FINAL

MODELING FRAMEWORK FOR SIMULATING HYDRODYNAMICS AND WATER QUALITY IN THE LIBERTY RESERVOIR, BALTIMORE AND CARROLL COUNTIES, MARYLAND

Prepared by:

Interstate Commission on the Potomac River Basin

51 Monroe Street

Suite PE-08

Rockville, MD 20850

Prepared for:

Maryland Department of the Environment

1800 Washington Boulevard, Suite 540

Baltimore, MD 21230

September 21, 2012

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AMLE	Adjusted Maximum Likelihood Estimation
BCDEPRM	Baltimore County Department of Environmental Protection and Resource Management
BCDPW	Baltimore City Department of Public Works
BMP	Best Management Practice
BOD	Biological Oxygen Demand
CBOD	Carbonaceous Biochemical Oxygen Demand
CBLCD	Chesapeake Bay Watershed land Cover Database
CBP	Chesapeake Bay Program
CBPO	Chesapeake Bay Program Office
CCAP	Coastal Change Analysis Program
CE-QUAL-W2	U.S. Army Corps of Engineers Water Quality and Hydrodynamic Model, Version 3
Chla	Active Chlorophyll a
COD	Chemical Oxygen Demand
COMAR	Code of Maryland Regulations
CWA	Clean Water Act
CWAP	Clean Water Action Plan
DIP	Dissolved Inorganic Phosphorus
DO	Dissolved Oxygen
DOP	Dissolved Organic Phosphorus
EOF	Edge-of-Field
EOS	Edge-of-Stream
EPA	Environmental Protection Agency
ETM	External Transfer Module
FSA	Farm Service Administration
GIS	Geographic Information System
HSPF	Hydrological Simulation Program Fortran
ICPRB	Interstate Commission on the Potomac River Basin
LA	Load Allocation
LAD	Least Absolute Deviation
lbs/yr	Pounds per Year
MD	Maryland
MDA	Maryland Department of Agriculture
MDE	Maryland Department of the Environment
MDP	Maryland Department of Planning
MGS	Maryland Geological Survey
mg/l	Milligrams per Liter
MGD	Million Gallons per Day

MLE	Maximum Likelihood Estimation
MOS	Margin of Safety
MRLC	Multi-Resolution Land Characteristics
MS4	Municipal Separate Storm Sewer System
MSL	Mean Sea Level
MVUE	Minimum Variance Unbiased Estimation
NLCD	National Land Cover Data
NRCS	Natural Resource Conservation Service
NRI	Natural Resource Inventory
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NPS	Nonpoint Source
NRI	Natural Resource Inventory
P5	Phase 5 Watershed Model
PIP	Particulate Inorganic Phosphorus
POM	Particulate Organic Matter
PO4	Phosphate
POP	Particulate Organic Phosphorus
RESAC	Regional Earth Science Applications Center
RIM	River Input Monitoring
RTAG	Reservoir Technical Advisory Group
SCWQP	Soil Conservation and Water Quality Plan
SOD	Sediment Oxygen Demand
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TSI	Trophic State Index
TSS	Total Suspended Solids
USGS	U. S. Geological Survey
W2	CE-QUAL-W2
WDM	Watershed Data Management
WIP	Watershed Implementation Plan
WLA	Wasteload Allocation
WRAS	Watershed Restoration Action Strategy
WQA	Water Quality Analysis
WQLS	Water Quality Limited Segment
WWTP	Waste Water Treatment Plant
µg/l	Micrograms per Liter

EXECUTIVE SUMMARY

This report documents the development of a modeling framework for determining Total Maximum Daily Loads (TMDLs) in Liberty Reservoir for nutrients and sediment. The modeling framework follows the methodology already developed for TMDLs for other Maryland drinking water reservoirs: Prettyboy and Loch Raven Reservoirs (MDE, 2006; ICPRB and MDE, 2006); and Triadelphia and Rocky Gorge Reservoirs (MDE, 2008; ICPRB, 2008). The same methodology was recently employed in developing a water quality analysis (WQA) for Deep Creek Lake (MDE, 2010; ICPRB 2010).

The modeling framework consists of a CE-QUAL-W2 model (W2) of the reservoir linked to a Hydrological Simulation Program Fortran (HSPF) model of the watershed. The HSPF model provides the input flows and loads that drive the simulation of the W2 model. The HSPF model is a refined version of the Chesapeake Bay Program’s (CBP) Phase 5 Watershed Model (P5) (USEPA, 2010). W2 is a laterally-averaged two-dimensional continuous simulation model capable of simulating hydrodynamics, temperature, sediment, and eutrophication dynamics (Cole and Wells, 2003). It is particularly suitable to simulating seasonal temperature stratification and its impact and dissolved oxygen concentrations, an important aspect of reservoir water quality. The version of W2 used to simulate Liberty Reservoir was modified to make it more suitable for use in Maryland TMDLs.

The Revised P5 Liberty Reservoir Watershed Model

Liberty Reservoir is represented in the CBP P5 Model as a single watershed; the reservoir itself is the only river reach simulated in the original P5 Model. In the refined version developed for this project, the single Liberty Reservoir watershed was divided into 11 sub-watersheds and major tributaries to the reservoir, such as Beaver Run, Morgan Run, and the North Branch of the Patapsco River, were explicitly represented by river reaches in the refined model.

The original land use was distributed among the eleven subwatersheds based on the Regional Earth Science Applications Center (RESAC) land cover used to develop the land use for the original P5 Model (Goetz et al. 2004). The revised land use preserves both the size of the subwatersheds and the total acreage of each land use type in the original P5 Liberty Reservoir segment. With the exception of forest and harvested forest land uses, the edge-of-stream (EOS) loads for each land use type are used directly in the revised model without alteration or recalibration.

The EOS loads from watershed land uses were used as input loads to the Liberty Reservoir W2 Model. No in-stream contributions from processes like scour or deposition were simulated in the revised P5 Model. The EOS loads from the P5 Model were verified by comparing them to average annual loads developed using the USGS software LOADEST (Runkel et al, 2004) and available water quality monitoring data collected by the City of Baltimore’s Department of Public Works (BCDPW) in Beaver Run, Morgan Run, and the North Branch of the Patapsco River. The average annual sediment load for the period 2000-2005 for the entire Liberty Reservoir watershed is 28,411 tons/year. The average annual total phosphorus load for the same period is 82,017 lbs/yr and the average annual total nitrogen load is 2,368,571 lbs/yr.

The Liberty Reservoir W2 Model

The Liberty Reservoir W2 Model simulates the period 2000-2005. The model divides the reservoir into 48 active segments in five branches. There are a maximum number of 45 active layers in any segment. The maximum number of active cells is 1,134.

The W2 model simulates inflows and outflows; temperature; sediment transport; dissolved oxygen (DO) dynamics; and eutrophication dynamics. The model was calibrated against water quality monitoring data collected by BCDPW. The model reproduces the vertical temperature stratification that regularly occurs in Liberty Reservoir each summer, as well as the hypoxia in the epilimnion that occurs as a consequence of the temperature stratification. The model was calibrated to match or exceed the maximum observed chlorophyll *a* (Chla) concentration on a seasonal basis.

The primary purpose of the Liberty Reservoir modeling framework, including the W2 models of Liberty Reservoir, is to determine the maximum total phosphorus load which allow the reservoir to meet the TMDL endpoints for chlorophyll and dissolved oxygen. The W2 model of Liberty Reservoir was used to determine the maximum total phosphorus loads compatible with water quality standards. Simulated loads were reduced until two conditions were met: (1) no simulated Chla concentration in any cell was above 30 µg/l, and (2) the 30-day moving average Chla concentration of each modeling cell within 15 meters of the surface was not greater than 10 µg/l. It was determined that a total phosphorus (TP) load reduction of 50% in Liberty Reservoir met the TMDL endpoints for chlorophyll. This TMDL Scenario also met the dissolved oxygen endpoints in the well-mixed surface layer under stratified conditions. Hypoxia still occurred, however, in the bottom layers even under reduced loading rates.

An All-Forest Scenario was developed in which the flows and temperature from the Calibration Scenario were simulated but the EOS nutrient and sediment loads were determined by representing the watershed as if it were 100% forested. The purpose of the All-Forest Scenario is to determine to what extent hypoxic conditions in the hypolimnion are a function of external loading rates or reservoir morphology. If hypoxia occurs even under all-forested loading rates, then reservoir stratification is the primary cause of hypoxia and it can be concluded that the reservoir meets the water quality standards for DO.

The All-Forest Scenario represents a reduction in TP loads of approximately 75%. Under that reduction, average DO in the bottom layer of the reservoir improves considerably, but the minimum DO concentration frequently drops below 5.0 mg/l and hypoxia continues to occur in the hypolimnion. The All-Forest Scenario demonstrates that current loads, and loads simulated under the TMDL Scenario, do not result in hypoxia that significantly exceeds that associated with natural conditions in the watershed. Low DO concentrations in the bottom layer of the reservoir are therefore a naturally occurring condition, and TMDL Scenario thus meets water quality standards for DO.

Recommendations

There is no model which could not be improved if additional monitoring data were available, and these models are no exception. From the modeling point-of-view, the reservoir monitoring program could be improved by analyzing both tributary and reserovoir samples for (1) dissolved inorganic phosphorus (DIP); (2) Total Kjeldahl Nitrogen (TKN); and (3) some measures of oxygen-demanding material and organic carbon, such as Carbonaceous Biochemical Oxygen Demand (CBOD), Total Organic Carbon (TOC); or Chemical Oxygen Demand (COD). The first is important for determining how much phosphorus is bioavailable, the second for better understanding the nitrogen cycle in the reservoirs, and the last for quantifying water column oxygen demand and potential contributors to sediment oxygen demand. An additional benefit to analyzing tributary storm samples for TKN is that the monitoring data could be used to improve the characterization of total nitrogen (TN) yields in MD's Western Shore in the Chesapeake Bay Program's Watershed Model.

INTRODUCTION

Liberty Reservoir on the North Branch of the Patapsco River is one of three public water supply reservoirs operated by the City of Baltimore's Department of Public Works. Together with Prettyboy Reservoir and Loch Raven Reservoir, both of which are on Gunpowder Falls, they provide water to over a million and a half people in City of Baltimore and the surrounding counties.

Liberty Reservoir has been designated as Use I-P (water contact recreation, protection of aquatic life, and public water supply) waterbody in the Code of Maryland Regulations (COMAR 26.08.02.08K(1)). The Maryland Department of the Environment (MDE) placed Liberty Reservoir on Maryland's 1996 303 (d) List of impaired waters due to signs of eutrophication, expressed as high chlorophyll *a* (Chla) levels, Eutrophication is the over-enrichment of aquatic systems by excessive inputs of nutrients, especially nitrogen and/or phosphorus. The nutrients act as a fertilizer leading to the excessive growth of aquatic plants, which eventually die and decompose, leading to bacterial consumption of dissolved oxygen (DO). Liberty Reservoir is also listed as impaired because of sediment.

Waters placed on the 303(d) List are not meeting water quality standards and are not expected to do so by the implementation of technology-based controls on permitted point sources. Under these conditions, the Clean Water Act specifies that a Total Maximum Daily Load (TMDL) must be determined. A TMDL is the maximum amount of a pollutant a waterbody can receive and still meet water quality standards. The water quality goal of the nutrient TMDLs is to reduce high chlorophyll *a* (Chla) concentrations that reflect excessive algal blooms, and to maintain dissolved oxygen (DO) at a level supportive of the designated uses for Liberty Reservoir. The water quality goal of the sediment TMDL for Liberty Reservoir is to increase the useful life of the reservoir for water supply by preserving storage capacity.

This report documents the development of a modeling framework for determining TMDLs in Liberty Reservoir for nutrients and sediment. The modeling framework follows the methodology already developed for TMDLs for other Maryland drinking water reservoirs: Prettyboy and Loch Raven Reservoirs (MDE, 2006; ICPRB and MDE, 2006); and Triadelphia and Rocky Gorge Reservoirs (MDE, 2008; ICPRB, 2008). The same methodology was recently employed in developing a water quality analysis (WQA) for Deep Creek Lake (MDE, 2010; ICPRB 2010).

The modeling framework consists of a CE-QUAL-W2 model (W2) of the reservoir linked to a Hydrological Simulation Program Fortran (HSPF) model of the watershed. The HSPF model provides the input flows and loads that drive the simulation of the W2 model. W2 is a laterally-averaged two-dimensional continuous simulation model capable of simulating hydrodynamics, temperature, sediment, and eutrophication dynamics. It is particularly suitable to simulating seasonal temperature stratification and its impact and dissolved oxygen concentrations, an important aspect of reservoir water quality. The version of W2 used to simulate Liberty Reservoir was modified to make it more suitable for use in Maryland TMDLs.

The HSPF model is perhaps the most widely used continuous simulation watershed model in TMDL development. HSPF models were developed independently for the Gunpowder reservoirs' watersheds and the Patuxent reservoirs'watersheds, but for the Deep Creek Lake watershed, a refined version of the Chesapeake Bay Program's (CBP) Phase 5 Watershed Model (P5) was used to determine the input loads and flows to Deep Creek Lake.

The P5 model is a HSPF model of the Maryland, the District of Columbia, Virginia, and the portions of Pennsylvania, New York, and West Virginia in the Chesapeake Bay basin. Its primary purposes are (1) to determine the sources of nitrogen, phosphorus, and sediment to the Chesapeake Bay, (2) to calculate nutrient and sediment loads to the Chesapeake Bay for use in the CBP model of water quality in the Bay, and (3) to estimate nutrient and sediment load allocations under nutrient and sediment TMDLs for impaired Chesapeake Bay segments. The P5 model is used to assign load and wasteload allocations for the Chesapeake Bay TMDL. The load estimates from the P5 model will therefore shape water quality management in MD for the foreseeable future. The results of the model will impact point source and MS4 permits, as well as nonpoint source management programs for agriculture, silviculture, and stream restoration. Using the P5 model as the basis for the reference watershed approach enables MD to integrate its non-tidal nutrient TMDLs into the management framework for the Chesapeake Bay.

The key features of the project will be discussed in more detail below. Chapter 2 provides a brief overview of the characteristics of Liberty Reservoir and its watershed. Chapter 3 discusses in detail the refinement and recalibration of the P5 model of the Liberty Reservoir watershed. Chapter 4 analyzes the water quality data in the collected in the Liberty Reservoir and explains the application of Maryland's water quality standards to the reservoir. Chapter 5 discusses the configuration of W2 model of the reservoir, the alterations in the W2 model that were necessary to make it suitable for use in nutrient TMDLs, and calibration of the hydrodynamics, DO dynamics, and eutrophication kinetics in the reservoir model. Chapter 6 discusses model sensitivity to external loads and other aspects of the modeling framework that allow the framework to be used to determine nutrient and sediment TMDLs for the Liberty Reservoir. Chapter 7 provides a brief summary and recommendations for collecting additional monitoring data.

2.0 DESCRIPTION OF THE LIBERTY RESERVOIR WATERSHED

2.1 Location of the Liberty Reservoir Watershed

The Liberty Reservoir watershed is located in Baltimore and Carroll Counties. The watershed is a subbasin of the Patapsco River watershed, which drains into western shore Chesapeake Bay. Figure 2-1 shows the location of Liberty Reservoir and its watershed.

2.2 Physical Characteristics of the Liberty Reservoir

Several relevant statistics for Liberty Reservoir are provided below in Table 2-1.

Table 2-1: Current Physical Characteristics of Liberty Reservoir

Location:	Baltimore County, MD Carroll County, MD Lat. 39˚ 22’ 36” N Long. 76˚ 53’ 30” W
Surface Area:	3,106 acres (107,343,000 ft2)
Normal Reservoir Depth:	132.8 feet
Purpose:	Water Supply Recreation
Basin Code:	02-13-09-07
Volume:	132,000 acre-feet
Drainage Area to Reservoir:	164 mi2 (104,960 acres)
Average Discharge:	20.0 ft3s-1

Source: Inventory of Maryland Dams and Hydropower Resources (Weisberg et al., 1985).

The Liberty Reservoir dam is a concrete gravity dam. The length of the dam is 704 feet with an uncontrolled spillway with length 480 feet. The elevation of the dam crest is 420 feet Mean Sea Level (MSL) and the dam crest is 160 feet above the stream bed. Construction of the dam started in 1951 and water first flowed over the crest in 1956. Water from the reservoir flows by gravity through a 10-foot tunnel to the Ashburton Treatment Plant 12.5 miles away (City of Baltimore Department of Public Works, 1981, 2010).

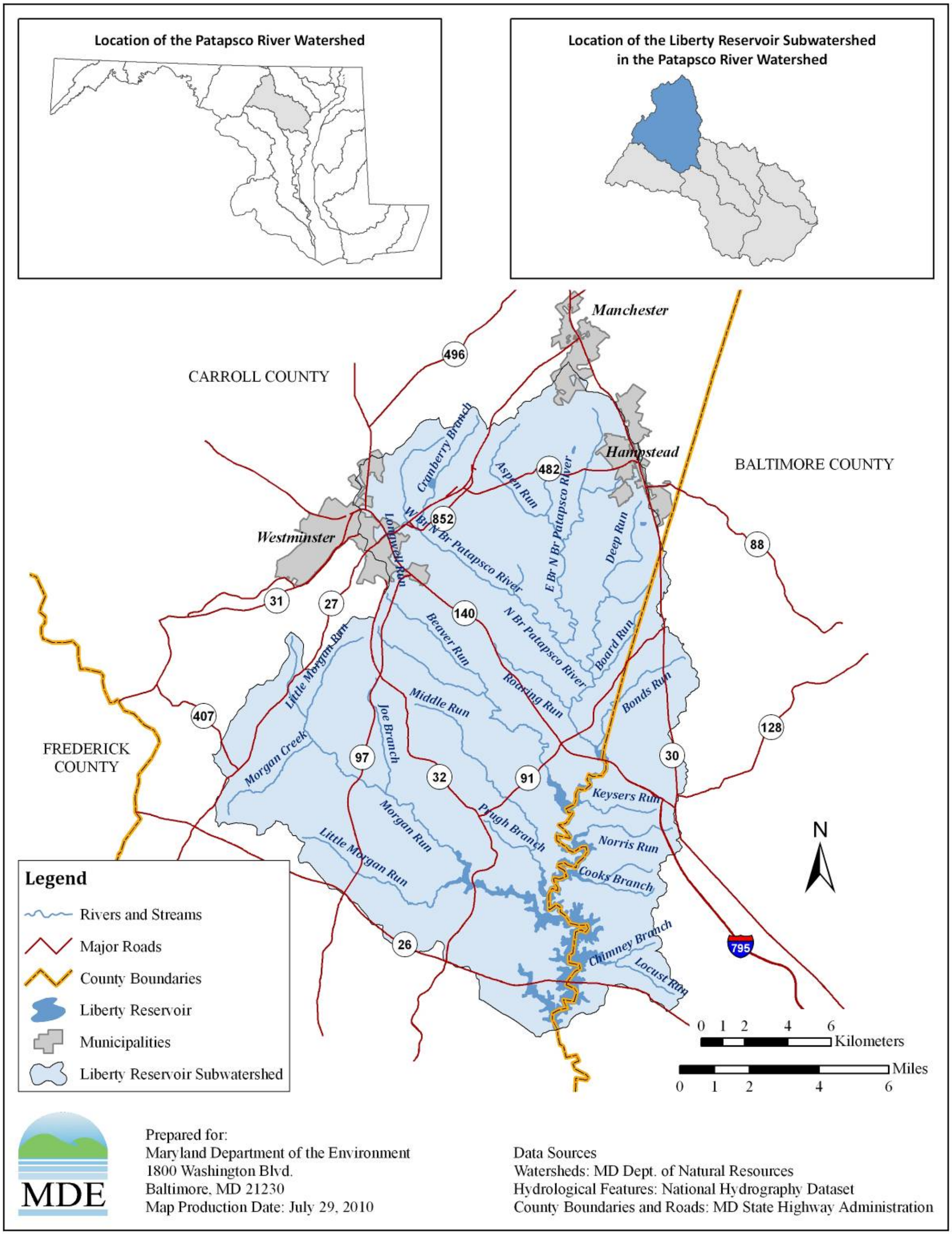

Figure 2-1: Location of Liberty Reservoir

2.3 Climate

The Liberty Reservoir watershed has a temperate continental climate. Table 2-2 shows the average maximum temperature and average minimum temperature by month, as well as the average monthly precipitation, based on daily meteorological observations taken at Westminster, MD, 1948 through 1999. The statistics are based on observations from two stations, Watminster 2 SSE (COOP ID 189435), for the period 1948-1979, and the Westminster Police Barracks (COOP ID 189440), for the period 1979-1999. Precipitation averages 42.6 inches per year annually is fairly evenly distributed throughout the year.

Table 2-2: Summary Statistics Meteorological Data Westminster, MD, 1948 – 1999

Month	Average Minimum Temperature (◦F)	Average Maximum Temperature (◦F)	Average Monthly Precipitation (in.)
January	23	39	3.1
February	25	43	2.7
March	31	51	3.8
April	41	64	3.5
May	51	74	4.0
June	59	82	3.8
July	64	86	4.1
August	62	84	3.8
September	55	77	3.7
October	45	66	3.2
November	36	54	3.4
December	27	43	3.5
Annual	43	64	42.6[1]

[1] Annual total - Reference: National Climatic Data Center (2001)

2.4 Geology and Soils

The Liberty Reservoir watershed lies in the Piedmont Physiographic Province. Bedrock from the micaceous shists of Wissahickon Formation underlies about 83% of the watershed, with small areas of metabasalt, schist, and marble primarily in the headwaters. Near the lower reaches of the reservoir itself, Lower Pelitic Schist and ultramafic rock dominate in Carroll County while boulder gneiss dominates in Baltimore County. (Maryland Department of Geology, Mines and Water Resources, 1946; DNR, 2002).

The dominant soil associations in the Carroll County portion of the watershed are the Glenelg-Chester-Manor Association and the Glenelg-Manor-Mt. Airy Association (USDA, 1969). The dominant soil association in the Baltimore County portion of the watershed is the Manor-Glenelg Association (USDA, 1976). Glenelg, Chester, and Manor soils tend to be deep and well-drained, though Manor soils can also be excessively drained or shallow. Mt Airy soils tend to be shallow and excessively drained (University of Maryland Cooperative Extension Service, 1976). Shallow soils, like the Mt Airy soil, cover about 27% of the watershed (DNR, 2002).

2.5 Land Use

Figure 2-2 shows the distribution of land uses in the Liberty Reservoir watershed. Table 2-3 shows the representation of land use acreage in the P5 Model (version 5.3.2) for 2002, which is the mid-point of the simulation period for both the refined P5 model of the Liberty Reservoir watershed and the W2 model. According to the land use for the Phase 5 Model, the watershed is fairly evenly divided between forest, agriculture, and developed land. Forest accounts for 36% of the watershed area, developed land occupies 28% of the watershed area, and crops and pasture represent 28% and 6%, respectively, of the watershed.

Sections 3.2 and 3.5.1 discuss in greater detail the representation of the land use in the Liberty Reservoir watershed in the P5 Model.

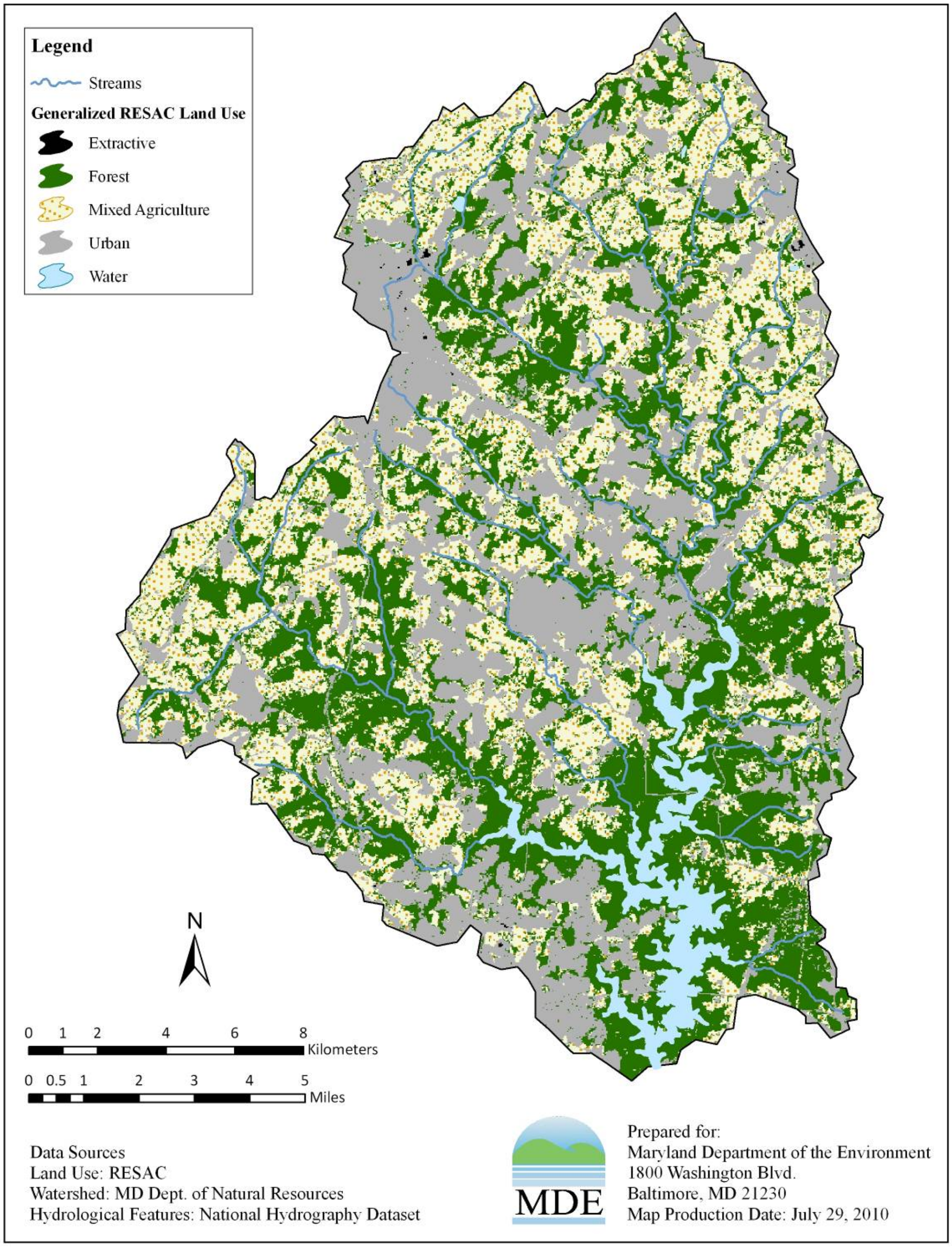

Figure 2-2: Land Use of the Liberty Reservoir Watershed

Table 2-3: Land Use Percentage Distribution for Liberty Reservoir Watershed

General Land Use	Detailed Land Use	Area (acres)	Percent (%)	Grouped Percent of Total
Forest	Forest	37,086	35.4%	35.7%
	Harvested Forest	375	0.4%	
AFOs	Animal Feeding Operations	73	0.1%	0.1%
CAFOs	Concentrated Animal Feeding Operations	0	0.0%	0.0%
Pasture	Pasture	6,298	6.0%	6.0%
Crop	Crop	29,210	27.9%	27.9%
Nursery	Nursery	95	0.1%	0.1%
Regulated Developed	Construction	1,023	1.0%	28.3%
	Developed	28,651	27.3%	
	Extractive	0	0.0%	
Water	Water	1,989	1.9%	1.9%
Total		**104,800**	**100.0%**	**100.0%**

3.0 REFINEMENT OF CBP WATERSHED MODEL REPRESENTATION OF LIBERTY RESERVOIR WATERSHED

Input flows and constituent loads for the CE-QUAL-W2 model of Liberty Reservoir were developed using the Chesapeake Bay Program's Phase 5Watershed Model (P5), version 5.3.2. The P5 model is a Hydrological Simulation Program Fortran (HSPF) model of the Maryland, the District of Columbia, Virginia, and the portions of Pennsylvania, New York, and West Virginia in the Chesapeake Bay basin. Its primary purposes are (1) to determine the sources of nitrogen, phosphorus, and sediment to the Chesapeake Bay, (2) to calculate nutrient and sediment loads to the Chesapeake Bay for use in the CBP model of water quality in the Bay, and (3) to estimate nutrient and sediment load allocations under nutrient and sediment TMDLs for impaired Chesapeake Bay segments.

Generally, river reaches that have average annual flows greater than 100 cfs are represented in the model, but MDE has worked with CBP to ensure that all of MD's 8-digit watersheds (the unit of water quality assessment in Maryland) are represented in the model, including those not draining to Chesapeake Bay. Bicknell et al. (2000) describe the HSPF model in greater detail. USEPA (2010) documents the development of the P5 model.

The Liberty Reservoir watershed is represented in P5, along with the rest of Maryland's portion of the Patapsco River watershed. Liberty Reservoir is represented by a single river reach. Figure 3-1 shows the location of the reach within the segmentation for the Patapsco River.

HSPF represents river reaches and reservoirs as a single one-dimensional longitudinal segment. It is therefore incapable of representing the effects of thermal stratification of dissolved oxygen and therefore testing whether the hypoxia observed in the bottom layers of Liberty Reservoir is a natural phenomenon. This is the reason why Liberty Reservoir had to be simulated by a two dimensional model like CE-QUAL-W2, as will be discussed in more detail in Section 5. The CE-QUAL-W2 model also requires a more refined longitudinal segmentation and therefore requires a more refined segmentation of the watershed.

This chapter describes how the P5 model's representation of the Liberty Reservoir watershed was refined to represent the subwatersheds of the reservoir's tributaries, and the resulting flows and loading rates to Liberty Reservoir associated with those subwatersheds. It begins with a brief discussion of HSPF in general and its implementation in the P5 model. It then describes the calibration of P5 model for Patapsco River. Next the resgmentation of the Liberty Reservoir watershed and its implementation in the P5 model are described, along with other changes that had to be made in P5 to simulate the Liberty Reservoir watershed on a finer scale. The simulation of river reaches and the calculation of target loads for reaches are also discussed. The chapter concludes with a summary of sediment, total phosphorus, and total nitrogen loads by source.

3.1 Overview of the Hydrologic Simulation Program Fortran (HSPF)

The HSPF Model simulates the fate and transport of pollutants over the entire hydrological cycle. Two distinct sets of processes are represented in HSPF: (1) processes that determine the fate and transport of pollutants at the surface or in the subsurface of a watershed, and (2) in-stream processes. The former will be referred to as land or watershed processes, the latter as in-stream or river reach processes.

Constituents can be represented at various levels of detail and simulated both on land and for in-stream environments. These choices are made in part by specifying the modules that are used, and thus the choices establish the model structure used for any one problem. In addition to the choice of modules, other types of information must be supplied for the HSPF calculations, including model parameters and time-series of input data. Time-series of input data include meteorological data, point sources, reservoir information, and other type of continuous data as needed for model development.

A watershed is subdivided into model segments, which are defined as areas with similar hydrologic characteristics. Within a model segment, multiple land use types can be simulated, each using different modules and different model parameters. There are two general types of land uses represented in the model: pervious land, which uses the PERLND module, and impervious land, which uses the IMPLND module. More specific land uses, like forest, crop, or developed land, can be implemented using these two general types. In terms of simulation, all land processes are computed for a spatial unit of one acre. The number or acres of each land use in a given model segment is multiplied by the values (fluxes, concentrations, and other processes) computed for the corresponding acre. Although the model simulation is performed on a temporal basis, land use information does not change with time.

Within HSPF, the RCHRES module sections are used to simulate hydraulics of river reaches and the sediment transport, water temperature, and water quality processes that result in the delivery of flow and pollutant loading to a bay, reservoir, ocean or any other body of water. Flow through a reach is assumed to be unidirectional. In the solution technique of normal advection, it is assumed that simulated constituents are uniformly dispersed throughout the waters of the RCHRES; constituents move at the same horizontal velocity as the water, and the inflow and outflow of materials are based on a mass balance. HSPF primarily uses the “level pool” method of routing flow through a reach. Outflow from a free-flowing reach is a single-valued function of reach volume, specified by the user in an F-Table, although within a time step, the HSPF model uses a convex routing method to move mass flow and mass within the reach. Outflow may leave the reach through as many as five possible exits, which can represent water withdrawals or other diversions.

3.2 Overview of the Chesapeake Bay Program Phase 5 Model

The P5 model represents the entire Chesapeake Bay basin, as well as the portions of Maryland and Virginia outside of the basin. Land segments are generally represented on a county basis, because data on nutrient inputs and other management information is generally consistently available at the county level across the basin. Counties are sometimes divided into separate land use segments because of potential orographic effects in mountainous regions. There are 254 counties represented in the model and 50 of those counties are divided into two or more segments. Both Baltimore and Carroll Counties, where Liberty Reservoir is located, are represented as single land segments.

Thirty-one land uses are represented in the model. Four of these represent land under combined sewer systems and there are no combined sewer systems in the Liberty Reservoir watershed. Table 3-1 shows the 27 remaining land uses, along with their General Land Use Class shown in Table 2-3. Each land use in a land segment is modeled individually, so there are 54 land simulations that are used to represent Baltimore and Carroll Counties. These are either PERLND or IMPLND simulations as described in the previous section.

The P5 model represents over a 1000 river segments. Some of these segments, like Liberty Reservoir, are reservoirs. On average, the watersheds representing these segments are 66 square miles (excluding the area of upstream segments). Figure 3-1 shows the river segments represented in Patapsco River basin above the fall line.

One of the key features that distinguishes the P5 model from standard HSPF models is that each land and river segment is simulated individually. The P5 model uses a suite of programs outside of HSPF to build the inputs to each river simulation out of the outputs from land and river simulations that contribute flows and loads to that reach. These external programs allow P5 to vary land use and management practices during the 21 year simulation period, 1985-2005, over which the model is calibrated. This would not be possible in standard HSPF models, where the land use is fixed throughout the simulation.

The External Transfer Module (ETM) is the name given to the set of programs that prepares the edge-of-stream (EOS) inputs for river reach simulations. The ETM calculates time series of flows and loads from the per acre land simulations of the land uses in each reach's watershed. This can include land uses from multiple counties, if land from more than one county is in the watershed. The output from each land simulation must be multiplied by the number of acres of the type of land use from a specific county that is in the watershed; the number of acres of land use is itself a time-varying quantity. The ETM also must take into account the impact of best management practices (BMPs) which reduce the loads from a land use entering a reach. The implementation level of BMPs also varies throughout the simulation. The load may also be adjusted by a delivery factor or regional factor, discussed below, before it is input into the reach. The ETM also prepares loads from point sources and septic systems which are dimulated as direct discharges to the reach.

Automated calibration is a second key feature which distinguishes the P5 modeling framework. It would be too time-consuming, and certainly beyond the powers of a single individual, to adjust model parameters by trial and error. Calibration by multiple individuals can also lead to inconsistent methods and inconsistent results. To provide a uniform and consistent standard of calibration across the Chesapeake Bay basin, the P5 model is calibrated by a set of programs which reiteratively adjust model parameters to better match selected statistics of observed monitoring data and model results. USEPA (2010) discusses the P5 model calibration procedures in more detail. Figure 3-1 shows the primary calibration station used to set the hydrology parameters for Patapsco River basin land uses and river reach water quality parameters. The calibration of nitrogen and phosphorus loads from land simulations is discussed in more detail below.

Table 3-1: CBP Phase 5 Watershed Model Land Uses

General Land Use Class	General Land Cover Class	P5 Model Land Use
Crop	Agriculture	Alfalfa
		Hay with nutrients
		High Till Crop with manure
		High Till Crop without manure
		Low Till Crop with Manure
		High Till Crop with Nutrient Management but without manure
		Hay without nutrients
		Alfalfa with Nutrient Management
		Hay with nutrients and Nutrient Management
		High Till Crop with Manure and Nutrient Management
		Low Till Crop with manure and Nutrient Management
Pasture		Trampled Pasture
		Pasture
		Pasture with Nutrient Management
AFOs		Animal Feeding Operations (AFOs)
CAFOs		Concentrated Animal Feeding Operations (CAFOs)
Nurseries		Nurseries
Forest	Forest	Forest
		Harvested Forest
Non-regulated Developed	Extractive	Non-regulated Extractive
	Developed	Non-regulated Pervious Developed
		Non-regulated Impervious Developed
Regulated Developed	Barren	Construction
	Extractive	Regulated Extractive
	Developed	Regulated Pervious Developed
		Regulated Impervious Developed
Water	Water	Water

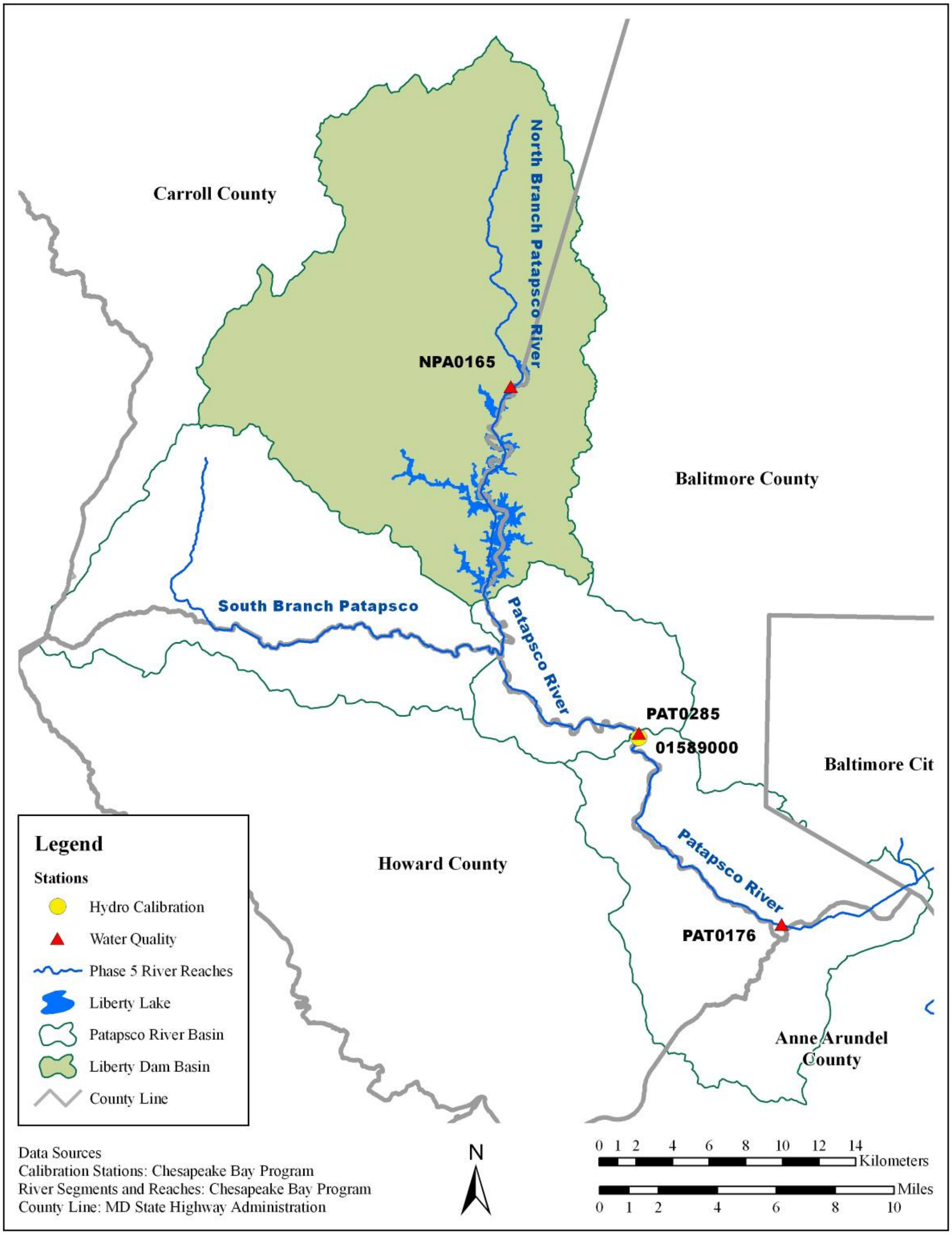

Figure 3-1: Patapsco River Segments and Calibration Stations in P5 Model

There have been several versions of the P5 Model. The latest version is P5.3.2. The P5 Model is a public model, developed explicitly as a community model, that is, a model that is publically available and can be modified and used for other purposes. The use of a refined version of the P5 to simulate input flows and loads for Liberty Reservoir is an example of such a purpose. CBPO has not, however, released a public version of P5.3.2, so the P5 Liberty Reservoir Model was developed using version P5.2 of the publically-available community model, modified to duplicate the land simulation and EOS loads in P.5.3.2. These modifications are explained in more detail in Section 3.5.

3.3 Sediment Edge-of-Stream Loading Targets

This section provides the background and methods for determining the nonpoint source baseline sediment edge-of-stream (EOS) loads generated within the Liberty Reservoir watershed.

3.3.1 General Load Estimation Methodology

Nonpoint source sediment loads generated within the Liberty Reservoir watershed are estimated based on the edge-of-field (EOF) calibration target loading rates from the CBP P5.3.2 model. This approach is based on the fact that not all of the EOF sediment load is delivered to the stream or river (some of it is stored on fields down slope, at the foot of hillsides, or in smaller rivers or streams that are not represented in the model). To calculate the actual edge-of-stream (EOS) loads, a sediment delivery ratio (the ratio of sediment reaching a basin outlet compared to the total erosion within the basin) is used. Details of the methods used to calculate sediment load have been summarized in the report entitled *Chesapeake Bay Phase 5.3 Community Watershed Model* (USEPA, 2010).

3.3.2 Edge-of-Field Target Erosion Rate Methodology

EOF target erosion rates for agricultural land uses and forested land use were based on erosion rates determined by the Natural Resource Inventory (NRI). NRI is a statistical survey of land use and natural resource conditions conducted by the Natural Resources Conservation Service (NRCS) (USDA 2006). Sampling methodology is explained by Nusser and Goebel (1997).

Estimates of average annual erosion rates for pasture and cropland are available on a county basis at five-year intervals, starting in 1982. Erosion rates for forested land uses are not available on a county basis from NRI; however, for the purpose of the Chesapeake Bay Program Phase 4.3 (CBP P4.3) watershed model, NRI calculated average annual erosion rates for forested land use on a watershed basis. These rates are still being used as targets in the CBP P5 model.

The average value of the 1982 and 1987 surveys was used as the basis for EOF target loads. The erosion rates from this period do not reflect best management practices (BMPs) or other soil conservation policies introduced in the wake of the effort to restore the Chesapeake Bay. Rates for urban pervious, urban impervious, and barren land were based on a combination of literature analysis and regression analysis. Table 3-2 lists erosion rates specific to the Baltimore and Carroll Counties.

Table 3-2: Summary of EOF Erosion Rate Calculations

Land Use	Data Source	Carroll Co., A24013 (tons/acre/year)	Baltimore Co., A24005 (tons/acre/year)
Forest	Phase 2 NRI	0.34	0.46
Harvested Forest1	Average Phase 2 NRI (x 10)	3	3
Animal Feeding Operations2	Pasture NRI (x 9.5)	8.08	12.26
Pasture	Pasture NRI (1982-1987)	0.85	1.29
Trampled Pasture2	Pasture NRI (x 9.5)	10.2	15.48
Hay2	Crop NRI (1982-1987) (x 0.32)	1.05	3.18
High Till without Manure2	Crop NRI (1982-1987) (x 1.25)	4.09	12.42
High Till with Manure2	Crop NRI (1982-1987) (x 1.25)	4.09	12.42
Low till with Manure2	Crop NRI (1982-1987) (x 0.75)	2.45	7.45
Construction	Literature Survey	24.7	24.7
Pervious Developed	Intercept Regression Analysis	0.74	0.74
Impervious Developed	100% Impervious Regression Analysis	5.18	5.18

Notes: [1]Based on an average of NRI values for the Chesapeake Bay Phase 5 segments.
[2]NRI score data adjusted based on land use.

3.3.3 Sediment Delivery Ratio

In order to account for the changes in sediment loads due to distance traveled to the stream, the CBP P5.2 model uses the sediment delivery ratio. The base formula for calculating sediment delivery ratios in the CBP P5.2 model is the same as the formula used by the NRCS (USDA 1983).

$$DF = 0.417762 * A^{-0.134958} - 0.127097 \qquad \text{(Equation 2.1)}$$

where
DF (delivery factor) = the sediment delivery ratio
A = drainage area in square miles

Land use specific *sediment delivery ratios* were calculated for each river segment using the following procedure:

(1) mean distance of each land use from the river reach was calculated;

(2) sediment delivery ratios for each land use were calculated (drainage area in Equation 2.1 was assumed to be equal to the area of a circle with radius equal to the mean distance between the land use and the river reach).

3.3.4 Edge-of-Stream Loads

Edge-of-stream (EOS) loads are the loads that actually enter the river reaches (i.e., the mainstem of a watershed). Such loads represent not only the erosion from the land but all of the intervening processes of deposition on hillsides and sediment transport through smaller rivers and streams.

3.4 Nitrogen and Phosphorus Edge-of-Stream Loading Targets

Automated calibration is also used for water quality simulations for land use land segments, but unlike the hydrology parameters for land uses or river reach water quality parameters, land simulations are calibrated against loading targets, not monitoring data. This section discusses the elements that determine EOS total nitrogen (TN) and total phosphorus (TP) loads and documents the targets used to calibrate land simulations in Baltimore and Carroll Counties.

EOS loads in the P5 model are determined by three factors, (1) median of land use-specific loading rates found in the scientific literature; (2) adjustment of the median loading rate based on the excess nutrient inputs applied to a land use; and (3) regional factors.

3.4.1 Literature Review

Using Beaulac and Rechow's (1982) literature survey as a starting point, CBP staff conducted a survey of the scientific literature to determine the range of observed nutrient loading rates from land uses. Most of these estimates were made from observations on small, homogeneous watersheds and thus represent edge-of-stream, rather than edge-of-field, nutrient loads. Table 3-3 gives the median phosphorus and nitrogen loading rates for major land use groups. Nutrient loads for urban land uses are based on median concentrations taken from Pitt et al. (2005) study of monitoring data collected by jurisdictions for their Municipal Separate Storm Sewer System (MS4) permits. For TN the median concentration was 2.0 mg/ and for TP the median concentration was 0.27 mg/l.

Table 3-3: Median Nutrient Export Yields (lbs/ac/yr) From Literature

Land Use	TP Yield (lbs/ac/yr)	TN Yield (lbs/ac/yr)
Alfalfa	0.7	5.5
High Till Crop Without Manure	2.5	23
High Till Crop With Manure	2	23
Hay Without Nutrients	0.4	4
Hay With Nutrients	0.8	6
Low Till Crop With Manure	2	23
Pasture	0.7	4.5

3.4.2 Excess Nutrient Inputs

Land processes in the P5 model are simulated by land use and land segment. Land segments are counties or, in some cases, sections of counties where precipitation is expected to vary because of orography. Each land segment and each land use not using nutrient management is assigned a calibration target.

The median literature loading rate is the starting point for determining calibration targets for EOS loads in the P5 model. These median rates were adjusted upwards or downwards depending how much the amount of nutrients applied to a land use in a land segment exceeded the needs of the vegetation on that land use, compared to the average Chesapeake Bay segment. In other words, land segment calibration targets were distributed around the median literature value in proportion to the excess nutrients applied to the segments. For urban land uses, the target load is the product of the target nutrient concentration and the average simulated runoff. For phosphorus, the target concentration was the median concentration of 0.27 mg/l for all land segments. For nitrogen, the target concentration was adjusted upwards or downwards depending on the atmospheric deposition of nitrogen in the segment. Target nitrogen loads for forests were also adjusted based on atmospheric nitrogen deposition.

CBP calculated the nutrient loading rates for manure, fertilizer, and atmospheric deposition, as well as crop and vegetative uptake, for each land use and land segment. These calculations were based on the agricultural census, the expert opinion of local and state agronomists, statistics on fertilizer sales, and a mass balance of animal waste based on animal population estimates. US EPA (2010) has further details on the calculation of loading rates.

Generally speaking, the fate and transport of nitrogen was simulated using the HSPF module AGCHEM, which keeps a mass balance of nitrogen species (ammonia, nitrate, labile organic nitrogen, and refractory organic nitrogen) and represents the transformation of nitrogen species. Organic phosphorus is not simulated separately from organic nitrogen, but is calculated from organic nitrogen export according to the ratio of 7.225 N:P by mass. On agricultural land, inorganic phosphorus is simulated using the mass-balance module AGCHEM, but on forest and urban land, fate and transport of inorganic phosphorus is simulated using the PQUAL, a simpler model which does not keep a mass balance of constituents. Since there is no mass balance of input and output phosphorus, targets for land uses using PQUAL are not varied by nutrient inputs.

Tables 3-4 and 3-5 give the TP and TN EOS targets, respectively, for non-nutrient management land uses in Baltimore and Carroll Counties. For land uses with nutrient management, EOS loads are determined by reducing nutrient inputs to their agronomic rates on the corresponding land use without nutrient management.

3.4.3 Regional Factors

The use of literature loading rates and their adjustment according to the excess nutrients applied to the land can be expected to provide a good estimate of land use loading rates relative to each other. To further determine loading rates, CBP applies a multiplicative regional factor to the simulated land segment loading rate. Regional factors are calculated in the calibration of river segments, where simulated output is compared observed monitoring data. They are determined by comparing simulated watershed loads to loads calculated using the USGS statistical program, ESTIMATOR, at fall line of major basins and at strategic locations upstream of the fall line where there is sufficient data to estimate loads (Langland *et al.*, 2005), or to remove bias in the relation between the distribution of observed and simulated nitrogen and phosphorus concentrations on a regional scale.

Regional factors are calculated on a river segment basis. For Liberty Reservoir, regional factors were calculated to remove the bias in the relation between the distribution of observed and simulated nutrient concentrations in the Patapsco River watershed. For Liberty Reservoir, the regional factor for phosphorus is 0.75, and the regional factor for nitrogen is 1.1 for both Baltimore and Carroll Counties.

Table 3-4: Target TP EOS Loading Rates (lbs/ac/yr) By Land Use and County

Land Use	Carroll Co., A24013	Baltimore Co., A24005
Forest	0.105	0.106
Harvested Forest	0.8	0.8
Alfalfa	0.7	0.7
Hay with Nutrients	0.716	0.726
Hay without Nutrients	0.4	0.4
High Till Crop with Manure	2.022	1.981
High Till Crop without Manure	2.696	2.772
Low Till Crop with Manure	2.008	1.97
Nursery	85	85
Pasture	1.113	1.024
Trampled Pasture	13.352	12.295
Construction	7	7
Pervious Developed	0.511	0.398
Impervious Developed	2.136	2.191

Table 3-5: Target TN EOS Loading Rates (lbs/ac/yr) By Land Use and County

Land Use	Carroll Co., A24013	Baltimore Co., A24005
Forest	3.513	3.632
Harvested Forest	30.0	30.0
Alfalfa	8.25	8.25
Hay with Nutrients	5.402	5.448
Hay without Nutrients	4.50	4.50
High Till Crop with Manure	30.956	29.297
High Till Crop without Manure	58.833	39.808
Low Till Crop with Manure	27.633	26.145
Nursery	240	240
Pasture	10.761	9.775
Trampled Pasture	102.236	92.851
Construction	37.5	37.5
Pervious Developed	11.436	11.038
Impervious Developed	19.094	20.209

3.5 Revision of the Representation of the Liberty Reservoir Watershed

The P5.3.2 Model is the current version of the P5 Watershed Model. It is being used to set the load allocations and wasteload allocations for the Chesapeake Bay TMDL at a local scale in Maryland's Phase II Watershed Implementation Plan (WIP). Since the Phase II WIP is tantamount to a state-wide nutrient reduction strategy, it is important that the baseline loads in the Liberty Reservoir phosphorus and sediment TMDLs be consistent with the assumptions of the P5.3.2 Model, so that environmental planning and TMDL implementation have a common starting point. CBP has not, however, made a community version of the P5.3.2 Model available. That is to say, there is no version of the P5.3.2 Model that can be installed and executed outside of the CBP offices. The P5.2 Community Model was therefore used as a framework for developing a refined version of the P5 Liberty Reservoir Watershed Model. As explained below, the P5.2. Community Model was updated with P5.3.2 land use, flows, and EOS loading rates in the refined model. Other revisions include

- Dividing the Liberty Reservoir watershed into subwatersheds to represent input flows and loads at a finer scale;
- Developing a river reach network to represent tributaries to the Liberty Reservoir watershed at the subwatershed scale; and
- Assigning BMPs and loads from point sources, septic systems, and atmospheric deposition to subwatershed river reaches.

Each of these revisions will be discussed in more detail below.

3.5.1 Resegmentation of Land Use

In the P5 model Liberty Reservoir is represented as a single reach in a single watershed. To determine input loads to the CE-QUAL-W2 model, it is necessary to represent input flows and loads at a finer scale. Figure 3-2 shows the initial delineation of the subwatersheds of Liberty Reservoir. Table 3-6 lists the delineated segments along with the names of the tributaries to Liberty Reservoir or the branches to which they drain. The six tributaries are all upstream of a monitoring station with water quality data collected by the City of Baltimore Department of Public Works. This monitoring program is discussed in more detail in Section 3.6. The other segments either represent the drainage of tributaries below the monitoring stations or direct drainage to the reservoir.

Several subwatersheds were later consolidated in the final version of the P5 Liberty Reservoir Watershed Model to match the inputs required by the Liberty Reservoir W2 Model. Section 3.5.6 discusses which subwatersheds were combined, and Table 3-10 in that section gives the correspondence between the initial subwatersheds and the final subwatersheds and their river reaches. Section 5.2.1 explains how the output from the Watershed Model was used as input to the Reservoir Model.

Table 3-6: Subwatersheds of Refined P5 Model of Liberty Reservoir Watershed

Subshed	Name	Drainage Type
1	Liberty Reservoir	Direct Drainage
2	North Branch Patapsco River	Tributary
3	Beaver Run	Tributary
4	Middle Run	Tributary
5	Morgan Run	Tributary
6	Little Morgan Run	Tributary
7	Snowden Run	Direct Drainage
8	Locust Run	Tributary
9	Liberty Reservoir	Direct Drainage
10	Bonds Run	Tributary
11	Beaver Run	Direct Drainage
12	Middle Run	Direct Drainage
13	Morgan Run	Direct Drainage
14	Beaver Run	Direct Drainage
15	Middle Run	Direct Drainage
16	Morgan Run	Direct Drainage
17	Snowden Run	Direct Drainage
18	Locust Run	Direct Drainage

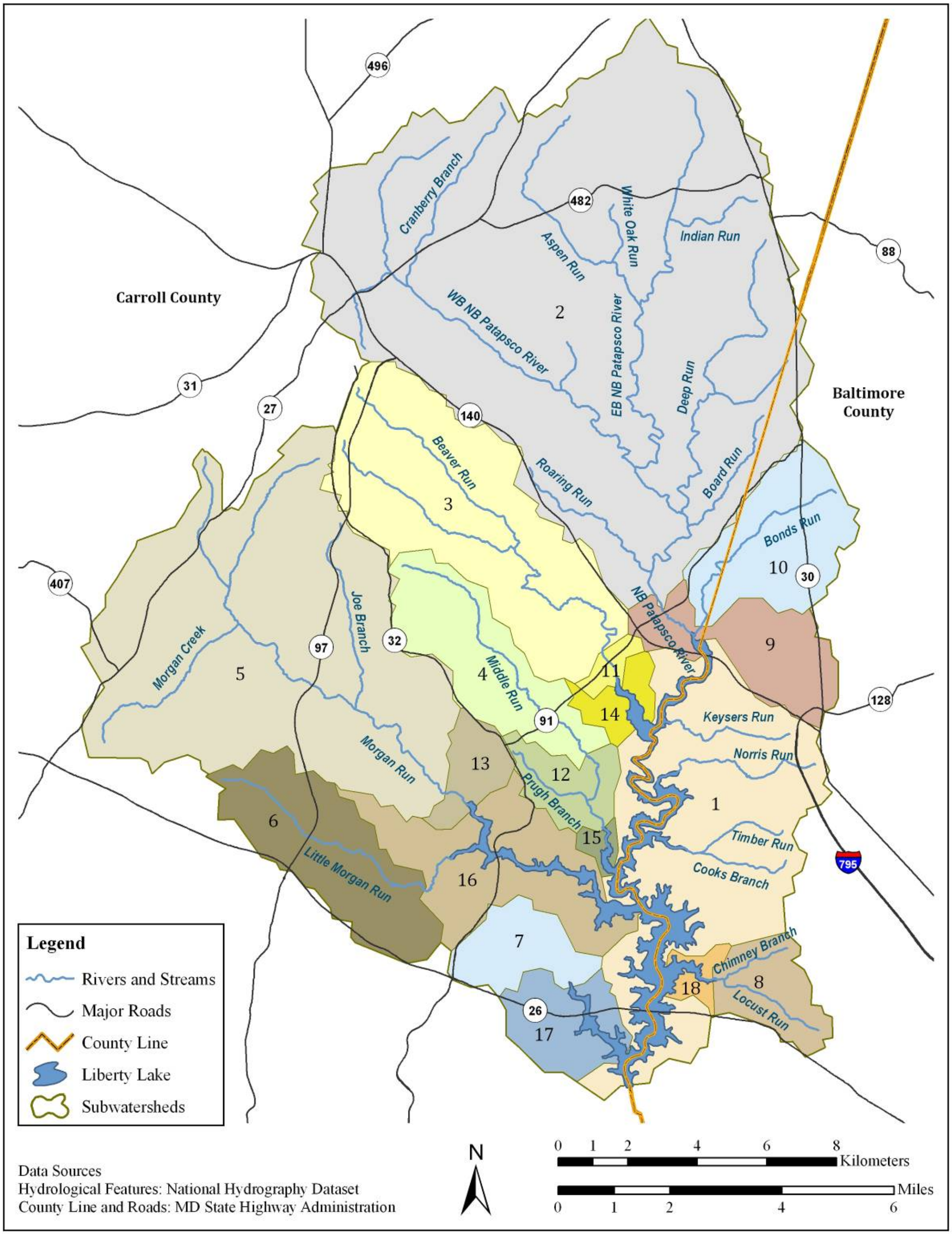

Figure 3-2: Initial Subwatersheds in Refined P5 Model of Liberty Reservoir Watershed

The next step is to assign the CBP acres of each type of land use in the Liberty Reservoir watershed to the delineated subwatersheds. This task is made more difficult by the fact that the CBP land use does not exist as a distinct Geographic Information System landuse layer, but only in tabular form.

The original CPB P5 land use was developed based on several sources of information. The Regional Earth Science Applications Center (RESAC) at the University of Maryland developed a land cover layer based on satellite imagery (Landsat 7-Enhanced Thematic Mapper (ETM) and 5-Thematic Mapper (TM)) (Goetz et al. 2004). RESAC also developed a separate cover of impervious surfaces. Starting with version P5.3.0, however, the RESEAC land cover was replaced by the Chesapeake Bay Watershed Land Cover Data (CBLCD) series of Geographic Information System (GIS) datasets. These datasets provide a 30 meter resolution raster representation of land cover in the Chesapeake Bay watershed, based on sixteen Anderson Level 2 land cover classes. The CBLCD basemap, representing 2001 conditions, was primarily derived from the Multi-Resolution Land Characteristics (MRLC) Consortium's National Land Cover Data (NLCD) and the National Oceanic and Atmospheric Administration's (NOAA) Coastal Change Analysis Program's (CCAP) Land Cover Data. By applying Cross Correlation Analysis to Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper satellite imagery, USGS's contractor, MDA Federal, generated CBLCD datasets for 1984, 1992, and 2006 from the 2001 baseline dataset. The "*Chesapeake Bay Phase 5.3 Community Watershed Model*" US EPA (2010) describes the development of the CBLCD series in more detail. USGS and NOAA also developed an impervious cover dataset from Landsat satellite imagery for the CBLCD basemap, which was used to estimate the percent impervious cover associated with CBLCD developed land-use classes.

The second stage consists of using ancillary information for: 1) the creation of a modified 2006 CBLCD raster dataset, and 2) the subsequent development of the CBP P5.3.2 land-use framework in tabular format. Estimates of the urban footprint in the 2006 CBLCD were extensively modified using supplemental datasets. NAVTEQ street data (secondary and primary roads) and institutional delineations were overlayed with the 2006 CBLCD land cover and used to reclassify underlying pixels. Certain areas adjacent to the secondary road network were also reclassified based on assumptions developed by USGS researchers, in order to capture residential development (*i.e.*, subdivisions not being picked up by the satellite in the CBLCD). In addition to spatially modifying the 2006 CBLCD, the following datasets were used to supplement the developed land cover data in the final CBP P5.3.2 land-use framework : U.S. Census housing unit data, Maryland Department of Planning (MDP) Property View data, and estimates of impervious coefficients for rural residential properties (determined via a sampling of these properties using aerial photography). This additional information was used to estimate the extent of impervious area in roadways and residential lots. Acres of construction and extractive land-uses were determined independently (Claggett *et al*. 2012). Finally, in order to develop accurate agricultural land-use acreages, the CBP P5.3.2 incorporated county level U.S. Agricultural Census data (USDA 1982, 1987, 1992, 1997, 2002). The

The result of these modifications is that CBP P5.3.2 land-use does not exist in a single GIS coverage; instead it is only available in a tabular format. The CBP P5.3.2 watershed model is comprised of 31 land-uses. Within each general land use type, most of the subcategories land-uses are differentiated only by their nitrogen and phosphorus loading rates. Land use, and consequently EOS nutrient loads, is directly available from the P5 model by county and river segment, but not at a finer scale.

For the revised P5 Liberty Reservoir Watershed Model, the RESAC land cover was used to determine the land use acreage for each subwatershed according to the following steps:

1. The acreage of RESAC land cover in each subwatershed was determined. Figure 2-2 shows the RESAC land cover in the Liberty Reservoir watershed.
2. The original RESAC land cover classification was aggregated into more general land cover classes as shown in Table 3-7.
3. These general classes correspond to general land cover classes used to describe model land use in Table 3-1. The P5.3.2 Model land use was also aggregated into these classes for each county.
4. The amount of each land cover class in each subwatershed was then adjusted until (1) the total land cover summed over the subwatersheds in the county agreed with the total model land cover for each county, and (2) the total size of the watershed was the same as the original size. Satisfying these two constraints meant that there was some deviation from the original proportion of each land cover class in individual subwatersheds. The resulting distribution land cover among the subwatersheds is shown in Table 3-8.
5. The acreage of land cover in Table 3-8 was converted to a matrix of the subwatershed fraction of each county's total land cover, by dividing the subwatershed acreage by the county total for each land cover class, as shown in Table 3-9.
6. The acreage of P5.3.2 Model land use by county was assigned to subwatersheds by multiplying the county land use acreage by the subwatershed fractions shown in Table 3-9, for each P5.3.2 land use.

Ideally, partitioning the model land use would satisfy the following constraints: (1) the area of each land use for each subwatershed would add up to the original model land use for the Liberty Reservoir segment; (2) the size of each subwatershed, as determined by the delineation, would be preserved; and (3) the proportion of model land use in each subwatershed would be the same as the proportion of acres of the general categories of land cover from the RESAC land cover in each subwatershed. These three constraints cannot be met simultaneously for all model land uses, because of the way the land cover is modified to produce the tabular land use. The general model land use was partitioned so that the first and second constraints were satisfied, while the third constraint was satisfied as closely as possible by trial and error.

Table 3-7: Classification of RESAC Land Cover

RESAC ID	RESAC Land Cover Class	General Class
1	Open water	Open water
3	Low-intensity developed	Urban
4	Medium-intensity developed	Urban
5	High-intensity developed	Urban
8	Transportation	Urban
10	Urban/residential deciduous trees	Urban
11	Urban/residential evergreen trees	Urban
12	Urban/residential mixed trees/forest	Urban
15	Urban/residential recreational grass	Urban
17	Extractive	Extractive
18	Barren	Construction
20	deciduous forest	Forest
21	evergreen forest	Forest
22	mixed forest	Forest
25	pasture/hay	Agriculture
26	croplands	Agriculture
30	natural grass	Agriculture
35	deciduous wooded wetland	Forest
36	evergreen wooded wetland	Forest
37	emergent wetland	Forest
38	mixed wetland	Forest

Table 3-8: Liberty Reservoir Land Cover by Subwatershed

County	Subshed	Developed	Extractive	Construction	Agriculture	Forest	Total
	1	1,013	0	35	1,304	6,240	8,592
	2	164	0	2	289	324	780
	8	211	0	21	160	1,359	1,751
	9	294	0	8	360	1,459	2,121
	10	519	0	11	1,175	1,490	3,195
	18	14	0	2	50	371	436
Baltimore	Total	2,215	0	78	3,339	11,243	16,875
	1	165	0	54	228	1,595	2,042
	2	10,188	0	294	14,972	9,440	34,894
	3	4,085	0	146	2,969	1,797	8,997
	4	1,477	0	13	1,776	657	3,924
	5	3,619	0	221	7,939	6,178	17,956
	6	1,515	0	57	1,470	1,413	4,455
	7	1,192	0	11	324	261	1,788
	9	482	0	6	58	205	751
	10	201	0	0	146	168	515
	11	211	0	3	112	62	387
	12	242	0	4	510	677	1,433
	13	276	0	8	359	493	1,136
	14	182	0	29	273	365	849
	15	8	0	1	40	215	264
	16	1,411	0	70	1,038	2,051	4,570
	17	1,183	0	29	123	594	1,929
Carroll	Total	26,436	0	944	32,338	26,170	85,888
	Total	28,651	61	133	30,829	37,413	28,651

Table 3-9: Liberty Reservoir Land Cover Fractions by Subwatershed

County	Subshed	Developed	Extractive	Construction	Agriculture	Forest
	1	0.46	0.00	0.45	0.39	0.55
	2	0.07	0.00	0.02	0.09	0.03
	8	0.10	0.00	0.27	0.05	0.12
	9	0.13	0.00	0.10	0.11	0.13
	10	0.23	0.00	0.14	0.35	0.13
	18	0.01	0.00	0.02	0.01	0.03
Baltimore	Total	1	0	1	1	1
	1	0.01	0.00	0.06	0.01	0.06
	2	0.39	0.00	0.31	0.46	0.36
	3	0.15	0.00	0.15	0.09	0.07
	4	0.06	0.00	0.01	0.05	0.03
	5	0.14	0.00	0.23	0.25	0.24
	6	0.06	0.00	0.06	0.05	0.05
	7	0.05	0.00	0.01	0.01	0.01
	9	0.02	0.00	0.01	0.00	0.01
	10	0.01	0.00	0.00	0.00	0.01
	11	0.01	0.00	0.00	0.00	0.00
	12	0.01	0.00	0.00	0.02	0.03
	13	0.01	0.00	0.01	0.01	0.02
	14	0.01	0.00	0.03	0.01	0.01
	15	0.00	0.00	0.00	0.00	0.01
	16	0.05	0.00	0.07	0.03	0.08
	17	0.04	0.00	0.03	0.00	0.02
Carroll	Total	1	0	1	1	1

3.5.2. Incorporation of the P5.3.2 Land Simulation into the P5.2 Community Model

As described in Section 3.2, unlike the standard implementation of HSPF, in the P5 Model land segments and river segments are simulated separately and connected through the ETM. This structure provided a avenue through which the P5.3.2 land simulation could be incorporated into the P5.2 Community Model. In all version of P5, loading rates from the land simulation on a per acre basis are written to a Watershed Data Management (WDM) database file. The ETM reads the WDM files in preparing the EOS inputs to the river reach simulation. To simulate P5.3.2 EOS loads within the version P5.2 Model, the output WDM files from the P.5.3.2 land simulation were obtained from CBPO and placed into the Phase 5.2 Model as if they had been produce by P5.2. This enables the P5.2 Model to mimic the EOS loads of P5.3.2.

Since the developed land use categories differ between P5.2 and P.3.2, regulated and non-regulated categories of pervious and non-pervious developed land were treated as if they were high density and low density urban land, respectively. The animal feeding operations (AFO) land use had to be treated differently, because under P5.3.2 AFO EOS loads are processed differently in the ETM than they are in P5.2. For this reason AFO

EOS loads were recalibrated within the P5.2 Model to approximate the P5.3.2 EOS loadning rates.

3.5.3 Forest Land Simulation Loads

Unlike other land uses, forest EOS loads were not taken from the P5.3.2 Model, but were calibrated separately so that the forest loading rates in Liberty Reservoir are consistent with the forest loading rates in the Gunpowder and Patuxent Reservoirs. As is explained in Section 6.0, to demonstrate that MD's DO standards are met, an All-Forest Scenario is simulated using the calibrated W2 Model to test whether hypoxia would still occur if the watershed was all-forested, i.e. under natural conditions. If hypoxia would persist under all-forested conditions, then the low DO concentrations observed in the bottom layers of Liberty Reservoir are a natural consequence of thermal stratification and not violations of MD's DO standards. It is therefore important to use the best available estimate of forest loading rate.

A forest loading rate was estimated for the Gunpowder Falls reservoir TMDLs from (1) the minimum background phosphorus concentrations found in soils of the MD Piedmont. 430 mg P/kg, as reported in McElroy *et al.* (1976); and (2) baseflow load of 0.06 lbs/ac/yr derived from monitoring data collected by the Baltimore County Department of Environmental Protection and Resource Management (BCDEPRM) in Mingo Branch, a primarily forested watershed (BCDEPRM, 2000). Conservatively assuming that stormflow phosphorus loads primarily transport eroded particulate phosphorus, the estimated phosphorus loading rate from forest is approximately 0.2 lbs/ac/yr. This rate is in agreement with median literature value reported by Beaulac and Rechow (1982).

In the P5 Model, a unit loading rate of 0.1 lbs/ac/yr is used across the Chesapeake Bay watershed as the target loading rate for forest land. In addition, a regional factor of 0.75 is applied to the forest loading rate in the Liberty Reservoir watershed, leading to an EOS load of 0.075 lbs/ac/yr. This rate is almost as small as the baseflow load observed in Mingo Branch and therefore appears to underestimate the phosphorus load from forests. For this reason, forest loading rates were calibrated to correspond to the rates used in the previous reservoir TMDLs. For consistency, the phosphorus loading rate from harvested forest was also adjusted to preserve the 10:1 ratio between forest and harvested forest loading rates generally used in the P5 Model.

3.5.4 BMPs

The P5 Model tracks the implementation of best management practices (BMPs) over time. The ETM takes into account the impact of BMPs by applying a reduction to EOS loads based on the number of acres under each BMP type on each land use and other factors. BMPs were simulated in the refined P5 Liberty Reservoir Watershed Model using the BMP acres from the P5.2 simulation of the Liberty Reservoir watershed. For each land use, the acres under each BMP type were distributed among the subwatershed in proportion to the percent of the county land use in the subwatershed.

3.5.5 EOS Loads

To summarize, in the P5 Model, the EOS load for a land use is equal to the product of (1) the per acre land simulation load; (2) number of acres of land use; (3) net BMP reduction; and (4) delivery factor (in the case of sediment) or regional factor In the case of nitrogen and phosphorus). Factors (1), (2), and (4) were taken from the version 5.3.2 of the P5 Watershed Model for all land uses except forest, harvested forest, and animal feeding operations. Factor (3) was taken from version 5.2. The level of simulated BMP implementation is small over the 2000 to 2005 simulation period in both versions of the P5 Model, so the P5 Liberty Reservoir Watershed Model EOS loads are equivalent to the P5.3.2 Model EOS loads. AFO loads were also adjusted to match P5.3.2 loads. Only EOS loads for forest and harvested forest diverge from their P5.3.2 counterparts, in order that their loading rates agree with previous reservoir phosphorus TMDLs.

3.5.6 Simulation of River Reaches in the Refined Liberty Reservoir Watershed Model

Some of the subwatersheds in the refined Liberty Reservoir Watershed Model represent well-defined tributaries to the reservoir; some of the subwatersheds represent direct drainage to the reservoir, or the drainage to tributaries below monitoring stations. The drainage representing tributaries below monitoring stations were combined with the direct drainage of their branches to simply the representation of subwatersheds. Table 3-10 shows which of the subwatersheds were combined to produce the final representation of Liberty Reservoir subwatersheds. It also shows the P5 ID given to the subwatershed and its associated reach. Figure 3-3 shows the final delineation of the Liberty Reservoir subwatersheds.

All subwatersheds--both tributaries and direct drainage--were represented by HSPF reaches, however, to facilitate imputing their flows and loads into the W2 model. F-Tables for the reaches were calculated using the methodology which the U. S. Geological Survey developed to calculate F-Tables for the P5 model. The USGS methodology calculates F-Tables from watershed area and hydrogeomorphic region (Moyer and Bennett, 2007). It is based on regressions relating average stream width and depth to watershed area by hydrogeomorphic region.

3.5.7 Point Sources, Atmospheric Deposition and Septic Systems

In addition to EOS loads, each simulated reach in the P5 Model receives loads from industrial and municipal point sources, septic systems, and direct atmospheric deposition. In the original version of the P5 Model, these sources are directly input into the reach representing Liberty Reservoir itself. In the revised P5 Liberty Reservoir Watershed Model, the original P5.3.2 loads from these sources were distributed among the refined reach network as follows:

Septic system loads consist solely of nitrate. The P5.3.2 septic system load was distributed among the refined reaches in proportion to the amount of pervious developed land in the subwatershed associated with the reach.

There are no municipal wastewater treatment plants in the Liberty Reservoir watershed. There are however, several industrial dischargers. Table 3-11 lists the industrial facilities and their associated average annual loads. Point source loads were taken from the P5.3.2 Model. These are aggregated loads for Baltimore and Carrroll Counties, not for individual facilities. These were assigned to the North Branch of the Patapsco River segment ZL1_9970_0001, where the majority of the facilities are located.

Atmospheric deposition loads of nitrogen and phosphorus are input into the P5 model on a per acre basis for land use acres classified as "water." In the original Liberty Reservoir segment, these water acres represent the reservoir itself. In the revised P5 Liberty Reservoir Model, atmospheric deposition of nitrogen and phosphorus were input into the reaches of the direct drainage segments shown in Table 3-6. The original P5.3.2 nitrogen and phosphorus loads of direct deposition were distributed among the segments in proportion to the contribution of the surface area of the section of the reservoir to which they drain. No atmospheric deposition of sediment on the reservoir itself was represented.

Table 3-10: Refined P5 Model Segments in Liberty Reservoir Watershed

Subshed	P5 ID	Name
2	ZL1_9970_0001	N. Branch Patapsco
3	ZL1_9971_0001	Beaver Run
4	ZL1_9972_0001	Middle Run
5	ZL1_9973_0001	Morgan Run
6	ZL1_9974_0001	Little Morgan Run
10	ZL1_9975_0001	Bonds Run
1,9, 11,14	ZL0_9980_0001	Liberty Direct Drainage
12,15	ZL0_9982_0001	Middle Run Direct Drainage
13,16	ZL0_9983_0001	Morgan Run Direct Drainage
7,17	ZL0_9984_0001	Snowden Run Direct Drainage
8,18	ZL0_9985_0001	Locust Run Direct Drainage

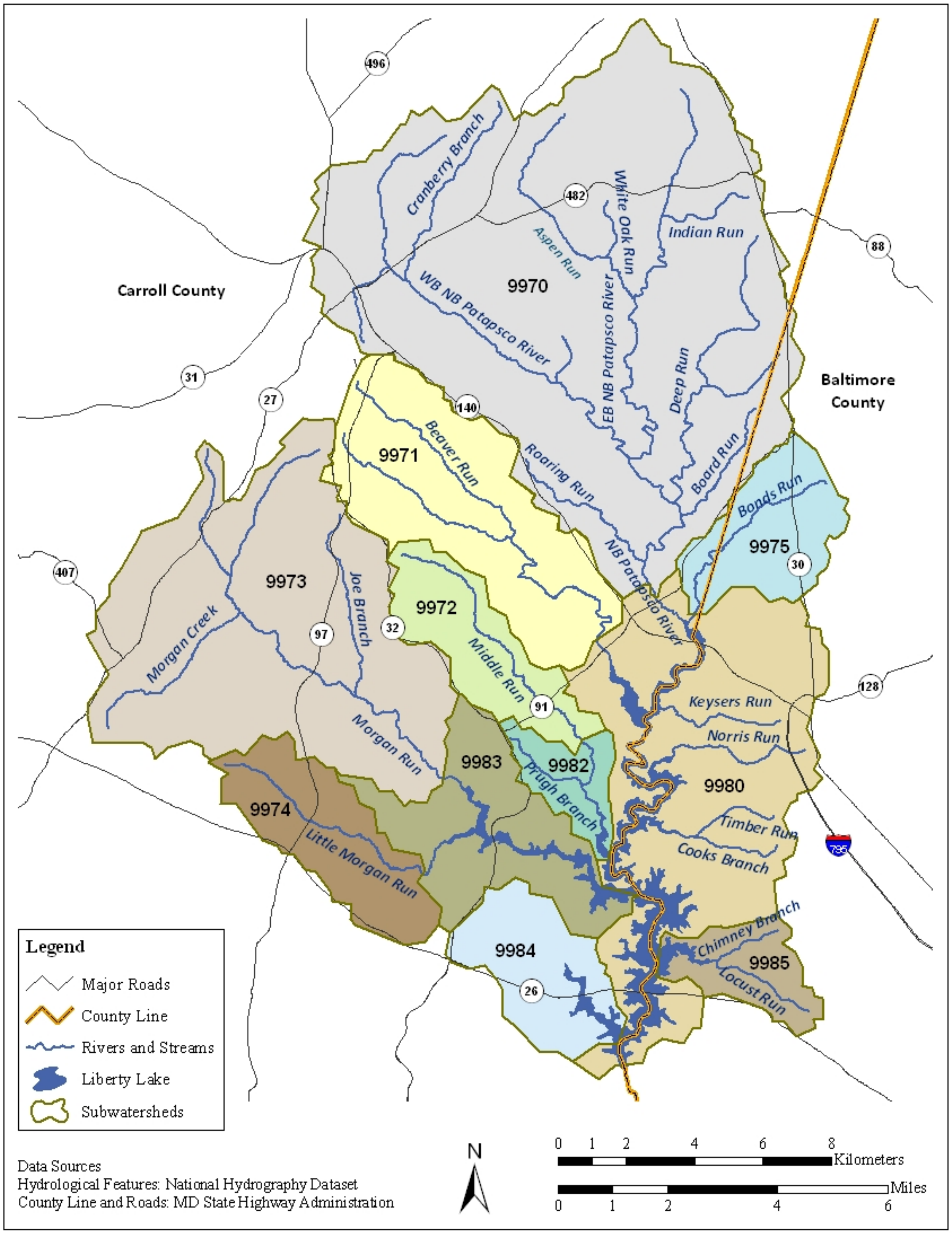

Figure 3-3: Final Subwatersheds in Refined P5 Model of Liberty Reservoir Watershed

Table 3-11: Average Annual Point Source Loads in P5 Liberty Reservoir Model

NPDES	FACILITY	Phosphorus	Sediment
MD0066982	MARYLAND MILITARY DEPT. - CAMP FRETTERD	4	<1
MD0001384	CONGOLEUM CORPORATION	166	2
MD0001881	BTR HAMPSTEAD, LLC.	3,234	4
MD0058556	CITY OF WESTMINSTER KOONTZ WELL	92	10
MDG492472	S & G CONCRETE - FINKSBURG PLANT	<1	<1
MD0068934	WESTMINSTER LAWN SERVICE,INC.	1	<1
Total		3,497	16

3.6 Monitoring Data in the Liberty Reservoir Watershed

Both flow and water quality monitoring data has been collected in the Liberty Reservoir watershed. This data was not used to calibrate the CBP P5 Model representation of Liberty Reservoir, because it is a single segment with its outlet at the outlet of the reservoir, but it is available for calibration on a smaller scale. Sections 3.6.1 and 3.6.2 describe the available flow and water quality data, respectively.

As stated earlier, the purpose of the Liberty Reservoir watershed model is to provide flows and constituent loads on a refined scale to the W2 model of the Liberty Reservoir. For this reason, the simulation of reach processes was compared to estimates of sediment and nutrient loads determined using the USGS software LOADEST. Section 3.6.3 describes the development of sediment and nutrient load targets based on LOADEST.

3.6.1 USGS Flow Daily Flow Data

There were four active USGS gages in the Liberty Reservoir watershed. Table 3-12 gives the name, gage number, drainage area, and modeling segment for each gage. The gage on Cranberry Branch (01585500) drains an area of only three square miles which is below the scale of even the refined segmentation. Figure 3-4 shows the location of the other gages.

Table 3-12: USGS Gages in the Liberty Reservoir Watershed

Gage ID	Name	Drainage Area (mi^2)	Period of Record	Segment
01585500	Cranberry Branch near Westminster	3.29	1949-	Not Applicable
01586000	North Branch Pataspco River at Cedarhurst	56.5	1945-	ZL1_9970_0001
01586210	Beaver Run near Finkburg	14.0	1982-	ZL1_9971_0001
01586610	Morgan Run near Louisville	28.0	1982-	ZL1_9973_0001

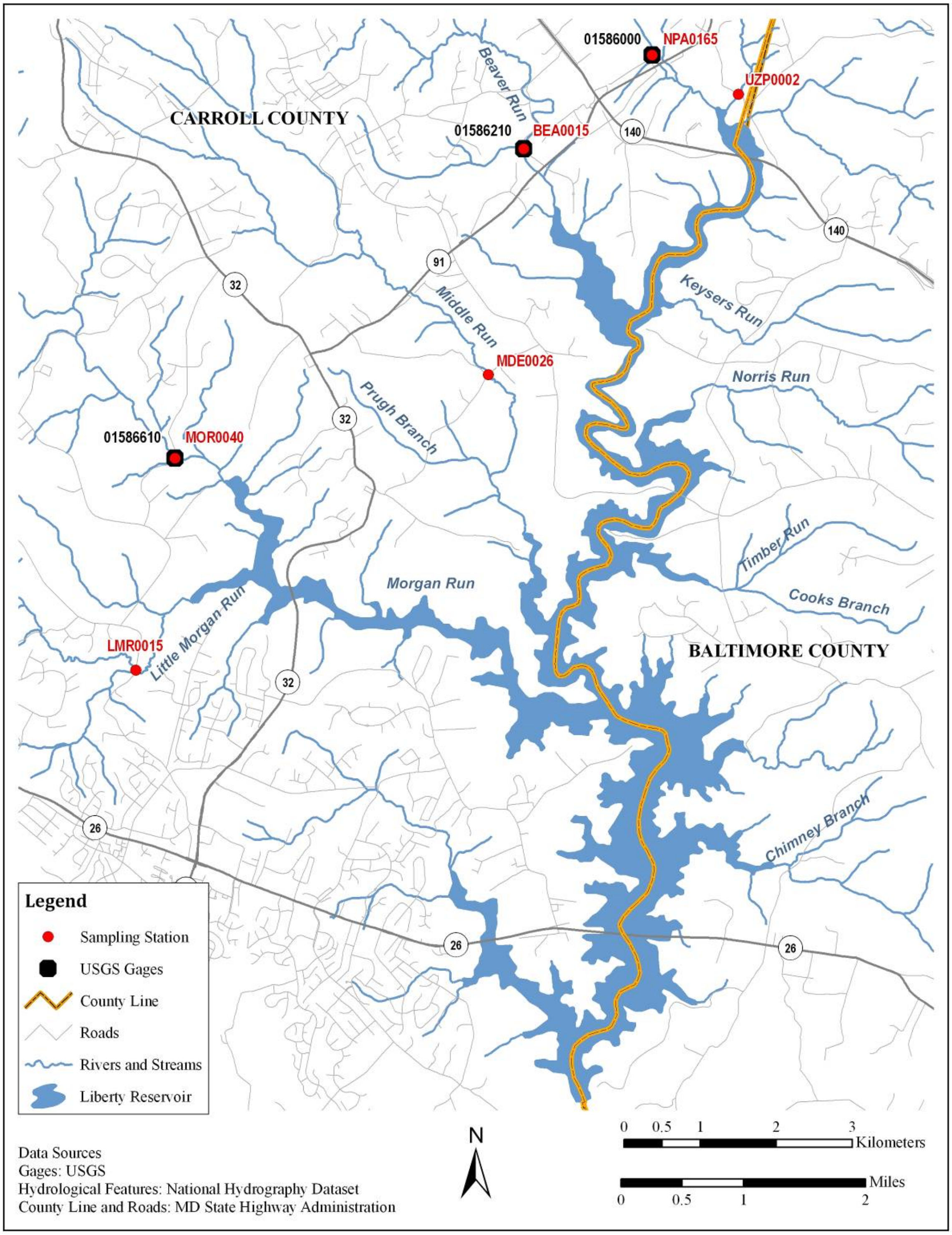

Figure 3-4: Location of USGS Gages and BCDPW Monitoring Stations in the Liberty Reservoir Watershed

3.6.2 Water Quality Monitoring in the Liberty Reservoir Watershed

BCDPW collects water quality monitoring data at six locations in the Liberty Reservoir watershed. Figure 3-4 shows the location of the monitoring stations. At three locations both storm sampling and ambient monitoring are conducted. These stations are coincident with USGS gages. At three other locations only ambient monitoring data is collected. Table 3-13 gives the location of the stations, the P5 IDs of the reaches they are located on in the watershed model, and the type of samples collected. Table 3-14 shows which constituents analyzed by sample type. Storm samples are collected irregularly; ambient samples are collected approximately once a month.

Table 3-13: Water Quality Monitoring Stations in the Liberty Reservoir Watershed

Station	Location Description	P5 Reach	Monitoring Type
BEA0015	Beaver Run at Hughes Rd.	ZL1_9971_0001	Storm
LMR0015	Little Morgan Run at Bartholow Rd.	ZL1_9974_0001	Ambient
MDE0026	Middle Run at Louisville Rd.	ZL1_9972_0001	Ambient
MOR0040	Morgan Run at London Bridge Rd.	ZL1_9971_0001	Storm
NPA0165	North Branch Patapsco at Rte. 91,	ZL1_9970_0001	Storm
UZP0002	Bonds Run at Hollingsworth Rd.	ZL1_9975_0001	Ambient

Table 3-14: Constituents Analyzed by Sample Type

Constituent	Ambient	Storm
Temperature	X	
Conductivity	X	
Volatile Suspended Solids	X	
Total Suspended Solids	X	X
Ammonia-Nitrogen	X	X
Nitrate-Nitrogen	X	X
Dissolved Phosphorus	X	
Total Phosphorus	X	X

3.6.3. Determination of Target Sediment and Nutrient Loads Using LOADEST

As will be shown in Section 4, phosphorus is the limiting nutrient in Liberty Reservoir, and the nutrient TMDL will be expressed in total phosphorus. Storm-driven sediment loads will transport much of the phosphorus loads to the reservoirs; Liberty Reservoir also has a sediment impairment that will be addressed by a sediment TMDL. It is important, therefore, that the Liberty Reservoir Watershed Model represent storm loads of phosphorus and sediment accurately.

It is difficult to determine, however, the nutrient and sediment loads in storms, unless continuous monitoring is performed, because storm concentrations of nutrients and sediments are highly variable. It is generally agreed that concentrations of sediment and total phosphorus increase with flow. Concentrations vary, however, both between storms and within storms. Statistical inference is therefore necessary to determine storm loads from monitoring data.

The USGS has developed a software program, LOADEST, for that purpose (Runkel et al, 2004). LOADEST calculates daily, monthly, or annual constituent loads based on observed daily average flows and grab-sample monitoring data. LOADEST is the official enhanced version of the software ESTIMATOR, which was used in previous MD phosphorus and sediment TMDLs to calculate loads from gauged flows and monitoring data (ICPRB and MDE, 2006; ICPRB, 2008) ESTIMATOR has also been used to calculate nutrient and sediment loads for the RIM (River Input Monitoring) program for the Chesapeake Bay Program, as well as estimate sediment and nutrient trends in the region. Cohn et al. (1989) and Cohn et al. (1992) give the theory behind ESTIMATOR. Langland et al. (2001, 2005) demonstrate the application of ESTIMATOR in the Chesapeake Bay Watershed.

LOADEST is capable of estimating loads using three different methods: Maximum Likelihood Estimation (MLE); Adjusted Maximum Likelihood Estimation (AMLE); and Least Absolute Deviation (LAD). The AMLE method is the LOADEST implementation of ESTIMATOR. It contains four elements. The heart of AMLE is a multiple regression equation which relates the log of constituent concentrations to flow, time and season. The equation for C, the constituent concentration, takes the following form:

$$\ln[C] = \beta_0 + \beta_1 \ln[Q] + \beta_2 \ln[Q]^2 + \beta_3 T + \beta_4 T^2 + \beta_5 \mathrm{Sin}[2^* \pi T] + \beta_6 \mathrm{Cos}[2^*\pi T] + \varepsilon$$

Where

Q is the daily discharge
T is time, expressed in years

The flow and time variables are centered so that terms are orthogonal. The regression relation is essentially a multivariate rating curve, which takes into account temporal trends and seasonal trends as well as trends in flow.

The second element of AMLE is the use of a minimum variance unbiased estimator (MVUE) procedure to obtain estimates of concentrations and loads from the log of constituent concentrations determined from the regression. Cohn et al. (1989) describe the motivations for using the MVUE procedure, as opposed to simpler methods.

The third element of AMLE is the use of tobit regression to estimate the regression equation when there is observations below the detection limit. Tobit regression, in contrast to ordinary least squares, uses the method of maximum likelihood to estimate regression parameters.

The final element, and the one which distinguishes AMLE from MLE, is the use of adjusted likelihood estimate to remove first-order bias introduced by the use of tobit regression. Runkel *et al*. (2004) discusses in more detail the AMLE methodology and LOAEDEST in general.

The transformed constituent concentrations are combined with daily flows to estimate daily, monthly, and annual loads. Standard errors, confidence intervals, and standard errors of prediction can also be calculated.

In order for LOADEST to provide good estimates of nutrient and sediment loads, monitoring data must be available over the range of flows for which loads are to be calculated. In particular, there must be monitoring data taken during storm events. As noted in Section 3.6.2, BCDPW has performed storm sample monitoring in the Liberty Reservoir watershed at USGS gage locations on the North Branch of the Patapsco River, Beaver Run, and Morgan Run. LOADEST was used to calculate the total load of suspended sediment and total phosphorus at these locations. LOADEST was run using all available monitoring data 1984-2008. Average annual loads are reported for the simulation period 2001-2005. Tables 3-15, 3-16, 3-17, and 3-18 show the LOADEST results for sediment, total phosphorus, ammonia, and nitrate, respectively, at these locations. The coefficient of determination is between 0.7 and 0.87 for all regressions, which shows that the LOADEST models reasonably represent the variability in the observed data. The serial correlation coefficients are generally higher than desirable, but that is typical when storm sampling is used to fit the regression equations.

Table 3-15: Coefficients of Regression Equation and Regression Statistics, Total Suspended Sediment

Coefficient or Statistic	Beaver Run	Morgan Run	North Branch Patapsco River
Constant	7.3219	7.8850	9.1724
Log Flow	2.7455	2.6933	2.5532
Log Flow2	-0.0518	-0.0097	0.0026
Sin (2π*Time)	0.7454	0.2605	0.2476
Cos(2π*Time)	-0.3215	-1.0142	1.0028
Time (years)	-0.0758	-0.0472	-0.0341
Time2	0.0038	0.0033	0.0029
Number of Observations	733	722	730
Coefficient of Determination (R^2)	69.81	74.42	78.27
Probability Plot Correlation Coefficient	0.9980	0.9959	0.9976
Serial Correlation Coefficient	0.5537	0.5722	0.5028
Average Annual Load (tons)	3,781	11,292	16,224

Table 3-16: Coefficients of Regression Equation and Regression Statistics, Total Phosphorus

Coefficient or Statistic	Beaver Run	Morgan Run	North Branch Patapsco River
Constant	1.5717	2.1749	3.1961
Log Flow	2.1938	2.1509	2.1095
Log Flow2	0.0091	0.0094	0.0638
Sin (2π*Time)	0.6414	-0.2319	0.5723
Cos(2π*Time)	-0.2359	-0.7650	-0.1856
Time (years)	-0.0439	-0.0313	-0.0354
Time2	0.0027	0.0039	0.0041
Number of Observations	587	597	623
Coefficient of Determination (R^2)	78.37	81.35	85.53
Probability Plot Correlation Coefficient	0.9949	0.9967	0.9939
Serial Correlation Coefficient	0.4553	0.5025	0.4230
Average Annual Load (lbs)	6,130	17,342	32,770

Table 3-17: Coefficients of Regression Equation and Regression Statistics, Ammonia Nitrogen

Coefficient or Statistic	Beaver Run	Morgan Run	North Branch Patapsco River
Constant	0.6300	1.2435	2.2697
Log Flow	1.8309	1.6154	1.7186
Log Flow2	0.1070	0.0883	0.2172
Sin (2π*Time)	-0.0234	-0.0035	0.0211
Cos(2π*Time)	-0.1836	-0.0303	0.2033
Time (years)	-0.0915	-0.0631	-0.0743
Time2	-0.0013	0.0004	-0.0007
Number of Observations	532	528	535
Coefficient of Determination (R^2)	78.35	80.14	80.89
Probability Plot Correlation Coefficient	0.9887	0.9923	0.9972
Serial Correlation Coefficient	0.4064	0.4384	0.4489
Average Annual Load (lbs)	1,133	2,623	8,541

Table 3-18: Coefficients of Regression Equation and Regression Statistics, Nitrate Nitrogen

Coefficient or Statistic	Beaver Run	Morgan Run	North Branch Patapsco River
Constant	5.3095	6.0351	6.8412
Log Flow	0.7850	0.8184	0.7386
Log Flow2	-0.0547	-0.0295	-0.0416
Sin (2π*Time)	0.1322	0.1459	0.0320
Cos(2π*Time)	-0.1269	-0.0317	0.1750
Time (years)	-0.0034	-0.0103	-0.0180
Time2	-0.0015	-0.0035	-0.0038
Number of Observations	520	521	527
Coefficient of Determination (R^2)	86.53	79.57	73.01
Probability Plot Correlation Coefficient	0.8049	0.7865	0.8016
Serial Correlation Coefficient	0.4515	0.5249	0.4672
Average Annual Load (lbs)	106,907	183,993	435,843

3.7 River Reach Simulation

In the TMDLs for the Gunpowder and Patuxent Reservoirs, simulated nutrient and sediment loads from the river reach network were calibrated against the average annual loads as calculated using ESTIMATOR. The calibration of in-stream processes, primarily deposition and scour, were used to adjust the EOS loads entering the reaches with the ESTIMATOR targets. The net contribution of these river reach processes was reported as a source, along side land uses sources and point sources.

Within the P5 Model framework, however, EOS loads represent the load entering the river reach. In the case of the Liberty Reservoir reach segment, that reach is Liberty Reservoir itself. Conceptually, therefore, the EOS loads from the P5.3.2 Model represent the input loads from the Liberty Reservoir tributaries, and already account for deposition and scour of sediment and other constituents in those tributaries. The land use EOS loads in effect include the in-stream contribution of tributaries to Liberty Reservoir such as the North Branch of the Paptasco River or Morgan Run.

The adequacy of this conception of EOS loads from the P5.3.2 Model was tested by comparing the simulated EOS loads with the average annual loads from LOADEST for the simulation period 2000-2005. As discussed in Section 3.7.3 below, average annual sediment and nutrient loads from the P5 Liberty Reservoir Watershed Model are within the confidence interval for the corresponding average annual loads from LOADEST. Total phosphorus and nitrate loads also match the average annual loads fairly closely; sediment loads do not, but, as is explained in Section 3.7.3, there is evidence that the average annual sediment load calculated using LOADEST overestimates the actual sediment loads during the 2000-2005 simulation period.

Although agreement with the observed data was primarily measured by the relation between the confidence interval of the average annual load in LOADEST and the average annual load simulated by the P5 Liberty Reservoir Watershed Model, model results were also compared with LOADEST estimates at annual and monthly scales. As can be expected, there is less agreement at smaller time intervals; however, since residence time in Liberty Reservoir over the simulation period, as estimated by the W2 model, is approximately 500 days, the impact on water quality at smaller time scales can be expected to be small.

In contrast, therefore to the watershed models for previous reservoir TMDLs, there was no extensive calibration of the river reach simulation in the Liberty Reservoir Watershed Model. As described in Section 3.7.1, the hydrology simulation was compared with observed flows from the USGS gages in the watershed. Although the correlation between simulated and observed daily average flows was not as strong as in other reservoir TMDLs, the correlation between monthly average flows was good. The temperature simulation, as described in Section 3.7.2, was calibrated successfully. The nitrification rate, which controls the transformation of ammonia into nitrogen, was adjusted to calibrate ammonia and nitrate loads. In all other respects in-stream processes were turned off so that river reaches conservatively conveyed the EOS loads to the reservoir.

3.7.1 Hydrology Simulation

The hydrology simulation in HSPF is primarily a function of the land simulation. The PERLND and IMPLND simulation determine the water balance and the routing of flows through the hydrological cycle. Table 3-19 shows the results of comparing observed and simulated flow volumes and the coefficient of determination (R^2) for the simulation of the North Branch of the Patapsco River, Beaver Run, and Morgan Run, where daily average flow data were available from the USGS gages described in Section 3.6.1. There is good agreement in the overall water balance. Total storm flow volume is captured by the hydrology simulation, but low flows (flows less than the 50^{th} percentile flow) are undersimulated. Agreement between observed and simulated daily flows, as measured by the coefficient of determination, is fair at best and rather poor in the case of the North Branch of the Patapsco River. The agreement between monthly flows is good, with the coefficient of determination above 0.75 for all three reach simulations.

Table 3-19: Hydrology Calibration Results

Statistic	North Branch of Patapsco River	Beaver Run	Morgan Run
Water Balance	103%	111%	103%
Flows < 50^{th} Percentile	79%	67%	78%
Flows > 90^{th} Percentile	109%	98%	98%
Daily R^2	0.37	0.52	0.50
Monthly R^2	0.76	0.78	0.77

Figures A-1 through A-3 show the time series, scatter plot, and cumulative distribution, respectively, of daily observed and simulated flows for the North Branch of the Patapsco River. Figure A-4 shows a scatter plot of observed and simulated average monthly flow for the Patapsco River. Figures A-5 through A-8 and A-9 through A-12 show the same series of graphs for Beaver Run and Morgan Run, respectively.

An attempt was made to improve the hydrology calibration using PEST (Doherty, 2001), the parameter optimization software, as has been used to calibrate the hydrology in both the HSPF models for both the Patuxent Reservoirs and the Gunpowder Falls reservoirs. The results were disappointing. The improvement in the calibration statistics were minor and certainly not worth the effort that would have been required to recalibrate the EOS loads for sediment, nitrogen, and phosphorus if the P5 hydrology simulation had been changed.

3.7.2 Temperature Calibration

Inflow temperatures are an important factor in determining temperature dynamics and the dynamics of stratification in reservoirs. PEST was successfully used to help calibrate the simulation of water temperatures in river reaches. Because temperature can vary considerably during the day, the objective function used in the calibration was the sum of the differences between observed and simulated hourly temperatures. Table 3-20 shows the parameters varied during the calibration for each reach with temperature monitoring data on it. Table 3-21 shows the final calibration parameters and the coefficient of determination between observed and simulated hourly temperature at the calibration points.

Table 3-20: Temperature Calibration Parameters

Parameter	Description
CFSAEX	Solar radiation correction factor; fraction of exposed reach surface.
KATRAD	Longwave radiation coefficient.
KCOND	Conduction convection heat transport coefficient.
KEVAP	Evaporation coefficient.

Table 3-21: Calibrated Reach Temperature Parameters and Coefficient of Determination (R^2)

Reach	CFSAEX	KATRAD	KCOND	KEVAP	R^2
9970	0.00632	10.70	19.50	1.65	0.969
9971	0.00269	10.73	20.00	1.00	0.970
9972	0.00237	11.21	20.00	1.00	0.970
9973	0.00739	11.32	20.00	3.70	0.965
9974	0.00420	10.50	20.00	1.40	0.960
9975	0.00960	10.89	18.64	1.01	0.969

3.7.3 River Reach Simulation

Table 3-22 compares the average annual loads, 2000-2005, from the P5 Liberty Reservoir Watershed Model with the average annual loads determined by LOADEST. It also shows the upper and lower bounds for the 95% confidence interval for the average annual LOADEST loads. No gains or losses from instream processes are simulated for phosphorus and sediment in the Liberty Reservoir Watershed Model; the average annual loads are the EOS loads for those constituents. For ammonia and nitrate, adjustments were made to the nitrification rate so that the average annual loads from the Watershed Model better matched the loads from LOADEST. There is no net gain or loss of inorganic nitrogen in the river reaches, so the combined total of the average annual load of these two constituents is the same as the combined total of the EOS loads.

As Table 3-22 shows, the average annual loads from the Watershed Model are within the confidence intervals for the corresponding average annual loads from LOADEST for all four constituents for all three watersheds except for nitrate in Beaver Run. Moreover, if the loads from the three watersheds are combined, with the exception of sediment, the total combined average annual loads of ammonia, nitrate, and total phosphorus from the Watershed Model are within 6% of the corresponding combined average annual loads from LOADEST. These combined loads are the best guide to whether the total watershed load of these constituents as simulated by the Watershed Model would match the corresponding total loads if the LOADEST results were extrapolated from these three watersheds, which account for approximately 60% of the total watershed area, to the entire watershed. Thus the comparison of the average annual loads from the Watershed

Model with the corresponding loads from LOADEST validates that the P5.3.2 EOS loads are the loads delivered to Liberty Reservoir and that no contribution from instream sources in the tributaries needs to be explicitly simulated.

Table 3-22: Comparison of Average Annual Loads between P5 Liberty Reservoir Model and LOADEST (Sediment in tons/yr; all other constituents in lbs/yr)

Watershed	Constituent	P5 Average Annual Load	LOADEST Average Annual Load	LOADEST 95% Lower CI	LOADEST 95% Upper CI	P5 With LOADEST CI?	Difference in Average Annual Loads
NB Patapsco River	NH3X	7,878	8,541	5,078	13,503	TRUE	-8%
	NO23	404,620	435,843	402,963	470,549	TRUE	-7%
	TOTP	33,096	32,770	18,972	52,864	TRUE	1%
	TSED	9,542	16,224	3,854	45,827	TRUE	-41%
Beaver Run	NH3X	1,110	1,133	687	1,768	TRUE	-2%
	NO23	95,745	106,907	101,544	112,479	FALSE	-10%
	TOTP	7,510	6,130	2,853	11,592	TRUE	23%
	TSED	2,631	3,781	354	15,779	TRUE	-30%
Morgan Run	NH3X	2,755	2,623	1,480	4,318	TRUE	5%
	NO23	185,870	183,993	170,253	198,533	TRUE	1%
	TOTP	14,685	17,342	6,152	39,120	TRUE	-15%
	TSED	4,817	11,292	855	50,518	TRUE	-57%
Combined Watersheds	NH3X	11,743	12,297				-5%
	NO23	686,235	726,743				-6%
	TOTP	55,291	56,243				-2%
	TSED	16,990	31,298				-46%

Although the average annual sediment loads from the Watershed Model are within the confidence intervals for the average annual LOADEST loads in all three watersheds, the combined average annual sediment load from the three watersheds is only about half the value determined by LOADEST. Of course, the fact that the Watershed Model sediment loads could be half the LOADEST loads and still be within the confidence interval of the LOADEST loads is indicative in the uncertainty in the LOADEST estimates. Nevertheless, this mismatch in average annual loads seems to violate the spirit of the methodology used in previous reservoir TMDLs, where the average annual loads from ESTIMATOR were used to set the load targets for the river reach simulations in the HSPF models of the reservoir watersheds.

There are two strands of evidence, however, that the average annual LOADEST sediment loads overestimate the sediment loads delivered to Liberty Reservoir from the watershed. First, if the average annual LOADEST sediment loads are accurate, then at least half of the sediment load in the watershed would have to be derived from instream scour. As explained in Section 3.3.2, Crop and pasture sediment loads account for half of the EOS loads in the Liberty Reservoir watershed. EOF loads from crop and pasture are based on local estimates from the NRI, and are therefore not likely to have as much uncertainty associated with them as the LOADEST average annual loads. Sediment loads from developed land account for 37% of the total load. EOS loads from developed land incorporate the effect of impervious cover on instream scour, and the total erosion rate from developed load primarily is associated with instream sources, rather than "end-of-pipe" discharges from storm sewers. Instream erosion therefore have to be approximately the difference between the LOADEST estimate and the loads attributable to crop and pasture, adjusted for minor sources, and there should be extensive evidence of fairly severe bank and bed erosion in the tributaries to Liberty Reservoir.

This, however, is not the case. MDE performed a Biological Stressor Identification (BSID) analysis to determine the cause of biological impairments in the 1st through 4th order streams in the Liberty Reservoir watershed (MDE, 2012b). For each potential stressor, the BSID analysis compares impaired biological sites in the watershed to control or reference sites in the same ecoregion using a methodology adopted from epidemiology: the odds ratio. The odds ratio measures the strength of association between a stressor and biological impairment by calculating whether the presence of the stressor significantly increases the odds of biological impairment, when compared to control or reference sites. Twelve sediment-related stressors were tested, including poor bank stability index scores, high embeddedness, and the presence of moderate to severe erosion. None of the twelve showed significantly higher odds of impairment than the control group. Therefore, the BSID analysis did not identify sediment as a biological stressor.

The BSID analysis is corroborated by a watershed characterization and stream corridor assessment survey performed by the Maryland Department of Natural Resources in support of Carroll County's Watershed Restoration Action Strategy (WRAS) for the Liberty Reservoir Watershed. According to the watershed characterization (DNR, 2002), although stream erosion contributed to the degradation of habitat in those sites where habitat was degraded, generally physical stream habitat in the Liberty Reservoir watershed is in good condition. DNR also performed a stream corridor assessment survey on the West Branch of the Patapsco River, Middle Run, and Snowden Run as part of the WRAS (DNR, 2003). These three watersheds account for approximately one-quarter of the overall Liberty Reservoir watershed. Overall 121 miles of stream were surveyed, and 31 miles total were identified as having erosion problems. Only 50 of 150 sites with erosion problems had evidence of severe erosion, while 41 sites had moderate erosion and 59 sites had mild erosion.

The second strand of evidence comes from the Maryland Geological Survey (Ortt and Wells, 2001), who conducted at bathymetric survey of Liberty Reservoir in 2001. MGS estimated that between 1975 and 2001, the reservoir lost on an average annual basis 28.8 acre-ft/yr of capacity per year. MGS also took 45 sediment samples; measurements of the percent water weight of the sediment averaged about 61%. Assuming a sediment density of 2.72 g/cm^3 and a 100% trapping efficiency, the average annual sediment load deposited in Liberty Reservoir is approximately 23,000 tons/yr, which is close the average annual load from the P5 Model and again only about half of the LOADEST estimate.

Based on these two lines of evidence, together with the fact that the P5 EOS loads are within the range of uncertainty of LOADEST (and therefore, in effect, of the observed data), it seems reasonable to accept the CBP interpretation of the EOS sediment loads as the loads delivered to Liberty Reservoir from its tributaries, even though this violates the spirit of the methodology used in the previous reservoir TMDLs. Therefore, even for sediment, in-stream processes like scour were not simulated and make no explicit contribution to the input loads to Liberty Reservoir. Implicitly, however, they are incorporated into the EOS loads from specific land uses.

3.7.3.1 Sediment Simulation

Figures A-13, A-14 and A-15 in Appendix A show time series of annual sediment loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-16, A-17 and A-18 in Appendix A show scatter plots comparing annual sediment loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. In the North Branch of the Patapsco and Beaver Run, the P5 Model simulates the interannual variability found in LOADEST: the coefficient of determination (R^2) is 0.68, and 0.70, respectively. In Morgan Run there is less agreement in the P5 and LOADEST loads on an annual basis, with a coefficient of determination of 0.31. Generally, in all three watersheds, P5 annual loads are higher than LOADEST loads in the dry years (2000-2002) and lower in the wet years (2003-2005). In most cases, however, the P5 annual loads are within the 95% confidence interval for the LOADEST loads.

Figures A-19, A-20 and A-21 in Appendix A show time series of monthly sediment loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-22, A-23 and A-24 in Appendix A show scatter plots comparing monthly sediment loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Both set of figures use log scale, because monthly loads vary by several orders of magnitude. The coefficients of determination (R^2) between P5 monthly loads and LOADEST loads are 0.43, 0.46, and 0.42, for the Patpasco River, Beaver Run, and Morgan Run, respectively. For the Pataspco River, Beaver Run, and Morgan Run, 78%, and 57% of the monthly P5 loads are within the confidence interval for the monthly LOADEST loads, respectively.

In general, there is less agreement between P5 and LOADEST in Morgan Run than in the other two watersheds. This is due in part to the fact that 66%, 62%, and 51% of the sediment, phosphorus, and ammonia loads, respectively, in Morgan Run during the simulation period occur in the very wet year 2003; in contrast, only about 40% of the total loads occur in 2003 in the other two watersheds (Nitrate loads are not as strongly correlated with flow as the other constituents.). The difference in the estimate of 2003 loads, where the uncertainty is highest, counts for more in Morgan Run than in the Patapsco River and Beaver Run.

3.7.3.2 Phosphorus Simulation

Figures A-25, A-26 and A-27 in Appendix A show time series of annual total phosphorus loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-28, A-29 and A-30 in Appendix A show scatter plots comparing annual total phosphorus loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Like sediment, annual P5 phosphorus loads are higher than their LOADEST counterparts in the wet years and lower in the dry years. P5 annual loads are within the 95% confidence interval of the LOADEST loads only in the wet years. The coefficients of determination (R^2) are stronger for phosphorus than sediment, with R^2 values of 0.94, 0.92, and 0.78 for the Patpasco River, Beaver Run, and Morgan Run, respectively.

Figures A-31, A-32, and A-33 in Appendix A show time series of monthly total phosphorus loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-34, A-35, and A-36 in Appendix A show scatter plots comparing monthly total phosphorus loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Both set of figures use log scale, because monthly loads vary by several orders of magnitude. The coefficients of determination (R^2) between P5 monthly loads and LOADEST loads are 0.52, 0.58, and 0.53, for the Patpasco River, Beaver Run, and Morgan Run, respectively. About half the P5 monthly loads are within the corresponding confidence intervals of LOADEST loads, and these are fairly evenly spread throughout the simulation period.

3.7.3.3 Nitrogen Simulation

Figures A-37, A-38 and A-39 in Appendix A show time series of annual ammonia loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-40, A-41 and A-42 in Appendix A show scatter plots comparing annual ammonia loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. The coefficients of determination (R^2) between P5 are loads and LOADEST loads fairly low: all values are below 40%. Two-thirds of the P5 annual loads are within the confidence intervals of their LOADEST counterparts, however.

Figures A-43, A-44, and A-45 in Appendix A show time series of monthly ammonia loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-46, A-47, and A-48 in Appendix A show scatter plots comparing monthly ammonia loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Both set of figures use log scale, because monthly loads vary by several orders of magnitude. The coefficients of determination (R^2) between P5 monthly loads and LOADEST loads are 0.51, 0.43, and 0.59, for the Patpasco River, Beaver Run, and Morgan Run, respectively, and more than half the P5 monthly loads are within the corresponding confidence intervals of LOADEST loads.

Figures A-49, A-50 and A-51 in Appendix A show time series of annual nitrate loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-52, A-53 and A-54 in Appendix A show scatter plots comparing annual nitrate loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Nitrate loads do not vary with flow as much as the other constituents, and generally speaking, there is less variability and less uncertainty in the LOADEST annual loads. The coefficients of determination (R^2) between P5 annual loads and LOADEST loads are high: 0.85, 0.96, and 0.96, for the Patpasco River, Beaver Run, and Morgan Run, respectively, but in contrast to the other constituents, annual P5 loads are within the confidence intervals of their LOADEST counterparts no more than half the time.

Figures A-55, A-56, and A-57 in Appendix A show time series of monthly nitrate loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Figures A-58, A-59, and A-60 in Appendix A show scatter plots comparing monthly nitrate loads from the P5 Model and LOADEST for the North Branch of Patapsco River, Beaver Run, and Morgan Run, respectively. Because the variation in monthly nitrate loads is smaller than for other constituents, the figures are not log-transformed. The coefficients of determination (R^2) between P5 monthly loads and LOADEST loads are 0.54, 0.59, and 0.46, for the Patpasco River, Beaver Run, and Morgan Run, and 43%, 19%, and 39% of the monthly P5 loads are within the confidence interval for the monthly LOADEST loads, respectively.

3.8 Sediment, Phosphorus, and Nitrogen Loads from the Refined Liberty Reservoir Watershed Model

Table 3-23 shows the average annual sediment loads, 2000-2005, from the refined Liberty Reservoir P5 Watershed Model. Tables 3-24 and 3-25 show the average annual total phosphorus and total nitrogen loads, respectively, from the Liberty Reservoir Watershed Model.

Crops are the largest source of sediment, contributing about 47.7% of the load. Regulated urban land contributes about 37.1% of the load, and forests contribute 11.5% of the load.

Crops are also the largest source of phosphorus, contributing 39.6% the average annual load. Regulated urban land is the next largest source, contributing 29.0% of the load. Forest (8.8%), nurseries (8.0%), and pasture (6.2%) also contribute significantly to the average annual phosphorus load.

Crops are again the largest source of total nitrogen, contributing 31.6% of the average annual load. Animal feeding operations are the second largest source, accounting for 25.7% of the load. Regulated developed land contributes 17.2% of the load and forests contribute 12.6% of the load.

Table 3-23: Liberty Reservoir Watershed Detailed Baseline Total Sediment Loads

General Land-Use	Detailed Land-Use	Maryland		
		Load (lbs/yr)	**Percent** (%)	**Grouped Percent of Total %**
Forest	Forest	3,058	10.8%	11.5%
	Harvested Forest	212	0.7%	
AFOs	Animal Feeding Operations	84	0.3%	0.3%
Pasture	Pasture	801	2.8%	2.8%
Crop	Crop	13,542	47.7%	47.7%
Nursery	Nursery	147	0.5%	0.5%
Regulated Urban	Construction	3,606	12.7%	37.1%
	Developed	6,945	24.4%	
	Extractive	0	0.0%	
Septic	Septic	0	0.0%	0.0%
CSO	CSO	0	0.0%	0.0%
Point Sources	Industrial Point Sources	16	0.1%	0.1%
	Municipal Point Sources	0	0.0%	
Atmospheric Deposition	Non-tidal Atmospheric Deposition	0	0.0%	0.0%
Total		**28,411**	**100.0%**	**100.0%**

Table 3-24: Liberty Reservoir Watershed Detailed Baseline Total Phosphorus Loads

General Land-Use	Detailed Land-Use	Maryland Load (lbs/yr)	Maryland Percent (%)	Maryland Grouped Percent of Total %
Forest	Forest	6,974	8.5%	8.8%
	Harvested Forest	280	0.3%	
AFOs	Animal Feeding Operations	2,199	2.7%	2.7%
Pasture	Pasture	5,119	6.2%	6.2%
Crop	Crop	32,449	39.6%	39.6%
Nursery	Nursery	6,539	8.0%	8.0%
Regulated Urban	Construction	5,509	6.7%	29.0%
	Developed	18,267	22.3%	
	Extractive	0	0.0%	
Septic	Septic	0	0.0%	0.0%
CSO	CSO	0	0.0%	0.0%
Point Sources	Industrial Point Sources	3,497	4.3%	4.3%
	Municipal Point Sources	0	0.0%	
Atmospheric Deposition	Non-tidal Atmospheric Deposition	1,185	1.4%	1.4%
Total		**82,017**	**100.0%**	**100.0%**

Table 3-25: Liberty Reservoir Watershed Total Nitrogen Loads

General Land-Use	Detailed Land-Use	Maryland		
		Load (lbs/yr)	**Percent** (%)	**Grouped Percent of Total %**
Forest	Forest	274,523	11.6%	12.6%
	Harvested Forest	22,817	1.0%	
AFOs	Animal Feeding Operations	608,903	25.7%	25.7%
Pasture	Pasture	56,976	2.4%	2.4%
Crop	Crop	747,589	31.6%	31.6%
Nursery	Nursery	25,564	1.1%	1.1%
Regulated Urban	Construction	38,992	1.6%	17.2%
	Developed	369,318	15.6%	
	Extractive	0	0.0%	
Septic	Septic	167,783	7.1%	7.1%
CSO	CSO	0	0.0%	0.0%
Point Sources	Industrial Point Sources	30,697	1.3%	1.3%
	Municipal Point Sources	0	0.0%	
Atmospheric Deposition	Non-tidal Atmospheric Deposition	25,409	1.1%	1.1%
Total		**2,368,571**	**100.0%**	**100.0%**

4.0 WATER QUALITY CHARACTERIZATION

4.1 Water Quality Monitoring Programs

Baltimore City Department of Public Works (BCDPW) is the only entity that monitors water quality in the reservoir. Table 4-1 summarizes the characteristics of the monitoring programs. BCDPW samples at four locations in Liberty Reservoir. Figure 4-1 shows the sites of these sampling locations.

Water column samples are analyzed for temperature, DO, TP, ammonia (NH_3), nitrate (NO_3), turbidity, and Secchi depth, among other constituents. Samples are not analyzed for phosphorus species and organic or total nitrogen. Starting at the surface, samples are taken every five feet until reaching sixty feet in depth; samples are taken at ten-foot intervals thereafter.

Not every sample is analyzed for the entire suite of parameters. Generally, only field measurements like temperature and DO are measured at every depth sampled. Lab analysis is performed for Chla for each sample collected at the surface and at ten-foot depth intervals down to 50 feet. Chemical analysis is performed on samples collected at the surface and at ten–foot depth intervals down to sixty feet.

Table 4-1: Summary of BCDPW Liberty Reservoir Monitoring Program

Characteristic	Reservoir
Collection Period	3/98-11/04
Number of locations	4
Temperature and DO measurements/Monitoring Station	Samples taken at approximately 5-10 ft. intervals from surface to bottom
Water quality Samples/Monitoring Station	Samples taken at approximately 10 ft. intervals from surface to bottom
Water Quality Analysis Parameters	NH_3, NO_3, NO_{23}, TP, DS, Chla, Turbidity, Secchi depth[1]

Note: [1] NO_{23}: Nitrite plus Nitrate; DS: Dissolved Solids.

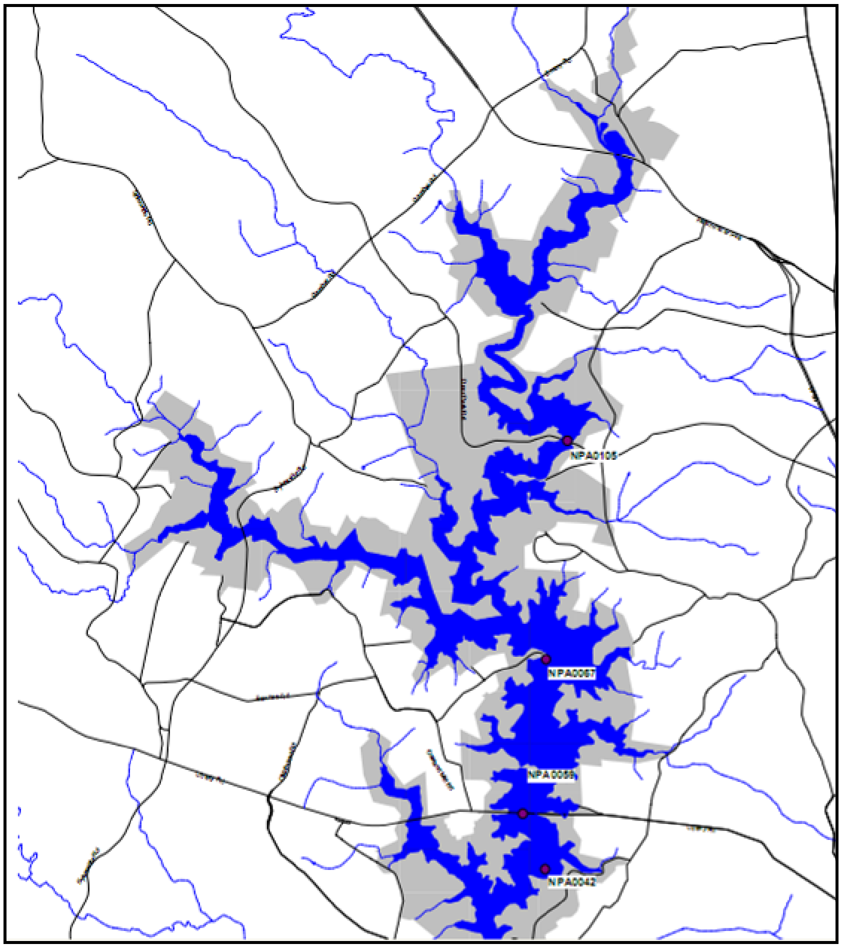

Figure 4-1: Sampling Locations in Liberty Reservoir

4.2 Temperature Stratification

Liberty Reservoir regularly exhibits temperature stratification starting in April or May and lasting until November. Stratification sometimes occurs in winter but it does not have a significant effect on water quality at this time. Under stratified conditions during the summer and early fall, bottom waters in the reservoir can become hypoxic, or oxygen deficient, because stable density differences inhibit the turbulent mixing that usually transports oxygen from the surface. Under such conditions, the reservoirs can be divided vertically into a well-mixed surface layer, or epilimnion; a relatively homogeneous bottom layer or hypolimnion; and a transitional zone between them, the metalimnion, characterized by a sharp density gradient.

Contour plots of isotherms effectively illustrate the seasonal position of the well-mixed surface layer, or epilimnion. Figure 4-2 presents a contour plot of isothermals for BCDPW station NPA0042 in Liberty Reservoir. Contours are shown only for the first 30 feet from the surface. In the winter, isothermal lines are vertical, indicating that the reservoir has a fairly uniform temperature over the first 30 feet of depth. In spring, isothermal lines begin to shift from a vertical alignment to a horizontal alignment, and by May, at depths greater than approximately 15 to 20 feet, they are horizontally parallel to each other. At the surface, isothermal lines run vertically to a depth of 10 to 15 feet; this defines the epilimnion.

Figures B-1 through B-4 in Appendix B present contour plots for each BCDPW monitoring location for the period 2000-2005. Generally, the epilimnion is limited to a depth of 5 to 10 feet in the summer. For the purposes of this analysis, the surface layer is considered to be 10 feet deep, with the understanding that in the spring and fall the epilimnion can extend deeper than 10 feet, and in the summer, it is likely to be shallower. For screening purposes, samples taken at depths of 70 feet or greater are considered to be part of the bottom layer, or hypolimnion.

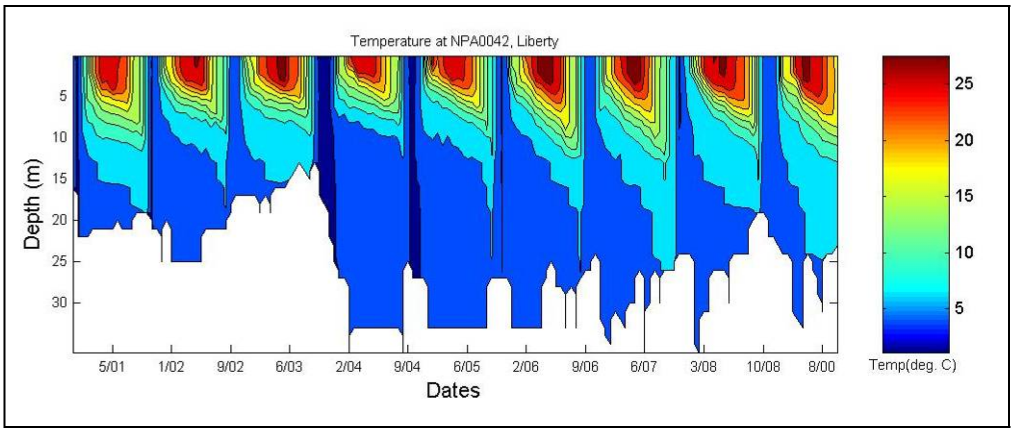

Figure 4-2: Liberty Reservoir BCDPW Station NPA0042 Isothermal Contours (2000-2008)

4.3 Dissolved Oxygen

Figures B-5 through B-8 in Appendix B show contour plots of DO concentrations at NPA0042, NPA0059, NPA0067, and NPA0105 in Liberty Reservoir, 2000-2005. As demonstrated in these plots, low dissolved oxygen occurs in the Liberty Reservoir hypolimnion regularly.

Generally, the low DO concentrations in the hypolimnion are due to two related causes. First is temperature stratification, as explained above; second is the entrainment of low DO waters into the epilimnion. Entrainment refers to the process by which turbulent layers spread into a non-turbulent region (Ford and Johnson 1986). The onset of cool weather causes the epilimnion to increase in depth by entraining water from the metalimnion. This water can be low in oxygen and thereby reduce the DO concentrations in the epilimnion. This can occur any time under stratified conditions when the well-mixed surface layer deepens, often well before the fall overturn, when the surface and bottom layers displace one another, which is typical of many lakes and reservoirs (including Liberty).

Figure 4-3 shows the DO contour at station BCDPW NPA0042. Figure 4-2 in the previous section, shows the temperature contour. A comparison of the figures indicates that at the end of August at this particular location, the reservoir was highly stratified, with the well-mixed layer extending to about 10 feet deep. Throughout September, the surface waters cooled, and the epilimnion deepened. The layers with low oxygen concentrations in the summer were drawn into the epilimnion. By October, the epilimnion once again had fairly uniform DO concentrations, although the reservoir had not completely overturned.

Entrainment and the fall overturn account for the other low DO observations in the epilimnion of the Liberty Reservoir. In a typical reservoir system, there is also another factor that can influence entrainment, which is drawdown. Withdrawals from a reservoir can induce currents that enhance mixing. Figure 4-4 shows the surface elevation of Liberty Reservoir from 2000 through 2005. In 2002 (a drought year), withdrawals from Liberty Reservoir dropped the surface elevation by about ten feet. These drawdowns are more than likely contributing to the low DO concentrations in the well-mixed surface layer of the reservoir.

Figures B-9 through B-12 in Appendix B show time series of DO at the surface and at five-foot intervals up to 10 feet, the screening-level definition of the epilimnion. DO concentrations are above the 5.0 mg/l criterion discussed in Section 4.9.2.

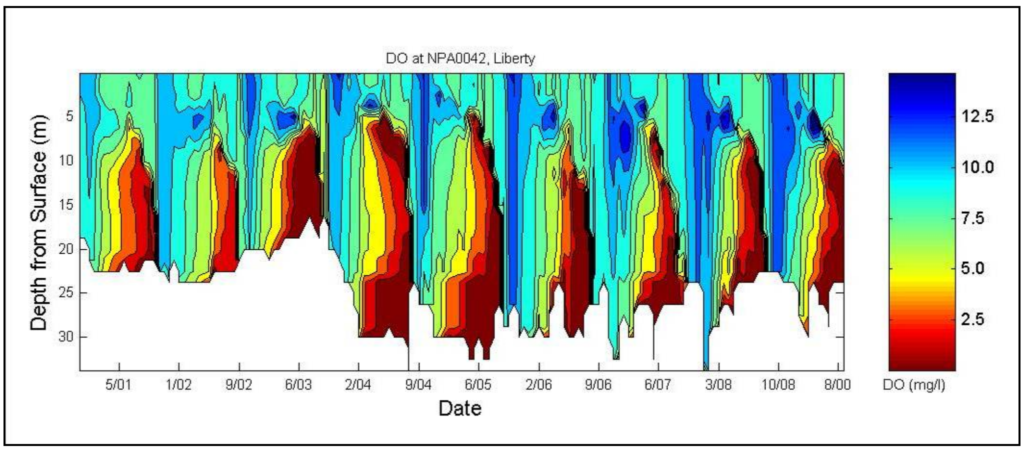

Figure 4-3: Liberty Reservoir BCDPW Station NPA0042 DO Contour (2000-2008)

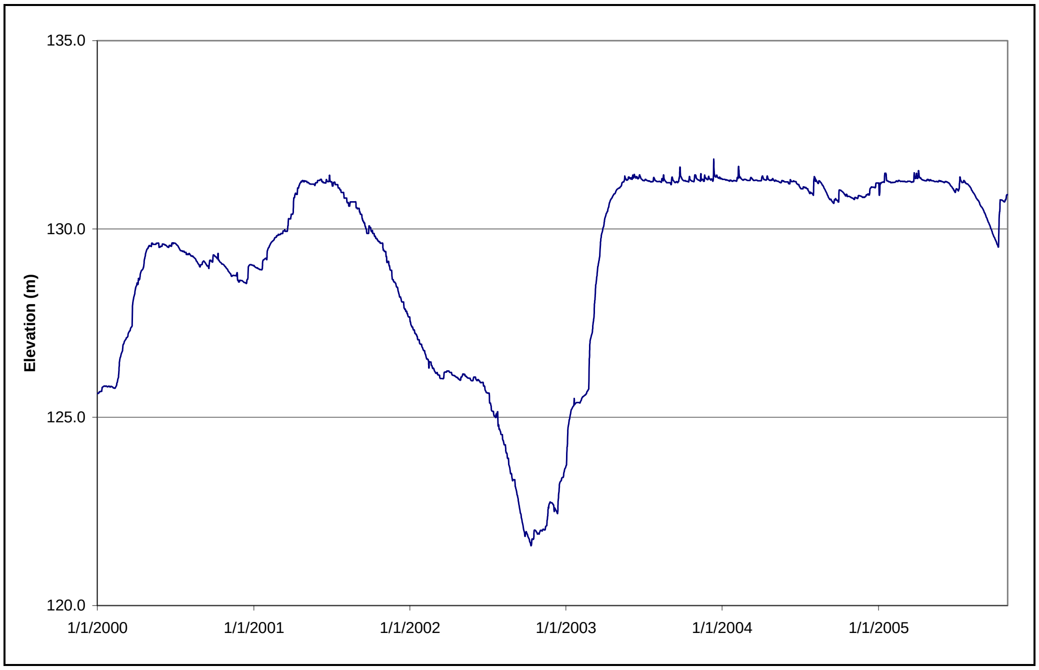

Figure 4-4: Liberty Reservoir Surface Water Elevations (2000-2005)

4.4 Phosphorus

Figures B-13 through B-16 in Appendix B show average total phosphorus concentrations in the top and bottom sampling depths at each monitoring location in Liberty Reservoir, 2000-2005. Surface TP concentrations represent an average of the samples taken at depths less than 10-feet. Bottom concentrations represent an average of samples taken at depths of 70 feet or greater. Table 4-2 gives summary statistics for TP concentrations in Liberty Reservoir.

Table 4-2: Liberty Reservoir Total Phosphorus Summary Statistics (2000-2008)

	TP Concentrations (mg/L)						
	Surface Monitoring Stations				**Bottom Monitoring Stations**		
Statistic	**NPA0042** (n = 96)[1]	**NPA0059** (n = 53)	**NPA0067** (n=53)	**NPA0105** (n = 96)	**NPA0042** (n = 91)	**NPA0059** (n = 51)	**NPA0067** (n = 45)
Mean	0.024	0.018	0.018	0.035	0.028	0.020	0.021
Standard Deviation	0.038	0.014	0.013	0.053	0.042	0.016	0.013
Minimum	0.005	0.005	0.005	0.004	0.002	0.005	0.005
1st Quartile	0.012	0.011	0.012	0.017	0.014	0.012	0.013
Median	0.015	0.015	0.015	0.022	0.018	0.016	0.017
3rd Quartile	0.023	0.022	0.023	0.031	0.028	0.021	0.023
Maximum	0.354	0.072	0.070	0.440	0.340	0.107	0.064

Note: [1] n: number of samples

4.5 Nitrogen

Figures B-17 through B-24 in Appendix B present the average surface and bottom ammonia and nitrate concentrations in Liberty Reservoir from 2000 through 2008. Since the surface layer of the reservoir is not nitrogen limited, bottom ammonia and nitrate concentrations are more relevant as a water quality indicator for two reasons.

First, the time series graphs of ammonia concentrations indicate that there are significant releases of ammonia from the bottom sediments. This contributes to greater oxygen demand. Second, for the most part, nitrate concentrations remained above 0.5 mg/l. Nitrate is preferred to ferric iron (III) as an electron acceptor in diagenesis. The phosphate attached to the bottom sediments is bound to the sediment via ferric iron. It is not likely that phosphate will detach from sediment until ferric iron concentrations are reduced via diagenesis. Therefore, the phosphorus release rate from the sediments in the reservoir should remain low.

4.6 Nutrient Limitation

Nitrogen and phosphorus are essential nutrients for algal growth. If one nutrient is available in great abundance relative to the other, then the nutrient that is less available limits the amount of plant matter that can be produced, and it is said to be the "limiting nutrient". The amount of the nutrient in greater abundance does not matter because both nutrients are needed for algal growth. In general, a Total Nitrogen: Total Phosphorus (TN:TP) ratio in the range of 5:1 to 10:1 by mass indicates that plant growth is not limited by phosphorus or nitrogen concentrations. If the TN:TP ratio is greater than 10:1, phosphorus tends to be limiting; if the N:P ratio is less than 5:1, nitrogen tends to be limiting (Chiandani et al. 1974).

Since there are no data available for organic nitrogen concentrations in the reservoir, nitrate is substituted for total nitrogen (TN) in the TN:TP ratio assessment, and the TN:TP ratio is thereby inherently underestimated. In Liberty Reservoir, only about 7% of the samples taken at the 10- and 20-foot depths have NO_3:TP ratios less than 10:1, which is applied as the threshold for distinguishing nitrogen limitation from phosphorus limitation. The median NO_3:TP ratio in Liberty Reservoir is 38:1. Storm events are likely to have high concentrations of particulate nitrogen and phosphorus, but while particulate phosphorus is accounted for in NO_3:TP ratios, particulate organic nitrogen is not. Storm events therefore inflate TP concentrations and exacerbate the underestimation of TN, so the resultant ratios are considered anomalous. Based on the available monitoring data and high N:P ratios, it is clearly evident that Liberty Reservoir is phosphorus limited.

4.7 Algae and Chlorophyll *a*

Figures B-25 through B-28 in Appendix B present the time series graphs of maximum Chla concentrations in the surface layer at the four Liberty Reservoir BCDPW monitoring stations. Chla concentrations tend to be higher in the upstream portion of the reservoir, as represented by station NPA0105 in Figure B-28. Table B-1 in Appendix B presents the maximum Chla concentrations by month and year from 2000 through 2008.

As the table indicates, Chla concentrations above 10 micrograms per liter (µg/l) occur regularly, and concentrations above 30 µg/l occur frequently. Concentrations above 10 µg/l occur in every season, but concentrations above 30 µg/l tend to occur more frequently in the summer months.

As per Table B-1, an algal bloom occurred in the winter of 2004 following the extremely wet conditions in 2003. Peak Chla concentrations reached 225 µg/l in the upper reaches of the reservoir at station NPA0105. An analysis of algal taxa performed at the Ashburn WTP showed that there was a significant blue-green algal component in the algal assemblage during the bloom, which is unusual for winter months. The bloom was localized to the upper reaches in the reservoir, as Chla concentrations observed during the bloom at station NPA0042, just upstream of the dam, were below10 µg/l. The magnitude of the bloom in the winter of 2004, the largest observed in the reservoir in the last twenty years, seems unique to the extreme hydrological conditions preceding the event, and it is not considered representative of long-term average conditions in the reservoir.

4.8 Sedimentation

The Maryland Geological Survey (MGS) developed new bathymetry for Liberty Reservoir in 2001 (Ortt and Wells 2001). Table 4-3 summarizes capacity loss and the average sediment accumulation rate for the reservoir.

Table 4-3: Liberty Reservoir Sedimentation Rates[1]

Capacity Prior to 1953 Construction (acre-ft)[2]	118,148
2001 Capacity (acre-ft)	115,617
Capacity Loss (acre-ft)	2,531
Average Annual Capacity Loss (acre-ft/yr)[3]	54
Sediment Accumulation Rate (in/yr)[4]	0.21

Note: [1]Source: Ortt and Wells 2001.
[2]acre-ft: acres by feet.
[3]acre-ft/yr: acre by feet per year.
[4]in/yr: inches per year.

4.9 Applicable Water Quality Criteria

MDE has adopted an interpretation of Maryland's narrative criterion, applied to Chla, and of DO criteria for application to drinking water reservoirs. The elements of that interpretation are presented below.

4.9.1. Chlorophyll *a* Criterion

Maryland's General Water Quality Criteria prohibit pollution of waters of the State by any material in amounts sufficient to create a nuisance or interfere directly or indirectly with designated uses (COMAR 26.08.02.03B(2)). Excessive eutrophication, indicated by elevated levels of Chla, can produce nuisance levels of algae and interfere with designated uses such as fishing and swimming. The excess algal blooms eventually die off and decompose, consuming oxygen. Excessive eutrophication in Liberty Reservoir is ultimately caused by nutrient overenrichment.

The chlorophyll TMDL endpoints selected for the reservoirs are (1) a 90th percentile permissible instantaneous chlorophyll concentration of 30 µg/l in the surface layers and (2) a 30-day moving average concentration not to exceed 10 µg/l in the surface layers. A concentration of 10 µg/l corresponds to a score of approximately 53 on the Carlson Trophic State Index (TSI). This is at the boundary of mesotrophy and eutrophy, which is an appropriate trophic state at which to manage these reservoirs and should avoid nuisance algal blooms. Reduction of the phosphorus loads is predicted to reduce excessive algal growth and therefore prevent violations of narrative criteria associated with nuisances such as taste, and odor problems or the physical impedance of direct contact use.

4.9.2 Dissolved Oxygen Criteria

Use I waters are subject to DO criteria of not less than 5.0 mg/l at any time (COMAR 26.08.02.03-3E(2)) unless natural conditions result in lower levels of DO (COMAR 26.08.02.03A(2)). New standards for tidal waters of the Chesapeake Bay and its tributaries take into account stratification and its impact on deeper waters. MDE recognizes that stratified reservoirs and impoundments (there are no natural lakes in Maryland) present circumstances similar to stratified tidal waters, and is applying an interpretation of the existing standard to allow for the impact of stratification on DO concentrations. This interpretation recognizes that, given the morphology of the reservoir or impoundment, the resulting degree of stratification, and the naturally occurring sources of organic material in the watershed, hypoxia in the hypolimnion is a natural consequence. The interpretation of the non-tidal DO standard, as applied to reservoirs, is as follows:

- A minimum DO concentration of 5.0 mg/l will be maintained throughout the water column during periods of complete and stable mixing;
- A minimum DO concentration of 5.0 mg/l will be maintained in the mixed surface layer at all times, including during stratified conditions, except during periods of overturn or other naturally-occurring disruptions of stratification; and
- Hypolimnetic hypoxia will be addressed on a case-by-case basis, taking into account morphology, degree of stratification, sources of diagenic organic material in reservoir sediments, and other such factors.

4.9.3 Sediment Criterion

Excessive sediment loads result in a shortened projected lifespan of a reservoir. The bulk of phosphorus entering a reservoir is usually bound to sediment. Any control strategy directed toward reducing total phosphorus entering a reservoir will concurrently reduce sediment. In reservoirs and impoundments where both a nutrient and sediment impairment exits, MDE believes that the implementation of the total phosphorus TMDL will also remove the sediment impairment.

4.9.4 Impairment Status of Liberty Reservoir

Liberty Reservoir is listed as impaired by both nutrients and sediment. It is difficult to tell from the monitoring data alone whether the listing is justified. No DO concentrations below 5 mg/l have been observed in the surface layer of Liberty Reservoir, but hypoxia occurs regularly in the hypolimnion under stratified conditions. The question, then, is whether the hypoxia is a natural condition, caused by thermal stratification alone, or due to anthropogenic inputs. The 90th percentile observed Chla concentration for the period 200-2005 is only18 µg/l, but the average observed concentration over the same period is 11µg/l. It is therefore not possible to tell whether the 30-day average Chla criterion is met. The purpose of the modeling framework for Liberty Reservoir is to resolve these questions and determine the nutrient and sediment controls consistent with Liberty Reservoir meeting its designated uses.

5.0 STRUCTURE AND CALIBRATION OF THE CE-QUAL-W2 MODELS

This chapter describes the CE-QUAL-W2 models in general and the modifications made to the W2 model to facilitate it use in TMDL development for Maryland's large drinking water reservoirs (ICPRB and MDE, 2006; ICPRB, 2008). It further describes the implementation of the W2 model in Liberty Reservoir, and the calibration of the models representing the reservoirs.

5.1 Overview of the CE-QUAL-W2 Model

CE-QUAL-W2 is a laterally-averaged two-dimensional computer simulation model capable, in its most recent formulations, of representing the hydrodynamics and water quality of rivers, lakes, and estuaries. It is particularly suited for representing temperature stratification that occurs in reservoirs like Liberty Reservoir.

The original version of CE-QUAL-W2 was the LARM (Laterally Averaged Reservoir Model) by Edinger and Buchak (1975). US Army Engineer Waterways Experiment Station (WES) added a water quality component to make CE-QUAL-W2 version 1. Version 2 (Cole and Buchak, 1995) added many computational improvements and permitted the simulation of reservoirs with multiple branches. Version 3 (Cole and Wells, 2003) expanded the hydrodynamic simulation capacities of the model so that rivers and estuaries could also be simulated.

Waterbodies represented in CE-QUAL-W2 are divided longitudinally into segments and vertically into layers. A model cell is defined by the intersection of layers and segments. The bottom cell in a segment is fixed by the waterbody's bathymetry. The number of cells in a segment varies with the position of the free surface of the waterbody. Every time step CE-QUAL-W2 simulates the location of the free surface in each segment.

Cole and Buchak (1995) provide a clear exposition of the CE-QUAL-W2 model structure as it is implemented for simulating reservoirs. Figure 5-1 gives six basic equations which constitute the W2 model. There are six unknowns associated with these six equations: (1) the free surface ,η; (2) the pressure, P; (3) the horizontal velocity ,U; (4) the vertical velocity, W; (5) the constituent concentration, φ; and (6) the density, ρ. Substituting the horizontal momentum equation (A-1), the pressure equation (A-4), and the equation of state (A-6) into the free surface equation and integrating in the vertical direction, an equation for the free surface can be determined which is a function of waterbody geometry and the hydrodynamic variables from the previous time step:

Figure 5-1: The Basic Equations of CE-QUAL-W2
(Cole and Buchak, 1995)

Horizontal Momentum

$$\frac{\partial UB}{\partial t} + \frac{\partial UUB}{\partial x} + \frac{\partial WUB}{\partial z} = -\frac{1}{\rho}\frac{\partial BP}{\partial x} + \frac{\partial\left(BA_x \frac{\partial U}{\partial x}\right)}{\partial x} + \frac{\partial B\tau_x}{\partial z} \qquad \text{(A-1)}$$

where

- U = longitudinal, laterally averaged velocity, *m sec*$^{-1}$
- B = waterbody width, m
- t = time, *sec*
- x = longitudinal Cartesian coordinate: x is along the lake centerline at the water surface, positive to the right
- z = vertical Cartesian coordinate: z is positive downward
- W = vertical, laterally averaged velocity, *m sec*$^{-1}$
- ρ = density, *kg m*$^{-3}$
- P = pressure, N *m*$^{-2}$
- A_x = longitudinal momentum dispersion coefficient, *m2 sec*$^{-1}$
- τ_x = shear stress per unit mass resulting from the vertical gradient of the horizontal velocity, U, m^2 *sec*$^{-2}$

Constituent Transport

$$\frac{\partial B\Phi}{\partial t} + \frac{\partial UB\Phi}{\partial x} + \frac{\partial WB\Phi}{\partial z} - \frac{\partial\left(BD_x \frac{\partial \Phi}{\partial x}\right)}{\partial x} - \frac{\partial\left(BD_z \frac{\partial \Phi}{\partial z}\right)}{\partial z} = q_\Phi B + S_\Phi B \qquad \text{(A-2)}$$

where

- Φ = laterally averaged constituent concentration, g m^{-3}
- D_x = longitudinal temperature and constituent dispersion coefficient, m2 sec^{-1}
- D_z = vertical temperature and constituent dispersion coefficient, m2 sec^{-1}
- q_Φ = lateral inflow or outflow mass flow rate of constituent per unit volume, g m^{-3} sec^{-1}
- S_Φ = kinetics source/sink term for constituent concentrations, g m^{-3} sec^{-1}

Free Water Surface Elevation

$$\frac{\partial\ B_\eta \eta}{\partial\ t} = \frac{\partial}{\partial\ x} \int_\eta^h UB\ dz - \int_\eta^h qB\ dz \qquad \text{(A-3)}$$

Where

B_η = time and spatially varying surface width, m
η = free water surface location, m
h = total depth, m
q = lateral boundary inflow or outflow, m3 sec^{-1}

Hydrostatic Pressure

$$\frac{\partial\ P}{\partial\ z} = \rho g \qquad \text{(A-4)}$$

Where

g = acceleration due to gravity, m sec^{-2}

Continuity

$$\frac{\partial\ UB}{\partial\ x} + \frac{\partial WB}{\partial\ z} = qB \qquad \text{(A-5)}$$

Equation of State

$$\rho = f\left(T_w, \Phi_{TDS}, \Phi_{ss}\right) \qquad \text{(A-6)}$$

Where

$f(T,\Phi_{TDS},\Phi_{ss})$ = density function dependent upon temperature, total dissolved solids or salinity, and suspended solids

$$\frac{\partial B\eta}{\partial t} - g\,\Delta t\,\frac{\partial}{\partial x}\left(\frac{\partial \eta}{\partial x}\int_{\eta}^{h} B\,dz\right) = \frac{\partial}{\partial x}\int_{\eta}^{h} UB\,dz - \frac{g\Delta t}{\rho_{\eta}}\frac{\partial}{\partial x}\int_{\eta}^{h}\left[B\int_{\eta}^{z}\frac{\partial \rho}{\partial x}\,dz\right]dz$$

$$+\frac{\partial}{\partial x}\left[B_h\tau_h - B_{\eta}\tau_{\eta} - \int_{\eta}^{h}\tau_x\frac{\partial B}{\partial z}\,dz\right]\Delta t \tag{A-7}$$

$$+\frac{\partial}{\partial x}\left[\int_{\eta}^{h}F_x\,dz\right]\Delta t - \int_{\eta}^{h}qB\,dz$$

(Cole and Burchak, 1995)

Each time step, the following computations are performed:

1. Equation A-7 is solved implicitly for the free surface elevation, η;
2. Horizontal velocities are calculated from wind shear, bottom shear, and the baroclinic and bartropic pressure gradients;
3. Vertical velocities are determined from the free surface elevations, horizontal velocities, and the continuity equation; and
4. Constituent concentrations are calculated using equation A-2.

More details of the CE-QUAL-W2 model structure can be found in Cole and Buchak (1995) and Cole and Wells (2003).

Model parameters specify, among other things, the kinetic rates which control how constituents are transformed among themselves. These transformations are counted among the sources and sinks of constituents in Equation A-2. In addition to model parameters, W2 requires (1) the specification of a time series of inflow volumes, temperatures, and constituent concentrations; (2) meteorological inputs such as wind speed, air temperature, dew point, and cloud cover; and (3) boundary conditions such as outflows or water surface elevations.

5.2 Implementation of the CE-QUAL-W2 Model of Liberty Reservoir

As described in Section 4, extensive water quality monitoring data from Liberty Reservoir is available for 2000-2008. The P5 model, which provides the input flows and constituent loads for the W2 model, only simulates the years 1985-2005. The W2 model was calibrated against water quality monitoring data from 2000 through 2005, and all model scenarios were run for this simulation period.

5.2.1. Segmentation and Model Cell Properties

Figure 5-2 shows the model segmentation. Overall, there are 48 active segments (not counting boundary segments which are used for computations) and 5 branches, including the mainstem.

Model bathymetry was based on the Maryland Geological Survey's (MGS) bathymetric mapping of Liberty Reservoir (Ortt and Wells, 2001). Bathymetry is represented in W2 by specifying (1) segment length; (2) the number and height of layers in a segment; and (3) average width of each cell. Table C-1 in Appendix C gives the segment length and average width of each cell. Each layer is one meter thick. There are a maximum of 45 active layers. The maximum number of active cells is 1,134. Figure 5-3 shows compares the drawdown curve calculated from MGS bathymetric data and the curve from the W2 model's representation of the bathymetry. As Figure 5-3 shows, the model bathymetry almost exactly reproduces the original MGS data.

Table 5-1 shows the linkages between reservoir segments and HSPF subwatersheds. There are three kinds of linkages. Output from subwatersheds can be input to the W2 model as (1) upstream inflows, (2) tributary inflows, or (3) distributed tributary inflows. Upstream inflows represent the main inputs into a branch. The Liberty W2 Model, these are associated with the subwatershed tributaries represented in Table 3-6.

Tributaries represent additional localized inflows to a branch that are not associated with the main inflow to the branch. Beaver Run, Little Morgan Run and Bonds Run are the tributaries in the Liberty Reservoir W2 Model.

Distributed tributaries are flows associated with a branch but not with a particular segment in a branch. Their flows and constituent inputs are "distributed" over the segments in a branch in proportion to the contribution the segment makes to the total surface area of the branch. Distributed tributaries are used to represent the direct drainage subwatersheds.

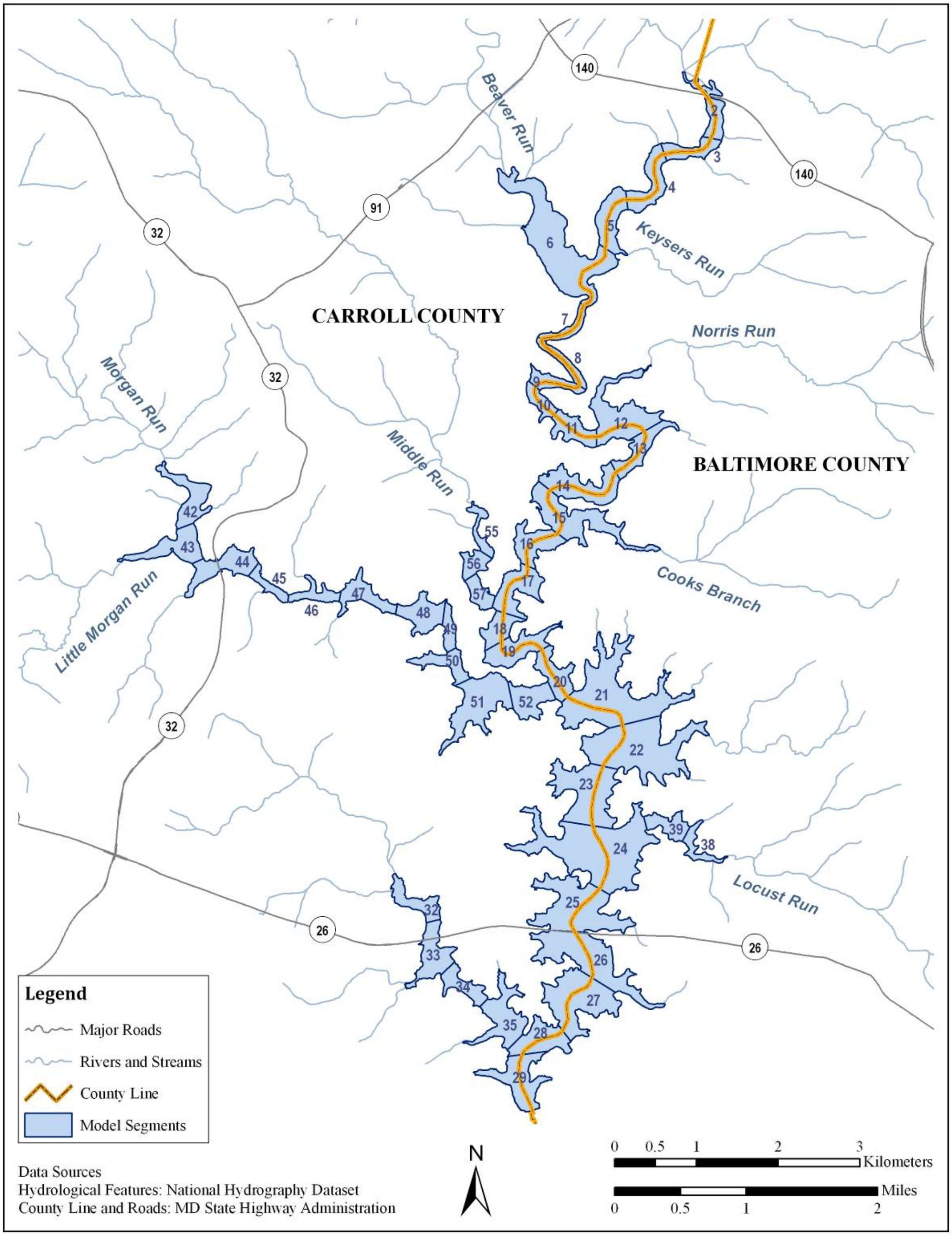

Figure 5-2: Liberty Reservoir W2 Model Segmentation

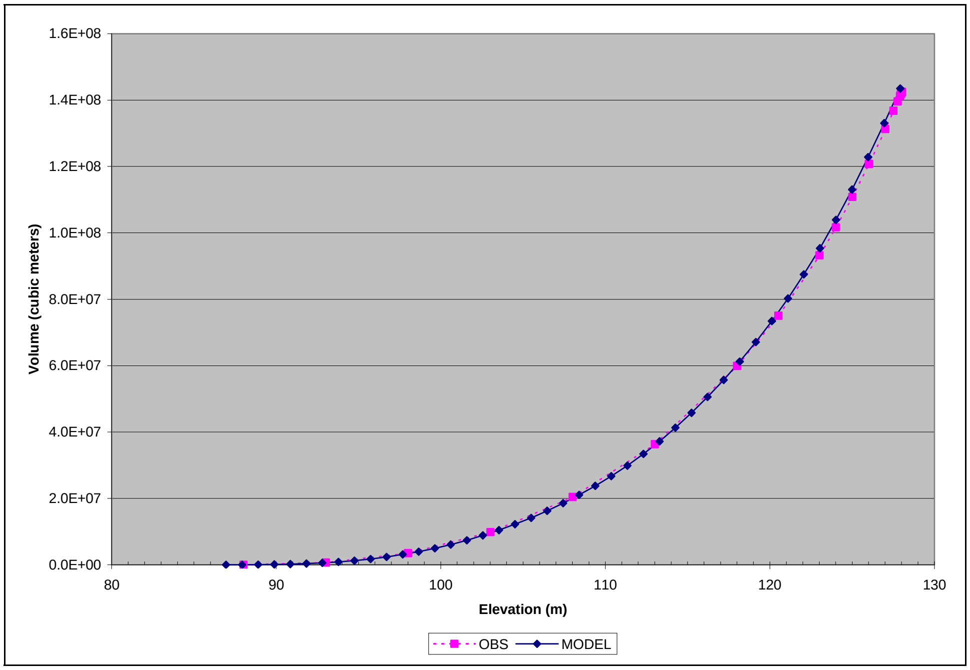

Figure 5-3: Drawdown Curve (Volume vs. Elevation), Liberty Reservoir W2 Model and Original MGS Data

Table 5-1: Linkage between P5 Subwatersheds and W2 Segments and Branches

	Branch No.	Name	Upstream Inflow P5 Subwatersheds	Distributive Tributary P5 Subwatersheds	Tributary P5 Subwatersheds
Inflow to Branch	1	N. Branch Patapsco	9970		
	2	Snowden Run	N/A		
	3	Locust Run	N/A		
	4	Morgan Run	9973		
	5	Middle Run	9972		
Distributive Watershed	1	Liberty Direct Drainage		9980	
	2	Snowden Run Direct Drainage		9984	
	3	Locust Run Direct Drainage		9985	
	4	Morgan Run Direct Drainage		9983	
	5	Middle Run Direct Drainage		9982	
Tributary	1	Beaver Run			9971
	4	Little Morgan Run			9974
	1	Bonds Run			9975

5.2.2. Inflows, Meteorological Data and Boundary Conditions

The CE-QUAL-W2 Model requires time series of inflows, inflow temperature, and inflow constituent concentrations. These were all taken from the output of the refined P5 Model of Liberty Reservoir, according to the linkage between P5 subwatersheds and W2 model segments described in Table 5-1. Hourly time series were used to represent inflows and temperature and constituent concentrations.

The W2 model requires time series of air temperature, dewpoint temperature, cloud cover, wind speed and wind direction. All meteorological data except wind direction were taken from the P5 Model's meteorological inputs for Carroll County. Hourly temperature values were estimated using a U.S. Geological Survey regional regression model. In the P5 Model, hourly time series were used to input meteorological data. Direct precipitation to the reservoir was not simulated.

Boundary conditions for W2 can be specified as either the elevation or flows across the model boundaries in the most upstream and downstream segments. The upstream boundary conditions were specified by the inflows from the P5 model. Downstream boundary conditions were specified by reservoir outflows. The time series of reservoir outflows was determined in the water balance calibration described in Section 5-3. The elevation of the outflow was determined in the temperature calibration described in Section 5-4. Outflows were represented by a generic outflow for W2 Segment 29 near the Liberty Reservoir Dam. No specific outflow structures, such as spillways or withdrawal intakes, were explicitly modeled.

5.2.3. Configuration of Water Quality Constituents

Table 5-2 shows the state variables that represent water quality constituents in Version 3.2 of the CE-QUAl-W2 model. This version of W2 was modified to facilitate using W2 to develop TMDLs for Maryland's reservoirs (ICPRB and MDE, 2006; ICPRB 2008; and ICPRB 2010). The model can represent any number of user-specified inorganic solids, Carbonaceous Biochemical Oxygen Demand (CBOD) species, or algal species.

In version 3.2 of the W2 model, dissolved inorganic phosphorus (DIP) is the only phosphorus species directly represented as a state variable in the W2 model. Phosphorus attached to sediment can be modeled by specifying the concentration of phosphorus on attached sediment. Organic phosphorus is modeled by specifying the stoichiometric ratio between phosphorus and organic matter or oxygen demand (in the case of CBOD species).

It is not possible to maintain a mass balance on total phosphorus by fixing a ratio to a state variable unless the quantity of the state variable is determined by its phosphorus content. This is exactly how the mass balance of phosphorus was implemented in the reservoir models using version 3.2 of W2. Specifically, the state variables in the W2 model were configured as follows:

The inorganic phosphorus attached to silt and clay was modeled as distinct inorganic solids. Sorption between sediment and the water column was not simulated in the model. Three CBOD variables were used to represent allochthanous organic matter inputs to the reservoirs: (1) labile dissolved CBOD, (2) labile particulate CBOD, and (3) refractory particulate CBOD. The concentration of these CBOD inputs were calculated based on the concentration of organic phosphorus determined by the HSPF model, using the stoichiometric ratio between phosphorus and oxygen demand in the reservoir models. The fraction of total CBOD in each species was calibrated based on reservoir response. The organic matter state variables were reserved to represent the recycling of nutrients within the reservoir between algal biomass and reservoir nutrient pools. No organic matter, as represented by these variables, was input into the reservoirs. They were used only to track nutrients released from algal decomposition.

To use the W2 model in this configuration, several minor changes had to be made to the version 3.2 W2 code. Inorganic solids contribute to light extinction. The inorganic solids representing solid-phase phosphorus do not contribute to light extinction over and above the sediment to which they are attached. The W2 code was changed so that they don't contribute to light extinction.

The original CBOD variables in W2 in version 3.2 do not contribute to light extinction, do not settle, and do not contribute to the organic matter in the sediment available for diagenesis. The W2 code was altered to represent BOD species which settled and which could contribute to both light extinction and sediment organic matter.

Subsequent versions of W2, versions 3.5 and 3.6, were released during the development of the Liberty Reservoir W2 Model. These versions incorporated some, but not all, of the modifications made to version 3.2 for development of TMDLs for MD's large drinking water reservoirs. Versions 3.5 and 3.6 have settling rates for CBOD variables. They also track the nutrient content of organic matter state variables. Neither version 3.5 nor 3.6 yet track the nutrient content of the CBOD variables that are used to represent allochthonous organic material, and so does not yet address the most significant problem in keeping a phosphorus mass balance for TMDLs.

Table 5-2 summarizes the water quality state variables used in the CE-QUAL-W2 model of Liberty Reservoir. More of the details of the implementation of water quality simulation will be provided in sections on the calibration of constituents.

5.2.4 Other Modifications to the W2 Model

The larger size of the Liberty Reservoir W2 Model, both in terms of the depth and the number of cells, makes it more difficult to represent the fate and transport of diagenic material. Version 3.6 explicitly formulates a mechanism for transporting organic sediments laterally across a segment so that material deposited on the bottom of shallow layers is eventually transported to the deeper layers of the segment. In version 3.2 of the model, this process, called "focusing," was controlled by the particulate organic matter settling velocity. In version 3.6, the focusing velocity was introduced as an explicit input parameter, a practice adopted for the modified version of 3.2 used to simulate Liberty Reservoir. The focusing process does not address the potential for the longitudinally transporting organic sediments by the same mechanism of sediment resuspension and subsequent migration to greater depths. Longitudinal transport of organic sediments is mimicked in the Liberty Reservoir W2 Model by introducing a variable settling velocity for particulate CBOD inputs.

Table 5-2: Water Quality State Variables in CE-QUAL-W2 and their Realization in the Liberty Reservoir W2 Model

W2 State Variable	P5 State Variable	Description
DO	DO	Dissolved Oxygen
NH4	NH4	Ammonia Nitrogen
NO3	NO3	Nitrate Nitrogen
PO4	PO4	Dissolved Inorganic Phosphorus
LPOM	LPOM	Autochthonous Labile Particulate Organic Matter
RPOM	RPOM	Autochthonous Refractory Particulate Organic Matter
LDOM	LDOM	Autochthonous Labile Dissolved Organic Matter
RDOM	RDOM	Autochthonous Refractory Dissolved Organic Matter
CBOD	CBOD1	Allochthonous Labile Dissolved Organic Matter
	CBOD2	Allochthonous Labile Particulate Organic Matter
	CBOD3	Allochthonous Refractory Particulate Organic Matter
ISS (inorganic solids)	ISS1	Sand
	ISS2	Silt
	ISS3	Clay
	ISS4	Particulate Inorganic Phosphorus on Silt
	ISS5	Particulate Inorganic Phosphorus on Clay
AGL (algal biomass)	ALG1	Winter: diatoms
	ALG2	Spring: summer diatoms; green algae
	ALG3	Summer or fall: blue-green algae, diatoms

5.3 Water Balance Calibration

The objective of the water balance calibration is to calibrate the time series of inflows and outflows so that simulated water surface elevations match observed levels. BCDPW provided daily water elevation levels at the dam on Liberty Reservoir for the period 2000-2005.

CE-QUAL-W2 comes with a calibration utility, waterbalance.exe, which, when given the time series of observed water surface elevations, determines how much the inflows or outflows need to be adjusted in order to minimize the error in the simulated water surface elevations. The inflows to the W2 model can be adjusted by using distributed tributary file for the main branch. The distributed tributary inflow file applies a time series of inflows across all segments, in proportion to their surface area. It is intended to be used in conjunction with the waterbalance.exe to adjust inflows to match observed surface elevations (Cole and Wells, 2003).

The water balance was calibrated as follows. First, only the outflow time series were adjusted until the net adjustment in outflows, as determined by the water balance utility, were insignificant. At this point, if any adjustment needed to be made to the inflows, they were made by adjusting the flows distributed tributary of the main branch.

Figure 5-4 compares the simulated and observed water surface elevations at the Liberty Reservoir dam. As the figures indicate, the error in simulated surface elevations is almost insignificant.

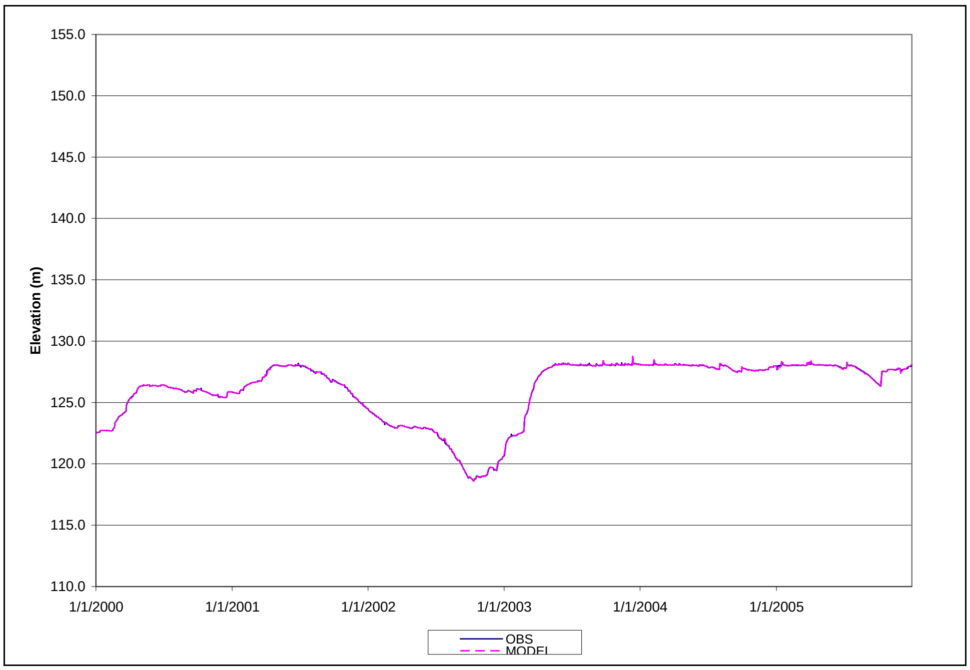

Figure 5-4: Observed and Simulated Water Surface Elevation, Liberty Reservoir

5.4 Temperature Calibration

The simulation of temperature is among the most important aspects of reservoir modeling. Water temperature is the cause of the density differences that constitute stratification in the reservoirs and inhibit turbulent mixing between layers. The inhibition of mixing of course leads to low dissolved oxygen concentration in the hypolimnion during stratified conditions. In addition, most of the kinetic processes, including algal growth rates, are temperature dependent, and thus an accurate representation of temperature facilitates simulating eutrophication dynamics.

Calibrating the temperature simulation of the W2 model primarily involves balancing the magnitude and timing of mixing forces—primarily wind but also inflow and outflows—with heat exchange and transport. The sensitivity of the temperature simulation to about a dozen variables was tested, but, in the end, four variables were identified as significantly impacting the calibration: BETA, the fraction of radiation absorbed at the water surface;

WSC, the wind sheltering coefficient; SHD, the shading coefficient; and ESTR, the elevation of the outflows from the reservoir. The latter two parameters can vary with time; the former are fixed for the simulation period. The values of the paramters are summarized in Table 5-3.

Table 5-3: Parameters Used in W2 Temperature Calibration

Year	BETA	SHD	WSC	ESTR (m)
2000	0.64	1.105	0.65	120
2001			0.65	125
2002			0.65	125
2003			0.56	125
2004			0.65	129
2005			0.65	120

The values of these parameters were calibrated as follows: The W2 model is run without simulating water quality constituents. Multiple parameter combinations were tested using the PEST utility, SENSAN, which automates the process of substituting parameter sets into model input files, performing multiple model runs, and recording the outcomes from the simulations (Doherty, 2001). The outcomes measured were the root mean square error between observed and simulated temperatures and the mean absolute error of the same quantities. SENSAN also saved the output files so the simulations could be examined graphically. The first sets of parameters spanned the entire range of parameter values. Subsequent sets refined the results of previous sets. Hundreds, if not thousands of parameter combinations were simulated for each simulation year.

Cole and Wells (2003) suggest that it should be possible to achieve a temperature simulation in which the absolute mean error is less than 1° C. Parameter values determined in the reservoir simulations are given in Table 5-3. The calibrated overall absolute mean square error for the Liberty Reservoir W2 Model was 0.96 º C. When the model is run with water quality constituents, the absolute mean square error is 1.04 º C, due primarily to additional absorption of light by sediment and organic matter.

5.5 General Features of the W2 Calibration

Sections 5.6, 5.7, 5.8, and 5.9 discuss the calibration of the simulations of phosphorus, DO, Chla, and nitrogen, respectively. In each case observed and simulated values are compared, but with exception of Chla, the comparison is made between the average concentrations in the surface and bottom of the lake at the monitoring location. The surface and bottom layers are defined as in Section 4: the surface layers have depth less than or equal to ten feet, while the bottom layers have depths greater than 70 feet. For nutrients, there may be only one observation in the layer, and that observation is compared to the average of all the simulated concentrations in the layer.

A similar procedure is used for Chla, except instead of the average concentrations in the surface layer, the maximum concentrations are compared. The surface layer is also defined to include observations up to 50 feet in depth. This calibration strategy produces a conservative calibration of the Chla simulation when the W2 model is used to develop

TMDLs (ICPRB and MDE, 2006; ICPRB, 2008). The Chla concentrations in the bottom layer are not used in the calibration.

The difficulty with this methodology is that while the fixed definitions of surface and bottom layers approximate on average the epilimnion and hypolimnion, respectively, for any particular sampling date, the actual location of the boundaries of the epilimnion or hypolimnion could be above or below the fixed surface or bottom layers. Generally, however, the conceptual and computational simplicity of the calibration method outweighs any errors introduced by the fixing the boundaries of the surface and bottom layers.

5.6 Phosphorus Calibration

For the previous W2 models of reservoirs in Maryland (ICPRB and MDE, 2006; ICPRB, 2008), the goal of the calibration was to reproduce the distribution of observed TP concentrations in the surface and bottom of the reservoirs, and the tools used were adjustments to (1) the PO4 fraction in input loads and (2) the decay and settling rates for CBOD, algae, and autoochthonous organic matter. Table 5-4 and 5-5 show key parameter values used in the simulation. Tables 5-6 shows summary statistics for observed and simulated for TP concentrations. Figures 5-5 and 5-6 show the cumulative distribution of observed and simulated surface and bottom TP concentrations in Liberty Reservoir. Figures D-1 through D-7 in Appendix D show time series comparing observed and simulated TP concentrations in the surface and bottom of Liberty Reservoir by station.

On average, simulated TP concentrations in the surface layer are somewhat lower than the observed concentrations. Observed concentrations are highly skewed whereas the simulated concentrations are more evenly distributed, so that the distribution of simulated concentrations is higher than observed at percentiles less than the median concentration. Overall, however, there is a reasonably good match in the distribution of observed and simulated TP concentrations in the surface layer. Simulated TP concentrations in the bottom layer tend to be larger than observed concentrations. This has been a general feature of other reservoir simulations in MD (ICPRB and MDE, 2006; ICPRB, 2008), and it may be related to some of the difficulties in simulating the transport of sediments in a two-dimension model, which were alluded to in Section 5.2.4.

Table 5-4: Decay Rates and Settling Rates for Organic Matter

Constituent	Decay Rate (1/d)	Settling Rate (m/d)
CBOD1	0.125	0.0
CBOD2	0.001	0.7
CBOD3	0.000	5.0
Dissolved Organic Matter	0.08	0.0
Particulate Organic Matter	0.001	0.5

Table 5-5: Settling Rates for Inorganic Sediments and Adsorbed Particulate Phosphorus

Size Fraction	Settling Rate (m/d)
Sand	10.0
Silt	5.0
Clay	1.0

Table 5-6: Summary Statistics for Simulated and Observed TP (mg/l)

Statistic	Surface		Bottom	
	Observed	Simulated	Observed	Simulated
Min	0.005	0.009	0.005	0.016
1st Q	0.013	0.017	0.012	0.023
Median	0.016	0.023	0.017	0.028
3rd Q	0.024	0.027	0.021	0.039
Max	0.440	0.069	0.340	0.163
Mean	0.025	0.023	0.022	0.033
Std. Dev.	0.044	0.009	0.031	0.016
R^2	0.029		0.005	

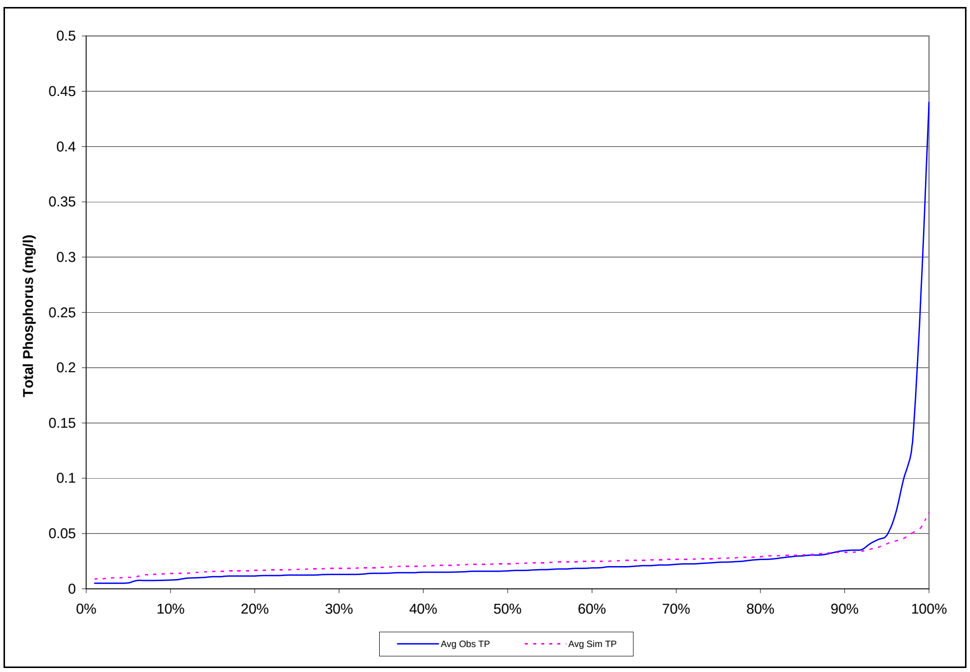

Figure 5-5: Cumulative Distribution of Observed and Simulated Average TP Concentrations, Surface Layer, Liberty Reservoir

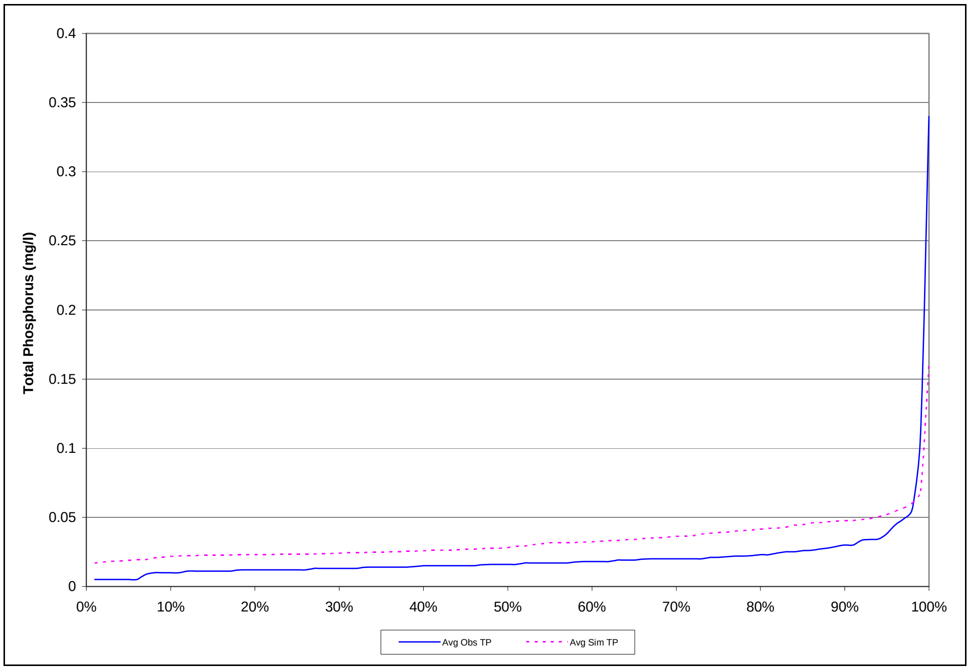

Figure 5-6: Cumulative Distribution of Observed and Simulated Average TP Concentrations, Bottom Layer, Liberty Reservoir

5.7 Chlorophyll a Calibration

Just as in previous reservoir models in MD (ICPRB and MDE, 2006; ICPRB, 2008), six species of algae were simulated in the Liberty Reservoir W2 Model. Table 5-7 identifies the species used in each season. Unlike previous models, the same species were used for the winter and spring seasons, because unlike other drinking water reservoirs in MD, observed Chla concentrations in the winter monthly are frequently greater than10 µg/l therefore not significantly different in magnitude from spring concentrations. See Section 4.7 for additional discussion of the observed data. Simulated Chla concentrations were adjusted primarily by adjusting the algal growth rate and temperature parameters. The calibrated values of these parameters are shown in Table 5-8.

The goal of the Chla calibration is, for each season in which the observed Chla concentration is greater than 10 ug/l, that the maximum simulated Chla concentration, at the dates and locations monitored, should be equal to or greater than maximum observed concentration in that season. In other words, the maximum observed concentration from all the observations taken in a reservoir in a season is compared to the maximum simulated concentration from the corresponding sampling location and dates in a given season. The calibration target is thus less restrictive than a strict pair-wise comparison of observed and simulated concentrations: the maximum simulated concentration can occur at any sample location at any sample date within a season. It is nevertheless a very conservative calibration strategy. The unprecedented 2004 winter bloom, which is unrepresentative of long-term conditions in the reservoir, was not simulated in the W2 model for the reasons explained in Section 4.7.

Figure 5-7 compares the monthly maximum observed and simulated concentrations at sampling dates and locations by season in Liberty Reservoir. As the figures show, the Chla calibration generally met its objective. Maximum simulated concentrations by season tend to be equal or greater than their observed counterparts. The only exception, other than the 2004 winter bloom, is the winter of 2003. Figure 5-8 compares the maximum simulated and observed Chla concentrations by date. As the figure shows, the W2 model captures the seasonal trend in the observed concentrations. Figures D-8 through D-11 in Appendix D show time series of observed and simulated maximum Chla concentrations for individual stations.

Table 5-9 shows the summary statistics for the observed and simulated maximum Chla concentrations. Figure 5-9 shows the observed and simulated distributions of maximum Chla concentrations by date and sampling location. The distribution of simulated concentrations tends to lower than observed concentrations for concentrations less than 15 µg/l. These concentrations are not significant for determining whether water quality standards are met by load reduction scenarios, because standards are already met in Liberty Reservoir for this range of concentrations. Simulated concentrations tend to match observed concentrations at higher concentrations (with the exception of the observations from the anomalous 2005 winter bloom).

Table 5-7: Dominant Algal Species By Season and Year

Year	Winter/Spring	Summer
2000	1	6
2001	1	2
2002	1	3
2003	4	4
2004	4	5
2005	4	6

Table 5-8: Algal Growth Rates and Temperature Parameters

Season	Rate	Temp1	Temp2	Temp3	Temp4	Fraction1	Fraction2	Fraction3	Fraction4
1	2.22	-1	4	6	8.5	0.4	0.99	0.80	0.7
2	3.205	18	20	28.5	30	0.2	0.99	0.99	0.2
3	3.525	18	20	28.5	30	0.2	0.99	0.99	0.2
4	2.5	-1.5	1.5	5.5	8.5	0.4	0.99	0.80	0.7
5	1.3	18	20	28.5	30	0.2	0.99	0.99	0.2
6	2.55	18	25	27.5	30	0.2	0.5	0.75	0.2

Table 5-9: Summary Statistics for Simulated and Observed Maximum Chla (µg/l)

Statistic	By Location and Date	
	Observed	Simulated
Min	0.7	0.0
1st Q	5.3	1.0
Median	8.2	4.0
3rd Q	12.3	10.3
Max	224.9	46.5
Mean	10.4	6.6
Std. Dev.	13.6	7.3
R^2	0.02	

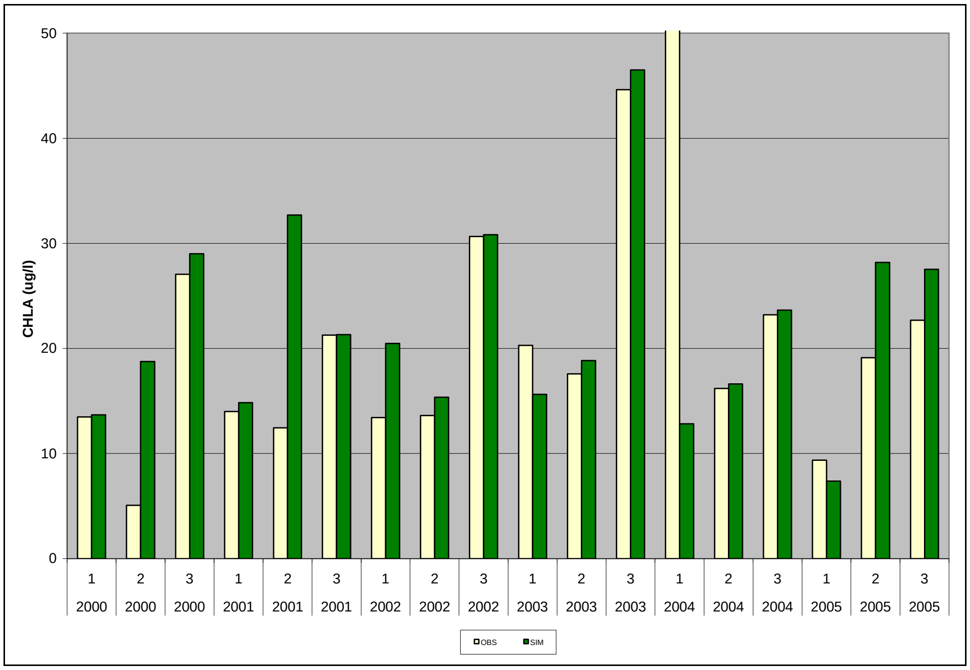

Figure 5-7: Cumulative Distribution of Observed and Simulated Chla Concentrations By Sampling Date, Liberty Reservoir

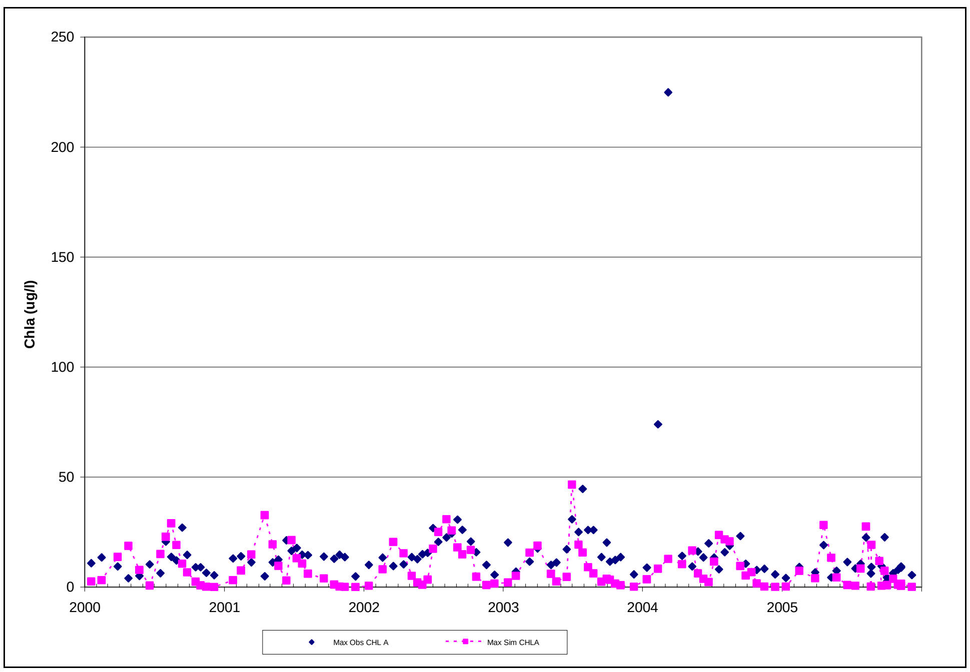

Figure 5-8: Observed and Simulated Maximum Chla Concentrations by Sampling Date, Liberty Reservoir

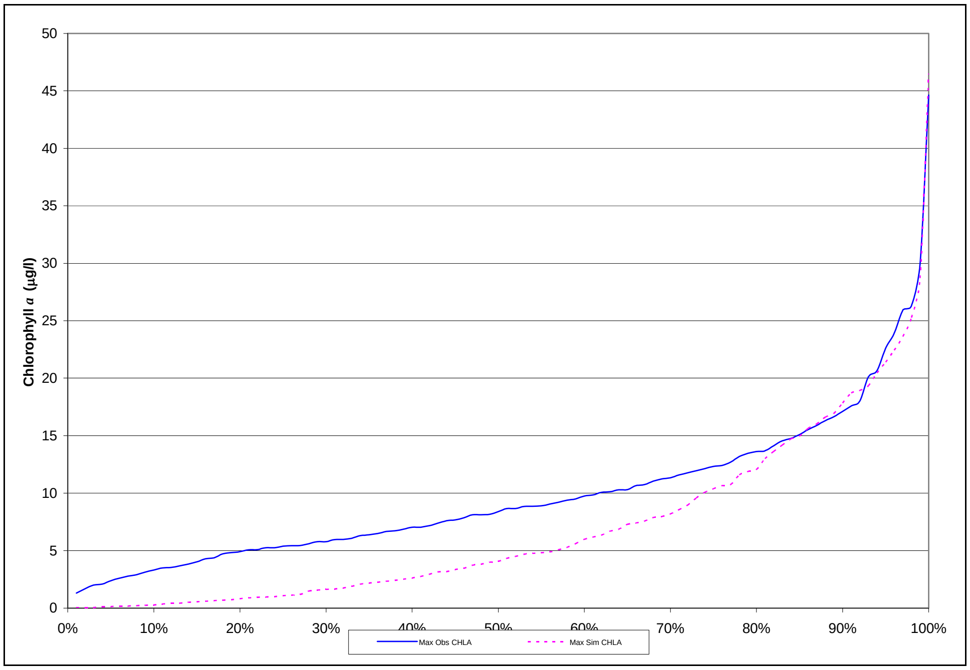

Figure 5-9: Cumulative Distribution of Observed and Simulated Chla Concentrations, Liberty Reservoir (excluding winter 2004 Algal Bloom)

5.8 Dissolved Oxygen Calibration

Since the primary function of the Liberty Reservoir W2 Model is to test the hypothesis that low dissolved oxygen concentrations observed in the bottom layers of Liberty Reservoir are a natural consequence of thermal stratification, the calibration of the simulation of dissolved oxygen, particularly in the bottom layers, is one of the most important tasks of the simulation.

Simulated surface dissolved oxygen concentrations are controlled by (1) consumption of oxygen by BOD decay and nitrification; (2) algal biomass production; and (3) reaeration. Since the concentration of algae and oxygen consuming materials are relatively low, reaeration and the physical exchange of oxygen across the air-water interface, as a function of meteorological conditions, is the most important process in determining simulated surface dissolved oxygen concentrations. A three-parameter reaeration formula which gives reaeration as a function of wind speed was used to simulate Liberty Reservoir. The same formula and parameter values were used for the Patuxent reservoirs. Values of the parameters are given in Table 5-10.

Simulated bottom dissolved oxygen concentrations are controlled by (1) loading rates of allochthonous and autochthonous organic material; (2) organic matter settling rates; and (3) decay rate and temperature parameters of the decay of organic material in the sediments. Table 5-10 shows the parameter values used in the Liberty Reservoir W2 Model. The settling rate of organic material is given in Table 5-4. The focusing velocity controls the lateral transport of organic material in a segment. The loading rate of allochthonous organic material was determined by adjusting how much of particulate

CBOD was labile, i.e. how much is CBOD2 and how much is CBOD3. Setting the labile fraction to 40% produced the best overall calibration results.

Table 5-11 shows the summary statistics for observed and simulated average dissolved oxygen in both the surface and bottom layers. Figure 5-10 shows the cumulative distribution of observed and simulated average surface dissolved oxygen concentrations. The coefficient of determination (R^2) between observed and simulated average surface DO concentrations is 0.51. Figure 5-11 shows the cumulative distribution of observed and simulated average bottom dissolved oxygen concentrations. The correlation between observed and simulated values is 0.75. Figures D-12 through D-18 in Appendix D show the time series of observed and simulated dissolved oxygen by monitoring station. These figures show the W2 model reproduces the seasonal variation in both surface and bottom DO concentrations.

Table 5-10: DO Calibration Parameter Values

Parameter	**Value**
Reaeration Coefficient-1	2.0
Reaeration Coefficient-2	0.15
Reaeration Coefficient-3	2.0
Organic Sediment Decay Rate (day-1)	0.04
Focusing Velocity (m/d)	8.5
Sediment Decay Temperature Start °C (% decay rate)	4.75 (10%)
Sediment Decay Temperature Max °C (% decay rate)	8.0 (95%)

Table 5-11: Summary Statistics for Observed and Simulated DO

Statistic: Bottom DO	**Surface**		**Bottom**	
	Observed	**Simulated**	**Observed**	**Simulated**
Min	6.6	7.5	0.0	0.0
1st Q	8.5	8.3	1.6	0.8
Median	9.1	8.8	4.1	3.3
3rd Q	10.1	9.6	7.2	6.4
Max	14.1	15.3	12.6	14.0
Mean	9.4	9.3	4.6	4.1
Std. Dev.	1.4	1.6	3.4	3.8
R^2	0.51		0.75	

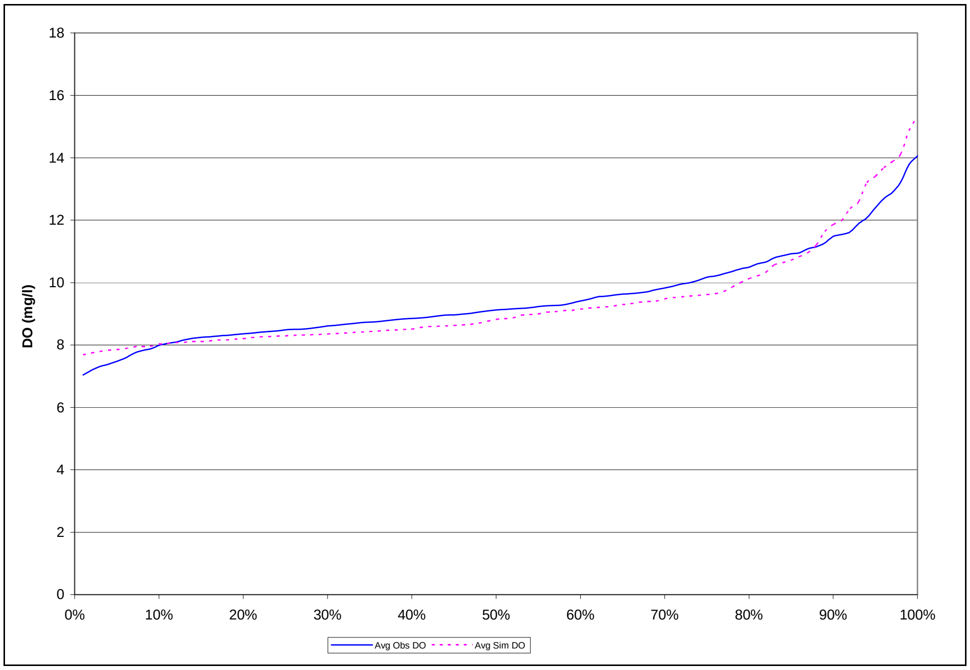

Figure 5-10: Observed and Simulated Cumulative Distribution of Surface DO Concentrations, Liberty Reservoir

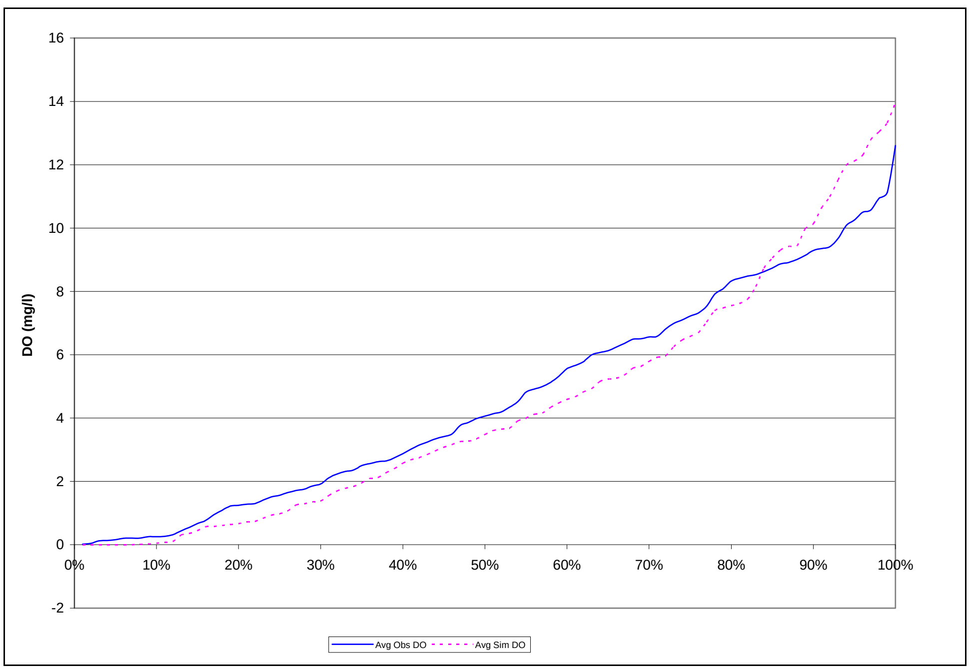

Figure 5-11: Observed and Simulated Cumulative Distribution of Bottom DO Concentrations, Liberty Reservoir

5.9 Nitrogen Calibration

Section 4.6 shows that Liberty Reservoir is phosphorus limited. Since algal growth dynamics and the decay organic material were determined through the calibration of phosphorus and chlorophyll, only three nitrogen processes could be parameterized to calibrate NH4 and NO3: (1) the release of NH4 from sediments through diagenesis, (2) nitrification or the conversion of NH4 to NO3, and (3) denitrification of NO3 under anaerobic conditions in the sediment and water column. Table 5-12 shows the key rate parameters for these processes. The release of NH4 from the sediments is determined by the SOD rate, the fixed nitrogen content of organic material, and a parameter which specifies release of ammonia from diagenesis as a proportion of organic sediment decay rate. It should be noted that there are two denitrification pathways, one is based on water-column denitrification under anaerobic conditions, and the other represents the flux of nitrate into the sediments as a "settling" velocity.

Table 5-12: Key Nitrogen Calibration Parameters

Parameter	Value
Nitrification Rate (1/d)	0.4
Ammonia Sediment Release Rate	0.1
Denitrification Rate (1/d)	0.05
Denitrification Velocity (m/d)	0.08

Table 5-13 shows summary statistics for average observed and simulated ammonia concentrations in the surface and bottom layers of Liberty Reservoir. Figures 5-12 and 5-13 show the distributions of observed and simulated average NH4 concentrations in the surface and bottom layers, respectively. Figures D-19 through D-25 in Appendix D show the time series of observed and simulated NH4 by monitoring station. Surface NH4 concentrations are undersimulated, probably due to the demand for ammonia by algae. Bottom simulated ammonia concentrations don't match the higher observed concentrations but capture the overall trend in observed bottom ammonia concentrations.

Table 5-14 shows summary statistics for average observed and simulated nitrate concentrations in the surface and bottom layers of Liberty Reservoir. Figures 5-14 and 5-15 show the distributions of observed and simulated average NO3 concentrations in the surface and bottom layers, respectively. Figures D-26 through D-32 in Appendix D show the time series of observed and simulated NO3 by monitoring station. Simulated surface nitrate concentrations closely match the distribution and seasonal trend in observed nitrate concentrations. Simulated bottom nitrate concentrations generally match the distribution of observed nitrate concentrations in the bottom layers.

Table 5-13: Summary Statistics for Observed and Simulated NH4

Statistic	**Surface**		**Bottom**	
	Observed	**Simulated**	**Observed**	**Simulated**
Min	0.005	0.001	0.005	0.008
1st Q	0.010	0.003	0.010	0.036
Median	0.025	0.006	0.030	0.053
3rd Q	0.055	0.033	0.080	0.082
Max	0.425	0.158	0.890	0.182
Mean	0.051	0.024	0.070	0.063
Std. Dev.	0.072	0.032	0.111	0.037
R^2	0.134		0.02	

Table 5-14: Summary Statistics for Observed and Simulated NO3

Statistic	**Surface**		**Bottom**	
	Observed	**Simulated**	**Observed**	**Simulated**
Min	0.250	0.785	0.6	0.7
1st Q	1.510	1.580	1.6	1.8
Median	1.740	1.865	1.9	2.0
3rd Q	2.095	2.225	2.2	2.1
Max	4.130	3.660	3.3	2.5
Mean	1.812	1.951	1.9	1.9
Std. Dev.	0.566	0.474	0.4	0.4
R^2	0.051		0.02	

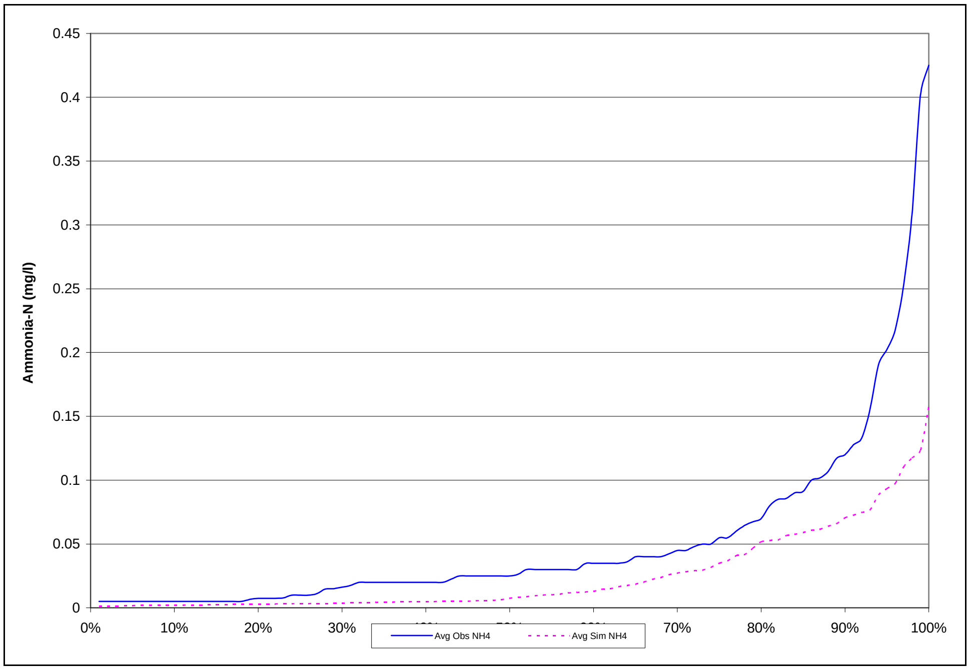

Figure 5-12: Cumulative Distribution of Observed and Simulated Average NH4 Concentrations, Surface Layer, Liberty Reservoir

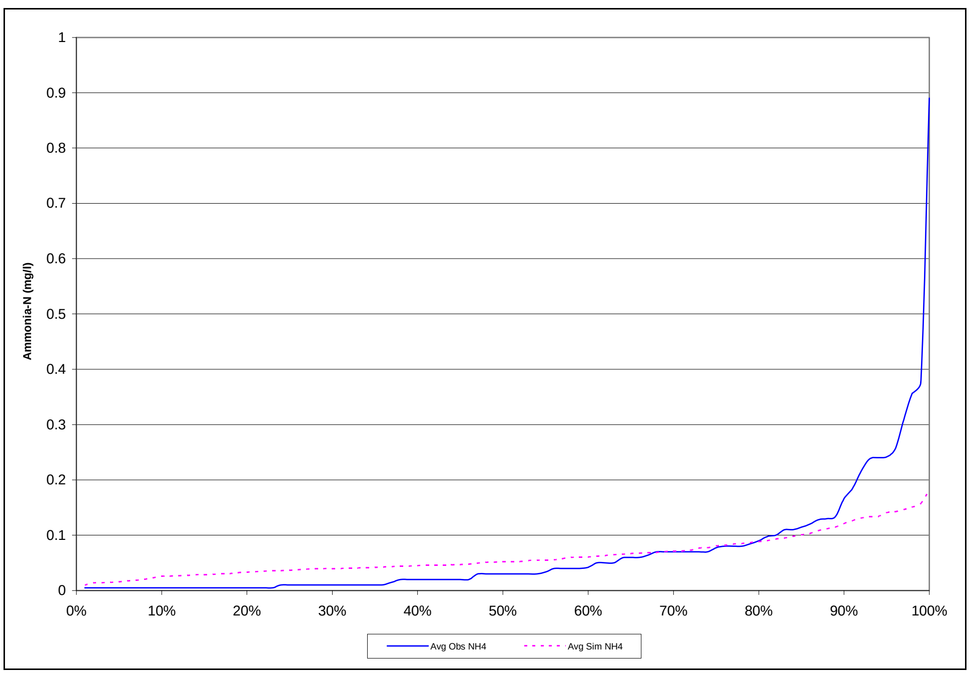

Figure 5-13: Cumulative Distribution of Observed and Simulated Average NH4 Concentrations, Bottom Layer, Liberty Reservoir

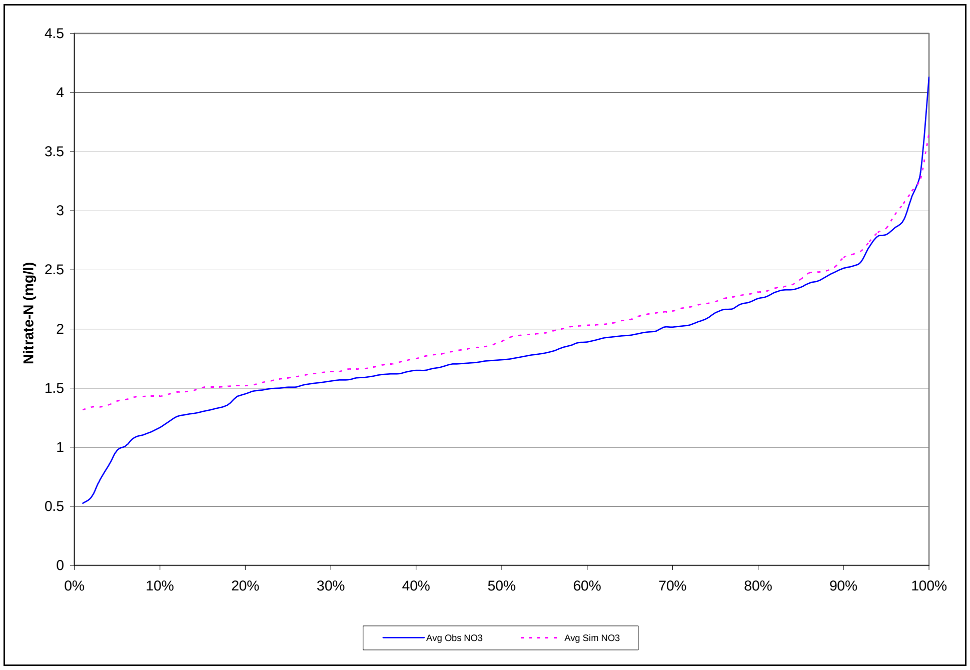

Figure 5-14: Cumulative Distribution of Observed and Simulated Average NO3 Concentrations, Surface Layer, Liberty Reservoir

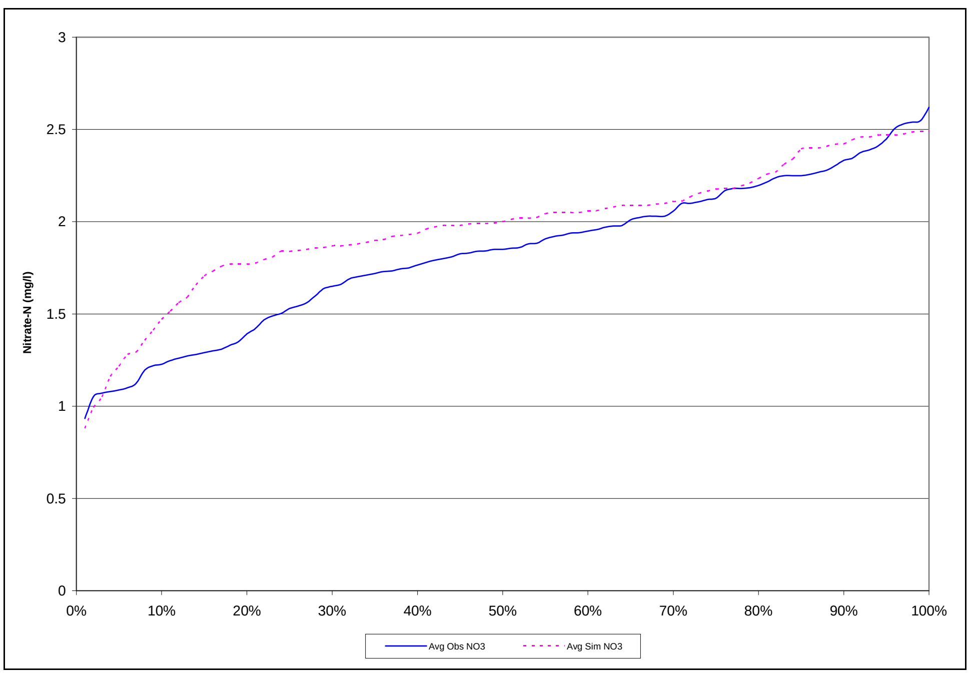

Figure 5-15: Cumulative Distribution of Observed and Simulated Average NO3 Concentrations, Bottom Layer, Liberty Reservoir

6.0. LOAD REDUCTION ANALYSIS AND SENSITIVITY SCENARIOS

The primary purpose of the Liberty Reservoir modeling framework, including the W2 models of Liberty Reservoir, is to determine the maximum total phosphorus load which allow the reservoir to meet the TMDL endpoints for chlorophyll and dissolved oxygen.

Using the calibrated reservoir model, phosphorus loads were reduced until a simulated load reduction achieved the desired TMDL endpoints. It was determined that a total phosphorus load reduction of 50% in Liberty Reservoir met the TMDL endpoints for chlorophyll. This TMDL Scenario also met the dissolved oxygen endpoints in the well-mixed surface layer under stratified conditions; deviations from the endpoints only occurred when oxygen–poorer layers from the metalimnion were mixed into the surface layer. Hypoxia still occurred in the bottom layers even under reduced loading rates.

The DO criteria for reservoirs recognize that hypolimnetic hypoxia may be a natural condition determined by reservoir morphology and stratification. A scenario was developed which represented the loads that would occur if the watersheds draining to Liberty Reservoir was entirely forested. The All-Forest Scenario was used to test whether hypoxia would occur in the hypolimnion even under natural conditions. The scenario confirmed that hypoxia would occur even under all-forested conditions and that therefore, Liberty Reservoir would meet the DO criteria under the TMDL Scenarios.

The actual TMDLs for Liberty Reservoir, specified according to the provisions of the Clean Water Act, are described in the TMDL documentation (MDE, 2012a). This chapter describes the TMDL Scenario and All-Forest Scenario in the context of model sensitivity analysis, after providing technical details on how the scenarios and other sensitivity analyses were implemented.

6.1. Scenario Descriptions

6.1.1. TMDL Scenario

The TMDL load reduction scenario was taken equally across all species of phosphorus: dissolved phosphate, particulate organic and inorganic phosphorus, and the phosphorus in labile CBOD, dissolved labile organic matter.

6.1.2. All Forest Scenario

In the all-forest scenario, flows were taken from all land uses, but constituent EOS loads were determined as if all the land in each subwatershed was forested. The parameterization of all in-stream processes were taken from the Calibration Scenario. If the reservoir watershed were truly all-forested, inflows to the reservoir would be different, but different inflows would demand different outflows, and setting the outflows would require determining how the reservoirs would be operated under all-forested conditions. The All-Forest Scenario constructed here represents a controlled simulation experiment, in which only one set of factors, the loads of dissolved and labile particulate organic phosphorus, are changed from the Calibration Scenario. Under this scenario, all other factors, including reservoir stratification, remain unchanged, and are therefore comparable to the Calibration Scenario.

Sensitivity runs on the All-Forest Scenario were conducted by making an across-the-board cut in labile particulate organic phosphorus, which is the W2 state variable that represents particulate labile particulate organic matter.

6.1.3. Comparison of Scenario Loading Rates

Table 6-1 compares the loading rates of phosphorus species for the Calibration, TMDL, and All-Forest Scenarios. The Forest Scenario phosphorus loads are about half the TMDL Scenario Loads. Since the TMDL Scenario is a 50% across-the-board reduction in TP, the relative fractions of each species in the TMDL Scenario is the same as the Calibration Scenario. The All-Forest Scenario has more dissolved organic phosphorus, and a higher percentage of organic phosphorus, than the Calibration Scenario.

Table 6-1: Scenario Average Annual Phosphorus Load (lbs/yr) By Species and Percent of Calibration Load

Phosphorus Species	Calibration	TMDL		All-Forest	
		Average Annual Load	Percent of Calibration	Average Annual Load	Percent of Calibration
DOP	1,192	596	50%	1,396	117%
DIP	12,727	6,364	50%	1,610	13%
PIP	26,919	13,459	50%	2,926	11%
POP	41,180	20,590	50%	13,443	33%
TP	82,017	41,009	50%	19,375	24%

DOP: Dissolved Organic Phosphorus; **DIP**: Dissolved Organic Phosphorus; **PIP**: Particulate Inorganic Phosphorus; **POP**: Particulate Organic Phosphorus

6.2. Criteria Tests

Up to this point much of the evaluation of model performance focused on comparing simulated concentrations with their observed counterparts. In evaluating whether a scenario meets water quality standards, simulated concentrations must be evaluated everywhere in the reservoir in the reservoir where relevant, not just at the sampling locations and sampling depths. At its maximum surface water elevation, Liberty Reservoir contains 1,134 cells. Advances in computer speed and memory has fortunately made processing the sheer amount of output to be evaluated only a minor challenge. The primary challenge is determining, when applying the dissolved oxygen criteria, whether under stratified conditions a cell is the mixed surface layer.

6.2.1. Chlorophyll Tests

Each cell in the first 15 layers (15 meter depth) was tested to determine whether (1) the instantaneous concentration of chlorophyll was above 30 µg/l and (2) whether the 30-day moving average of the chlorophyll concentration was above 10 µg/l. Daily output was used to make the test. A cell's identity was fixed relative to the surface for the 30-day moving average. In other words, the average was made over the cell that was, for example six meters deep in segment four, even if a layer was added or subtracted during the 30-day period so that the cell's indices changed. Tracking cells relative to the surface better simulates how monitoring would actually be performed and can in many cases better track identify of the mass of material.

6.2.2. Dissolved Oxygen Tests

Determining whether the reservoirs meet the DO standards can be broken down into three steps. First, the DO concentrations in a cell must be checked to determine if the concentration is below 5 mg/l. If a cell's concentration is below 5 mg/l, it must be determined whether or not it is in the surface layer. If it is below 5 mg/l and is in the surface layer it must be further determined whether or not it is impacted by the entrainment of low DO caused by the deepening of the surface layer or, as can also happen, the cell was itself previously below the well-mixed surface layer and has been recently mixed into the surface layer. Finally, it must be determined whether the low DO under stratified conditions is due primarily to constituent loads or is a naturally-occurring consequence of stratification and reservoir morphology.

The All-Forest Scenario and subsequent sensitivity analyses will demonstrate that hypoxia would occur even under the low constituent loading rates associated with an all-forested watershed. If the hypoxia in the reservoirs is a naturally-occurring condition, then the DO criteria would be violated if the all of the following conditions are met:

1. DO concentrations in a cell are below 5 mg/l;
2. The cell is in the well-mixed surface layer or the reservoirs are unstratified; and
3. The low DO concentration in the cell is not explainable as a result the entrainment of low DO layers in the metalimnion such as occurs during the fall overturn.

To determine the instantaneous DO concentrations in a cell, DO concentrations for potential surface layer cells were output every half of a day at 6AM and 6PM. Each concentration was checked to determine whether it was below 5 mg/l.

<u>Determination of the Position of the Surface Layer</u>

The key difficulty is determining whether a cell is in the well-mixed surface layer. There are no agreed-upon numerical criteria for defining the boundaries of epilimnion, metalimnion, and hypolimnion. A temperature gradient of 1 ºC/m is often used as a rule-of-thumb to determine the location of the theormocline (Wetzel, 2005), but others reject that criteria (Hutchinson, 1967; Ford and Johnson, 1986). A glance at the Figure 4-1 or the temperature contours in Appendix B clearly show that temperature stratification regularly takes place in Liberty Reservoir; it is difficult to determine a simple numerical criteria that captures the evident stratification. The temptation to paraphrase what one Supreme Court justice said in another context is strong: "I can't define stratification but I know it when I see it."

The following more-sophisticated procedure was used to determine the location of the surface layer on a daily basis:

1. A preliminary criterion is chosen which represents the temperature gradient that marks the boundary between the epilimnion and metalimnion.
2. On each day the average temperature in a layer was calculated for all model segments less than 30 meters deep.
3. The temperature difference between layers was calculated, starting from the surface layer. Since each layer except the surface layer is one meter thick, the temperature difference is easily translated into a temperature gradient.
4. Starting from the surface, the temperature differences are compared to the predetermined criterion. The bottom of the surface layer is the place where the temperature difference or gradient is larger than the criterion.
5. The location of the surface layer is checked for continuity. The reservoirs should be stratified between May and September. If there are days during that time when there were no temperature differences between layers greater than the criterion, then a smaller temperature gradient criterion was chosen and steps 3 and 4 were repeated.
6. Step 5 was repeated until there was continuous stratification from May into September.

The initial criterion chosen was the rule-of-thumb of 1 ºC/m. The final criterion used was 0.75ºC/m in Liberty Reservoir. The average temperature difference defining the surface layer is much larger than the criteria, average about 1.25 ºC/m. Table 6-2 shows the monthly average of daily temperature difference used to determine the surface layer in Liberty Reservoir.

As described in Section 4-2, low DO concentrations caused by fluctuations in the position of the surface layer are an effect of stratification and are compatible with the interpretation of the DO standards for impoundments. To facilitate analyzing simulated low DO concentrations, the surface layer was smoothed by defining an envelop of the minimum surface layer so that low DO concentrations caused by fluctuations in the surface layer position could be more easily indentified. Figure 6-1 shows the position of the interface between epilimnion and metalimnion in Liberty Reservoir, May through September, for the simulation period. As the figures show, there is considerable fluctuation in the position of the layer. Fluctuations as much as five meters can occur in summer months. Figure 6-1 also shows the location of the smoothed surface layer used to facilitate the analysis of low DO concentrations.

Table 6-2: Monthly Average Daily Temperature Gradient (°C/m) Determining Relative Position of Epilimnion and Metalimnion in Liberty Reservoir

Year	April	May	June	July	August	September	October
2000	0.23	1.84	1.51	1.18	1.09	1.10	0.88
2001	1.07	1.77	1.39	1.52	1.43	1.25	0.87
2002	1.32	1.24	1.68	1.50	1.39	1.14	0.84
2003	1.00	1.41	1.64	1.75	1.46	1.03	0.75
2004	0.87	1.94	1.68	1.59	1.33	1.08	0.55
2005	1.21	1.21	1.82	1.17	1.22	1.10	0.61
Average	0.95	1.57	1.62	1.45	1.32	1.12	0.75

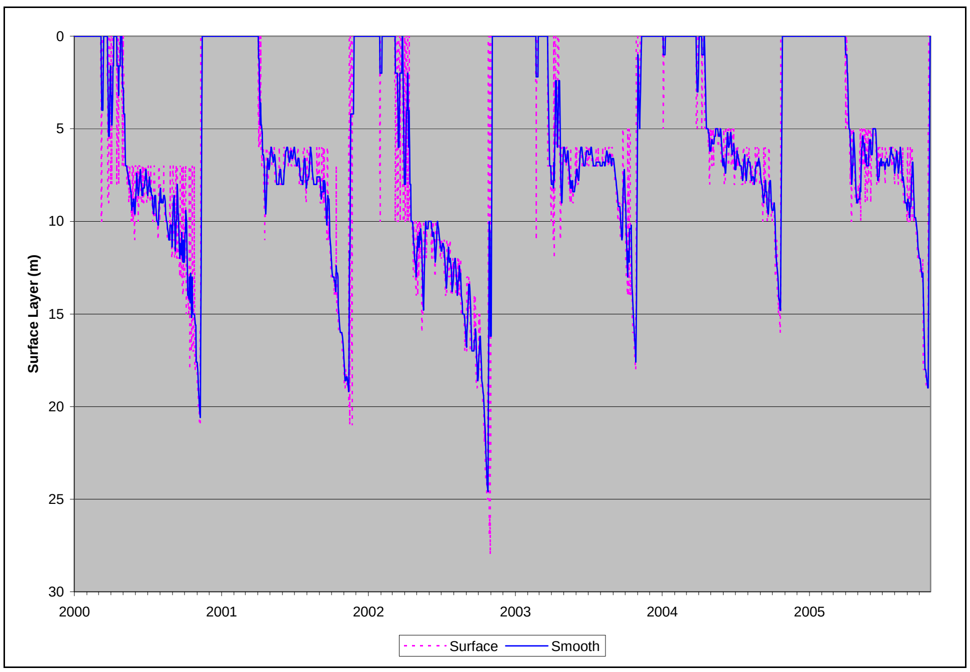

Figure 6-1: Position of the Interface between Epilimnion and Metalimnion, Liberty Reservoir

6.3. Response of Chlorophyll Concentrations to Reductions in Phosphorus Loads

As input loads to the reservoirs decrease, TP concentrations in the reservoirs decrease. Table 6-3 gives summary statistics for average surface TP concentrations in the reservoirs under the Calibration, TMDL, and All-Forest Scenarios.

Table 6-3: Scenario Summary Statistics for the Simulated Average Surface Concentrations (mg/l) of Total Phosphorus at Sampling Locations in Liberty Reservoir

Statistic	Calibration	TMDL	Forest
Minimum	0.009	0.006	0.004
1stQ	0.017	0.012	0.006
Median	0.023	0.014	0.008
3rdQ	0.027	0.017	0.010
Maximum	0.069	0.035	0.028
Average	0.023	0.014	0.009
St. Dev.	0.009	0.004	0.004

The reservoir models are responsive to reductions in chlorophyll loads. Figure 6-2 shows the maximum chlorophyll concentrations by sampling date in Liberty Reservoir under the TMDL Scenario and All Forest Scenario and contrast them with the maximum observed concentrations and the maximum simulated concentrations under the Calibration Scenario. Chla concentrations are at a minimum in the All Forest Scenario. The average maximum concentration on sampling dates for the TMDL Scenario is about 2 ug/l and in the Forest Scenario it is 0.4 ug/l, in contrast to the Calibration Scenario, which has an average Chla concentration of 6.6 ug/l. Chla concentrations in the All-Forest Scenario are proportionally less than the difference in loading rates because organic phosphorus constitutes a larger fraction total phosphorus under the All-Forest Scenario.

Figures E-1 through E-4 in Appendix E show the maximum Chla concentrations for all scenarios at NPA0042, NPA0059, NPA0067, and NPA0105, respectively, in the Liberty Reservoir.

.

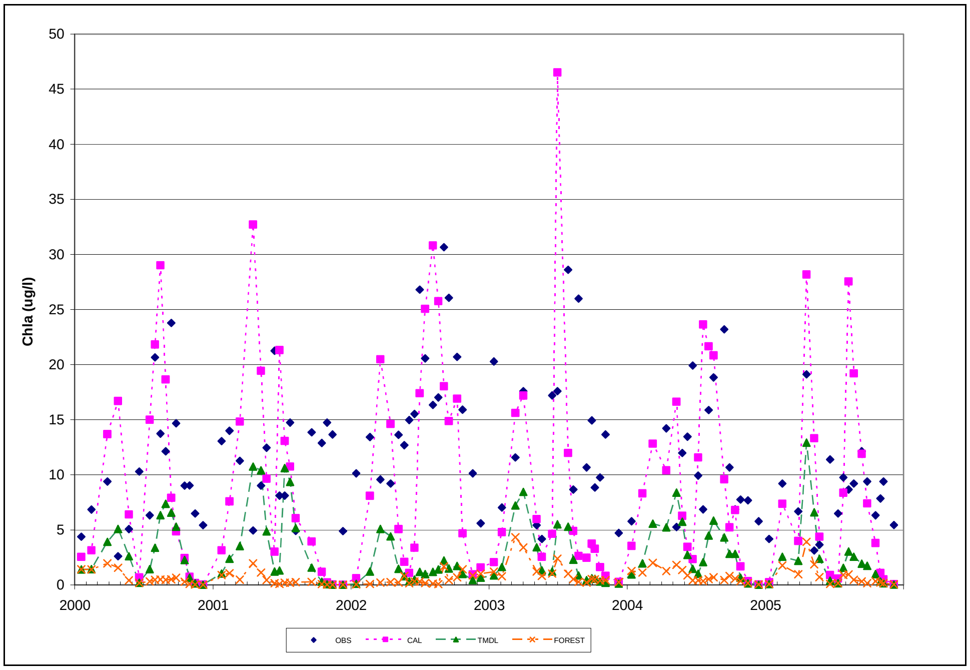

Figure 6-2: Observed and Simulated Maximum Chlorophyll Concentrations by Date, Liberty Reservoir

6.4. The Response of DO Concentrations to Load Reductions

Since the factors which determine DO concentrations in the surface layer and the bottom layer are different, and they are treated differently under MD's DO criteria, the simulated response of DO concentrations to load reductions will be discussed separately below.

6.4.1. The Response of Simulated Surface DO Concentrations to Load Reductions

As discussed in Section 4.3, there is no evidence that DO concentrations fall below 5 mg/l in the surface layer except during periods of overturn or other fluctuations in the depth of the surface layer. Thus, there is no evidence that the instantaneous DO criterion of 5 mg/l is violated, provided that it can be shown that the low DO that occurs under stratification is a natural phenomenon.

Nonetheless, it is necessary to evaluate the simulation of DO in the TMDL Scenario to make sure that the scenario predicts that water quality standards for DO will be met under the TMDL loading rates. The procedures described in 6.2.2 were applied to the TMDL Scenario. No cells in the surface layers of Liberty Reservoir failed to meet DO under the screening procedure.

Figure 6-3 shows the average surface DO concentration for the Calibration Scenario, TMDL Scenario and All-Forest Scenario, as well as the observed data, at TR1 in Liberty Reservoir. Figures E-7 through E-9 show surface DO for all scenarios at NPA0059, NPA0067, and NPA0105, respectively, in Liberty Reservoir. As the figures show, surface DO concentrations show at best very modest increases with reductions in phosphorus and, consequently, organic matter loading rates. The increases are very modest because the surface oxygen deficit is very modest; to reiterate, there is no evidence of low dissolved oxygen concentrations in the surface layer of the reservoirs that is not a result of stratification.

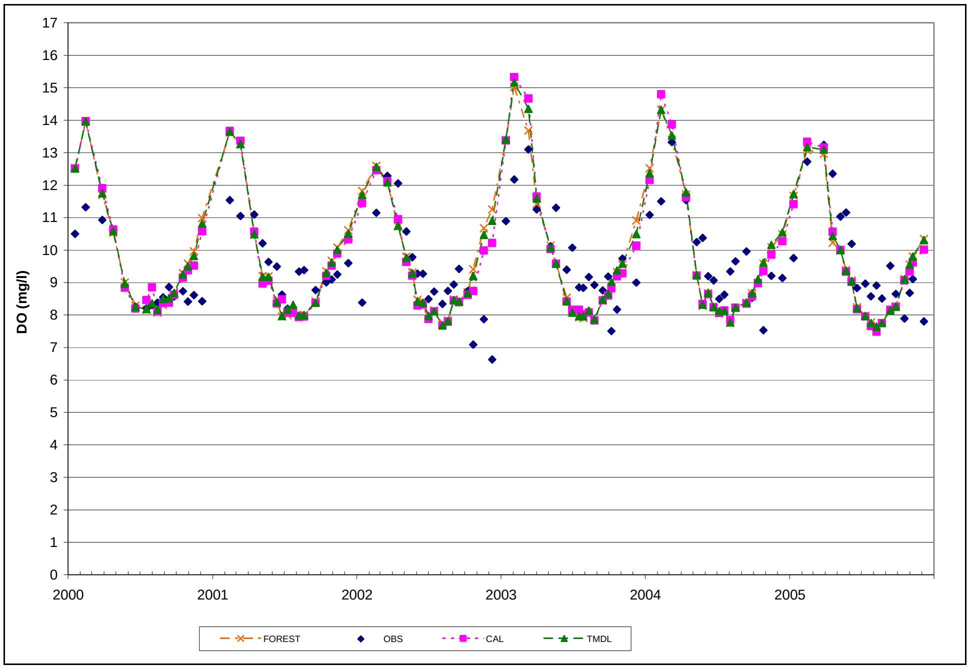

Figure 6-3: Surface DO, Observed Data and All Scenarios, NPA0042, Liberty Reservoir

6.4.2. The Response of Simulated Bottom DO Concentrations to Load Reductions

Figure 6-4 shows the average bottom DO concentration for the Calibration Scenario, TMDL Scenario, and All-Forest Scenario, as well as the observed data, at NPA0042 in Liberty Reservoir. Figures E-5 and E-6 in Appendix E show the average bottom DO concentration at NPA0059 and NPA0067, respectively. The models respond to reductions in particulate organic phosphorus, but clearly do not meet the 5 mg/l DO criterion, even averaged over the bottom layers. Figure 6-5 compares the cumulative distribution of bottom DO concentrations among the scenarios.

The All-Forest Scenario, as described in Section 6.1, was simulated to determine whether the source of the hypoxia in the hypolimnion is a natural consequence of stratification and would occur under the loading rates of an all-forested watershed. Average bottom DO concentrations improve significantly under the All-Forest Scenario, but hypoxia persists in both reservoirs in the summer of some of the years simulated. A sensitivity analysis was performed to reinforce the conclusion that hypoxia in the hypolimnion of Liberty Reservoir is a natural condition due to thermal stratification. Given the low concentration of algal biomass in the All-Forest Scenario, the allochthonous sources of sediment oxygen demand, as represented by labile particulate organic phosphorus, are the primary cause of hypoxia in the hypolimnia of the reservoirs. The forest TP loading rates were based on available data, but some uncertainly may linger over (1) the fraction of phosphorus that is labile or (2) the oxygen equivalence of the organic material associated with organic phosphorus. These were calibrated in general but not specifically for forest loads. The loading rate of labile particulate phosphorus was reduced to 50%, 20%, and 10% of its value in the All-Forest Scenario in both reservoirs. Figure 6-6 shows the results, summarized as the percent of sampling dates under each sensitivity scenario in which the minimum DO concentration was less than 2 mg/l. Hypoxia persists even when loads are reduced to only 20% of the All-Forest Scenario.

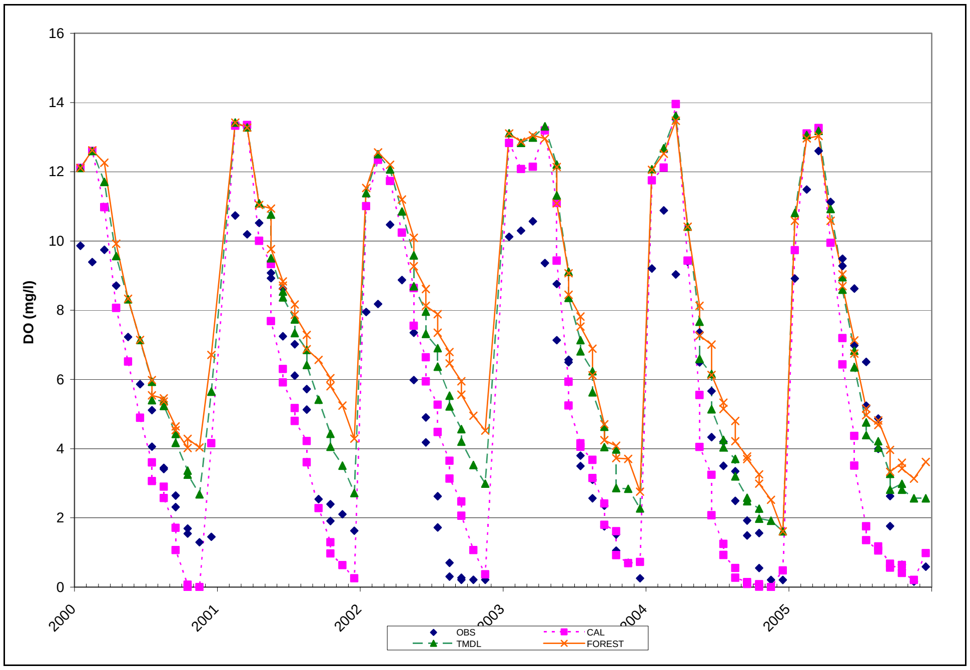

Figure 6-4: Average Bottom DO, Observed Data and All Scenarios, NPA0042, Liberty Reservoir

The All-Forest Scenario and the associated sensitivity tests have been a part of the methodology of testing whether DO criteria have been met in both the Gunpowder Reservoirs (ICPRB and MDE, 2006) and the Patuxent Reservoirs (ICPRB 2008), and the persistence of hypoxia in the epilimnion under the All-Forest Scenario was generally more pronounced in these other drinking water reservoirs. To a large extent, this is not due to differences in the response of the reservoirs to allochthonous loading rates, but to the depths at which the reservoirs are sampled. Liberty Reservoir is significantly deeper than the other major MD drinking water reservoirs. The deepest sampling location in Liberty Reservoir at NBP0042 is represented by 44 one-meter layers in the W2 model; in contrast, at their deepest sampling locations, Prettyboy Reservoir is represented by 37 layers and Loch Raven Reservoir is represented by 24 layers.

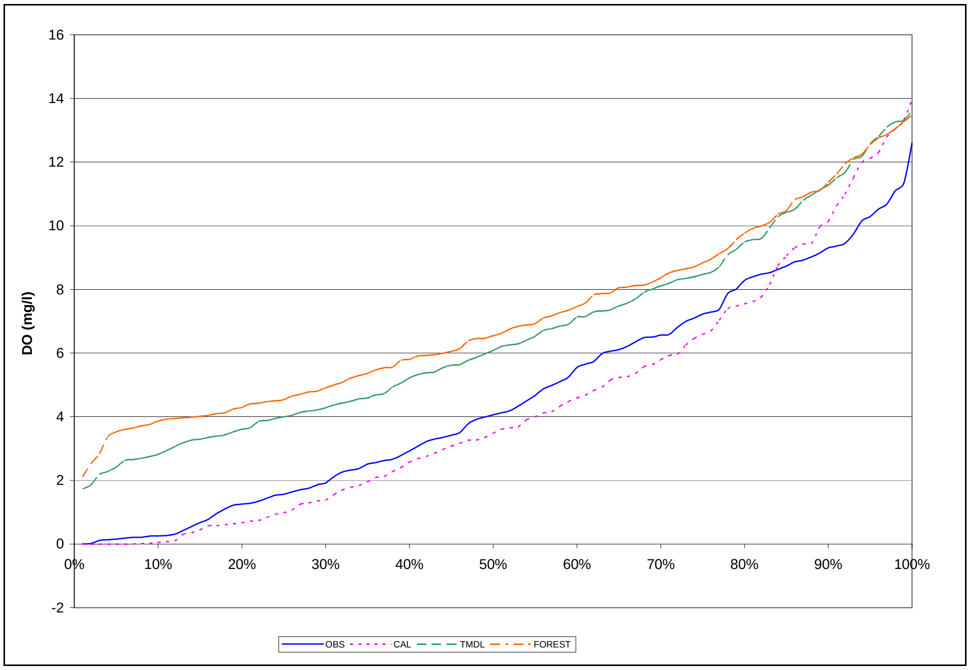

Figure 6-5: Cumulative Distribution of Bottom DO Concentrations in Liberty Reservoir

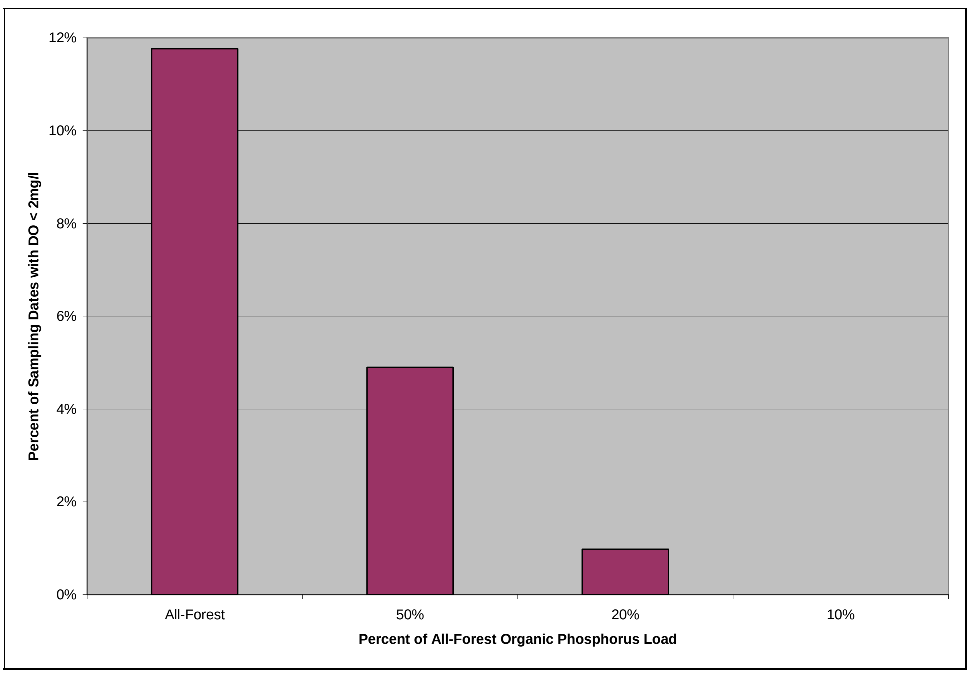

Figure 6-6: Percent of Sampling Dates on which DO < 2mg/l, as a Function of Percent Labile Particulate Organic Phosphorus, Liberty Reservoir

On the other hand, the median layer for the deepest sample taken in Liberty Reservoir is nine meters from the bottom, while the median layer for the deepest sample is five meters from the bottom in Prettyboy Reservoir and four meters from the bottom in Loch Raven Reservoir. The deepest samples in the Patuxent Reservoirs, which are smaller than the Gunpowder Reservoirs, are generally taken one meter from the bottom. Figure 6-7 shows the simulated DO profiles for the Calibration Scenario, the All-Forest Scenario, and the All-Forest sensitivity tests on November 15, 2004. Observed concentrations are also shown in the Figure. 6-7. Statistics for model scenarios are based only on simulated concentrations in the layers where observations are taken. In other words, average simulated bottom DO on this date is an average of the simulated concentrations in the four layers (28, 31, 35, and 37) shown in Figure 6-7. The minimum simulated DO on this sample date is the minimum simulated concentration from these four layers (taking into account the other sampling locations). The impact of sampling depth on capturing bottom hypoxia in Liberty Reservoir is apparent. Had a sample been taken at depth five meters above the bottom (as in Prettyboy Reservoir), all the sensitivity test scenarios would have indicated hypoxia on this date. On the other hand, had the deepest sample been taken at the median layer for the bottom sample, none of the sensitivity test scenarios would have indicated hypoxia on this date. A consequence of the comparatively shallower sampling depth in Liberty Reservoir, therefore, is an underestimation of the extent of hypoxia in the hypolimnion under the All-Forest Scenario and sensitivity tests.

Taking into account the impact of the sampling depth, the sensitivity analysis shows that low DO in the bottom layers of the reservoirs is relatively insensitive to the particular assumptions used to determine organic matter loads in the models, and demonstrates that hypolimnetic hypoxia is primarily driven by stratification and reservoir morphology, rather than by external loads.

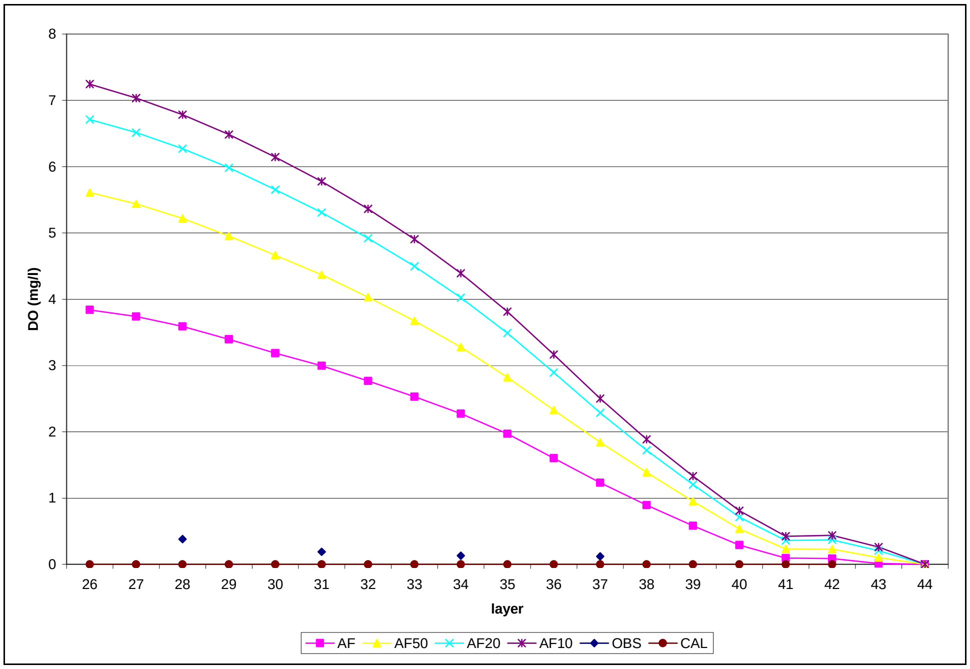

Figure 6-7: DO Concentration Profiles for Calibration Scenario, All-Forest Scenario, and All-Forest Sensitivity Tests, along with Observed Data at NBP0042, November 15, 2004

7.0 SUMMARY AND RECOMMENDATIONS

7.1 Summary

The modeling framework for Liberty Reservoir outlined in this report generally meets the following major objectives set for its design:

1. By using a refined version of the Chesapeake Bay Program Phase 5 Watershed Model, the edge-of-stream (EOS) loads used from watershed land uses are in principle in agreement with the estimated EOS loads for the Chesapeake Bay TMDL. This simplifies the management of environmental objectives both at the state and local scale and provides a common currency for managing competing objectives.

2. Through a refined river reach network and the verification of simulated river reaches to average annual LOADEST loads based on local water quality monitoring, the refined version of the P5 Watershed Model has taken into account available data for estimating nutrient and sediment loads to Liberty Reservoir.

3. A CE-QUAL-W2 model of Liberty Reservoir has been calibrated to simulate hydrodynamics, temperature, nutrient concentrations, chlorophyll a concentrations, and dissolved oxygen dynamics.

4. The W2 model establishes linkage between phosphorus loads, on the one hand, and Chla concentrations in terms of which the nutrient TMDL endpoint is expressed. The Chla simulation was calibrated conservatively, so that simulated Chla concentrations matched or exceeded seasonal maximum Chla concentrations.

5. The W2 model also establishes a linkage between observed hypoxia in the hypolimnion of the reservoirs and internal and external organic matter loading rates. The loading rates for external organic matter have been expressed in terms of organic phosphorus, thus linking nutrient loading rates with SOD and bottom DO concentrations in the reservoirs.

6. Both in respect to simulated Chla concentrations and bottom DO, the W2 model has been shown to be sensitive to external phosphorus loading rates.

7. An All-Forest Scenario, which simulates the effect on the reservoirs of loading rates characteristic of all-forested watershed, demonstrates that hypolimnetic hypoxia is primarily the result of stratification, not autothchonous or allochthonous organic matter loading rates.

7.2 Recommendations

There is no model which could not be improved if additional monitoring data were available, and these models are no exception. Additional water quality monitoring could reduce some of the uncertainty associated with constituent loads and the reservoir's response to those loads.

From the modeling point-of-view, the reservoir monitoring program could be improved by analyzing both tributary and reservoir samples for (1) DIP, (2) TKN, and (3) some measures of oxygen-demanding material and organic carbon, such as CBOD, Total Organic Carbon (TOC), or Chemical Oxygen Demand (COD). The first is important for determining how much phosphorus is bioavailable, the second for better understanding the nitrogen cycle in the reservoirs, and the last for quantifying water column oxygen demand and potential contributors to sediment oxygen demand.

There is an additional benefit to analyzing tributary storm samples for TKN. Since phosphorus is the limiting nutrient is Liberty Reservoir, the nutrient TMDL was restricted to phosphorus, and no allocations were set for total nitrogen. Both Baltimore County and Carroll County are, however, subject to total nitrogen allocations under the Chesapeake Bay TMDL. Total nitrogen yields in MD's Western Shore are perhaps more uncertain than elsewhere in the state, because there are fewer P5 Model calibration points in the Western Shore where there is available storm water monitoring data. If BCDPW analyzed storm samples for TKN or TN, not just in the Liberty Reservoir watershed but at their other storm water monitoring locations in the Gunpowder Falls watershed, it would go a long way to better characterizing total nitrogen loads in the Western Shore.

REFERENCES

Baltimore City Department of Public Works (BCDPW).1981. The Story of Baltimore's Water Supply. Baltimore, MD.

____________________. 2010. http://www.baltimorecity.gov/Government/AgenciesDepartments/PublicWorks/BureauofWaterWastewater/FactSheet.aspx

Baltimore County Department of Environmental Protection and Resource Management (BCDEPRM). Gunpowder Watershed Study Monitoring Results. 2000.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle, Jr., and A.S. Donigian, Jr. 2000. Hydrological Simulation Program - Fortran (HSPF): User's Manual for Release 12.

Beulac, M. N., and K. H. Reckhow. 1982. An Examination of Land Use – Nutrient Export Relationships. Water Resources Bulletin. 15. pp. 1013-1022.

Carlson, R. E. 1977. A Trophic State Index for Lakes. *Limnology and Oceanography* 22:361-369.

Chiandani, G. and M. Vighi. 1974. The N:P Ratio and Tests with *Selanastrum* to Predict Eutrophication in Lakes. *Water Research*, Vol. 8, pp. 1063-1069.

Claggett, P., F. M. Irani, and R. L. Thompson. 2012. Estimating the Extent of Impervious Surfaces and Turf Grass across Large Regions. Submitted to American Water Resources Association (AWRA) Spring Specialty Conference: GIS and Water Resources VII. New Orleans, LA. March 26-27, 2012.

Cohn, T. A. , L. L. Delong, E. J. Gilroy, R. M. Hirsch, and D. Wells. 1989. Estimating Constituent Loads. Water Resources Research 28. pp.937-942.

Cohn, T. A., D. L. Caulder, E. J. Gilroy, L. D. Zynjuk, and R. M. Summers. 1992. The Validity of a Simple Log-linear Model for Estimating Fluvial Constituent Loads. Water Resources Research 28. pp. 2353-2364.

Cole, T. M. and E. M. Buchak. 1995. CE-QUAL-W2: A Two-Dimensional Laterally Averaged, Hydrodynamic and Water Quality Model, Version 2.0. User Manual. Washington, DC. U.S. Army Corps of Engineers. Instruction Report EL-95-1.

Cole, T. M. and S. A. Wells. 2003. CE-QUAL-W2: A Two-Dimensional Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.2. User Manual. Washington, DC. U.S. Army Corps of Engineers. Instruction Report EL-03-1.

COMAR (Code of Maryland Regulations). 2009a. 26.08.02.08K(1). http://www.dsd.state.md.us/comar/26/26.08.02.08.htm(Accessed March, 2010).

Doherty, J. 2001. PEST: Model independent parameter estimation - User's Manual. Watermark Numerical Computing.

Edinger, J. E. and E. M. Buchak. 1975. A Hydrodynamic, Two-Dimensional Reservoir Model: The Computational Basis. U. S. Army Engineer Division, Ohio River. Cincinnati, OH.

Ford, D. E. and L. S. Johnson. 1986. An Assessment of Reservoir Mixing Processes. U.S. Army Corps of Engineers Waterways Experimental Station. Vicksburg, MS. Technical Report E-86-7.

Goetz, S. J., C. A. Jantz, S. D. Prince, A. J. Smith, R. Wright, and D. Varlyguin. 2004. Integrated Analysis of Ecosystem Interactions with Land Use Change: the Chesapeake Bay Watershed. In *Ecosystems and Land Use Change*, edited by R. S. DeFries, G. P. Asner, and R. A. Houghton. American Geophysical Union. Washington, DC.

Hutchinson, G. E. 1967. A Treatise on Limnology. 3 volumes. John Wiley and Sons. New York.

ICPRB (Interstate Commission on the Potomac River Basin) and Maryland Department of the Environment. 2006. Modeling Framework for Simulating Hydrodynamics and Water Quality in the Prettyboy and Loch Raven Reservoirs. Rockville, MD.

ICPRB 2008. Modeling Framework for Simulating Hydrodynamics and Water Quality in the Triadelphia and Rocky Gorge Reservoirs, Patuxent River Basin, Maryland. Rockville, MD.

ICPRB 2010. Modeling Framework for Water Quality Analysis For Eutrophication in Deep Creek Lake. Rockville, MD.

Langland, M.J., R. E. Edwards, L. A. Sprague, and S. E. Yochum, 2001. Summary of Trends and Status Analysis for Flow, Nutrients, and Sediments at Selected Nontidal Sites, Chesapeake Bay Basin, 1985-99: U.S. Geological Survey Open File Report 01-73.

Langland, M.J., S. W. Phillips, J. P. Raffensperger, and D. L. Moyer. 2005. Changes in streamflow and water quality in selected nontidal sites in the Chesapeake Bay Basin, 1985-2003: U.S. Geological Survey Scientific Investigations Report 2004-5259.

MDE (Maryland Department of the Environment). 2006. *Total Maximum Daily Loads of Phosphorus and Sediments for Loch Raven Reservoir and Total Maximum Daily Loads of Phosphorus for Prettyboy Reservoir, Baltimore, Carroll and Hartford Counties, Maryland*. Baltimore, MD: Maryland Department of the Environment. http://www.mde.state.md.us/Programs/WaterPrograms/TMDL/ApprovedFinalTMDL/TMDL_final_gunpowder_P_sed.asp

————. 2008. *Total Maximum Daily Loads of Phosphorus and Sediments for Triadelphia Reservoir and Total Maximum Daily Loads of Phosphorus for Rocky Gorge Reservoir, Howard, Montgomery and Prince George's Counties, Maryland*. Baltimore, MD: Maryland Department of the Environment. http://www.mde.state.md.us/Programs/WaterPrograms/TMDL/ApprovedFinalTMDL/TMDL_Pax_Res_P_Sed.asp.

________________. 2010. *Water Quality Analysis for Eutrophication for the Deep Creek Lake Watershed in Garrett County, Maryland*. Baltimore, MD: Maryland Department of the Environment.

________________. 2012a. *Total Maximum Daily Loads of Phosphorus and Sediment for the Liberty Reservoir in Baltimore and Carroll Counties, Maryland*. Baltimore, MD: Maryland Department of the Environment.

________________, 2012b. Watershed Report for Biological Impairment of the Liberty Reservoir Watershed in Baltimore and Carroll Counties, Maryland. Biological Stressor Identification Analysis. Results and Interpretation. Baltimore MD:Maryland Department of the Environment.

Maryland Department of Geology, Mines, and Water Resources. 1946. The Physical Features of Carroll County and Frederick County. Baltimore, MD.

Maryland Department of Natural Resources (DNR). 2002. *Liberty Reservoir Watershed Characterization*. Annapolis, MD.

__________________. 2003. *Liberty Reservoir Stream Corridor Assessment Survey*. Annapolis, MD.

McElroy, A.D., S.Y. Chiu, J.W. Nebgen, A. Aleti and F.W. Bennett. 1976. Loading Functions for Assessment of Water Pollution from Nonpoint Sources. EPA-600/2-76-151. U.S. Environmental Protection Agency. Washington, D.C.

MGS (Maryland Geological Survey).2001. Bathymetric Map of Liberty Reservoir. http://www.mgs.md.gov/coastal/maps/lr/liberty.html

Moyer, D.L., and M. R. Bennett. 2007. Development of relations of stream stage to channel geometry and discharge for stream segments simulated with Hydrologic Simulation Program-Fortran (HSPF), Chesapeake Bay Watershed and adjacent parts of Virginia, Maryland, and Delaware. U.S. Geological Survey Scientific Investigations Report 2007-5135.

National Climatic Data Center. 2001.

Nusser, S. M., and J. J. Goebel. 1997. The National Resources Inventory: A Long-Term Multi-Resource Monitoring Program. *Environmental and Ecological Statistics* 4: 181-204.

Ortt, R. A. Jr., and D. V. Wells. 2003. Bathymetric Survey and Sedimentation Analysis of Liberty Reservoir (Draft). Coastal and Estuarine Geology File Report No. 02-03. Maryland Geological Survey.

Pitt, R., A. Maestre, R,. Morquecho, T. Brown, C. Swann, K. Cappiella, and T. Schuler. 2005. Evaluation of NPDES Phase 1 Municipal Stormwater Monitoring Data. http://www.epa.gov/owow/nps/natlstormwater03/28Pitt.pdf

Portland State University. 2012. CE-QUAL-W2 Hydrodynamic Model website. http://www.cee.pdx.edu/w2/

Reservoir Technical Group. 2004. Baltimore Reservoir Watershed Management Program. Reservoir Program Technical Report: Water Quality Assessment, Targeted Studies, and Ongoing Water Quality Issues in the Baltimore Metropolitan Water Supply Reservoirs and Their Watersheds. Baltimore Metropolitan Council. Baltimore, MD.

______________. 2005. Baltimore Reservoir Watershed Management Program. Action Strategy for the Reservoir Watersheds. Baltimore Metropolitan Council. Baltimore, MD.

Runkel, R. L., C. G. Crawford, and T. A. Cohn. 2004. Load Estimator (LOADEST): A FORTRAN Program for Estimating Constituent Loads in Streams and Rivers. Techniques and Methods Book 4, Chapter A5. U. S. Geological Survey. Reston, VA.

Thomann, Robert V., John A. Mueller. 1987. *Principles of Surface Water Quality Modeling and Control*. HarperCollins Publisher Inc., New York.

University of Maryland Cooperative Extension Service. 1976. Maryland Soils. Extension Bulletin 212. College Park, MD.

USDA (U.S. Department of Agriculture). 1969. Soil Survey Carroll County, Maryland. Washington, DC.

_____________. 1976. Soil Survey Baltimore County, Maryland. Washington, DC.

_____________. 1982. *1982 Census of Agriculture*. United States Department of Agriculture. Washington, DC.

_____________. 1987. *1987 Census of Agriculture*. United States Department of Agriculture. Washington, DC.

_____________. 1992. *1992 Census of Agriculture*. United States Department of Agriculture. Washington, DC.

_____________. 1997. *1997 Census of Agriculture*. United States Department of Agriculture. Washington, DC.

_____________. 2002. *2002 Census of Agriculture*. United States Department of Agriculture. Washington, DC.

_____________. 2007. *State Soil Geographic (STATSGO) Database for Maryland*. http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/index.html (Accessed March, 2007).

U.S. Environmental Protection Agency (USEPA). 2010. *Chesapeake Bay Phase 5.3 Community Watershed Model*. EPA 903S10002 - CBP/TRS-303-10. U.S. Environmental Protection Agency, Chesapeake Bay Program Office, Annapolis MD. December 2010. Also available at http://ches.communitymodeling.org/models/CBPhase5/documentation.php#p5modeldoc

U. S. Geological Survey (USGS). 2000. Water Resources Data - Maryland and Delaware, Water Year 2000 Volume 1: Surface-Water Data WDR-MD-DE-00-1

Walker, W.W., Jr. 1984. *Statistical Bases for Mean Chlorophyll a Criteria*. Lake and Reservoir Management: Proceedings of Fourth Annual Conference. North American Lake Management Society, pp. 57 – 62.

Wetzel.2005. Limnology. Academic Press. New York, NY.

Weisberg, S. B., K. A. Rose, B. S. Clevenger, and J. O. Smith. 1985. Inventory of Maryland Dams and Assessment of Hydropower Resources. Martin Marietta Environmental Systems. Columbia, Maryland.