1 Spatial Domain, Lake Shoreline and Bathymetry

The 3-dimensional EFDC lake model will represent the entire surface area of the reservoir including tributary arms of the reservoir (e.g., Ledge Creek, Lick Creek) and the 900-acre sub-impoundment of Beaverdam Lake. At the conservation pool elevation of 251.5 ft MSL (ngvd29), Falls Lake is defined by 245 miles of shoreline with a surface area of 12,410 acres and storage volume of 131,395 acre-ft (USACE, 2013). Historic USGS topographic data and recent bathymetric data collected during a mapping survey of Falls Lake and Beaverdam Lake by UNRBA (2017) will be used to develop a digital elevation model (DEM) to support construction of the computational grid for the EFDC model.

Table 6. Data Requirements for EFDC Model of Falls Lake

Data Requirement	Numerical Grid	Hydrodynamics		Sediment Transport	Water Quality	Sediment Diagenesis
		Water Balance	Density Water temperature			
Model Setup						
Watershed-lake spatial domain	●					
Lake shoreline and bathymetry	●					
Lake water level, volume, area	●	●				
Boundary Conditions/inflows		●				
Tributary (Point source)		●	●	●	●	
Overland Runoff (Nonpoint source)		●	●	●	●	
Boundary outflows		●				
Dam release		●	●	●	●	
Water supply withdrawals		●	●	●	●	
Meteorological forcing			●	●		
Atmospheric deposition (N, P)					●	
Lake Observations						
Vertical profiles (T, DO, SpCond)			●		●	
Sediment (Water Column/Bed)				●		
Water Chemistry (Water Column)					●	
Sediment Bed (C,N,P)						●
Sediment Flux (SOD, N,P)						●

Shoreline, topographic and bathymetric data sources will be processed, as needed, to convert input data horizontal (x,y) coordinates to the UTM projection for Zone 17 with Northing and Easting coordinates as meters. Vertical (z) elevation data will be converted to the NAVD88 vertical datum as meters above mean sea level. Corpscon Version 6.0.1 (USACE, 2004) will be used to convert horizontal coordinates and elevation input data to the UTM Zone 17 projection and NAVD88 vertical datum adopted as the standard reference for horizontal and vertical units of measurement for the Falls Lake EFDC model and all other maps and data files for the project based on geographic coordinates and vertical elevations.

The orthogonal curvilinear grid for the Falls Lake EFDC model will be developed using Delft3D RGFGRID generation software (Delft, 2007). Files developed for the curvilinear grid and the topographic/bathymetric digital elevation model will be imported into EFDC_Explorer Version 8 software (Craig, 2016) to develop the computational grid for the lake model. Elevation data will be interpolated with EFDC_Explorer to assign bottom elevations to each cell developed for the curvilinear grid. Initial conditions for water level and water column depth of each grid cell will be assigned using the observed condition for August 2014 which will begin the spin up period (a pre-simulation period used to establish initial conditions prior to evaluation of simulation results).

The product of these steps will be the curvilinear grid used for development of the Falls Lake hydrodynamic, sediment transport, water quality, and sediment diagenesis model. EFDC input files created with EFDC_Explorer pre-processing tools for building the model grid include:

- EFDC.INP (main control file for EFDC model)
- CELL.INP; CELLLT.INP (horizontal map of water and land grid cells)
- DXDY.INP (length/width, water depth, bottom elevation, bottom roughness)
- LXLY.INP (XY UTM coordinates, coefficients for curvilinear cell, wind shelter)
- CORNERS.INP (XY UTM coordinates of each corner of grid cells for map display)
- MASK.INP (blockage of flow across specified cell interfaces)

4.1.2 Boundary Inflows and Outflows

External boundary inflows to the EFDC lake model will be provided as output files from the WARMF watershed model. Boundary outflows from the lake include releases of water through the Falls Lake dam and withdrawal of water from the lake at water supply intakes for the City of Raleigh. Flow release and lake level data at the Falls Lake dam are recorded by the USACE Wilmington District and the USGS maintains records of stage height at the Beaverdam Lake dam. Water supply withdrawal data is recorded by the City of Raleigh. The USACE reports lake level and flow release data at the Falls Lake dam.

Point source inflows to the lake from tributaries will be mapped onto the curvilinear grid to identify grid cells defined for external boundary inflows. Similarly, overland runoff catchments of the watershed model will be mapped onto the grid to identify grid cells defined for nonpoint source inflow to the lake. The location of boundary outflows at the Falls Lake dam will be mapped onto the EFDC grid to identify grid cells for this outflow.

The modeling team will perform pre-processing and linkage of all boundary inflow and outflow files to prepare the format required for boundary flow data for EFDC input. WARMF flow data and flow release at the Falls Lake dam and water supply withdrawal data will be converted, as needed, to units of cubic meters/sec for input to the EFDC model. EFDC_Explorer will be used to import the EFDC-formatted boundary flow files to create the following EFDC input file needed to assign time series of inflow and outflow data for the setup of boundary flows for the lake model:

- QSER.INP (boundary flow)

4.1.3 Boundary Conditions

External boundary conditions are defined by point source tributary inputs and nonpoint source overland runoff inputs to the lake. External boundary condition inputs for water temperature, sediment, and water quality constituents will be provided as output files from the WARMF watershed model for input to the EFDC lake model.

State variables of the WARMF watershed model include flow, water temperature, total suspended solids (TSS), total nitrogen (TN), organic nitrogen (Org-N), ammonium (NH4-N), nitrate (NO3-N), total phosphorous (TP), orthophosphate (PO4-P), total organic carbon (TOC), dissolved oxygen, and phytoplankton biomass as chlorophyll-a.

State variables of the EFDC hydrodynamic and sediment transport model include water temperature, salinity, and inorganic sediment (cohesive and non-cohesive). Salinity is not represented in the Falls Lake model because the low levels of salinity (< 0.5 ppt) are not a significant component of water density in the lake. Non-cohesive sediment is not represented in the model because the high settling velocity and rapid deposition of non-cohesive particles results in a negligible effect of these large particles on light attenuation. The non-cohesive fraction of WARMF simulated TSS will be filtered out to assign cohesive sediment boundary conditions for input to the EFDC model.

The modeling team will perform pre-processing and linkage of all boundary condition files to prepare the file format required for boundary condition data for input to the EFDC hydrodynamic and sediment transport models. WARMF constituent state variables will be transformed and converted, as needed, to EFDC units for input to the lake model. EFDC_Explorer pre-processing tools will be used to import the EFDC-formatted files to create the following EFDC boundary condition files for setup of the lake model.

- TSER.INP (water temperature)
- SDSER.INP (cohesive suspended solids)

State variables of the EFDC water quality model include phytoplankton biomass, organic carbon, nutrients, and dissolved oxygen as shown in Table 7.

Table 7. State Variables of the EFDC Water Quality Model

CWQSR	EFDC Water Quality State Variable			Units	Falls Lake
1	BlueGreen	Phytoplankton	BC	mg-C/L	Yes
2	Diatoms	Phytoplankton	BD	mg-C/L	Yes
3	Greens	Phytoplankton	BG	mg-C/L	Yes
4	Refractory Particulate	Org-Carbon	RPOC	mg-C/L	Yes
5	Labile Particulate	Org-Carbon	LPOC	mg-C/L	Yes
6	Dissolved	Org-Carbon	DOC	mg-C/L	Yes
7	Refractory Particulate	Org-Phosphorus	RPOP	mg-P/L	Yes
8	Labile Particulate	Org-Phosphorus	LPOP	mg-P/L	Yes
9	Dissolved	Org-Phosphorus	DOP	mg-P/L	Yes
10	OrthoPhosphate-P	InOrg-Phosphorus	TPO4	mg-P/L	Yes
11	Refractory Particulate	Org-Nitrogen	RPON	mg-N/L	Yes
12	Labile Particulate	Org-Nitrogen	LPON	mg-N/L	Yes
13	Dissolved	Org-Nitrogen	DON	mg-N/L	Yes
14	Ammonium-N	InOrg-Nitrogen	NH4N	mg-N/L	Yes
15	Nitrate+Nitrite-N	InOrg-Nitrogen	NO23N	mg-N/L	Yes
16	Particulate Biogenic	Silica	SU	mg-Si/L	No
17	Available (dissolved)	Silica	SA	mg-Si/L	No
18	Chemical-Oxygen-Demand		COD	mg-O2/L	Yes
19	Dissolved Oxygen		DO	mg-O2/L	Yes
20	Total-Active-Metal		TAM	mg/L	No
21	Fecal-Coliform-Bacteria		FCB	mpn/100mL	No

The modeling team will perform pre-processing and linkage of all boundary condition files for EFDC water quality state variables to prepare the file format required for boundary condition files for input to EFDC. Water quality variables simulated with the WARMF watershed model will be converted, as needed, using appropriate stoichiometric ratios between the WARMF state variables and the EFDC state variables shown in Table 2. Dissolved and refractory/labile forms of particulate organic matter will be derived from fractional splits of total organic matter for carbon, nitrogen and phosphorus. EFDC_Explorer pre-processing tools will be used to import the EFDC-formatted files to create the set of 21 EFDC boundary condition files needed for setup of the water quality model.

4.1.4 Meteorological Forcing

The EFDC hydrodynamic model requires meteorological data to assign time series input for atmospheric forcing (barometric pressure, dry/wet bulb temperature, relative humidity, rainfall, evaporation, solar radiation, and fractional cloud cover) and wind forcing (wind speed and direction). Meteorological data is obtained from NOAA's National Climatic Data Center (NCDC) for stations located within, or near, the watershed.

The modeling team will perform pre-processing of meteorological station file records to prepare the time series format and conversion of input file data, as needed, to EFDC units required for atmospheric and wind parameters. EFDC_Explorer pre-processing tools will be used to import the EFDC-formatted meteorological data files to create the two EFDC input files needed to assign time series of atmospheric and wind forcing data for setup of the lake model.

- ASER.INP (atmospheric forcing)
- WSER.INP (wind forcing)

4.1.5 Atmospheric Deposition of Nutrients

The EFDC water quality model represents atmospheric deposition to assign dry and wet deposition for the inorganic forms of nitrogen (ammonia-N and nitrate/nitrite-N) and phosphorus (orthophosphate-P). Data sources include EPA's National Atmospheric Deposition Program (NADP) and the Clean Air Status and Trends Network (CASTNET) and the City of Durham Atmospheric Deposition Monitoring Study (AMEC, 2012).

Wet and dry deposition of nutrients is represented in the EFDC model as time-averaged parameter values that are applied uniformly over the surface area of the entire lake. Dry deposition data will be compiled to develop annual average deposition rates (as g m-2 day-1) for the years selected for model calibration (2015-2016) and model validation (2017-2018). Wet deposition of nutrients in EFDC is defined by assignment of constant nutrient concentrations in rainfall with the nutrient flux rate onto the lake surface computed internally in the model from time varying rainfall data. Nutrient concentration data for rainfall will be compiled to develop annual average concentrations of inorganic N and P (as mg/L) to represent constant concentration values for the years selected for model calibration (2015-2016) and model validation (2017-2018). Data will also be processed to support modeling for years 2005 -2007 for comparison to past modeling of Falls Lake. The modeling team will perform pre-processing and statistical analysis of dry deposition data and nutrient concentrations in rainfall to derive annual average values for wet and dry deposition input data for model calibration and validation time periods. Wet and dry atmospheric deposition data is input to this water quality model input file:

- WQ3DWC.INP (Card Groups C49 and C50)

4.1.6 Lake Observations

Data sets available for Falls Lake include vertical profiles (water temperature, dissolved oxygen, specific conductance, pH, etc.); water column measurements at discrete depths (or photic zone composites) of suspended sediment, water chemistry (nutrients, chlorophyll-a, organic carbon); and light attenuation (Secchi depth and limited paired measurements of photosynthetically active radiation). In addition to water column measurements, sediment bed data collected for the UNRBA (2015b) Lake Sediment Evaluation and the UNRBA (2017) bathymetric and sediment mapping survey provides bed data for solids properties, organic carbon and nutrient content, porewater nutrients, and benthic flux rates for sediment oxygen demand and nutrients. The UNRBA (2015a) lake constriction point survey provides velocity and water quality measurements at bridge causeways. Two events were conducted as part of this survey. During each event, measurements were collected multiple times during an approximately week-long period targeting times when recent rainfall resulted in water moving through the constriction points.

4.2 Initial Conditions

Water column and sediment bed observations in Falls Lake will be processed to assign initial conditions for setup for the hydrodynamic, sediment, water quality and sediment diagenesis models for the spin-up periods. The vertical domain of the lake model grid will be setup with 6-10 layers to represent thermal stratification.

4.2.1 Lake Level and Grid Cell Depth

Initial conditions for the total depth of each grid cell are defined by the bottom elevation of a grid cell and the initial condition for water level of the lake. Time series of water level data obtained from the USACE will be used to assign the initial water level elevation for the beginning dates for model calibration and model validation. EFDC_Explorer pre-processing tools will be used to compute the depth of each grid cell to create the initial conditions file for water column depth of each grid cell for setup of the hydrodynamic model:

- DXDY.INP (length/width, water depth, bottom elevation, bottom roughness)

4.2.2 Water Temperature

The spatial distribution of observed water temperature measured for the beginning date ranges of the model spin up periods will be used to assign water temperature for each vertical layer of the model grid. EFDC_Explorer pre-processing tools will be used to import spatial distributions of observed water temperature data to create the initial conditions file for setup of the hydrodynamic model:

- TEMP.INP (water temperature)

4.2.3 Sediment

EFDC state variables for the sediment transport model represent inorganic cohesive and non-cohesive solids. Non-cohesive solids, however, are not represented in the Falls Lake model because the high settling velocity for large non-cohesive particles results in a negligible effect on light attenuation because of rapid settling out of these particles from the water column to the sediment bed. Pre-processing of total suspended solids (TSS) measurements is needed to filter out the particulate organic matter component from TSS measurements to derive initial conditions for inorganic cohesive solids. Stoichiometric ratios for organic carbon, dry weight, phytoplankton biomass and inorganic/organic fractions of TSS will be used to derive the inorganic fraction of suspended solids for input to the EFDC model by subtracting out detrital organic matter and phytoplankton biomass from measured TSS data.

Sediment bed data collected for the UNRBA (2015b) Lake Sediment Evaluation and the UNRBA (2017) bathymetric and sediment mapping survey will be used to assign bed properties as initial conditions for the cohesive class of inorganic sediment for the sediment transport model. EFDC_Explorer pre-processing tools will be used to import spatial distributions of water column sediment data and sediment bed data to create the initial conditions files for setup of the cohesive sediment model:

- SEDW.INP (water column cohesive sediment)

- SEDB.INP (sediment bed cohesive solids)

4.2.4 Water Quality

The modeling team will perform pre-processing of lake water quality observations to derive initial conditions for the state variables of the EFDC water quality model. Water quality observations from lake monitoring sites will be converted, as needed, using appropriate stoichiometric ratios between observed water quality constituents to assign data for the EFDC state variables listed in Table 2. Dissolved and refractory/labile forms of particulate organic matter will be derived from fractional splits of total organic matter for carbon, nitrogen, and phosphorus. EFDC_Explorer pre-processing tools will be used to import the EFDC-formatted files to create the initial conditions file for setup of the water quality model:

- ICIFN.INP (file includes water column data for 21 water quality state variables)
- WQWCMAP.INP (water quality spatial zones)

4.2.5 Sediment Diagenesis

State variables of the sediment diagenesis model include sediment bed content of organic C,N,P, porewater concentrations of inorganic ammonia, nitrate/nitrite and orthophosphate, and benthic fluxes of dissolved oxygen and nutrients (Di Toro, 2001). The modeling team will perform pre-processing of lake sediment bed observations to derive initial conditions for model calibration and validation for the EFDC sediment diagenesis model. Sediment bed data collected for the UNRBA (2015b) Lake Sediment Evaluation and the UNRBA (2017) bathymetric and sediment mapping survey will be converted, as needed, using appropriate stoichiometric ratios between observed bed constituents to assign data for EFDC state variables. Refractory, labile, and inert forms of bed particulate organic matter will be derived from G-Class fractions of particulate organic matter for carbon, nitrogen, and phosphorus. EFDC_Explorer pre-processing tools will be used to import the EFDC-formatted files to create the initial conditions file for setup of the sediment diagenesis model:

- WQSDICI.INP (file includes bed data for 27 sediment diagenesis model state variables)
- WQSDMAP.INP (sediment bed spatial zones)

4.3 Model Calibration and Validation

Model calibration and validation will be accomplished by comparison of model results to observed data sets available from monitoring sites in the lake. Observed data and model results will be post-processed in EFDC_Explorer to display model vs. observed data comparisons for selected station locations for visual comparison as time series plots and vertical profile plots. The data sets used to prepare time series plots of model results compared to observed data will also be used to post-process model performance statistics to assess how well model results are in agreement with observed data.

4.3.1 Time Series Plots

Time series data sets will be processed for selected stations in Falls Lake to prepare files formatted for input to the EFDC_Explorer post-processing utility for time series plots. Station data will be extracted for sampling depths at the surface or near surface and bottom or near bottom depths to setup observed station data files for graphical overlay with surface layer and bottom layer EFDC model results. A set of separate time series files of observed data will be prepared for each selected station/water quality variable for the surface and bottom layers of the model. Time series files will include observed data sets for both model calibration and model validation time periods. The modeling team will use a consistent filename convention to track station-ID and water quality variables for surface and bottom layer data sets. The modeling team will setup the model calibration table in the format required by the EFDC_Explorer time series utility to properly link

EFDC results (grid cell, depth layer and output variable) with the user-assigned filenames for the observed data set (station, surface/bottom layer and water quality variable).

Most station observations of water quality constituents available from the Falls Lake database will be directly compared to time series of EFDC model results without any transformation needed for the observed data sets. Some observed water quality constituents, however, will be pre-processed to derive observed variables not available for comparison to EFDC output variables. Observations of particulate organic carbon (POC), for example, will be derived from paired observations of total organic carbon (TOC) and dissolved organic carbon (DOC). Other derived observations of water quality constituents for comparison to model results will include Total Organic Nitrogen (TON), Total Organic Phosphorus (TOP), and Total Nitrogen (TN).

4.3.2 Vertical Profile Plots

Vertical profile data sets will be processed for selected stations in Falls Lake to prepare files formatted for input to the EFDC_Explorer post-processing utility for vertical profile plots. Station data will be extracted for all available sampling dates for all sample depths in the water column to setup observed station data files for graphical overlay with EFDC model results as vertical profiles. Typically, water temperature, dissolved oxygen and dissolved oxygen saturation are the model variables processed to show vertical profiles since these physical-chemical measurements are available at multiple depth intervals in the water column from multi-parameter instruments (e.g., data sondes such as YSI and Hydro Lab). A set of separate vertical profile files of observed data will be prepared for each selected station/water quality variable for a sequence based on available sample dates. Vertical profile files will include observed data sets for both model calibration and model validation time periods. The modeling team will use a consistent filename convention to track station-ID and water quality variables for vertical profile data sets. The modeling team will set up the model calibration table in the format required by the EFDC_Explorer vertical profile utility to link EFDC grid cell and output results with the user-assigned filenames for the water quality variable and station.

4.3.3 Model Calibration

Having set up the EFDC model as described above, the Falls Lake EFDC model will be calibrated using a systematic sequence of steps as follows:

- Hydrodynamic model (grid and water balance)
- Hydrodynamic model (water temperature and density)
- Sediment transport model
- Water quality model
- Sediment diagenesis model

Model performance will be evaluated to determine the endpoint for model calibration using a “weight of evidence” approach that has been adopted for many water quality modeling studies including several other Dynamic Solutions lake modeling projects. The “weight of evidence” approach includes the following steps: (a) visual inspection of plots of model results compared to observed data sets (e.g., station time series, vertical profiles); and (b) analysis of model-data performance statistics for the Relative Error (RE) and the Root Mean Square Error (RMSE). Model performance statistics will be used, not as absolute criteria for acceptance of the model, but rather, as guidelines to supplement our visual inspection of model-data plots to determine the appropriate endpoint for calibration of the Falls Lake model. The “weight of evidence” approach thus acknowledges the approximate nature of the lake model and the inherent uncertainty in both input data and observed data sets. The data sets used to prepare surface and bottom layer time series plots of observed data for comparison to model results will be used in EFDC_Explorer to post-process model performance statistics to assess how well model results agree with observed data sets.

Following standard laboratory notebook procedures, detailed records of each step taken to calibrate the EFDC model of Falls Lake will be tracked in internal modeling logbook(s) that will be maintained by the modeling team for the Falls Lake project. The modeling logbook (electronic or hardcopy) will record dates, staff name, rationale and actions taken for assignment of a model coefficient/parameter, model run-ID, input and output filenames, outcome of model run, comments and significant findings. The purpose of maintaining a detailed modeling logbook is to provide the data and information needed for another person to be able to follow the steps taken and files created to develop and calibrate the EFDC lake model. The QA/QC checklist developed by the modeling team will be used to ensure adherence to the UNRBA Modeling Quality Assurance Project Plan available at (https://www.unrba.org/reexamination).

Hydrodynamic Model (Grid and Water Balance)

Bathymetric data collected by the UNRBA and observed USACE relationships of water level, storage volume, and surface area for Falls Lake will be used to calibrate accuracy of the model grid and water balance setup for the hydrodynamic model. In the first step for calibration of the lake model, the representation of the curvilinear grid shoreline and interpolation of DEM data to bottom elevations for grid cells will be adjusted, as needed, to obtain accurate agreement between the observed vs. model relationships for water level, storage volume and surface area.

Calibration of the model with observed water level, volume and surface area data, will, if needed, result in updates of the following files created with EFDC_Explorer pre-processing tools for setup of the model grid:

- DXDY.INP (length/width, water depth, bottom elevation, bottom roughness)
- LXLY.INP (XY UTM coordinates, coefficients for curvilinear cell, wind shelter)
- CORNERS.INP (XY UTM coordinates of each corner of grid cells for map display)

In the second step for calibration of the water balance, the discrepancy between observed and simulated water level will be used to estimate a flow balance time series derived from unknown inflows and outflows. With typical errors of about 10% for flow measurements and unknown exchange with groundwater, a flow balance is needed to obtain an accurate simulation of observed water level for lake and reservoir models. The derived flow balance data set will be formatted for input as a new inflow for the EFDC input file for boundary inflows:

- QSER.INP (flow balance added as new boundary inflow/outflow)

Detailed records of any grid adjustments made to either the shoreline or bottom elevation to improve agreement with the observed water level, volume and surface area relationships will be recorded in the modeling logbook. Steps taken to derive the flow balance for calibration of the water balance for the hydrodynamic model will be tracked in the modeling logbook. Grid cell locations assigned for distributed input of the flow balance data will be documented in the modeling logbook, along with input/output filenames created for derivation of the flow balance data set.

Hydrodynamic Model (Water Temperature and Density)

Water temperature and density effects will be activated in the EFDC model by adding EFDC-formatted files to assign boundary conditions (TSER.INP) and initial conditions (TEMP.INP) for water temperature. Meteorological data that control heat balance terms in the model will be provided as atmospheric forcing (ASER.INP) and wind forcing (WSER.INP) data sets. The initial set of model coefficients and parameters for hydrodynamic mixing and heat transfer assigned in EFDC_Explorer will be based on the literature and previous lake models.

Hydrodynamic model runs will be evaluated using EFDC_Explorer post-processing tools to visually assess how well model results reproduce the onset, persistence, and erosion of thermal stratification in surface and bottom time series observations and vertical profiles. Model performance statistics will be computed for the model results and observed data set time series using post-professing tools in EFDC_Explorer.

Model calibration for water temperature will include the following steps to assess, and improve, agreement between observations and simulated results for water temperature:

- Review effects of WARMF water temperature input on simulation results and timing of watershed model results with lake observations.
- Review effects of atmospheric and wind forcing on water temperature simulation.
- Review shade coverage and wind sheltering for model grid and assign/adjust as needed.
- Test and change, as needed, number of vertical layers to represent lake stratification.
- Revise hydrodynamic mixing or heat transfer coefficients and parameters; as needed, within accepted range of values from literature (e.g., Ji, 2008).

Final calibration of water temperature will, as needed, result in updates of the following input files created with EFDC_Explorer for setup of water temperature for the hydrodynamic model.

- EFDC.INP (hydrodynamic mixing and heat transfer coefficients/parameters)
- ASER.INP (atmospheric forcing)
- WSER.INP (wind forcing)
- PSHADE.INP (shade coverage of lake surface)
- LXLY.INP (XY UTM coordinates, coefficients for curvilinear cell, wind shelter)

Detailed records of any changes made to adjustable hydrodynamic mixing or heat transfer coefficients and parameters to improve agreement with observed water temperature will be recorded in the modeling logbook. Tests made to evaluate effect of different number of vertical layers will be recorded in the modeling logbook with documentation of changes made and assessment of the outcome for improvement of the water temperature simulation. Steps taken to review, and revise if needed, atmospheric and wind forcing data, review, revise or assign if needed, shade coverage and wind shelter for the model grid will be recorded in the modeling logbook with documentation of changes made and assessment of the outcome for improvement of the water temperature simulation. Grid cell locations for shade cover and wind sheltering will be documented as well as input/output filenames created to support calibration of the water temperature model will be recorded in the modeling logbook.

Sediment Transport

Cohesive sediment will be activated in the EFDC model by adding EFDC-formatted files to assign boundary conditions (SDSER.INP) and initial conditions for the water column (SEDW.INP) and sediment bed (SEDB.INP). The initial set of model coefficients and parameters for fine-grained cohesive sediment assigned in EFDC_Explorer will be based on the literature and previous lake models. Model parameters for cohesive sediments include critical stresses for resuspension and deposition, particle density, and settling velocity.

Sediment transport model runs will be evaluated using EFDC_Explorer post-processing tools to visually assess how well model results reproduce patterns of TSS observations in surface and bottom time series observations and vertical profiles. Model performance statistics will be computed for the model results and observed data set time series using post-professing tools in EFDC_Explorer.

Model calibration for cohesive sediment will include the following steps to assess, and improve, agreement between observations and simulated results for fine-grained cohesive sediment:

- Review effects of WARMF TSS input on simulation results for lake sediment and timing of watershed model results for baseflow and storm driven lake observations.
- Review effects of wind forcing and wind sheltering on cohesive sediment simulation particularly in shallow coves of the reservoir arms.
- Consider linkage of wind-wave model with sediment transport model
- Change cohesive sediment coefficients and parameters; as needed, within accepted range of values from literature (e.g., Ji, 2008; Lick, 2009)

Final calibration of cohesive sediment will, as needed, result in updates of the following input files created with EFDC_Explorer for setup of the sediment transport model:

- EFDC.INP (cohesive sediment coefficients and parameters)
- WSER.INP (wind forcing)
- LXLY.INP (XY UTM coordinates, coefficients for curvilinear cell, wind shelter)
- SEDW.INP (initial conditions water column cohesive sediment)
- SEDB.INP (initial conditions sediment bed cohesive solids)
- Wind-wave sub-model files

After satisfactory calibration of the cohesive sediment model is achieved, the modeling team will review the effects of the cohesive sediment simulation on calibration of water temperature. Cohesive sediment affects water temperature simulation through light attenuation and adsorption of heat in the water column. Changes to key adjustable heat transfer coefficients and parameters may be needed to account for the effect of the sediment model on water temperature calibration.

Detailed records of any changes made to adjustable cohesive sediment properties, coefficients and parameters to improve agreement with the observed time series and vertical profiles of TSS will be recorded in the modeling logbook. Steps taken to revise sediment bed properties, if needed, will be recorded in the modeling logbook with documentation of changes made, rationale for the changes, and outcome for improvement of the cohesive sediment simulation. Steps taken to review, and revise if needed, wind forcing data and wind sheltering data will be recorded in the modeling logbook with documentation of changes made and assessment of the outcome for improvement of the cohesive sediment simulation. Steps taken, and the rationale, to activate linkage of the wind-wave model to improve the simulation of cohesive sediment in shallow areas of the lake will be documented, as needed, in the modeling logbook. Input and output filenames created to support development of the cohesive sediment model will be recorded in the modeling logbook. Any changes to heat transfer coefficients and parameters required for temperature calibration in response to TSS calibration will also be documented in the logbook.

Water Quality Model

Water quality constituents will be activated in the EFDC model by adding EFDC-formatted files to assign boundary conditions for the 21 state variables (CWQSR01.INP, ... CWQSR21.INP), water quality spatial zones (WQWCMAP.INP), initial conditions for the water column (ICIFN.INP) and kinetic coefficients and model parameters (WQ3DWC.INP). The initial set of model kinetic coefficients and parameters for water quality constituents assigned in EFDC_Explorer will be based on the literature and previous lake models. There are numerous kinetic coefficients and model parameters for the water quality model that include, for example, phytoplankton growth rates and half-saturation constants, organic matter hydrolysis and mineralization rates, and settling velocities.

Preliminary calibration of the water quality model will input user-assigned spatial and temporal forcing of sediment oxygen demand and benthic flux rates for nutrients. User-assigned forcing functions for sediment flux rates will be based on sediment-water interface measurements collected for the UNRBA (2015b) Lake Sediment Evaluation.

Water quality model runs will be evaluated using EFDC_Explorer post-processing tools to visually assess how well model results reproduce patterns of dissolved oxygen, organic carbon, nutrients, and phytoplankton chlorophyll-a in surface and bottom time series observations and vertical profiles. Model performance statistics will be computed for the model results and observed data set time series using post-professing tools in EFDC_Explorer.

Model calibration for water quality constituents will include the following steps to assess, and improve, agreement between observations and simulated results for water quality variables:

- Incorporate site-specific data collected in Falls Lake (e.g., light extinction evaluations, previous model performance evaluations, lake constriction analyses)
- Review effects of WARMF water quality constituents input on simulation results for lake water quality and timing of watershed model results for baseflow and storm driven lake observations.
- Change water quality kinetic coefficients and parameters; as needed, within accepted range of values from literature (e.g., Ji, 2008; Cerco and Cole, 1994; Cole and Wells, 2008)

Final calibration of the water quality model will, as needed, result in updates of the following input files created with EFDC_Explorer for setup of the water quality model:

- WQ3DWC.INP (water quality kinetic coefficients and parameters)
- ICIFN.INP (water column initial conditions for water quality constituents)
- KINETICS.INP (water quality reaction rates)
- WQALGG.INP (phytoplankton rates and stoichiometric coefficients)
- WQSETL.INP (settling velocities for detritus and phytoplankton)

After satisfactory calibration of the water quality model is achieved, the modeling team will review the effects of the water quality simulation on calibration of water temperature. The results of the water quality model affect the water temperature simulation through light attenuation and adsorption of heat in the water column. The water quality model represents light attenuation from cohesive sediment, particulate organic matter, phytoplankton and dissolved organic carbon. Changes to key adjustable heat transfer coefficients and parameters may be needed to account for the effect of the water quality model on water temperature calibration.

Detailed records of any changes made to adjustable water quality constituent kinetic coefficients and parameters to improve agreement with the observed time series and vertical profiles of dissolved oxygen, organic carbon, nutrients, and phytoplankton chlorophyll-a will be recorded in the modeling logbook. Steps taken to revise user-assigned sediment flux rates for dissolved oxygen and nutrients, if needed, will be recorded in the modeling logbook with documentation of changes made, rationale for the changes, and outcome for improvement of the water quality simulation. Input and output filenames created as working files to support development of the water quality model will be recorded in the modeling logbook. Any changes to heat transfer coefficients and parameters required for temperature calibration in response to water quality calibration will also be documented in the logbook.

Sediment Diagenesis Model

Sediment flux model state variables will be activated in the EFDC model by adding EFDC-formatted files to assign sediment flux spatial zones (WQSDMAP.INP), initial conditions for the sediment bed (WQSDICI.INP) and kinetic coefficients and model parameters (WQ3DSD.INP). The initial set of kinetic coefficients and parameters for the sediment flux model assigned in EFDC_Explorer will be based on the literature and previous lake models. There are numerous kinetic coefficients and model parameters for the sediment flux model that include, for example, organic matter stoichiometry and diagenesis rates, sediment bed mixing rates, nitrification and denitrification rates. Calibration of the sediment diagenesis model will represent the internal coupling of particulate organic matter deposition from the water column to the bed with simulated sediment-water interface benthic flux rates for sediment oxygen demand and nutrients. Results obtained with the sediment diagenesis model will be compared to sediment-water interface measurements collected for the UNRBA (2015b) Lake Sediment Evaluation.

Sediment diagenesis model runs will be evaluated using EFDC_Explorer post-processing tools to assess visually how well model results reproduce observed distributions of sediment bed organic matter and porewater (N, P) and flux rates for sediment oxygen demand and benthic nutrient fluxes.

Model calibration for sediment diagenesis state variables will include the following steps to assess, and improve, agreement between observations and simulated results for sediment flux model variables:

- Incorporate site-specific data collected in Falls Lake (e.g., sediment depth surveys, sediment core analyses, and benthic flux estimates, including relationships developed among these data sets)
- Review assignment of sediment bed initial condition data for spatial zones and adjust as needed
- Change sediment flux model kinetic coefficients and parameters; as needed, within accepted range of values from literature (e.g., Di Toro, 2001).

Calibration of the sediment flux model will, as needed, result in updates of the following input files created with EFDC_Explorer for setup of the sediment diagenesis model.

- WQ3DSD.INP (sediment flux kinetic coefficients and parameters)
- WQSDICI.INP (sediment bed initial conditions for sediment flux model)

Detailed records of any changes made to adjustable sediment diagenesis model kinetic coefficients and parameters to improve agreement with the observed measurements of sediment bed carbon, nitrogen, and phosphorus, and benthic flux rates for dissolved oxygen will be recorded in the modeling logbook. Steps taken to revise spatial zone input for sediment bed initial conditions, if needed, will be recorded in the modeling logbook with documentation of changes made, rationale for the changes, and outcome for improvement of the sediment flux model simulation. Input and output filenames created as working files to support development of the sediment diagenesis model will be recorded in the modeling logbook.

4.3.4 Documentation and Reporting

Documentation will consist of:

- Reporting updates in the form of progress reports to the client and formal technical memoranda and/or reports documenting data sources, development and findings of the Falls Lake model.
- Internal modeling notebooks listing dates, actions taken, and significant findings.

A notebook record (paper or electronic) will be kept by each modeler, following standard laboratory notebook procedures. Daily entries will be made providing all information needed for another person to be able to follow and recreate the steps if needed. Entries will include project name, date, recorder's name, task number, coefficients and parameter values used, filenames used as input and output, and comments on results.

4.4 Long-term Storage and Distribution

All files necessary to run the model and to replicate scenarios presented in model reports will be archived as complete packages and provided to the UNRBA for long-term storage and distribution. In addition, Brown and Caldwell will maintain all model files for a minimum of five years following project completion.

Section 5: Statistical Model

Like the WARMF and EFDC models, the statistical model will use a combination of spatial and discrete time series data including water quality, bathymetry, sediment quality, atmospheric deposition, tributary flow and loading, and outflow data. It may also incorporate information types not used in the mechanistic models such as fisheries and other ecological data, recreational use data, and expert elicitation of factors that generally lack data or are otherwise difficult to quantify. Unlike the EFDC and WARMF models, the statistical model does not use pre-existing model code, but rather will be developed using local and regional data. The model code can therefore be considered a form of data to be managed under this plan.

5.1 Input files

All data used as input to the statistical model will be archived in the form they were initially obtained. The archives will include associated metadata that identifies the data source and when and how it was obtained. Complete records of data transformations necessary to develop model input files from the original data sources will be stored with the data as described in Section 2. Input files developed for the model will be stored as plain text files.

5.2 Model code and output files

In addition to input data files, model code and output files will be produced throughout the model development process. These files will be periodically archived and an electronic log of model versions will be maintained with the date, developer(s), version number, and notes regarding any major updates to the model. All input files, model files, and output files will be archived as a complete package at significant project milestones, any time that draft model results are presented in technical reports, and for all scenarios presented in the final modeling report.

5.3 Backup, distribution, and long-term storage

Model files will be backed up daily during the development process to off-site servers. Upon completion of the modeling project, the final set of model files and associated documentation will be provided to the UNRBA for long-term storage and distribution. Brown and Caldwell will also retain the complete model and development records for a minimum of five years following project completion.

Section 6: Summary

The mechanistic and statistical models under development by the UNRBA are complex models that rely on a significant amount of time series and spatial data for their development and calibration. The modeling team has developed the Modeling QAPP and this data management plan with description of the modeling process to govern the handling and storage of the input data and output data for these applications. By documenting and following the procedures described in these documents, the modeling team can ensure a transparent, quality-assured process for developing and applying the models associated with the reexamination.

References Cited

AMEC. 2012. Atmospheric Deposition Study for the City of Durham, North Carolina: Data Report. AMEC Project Number 648010G006. Prepared for City of Durham Public Works Department, Stormwater Services.

Cerco, C.F. and T. M. Cole. 1994. Three-dimensional eutrophication model of Chesapeake Bay, Volume 1: Main Report, Technical report prepared for U.S. Environmental Protection Agency and U.S. Army Corps of Engineers, Baltimore District, Tech. Report EL-94-4, May.

Cole, T.M. and Wells, S.A. 2008 CE-QUAL-W2: A Two-Dimensional, Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.6. Instruction Report EL-08-1, U.S. Army Corps of Engineers, Washington, DC, 712 p.

Craig, P.M. 2016. User's Manual for EFDC_Explorer: A Pre/Post-Processor for the Environmental Fluid Dynamics Code, (Ver 160307), Dynamic Solutions-International, LLC, Edmonds, WA.

Di Toro, D.M. 2001. Sediment Flux Modeling. Wiley-Interscience, John Wiley & Sons, Inc., New York, NY, 624 pp.

Herr, J. and Chen, C. (2012). WARMF: Model use, calibration, and validation. Transactions of the ASABE. 55. 1385-1394. 10.13031/2013.42249.

Ji, Z-G. 2008. Hydrodynamics and Water Quality Modeling Rivers, Lakes and Estuaries. Wiley Interscience, John Wiley & Sons, Inc., Hoboken, NJ, 676 pp.

Lick, W. 2009. Sediment and Contaminant Transport in Surface Waters. IWA Publishing, CRC Press, Taylor & Francis Group, Boca Raton, FL, 398 pp.

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/

Sheeder, S. and Herr, J. (2017) Watershed Analysis Risk Management Framework (WARMF): User's guide and documentation of the graphical user interface (GUI). Systech Water Resources Inc., Walnut Creek CA.

Systech Water Resources. (2017). Watershed Analysis Risk Management Framework (WARMF): Technical model documentation. Systech Water Resources Inc., Walnut Creek CA.

UNRBA. 2015a. Constriction Point Study. https://www.unrba.org/sites/default/files/UNRBA%20Special%20Study%20Plan%20-%20Constriction%20Point%20Study%20-%202015-11-24.pdf

UNRBA. 2015b. Lake Sediment Evaluation. https://www.unrba.org/sites/default/files/UNRBA%20Special%20Study%20Plan%20-%20Lake%20Sediment%20Evaluation%2082515.pdf

UNRBA. 2017. Bathymetry Study Plan. https://www.unrba.org/sites/default/files/Bathymetry%20Study%20Plan%20FY2017.pdf

USACE 2004. Corpscon Version 6.x, Technical Documentation and Operating Instructions, U.S. Army Corps of Engineers, Engineer Research and Development Center, Topographic Engineering Center, Alexandria, VA, http://www.tec.army/mil.

USACE. 2013. Falls Lake Master Plan Neuse River Basin. May 2013.