Total Maximum Daily Loads of Phosphorus and Sediments for Triadelphia Reservoir (Brighton Dam) and Total Maximum Daily Loads of Phosphorus for Rocky Gorge Reservoir, Howard, Montgomery, and Prince George's Counties, Maryland

FINAL

DEPARTMENT OF THE ENVIRONMENT
1800 Washington Boulevard, Suite 540
Baltimore, MD 21230-1718

Submitted to:
U.S. Environmental Protection Agency, Region III
Water Protection Division
1650 Arch Street
Philadelphia, PA 19103-2029

June 2008

EPA Submittal Date: September 26, 2007
EPA Approval Date: November 24, 2008

Table of Contents

List of Figures

List of Tables

List of Abbreviations

BMP	Best Management Practice
BOD	Biochemical Oxygen Demand
CBOD	Carbonaceous Biochemical Oxygen Demand
CE-QUAL-W2	U.S. Army Corps of Engineers Water Quality and Hydrodynamic Model, Version 3
Chla	Active Chlorophyll *a*
COMAR	Code of Maryland Regulations
CWA	Clean Water Act
CWAP	Clean Water Action Plan
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
HSPF	Hydrological Simulation Program Fortran
ICPRB	Interstate Commission on the Potomac River Basin
LA	Load Allocation
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
MNCP&PC	Maryland National Capital Parks and Planning Commission
MOS	Margin of Safety
MS4	Municipal Separate Storm Sewer System
NBOD	Nitrogenous Biochemical Oxygen Demand
NMP	Nutrient Management Plan
NOAA	National Oceanic and Atmospheric Administration
NO23	Nitrite-Nitrate-N
NPDES	National Pollutant Discharge Elimination System

NPS	Nonpoint Source
POM	Particulate Organic Matter
PO4	Phosphate
SCWQP	Soil Conservation and Water Quality Plan
SOD	Sediment Oxygen Demand
TAC	Patuxent Reservoirs Technical Advisory Committee
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TOP	Total Organic Phosphorus
TP	Total Phosphorus
TSI	Trophic State Index
TSS	Total Suspended Solids
W2	CE-QUAL-W2
WLA	Wasteload Allocation
WQIA	Water Quality Improvement Act
WQLS	Water Quality Limited Segment
WSSC	Washington Suburban Sanitary Commission
WWTP	Waste Water Treatment Plant
μg/l	Micrograms per Liter

EXECUTIVE SUMMARY

This document, upon approval by the U.S. Environmental Protection Agency (EPA), establishes Total Maximum Daily Loads (TMDLs) for phosphorus and sediments in Brighton Dam, also known as Triadelphia Reservoir (basin code 02-13-11-08), and for phosphorus in Rocky Gorge Reservoir (basin code 02-13-11-07). Section 303(d) of the federal Clean Water Act (CWA) and EPA's implementing regulations direct each state to identify and list waters, known as water quality limited segments (WQLSs), in which current required controls of a specified substance are inadequate to achieve water quality standards. For each WQLS, the State is required to either establish a TMDL of the specified substance that the waterbody can receive without violating water quality standards, or demonstrate that water quality standards are being met.

Triadelphia Reservoir and Rocky Gorge Reservoir have been designated as Use IV-P and Use I-P waterbodies, respectively, in the Code of Maryland Regulations (COMAR 26.08.02.08M(6) and COMAR 26.08.02.08M(1)). Both reservoirs were identified on the 303(d) list submitted to EPA by the Maryland Department of the Environment (MDE) as impaired by the following (years listed in parentheses): nutrients (1998) and impacts to biological communities (2002 and 2004). In addition, Triadelphia Reservoir was listed as impaired by sediment in 1998. This document, upon approval by EPA, establishes TMDLs for the nutrient and sediment impairments. Biological impairments within these watersheds will be addressed separately at a future date.

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 Triadelphia and Rocky Gorge Reservoirs. The water quality goal of the sediment TMDL for Triadelphia Reservoir is to increase the useful life of the reservoir for water supply by preserving storage capacity.

The TMDLs for the nutrient total phosphorus were determined using a time-variable, two-dimensional water quality eutrophication model, CE-QUAL-W2 ("W2"), to simulate water quality in each reservoir. The TMDLs are based on average annual total phosphorus (TP) loads for the simulation period 1998-2003, which includes both wet and dry years, thus taking into account a variety of hydrological conditions. Chla concentrations indicative of eutrophic conditions can occur at any time of year and are the cumulative result of phosphorus loadings that span seasons. Thus, although daily loads were calculated for these TMDLs, average annual TP loads are the most appropriate measure for expressing the nutrient TMDLs for Triadelphia and Rocky Gorge Reservoirs. Similarly, the sediment TMDL for Triadelphia Reservoir, which is based on the water quality modeling performed for the nutrient TMDLs, is expressed as an average annual load in keeping with the long-term water quality goal of preserving the storage capacity of the reservoir.

The TMDLs include (1) a wasteload allocation (WLA) to one municipal wastewater treatment plant and to municipal separate storm sewer systems (MS4s), (2) a load allocation (LA) to nonpoint sources, and (3) a 5% margin of safety (MOS) for the nutrient TMDLs and an implicit MOS for the sediment TMDL. The table below summarizes the nutrient and sediment TMDLs. The table also shows baseline loads and the percent reductions in loads necessary to meet the TMDLs.

The Elements of Nutrient and Sediment TMDLs for Triadelphia and Rocky Gorge Reservoirs

Waterbody	Triadelphia Reservoir	Rocky Gorge Reservoir	Triadelphia Reservoir
Constituent	TP (lbs/yr)	TP (lbs/yr)	Sediment (tons/yr)
Baseline Load	65,953	46,935	32,141
Percent Reduction	58%	48%	29%
TMDL	27,700	24,406	22,820
WLA	5,288	7,429	400
LA	21,027	15,757	22,420
MOS	1,385	1,220	Implicit

Maximum daily loads were calculated by flow regime. The table below shows the maximum daily loads under low flow and high flow conditions for the nutrient and sediment TMDLs for the Patuxent Reservoirs.

Maximum Daily Loads By Flow Regime

Total Phosphorus, Triadelphia Reservoir (lbs/day)				
Flow Regime (cfs)	**TMDL**	**WLA**	**LA**	**MOS**
<326	852	356	453	43
>326	17,003	1,504	14,649	850
Total Phosphorus, Rocky Gorge Reservoir (lbs/day)				
Flow Regime (cfs)	**TMDL**	**WLA**	**LA**	**MOS**
<291	770	314	418	39
>291	4,003	1,102	2,701	200
Sediment, Triadelphia Reservoir (tons/day)				
Flow Regime (cfs)	**TMDL**	**WLA**	**LA**	**MOS**
<326	662	40	621	Implicit
>326	25,468	157	25,311	Implicit

Five factors provide assurance that these TMDLs will be implemented. First, National Pollutant Discharge Elimination System (NPDES) permits for both wastewater treatment plants and urban stormwater systems will play an important role in ensuring implementation. Second, Maryland has several well-established programs that may be drawn upon, including Maryland's Tributary Strategies for Nutrient Reductions, developed in accordance with the Chesapeake Bay Agreement. Third, Maryland's Water Quality Improvement Act of 1998 requires that nutrient management plans be implemented for all agricultural lands throughout Maryland. Fourth, local jurisdictions, soil conservations districts, and the Washington Suburban Sanitary Commission (WSSC) have implemented a formal agreement, the Patuxent Reservoirs Protection Agreement, to protect water quality in the reservoirs. Finally, Maryland has adopted a watershed cycling strategy, which will assure that routine future monitoring and TMDL evaluations are conducted.

1.0 INTRODUCTION

This document, upon approval by the U.S. Environmental Protection Agency (EPA), establishes Total Maximum Daily Loads (TMDLs) for phosphorus and sediments in Brighton Dam, also known as Triadelphia Reservoir (basin code 02-13-11-08), and for phosphorus in Rocky Gorge Reservoir (basin code 02-13-11-07). Section 303(d) of the federal Clean Water Act (CWA) and the EPA's implementing regulations direct each state to identify and list waters, known as water quality limited segments (WQLSs), in which current required controls of a specified substance are inadequate to achieve water quality standards. For each WQLS, the State is required to either establish a TMDL of the specified substance that the waterbody can receive without violating water quality standards, or demonstrate that water quality standards are being met.

TMDLs are established to achieve and maintain water quality standards. A water quality standard is the combination of a designated use for a particular body of water and the water quality criteria designed to protect that use. Designated uses include activities such as swimming, drinking water supply, and shellfish propagation and harvest. Water quality criteria consist of narrative statements and numeric values designed to protect the designated uses. Criteria may differ among waters with different designated uses.

Triadelphia Reservoir and Rocky Gorge Reservoir have been designated as Use IV-P and Use I-P waterbodies, respectively, in the Code of Maryland Regulations (COMAR 26.08.02.08M(6) and COMAR 26.08.02.08M(1))). Both reservoirs were identified on the 303(d) list submitted to EPA by the Maryland Department of the Environment (MDE) as impaired by the following (years listed in parentheses): nutrients (1998) – due to signs of eutrophication, expressed as high chlorophyll *a* (Chla) levels – and impacts to biological communities (2002 and 2004). In addition, Triadelphia Reservoir was listed as impaired by sediment in 1998.

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). Seasonally low DO concentrations in the hypolimnion were also cited as a basis for the nutrient listing in Triadelphia Reservoir. This document, upon approval by EPA, establishes TMDLs for the nutrient and sediment impairments. Biological impairments within these watersheds will be addressed separately at a future date.

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 Triadelphia and Rocky Gorge Reservoirs. The water quality goal of the sediment TMDL for Triadelphia Reservoir is to increase the useful life of the reservoir for water supply by preserving storage capacity.

2.0 SETTING AND WATER QUALITY DESCRIPTION

2.1 General Setting and Source Assessment

Both Triadelphia Reservoir and Rocky Gorge Reservoir (also referred to as the Patuxent Reservoirs) lie in the Patuxent River watershed (Figure 1). The Patuxent River drains into Chesapeake Bay between Washington, DC and Annapolis, MD. The portion of the watershed draining to the reservoirs lies primarily in Howard and Montgomery Counties, but also includes a small portion of Prince George's County. Both reservoirs are part of the Washington Suburban Sanitary Commission's (WSSC) water supply system for Montgomery and Prince George's Counties. Water supply intakes in Rocky Gorge Reservoir feed WSSC's Patuxent Water Filtration Plant near Burtonsville, MD. Triadelphia Reservoir, which is upstream of Rocky Gorge Reservoir, is used to maintain capacity in Rocky Gorge Reservoir.

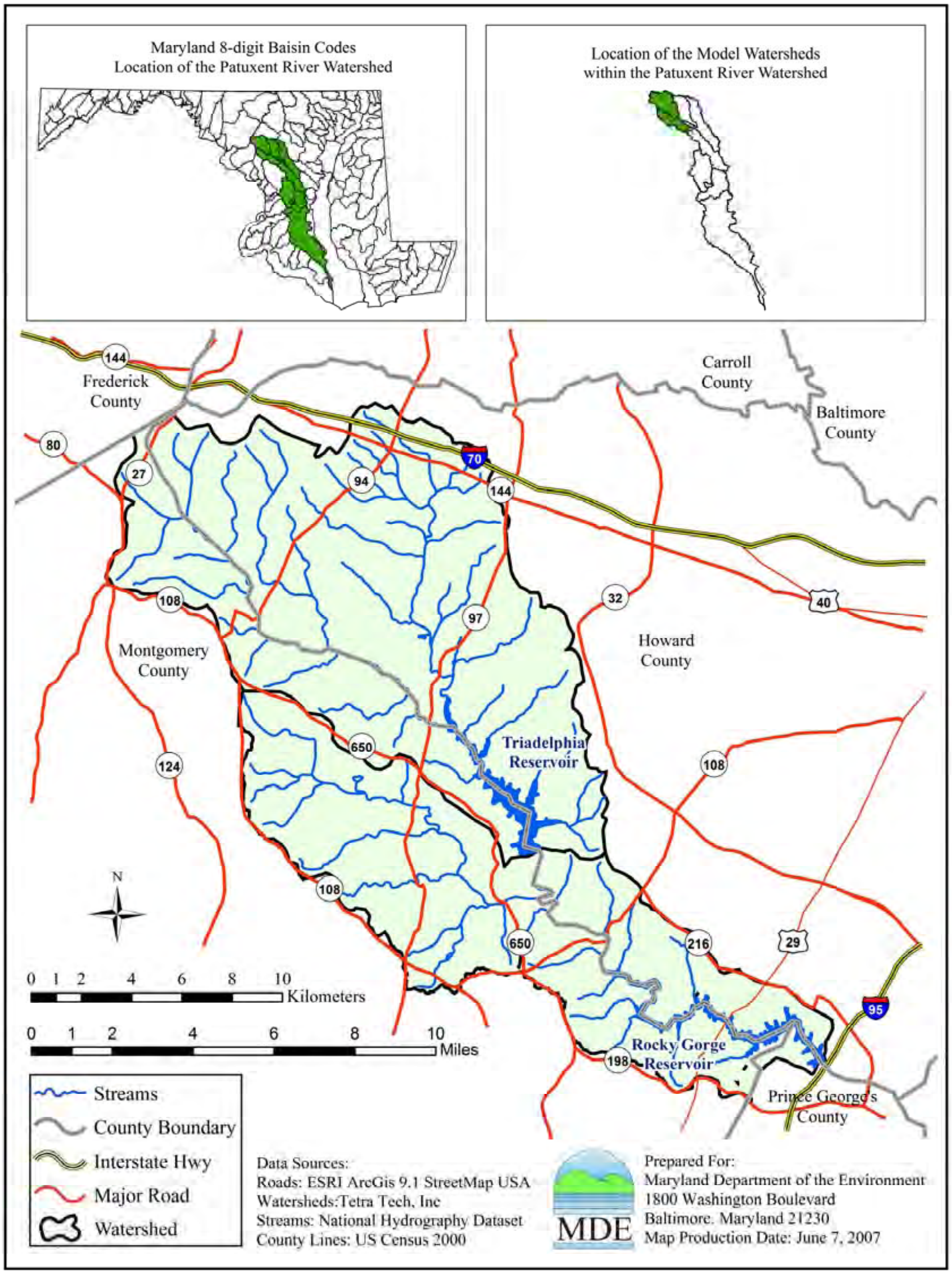

Figure 1: Location of Triadelphia and Rocky Gorge Reservoirs

Several relevant statistics for Triadelphia Reservoir and Rocky Gorge Reservoir are provided below in Table 1.

Table 1: Current Physical Characteristics of Triadelphia and Rocky Gorge Reservoirs

Characteristic	**Triadelphia**	**Rocky Gorge**
Location:	Howard County, MD Montgomery County, MD Lat. 39˚ 11’ 36” N Long. 77˚ 00’ 18” W	Howard County, MD Montgomery County, MD Prince George’s County MD Lat. 39˚ 07’ 00” N Long. 76˚ 52’ 36” W
Surface Area:	800 acres (34,848,000 ft^2)	773 acres (33,672,000 ft^2)
Normal Reservoir Depth:	52.0 feet	74.0 feet
Purpose:	Water Supply Recreation	Water Supply Recreation
Basin Code:	02-13-11-08	02-13-11-07
Volume:	19,000 acre-feet	17,000 acre-feet
Drainage Area to Reservoir:	77.3 mi^2 (49,500 acres)	132 mi^2 (84,480 acres)
Average Discharge[1]:	82.4 ft^3s^{-1}	85.9 ft^3s^{-1}

Source: Inventory of Maryland Dams and Hydropower Resources (Weisberg et al. 1985).
[1] Water Resources Data Maryland and Delaware Water Year 2000 (USGS 2000).

2.1.1 Land Use

Figure 2 shows the land use in the Triadelphia and Rocky Gorge watersheds. The land use is based on 1997 Maryland Department of Planning Land Use/Land Cover data. Triadelphia Reservoir watershed covers approximately 50,000 acres or 77 square miles. About half of the watershed is in crops or pasture, 32% in forest, and 15% in residential, commercial, or industrial land uses (Figure 3). The Rocky Gorge Reservoir watershed, excluding the drainage to Triadelphia Reservoir, covers approximately 35,000 acres or 55 square miles. Approximately 28% of the watershed is developed and 39% is forest, with the remainder in crops or pasture (Figure 4).

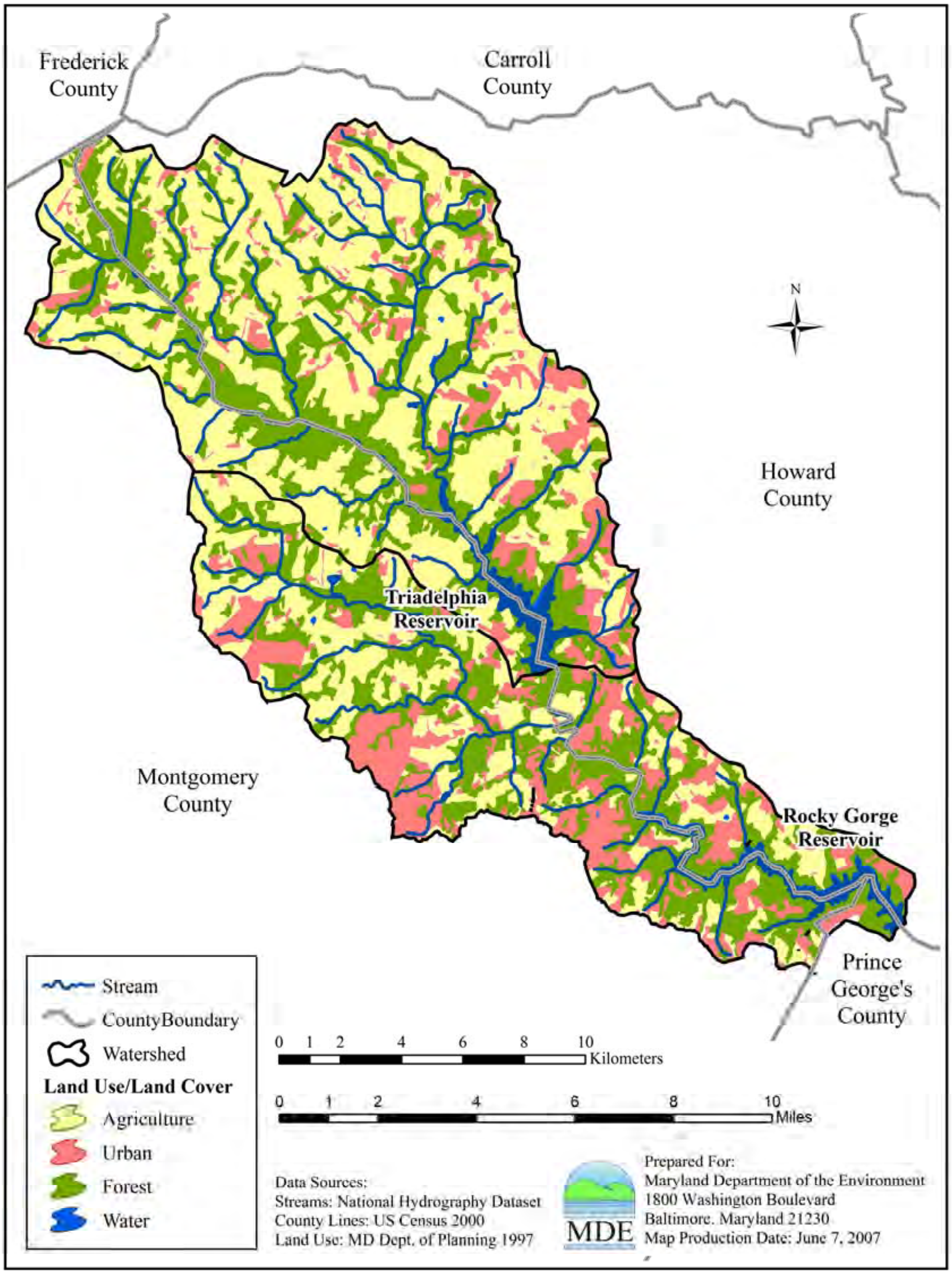

Figure 2: Land Use in Patuxent River Watershed

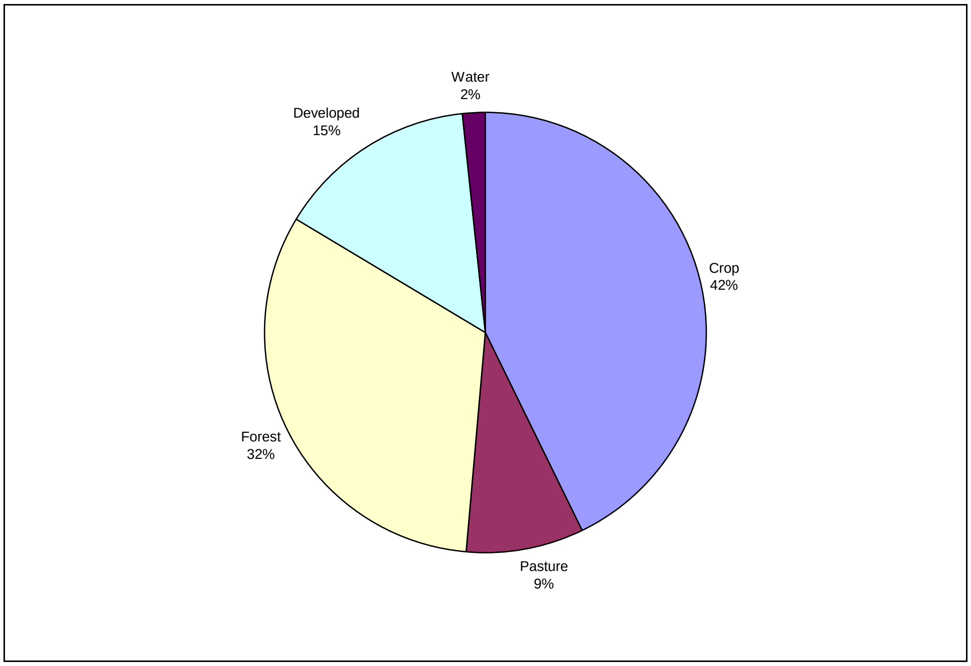

Figure 3: Proportion of Land Use in the Triadelphia Reservoir Watershed

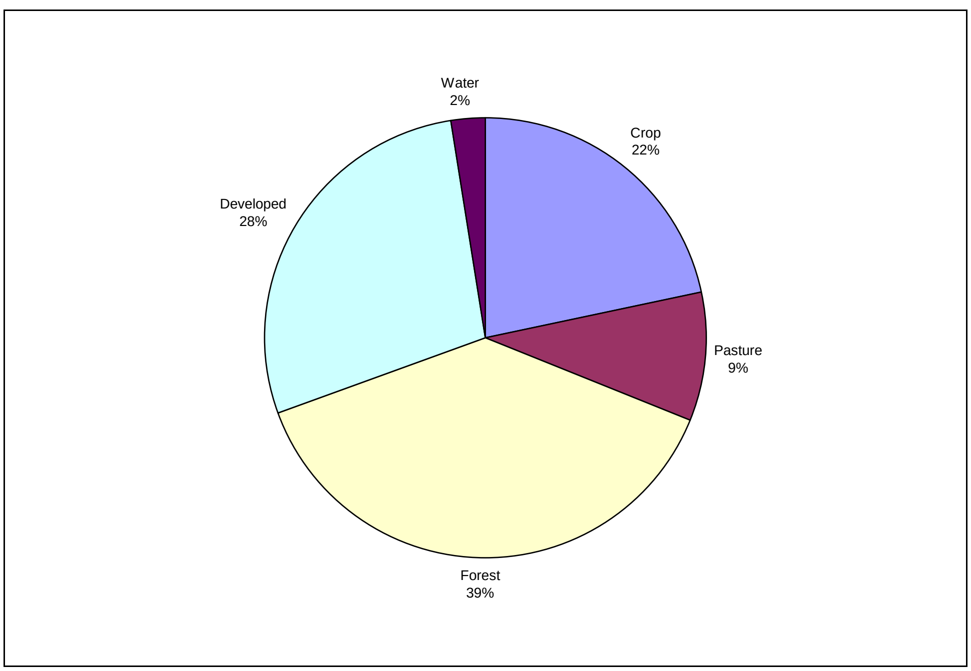

Figure 4: Proportion of Land Use in the Rocky Gorge Reservoir Watershed

2.1.2 Geology and Soils

The watersheds of Triadelphia and Rocky Gorge Reservoirs lie in the Piedmont physiographic province. The surficial geology is characterized by metamorphic rock of Late Precambrian age. The headwaters of the Patuxent River lie in the schists and meta-sedimentary rock of the Marburg Formation. Almost all of the rest of the watershed lies in the Wissahickon Formation of gneisses and schists. Upper Pelitic schist is the dominant bedrock of the headwaters of Cattail Creek and Hawlings River. Gneiss of the Sykesville Formation underlies the Patuxent River and Cattail Creek drainage to Triadelphia Reservoir, as well as Hawlings River. Lower Pelitic schist is the primary underlying bedrock of the direct drainage to Rocky Gorge and Triadelphia Reservoirs.

The soils found in the reservoir watersheds are primarily deep and well-drained to excessively drained (Mathews and Hershberger 1968; Brown and Dyer 1995). The dominant soil associations in the Rocky Gorge Reservoir watershed are the Glenelg-Manor-Chester and the Glenelg-Gaila-Occoquan associations. The Glenelg-Chester-Manor association forms the dominant soils of Cattail Creek and areas northwest of Triadelphia Reservoir, while the Mt.Airy-Glenelg-Chester association is dominant in the Patuxent River watershed draining into Triadelphia Reservoir. Mt. Airy soils belong to hydrologic group “A,” while the rest of the dominant soils belong to group “B.”

2.1.3 Point Sources and Wastewater Treatment Plant Loads

The development of nutrient TMDLs for Triadelphia and Rocky Gorge Reservoirs was based on computer simulation modeling of water quality conditions from 1998 to 2003. During that time, there was only one permitted facility discharging nutrients in the Triadelphia and Rocky Gorge watersheds, the Federal Emergency Management Agency Region 2 Wastewater Treatment Plant (WWTP) (MD0025666), which discharges into the Hawlings River. Table 2 shows the annual phosphorus loads from this facility during the simulation period, 1998-2003.

Table 2: Annual Municipal Wastewater Treatment Plant Loads 1998-2003

	Federal Emergency Management Agency (MD0025666)			
Year	Flow (MGD)	PO4[1] (lbs/yr)	TOP[2] (lbs/yr)	TP[3] (lbs/yr)
1998	0.001	2.92	0.37	3.29
1999	0	1.46	0.37	1.83
2000	0	0.37	0.37	0.73
2001	0	0.37	0.37	0.73
2002	0.001	2.19	0.37	2.56
2003	0.007	21.54	4.02	25.55
Average	0.0015	4.81	0.97	5.78

[1]Phosphate [2]Total Organic Phosphorus [3]Total Phosphorus

There are no industrial sources permitted for discharging nutrients or sediments in the watershed of either reservoir.

2.1.4 Nonpoint Source Loads and Urban Stormwater Loads

Nonpoint source loads and urban stormwater loads entering the Triadelphia and Rocky Gorge Reservoirs were estimated using the Hydrologic Simulation Program-Fortran (HSPF). The HSPF model is used to estimate flows, suspended solids and nutrient loads from the watershed's sub-basins, which are linked to two-dimensional CE-QUAL-W2 models of each reservoir. These are used to determine the maximum loads of total phosphorus (TP) that can enter each reservoir while maintaining the water quality criteria associated with their designated uses. The water quality modeling framework is addressed in more detail in Section 4.2.

The simulation of the Triadelphia and Rocky Gorge Reservoir watersheds used the following assumptions: (1) variability in patterns of precipitation was estimated from existing National Oceanic and Atmospheric Administration (NOAA) meteorological stations; (2) hydrologic response of land areas was estimated for a simplified set of land uses in the basin; and (3) agricultural information was estimated from the Maryland Department of Planning (MDP) land use data, and the Agricultural Census Data (U. S. Department of Commerce, 1997). The HSPF simulates nonpoint source and urban stormwater loads and integrates all natural and human induced sources, including direct atmospheric deposition, and loads from septic tanks, which are associated with river base flow during low flow conditions. Details of the HSPF watershed model developed to estimate these urban and non-urban loads can be found in *Modeling Framework for Simulating Hydrodynamics and Water Quality in Triadelphia and Rocky Gorge Reservoirs* (ICPRB 2007).

Figures 5 and 6 show the relative size of the contribution of total phosphorus sources to Triadelphia and Rocky Gorge Reservoirs, respectively, 1998-2003. Figure 7 shows the relative size of the contribution of sediment sources to Triadelphia Reservoir over the same period.

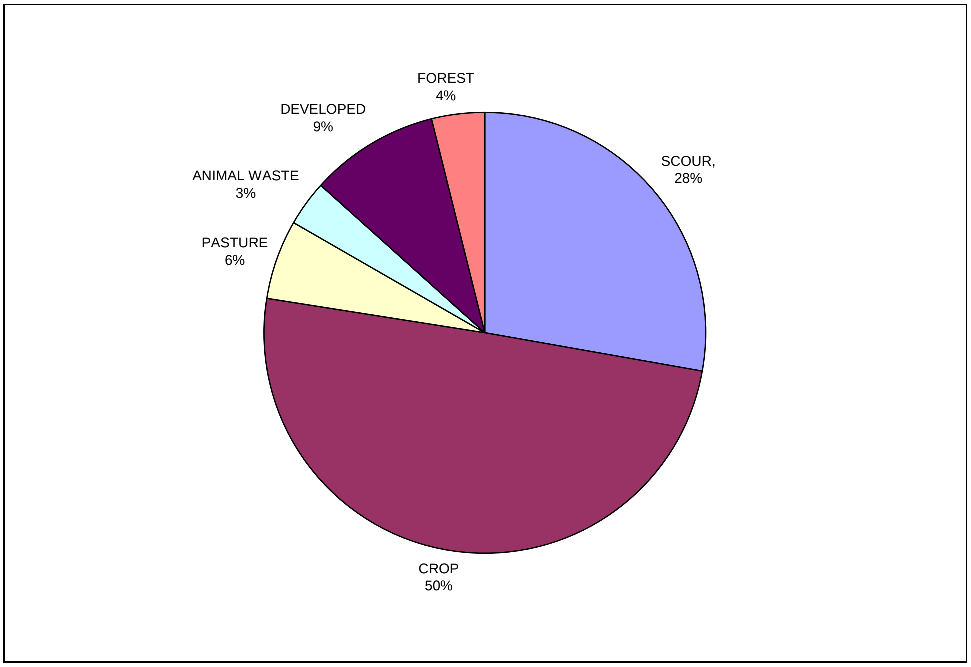

Figure 5: Percent Contribution of Sources to Total Phosphorus Loads to Triadelphia Reservoir

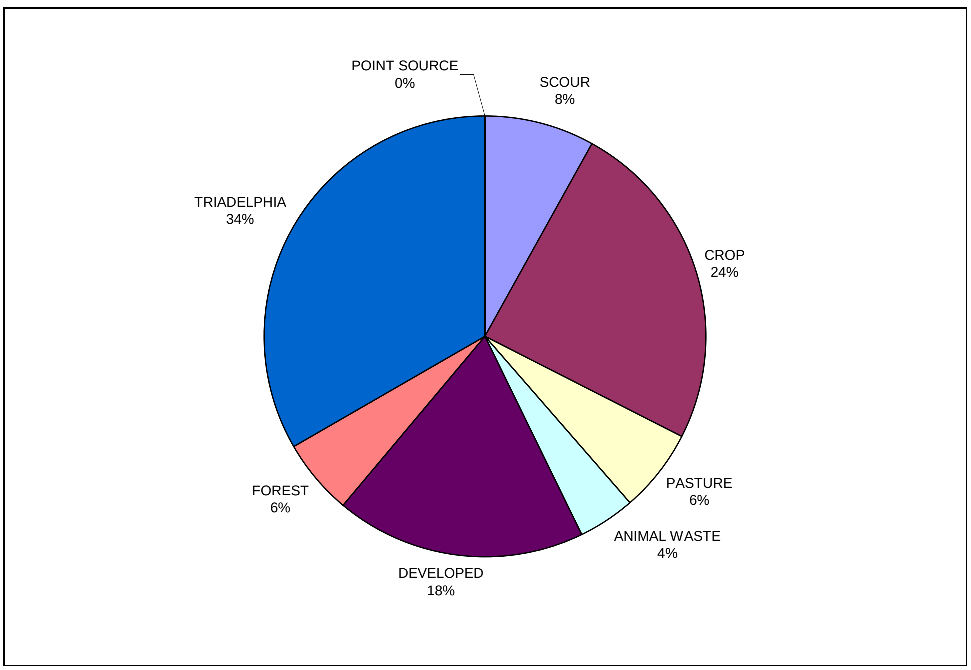

Figure 6: Percent Contribution of Sources to Total Phosphorus Loads to Rocky Gorge Reservoir

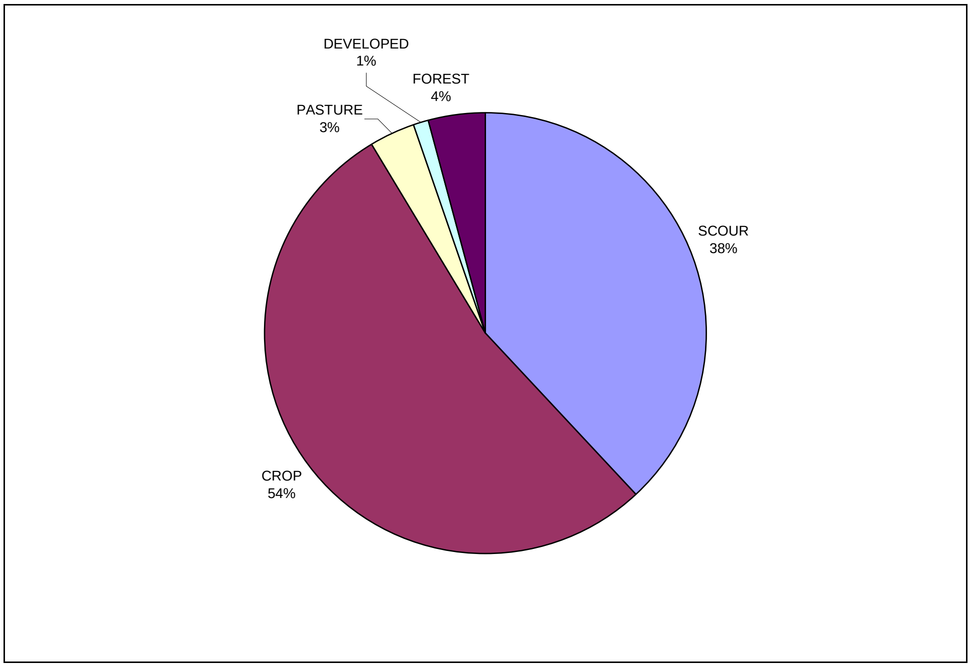

Figure 7: Percent Contribution of Sources to Sediment Loads to Triadelphia Reservoir

2.2 Water Quality Characterization

2.2.1 Water Quality Monitoring Programs

Both WSSC and MDE performed water quality monitoring in the reservoirs during the period 1998-2003. Table 3 summarizes the characteristics of the monitoring programs.

WSSC maintains a regular water quality monitoring program. Each reservoir is sampled at three locations. Figure 8 shows the locations monitored by WSSC in Triadelphia Reservoir and Figure 9 shows the locations in Rocky Gorge Reservoir. Sampling is performed monthly from March or April through October or November, and sometimes semimonthly in the summer months. At each location, temperature and dissolved oxygen (DO) are measured at each meter of depth, and water quality samples are collected at the surface, bottom, and middle of the reservoir. If the reservoir is stratified, the middle sample is collected in the metalimnion; otherwise, it is collected at the midpoint of reservoir depth. Water quality samples are analyzed for ammonia, nitrite, nitrate, total Kjeldahl nitrogen (TKN), phosphate, total phosphorus, total organic carbon, chlorophyll *a*, iron, manganese, turbidity, and alkalinity. Secchi depth measurements are made at each sampling location.

MDE performed a special water quality monitoring study in support of TMDL development in 2000. Four locations were sampled in each reservoir, shown in Figures 8 and 9. Six samples were taken at approximately monthly intervals between March and September. Approximately five measurements of temperature and DO were taken at different depths at each monitoring location per sampling date. Water quality samples were taken from the surface and bottom at the location just upstream of the dam; otherwise samples were taken only at the surface at a depth of 0.5 m. MDE's samples are analyzed for the same constituents as WSSC's, but in addition, samples are analyzed for dissolved and particulate nitrogen, phosphorus, and organic carbon species, BOD5, and TSS.

Table 3: Characterization of Reservoir Monitoring Programs

Characteristic	**WSSC**	**MDE**
Collection Period	3/98-11/03	3/00-9/00
Number of locations per reservoir	3	4
Temperature and DO measurements	One per meter starting from surface	Approximately 5 from surface to bottom
Water quality samples per location	Surface, middle, and bottom	Surface only, except surface and bottom just above dams
Key water quality constituents	NH3, NO23, PO4, TKN, TP, TOC, Chla, Turbidity, Secchi depth	NH3, NO2, NO3, TKN, DON, PON, TN, PO4, POP, DOP, PIP, TP, CBOD, DOC, POC, TOC, Chla, TSS, Turbidity, Secchi depth

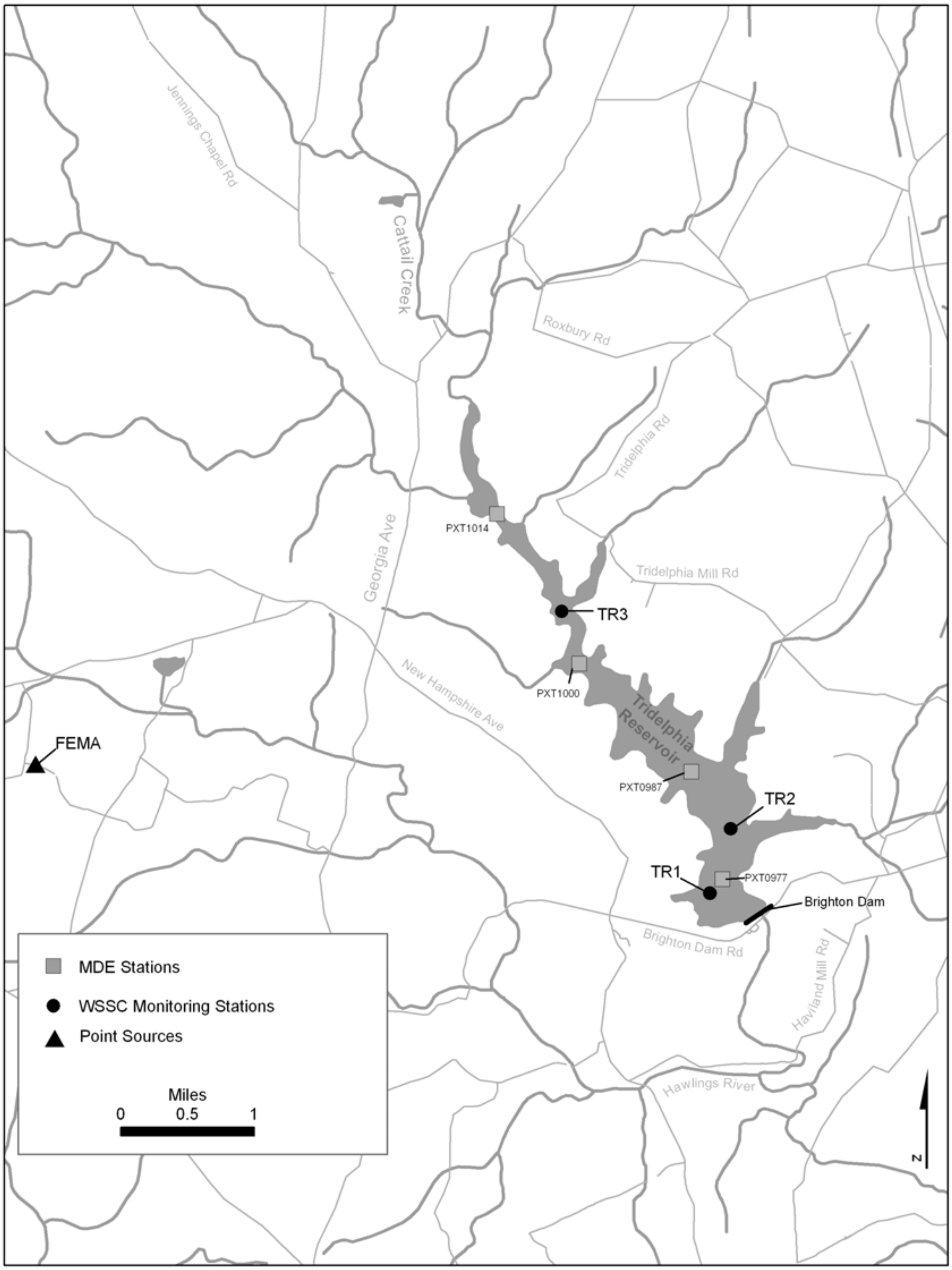

Figure 8: Sampling Locations in Triadelphia Reservoir

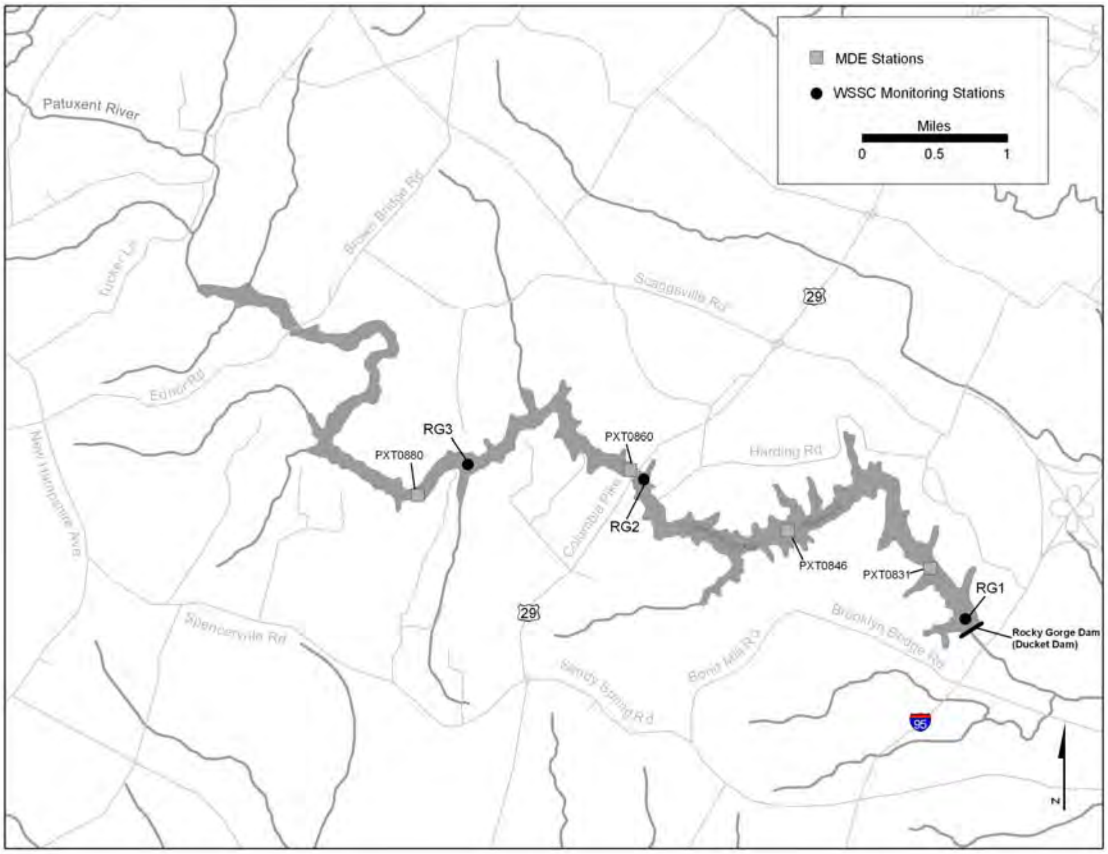

Figure 9: Sampling Locations in Rocky Gorge Reservoir

2.2.2 Temperature Stratification

Triadelphia and Rocky Gorge Reservoirs both regularly exhibit temperature stratification starting in late spring and lasting to early fall. Under stratified conditions during the summer and early fall, bottom waters in both reservoirs can become hypoxic, because stable density differences inhibit the turbulent mixing that 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 seasonal position of the well-mixed surface layer or epilimnion. Figure 10 presents a contour plot of isothermals for TR1 in Triadelphia Reservoir. In the winter, isothermal lines are vertical, showing that the reservoir has fairly uniform temperature. In spring, isothermal lines begin to tilt away from the vertical, until by summer at depths greater than about four meters they are nearly parallel to each other horizontally. At the surface, isothermal lines run vertically to a depth of about four meters; this defines the epilimnion.

Figures A1 – A5 in Appendix A present contour plots for each WSSC monitoring location for the period 1998-2003. The thermal profile at RG1, the station just above the dam and water intakes in Rocky Gorge Reservoir, shows less stratification here than other locations. It may be impacted not only by water withdrawals, but also by WSSC's aeration of water adjacent to the intakes, which may cause mixing that dampens stratification.

Generally, in both reservoirs, the epilimnion is limited to a depth of no more than four meters in the summer. For the purposes of data analysis, the surface layer is considered to be four meters deep, with the understanding that in spring and fall the epilimnion can extend deeper than six to seven meters, and in the summer it is likely as shallow as one to two meters. For screening purposes, samples taken at depths of ten meters or greater are considered to be in the bottom layer or hypolimnion.

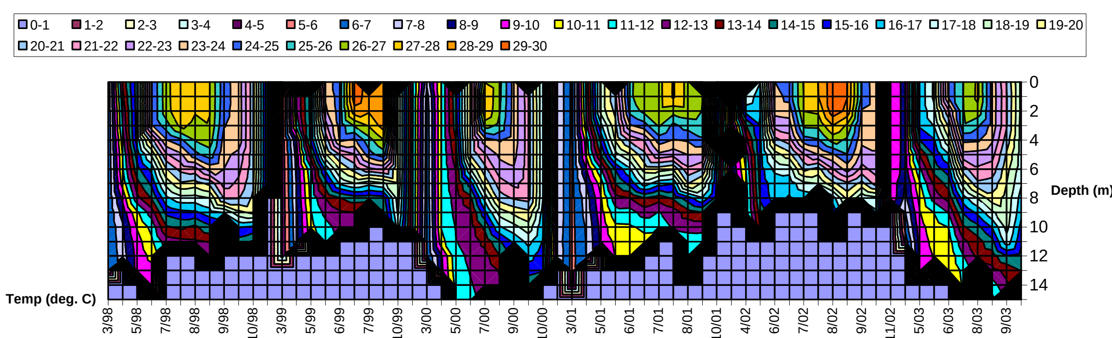

Figure 10: Isothermal Contours, Triadelphia Reservoir just above Brighton Dam, TR1, 1998-2003

2.2.3 Dissolved Oxygen

Figure 11 shows a contour plot of observed DO concentrations at TR1 in Triadelphia Reservoir, 1998-2003, corresponding to the temperature contour plot in Figure 10. There is a clear seasonal pattern to DO concentrations. In the early spring and late fall, DO concentrations are fairly uniform with depth. As temperature stratification sets in, DO concentrations in the surface layer remain relatively uniform, but the metalimnion shows a gradient in DO concentrations that grows stronger as the summer progresses. A region of hypoxia in the hypolimnion increases with thickness from late spring through summer.

Figures A6 and A7 in Appendix A show contour plots of DO concentrations at TR2 and TR3 in Triadelphia Reservoir, 1998-2003. Figures A8, A9, and A10 show contour plots of DO concentrations at RG1, RG2, and RG3 in Rocky Gorge Reservoir over the same period. Quite clearly, hypoxia occurs in the hypolimnion of both Triadelphia and Rocky Gorge Reservoirs with regularity.

Generally, DO concentrations remain above 5.0 mg/l in the surface layers of the reservoirs, but there are exceptions. There are two related causes of these low DO concentrations. The first is temperature stratification. As mentioned earlier, sometimes the epilimnion in the reservoirs is no more than one to two meters deep. DO is not transported below the well-mixed surface layer and DO concentrations decrease relative to the well-mixed layer. The second cause of low DO in surface layers 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 reduce the DO concentration in the well-mixed layer. This can occur any time under stratified conditions when the surface mixed-layer deepens, often well before the fall overturn typical of many lakes and reservoirs (including Triadelphia and Rocky Gorge), when the surface and bottom layers displace one another.

Another factor that can influence entrainment is drawdown. Withdrawals from a reservoir can induce currents that enhance mixing. Figure 12 shows the surface elevation of Triadelphia Reservoir from 1998 through 2003. In 1999 and 2002 (drought years), releases from Triadelphia to fill Rocky Gorge dropped the surface elevation by as much as 25 feet. These drawdowns are probably a contributing factor in mixing low DO concentrations into the surface levels of the reservoir.

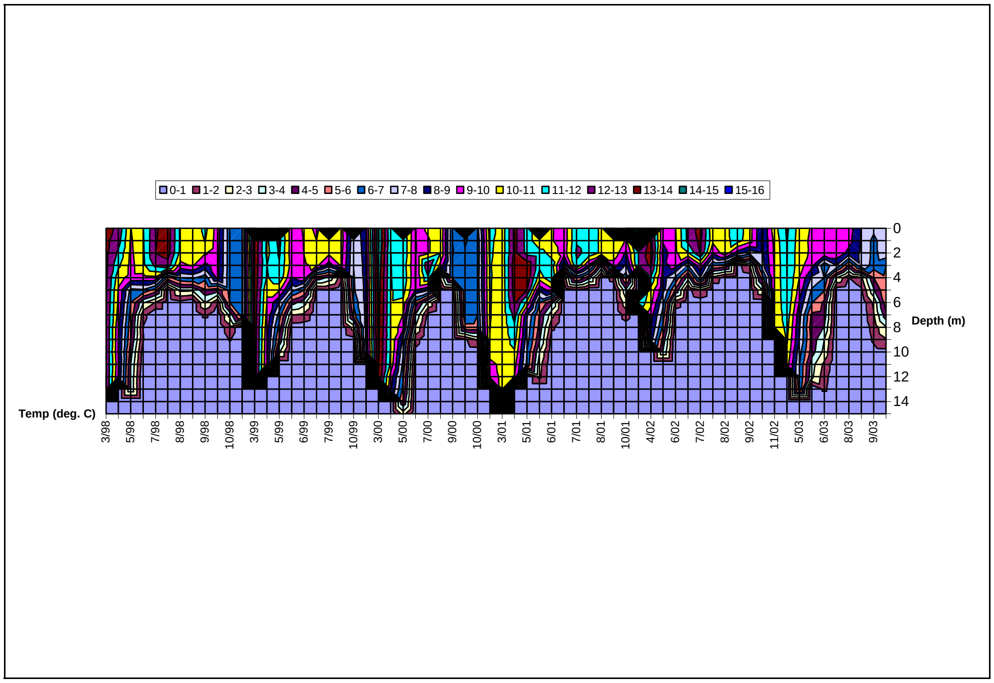

Figure 11: DO Contour, Triadelphia Reservoir just above Brighton Dam, TR1, 1998-2003

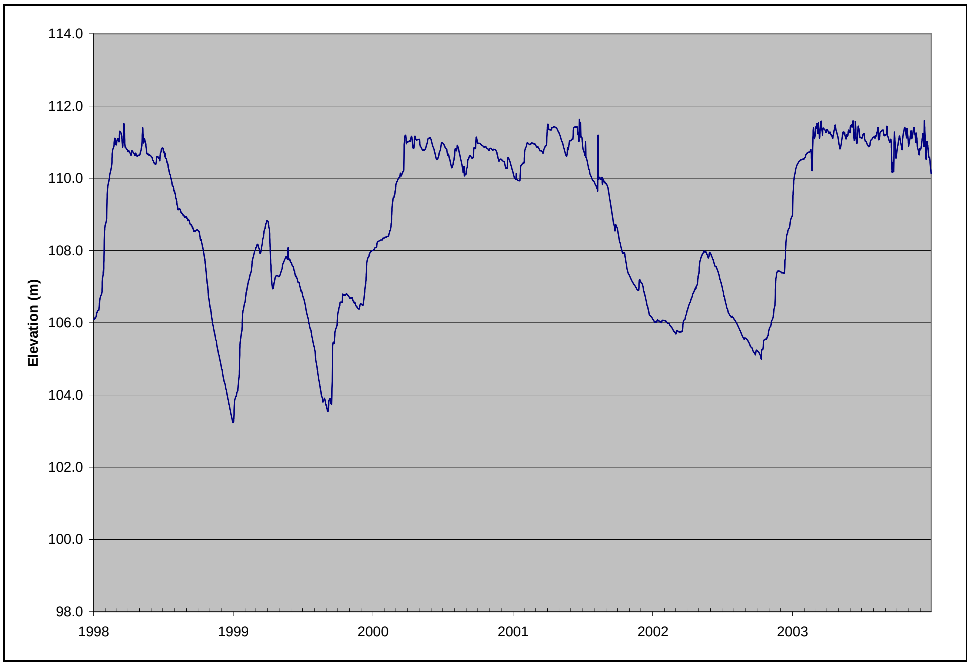

Figure 12: Surface Water Elevations in Triadelphia Reservoir, 1998-2003

2.2.4 Phosphorus

Figures A11 – A13 in Appendix A show observed total phosphorus concentrations at each sampling depth at TR1, TR2, and TR3 in Triadelphia Reservoir. Figures A14 – A16 in Appendix A show observed concentrations at RG1, RG2, and RG3 in Rocky Gorge Reservoir. Figures A17 and A18 show the concentrations observed at the MDE monitoring locations in Triadelphia and Rocky Gorge Reservoirs, respectively. Tables 4 and 5 give summary statistics for TP concentrations in Triadelphia and Rocky Gorge Reservoirs, respectively.

As Tables 4 and 5 show, median TP concentrations in the surfaces of the reservoirs is at or above 34 µg/l, which is the boundary between eutrophic and mesotrophic conditions according to the Carlson Trophic Index, a widely used measure of eutrophic conditions (Carlson 1977). Tables 4 and 5 also show little evidence of a pronounced longitudinal gradient in phosphorus concentrations, which is frequently a feature of reservoirs.

Table 4: Summary Statistics: TP Concentrations (mg/L) in Triadelphia Reservoir,1998-2003

Station	Depth	Mean	St.Dev.	Min	1st Q	Median	3rd Q	Max	Count
TR1	Surface	0.040	0.023	0.000	0.022	0.035	0.056	0.095	47
	Middle	0.047	0.039	0.011	0.019	0.036	0.062	0.204	28
	Bottom	0.067	0.052	0.013	0.035	0.057	0.080	0.295	46
TR2	Surface	0.044	0.028	0.002	0.024	0.038	0.058	0.155	47
	Middle	0.045	0.036	0.000	0.019	0.034	0.064	0.174	28
	Bottom	0.065	0.043	0.004	0.030	0.053	0.085	0.211	46
TR3	Surface	0.063	0.048	0.000	0.029	0.051	0.086	0.205	47
	Middle	0.068	0.056	0.018	0.030	0.047	0.096	0.244	27
	Bottom	0.093	0.058	0.012	0.056	0.077	0.110	0.297	45

Table 5: Summary Statistics: TP Concentrations (mg/L) in Rocky Gorge Reservoir, 1998-2003

Station	Depth	Mean	St.Dev.	Min	1st Q	Median	3rd Q	Max	Count
RG1	Surface	0.044	0.042	0.012	0.023	0.037	0.048	0.280	44
	Middle	0.037	0.025	0.010	0.018	0.024	0.049	0.102	27
	Bottom	0.055	0.034	0.014	0.027	0.048	0.071	0.142	43
RG2	Surface	0.046	0.041	0.009	0.024	0.034	0.048	0.225	44
	Middle	0.039	0.030	0.006	0.020	0.026	0.056	0.128	27
	Bottom	0.063	0.040	0.012	0.033	0.053	0.085	0.214	43
RG3	Surface	0.044	0.035	0.005	0.024	0.033	0.053	0.219	44
	Middle	0.043	0.037	0.011	0.026	0.032	0.048	0.203	27
	Bottom	0.077	0.094	0.011	0.033	0.051	0.081	0.568	43

Figures A19 – A21 in Appendix A show observed phosphate-P concentrations at each sampling depth at TR1, TR2, and TR3 in Triadelphia Reservoir. Figures A22 – A24 in Appendix A show observed concentrations at RG1, RG2, and RG3 in Rocky Gorge Reservoir. Figures A25 and A26 show the concentrations observed at the MDE monitoring locations in Triadelphia and Rocky Gorge Reservoirs, respectively.

In Triadelphia Reservoir, the median value of the percent phosphate in total phosphorus in observed samples is 13%. In Rocky Gorge Reservoir, the median percent of phosphate in samples was about 15%. Bottom samples tended to have a slightly lower fraction of phosphate.

Bottom concentrations of total phosphorus and phosphate in both reservoirs tend to be larger than concentrations at other depths. This is more likely due to the accumulation of solid-phase phosphorus and resuspension during storm events, rather than the release of phosphate under anoxic conditions. As a comparison of the corresponding figures shows, large increases in bottom total phosphorus concentrations are not matched by increases in phosphate concentrations of the same magnitude.

2.2.5 Nitrogen

Figures A27 – A29 in Appendix A show observed ammonia-N concentrations at each sampling depth at TR1, TR2, and TR3 in Triadelphia Reservoir. Figures A30 – A32 in Appendix A show observed concentrations at RG1, RG2, and RG3 in Rocky Gorge Reservoir. Figures A33 and A34 show the concentrations observed at the MDE monitoring locations in Triadelphia and Rocky Gorge Reservoirs, respectively.

The Figures A27, A28, A30, and, to a lesser extent, A31, which represent the deeper portions of the reservoirs, all show that in both reservoirs there are regular significant increases in ammonia in the summer months due to diagenesis in the sediments. The same phenomenon occurs in the shallower, upstream stations, TR3 and RG3 shown in Figures A29 and A32, but perhaps not as regularly. The release of ammonia from the sediments contributes to oxygen demand. Although observed ammonia concentrations range as high as 2.7 mg/l, Maryland's ammonia water quality criteria (COMAR 26.08.02.03-2H(1)) were not exceeded.

Figures A35 – A37 in Appendix A show observed nitrate-N concentrations at each sampling depth at TR1, TR2, and TR3 in Triadelphia Reservoir. Figures A38 – A40 in Appendix A show observed concentrations at RG1, RG2, and RG3 in Rocky Gorge Reservoir. Figures A41 and A42 show the concentrations observed at the MDE monitoring locations in Triadelphia and Rocky Gorge Reservoirs, respectively.

Nitrate concentrations in the reservoirs show a strong seasonal pattern, decreasing significantly at all depths during the summer months. In the surface layers, the seasonal decrease in both ammonia and nitrate is most likely due to the uptake of nitrogen by algae. In the bottom layers, after anoxia is established, nitrate is the preferred electron acceptor in metabolic processes, and significant denitrification takes place in the sediments and the water column. Nitrate concentrations can reach very low levels in the bottom layer, suggesting that sometimes iron oxides, which help bind phosphorus to the sediments, may be reduced by biologically-mediated reactions, and that at least some limited phosphorus release from the sediments does take place.

Figures A43 – A45 in Appendix A show observed TN concentrations at each sampling depth at TR1, TR2, and TR3 in Triadelphia Reservoir. Figures A46 – A48 in Appendix A show observed concentrations at RG1, RG2, and RG3 in Rocky Gorge Reservoir. Figures A49 and A50 show the concentrations observed at the MDE monitoring locations in Triadelphia and Rocky Gorge Reservoirs, respectively.

As the figures show, TN concentrations follow the pattern of nitrate concentrations. This is not surprising, since the median value of the percent of TN that is nitrate is 69% for observations from Triadelphia Reservoir and 68% from Rocky Gorge Reservoir, and varies little with depth.

2.2.6 Nutrient Limitation

Nitrogen and phosphorus are essential nutrients for algae 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; this is known as the "limiting nutrient." The amount of the abundant nutrient does not matter because both nutrients are needed for algae growth. In general, a Nitrogen:Phosphorus (N:P) ratio in the range of 5:1 to 10:1 by mass is associated with plant growth being limited by neither phosphorus nor nitrogen. If the N:P 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).

Table A1 in Appendix A gives summary statistics for the N:P ratio observed in samples collected at the WSSC monitoring stations. Fewer than 2% of the samples had N:P ratios less than 10:1, strongly indicating that both reservoirs are phosphorus limited.

2.2.7 Algae and Chlorophyll *a*

Figures A51 and A52 in Appendix A show the time series of Chla concentrations in the WSSC sampling locations in Triadelphia and Rocky Gorge Reservoirs, 1998-2003. Figures A53 and A54 show observed Chla concentrations observed at MDE's sampling locations in 2000. Tables A2 and A3 in Appendix A show maximum Chla concentrations by month and year, 1998-2003, for Triadelphia and Rocky Gorge Reservoirs, respectively.

As these tables indicate, Chla concentrations above 10 μg/l occur frequently. Forty-four percent of samples taken at WSSC's monitoring locations in Triadelphia Reservoir and 23% of the samples taken in Rocky Gorge Reservoir had concentrations above 10 μg/l. Concentrations above 30 μg/l are infrequent but not unusual in Triadelphia Reservoir. In Triadelphia Reservoir, three samples collected by WSSC over the period 1998 through 2003 and two samples collected by MDE in 2002 had concentrations above 30 μg/l. None of the samples collected by WSSC in Rocky Gorge Reservoir, 1998 through 2003, had concentrations over 30 μg/l. One sample collected by MDE at PXT0860 in August 2000 had a Chla concentration of 31 μg/l. Generally, Triadelphia Reservoir has higher Chla concentrations than Rocky Gorge Reservoir, though in any given month, Rocky Gorge Reservoir can have higher concentrations. In both reservoirs, higher concentrations tend to occur in early spring (March or April) or late summer (August or September), though a concentration just under 30 μg/l was observed in Rocky Gorge Reservoir in October, 1998.

2.2.8 Sedimentation

Resource Management Concepts (2002) analyzed the changes in bathymetry and loss of volume in Triadelphia Reservoir due to sedimentation. They calculated the original volume capacity of the reservoir when it was constructed in 1942 and compared it to the capacity reported by Ocean Surveys (1997) based on their 1995 bathymetry survey. Table 6 summarizes the capacity losses for Triadelphia Reservoir.

The annual percent capacity loss (volumetric reduction) rate in Triadelphia Reservoir, 0.18%, compares favorably with the national averages. The mean average capacity loss rate for comparably sized reservoirs is 0.43%; the median is 0.27% *(*Ortt et al., *2000)*.

Table 6: Sedimentation Rates in Triadelphia Reservoir

Original (1942) Surface Area (acres)	882
Original (1942) Capacity (acre-ft.)	21,903
Capacity (1995) Bathymetric Survey (acre-ft)	19,785
Capacity Lost Since Construction (acre-ft)	2,118
Average Annual Capacity Loss (acre-ft/yr)	40
Annual Average Capacity Lost (%)	0.18%

Source: Resource Management Concepts (2002).

2.3 Water Quality Impairments

The Maryland Water Quality Standards Stream Segment Designation for Triadelphia Reservoir is Use IV-P: Recreational Trout Waters and Public Water Supply (COMAR 26.08.02.08M(6)). Rocky Gorge Reservoir is designated Use I-P: Water Contact

Recreation, Fishing and Protection of Aquatic Life and Wildlife, and Public Water Supply (COMAR 26.08.02.08M(1)). Designated Uses present in the Triadelphia and Rocky Gorge Reservoirs are: 1) capable of holding and supporting adult trout for put-and-take fishing and 2) public water supply.

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 Triadelphia and Rocky Gorge Reservoirs is ultimately caused by nutrient overenrichment. An analysis of the available water quality data presented in Section 2.2 has demonstrated that phosphorus is the limiting nutrient. In conjunction with excessive nutrients, Triadelphia Reservoir has experienced excessive sediment loads, resulting in a shortened projected lifespan of the reservoir.

Use I and Use IV 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 interim 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 interim 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.

The analysis of water quality data in Section 2.2 has shown that all observed DO concentrations below 5.0 mg/l in the surface layers of Triadelphia and Rocky Gorge Reservoirs are associated with stratification or the mixing of stratified waters into the surface layers during periods of reservoir overturn or drawdown. On the other hand, seasonal hypoxia occurs regularly in both reservoirs in the hypolimnion.

3.0 TARGETED WATER QUALITY GOALS

The overall objective of the TMDLs proposed in this document is to reduce phosphorus and sediment loads to levels that are expected to result in the attainment of the water quality criteria that support the Use I-P and IV-P designation for Rocky Gorge and Triadelphia Reservoirs. The Chla endpoints selected for the reservoirs are (1) a ninetieth-percentile instantaneous Chla concentration not to exceed 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 the approximate boundary between mesotrophic and eutrophic conditions, which is an appropriate trophic state at which to manage these reservoirs. Mean Chla concentrations exceeding 10 µg/l are associated with peaks exceeding 30 µg/l, which in turn are associated with a shift to blue-green assemblages, which present taste, odor and treatment problems (Walker 1984). These Chla endpoints should thus 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.

Maryland does not have an explicit standard for sedimentation rates in impoundments. The rate of sedimentation in impoundments in Maryland and elsewhere is highly variable, and there is no universally accepted methodology for determining an appropriate sedimentation rate in a reservoir. Accordingly, the targeted water quality goal for sedimentation is based on assuring the continued meeting of the reservoir's designated use. In the case of Triadelphia Reservoir, the reduction in sediment load projected to result as a consequence of phosphorus reductions has been determined to result in an acceptable lifespan of the reservoir.

In summary, the TMDLs for phosphorus and sediment are intended to: 1) resolve violations of narrative criteria associated with phosphorus enrichment of Triadelphia and Rocky Gorge Reservoirs, leading to excessive algal growth; 2) resolve violations of narrative criteria associated with excess sedimentation of Triadelphia Reservoir; and 3) ensure that both Triadelphia and Rocky Gorge Reservoirs meet the interim interpretation of the non-tidal DO criteria, as applied to reservoirs.

4.0 TOTAL MAXIMUM DAILY LOADS (TMDLs) AND ALLOCATIONS

4.1 Overview

Section 4.2 describes the modeling framework for simulating hydrodynamics, nutrient and sediment loads, and water quality responses in Triadelphia and Rocky Gorge Reservoirs. Section 4.3 describes the scenarios developed on the basis of modeling results. Section 4.4 explains how the nutrient TMDLs and load allocations for point sources and nonpoint sources were developed for the reservoirs, based on computer modeling of the water quality response to reduced nutrient and sediment loads. Section

4.5 presents the modeling results in the proper format for TMDLs and allocates the TMDLs between point sources and nonpoint sources. Section 4.6 explains the rationale for the margin of safety (MOS). Finally, in Section 4.7 the elements of the equations are combined in a summary of TMDLs for total phosphorus for both Triadelphia and Rocky Gorge Reservoirs, as well as a TMDL for sediments for Triadelphia Reservoir.

4.2 Computer Modeling Framework

To develop a TMDL, a linkage must be defined between the selected targets or goals and the identified sources. This linkage establishes the cause-and-effect relationship between the pollutant of concern and the pollutant sources. The relationship can vary seasonally, particularly for nonpoint sources, with factors such as precipitation. Once defined, the linkage yields the estimate of total loading capacity or TMDL (U.S. EPA 1999).

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 Triadelphia and Rocky Gorge Reservoirs. The W2 reservoir models were used to simulate not only hydrodynamics and temperature but dissolved oxygen and eutrophication dynamics as well. The reservoir models use version 3.2 of CE-QUAL-W2. Cole and Wells (2003) give a general description of the CE-QUAL-W2 model.

Triadelphia Reservoir was represented by twenty-three active longitudinal segments. Each segment contains from two to seventeen one-meter thick layers. Rocky Gorge Reservoir is represented by twenty-seven segments, each with two to twenty-eight one-meter thick layers. The simulation period was set to 1998-2003 when Chla monitoring data was available. These six years provide a range of hydrological conditions, including a wet year (2003), dry years (1999, 2002), and average years (1998, 2000, and 2001), thus fulfilling the requirement that TMDLs take into account a variety of hydrological conditions.

State variables in the CE-QUAL-W2 model include dissolved oxygen, ammonia, nitrate, dissolved inorganic phosphorus, and both dissolved and particulate organic matter (POM) in labile and refractory forms. In addition, any number of inorganic solids, carbonaceous biochemical oxygen demand (CBOD) variables or algal species can be represented in the model. Organic nitrogen and phosphorus, however, are only implicitly represented through CBOD, organic matter, and algal biomass state variables. In order to preserve a mass balance of all species of phosphorus, the state variables in the W2 models were configured as follows:

1. 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.

2. Three biochemical oxygen demand (BOD) variables were used to represent allochthonous organic matter inputs to the reservoirs: (1) labile dissolved BOD, labile particulate CBOD, and refractory particulate CBOD. The concentration of these CBOD inputs was 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.
3. 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 to track nutrients released from algal decomposition.

To use the W2 model in this configuration, several minor changes had to be made to the W2 code. Inorganic solids contribute to light extinction, but 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 altered so solid-phase phosphorus would not contribute to light extinction. Second, in the W2 model, sediment oxygen demand (SOD) can be represented as a first-order reaction based on the quantity of labile organic matter that has settled to the bottom of a segment. In the original code the CBOD variables do not settle and do not contribute to the pool of organic material in the sediments. The code was altered so that (1) CBOD species could be assigned a settling velocity and (2) labile particulate CBOD contributed to sediment organic matter.

4.3 Scenario Descriptions and Results

4.3.1 Scenario Descriptions

TMDL development for the Patuxent reservoirs involved the following three scenarios:

1. **Calibration or Baseline Scenario**: The Calibration or Baseline Scenario represents actual loads over the simulation period 1998-2003. As the name suggests, the loads in this scenario were used to calibrate the CE-QUAL-W2 models of Triadelphia and Rocky Gorge Reservoirs. Loads from the wastewater treatment plant are based on reported flows and concentrations for the period. Loads from developed land falling under the National Pollutant Discharge Elimination System (NPDES) permit for stormwater facilities, as well as nonpoint source loads from forests and agricultural land, were determined through the calibration of the Patuxent HSPF Model.

2. **TMDL Scenario**: The TMDL Scenario represents the maximum allowable loads from developed land falling under NPDES stormwater permits and the maximum allowable loads from nonpoint sources such that computer simulation predicts water quality standards will be met in Triadelphia and Rocky Gorge Reservoirs. Loads from the wastewater treatment plant are calculated based on the design flow of the permit and the maximum permitted concentration.

3. **All-Forest Scenario**: The All-Forest Scenario simulates the response of the reservoirs to the phosphorus, sediment, nitrogen, and BOD loading rates that would occur if all of the land in the reservoirs' watersheds were forested. The All-Forest Scenario is used to determine to what extent hypoxic conditions in the hypolimnion are a function of external loading rates or reservoir morphology. The All-Forest Scenario constitutes an estimate of hypolimnetic DO concentrations under natural conditions. Flows and temperature were taken from the Calibration Scenario, while constituent loads were taken from the HSPF model simulation whereby all land in the watershed was forested.

4.3.2 Calibration Scenario Results

The primary function of the CE-QUAL-W2 models of Triadelphia and Rocky Gorge Reservoirs is to link algae biomass concentrations, as represented by Chla concentrations, to total phosphorus loads. The models were calibrated conservatively, to ensure that simulated Chla concentrations were at least as high as observed concentrations, even if maximum seasonal concentrations were shifted upstream or downstream in simulation, or occurred a month earlier or later than the corresponding observed concentrations.

Figures B1 and B2 in Appendix B compare simulated and observed maximum Chla concentrations in the surface layers of Triadelphia and Rocky Gorge Reservoirs, respectively, by sampling date. The models generally capture the observed peak seasonal average Chla concentrations, though sometimes shifted spatially or temporally. Similarly, Figures B3 and B4 show the cumulative distribution of simulated and observed maximum Chla concentrations. In both reservoirs, simulated concentrations are higher than observed concentrations above the 10 µg/l level, demonstrating further the conservative character of the calibration.

Figures B5 and B6 in Appendix B compare simulated and observed average surface DO concentrations at the downstream sampling locations in Triadelphia and Rocky Gorge Reservoir, respectively. The models follow the seasonal trend in DO but tend to under-simulate DO in winter while sometimes over-simulating DO in summer. Figures B7 and B8 show the simulated and observed average bottom DO concentrations. The models capture the seasonal trend in bottom DO, though in some years the simulation underestimates the extent of hypoxia in Rocky Gorge Reservoir. The coefficients of determination between observed and simulated values are 0.90 and 0.54 for Triadelphia and Rocky Gorge Reservoirs, respectively.

Appendix C contains time series plots comparing simulated and observed concentrations at other locations. It also shows time series plots for phosphate, total phosphorus, nitrate, ammonia, and total nitrogen.

4.3.3 TMDL Scenario Results

The CE-QUAL-W2 models of Triadelphia and Rocky Gorge Reservoirs were used to determine the maximum total phosphorus loads compatible with water quality standards. Simulated loads were reduced until two conditions were met: (1) the 90^{th} percentile simulated Chla concentration in any cell was no greater than 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. Figures B9 and B10 in Appendix B compare maximum Chla concentrations by date under the Calibration and TMDL Scenarios to observed concentrations in the surface layer of Triadelphia and Rocky Gorge Reservoirs, respectively.

The TMDL Scenario was also analyzed to determine whether the reservoirs would meet the DO criteria for Use I-P and IV-P waters under TMDL loading rates. Figures B11 and B12 show the average surface DO concentrations at the downstream sampling locations in Triadelphia and Rocky Gorge Reservoirs, based on a screening depth of four meters. To more accurately screen for potential violations, the position of the well-mixed surface layer was more precisely determined on a daily basis. Instantaneous DO concentrations were output from all cells in the surface layer at half-day intervals. Under the TMDL scenario, there is no cell in the surface layer of either reservoir with an instantaneous DO concentration less than 5.0 mg/l except during periods such as the fall overturn when the surface layer deepens and entrains water with low DO concentrations from the metalimnion.

Seasonal hypoxia persists in the hypolimnion in both reservoirs even under the TMDL Scenario. Figures B13 and B14 in Appendix A show the average bottom DO concentrations at the downstream sampling locations in Triadelphia and Rocky Gorge Reservoirs. As the figures indicate, although the average DO in the bottom layers improves under the TMDL Scenario, neither reservoir maintains a DO concentration of 5.0 mg/l in the hypolimnion throughout the simulation period.

4.3.4 All-Forest Scenario Results

As explained earlier, the purpose of the All-Forest Scenario is to help determine whether hypoxia in the bottom layers of Triadelphia and Rocky Gorge Reservoirs is primarily due to the stratification induced by reservoir morphology, or to input loads. 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 as described in Section 2.3.

Average annual TP loads in the All-Forest Scenario are 18% of the load in the Calibration Scenario in Triadelphia Reservoir, and 15% of the load in the Calibration Scenario in Rocky Gorge Reservoir. The reduction in average annual loads of POM, the precursor to sediment oxygen demand, is not as large. Average annual POM loads in the

All-Forest Scenario are 29% of the load in Calibration Scenario in Triadelphia and 31% of the load in Calibration Scenario in Rocky Gorge. The POM load decrease is less in the Rocky Gorge watershed because of the high percentage of forested and developed land.

Figures 13 and 14 below show the average bottom DO concentrations at lower sampling locations in the reservoirs under the All-Forest Scenario. Minimum concentrations at the sampling locations are also shown. Average DO in the bottom layers of both reservoirs improves considerably under the All-Forest Scenario. The minimum DO concentration, however, frequently drops below 5.0 mg/l. Even under the All-Forest Scenario, the hypolimnion remains hypoxic in many (but not all) years of the simulation. The hypoxia tends to be worse in the downstream stations of the reservoirs where the depths are greatest.

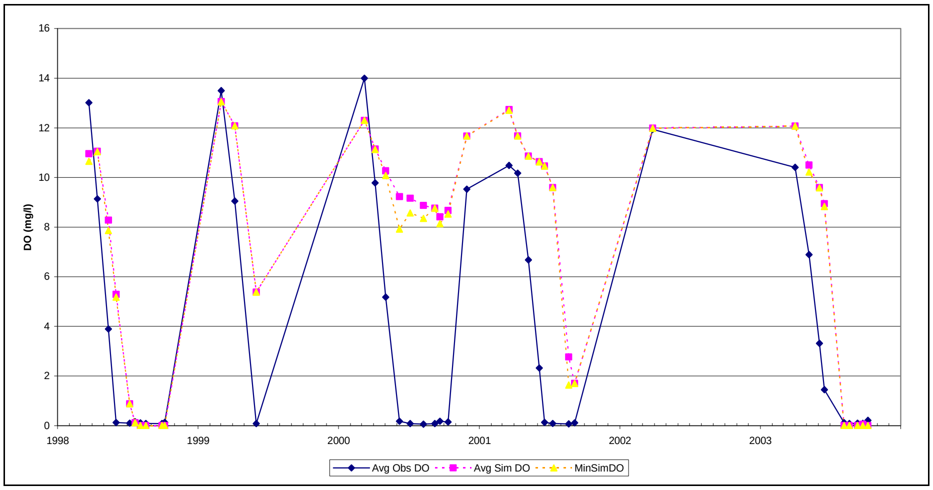

Figure 13: Observed and Simulated Average Bottom DO Concentrations, Station TR1, All-Forest Scenario, Triadelphia Reservoir

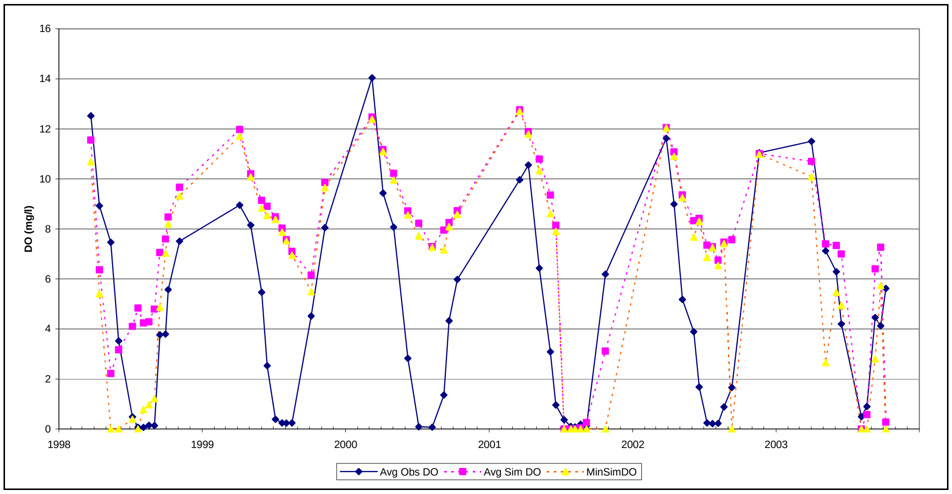

Figure 14: Observed and Simulated Average Bottom DO Concentrations, Station RG1, All-Forest Scenario, Rocky Gorge Reservoir

A sensitivity analysis was performed to better determine how phosphorus and organic matter loading rates impact hypoxia in the hypolimnion. POM and TP loading rates were reduced to 50%, 20% and 10% of the loads of the All-Forest Scenario, and the percent of sampling dates where DO < 2.0 mg/l at the sampling locations was calculated. Figure 15 shows the results. Significant hypoxia persists even when loads are reduced to only 10% of the All-Forest Scenario in Rocky Gorge Reservoir. Although hypoxia disappears in Triadelphia Reservoir when loading rates are 10% of the All-Forest Scenario, 5% of sampling dates under those loading conditions still have DO concentrations less than 5 mg/l in the hypolimnion. 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. 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 layers of the reservoirs are therefore a naturally occurring condition, as described by the interim interpretation of Maryland's water quality standards. The TMDL Scenario thus meets water quality standards for DO under the interim interpretation.

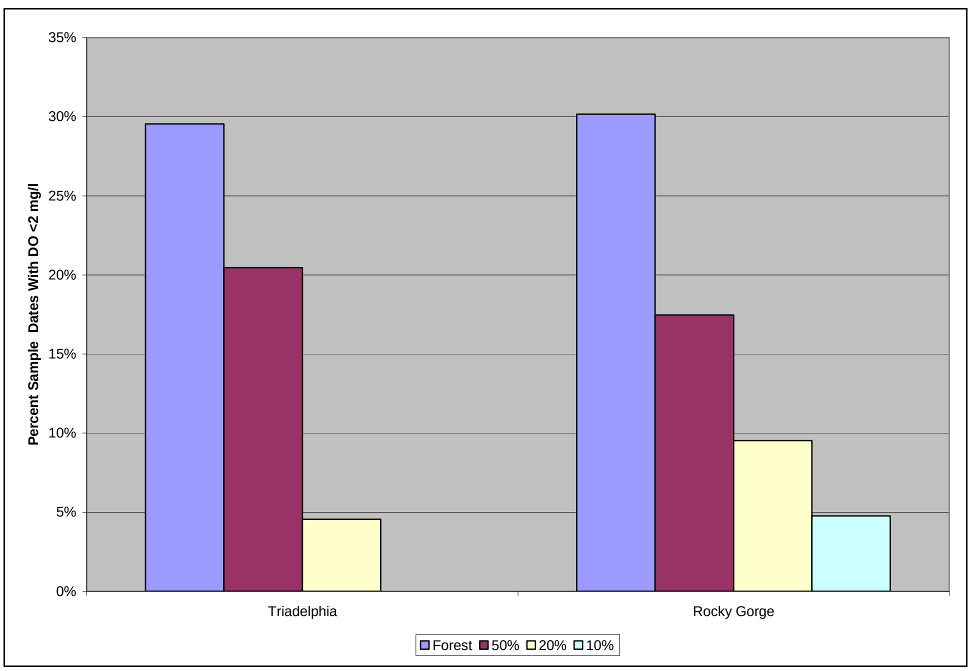

Figure 15: Percent of Sampling Dates on which DO < 2.0 mg/l as a function of proportion of All-Forest Scenario

4.4 TMDL Loading Caps

4.4.1 Phosphorus TMDL Loading Caps

This section presents the TMDLs for phosphorus for Triadelphia and Rocky Gorge Reservoirs. The TMDLs were estimated based on the phosphorus loadings as explained in Section 4.3 and the resulting water quality in the reservoirs for the simulated years 1998-2003. This period was selected to estimate the TMDLs because it includes dry years as well as very wet years and thus takes into account a variety of hydrological conditions. Chla concentrations indicative of eutrophic conditions can occur at any time of year, and the simulation period encompasses the spectrum of observed seasonal concentrations (see Tables 3A and 4A, Appendix A). Seasonal low DO concentrations in the hypolimnia that occur regularly each year are also represented in the simulation models.

TMDL loads were calculated on an average annual basis. The average residence time of Triadelphia Reservoir is approximately four months while the residence time of Rocky Gorge is approximately three months. Water quality conditions in both reservoirs are the cumulative result of loadings that span seasons, or even, in the case of hypolimnetic hypoxia, years. Average annual TP loads are therefore the appropriate measure in which to express nutrient TMDLs for Triadelphia and Rocky Gorge Reservoirs. Flow-variable maximum daily loads are presented in Appendix D.

For Triadelphia Reservoir:

Total Phosphorus TMDL 27,700 lbs/year

For Rocky Gorge Reservoir:

Total Phosphorus TMDL 24,406 lbs/year

The TMDLs reflect a reduction of 58% from baseline TP loads in Triadelphia Reservoir and 48% from baseline loads in Rocky Gorge Reservoir.

4.4.2 Sediment TMDL Loading Caps for Triadelphia Reservoir

Excessive sedimentation reduces a reservoir's storage capacity and therefore negatively impacts its ability to function as a water supply reservoir. Excessive sedimentation can also negatively impact a reservoir's fishery and interfere with its recreational uses. Although the maximum sedimentation rates occur during wet weather events, it is the cumulative effect of sedimentation that impacts the reservoir. No single critical period can be defined for the water quality impact of sedimentation. An excessive sedimentation rate negatively impacts a reservoir regardless of when it occurs. Therefore, the efforts to reduce sediment loading to the lake should focus on achieving effective, long-term sediment control. Since some measures to control phosphorus from agriculture sources can also effectively reduce sedimentation, the expected sediment reduction can be estimated based on the degree of phosphorus control needed to improve the water quality of the reservoir.

To quantify the sediment reduction associated with this phosphorus reduction, the EPA Chesapeake Bay Program watershed modeling assumptions were consulted. For the agricultural best management practices (BMPs) that affect both phosphorus and sediments, EPA estimates a 1-to-1 reduction in sediments as a result of controlling phosphorus (EPA, Chesapeake Bay Program Office, 1998). However, this ratio does not account for phosphorus controls that do not remove sediments.

To estimate the applicable ratio, hence the sediment load reduction, it is necessary to estimate the proportion of the phosphorus reduction controls that remove sediments versus those that do not. In general, soil conservation and water quality plans (SCWQPs) remove sediments along with the phosphorus removal, while nutrient management plans (NMPs) do not. It has been assumed that 50% of the phosphorus reduction will come from SCWQPs and 50% from NMPs. This results in a 0.5-to-1 ratio of sediment reduction to phosphorus reduction. The net sediment reduction associated with a 58% NPS phosphorus reduction is about 29% (0.58 * 0.5 = 0.29).

It is assumed that this reduced sediment loading rate would result in a similar reduction in the sediment accumulation rate. The sediment accumulation rate predicted to result from this reduced loading rate would allow for the retention of 95% of the impoundment's volume after 40 years.

MDE has determined that this volumetric retention will support the designated uses of Triadelphia Reservoir (Use IV-P) for which it is protected: recreational trout and public water supply. This estimate is reasonably consistent with technical guidance provided by EPA Region III of a 0.7-to-1.0 reduction in sediment in relation to the reduction in phosphorus (EPA 1998). This rule-of-thumb would yield a 41% estimated reduction in sediment [100*(0.58 * 0.70) = 41%]

Assuming that a 58% reduction in total phosphorus load results in a 29% reduction in sediment load, the sediment loading cap for Triadelphia Reservoir is as follows:

For Triadelphia Reservoir:

Sediment TMDL	**22,820 tons/year**

Flow-variable maximum daily loads are presented in Appendix D.

4.5 Total Load Allocations Between Point Sources and Nonpoint Sources

The allocations described in this section demonstrate how the TMDLs can be implemented to achieve water quality standards in Triadelphia and Rocky Gorge Reservoirs. Specifically, these allocations show that the sum of phosphorus loadings to the reservoirs from existing point and nonpoint sources can be maintained safely within the TMDLs established herein. The State reserves the right to revise these allocations provided such revisions are consistent with the achievement of water quality standards.

4.5.1 Phosphorus TMDL Allocations

- Nonpoint Source (NPS) Loads

  Nonpoint source loads including agricultural and forest loads are assigned to the TMDL as the Load Allocation (LA). The Calibration or Baseline Scenario loads were based on the HSPF model of the Patuxent River Watershed. The modeling of the watershed accounted for both natural and human-induced components, including atmospheric deposition and septic loadings. Details on the HSPF model can be found in *Modeling Framework for Simulating Hydrodynamics and Water Quality in Triadelphia and Rocky Gorge Reservoirs* (ICPRB 2007).

- Stormwater Loads

  Although regulated stormwater dischargers like municipal separate storm sewer systems (MS4s) transport rainfall-driven nonpoint source loads to surface waters, they are technically categorized as *point sources*, because they are subject to NPDES permit regulations. As such, MS4s and other regulated stormwater entities are assigned wasteload allocations (WLAs) that may nevertheless include certain nonpoint sources of a pollutant that can enter the sewer system in storm event runoff. In the absence of any MS4s or other regulated stormwater dischargers, such nonpoint source loads are typically included in the load allocation (LA).

  MDE's Stormwater WLA policy is pursuant to EPA's guidance document, "Establishing Total Maximum Daily Load (TMDL) Wasteload Allocations (WLAs) for Storm Water Sources and NPDES Permit Requirements Based on Those WLAs" (November 2002), which advises states to treat both individual and general NPDES Phase I and Phase II stormwater permits as point sources subject to WLA assignment in the TMDL. The Agency document acknowledges that quantification of rainfall-driven nonpoint source loads is uncertain, stating that available data and information usually are not detailed enough to determine WLAs for NPDES-regulated stormwater discharges on an outfall-specific basis. Therefore, the EPA guidance allows the stormwater WLA to be expressed as an aggregate allotment, rather than individual allocations for separate pipes, ditches, construction sites, etc. Available information for the Patuxent River watershed allows the stormwater WLA for this analysis to be defined separately for Howard, Montgomery, and Prince George's Counties;

however, these WLAs aggregate municipal and industrial stormwater, including loads from construction activity.

WLAs from point source dischargers are usually based on the relative contribution of pollutant load to the waterbody. Estimating a load contribution to a particular waterbody from Phase I and II stormwater sources is imprecise, given the variability in sources, runoff volumes, and pollutant loads over time. Therefore, any stormwater WLA portion of the TMDL is based on a rough estimate.

- Wastewater Treatment Plant (WWTP) Loads

In addition to nonpoint source loads and stormwater point sources, a WLA to the FEMA WWTP plus a 5% MOS (see next section) make up the balance of the total allowable load for Rocky Gorge Reservoir. There are no permitted WWTPs in the Triadelphia Reservoir watershed. The FEMA WWTP maximum allowable design flow of 0.01 MGD is used for this scenario. A total phosphorus concentration of 6.0 mg/l year-round was used to set the WLA for the facility. All significant point sources are addressed by this allocation and are described further in the technical memorandum entitled "*Significant Nutrient and Sediment Point Sources in the Triadelphia and Rocky Gorge Reservoir Watersheds.*"

The TMDL, including loads from stormwater discharges, is now expressed as:

TMDL = WLA [non-stormwater point sources + regulated stormwater point sources] + LA + MOS

The phosphorus allocations for Triadelphia and Rocky Gorge Reservoirs are presented in Table 7.

Table 7: Total Phosphorus Allocations (lbs/yr) for Triadelphia and Rocky Gorge Reservoirs

	Triadelphia Reservoir	Rocky Gorge Reservoir
Nonpoint Source[1]	21,027	15,757
Point Source[2]	5,288	7,429
Margin of Safety[3]	1,385	1,220
Total Maximum Daily Load	27,700	24,406

[1] Excluding urban stormwater loads.
[2] Including urban stormwater loads.
[3] Representing 5% of TMDL loads.

4.5.2 Sediment Load Allocations for Triadelphia Reservoir

- Nonpoint Source (NPS) Loads

Nonpoint source loads including agricultural and forest loads are assigned to the TMDL as LA. The Calibration and Baseline Scenario loads were based on the HSPF model of the Patuxent River watershed. The modeling of the watershed accounted for both natural and human-induced components. The LA to nonpoint sources in the watershed represents a decrease of approximately 29% from baseline loads. Details on the HSPF model can be found in *Modeling Framework for Simulating Hydrodynamics and Water Quality in Triadelphia and Rocky Gorge Reservoirs* (ICPRB 2006).

- Stormwater Loads

  The reduction in total phosphorus loads from stormwater discharges will result in a reduction in sediment loads, but because of the uncertainty in BMP efficiencies for developed land, no reduction is assumed for sediment loads from stormwater discharges, and their share of the WLA is set equal to baseline conditions.

- Wastewater Treatment Plant Loads

  There are no permitted WWTPs in the Triadelphia Reservoir watershed.

- Permitted Industrial Facilities

  There are no industrial facilities with permits regulating the discharge of total suspended solids in the Triadelphia Reservoir watershed.

The TMDL for Suspended Sediment in Triadelphia Reservoir is as follows:

TMDL (tons/yr)	**=**	**LA**	**+**	**WLA**	**+**	**MOS**
22,820	**=**	**22,420**		**400**		**implicit**

4.6 Margins of Safety

A MOS is required as part of a TMDL in recognition of many uncertainties in the understanding and simulation of water quality in natural systems. For example, knowledge is incomplete regarding the exact nature and magnitude of pollutant loads from various sources and the specific impacts of those pollutants on the chemical and biological quality of complex, natural waterbodies. The MOS is intended to account for such uncertainties in a manner that is conservative from the standpoint of environmental protection.

Based on EPA guidance, the MOS can be achieved through two approaches (EPA, April 1991). One approach is to reserve a portion of the loading capacity as a separate term in the TMDL (*i.e*., TMDL = Load Allocation (LA) + Waste Load Allocation (WLA) + MOS). The second approach is to incorporate the MOS as conservative assumptions used in the TMDL analysis. Maryland has adopted a MOS for nutrient TMDLs using the first approach. The reserved load allocated to the MOS was computed as 5% of the total loads for phosphorus. These explicit phosphorus margins of safety are **1,385 lbs/yr** for Triadelphia Reservoir, and **1,220 lbs/yr** for Rocky Gorge Reservoir.

In establishing a MOS for sediments, Maryland has adopted an implicit approach by incorporating conservative assumptions. First, because phosphorus binds to sediments, sediments will be controlled as a result of controlling phosphorus. This estimate of sediment reduction is based on the load allocation of phosphorus (21,057 lbs/yr), rather than the entire phosphorus TMDL including the MOS. Thus, the explicit 5% MOS for phosphorus will result in an implicit MOS for sediments. This conservative assumption results in a difference of about 975 tons/yr (see Section 4.5 above for a discussion of the relationship between reductions in phosphorus and sediments). Secondly, as described in Section 4.4.2, MDE conservatively assumes a sediment-to-phosphorus reduction ratio of 0.5:1, rather than 0.7:1 sediment-to-phosphorus reduction ratio given in the technical guidance provided by EPA Region III. Table 8 compares the volumetric preservation under TMDL conditions in Triadelphia Reservoir with that of several other approved TMDLs.

Table 8: Volumetric Preservation of Various Impoundments Under Sediment TMDL Conditions

TMDL	VOLUMETRIC PRESERVATION (TMDL time-span)	VOLUMETRIC PRESERVATION (100 year time span)
Urieville Community Lake (MD)	76% after 40 years	40%
Tony Tank Lake (MD)	64% – 85% after 40 years	10% to 62.5%
Hurricane Lake (WV)	70% after 40 yrs	25%
Tomlinson Run Lake (WV)	30% after 40 yrs	Silted in
Clopper Lake (MD)	98% - 99% after 40 years	96% to 98%
Centennial Lake (MD)	68% - 87% after 40 years	20% to 69%
Lake Linganore (MD)	52% - 80% after 40 years	Silted in to 52%
Loch Raven Reservoir (MD)	85% after 50 years	80%
Triadelphia Reservoir (MD)	95% after 40 years	87%

4.7 Summary of Total Maximum Daily Loads

The following equations summarize the nutrient TMDLs for Triadelphia and Rocky Gorge Reservoirs, and the sediment TMDL for Triadelphia Reservoir:

For Total Phosphorus in Triadelphia Reservoir:

TMDL (lbs/yr)	**=**	**LA +**	**WLA +**	**MOS**
27,700	**=**	**21,027**	**5,288**	**1,385**

For Total Phosphorus in Rocky Gorge Reservoir:

TMDL (lbs/yr)	**=**	**LA +**	**WLA +**	**MOS**
24,406	**=**	**15,757**	**7,429**	**1,220**

For Suspended Sediment in Triadelphia Reservoir:

TMDL (tons/yr)	**=**	**LA +**	**WLA +**	**MOS**
22,820	**=**	**22,420**	**400**	**implicit**

Maximum daily loads were calculated by flow regime. Table 9 below shows the maximum daily loads under low flow and high flow conditions for the nutrient and sediment TMDLs for the Patuxent Reservoirs. See Appendix D for a full explanation of the technical approach used to develop these maximum daily loads.

Table 9: Maximum Daily Loads By Flow Regime

Total Phosphorus, Triadelphia Reservoir (lbs/day)				
Flow Regime (cfs)	**TMDL**	**WLA**	**LA**	**MOS**
<326	852	356	453	43
>326	17,003	1,504	14,649	850
Total Phosphorus, Rocky Gorge Reservoir (lbs/day)				
Flow Regime (cfs)	**TMDL**	**WLA**	**LA**	**MOS**
<291	770	314	418	39
>291	4,003	1,102	2,701	200
Sediment, Triadelphia Reservoir (tons/day)				
Flow Regime (cfs)	**TMDL**	**WLA**	**LA**	**MOS**
<326	662	40	621	Implicit
>326	25,468	157	25,311	Implicit

5.0 ASSURANCE OF IMPLEMENTATION

This section provides the basis for reasonable assurances that the phosphorus and sediment TMDLs will be achieved and maintained. For all three TMDLs, Maryland has several well-established programs that may be drawn upon: the Water Quality Improvement Act of 1998 (WQIA), the Clean Water Action Plan (CWAP) framework, and the Chesapeake Bay Agreement's Tributary Strategies for Nutrient Reduction. Also, Maryland has adopted procedures to assure that future evaluations are conducted for all TMDLs that are established.

The FEMA WWTP will continue to meet the requirements of its NPDES discharge permit. The NPDES permit of the FEMA WWTP should also be consistent with the assumptions made in the TMDL (e.g., flow, nutrients effluent concentrations, CBOD, DO, etc.).

Maryland’s WQIA requires that comprehensive and enforceable nutrient management plans be developed, approved and implemented for all agricultural lands throughout Maryland. This act specifically requires that nutrient management plans for nitrogen be developed and implemented by 2002, and plans for phosphorus be completed by 2005. Maryland’s CWAP has been developed in a coordinated manner with the State's 303(d) process. All Category I watersheds identified in Maryland's Unified Watershed Assessment process are totally coincident with the impaired waters list for 2002 approved by EPA. The State is giving a high priority for funding assessment and restoration activities to these watersheds.

In 1983, the States of Maryland, Pennsylvania, and Virginia, the District of Columbia, the Chesapeake Bay Commission, and the U.S. EPA joined in a partnership to restore the Chesapeake Bay. In 1987, through the Chesapeake Bay Agreement, Maryland made a commitment to reduce nutrient loads to the Chesapeake Bay. In 1992, the Chesapeake Bay Agreement was amended to include the development and implementation of plans to achieve these nutrient reduction goals. Maryland’s resultant Tributary Strategies for Nutrient Reduction provide a framework supporting the implementation of nonpoint source controls in the Patuxent Tributary Strategy Basin, which includes the watersheds of Triadelphia and Rocky Gorge Reservoirs. Maryland is in the forefront of implementing quantifiable nonpoint source controls through the Tributary Strategy efforts. This will help to ensure that nutrient control activities are targeted to areas in which nutrient TMDLs have been established.

In November 1990, EPA required jurisdictions with a population greater than 100,000 to apply for NPDES Permits for stormwater discharges. In 1983, the EPA Nationwide Urban Runoff Program found that stormwater runoff from urban areas contains the same general types of pollutants found in wastewater, and that 30% of identified cases of water quality impairment were attributable to stormwater discharges. The two Maryland jurisdictions where the majority of the Rocky Gorge and Triadelphia watersheds are located, Howard County and Montgomery County, are required to participate in the stormwater NPDES program, and have to comply with the NPDES Permit regulations for stormwater discharges. Several management programs have been implemented in different areas served by the counties. These jurisdiction-wide programs are designed to control stormwater discharges to the maximum extent practicable.

In 1996, Howard County, Montgomery County, Prince George's County, the Montgomery County Soil Conservation District, the Howard County Soil Conservation District, Maryland National Capital Parks and Planning Commission, and the Washington Suburban Sanitary Commission signed the Patuxent Reservoir Protection Agreement. The agreement recognized the importance of protecting water quality in the reservoirs, along with their contributing watersheds, and committed the parties to the long-term protection of the following six "priority resources": (1) water supply, (2) terrestrial habitat, (3) stream system, (4) aquatic biota, (5) rural character and landscape, and (6) public awareness and stewardship. Table 10 lists some of the major commitments made under the agreement that are most relevant to nutrient and sediment TMDLs for the Patuxent reservoirs.

Finally, Maryland uses a five-year watershed cycling strategy to manage its waters. Pursuant to this strategy, the State is divided into five regions and management activities will cycle through those regions over a five-year period. The cycle begins with intensive monitoring, followed by computer modeling, TMDL development, implementation activities, and follow-up evaluation. The choice of a five-year cycle is motivated by the five-year federal NPDES permit cycle. This continuing cycle ensures that every five years intensive follow-up monitoring will be performed. Thus, the watershed cycling strategy establishes a TMDL evaluation process that assures accountability.

Table 10: Implementation Actions Under the Patuxent Reservoirs Watershed Protection Group Agreement (TAC, 2005)

Agency or Organization	Implementation Action
WSSC	Continue to perform reservoir monitoring
WSSC	Perform bathymetric survey of reservoirs every ten years
MDNR, HC, MC, MNCP&PC & WSSC	Develop forest management action plan
WSSC, MNCP&P, HC, MC	Establish and maintain minimum 35-ft stream buffers on public land
WSSC, MNCP&PC, HC, MC, MCSCD, HCSCD	Accelerate program to establish and maintain minimum 35-ft buffers on private land
HSCD, MCSCD	Establish and maintain streamside fencing programs to keep livestock out of streams
HC, MNCP&PC, MC	Address channel instability through streambank restoration and stormwater retrofits
MNCP&PC, HC, MC, MCSCD, HCSCD	Pursue cost-share funds for agricultural BMPs, stream restoration, and stormwater retrofits
MNCP&PC, HC, MC	Use zoning and land use policies to maintain rural character of watersheds
HC, MC	Continue easement acquisitions through agricultural land preservation programs

HC: Howard County
HSCD: Howard County Soil Conservation District
MC: Montgomery County
MSCD: Montgomery County Soil Conservation District
MNCP&PC: Maryland National Capital Parks and Planning Commission
WSSC: Washington Suburban Sanitary Commission

REFERENCES

Brown, J. H. and S. T. Dyer. 1995. Soil Survey of Montgomery County, Maryland. Natural Resource Conservation Service. Washington, DC.

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.

COMAR (Code of Maryland Regulations). 2006. 26.08.02.03; 26.08.02.08.

Cole, T. M. and S. A. Wells. 2003. CE-QUAL-W2: A Two-Dimensional Laterally Averaged, Hydrodynamic and Water Quality Model, Version 3.2. Vicksburg, MS. U.S. Army Engineering and Research Center. Instruction Report EL-03-1.

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.

ICPRB (Interstate Commission on the Potomac River Basin) and Maryland Department of the Environment. 2007. Modeling Framework for Simulating Hydrodynamics and Water Quality in the Triadelphia and Rocky Gorge Reservoirs. Rockville, MD.

MDE (Maryland Department of the Environment). 2002. Total Maximum Loads of Phosphorus and Sediment For Lake Linganore, Frederick County, Maryland. Baltimore, MD.

MDE and DNR (Maryland Department of Natural Resources). 2004. 2004 List of Impaired Surface Waters [303(d) List] and Integrated Assessment of Water Quality in Maryland. Baltimore, MD.

Maryland Department of Planning. 1997. Land Use Data.

Matthews, E. D. and M.F. Hershberger. 1968. Soil Survey of Howard County, Maryland. Soil Conservation Service. Washington, DC.

Ocean Surveys, Inc. 1997. Sedimentation Surveys. Phases I, II, and III.

Patuxent Reservoirs Technical Advisory Committee. 2005. Supplemental Documentation in Support of the Patuxent Reservoirs Technical Advisory Committee's Annual Report.

Patuxent Reservoirs Technical Advisory Committee. 2006. Supplemental Documentation in Support of the Patuxent Reservoirs Watershed Annual Report.

Resource Management Concepts. 2002. Draft Reservoir Data Analysis. Lexington Park, MD.

U. S. Department of Commerce. 1997. Census of Agriculture. Volume 1. Geographic Area Series. Washington, DC.

U.S. EPA (United States Environmental Protection Agency). 2002. Establishing Total Maximum Daily Load (TMDL) Wasteload Allocations (WLAs) for Storm Water Sources and NPDES Permit Requirements Based on Those WLAs. Washington, DC. November 2002.

————. 1991. Technical Support Document for Water Quality-based Toxics Control. Office of Water/OW Environment Protection (OW/OWEP) and Office of Water Regulations and Standards (OWRS), Washington, DC. April 23, 1991.

————. 1999. Protocol for Developing Nutrient TMDLs. EPA 841-B-99-007. Office of Water (4503F), United States Environmental Protection Agency, Washington DC.

————. 1997. Technical Guidance Manual for Developing Total Maximum Daily Loads, Book 2: Streams and Rivers, Part 1: Biochemical Oxygen Demand/ Dissolved Oxygen and Nutrients/ Eutrophication. Office of Water, Washington DC. March, 1997.

————. Chesapeake Bay Program Office. 1996. Chesapeake Bay Program: Watershed Model Application to Calculate Bay Nutrient Loadings: Final Findings and Recommendations, and Appendices.

————. Chesapeake Bay Program Office. 1998. Table H.2.2, Chesapeake Bay Watershed Model BMP Matrix with Associated Nutrient Reduction Efficiencies, provided by Bill Brown, CBPO, Oct. 1998.

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.

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.

Appendix A

Appendix B

Appendix C

Appendix D

Appendix E