Total Maximum Daily Loads of Phosphorus to Broadford Lake, Garrett County, MD

Prepared by:

Maryland Department of the Environment

2500 Broening Highway
Baltimore, MD 21224

Submitted to:

Water Protection Division
U.S. Environmental Protection Agency, Region III

1650 Arch Street
Philadelphia, PA 19103-2029

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Table of Contents

PREFACE

Section 303(d) of the federal Clean Water Act directs States 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 to establish a Total Maximum Daily Load (TMDL) of the specified substance that the water can receive without violating water quality standards.

On the basis of water quality problems associated with nutrients, Broadford Lake was identified on Maryland’s 1998 list of WQLSs as being impaired. This report proposes the establishment of a TMDL for Broadford Lake for phosphorus.

Once the TMDL is approved by the United States Environmental Protection Agency (EPA), it will be incorporated into the State’s Continuing Planning Process. In the future, the established TMDL will support reservoir restoration and nonpoint source control measures needed to restore water quality in Broadford Lake.

EXECUTIVE SUMMARY

On the basis of water quality problems associated with nutrients, Broadford Lake in the Little Youghiogheny River watershed (5020202) was identified on Maryland's 1998 list of WQLSs as being impaired. This document establishes a Total Maximum Daily Load (TMDL) for the nutrient phosphorus entering Broadford Lake.

Broadford Lake is an impoundment located near Oakland in Garrett County, Maryland. The impoundment lies on Broadford Run, a tributary of the Little Youghiogheny River. The Little Youghiogheny River lies in the Youghiogheny River Drainage Basin, in the upper western corner of Maryland. Broadford Lake supplies drinking water for the Town of Oakland. In addition, it is a highly used recreational facility, with two swimming beaches and many picnic tables.

The death and decay of excessive algae can cause violations of the water quality standard for dissolved oxygen (DO), which can result in a disruption of the lake's ecosystem balance and cause fish kills. Analysis suggests that phosphorus is the limiting nutrient for the production of algae in freshwater lake systems such as Broadford Lake.

The water quality goal of this TMDL is to reduce long-term phosphorus loads to an acceptable level consistent with the physical characteristics of Broadford Lake. This reduced loading rate is predicted to resolve excess algae problems and maintain a dissolved oxygen concentration above the State water quality standard. The TMDL for phosphorus was determined using an empirical method known as the Vollenweider Relationship.

The average annual TMDL for phosphorus is about 1,217 lb/yr. There are no point sources in the Broadford basin. Consequently, the allocation is partitioned between nonpoint sources and the margin of safety.

Preliminary estimations of the phosphorus controls necessary to achieve the load reduction were conducted to provide a reasonable assurance that the TMDL could be implemented. It is estimated that a 38% reduction in phosphorus loads would be necessary to meet the TMDL for phosphorus.

1.0 INTRODUCTION

The Clean Water Act Section 303(d)(1)(C) and federal regulation 40 CFR 130.7(c)(1) direct each state to develop a Total Maximum Daily Load (TMDL) for all impaired waters on their Section 303(d) list. A TMDL reflects the maximum pollutant loading of an impairing substance a water body can receive and still meet water quality standards. A TMDL can be expressed in mass per time, toxicity, or any other appropriate measure (40 CFR 130.2(i)). TMDLs must take into account seasonal variations and a margin of safety (MOS) to allow for uncertainty. Maryland's 1998 303(d) list, submitted to EPA by the Maryland Department of the Environment (MDE), lists Broadford Lake for nutrients. The 1998 listing was prompted by an assessment of data associated with Broadford Lake (Maryland Department of Natural Resources [DNR], 1998).

2.0 SETTING AND WATER QUALITY DESCRIPTION

2.1 General Setting and Source Assessment

Broadford Lake is an impoundment located near Oakland in Garrett County, Maryland (Figure 1). The impoundment, which is owned by the City of Oakland, lies on Broadford Run, a tributary of the Little Youghiogheny River. An earthen dam was installed for the purpose of flood control, water supply and for recreational uses in 1971.

The Broadford Lake watershed lies in the Allegheny Plateau. The geological strata include shale, coal, and sandstone. Soils are formed in material weathered from bedrock of shale, sandstone and siltstone (Maryland Department of State Planning, 1973). Soils in the watershed are primarily Brinkerton and Andover silt loam, Elkins silt loams and Cookport channery loams. The soils consist of either deep, moderately well drained to very poorly drained soils on floodplains (U.S. Department of Agriculture, Soil Survey of Garrett County, 1974).

Inflow to the lake is primarily via Broadford Run and one unnamed tributary. Discharge from the lake is to Mountain Lake, which discharges to the Little Youghiogheny River. The watershed map (Figure 2) shows that land use in the watershed draining to Broadford Lake is predominantly forested/herbaceous. Land use distribution in the watershed is approximately 63% forested/herbaceous, 25% agricultural, 9% developed and 3% water (Figure 3) (Maryland Office of Planning, 1994).

The load reduction assessment uses Chesapeake Bay Program data to estimate the nonpoint source loading rates, which represent the cumulative impact from all sources—naturally-occurring and human-induced. Natural background sources of phosphorus are included in the assessment including direct atmospheric deposition to the water surface. The loads associated with each land use category include the naturally occurring as well as the human-induced contributions. No point source discharge permits for nutrients have been issued in the Broadford Lake Watershed.

Several relevant statistics for Broadford Lake are provided below in Table 1.

Table 1

Current Physical Characteristics of Broadford Lake

Location:	Garrett County, MD lat. 39^{o} 24’ 29” long. 79^{o} 22’ 20”
Surface Area:	138 acres = (6,011,280 ft^2)
Length:	1.24 mi
Maximum Width:	1200 feet
Average Lake Depth:	10.2 feet
Maximum Depth:	28.5 feet
Volume of Lake:	1407.6 acre-feet (2,383,199 m^3)
Drainage Area to Lake:	6.8 mi^2
Average Discharge:	14.9 cfs

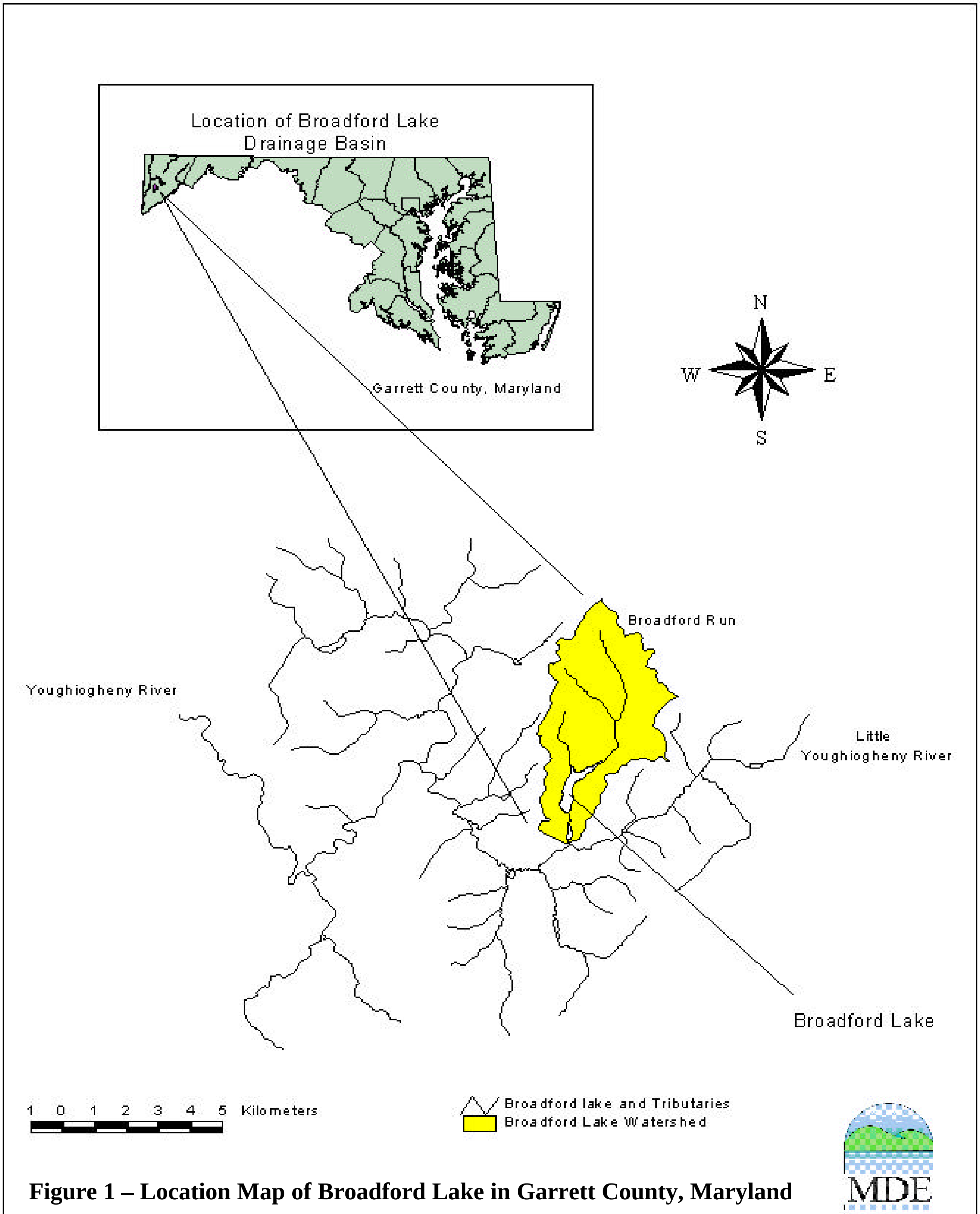

Figure 1 – Location Map of Broadford Lake in Garrett County, Maryland

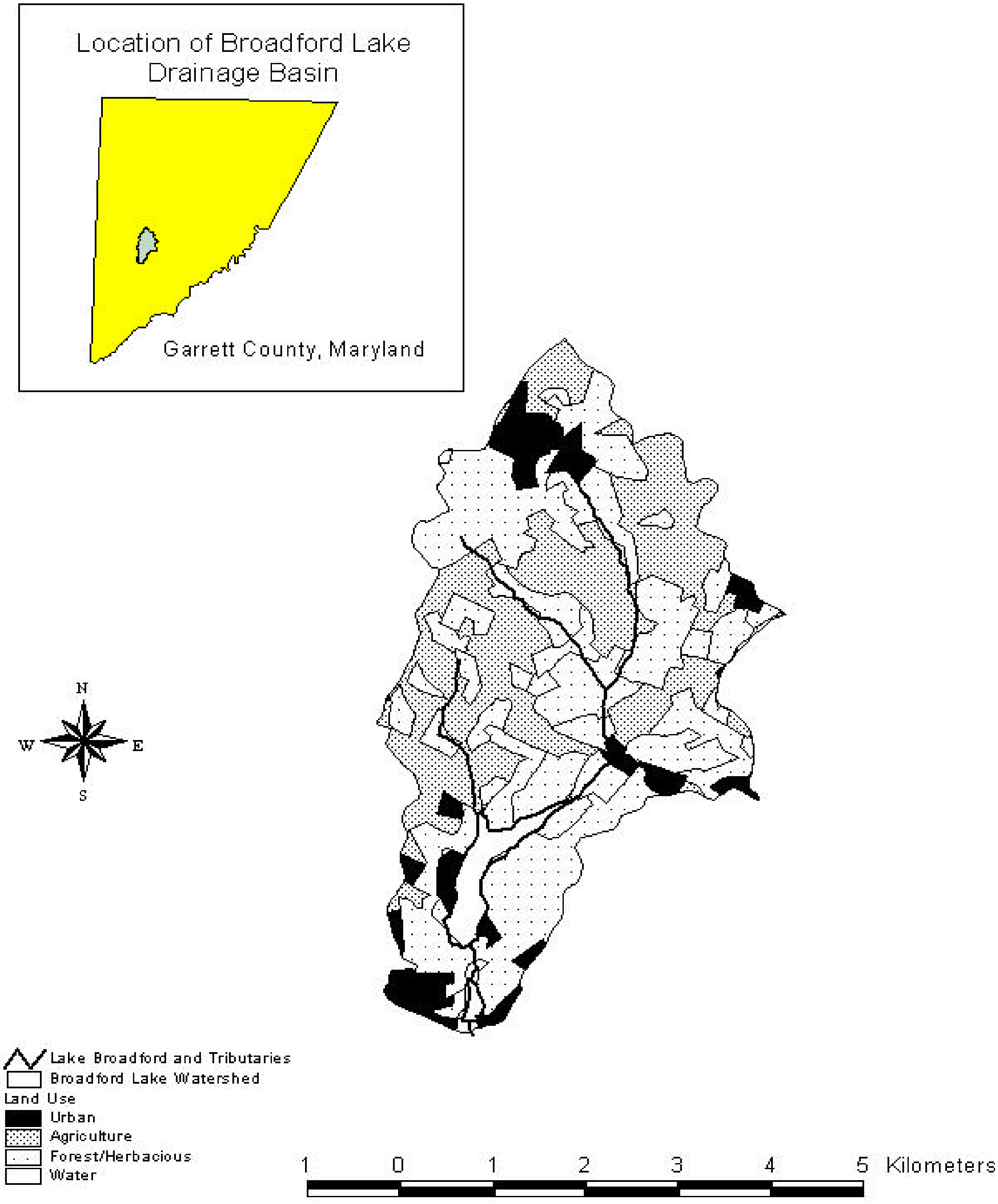

Figure 2 – Predominant Land Use in the Broadford Lake Watershed

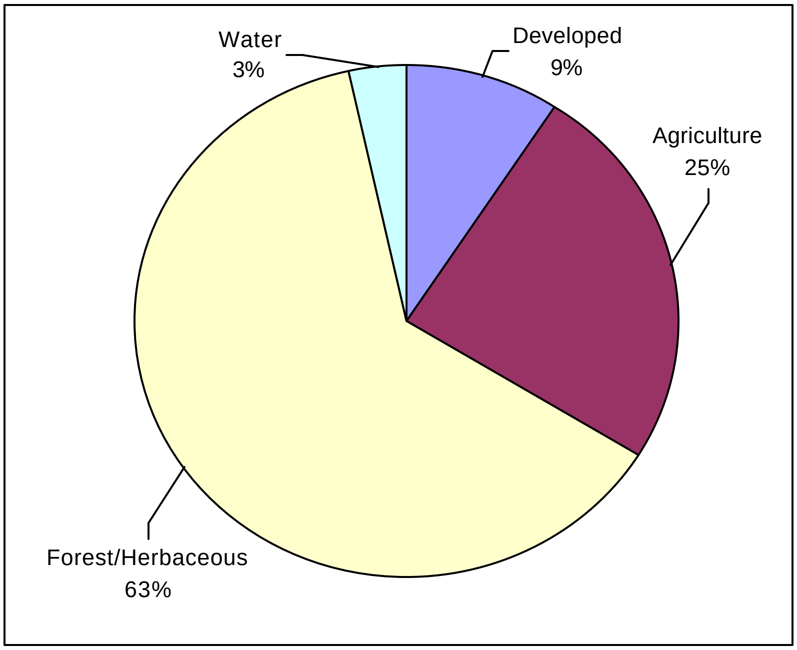

Figure 3. Land Use in Drainage Basin of Broadford Lake

2.2 Water Quality Characterization

Broadford Lake was identified as having low dissolved oxygen levels and nuisance levels of algae, in the *Maryland Lake Water Assessment Report* (March 1998). As a result of this evaluation, Broadford Lake was added to Maryland's 1998 303(d) list.

Broadford Lake was monitored in August and September of 1993 (MDE, 1995). Water quality samples were collected once in each month. Samples were collected from one station at 50 feet above the overflow structure, one station at mid-lake, and one station at approximately 600 feet below the fork in the upper end of the lake. Water samples were collected from a vertical profile of the water column. Samples were analyzed by the Maryland Department of Health and Mental Hygiene for total phosphorus, soluble orthophosphorus, nitrate and nitrite N, total Kjeldahl nitrogen, total organic solvents and chlorophyll *a*. Physical measurements of depths, water temperatures, pH, conductivity and dissolved oxygen were recorded in the field from the surface, middle and lower portion of the water column. A summary from the MDE Lake Water Quality Assessment Project follows. Detailed water quality data are presented in Appendix A.

Chlorophyll *a* concentrations ranging from 4.5 to 35.0 µg/l were observed in Broadford Lake. While not extreme when compared to peak concentrations (10 to 275 µg/l) in eutrophic lakes (Olem and Flock 1990), chlorophyll *a* levels above 10 µg/l are associated with eutrophic conditions (Chapra, 1997).

Dissolved oxygen (DO) concentrations ranged from 0.1 to 8.1 mg/l along the vertical profile. Oxygen depletion occurs discontinuously, coincident with the depth at which thermal stratification was observed (i.e. about 5 m) during the two sampling events.

Total phosphorus concentrations ranging from 0.017 mg/l to 0.062 mg/l exceeded the range of 0.01 mg/l to 0.03 mg/l for lakes that do not exhibit signs of over-enrichment (Reid 1961).

Total nitrogen ranged from 0.23 to 0.82 mg/l in Broadford Lake. High concentrations occurred during the September sampling event above the tropholytic zone.

Water temperatures taken during the sampling period ranged from 23.1°C to 23.8°C in the surface water depth (0.3-1 meter column); 21.3°C to 22.8°C in the 2-4 meter water column; and 11.5°C to 18.2°C in the 5-7 meter water column. This wide range of water temperatures, with an abrupt discontinuity at about 5 ft, indicates that Lake Broadford is thermally stratified and not well mixed.

2.3 Water Quality Impairment

The Maryland water quality standards Surface Water Use Designation (COMAR 26.08.02.07) for Broadford Lake is Use I-P - *Water Contact Recreation, and Protection of Aquatic Life and Public Water Supply*. The water quality impairments of Broadford Lake consist of a violation of the numeric water quality for dissolved oxygen, and violations of general narrative criteria for algal growth applicable to Use I-P waters. The substance causing these water quality violations is phosphorus (see the discussion of the nitrogen/phosphorus ratio, under Section 4.2 "Analysis Framework," for an explanation of how phosphorus was determined to be the limiting nutrient associated with the eutrophication problems).

According to the numeric criteria for dissolved oxygen (DO), concentrations may not be less than 5.0 mg/l at any time (COMAR 26.08.02.03-3A(2)) unless resulting from naturally occurring conditions (COMAR 26.08.02.03.A(2)). In lake environments, low levels of dissolved oxygen are expected in bottom waters even under optimal natural conditions. However, achievement of 5.0 mg/l is expected in the well-mixed surface waters.

Broadford Lake water temperatures taken during the sampling period indicate the lake is thermally stratified and not well mixed. During the 1993 sampling period (August and September), DO concentrations as high as 8.1 mg/l were observed at the surface (1 meter depth) of Broadford Lake, with DO values as low as 0.1 mg/l at a depth of 5-7 meter. Average DO at the surface was 7.7 mg/l, and 0.91mg/l at the range of 4-7 meter depth. The observed numeric values fall short of the applicable numeric criterion in the deeper parts of the lake.

3.0 TARGETED WATER QUALITY GOALS

The overall objective of the TMDL established in this document is to reduce phosphorus loads to levels that are expected to result in meeting all water quality criteria that support the Use I-P designation. Specifically, one goal is to reduce the phosphorus load. This is predicted to reduce excessive algae growth, which leads to violations of the numeric DO criteria and the violation of various narrative criteria associated with nuisances (i.e., odors and physical impedance of direct contact use.)

In summary, the TMDL for phosphorus is intended to:

1. Assure that minimum dissolved oxygen criteria are maintained both in the epilimnion and the deeper waters of Broadford Lake:

   ❒ 5 mg/l in the surface layer (epilimnion)
   ❒ A minimum D.O. saturation of 10% and associated temperature-dependent D.O. concentration below the epilimnion (See Appendix A);

2. Resolve violations of narrative criteria associated with phosphorus enrichment of Broadford Lake, leading to excessive algal growth.

4.0 TOTAL MAXIMUM DAILY LOAD AND ALLOCATIONS

4.1 Overview

This subsection describes how the nutrient TMDL and loading allocations were developed for Broadford Lake. The second subsection describes the analysis for determining that phosphorus is likely to be the limiting nutrient in Broadford Lake, and the methodological framework for estimating a permissible phosphorus load. The third subsection summarizes the analysis used to establish the maximum allowable phosphorus load. The fourth subsection provides a discussion of the analytical results. The fifth and sixth subsections describe the translation of these results into statements of a Total Maximum Daily Load and allocations. The seventh subsection describes the margin of safety. The last subsection summarizes the TMDL, and allocations to nonpoint sources and the margin of safety.

4.2 Analytical Framework

Broadford Lake suffers from excessive nutrient enrichment. The TMDL for phosphorus is based on a widely accepted empirical method known as the Vollenwieder Relationship. The relationship predicts the degree of a lake’s trophic status as a function of the areal phosphorus loading. R. A. Vollenweider (1968) developed the relationship by assessing a large number of lakes. He established a linear relationship between the log of the phosphorus loading (L_p) and the log of the ratio of the lake’s mean depth (♣) to hydraulic residence time (τ_w) (Figure 4). This method is advantageous for a number of reasons: It is based on observed data collected from a wide range of lakes; its application is conceptually simple and does not require the assumptions of many unknown parameters; and it is recognized by the scientific community as a reasonable method of predicting the trophic status of lakes.

There are other, more complex approaches (i.e., water quality models that simulate eutrophication processes) that can also yield acceptable results. However, such methods require extensive data and the investment of substantial resources to develop. In light of the data available for this TMDL and the small size of the watershed, the Vollenweider Relationship constitutes a sufficient, readily available tool.

Nitrogen and phosphorus are essential nutrients for algae growth. However, common types of algae require different amounts of these two nutrients. If one nutrient is available in great abundance relative to the other nutrient, then the nutrient that is less available restricts the amount of plant matter that can be produced, regardless of the amount of the other nutrient that is available. This latter nutrient is called the "limiting nutrient." Applying the Vollenweider Relationship necessitates that phosphorus be the limiting nutrient. Thus, before considering the application of the Vollenweider Relationship, it is necessary to examine the ratio of nitrogen to phosphorus to establish whether phosphorus is the limiting nutrient.

In general, an 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, and if the N:P ratio is less than 5:1, nitrogen tends to be limiting (Chiandani et al., 1974). An N:P ratio of 12.5:1 was computed using best readily available data (MDE Lake Water Quality Assessment Project, 1993), which supports the use of the Vollenweider Relationship. Supporting data are provided in Appendix A.

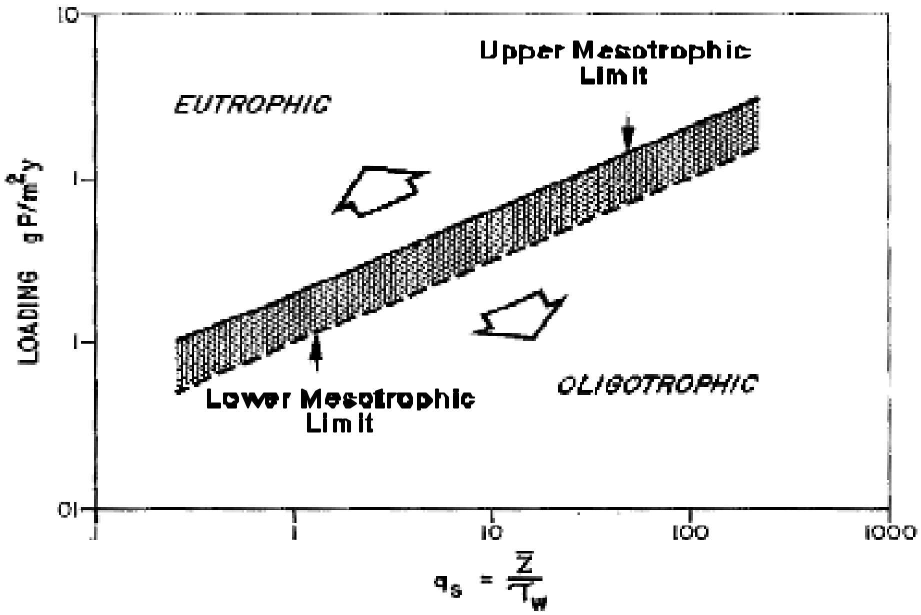

Figure 4. Vollenweider Relationship

4.3 Vollenweider Relationship Analysis

The Vollenweider Relationship establishes a linear relationship between the log of the phosphorus loading (L_p) and the log of the ratio of the lake's mean depth (♣) to hydraulic residence time (τ_w). Thus, the Vollenweider Relationship requires the computation of three key values: (1) the average annual phosphorus loading (L_p), (2) the lake's mean depth (♣), and (3) the hydraulic residence time (τ_w). The computations and results of the Vollenweider Relationship are summarized below. See Appendix A for details of the computations and supporting data.

Broadford Lake Mean Depth (♣):

The application of the Vollenweider assumes the lake's physical dimensions when the lake and dam were constructed in 1971. The mean lake depth was calculated using lake volume and surface area given in the Inventory of Maryland Dams and Hydropower Resources (DNR 1985). The cited surface area and volume of Broadford Lake are 138 acres (6,011,280 ft^2) and 1410 acre feet (61,419,600 ft^3), respectively.

The mean depth was thus calculated as follows:

- ***Broadford Lake Mean Depth (♣): (Volume)/(Surface Area) = 3.1 m or 10 ft***

Phosphorus Loading to Broadford Lake (Lp):

The current estimated total phosphorus loading is 1,699 lbs/year (or 770,612 g/year) based on loading coefficients from the Chesapeake Bay Program, segment 160, Phase 4 Watershed Model. Expressing this value as a loading per surface area of the lake gives:

- ***Annual Phosphorus Load (L_p) is: 1.4 g/m^2 yr***. Details are provided in Appendix A.

Broadford Lake Hydraulic Residence Time (τ_w)

Residence time (t_w) is computed by dividing the lake volume by annual discharge. For Broadford Lake, average discharge data are unavailable. Since discharge data are unavailable, this parameter was estimated by examining a number of watersheds of various sizes on the Youghiogheny Basin for which long-term flow data were readily available from the U.S. Geological Survey. Average daily flow from each of these stations was plotted against watershed area. Linear regression was used to estimate the average annual flow. Flow from Broadford Lake is estimated as follows (details are shown in Appendix A):

- **Flow (Q) = watershed area (6.8 mi^2) x 2.199 = 14.96 cfs = 10,837 acre feet/year**

The hydraulic residence time is computed as volume/outflow; the time it would take to drain the lake. Assuming a volume of 1,410 acre feet (DNR, 1985), from above, and a discharge rate of 10,837 acre per year (DNR, 1985) the hydraulic residence time is calculated as follows:

- **1,410 acre feet ÷ 10,837 acre feet/year =** 0.13 years

- ***Broadford Lake Hydraulic Residence Time (t_w): 0.13 years = 47.5 days***

The mean depth of the lake (3.1 m) is then divided by hydraulic residence time (0.13 years) to yield q_s, the parameter with which to compare phosphorus loading using the Vollenweider Relationship to assess the lake's trophic status. For Broadford Lake, **q_s = 23.84 m/yr**.

4.4 Vollenweider Relationship Results

The basic elements of the Vollenweider Relationship, established above, were combined to estimate both the current trophic status of Broadford Lake, and the maximum allowable unit loading. The current trophic status associated with a loading of 1.4 g/m^2 yr falls slightly into the eutrophic range, as indicated on figure 5 by a diamond "♦". The maximum allowable unit loading of 1.0 g/m^2 yr for a lake with mean depth of 3.1 m and hydraulic residence time of 0.13 years is indicated by the intersection of two segments. The TMDL implications are presented below in Section 4.5.

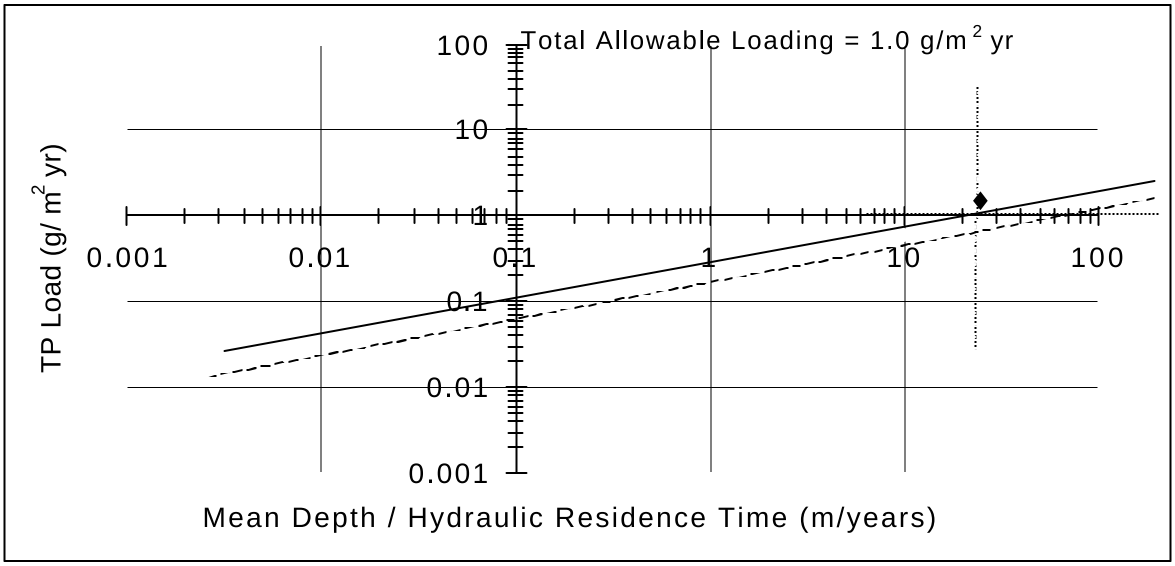

Figure 5. Vollenweider Results for Broadford Lake

4.5 Total Maximum Daily Loads

This TMDL considers seasonal variations by estimating loading rates over the entire year. This captures the dry weather loading rates, which generally occur during the warmer months when algae production is most prevalent. It also captures the wet-weather loading rates, which contribute significant sediment-bound sources of phosphorus. The Vollenweider Relationship specifically uses long-term loading estimates to avoid adopting a single transient loading pulse, which would yield erroneous results. The critical conditions are accounted for implicitly in the empirical Vollenweider Relationship. The resultant TMDL for phosphorus is based on the unit allowable loading indicated by the results of the Vollenweider Relationship. That is, the unit loading per square meter (1.0 g/m^2 year) times the total surface area of the lake (553,037 m^2) or 553,037 g/yr.

The link between DO concentration and the lake's trophic status (as defined by the Vollenweider Relationship) is indirect, but may be inferred as described below. Nutrient overenrichment causes excess algal blooms, which eventually die off and decompose, consuming DO.

The D.O. in the surface layer of Broadford Lake is currently within State Standards (see Table A-1, Appendix A). An assessment is made of the processes that determine D.O. concentration in the sub-epilimnetic portion of this lake (see Appendix A). These processes, as they apply to Broadford Lake, are outlined below. This assessment is based on critical conditions and uses conservative assumptions.

- Dissolved oxygen saturation capacity as a function of trophic status and water temperature.
- Sediment Oxygen Demand (SOD).
- Carbonaceous Biochemical Oxygen Demand (CBOD).

According to calculations presented in Appendix A, it is expected that an areal phosphorus load of 1.0 g/m^2 will result in an increase of hypolimnetic DO from the observed 0.1 mg/l to DO concentrations of about (**0.9-1.2**) mg/l. This would be consistent with consistent with Maryland's interim interpretation of the dissolved oxygen criterion as it applies to stratified lakes.

PHOSPHORUS TMDL 553,037 g*/yr* = 1,217 lb/yr

4.6 TMDL Allocation

The watershed that drains to Broadford Lake contains no permitted point source discharges. Hence, the entire allocation will be made to nonpoint sources. The model uses Chesapeake Bay Program, Phase 4 Phosphorus loading coefficients to estimate the loading rates, which represent the cumulative impact from all sources—naturally-occurring and human-induced. Details are described in the technical memorandum entitled "Significant Phosphorus Nonpoint Sources in the Broadford Lake Watershed".

4.7 Margin of Safety

A margin of safety (MOS) is required as part of a TMDL in recognition of the fact that there are many uncertainties in scientific and technical understanding of water quality in natural systems. Specifically, 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 water bodies. 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 one of 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 = WLA + LA + MOS). The second approach is to incorporate the MOS as part of the design conditions for the WLA and the LA computations.

Maryland has elected to incorporate an explicit margin of safety into this phosphorus TMDL. Following the first approach, the load allocated to the MOS was computed as 10% of the total allowable load. This value is considered reasonable in that it implies an additional 10% reduction in nonpoint source phosphorus loading beyond what would be expected to meet the goal.

4.8 Summary of Total Maximum Daily Loads

The annual TMDL **for Phosphorus (*lb/yr*):**

TMDL	=	WLA	+	LA	+	MOS

1,217	**=**	**0**	**+**	**1,095**	**+**	**122**

On average, this TMDL represents a daily phosphorus load of 3.0 lbs/day.

Where:

WLA = Point Source
LA = Nonpoint Source
MOS = Margin of Safety

5.0 ASSURANCE OF IMPLEMENTATION

Broadford Lake is located in a watershed in which the impairment is due to nonpoint source contributions. As such, the implementation provisions will need to be more rigorous and iterative. Significant phosphorus reductions are required to meet the load allocation of this TMDL. The certainty of implementation of the phosphorus reduction plan in this watershed will be enhanced by three specific programs: the Water Quality Improvement Act of 1998 (WQIA), and the EPA-sponsored Clean Water Action Plan of 1998 (CWAP).

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 these phosphorus nutrient management plans be developed and implemented by 2004. Thus, a specific milestone and benchmark, including a final expected attainment date have been established for this TMDL against which the adequacy of the initial load allocation and implementation plan can be measured. The water quality response accomplished by the date of this benchmark can be the basis for triggering appropriate load allocation revisions (either higher or lower). Additionally, as part of Maryland's Watershed Cycling Strategy, follow-up monitoring and assessments will be conducted to (1) determine the effect of the practices on water quality and related conditions, (2) determine the degree to which the selected practices are implemented, and (3) to the extent possible, determine the efficacy and impacts of the practices chosen. Based on this monitoring and assessment program, the TMDL will be evaluated as to whether additional practices must be employed in order to eliminate any remaining impairment.

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 1996 and 1998 approved by EPA. The State has given a high priority for funding assessment and restoration activities to these watersheds.

Maryland's Tributary Strategies have already established a voluntary program and an institutional framework in which to advance the goals of this TMDL. The findings of the TMDL analysis indicate that the implementation of the TMDL on the basis of external loading controls would require a 38 % reduction of external phosphorus loadings.

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Appendix A

Broadford Lake Water Quality

A study of Broadford Lake was conducted in 1993 MDE Lake Water Quality Assessment Project. A summary of the water quality data was provided in the main body of this report. Table A1 provides the underlying data from which the summaries were derived.

Assessment of the N:P Ratio for Broadford Lake

Before considering the application of the Vollenweider Relationship, it is necessary to examine the ratio of nitrogen (N) to phosphorus (P) to establish whether phosphorus is the limiting nutrient. In general, an N:P ratio in the range of 5:1 by mass is associated with plant growth being limited by neither phosphorus nor nitrogen. If the N:P ratio is greater than 10, phosphorus tends to be limiting, and if the N:P ratio is less than 5, nitrogen tends to be limiting (Chiandani, et al., 1974).

The N:P ratio was calculated using data from the two sampling events (MDE Lake Water Quality Assessment Project). The average of the two concentrations, Total Kjeldahl Nitrogen (TKN) and Total Phosphorus, of both sampling events were used to calculate the N:P ratio. The average N:P ratio is 0.45/0.036 or 12.5:1. The best available data were used to calculate the N:P ratio. TKN does not include all nitrogen; therefore, the N:P ratio as calculated is a conservative estimate of the true value of this parameter.

Table A1
Physical Water Quality Data—Broadford Lake, 1993

STATION	DATE	TIME	DEPTH (m)	WATER TEMP (°C)	pH FIELD	DO (mg/l)	COND (mg/l)
BFR0007	8/3/93	1320	0.3	23.8	7.9	8.1	68
BFR0007	8/3/93	1320	1.0	23.8	7.7	8.1	68
BFR0007	8/3/93	1320	2.0	23.1	7.4	8.1	69
BFR0007	8/3/93	1320	3.0	22.7	6.9	7.7	68
BFR0007	8/3/93	1320	4.0	21.9	6.6	5.6	96
BFR0007	8/3/93	1320	5.0	18.2	6.5	0.9	72
BFR0007	8/3/93	1320	6.0	13.5	6.8	0.2	83
BFR0007	8/3/93	1320	7.0	11.5	6.9	0.2	130
BFR0014	8/3/93	1353	0.3	23.5	7.8	8.0	68
BFR0014	8/3/93	1353	1.0	23.5	7.8	8.1	67
BFR0014	8/3/93	1353	2.0	22.4	7.5	8.1	68
BFR0014	8/3/93	1353	3.0	22.8	7.1	7.1	68
BFR0014	8/3/93	1353	3.4	22.7	7.1	7.1	67
BFR0007	9/8/93	0900	0.3	23.1	7.1	7.6	75
BFR0007	9/8/93	0900	1.0	23.1	7.0	7.5	75
BFR0007	9/8/93	0900	2.0	23.1	6.9	7.4	74
BFR0007	9/8/93	0900	3.0	22.8	6.6	6.1	74
BFR0007	9/8/93	0900	4.0	21.3	6.5	0.1	76
BFR0007	9/8/93	0900	5.0	17.6	6.7	0.1	90
BFR0007	9/8/93	0900	6.0	14.6	6.8	0.1	128
BFR0007	9/8/93	0900	6.7	12.8	6.9	0.1	157
BFR0014	9/8/93	0933	0.3	23.1	7.1	7.3	75
BFR0014	9/8/93	0933	1.0	23.1	7.1	7.3	75
BFR0014	9/8/93	0933	2.0	23.1	7.0	7.2	74
BFR0014	9/8/93	0933	3.0	23.0	6.9	6.6	74
BFR0014	9/8/93	0933	3.7	22.8	6.8	5.1	74

Table A2
Water Quality (Nutrient) Data Broadford Lake - 1993

STATION	DATE	TIME	DEPTH	TOC	TKN	TP
			(m)	(mg/l)	(mg/l)	(mg/l)
BFR0007	8/3/93	1320	0.3	-	0.26	0.042
BFR0014	8/3/93	1353	0.3	-	0.49	0.062
BFR0007	9/8/93	0900	0.3	3.41	0.82	0.021
BFR0014	9/8/93	0933	0.3	4.20	0.23	0.017

Table A3
Water Quality (Chlorophyll) Data Broadford lake - 1993

STATION	DATE	TIME	DEPTH	CHLA	PHEA
			(m)	(mg/l)	(mg/l)
BFR0007	8/3/93	1320	0.0	35.0	2.1
BFR0007	8/3/93	1320	0.3	6.6	0.6
BFR0014	8/3/93	1353	0.0	6.5	2.2
BFR0014	8/3/93	1353	0.3	9.3	0.6
BFR0007	9/8/93	0900	0.0	15.3	1.5
BFR0007	9/8/93	0900	0.3	12.6	1.2
BFR0014	9/8/93	0933	0.0	4.5	1.5
BFR0014	9/8/93	0933	0.3	4.20	0.23

Supporting Calculations for the Vollenweider Analysis

Broadford Lake Mean Depth (♣):

The mean lake depth was calculated using lake volume and surface area given in the Inventory of Maryland Dams and Hydropower Resources (DNR 1985). The cited surface area and volume of Broadford Lake are 138 acres (6,011,280 ft^2) and 1410-acre feet (61,419,600 ft^3), respectively.

Convert $feet^2$ to m^2 : 6,011,280 ft^2 x 0.92 m^2/ft^2 = 553,037 m^2

Convert acre feet to m^3 : 1410 acre feet x 1,233.5 m^3/ acre feet = 1,739,235 m^3

The mean depth of Broadford Lake is (Volume)/(Surface Area) is computed as:

1,739,235 m^3 ÷ 553,037 m^2 = **3.1 m or 10 ft**

Current Phosphorus Loading to Broadford Lake (Lp):

The total phosphorus loading from land is cited as 1771 lbs/year based on loading rates from the Chesapeake Bay Program Phase 4 Model, segment 160. The mean of the loading rates for each land use from Maryland, West Virginia, and Pennsylvania was used in the model.

Using the estimated 1971 lake surface area (553,037 m^2), this value can be converted to grams per square meter per year as follows: 805,000 g/yr ÷ 553,037 m^2 = **1.4 g/m^2 yr**.

Broadford Lake Hydraulic Residence Time (τ_w):

The hydraulic residence time is computed as volume/outflow; it is the time it would take to drain the lake.

Hydraulic residence time is calculated based on the lake volume and discharge rate. Since discharge data are unavailable, discharge was estimated by regressing watershed size versus all discharge data on record for six watersheds of varying size on the Youghiogheny Basin of Garrett County, Maryland, and adjacent Somerset County, Pennsylvania. Linear regression provided a correlation coefficient (R^2) of 0.9942 when the Y-intercept was not forced to zero, and 0.9919 when the Y-intercept was forced to zero. The high R^2 shows a very strong positive correlation between area and resulting flow for a given watershed on the Youghiogheny Basin. The insignificant change when the Y-intercept was forced to zero suggests that flow is not significantly affected by sources not proportional to direct runoff—for example, a spring-fed stream. This strengthens the case for estimating discharge of the lake as a function of watershed area. The regression line and equation are shown in Figure A-1 below. The overall Broadford Lake watershed measures 6.8 mi^2; the estimated discharge is thus 14.96 cfs (10,837 acre feet per year).

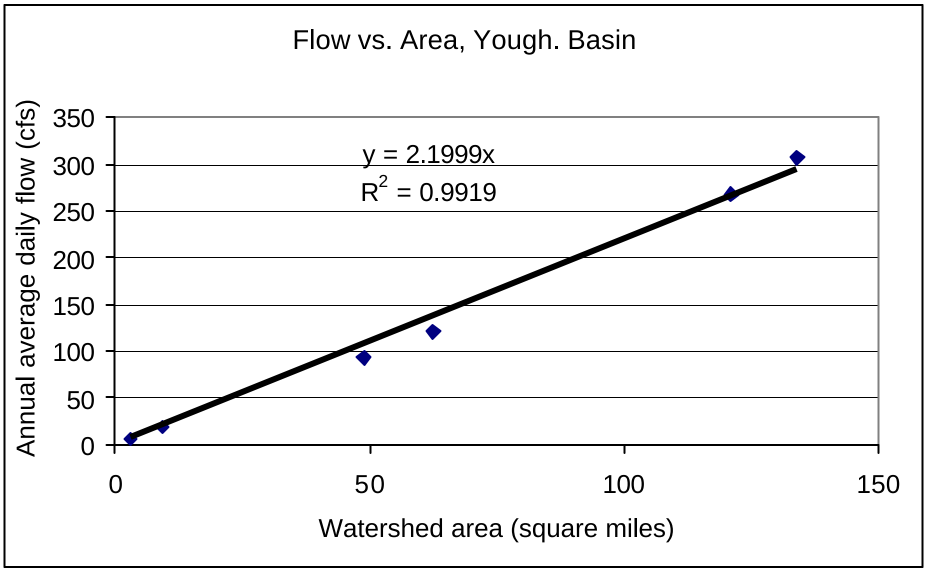

Figure A-1. Discharge as function of watershed area, Youghiogheny Basin of Maryland and Pennsylvania

Hydraulic residence time (τ_w) is calculated as follows:

(1410 acre feet) ÷ (29.7 acre feet per day) = 47.5 days.

47.5 days ÷ 365 days/yr = **0.13 yr**

<u>Ratio of Mean Depth to Hydraulic Residence Time (♣/τ_w)</u>

From the computations above the mean depth of Broadford Lake (♣) is 3.1 m, and the hydraulic residence time (τ_w) is 0.13 yr. The ratio was computed as:

3.1 m / 0.13 yr = **23.84 m/yr**

<u>Graphing of Trophic Status of Broadford Lake using the Vollenweider Relationship</u>

The intersection of the phosphorus loading rate (L_p) = 1.4 g/m^2yr and the ratio (♣/τ_w) = 23.8 m/yr was plotted on log log paper to establish the trophic status of Broadford Lake (See Figure 5).

Supporting Calculations for the TMDL Analysis

Graphing of Maximum Allowable Unit Phosphorus loading of Broadford Lake using the Vollenweider Relationship

Figure 5 (p.11) shows how the maximum allowable unit phosphorus loading can be read off of the log log paper. Point A represents the maximum allowable load, which includes the load allocation and the margin of safety (1.0 g/m^2 yr).

Computing the Phosphorus TMDL

The TMDL is computed from the maximum unit load read from Point A on Figure 5:

(Unit loading) x (Lake Surface Area) = Annual Loading
(1.0 g/m^2 yr) x (553,037 m^2) = 553,037 ***g/yr***

Converted to pounds per year:
(553,037 g/yr) x (0.0022 lb/g) = **1217 lbs/yr**

Computing the Phosphorus Margin of Safety

The Margin of Safety is computed as 10% of the total allowable unit loading:

0.10 x (Total allowable loading) = Annual Loading
(0.10) x (553,037) = 55,304 ***g/yr***

Converted to pounds per year:
55,304 g/*yr* x (0.0022 lb/g) **= 122 lb/yr**

Computing the Percentage Phosphorus Reduction

The necessary reduction in phosphorus loads, as a percentage of the current estimated load was computed as follows:

$$\frac{\text{(current load)} - \text{(allowable load*)}}{\text{(current load)}} =$$

$$\frac{(805{,}000\ \text{g/yr}) - (497{,}733\ \text{g/yr})}{(805{,}000\ \text{g/yr})} = 38\%\ \text{reduction}$$

* The allowable load does not include the margin of safety.

Supporting Determination of the Expected Minimum DO Below Epilimnion

As noted in the main body of this document, DO concentration in the surface waters currently meets State standards. The following analysis provides a linkage between the maximum allowable phosphorus load, as specified by the Vollenweider Relationship, and the assurance of meeting DO criteria in the lake's sub-epilimnetic waters.

During periods of thermal stratification in a lake, DO concentration below the epilimnion is largely determined by the relationship between trophic status and the saturation potential of oxygen. Because DO concentration is a function of temperature, the minimum allowable DO concentration cannot be specified *per se*, but can be determined graphically by reading the expected DO concentration at a specified percent saturation from a published nomogram.

Chapra (1997) presents ranges of hypolimnetic DO saturation as a function of trophic status in eutrophic, mesotrophic and oligotrophic lakes (Table A-4). MDE (1999) has adapted and extended this methodology to apply to the two additional trophic categories—oligo-mesotrophic and meso-eutrophic—used to classify Maryland's lakes (Table A-5).

Table A-4

Relationship between Lake Trophic Status and Dissolved Oxygen Saturation in the Hypolimnion of a Thermally Stratified Lake

Trophic Status	Hypolimnetic Dissolved Oxygen Saturation
Eutrophic	0% - 10%
Mesotrophic	10% - 80%
Oligotrophic	80% - 100%

Adapted from Chapra (1997)

Table A-5

Extended Relationship between Lake Trophic Status and Dissolved Oxygen Saturation in the Sub-Epilimnetic Waters of a Thermally Stratified Lake

Trophic Status	Minimum Hypolimnetic Dissolved Oxygen Saturation
Eutrophic	0%
Meso-eutrophic	10%
Mesotrophic	33%
Oligo-mesotrophic	56%
Oligotrophic	80%

MDE is establishing a phosphorus TMDL to manage the Broadford Lake at a meso-eutrophic status. Current phosphorus loading estimates place Broadford Lake slightly in the eutrophic status category. As phosphorus reductions result in a shift to a meso-eutrophic status, it is predicted that the DO saturation will increase to 10% in the waters below the epilimnion, as indicated in Table A-5. This increased saturation is consistent with interim interpretation of Maryland's water quality criterion for dissolved oxygen in thermally stratified lakes (MDE, 1999).

Because DO concentration is a function of water temperature, a single expected DO concentration cannot be predicted. However, the nomogram in Figure A-2 may be used to determine a range of dissolved oxygen concentrations expected to result as phosphorus loads are reduced. This is demonstrated below using temperatures observed in the deeper waters of Broadford Lake during critical summertime conditions.

Specifically, two line segments have been drawn from the ends of the observed range of temperatures (11 – 21 °C), through the point at 10% on the diagonal scale for DO saturation. These two line segments intersect the lower horizontal scale indicating an expected DO concentration ranging from 0.9 – 1.2 mg/l. This range reflects an increase over the current minimum observed DO concentration of 0.1 mg/l, and reflects the DO endpoint expected to result from the TMDL. This increased sub-epilimnetic DO concentration is consistent with the interim interpretation of Maryland's water quality criterion for dissolved oxygen in thermally stratified lakes (MDE, 1999).

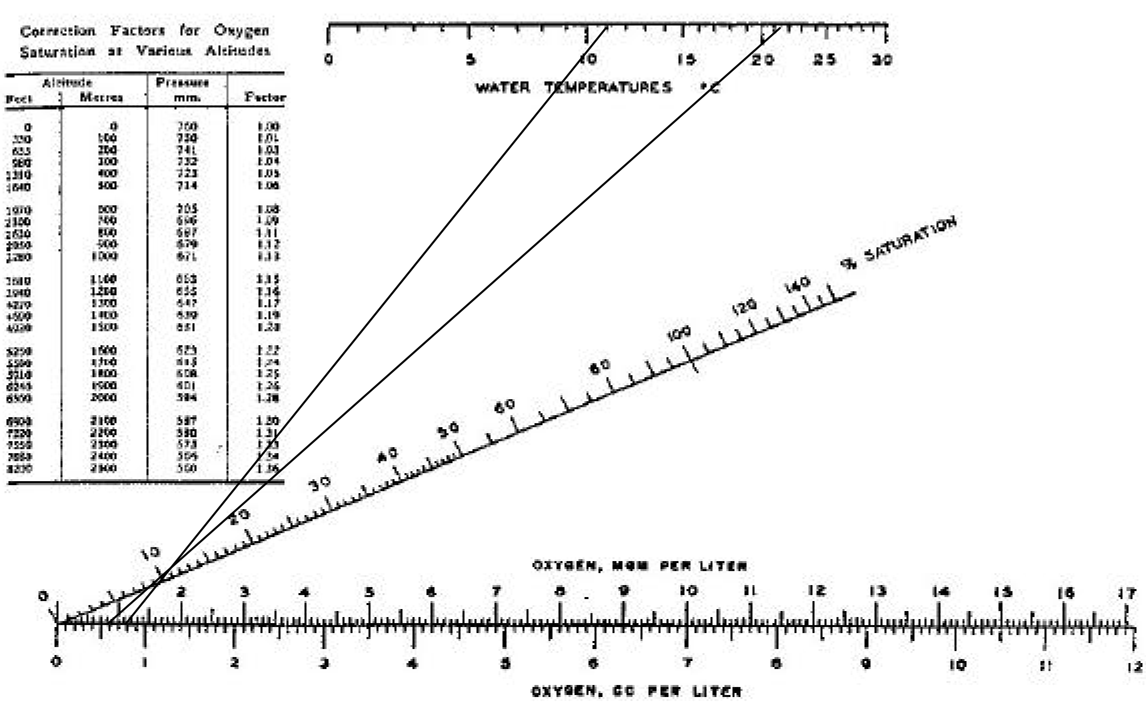

Figure A-2. Nomogram (adapted from Reid 1961) showing expected sub-epilimnetic DO concentrations at ambient temperatures in Broadford Lake during periods of stratification.