Total Maximum Daily Loads of Phosphorus and Sediment to Big Millpond, Worcester County, MD

FINAL

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FINAL

EXECUTIVE SUMMARY

On the basis of water quality problems associated with nutrients, Big Millpond, in the Chincoteague Bay watershed (02-13-01-06), was identified on Maryland's 1998 list of WQLSs as being impaired. Subsequent analysis associated with the nutrient TMDL evaluation revealed an excessive sedimentation problem. This document proposes to establish Total Maximum Daily Loads (TMDLs) for the nutrient phosphorus and sediments entering Big Millpond.

Big Millpond is an impoundment located near Welbourne in Worcester County, Maryland. The impoundment lies on Swans Gut Creek, draining to Chincoteague Bay. Swans Gut Creek lies in the Chincoteague Bay Drainage Basin, in the Lower Eastern Shore of Maryland. Big Millpond is an artificial impoundment owned by Worcester County. Its main purpose is for recreation.

Big Millpond is impacted by a high sediment load, resulting in excessive sedimentation of the reservoir and loss of reservoir volume. This threatens the ability of the water body to maintain and support fishing, and propagation of fish and other aquatic life. The reservoir also experiences occasional nuisance algal blooms, due to over enrichment by nutrients, which interfere with recreational uses. The death and decay of excessive algae can cause violations of the water quality standard for dissolved oxygen (DO), causing 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 Big Millpond. Due to the propensity of phosphorus to bind to sediments, the overall strategy is to simultaneously address the water quality problems associated with phosphorus and sediments

The water quality goals of these TMDLs are to reduce long-term phosphorus and sediment loads to an acceptable level consistent with the physical characteristics of Big Millpond. The reduced loading rate of phosphorus is predicted to resolve excess algae problems and maintain a dissolved oxygen concentration above the State's water quality standard. The TMDL for phosphorus was determined using empirical methods known as the Vollenweider Relationship. Because the reduction of sediments is a component of controlling external phosphorus loads, a sediment loading rate consistent with narrative water quality criteria is predicted to be achieved.

The average annual TMDL for phosphorus is about 880 lb/yr. There are no point sources in the Big Millpond basin. Consequently, the allocation is partitioned between nonpoint sources and the margin of safety. For sediments, the TMDL is established to achieve a reasonable loading rate predicted to occur as a result of the proposed control of phosphorus. This loading rate is estimated to result in preserving about 58% of the reservoir's design volume over a period of 101 years.

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 69% 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 each impaired water on its 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 Big Millpond for nutrients. The 1998 listing was prompted by an assessment of data associated with Big Millpond (Maryland Department of Natural Resources [DNR], 1998).

The water quality problems of Big Millpond include over enrichment of nutrients that result in excessive algal blooms. In addition, excessive sedimentation has resulted in loss of the pond's capacity.

2.0 SETTING AND WATER QUALITY DESCRIPTION

2.1 General Setting and Source Assessment

Big Millpond is an impoundment located in the Chincoteague watershed (02-13-01-06) near Welbourne in Worcester County, Maryland (Figure 1). The impoundment, which is owned by Worcester County, lies on Swans Gut Creek. Big Millpond was created for recreational uses in 1900.

Big Millpond lies in the Atlantic Coastal Plain physiographic province. The soils immediately surrounding the lake are the Fallsington-Woodstown-Sassafras association (Soil Conservation Service, 1973). These soils generally range from level to steep, poorly drained to well-drained soils that have subsoil dominantly of sandy clay loam. The outer watershed area is comprised of soils of the Mattapex-Matapeake-Othello association. These soils are typically level to steep, well drained to poorly drained soils that have subsoil dominantly of silty clay loam. A portion of the outer watershed contains soils of the Othello-Fallsington-Portsmouth association. These are level and nearly level, poorly drained and very poorly drained soils that have subsoil dominantly of sandy clay loam or silty clay loam (Soil Conservation Service, 1970). Several relevant statistics for Big Millpond are provided below in Table 1. Since a large volume of the lake has been lost to sedimentation, the TMDLs are developed under the assumption that the lake will be dredged to restore its approximate 1900 physical dimensions.

Inflow to the pond is primarily via three major tributaries, Little Mill Run, Marshall Ditch and Payne Ditch. The watershed map (Figure 1) shows that land use in the watershed draining to Big Millpond is predominantly forested. Land use distribution in the watershed is approximately 63% forested, 36% agricultural, and 1% wetland (Figure 3) (Maryland Department of Planning, 1997 Land use).

The load reduction assessment uses Chesapeake Bay Program data to estimate the nonpoint source loading rates of phosphorus, representing 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. Sediment reductions are estimated directly; however, sediment reductions are estimated as a function of proposed phosphorus reductions.

Table 1

Physical Characteristics of Big Millpond

Location:	Worcester County, MD Lat. 38° 00’ 56” long. 75° 27’ 22”
Surface Area:	60.2 acres (1900); 26.6 acres (current)
Owner:	Worcester County
Average Lake Depth:	3 feet (1900); 2.4 feet (current)
Maximum Depth	7.17 feet (1900)
Basin code:	02-13-01-06
Volume of Lake:	180.6 acre-feet (1900); 63.84 acre-feet (current)
Average Discharge:	8.94 cfs
Drainage Area to Lake:	8.2 mi^2
Purpose:	Recreation

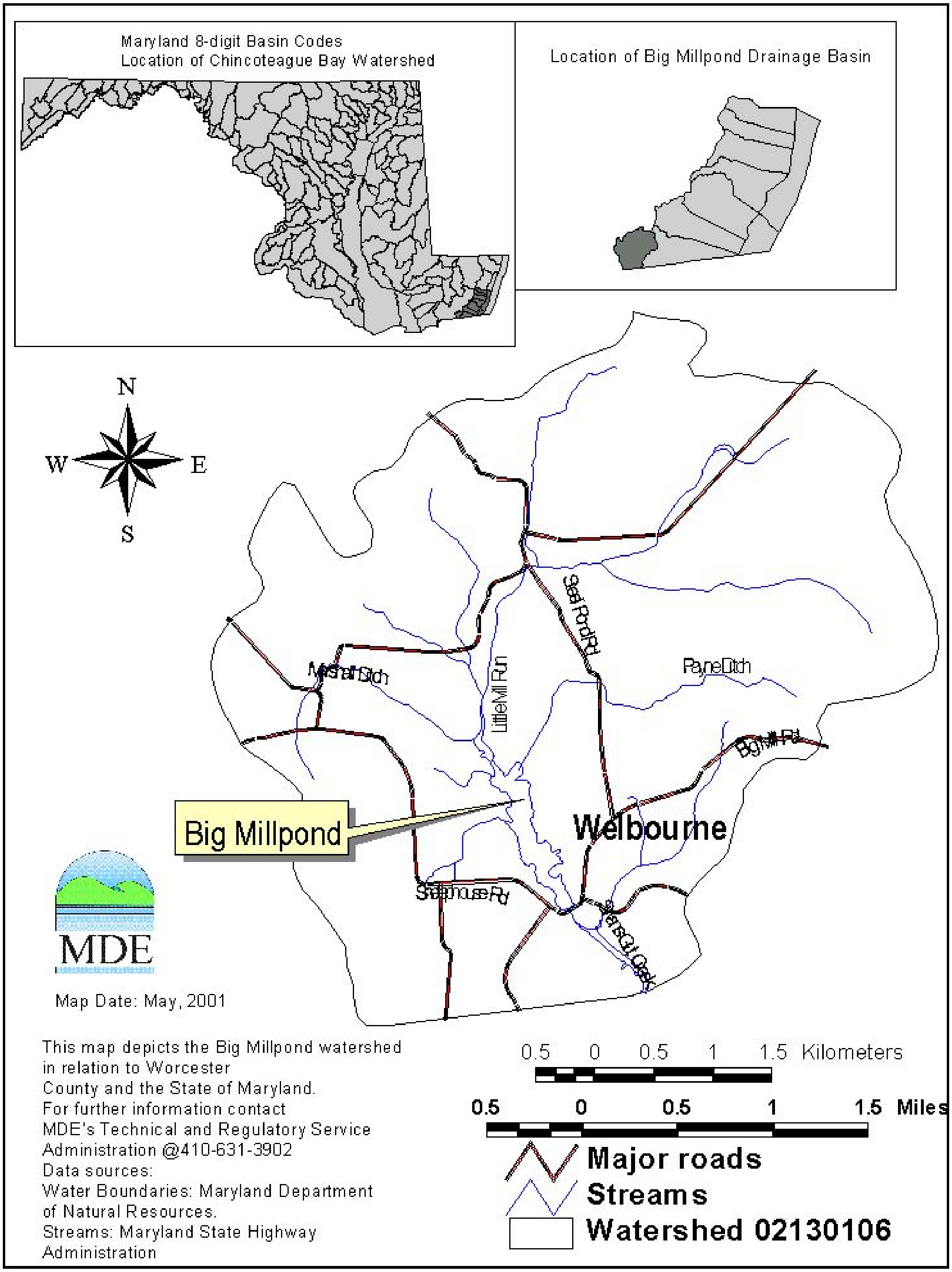
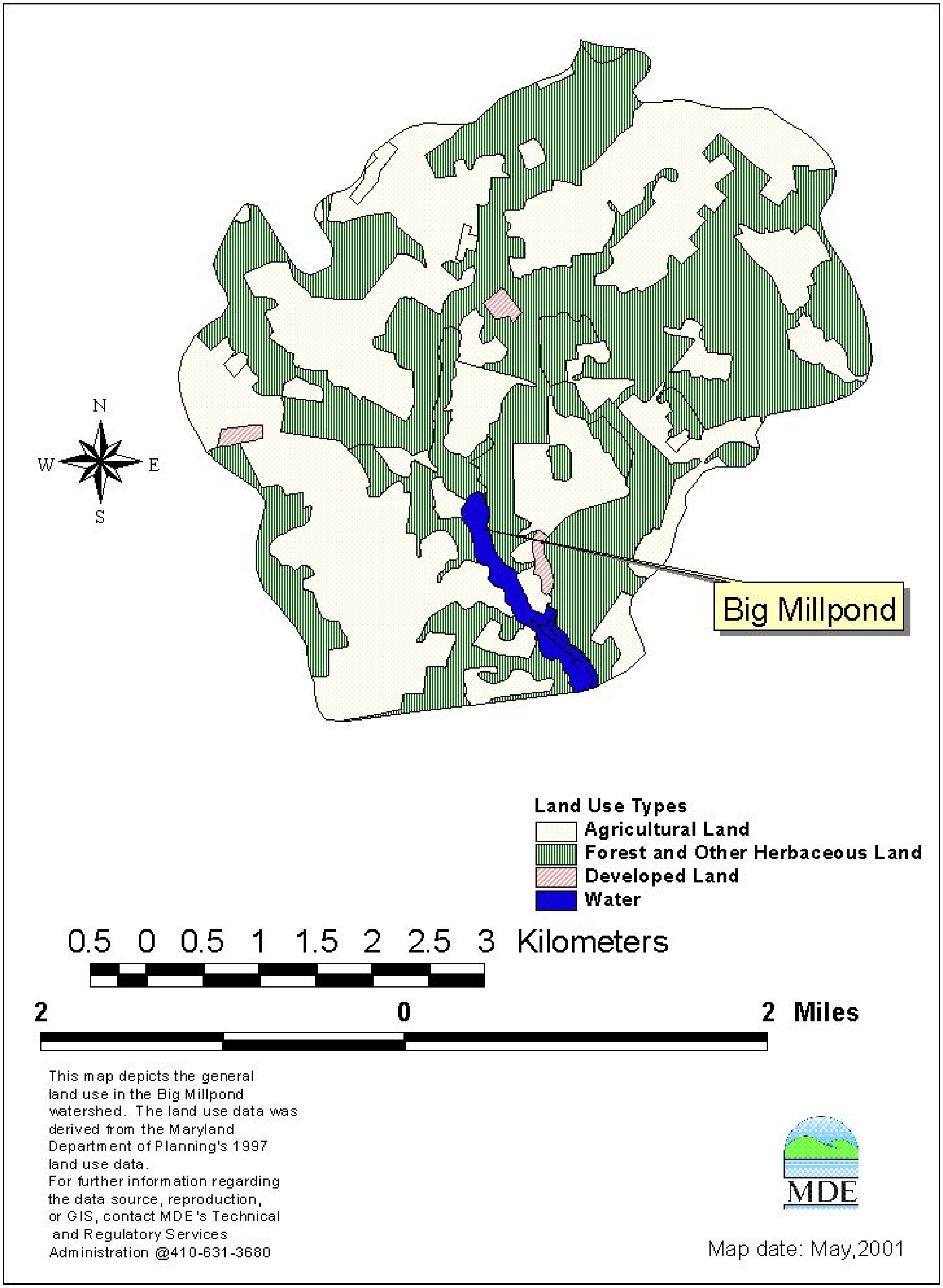


Figure 1. Location Map of Big Millpond in Worcester County, Maryland



This map depicts the general land use in the Big Millpond watershed. The land use data was derived from the Maryland Department of Planning's 1997 land use data.
For further information regarding the data source, reproduction, or GIS, contact MDE's Technical and Regulatory Services Administration @410-631-3680

Map date: May,2001

Figure 2. Land Use in the Big Millpond Watershed

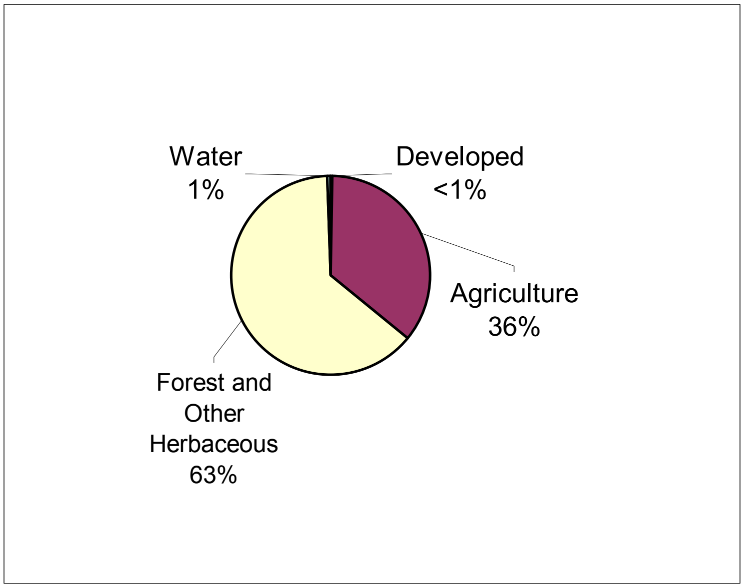


Figure 3. Land Use in the Big Millpond Watershed

2.2 Water Quality Characterization

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

Big Millpond was monitored in June and August of 1993 (MDE, 1995) as well as October, November, and December 2000 and January of 2001 (MDE, 2001). Water quality samples were collected near the surface once in each month from three stations. Water samples were collected from the surface of the water column. The Maryland Department of Health and Mental Hygiene analyzed samples for total phosphorus, soluble orthophosphorus, total Kjeldahl nitrogen, total organic solvents and chlorophyll *a*. Physical measurements of depths, water temperatures, P^H, conductivity and dissolved oxygen were recorded in the field. A summary from the MDE Lake Water Quality Assessment Project follows. Detailed water quality data are presented in Appendix A.

A chlorophyll *a* concentration of 10 µg/l is typically associated with the boundary between eutrophic and mesotrophic states of a lake (Chapra, 1997). Chlorophyll *a* concentrations ranging from 1.0 to 35.0 µg/l have been observed in Big Millpond (Maryland Lake Water Assessment Report, 1995). The maximum observed values in Big Millpond, though associated with eutrophic conditions, are not extreme when compared to peak concentration of 275 µg/l in hyper-eutrophic lakes (Olem and Flock 1990).

Dissolved oxygen (DO) concentrations ranged from 0.9 to 6.3 mg/l along the vertical profile. Total phosphorus concentrations ranging from 0.09 mg/l to 0.1 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 Kjeldahl nitrogen ranged from 0.82 to 1.1 mg/l in Big Millpond. High concentrations occurred during the December sampling event above the tropholytic zone. Water temperatures taken during the sampling period ranged from 22°C to 26.7°C in the surface water depth (0.3-1 meter column).

2.3 Water Quality Impairment

The water quality impairments of Big Millpond addressed by these TMDLs consist of violations of the applicable numeric dissolved oxygen (DO) criterion and general narrative water quality criteria.

Big Millpond, an impoundment on Swans Gut Creek near Welbourne, has been designated a Use I water body, pursuant to which it is protected for water contact recreation, fishing, aquatic life and wildlife. See COMAR 26.08.02.07. Use I waters are subject to a DO criterion of not less than 5.0 mg/l at any time (COMAR 26.08.02.03-3A(2)) unless natural conditions result in lower levels of dissolved oxygen (COMAR 26.08.02.03A(2)). The dissolved oxygen concentration in Big Millpond occasionally falls below the standard of 5.0 mg/l.

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. See COMAR 26.08.02.03B(2). Excessive eutrophication, indicated by elevated levels of chlorophyll *a*, can produce nuisance levels of algae and interfere with designated uses such as fishing and swimming. Violations of the dissolved oxygen and general water quality standards in Big Millpond are the result of over-enrichment by the nutrient phosphorus. Finally, in conjunction with excessive nutrients, Big Millpond has experienced excessive sediment loads. In addition to carrying nutrients, the excessive sediment loads are filling the pond at a high rate. Since 1900, sediment has reduced the pond's volume from 180.6 acre-ft to 63.84 acre-ft. Continued excessive infilling threatens the ability of the water body to maintain and support fishing, and propagation of fish and other aquatic life.

3.0 TARGETED WATER QUALITY GOALS

Big Millpond is classified as Use I—*Water Contact Recreation, and Protection of Aquatic Life*. The chlorophyll *a* endpoint selected for Big Millpond—20 µg /l, or approximately 60 on the Carlson's Tropic State Index (TSI)—is in the lower range of eutrophy, which is an appropriate trophic state at which to manage this impoundment.

Other states have adjusted their trophic-state expectation for lakes or impoundments with differing uses. Minnesota, for example, uses an ecoregion-based approach. Heiskary (2000) reports that individuals utilizing lakes for recreational purposes (water contact, fishing) demanded relatively clear, less enriched lakes in the Northern Lakes and Forest (NLF) and North Central Hardwood Forest (NCHF) ecoregions. In the Western Corn Belt Plains (WCBP) and Northern Glaciated Plains (NGP) ecoregions, however, users accepted relatively greater enrichment and less clarity. Under Minnesota's classification system, lakes in the NLF and NCHF ecoregions are considered to fully meet use support with TSIs of about 53 and 57, respectively. Lakes in the other two ecoregions, both of which are largely agricultural, are considered to fully support use with TSIs of about 60 (Heiskary 2000).

Big Millpond lies in the Mid-Atlantic Coastal Plain (MACP) ecoregion, which extends from central New Jersey to northern Georgia. Topography is low and flat, soils are sandy, the dominant land use is agricultural, and there are few natural lakes (none in Maryland). Impoundments tend to be shallow with large watershed/surface area ratios, resulting in a relatively high degree of allochthonous nutrient loading. This type of morphometry favors eutrophy. The MACP ecoregion is topographically and functionally similar to the two agricultural ecoregions Heiskary describes in Minnesota.

Big Millpond is used as a recreational warm-water fishery. Moderate degrees of eutrophication are compatible with sustenance and enhancement of such warm water fisheries. An appropriate management goal, therefore, is to enhance or maintain support of this fishery. An endpoint, seeking to maintain the productive fishery while avoiding nuisance algal blooms, is a maximum permissible chlorophyll *a* level of 20 µg/l. This corresponds approximately to a Carlson's TSI of 60.

The overall objectives of the TMDLs established in this document are to reduce phosphorus and sediment loads to levels that are expected to result in meeting associated water quality criteria that support the Use I designation. Specifically, one goal is to improve the trophic status of Big Millpond by reducing the total phosphorus loads. This is predicted, in turn, to reduce excessive plant and algae growth, which will lead to reductions in violations of the numeric DO criteria, and the violation of various narrative criteria associated with nuisances cited above (odors and physical impedance of direct contact use).

Since phosphorus binds to sediments, sedimentation rates will be reduced as a component of reducing phosphorus loads. It is expected that this reduction will be sufficient to prevent violations of narrative criteria.

In summary, the TMDLs for phosphorus and sediment are intended to:

1. Assure that a minimum dissolved oxygen concentration of 5.4 mg/l is maintained in Big Millpond;
2. Resolve violations of narrative criteria associated with excess phosphorus enrichment of Big Millpond; and
3. Resolve violations of narrative criteria associated with excess sedimentation of Big Millpond by reducing sedimentation to a reasonable rate.

4.0 TOTAL MAXIMUM DAILY LOAD AND ALLOCATIONS

4.1 Overview

This section describes how the nutrient and sediment TMDLs and loading allocations were developed for Big Millpond. The second subsection describes the analysis for determining that phosphorus is likely to be the limiting nutrient in Big Millpond, 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 TMDLs and allocations to nonpoint sources and the margin of safety.

4.2 Analytical Framework

Big Millpond suffers from excessive nutrient enrichment and sedimentation. The TMDL for phosphorus is based on widely accepted empirical methods known as the Vollenweider Relationship and Carlson's Trophic State Index. The Vollenweider Relationship predicts the degree of a lake's eutrophication as a function of the aerial 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 ($\overline{Z}$) to hydraulic residence time (τ_w) (Figure 4). This method is advantageous for a number of reasons: It is based on real 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.

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A frequently used biomass-related trophic state index is that developed by Carlson (1977). Carlson's trophic status index (TSI) uses Secchi depth (SD), chlorophyll a (Chl), and total phosphorus (TP), with each producing an independent measure of trophic state. Index values range from 0 (ultraoligotrophic) to 100 (hypereutrophic). The index is scaled so that TSI=0 represents a Secchi transparency of 64 meters (m). Each halving of transparency represents an increase of 10 TSI units. For example, a TSI of 50 represents a transparency of 2 m, the approximate division between oligotrophic and eutrophic lakes. A TSI can be calculated from Secchi depth, Chlorophyll-*a* concentration and phosphorus concentration as stated below (Carlson, 1977: Carlson and Simpson, 1996):

$$\text{TSI (Chl)} = 30.6 + 9.81 \ln(\text{Chl})$$
$$\text{TSI (TP)} = 4.15 + 14.42 \ln(\text{TP})$$
$$\text{TSI (SD)} = 60 - 14.41 \ln(\text{SD})$$

Trophic state indices can be used to infer trophic state of a lake and whether algal growth is nutrient or light limited. The following classification can be used to interpret the TSI (Moore and Thornton, 1988):

$\text{TSI} < 35$	most oligotrophic lakes
$35 < \text{TSI} < 55$	mesotrophic lakes
$\text{TSI} > 55$	eutrophic lakes
$\text{TSI} > 70$	hypertrophic 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 and Carlson's trophic status index constitute sufficient, readily available tools.

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, phosphorus tends to be limiting, and if the N:P ratio is less than 5, nitrogen tends to be limiting (Chiandani et al., 1974). An N: P ratio of well over 10 was computed, which supports the use of the Vollenweider Relationship. Supporting data are provided in Appendix A.

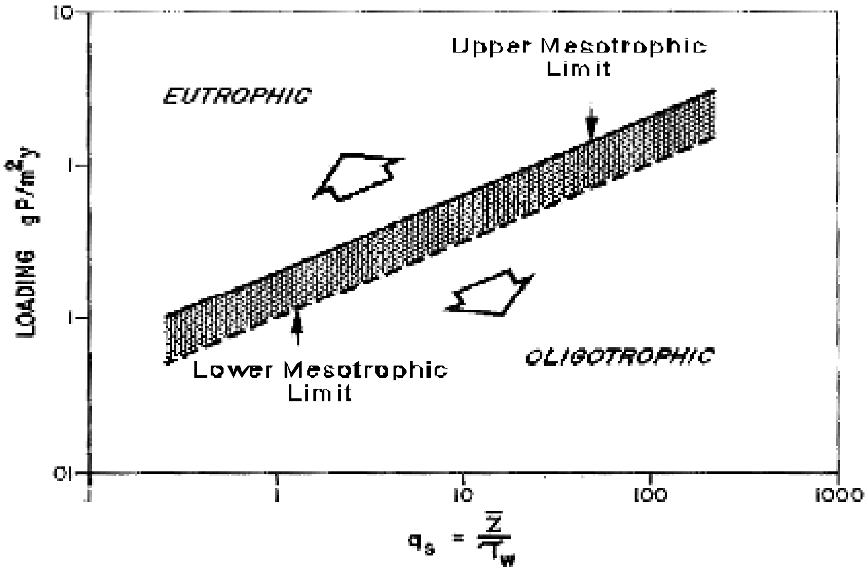

Figure 4. Vollenweider Relationship

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 ($\overline{Z}$) 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 ($\overline{Z}$); 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.

Big Millpond Mean Depth ($\overline{Z}$):

For the present case Vollenweider relationship was applied under an assumption of the lake's physical dimensions when the lake and dam were constructed in 1900. 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 Big Millpond are 60.2 acres and 180.6 acre feet respectively.

The mean depth was thus calculated as follows:

- ***Big Millpond Mean Depth ($\overline{Z}$): (Volume)/(Surface Area) = 0 .9 m or 3 ft***

Phosphorus Loading to Big Millpond (Lp):

The current estimated total phosphorus loading is 2,522 lbs/year (or 1,143,956 g/year) based on loading coefficients from the Chesapeake Bay Program, segment 430, Phase 4.3 Watershed Model. Expressing this value as a loading per surface area of the lake gives:

- ***Annual Phosphorus Load (L_p) is: 4.7g/m^2 yr***. Details are provided in Appendix A.

Big Millpond Hydraulic Residence Time (τ_w)

Residence time (τ_w) is computed by dividing the lake volume by annual discharge. For Big Millpond, average discharge data are unavailable. Since discharge data are unavailable, this parameter was estimated by examining a number of watersheds of various sizes in the Chester, Choptank, Nanticoke, and Pocomoke basins. These basins have long-term flow data 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 Big Millpond is estimated as follows (details are shown in Appendix A):

- **Flow (Q) = watershed area (8.2 mi^2) x 1.177-0.7126 = 8.94 cfs = 6,472 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 180.6 acre feet (DNR, 1985), from above, and a discharge rate of 6,472 acre per year (DNR, 1985) the hydraulic residence time is calculated as follows:

- **180.6 acre feet ÷ 6,472 acre feet/year = 0.028** years;

- ***Big Millpond Hydraulic Residence Time (τ_w): 0.028 years = 10.18 days.***

The mean depth of the lake (0.9m) is then divided by hydraulic residence time (0.028 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 Big Millpond, **q_s = 32.7 m/yr**.

4.4 Vollenweider Relationship Results

Figure 5 presents a Vollenweider plot of the loadings. The plot is shown on a log-log scale. Previously it was shown (Figure 4) that the Vollenweider relationship establishes a linear relationship between the log of the phosphorus loading and the log of the ratio of the lake's mean depth to hydraulic residence time. The relationship is shown graphically in Figure 4 as the upper solid line representing the upper mesotrophic limit and the lower dotted line representing the lower mesotrophic limit. Similarly, in Figure 5 the upper and lower mesotrophic limits are also shown with an upper solid line and a lower dotted line, respectively. The current trophic status associated with a loading of 4.7 g/m^2-yr falls into the eutrophic range, as indicated on Figure 5 by a diamond "◆". The maximum allowable unit loading of 1.64 g/ m^2-yr for a lake with a mean depth of 0.91 m and hydraulic residence time of 0.028 year is indicated by a circle "●". This loading corresponds to an estimated chlorophyll *a* level of 20 μg/l associated with a TSI of 60. The TMDL implications are presented in Section 4.5.

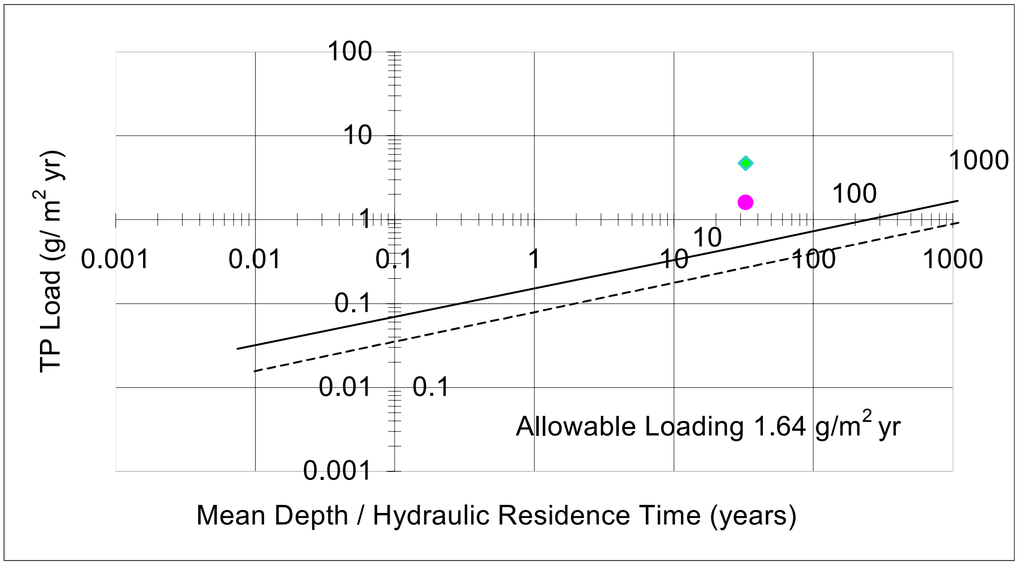

Figure 5. Vollenweider Results for Big Millpond

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 current TSI of 80 corresponds to a chlorophyll *a* concentration of 150 μg/l and a loading rate of 2,522lbs/yr. The TMDL water quality endpoint, which will maintain the warm water fishery and avoid nuisance algal blooms, is a maximum TSI of 60, which is associated with the lower range of eutrophic conditions. A TSI of 60 results in a chlorophyll concentration of 20 μg/l and a loading rate of 880 lbs/yr.

The link between DO concentrations and the lake's trophic status (as defined by the Vollenweider Relationship) is indirect, but may be inferred as described below. Nutrient over-enrichment causes excess algal blooms, which eventually die off and decompose, consuming DO. Several computations are provided to account for the key processes that determine DO concentration in the well-mixed surface layer of a lake (see Appendix A). These processes are outlined below:

- Dissolved oxygen saturation capacity as a function of water temperature.
- The diurnal variation in DO resulting from the shift between daytime photosynthetic activity and nighttime respiration of algae. This is calculated as a function of the concentration of active chlorophyll *a*, which is inputted from the lake's targeted slightly eutrophic status (defined by the Vollenweider Relationship) to range from 10 to 20 μg/l (Chapra, 1997).
- Sediment Oxygen Demand (SOD);
- Carbonaceous Biochemical Oxygen Demand (CBOD);
- Water reaeration.

According to calculations presented in Appendix A, it is expected that an areal phosphorus load of 1.64 g/m^2 will result in a minimum surface DO concentration of about 5.40 mg/l.

No single critical period can be defined for the water quality impact of sedimentation. An excessive sedimentation rate negatively impacts a lake regardless of when it occurs. The maximum sediment loading rate occurs during wet-weather events. 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 (Ag. BMPs) that affect both phosphorus and sediments, EPA estimates a 1-to-1 reduction in sediments as a result of controlling phosphorus (EPA, CBPO 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 reductions 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 69% NPS phosphorus reduction is about 34.5% (0.69 * 0.5 = 0.345). 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 58% of the impoundment's volume after 101 years. MDE believes that this volumetric retention will support the designated use of Big Millpond (See Appendix A for further details concerning this estimate).

PHOSPHORUS TMDL 399,297 g/*yr* = 880 lbs/yr

SEDIMENT TMDL 931.9 m^3/yr

4.6 TMDL Allocations

The watershed that drains to Big Millpond contains no permitted point source discharges. Hence, in addition to an expected margin of safety, the allocation will be made to nonpoint sources. The Chesapeake Bay Program, Phase 4.3 watershed model loading coefficients were used to estimate the loading rates. These represent the cumulative impact from all sources—naturally-occurring and human-induced. Load contributions from different land uses are described in the technical memorandum entitled "*Significant Phosphorus Nonpoint Sources in the Big Millpond 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 two approaches (EPA, April 1991). One approach is to reserve a portion of the loading capacity as an explicit term in the TMDL (*i.e.*, TMDL = WLA + LA + MOS). The second approach is to incorporate an implicit MOS in the form of conservative assumptions in the TMDL analysis.

Maryland has adopted an explicit margin of safety for phosphorus. Following the first approach, the load allocated to the MOS was computed as 10% of the total allowable load. Maryland has also incorporated conservative assumptions that effectively constitute an additional, implicit, margin of safety. In calculating minimum DO levels, MDE assumes a water temperature of 30^{o} C; the highest temperature observed during monitoring was 27.1^{o} C.

In establishing a margin of safety for sediments, Maryland has adopted an implicit approach by incorporating conservative assumptions. 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 (792 lbs./yr), rather than the entire phosphorus TMDL including the MOS. Thus, the explicit 10% MOS for phosphorus will result in an implicit MOS for sediments. This conservative assumption results in a difference of about 232 m^3/yr (see Section 4.5 above for a discussion of the relationship between reductions in phosphorus and sediments).

4.8 Summary of Total Maximum Daily Loads

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

TMDL	=	WLA	+	LA	+	MOS
880	=	0	+	792	+	88

On average, this TMDL represents a daily phosphorus load of 2.4 lbs/day.
Where:

WLA = Waste Load Allocation (Point Source)
LA = Load Allocation (Nonpoint Source)
MOS = Margin of Safety

The annual TMDL for **Sediments (*m^3/yr*):**

TMDL	=	WLA	+	LA	+	MOS
932	=	0	+	932	+	Implicit

On average, this TMDL represents a daily sediment load of 2.6 m^3/day.

5.0 ASSURANCE OF IMPLEMENTATION

Big Millpond 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. Two specific programs will enhance the certainty of implementation of the phosphorus reduction plan in this watershed: the Water Quality Improvement Act of 1998 (WQIA); the Maryland Tributary Strategies for implementing Chesapeake Bay Agreement and watershed Restoration Action Strategies (WRASs) associated with the EPA-sponsored Clean Water Action Plan of 1998 (CWAP).

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 (Ag. BMPs) that affect both phosphorus and sediments, EPA estimates a 1-to-1 reduction in sediments as a result of controlling phosphorus (EPA, CBPO 1998). However, this ratio does not account for phosphorus controls that do not remove sediments.

Maryland's Water Quality Improvement Act of 1998 requires that comprehensive and enforceable nutrient management plans be developed, approved and implemented for all agricultural lands throughout Maryland. This act specifically requires that nitrogen management plans be developed and implemented by 2004, and plans for phosphorus be implemented by 2005. 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 69 % reduction of external phosphorus loadings. This challenging goal can be put into perspective in two regards. First, the percentage of nutrient reduction associated with standard agricultural best management practices (BMPs) is greatest for easily erodible soils present in the Big Millpond drainage basin. Second, if this goal is an overestimation of the necessary load reductions, it can be refined using better data and analysis tools, while initial steps are taken to reduce the loads

Table 2
Phosphorus Removal Efficiencies of Various Agricultural BMPs

Best Management Practice	Estimated Range of Phosphorus Removal
Soil Conservation & Water Quality Plan (SCWQP)	11% - 35%
Treatment of Highly Erodible Land[1]	3 x the result of SCWQP on typical soil
Conservation Tillage	13% - 50%
Nutrient Management Plans	9% - 30%

Source: "Technical Appendix for Maryland's Tributary Strategy" (Maryland, 1995)

Notes:
[1] The soils in the Big Millpond watershed are considered easily erodible (DNR, Oct. 1996).

The sedimentation reduction goal is reasonable and implementable. A number of best management practices—both structural and non-structural—can significantly reduce sediment loads. For instance, maintained vegetated buffer strips along stream channels have been shown to capture a significant amount of sediment and dissipate the energy of the surface runoff during storm events. The vegetation also helps to reduce stream bank erosion. Recent estimates of the trap efficiency of buffer strips range from 70% to 90% (Qui and Prato, 1998).

REFERENCES

Ambrose, R. B., T. A. Wool, J. P. Connolly, and R. W. Schanz. WASP4, a hydrodynamic and water quality model: Model theory, user's manual, and programmer's guide. Environmental Research Laboratory, Office of Research and Development, EPA 600/3-87/039, Athens, GA, 1988.

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

Chapra, Steven C. Surface Water Quality Modeling. McGraw – Hill, 1997.

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

Maryland State, "Technical Appendix for Maryland's Tributary Strategies," National Atmospheric Deposition Program (IR-7) National Trends Network. (1989) NAPD/NTN Coordination Office, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO., March 12, 1996.

Maryland Department of the Environment, Maryland Lake Water Quality Assessment, 1993 Final Report, 1995.

Maryland Department of the Environment, Total Maximum Daily Loads of Phosphorus and Sediments to Urieville Community Lake, Kent County, MD, 1999.

Maryland Department of the Environment, "Water Quality Modeling of the St. Martin River, Assawoman and Isle of Wight Bays", p. 79, December 1994.

Maryland Department of the Environment, Maryland Department of Natural Resources, Maryland Department of Agriculture, Maryland Office of State Planning, Maryland's Governor's Office, University of Maryland, "Tributary Strategy for Nutrient Reduction in Maryland's Upper Eastern Shore Watershed," May, 1995.

Maryland Department of Natural Resources, Inventory of Dams and Assessment of Hydropower Resources, 1985.

Maryland Department of Natural Resources, Maryland Lake Water Assessment Report, March 1998.

Maryland Department of State Planning, 1973. "Natural Soil Groups of Maryland".

Olem, H. and G. Flock. Editors. Lake and Reservoir Restoration Guidance Manual. 2nd Edition. EPA 440/4-90-006. Prepared by N. Am. Lake Management Society for U.S. Environmental Protection Agency, Washington, D.C. 1990.

Qui, Z. and T. Prato, "Economic Evaluation of Riparian Buffers in an Agricultural Watershed," Journal of the American Water Resources Association, 34:4, pp. 877-890, 1998.

Thomann, R. V. and J. A. Mueller. Principles of Surface Water Quality Modeling and Control. Harper Collins, Inc., New York, 1987.

U.S. Department of Agriculture, Soil Conservation Service, Soil Survey of Worcester County, Maryland, May, 1973.

U.S. EPA, "Water Quality Assessment: A Screening Method for Nondesignated 208 Areas," Office of Research and Development, Athens Georgia, EPA/600/9-77-023, August 1977.

U.S. EPA, "Technical Support Document for Water Quality-based toxics Control," OW/OWEP and OWRS, Washington, D.C., April 23, 1991.

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

Vollenweider, R.A., "Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication," Technical Report to OECD, Paris, France, 1968.

Zison, S. W., Haven, K. F., Mills, W. B., and Tetra Tech Inc. "Water Quality Assessment, A Screening Method for Nondesignated 208 Area", Environmental Research Laboratory, Grant identification number. EPA-600, pp.340-42, 1977.

Appendix A

Big Millpond Water Quality

A study of Big Millpond was conducted in the 1993 and 2000 MDE Lake Water Quality Assessment Project. Supplementary data were collected by MDE in 2000 –2001.
A summary of the water quality data was provided in the main body of this report. Tables A1, A2, A3, A4 and A5 provide the underlying data from which the summaries were derived.

Assessment of the N: P Ratio for Big Millpond

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 three sampling events (MDE Lake Water Quality Assessment Project, 2000/2001). The average of the concentrations, Total Nitrogen and Total Phosphorus, of the three sampling events were used to calculate the N:P ratio. The average N:P ratio is above the 10:1 ratio (Table A3). The best available data were used to calculate the N:P ratio

Table A1
Physical Water Quality Data—Big Millpond, 2000-2001

STATION	DATE	TIME	DEPTH (m)	WATER TEMP (°C)	pH FIELD	DO (mg/l)	COND (µmhos/cm)
LML0021	10/31/00	910	0.0	8.3	6.4	7.0	212
PAD0008	10/31/00	0850	0.0	6.7	6.5	5.2	188
LML0000	10/31/00	0820	0.0	9.9	7.4	11.3	205
LML0021	11/28/00	1017	0.0	8.0	6.3	7.7	215
PAD0008	11/28/00	1005	0.0	6.8	6.3	6.0	189
LML0000	11/28/00	0930	0.0	9.3	7.2	11.8	203
LML0021	12/19/00	0950	0.0	5.1	8.7	10.2	212
PAD0008	12/19/00	1000	0.0	4.1	7.6	8.9	188
LML0000	12/19/00	1010	0.0	5.6	7.4	10.5	205
LML0021	01/23/01	0910	0.0	2.0	6.6	12.1	239
PAD0008	01/23/01	0925	0.0	0.5	6.2	11.1	177
LML0000	01/23/01	0945	0.0	3.7	6.8	12.2	183

Table A2
Physical Water Quality Data—Big Millpond, 1993

STATION	DATE	TIME	DEPTH (m)	WATER TEMP (°C)	pH FIELD	DO (mg/l)	COND (µmhos/cm)
LML0006	06/23/93	1045	0.3	23.0	7.1	6.3	188
LML0000	06/23/93	1105	0.3	26.7	6.7	4.0	185
LML0000	06/23/93	1105	1.0	26.1	6.7	3.4	185
LML0000	06/23/93	1105	1.5	26.0	6.7	3.7	186
LML0000	08/19/93	1010	0.3	25.4	6.5	1.1	201
LML0000	08/19/93	1010	1.0	25.3	6.5	0.9	201
LML0000	08/19/93	1010	1.5	25.3	6.5	1.1	201
LML0006	08/19/93	1030	0.3	23.0	6.6	3.3	209

Table A3
Water Quality (Nutrient) Data Big Millpond – 2000-2001

STATION	DATE	TIME	DEPTH	TOC	TN	TN:TP	TP
			(m)	(mg/l)	(mg/l)		(mg/l)
LML0021	10/31/00	910	0.0	3.9	2.8	138:1	0.020
PAD0008	10/31/00	0850	0.0	8.9	1.5	95:1	0.016
LML0000	10/31/00	0820	0.0	8.7	0.7	19:1	0.036
LML0021	11/28/00	1017	0.0	6.8	2.5	121:1	0.020
PAD0008	11/28/00	1005	0.0	10.1	1.3	74:1	0.017
LML0000	11/28/00	0930	0.0	8.0	1.1	45:1	0.024
LML0021	12/19/00	0950	0.0	6.8	4.0	192:1	0.021
PAD0008	12/19/00	1000	0.0	11.3	1.9	102:1	0.018
LML0000	12/19/00	1010	0.0	9.1	1.2	33:1	0.035
LML0021	01/23/01	0910	0.0	10.9	3.7	117:1	0.031
PAD0008	01/23/01	0925	0.0	14.9	1.8	97:1	0.019
LML0000	01/23/01	0945	0.0	13.4	2.1	49:1	0.043

Table A4
Water Quality (Nutrient) Data Big Millpond - 1993

STATION	DATE	TIME	DEPTH	TOC	TKN	TP
			(m)	(mg/l)	(mg/l)	(mg/l)
LML0006	06/23/93	1045	0.3	8.5	0.8	0.091
LML0000	06/23/93	1105	0.3	9.7	0.8	0.107
LML0006	08/19/93	1010	0.3	10.4	1.1	0.083
LML0000	08/19/93	1030	0.3	8.8	0.9	0.106

Table A5
Water Quality (Chlorophyll) Data Big Millpond – 2000-2001

STATION	DATE	TIME	DEPTH	CHLA	PHEA
			(m)	(μg/l)	(μg/l)
LML0021	10/31/00	910	0.0	35.0	-
PAD0008	10/31/00	0850	0.0	6.6	-
LML0000	10/31/00	0820	0.0	6.4	2.3
LML0021	11/28/00	1017	0.0	-	-
PAD0008	11/28/00	1005	0.0	-	-
LML0000	11/28/00	0930	0.0	1.0	0.0
LML0021	12/19/00	0950	0.0	-	-
PAD0008	12/19/00	1000	0.0	-	-
LML0000	12/19/00	1010	0.0	1.0	1.6
LML0021	01/23/01	0910	0.0	5.5	0.3
PAD0008	01/23/01	0925	0.0	1.2	0.1
LML0000	01/23/01	0945	0.0	3.2	1.3

Table A5
Water Quality (Chlorophyll) Data Big Millpond - 1993

STATION	DATE	TIME	DEPTH	CHLA	PHEA
			(m)	(μg/l)	(μg/l)
LML0006	06/23/93	1045	0.3	3.4	4.1
LML0000	06/23/93	1105	0.0	2.7	3.3
LML0000	06/23/93	1105	0.3	3.9	2.8
LML0000	08/19/93	1010	0.0	10.3	2.9
LML0000	08/19/93	1010	0.3	20.5	-0.1
LML0006	08/19/93	1030	0.3	8.1	2.6

Supporting Calculations for the Vollenweider Analysis

Big Millpond Mean Depth ($\overline{Z}$):

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 Big Millpond are 60.2 acres (2,622,312 ft^2) and 180.6-acre feet (222,766.82 m^3), respectively.

Convert $feet^2$ to m^2 : 2,622,312 ft^2 x 0.0929 m^2/ft^2 = 243,621 m^2

Convert acre feet to m^3 : 180.6 acre feet x 1,233.5 m^3/ acre feet = 222,766.82 m^3

The mean depth of Big Millpond is (Volume)/(Surface Area) is computed as:

222,766.82 $m^3 \div$ 243,621 m^2 = **0.914 m or 3 ft**

Current Phosphorus Loading to Big Millpond (Lp):

The total phosphorus loading from land is cited as 2,522 lbs/year based on loading rates from the Chesapeake Bay Program Phase 4.3 Model, segment 430, calculated as follows:

Agriculture P loading rate = 1.3 lb/acre-yr
Forested land P loading rate = 0.02lb/acre-yr
Land use: 36% agriculture, 63% forest
Watershed area = 8.2 $mile^2$ = 8.2 x 640 $acres/mile^2$ = 5,248 acres
P loading from agriculture source = 1.3 lb/acre-yr x 5,248 acres x 0.36= 2,456lbs/yr
P loading from forested land =0.02lb/acre-yr x 5,248 acres x 0.63 = 66lbs/yr
Total P loading from nonpoint sources = 2,456+ 66= 2,522 lbs/yr =1,143,956g/yr

Using the estimated 1900 Pond surface area (243,810 m^2), this value can be converted to grams per square meter per year as follows: 1,143,956g/yr $\div$ 243,810 m^2 = **4.7 g/m^2yr**.

Loading rates from the Chesapeake Bay Program Phase 4.3 Model, segment 430:

Land Use type	Total Phosphorus (lbs/yr)	Total Acres
Forest	5,606.3	271,205.1
Agriculture (Total Crop)	159,284	122,934

.

Big Millpond 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 watersheds of various sizes in the Chester, Choptank, Nanticoke, and Pocomoke basins. Linear regression provided a correlation coefficient (R^2) of 0.8918. The high R^2 shows a very strong positive correlation between area and resulting flow for a given watershed on the Chincoteague Basin. 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 Big Millpond watershed measures 8.2 mi^2; the estimated discharge is thus 8.94 cfs (6472 acre feet per year).

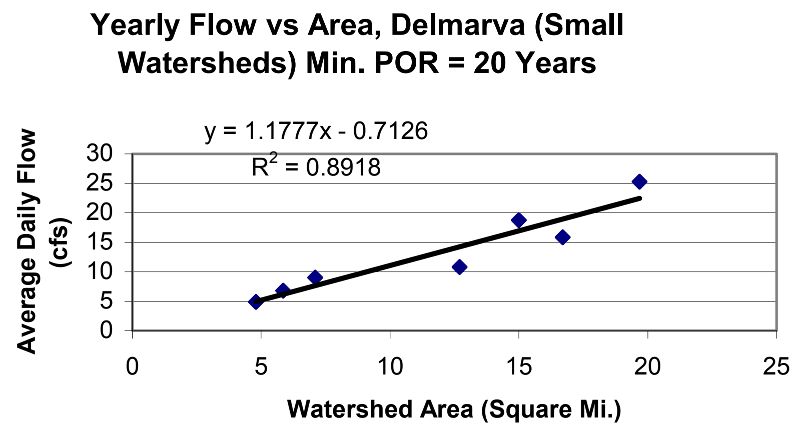

Figure A1. Discharge as function of watershed area

Hydraulic residence time (τ_w) is calculated as follows:

(180.6 acre feet) ÷ (17.7 acre feet per day) = 10.18 days.

10.18 days ÷ 365 days/yr = **0.028 yr**

<u>Ratio of Mean Depth to Hydraulic Residence Time ($\overline{Z}$ /τ_w)</u>

From the computations above the mean depth of Big Millpond ($\overline{Z}$) is 0.9m, and the hydraulic residence time (τ_w) is 0.028 yr. The ratio was computed as:

0.914 m / 0.028 yr = **32.7 m/yr**

Supporting Calculations for the TMDL Analysis

Graphing of Maximum Allowable Unit Phosphorus loading of Big Millpond using the Vollenweider Relationship

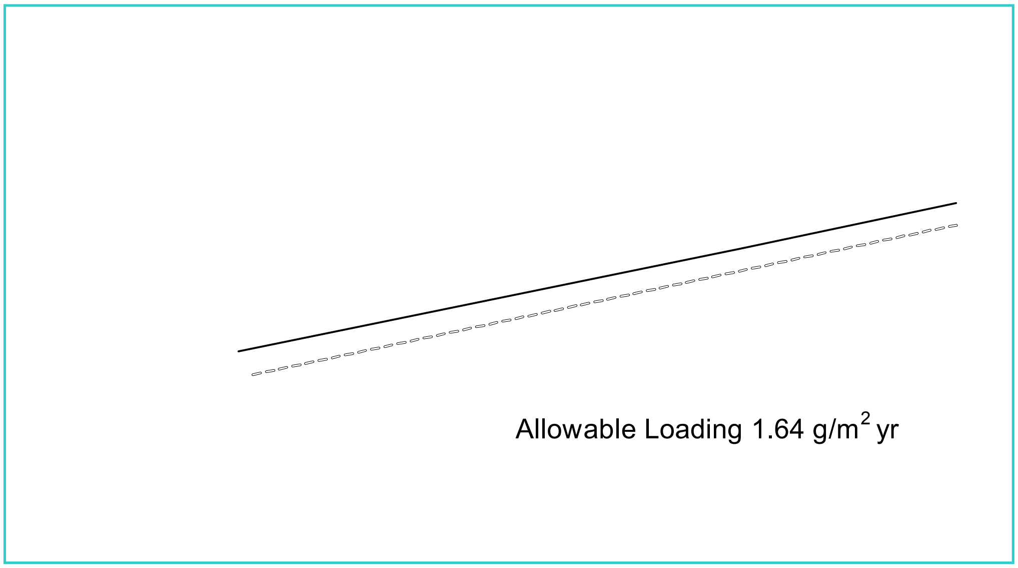

Figure A2

Figure A2, shows how the maximum allowable unit phosphorus loading can be read from the log log paper. Point "•" represents the maximum allowable load, including the load allocation and the margin of safety (1.64 g/m^{2}yr).

Computing the Phosphorus TMDL

The TMDL is computed from the maximum unit load read from Point "•" on Figure A2:

(Unit loading) x (Lake Surface Area) = Annual Loading
(1.64 g/m^{2}yr) x (243,621 m^2) = **399,538.4 *g/yr***

Converted to pounds per year:
(399,538.4 g/yr) x (0.0022 lb/g) = **880 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 (399,538.4) = **39,534.84 *g/yr***

Converted to pounds per year:

39,534.84 g/*yr* x (0.0022 lb/g) **= 88 lbs/yr**

Computing the Percentage Phosphorus Reduction

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

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

$$\frac{(2{,}522\ \text{lbs/yr}) - (792\ \text{lbs/yr})}{(2{,}522\ \text{lb/yr})} = 69\%\ \text{reduction}$$

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

Supporting Calculations of Expected Minimum DO in Mixed Surface Layer

The dissolved oxygen concentration in the mixed surface waters is a balance between oxygen sources (ambient DO levels in water flowing into the lake, photosynthesis, reaeration) and oxygen sinks (cellular respiration, sediment oxygen demand, and biochemical oxygen demand). Saturation DO concentration is a function of temperature. Conceptually, this balance is represented by the following equation:

$$DO = f(T)\left[\left(DO_{AMBIENT} + DO_{PSN} + \mathrm{Re}\,aeration\right) - \left(Metabolic\,Demands + SOD + CBOD\right)\right]$$

Where:

f(T) = Function of temperature on the following term;
$DO_{AMBIENT}$ = [DO] in water entering the lake;
DO_{PSN} = Photosynthetic DO contribution;
Reaeration = Diffusion of atmospheric O_2 into the water;
Metabolic demands = Metabolic oxygen consumption, including cellular respiration;
SOD = Sediment Oxygen Demand;
CBOD = Carbonaceous Biochemical Oxygen Demand.

Since we are especially concerned with minimum DO levels, a modification of this conceptual equation may be represented as:

$$DO_{MIN} = f(T)\left[(DO_{AMBIENT}) - (Max.Metabolic\,Depletion) - (SOD + CBOD)\right]$$

Where *Max. Metabolic Depletion* represents the maximum diurnal depletion of DO resulting from the calculated photosynthetic and respiratory fluctuation.

Following are two sets of computations. The first estimates the diurnal DO fluctuation resulting from photosynthesis and respiration, while the second addresses the effects of SOD and CBOD. Temperature and reaeration are implicit or explicit terms in both calculations.

Calculations of Dissolved Oxygen Diurnal Fluctuation:

Because the photosynthetic process is dependent on solar radiant energy, the production of oxygen proceeds only during daylight hours. Concurrently with this production, however, the algae (and other aquatic biota) require oxygen for respiration, which can be considered to proceed continuously. Minimum values of dissolved oxygen usually occur in the early morning predawn when the algae have been without light for the longest period of time. Maximum values of dissolved oxygen usually occur in the early afternoon. The diurnal range (maximum minus minimum) may be large, and if the daily mean level of dissolved oxygen is low, minimum values of dissolved oxygen during a day may approach zero and hence create a potential for fish kills.

The diurnal dissolved oxygen variation due to photosynthesis and respiration can be estimated based on the amount of chlorophyll *a* in the water. The phosphorus TMDL will result in a mesotrophic status for Big Millpond. Chlorophyll *a* concentrations ranging from 10 – 20 µg/l are typical in mesotrophic lakes (Chapra 1997). In order best to simulate critical conditions, MDE has assumed a chlorophyll *a* concentration of 20 µg/l, at the high end of this range. The equations used to calculate the diurnal dissolved oxygen are shown below:

Diurnal Dissolved Oxygen Calculations

$$p_{av} = p_s G(I_a) \qquad \text{where}: p_s = 0.25P$$

$$\frac{\Delta}{P_{av}} = \frac{\left(1-e^{-K_a f T}\right)\left(1-e^{-K_a T(1-f)}\right)}{f\,K_a\left(1-e^{-K_a T}\right)} \qquad \text{where}: \alpha_1 = \frac{I_a}{I_s}e^{-K_e z} \quad , \quad \alpha_o = \frac{I_a}{I_s}$$

$$G(I_a) = \frac{2.718f}{K_e H}\left[e^{-\alpha_1} - e^{-\alpha_0}\right]$$

Where:

p_{av} = average gross photosynthetic production of dissolved oxygen (*mg O_2/l day*)
p_s = light saturated rate of oxygen production (*mg O_2/l day*)
P = phytoplankton chlorophyll *a (*µ*g/l*)
$G(I_a)$ = light attenuation factor
f = photoperiod (fraction of a day)
H = the maximum depth (*m*)
K_e = the light extinction coefficient (m^{-1})
I_s = saturation light intensity for phytoplankton (*langley/day*)
I_a = average solar radiation during the day (*langley/day*)
z = depth at which photosynthetic activity is calculated (*m*)
Δ = Dissolved oxygen variation due to phytoplankton
K_a = reaeration coefficient (day^{-1})
T = period (day) (Thomann and Mueller 1987)

Input variables for Big Millpond diurnal DO swing calculations are shown below:

p_s = 0.25 P
P = 20.0 µ*g/l*
f = 0.6 day
H = 0.914 m (3 ft)
K_e = 1.04 m^{-1}
I_s = 350 langley/day
I_a = 500 langley/day
z = 0.914 m (3 ft)
K_a = 0.5 day^{-1}
T = 1 day

Using these input parameters, a step-by-step breakdown of the diurnal DO variation computation is provided below:

1. Determination of the average gross photosynthetic production of dissolved oxygen (p_a)

   a. $G(I_a)$ (light attenuation factor):

$$G(I_a) = \frac{2.718\ (0.6d)}{1.04\ m\ (0.914\ m)} \left[e^{-0.55} - e^{-1.43}\right]$$

$$G(I_a) = 0.579$$

   b. p_{sv} (light saturated D.O. production rate):

$$p_{av} = 5mg0_2 / l - d(0.579)$$

$$p_{av} = 2.90mg0_2 / l - d$$

2. Estimate of the diurnal dissolved oxygen range:

$$\frac{\Delta}{P_{av}} = \frac{\left(1 - e^{-(0.5/d)(0.6d)(1d)}\right)\left(1 - e^{--(0.5d)(1d)(0.4d)}\right)}{0.6d(0.5d)\left(1 - e^{-(0.5d)(1d)}\right)}$$

$$\frac{\Delta}{2.883\ mg\ 0_2\ /l - d} = 0.3994$$

$$\Delta = 1.147\ mg\ 0_2\ /l - d$$

For Big Millpond, the diurnal variation in DO is calculated as a range of **1.147 mg/l**—*i.e.*, **0.574 mg/l** in either direction from the average daily DO concentration.

Calculations of Sediment Oxygen Demand (SOD):

Sediment oxygen demand is included as a component of the overall DO concentration in the equation below (Thomann and Mueller 1987):

$$c = \left(\frac{Q}{Q + K_L A}\right) c_{in} + \left(\frac{K_L A}{Q + K_L A}\right) c_s - \left(\frac{VK_d}{Q + K_L A}\right) L - \left(\frac{S_B A}{Q + K_L A}\right)$$

Where:

c = lake wide DO accounting for SOD and CBOD
Q = lake discharge = 21,872.4 m^3/d
K_L = DO transfer rate = 0.87 m/d
K_d = effective deoxygenation rate = 0.3/d*
L = ambient lake CBOD 2.0 mg/l (common value for Maryland waters)
A = area = 243,810 m^2
V = volume = 222,766.8m^3
S_B = SOD rate = 0.92 g/m^2/d** (Ambrose *et al.* 1988)
c_{in} = DO concentration of water flowing into the pond = 6.78 mg/l*** c_s = saturation concentration of DO at T = 30o C = 7.559 mg/l (Thomann and Mueller 1987)

* K_d is 0.2/d at 20° C. To account for the assumed critical ambient temperature of 30° C, the formula below was used to calculate K_d:

$$(K_d)_T = (K_d)_{20} 1.047^{T-20}$$

Where $(K_d)_T$ and $(K_d)_{20}$ are deoxygenation rates at water temperature T(°C) and 20° C, respectively (Thomann and Mueller 1987). Thus,

$$(k_d)_{30} = (0.2/d)1.047^{30-20}$$
$$(k_d)_{30} = 0.3/d$$

** S_B is 0.5 $g/m^2/d$ at 20° C. To account for the assumed critical ambient temperature of 30° C, the formula below was used to calculate S_B:

$$(S_B)_T = (S_B)_{20}(1.065)^{T-20}$$

Where $(S_B)_T$ and $(S_B)_{20}$ are SOD rates at water temperature T(°C) and 20° C, respectively (Thomann and Mueller 1987). Thus,

$$(S_B)_T = 0.5 \text{ g } O_2/m^2/\text{day} * 1.065^{10}$$
$$(S_B)_T = 0.94 \text{ g } O_2/m^2/\text{day}$$

*** No instream DO data are available for the streams flowing into Big Millpond. Mean measured in-lake DO concentrations are above 7 mg/l. In the absence of data, and in order to provide a conservative estimate of this parameter, a value of 6.78 mg/l is used. This value is taken from the Urieville Community Lake TMDL analysis (MDE 1999). The topography and land use are similar for the two watersheds. Since the Urieville watershed contains a greater proportion of agricultural land than does that of Big Millpond (80% versus 36%), MDE believes that 6.78 mg/l represents a conservative estimate of the DO concentration of incoming water to the pond.

Using these input parameters, a step-by-step breakdown of the in-lake DO computation (including SOD) is provided below:

$$c = \left(\frac{21872 \; m^3/d}{21872 \; m^3/d + (0.87 \; m/d)(243621 \; m^2)}\right) 6.78 \; mgO_2/l +$$
$$\left(\frac{(0.87 \; m/d)(243621 \; m^2)}{21872 \; m^3/d + (0.87 \; m/d)(243621 \; m^2)}\right) 7.559 \; mgO_2/l -$$

$$\left(\frac{222767 \; m^3 (0.3/d)}{21872 \; m^3/d + (0.87 \; m/d)(243610 \; m^2)}\right) 2.0 \, mgO_2/l -$$
$$\left(\frac{0.94 \; g/m^2/d\,(243610 \; m^2)}{21872 \; .4 m^3/d + (0.87 \; m/d)(243621 \; m^2)}\right)$$

Thus, ***c*** =5.94 mgO_2/l.

Final Estimate of Minimum DO under Critical Conditions:

Including SOD, an adjusted lake wide DO of **5.95 mg/l** is estimated for Big Millpond. Incorporating the DO depletion estimated to result from diurnal variation (1.147 mg/l), the predicted theoretical minimum DO concentration under the assumed conditions is 5.94-0.574=**5.36 mg/l.**

Estimating the Sediment TMDL

The EPA Chesapeake Bay Program watershed modeling assumptions were adopted to quantify the sediment reduction associated with this phosphorus reduction. 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, CBPO 1998). The primary BMP in this category are the various land management practices that fall under Soil Conservation and Water Quality Plans (SCWQPs). The other broad category of phosphorus controls is nutrient management plans (NMPs), which manage fertilizer application, including animal waste. Thus, if nutrient management plans make up part of the control strategy, the ratio will be less than 1-to-1.

To estimate this ratio, hence the sediment load reduction, it is necessary to estimate the proportion of the phosphorus reduction that is anticipated to result from SCWQPs versus NMPs. Table 2 of the report, which shows estimated ranges of phosphorus reduction, is reproduced below for convenience. Note that the range in reduction of phosphorus is about the same for NMPs and SCWQPs. Since these BMPs are applied on a per-acre basis, an initial assumption might be that half the reduction would come from NMPs and half from SCWQPs, making the ratio about 0.5-to-1. This ratio has been adopted for estimating the reduction in sediment loads.

This ratio is conservative (gives a low estimate of sediment reductions) for two reasons. First, because soils are easily erodible in the Big Millpond watershed, the NMP removal efficiency should be compared to the “treatment of highly erodible land,” which is another term for a SCWQP in areas where soils are highly erodible. This interpretation of the BMPs gives a ratio of 1-to-0.75 or better. Second, the sediment reduction effects of conservation tillage have not been counted.

Table 2
Phosphorus Removal Efficiencies of Various Agricultural BMPs

Best Management Practice	Estimated Range of Phosphorus Reduction
Soil Conservation & Water Quality Plan (SCWQP)	11% - 35%
Treatment of Highly Erodible Land[1]	3 x the result of SCWQP on typical soil
Conservation Tillage	13% - 50%
Nutrient Management Plans	9% - 30%

Source: "Technical Appendix for Maryland's Tributary Strategy" (Maryland, 1995)
Notes: [1] The soils in the Big Millpond watershed are considered easily erodible (DNR, Oct. 1996).

To estimate the net sediment reduction associated with the 69 percent phosphorus reductions, we apply the ratio 0.5-to-1 ratio established above as follows:

100* (0.5 * 0.69) = **34.5 percent reduction in sediment loads**

Applying this reduction to the current estimation of 1422.8m^3 of sediments per year, results in the estimated reduction, the converse of which is the estimated allowable load:

(0.345 * 1422.8) = 490.9 m^3/year reduction
1422.8 - (0.345 * 1422.8) = 931.9 m^3/year allowable sediment load

The sedimentation reduction goal is reasonable and implementable. A number of best management practices—both structural and non-structural—can significantly reduce sediment loads. For instance, maintained vegetated buffer strips along stream channels (in this case, tributaries draining to Big Millpond) have been shown to capture a significant amount of sediment and dissipate the energy of the surface runoff during storm events. The vegetation also helps to reduce stream bank erosion. Recent estimates of the trap efficiency of buffer strips range from 70% to 90% (Qui and Prato, 1998)

To estimate annual accumulation associated with this loading rate, we first considered the current accumulation rate. That is, 116.5 acre feet of 180.6 acre feet, or 64.5% of the volume, was displaced between 1900 and 2001 (101 years). Assuming a 34.5% reduction in sediment loading, the current rate of lake volume displacement will be reduced accordingly. Thus, rather than a 64.5% loss of volume over 101 years, we would expect a **42.2% loss of volume over 101 years**, computed as:

$$\frac{\text{64.5\% displacement in 101 years}}{\text{100\% of current loading}} = \frac{\text{X\% displacement in 101 years}}{\text{65.5\% of current loading}}$$

Or, 0.645/1 = X/0.655
Or, X = 0.655 * 0.645 = 0.422 (a 42.2% volume displacement over 101 years).