Total Maximum Daily Loads of Sediments and Phosphorus to Centennial Lake, Howard County, MD

FINAL

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List of Abbreviations

7Q10	7-day consecutive lowest flow expected to occur every 10 years
BMP	Best Management Practice
BOD	Biochemical Oxygen Demand
CAFOs	Confined Animal Feeding Operations
CBOD	Carbonaceous Biochemical Oxygen Demand
CEAM	Center for Exposure Assessment Modeling
CFR	Code of Federal Regulations
cfs	Cubic Feet per Second
COMAR	Code of Maryland Regulation
CWAP	Clean Water Action Plan
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DNR	Department of Natural Resources
DO	Dissolved Oxygen
D_s	Secchi Depth
EPA	Environmental Protection Agency
EUTRO5.1	Eutrophication Module of WASP5.1
FNH_4	Ammonia Sediment Flux
FPO_4	Phosphate Sediment Flux
$g\ O_2/m^2$	Grams of Oxygen Per Square Meter
g/yr	Gram per year
HSPF	Hydrologic Simulation Program Fortran
K_e	Extinction Coefficient
km	Kilometers
LA	Load Allocation
lbs/month	Pounds Per Month
lbs/yr	Pounds Per Year
m	Meters
MACS	Maryland's Agricultural Cost Share Program
MDA	Maryland Department of Agriculture
MDE	Maryland Department of the Environment
mg/l	Milligrams Per Liter
mi^2	Square miles
MOS	Margin of Safety
NBOD	Nitrogenous Biochemical Oxygen Demand
NH_3	Ammonia
NMP	Nutrient Management Practice

NO_{23}	Nitrate + Nitrite
NPDES	National Pollutant Discharge Elimination System
NPS	Nonpoint Source
ON	Organic Nitrogen
OP	Organic Phosphorus
PO_4	Ortho-Phosphate
SCWQPs	Soil Conservation Water Quality Plans
SOD	Sediment Oxygen Demand
T	Temperature
TMDL	Total Maximum Daily Load
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
USGS	United States Geological Survey
WASP5.1	Water Quality Analysis Simulation Program 5.1
WLA	Waste Load Allocation
WQLS	Water Quality Limited Segment
WQIA	Water Quality Improvement Act
WRAS	Watershed Restoration Action Strategy
µg/l	Micrograms Per Liter

EXECUTIVE SUMMARY

On the basis of water quality problems associated with nutrients and sediments, Centennial Lake in the Little Patuxent River watershed (02-13-11-05) was identified on Maryland's 1998 list as being impaired. This document establishes Total Maximum Daily Loads (TMDLs) for the nutrient phosphorus and sediments entering Centennial Lake.

Centennial Lake is an impoundment located near Columbia in Howard County, Maryland. The impoundment lies on a tributary of the Little Patuxent River, which is in turn a tributary of the Patuxent River. The Little Patuxent River lies in the Patuxent River Drainage Basin, in Central Maryland. Centennial Lake was constructed for flood control and recreation.

Centennial Lake is impacted by a high sediment load. The lake also experiences occasional nuisance seasonal algal blooms, due to over-enrichment by nutrients, interfering with recreational uses. The death and decay of excessive algae can cause violations of the water quality standard for dissolved oxygen (DO), resulting in a disruption of the lake's ecosystem balance and fish kills. Analysis suggests that phosphorus is the limiting nutrient for the production of algae in Centennial Lake. 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 goal of these TMDLs is to reduce long-term phosphorus and sediment loads to acceptable levels consistent with the physical characteristics of Centennial Lake. The reduced phosphorus 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. 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 664 lbs/yr. There are no point sources in the Centennial Lake 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 20 - 69% of the lake's design volume over a period of 100 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 51% reduction in phosphorus loads would be necessary to meet the TMDL for phosphorus.

Three factors provide assurance that this TMDL will be implemented. First, Maryland has several well-established programs to draw upon, including Maryland's Tributary Strategies for Nutrient Reductions developed in accordance with the Chesapeake Bay Agreement. Second, Maryland's Water Quality Improvement Act of 1998 requires that nutrient management plans be implemented for all agricultural lands throughout Maryland. Finally, Maryland adopted a watershed cycling strategy, assuring that future monitoring and TMDL evaluations of Centennial Lake are conducted.

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 the U.S. Environmental Protection Agency (EPA) by the Maryland Department of the Environment (MDE), lists Centennial Lake for nutrients and sediments. The 1998 listing was prompted by an assessment of data associated with Centennial Lake (Maryland Department of Natural Resources [DNR], 1998).

2.0 SETTING AND WATER QUALITY DESCRIPTION

2.1 General Setting and Source Assessment

Centennial Lake is an impoundment located near Columbia in Howard County, Maryland (Figure 1). The impoundment, which is owned by Howard County and is managed by the Department of Recreation and Parks, lies on a tributary of the Little Patuxent River. An earthen dam was installed for the purpose of flood control and for recreational uses in 1985.

Centennial Lake lies in the Piedmont physiographic province. Soils are formed in material weathered in place from crystalline, and commonly micaceous, rocks. The soils immediately surrounding the lake are the Glenelg-Chester-Manor association (Soil Conservation Service, 1967). The soils consist of deep, well drained, gently sloping and sloping soils on the uplands of the Piedmont plateau that have subsoil dominantly of either silt loam or silty clay loam (U.S. Department of Agriculture, Soil Survey of Howard County, 1968). The outer watershed area is comprised of soils of the Glenelg-Manor-Chester association. These soils are deep, well drained and moderately steep.

Inflow to the lake is primarily via Clark's Creek and an unnamed tributary. Discharge from the lake is to the Little Patuxent River. The watershed map (Figure 2) shows that the land use in the watershed draining to Centennial Lake is predominantly agricultural and developed land. Land use distribution in the watershed is approximately 24% forested/herbaceous, 39% agricultural, 35% developed and 2% water (Figure 3) (Maryland Office of Planning, 1997).

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 Centennial Lake Watershed.

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

Table 1

Physical Characteristics of Centennial Lake (1985)

Location:	Howard County, MD Lat. 39° 14' 28" long. 76° 51' 12"
Average Discharge	6.75 cfs
Maximum Depth	20 feet
Surface Area:	50 acres = (202,342.8 m^2)
Owner:	Howard County
Average Lake Depth:	10.2 feet
Basin code:	02-13-11-05
Volume of Lake:	510 acre-feet (629,075.8 m^3)
Drainage Area to Lake:	3.47 mi^2
Purpose:	Recreation and Flood Control

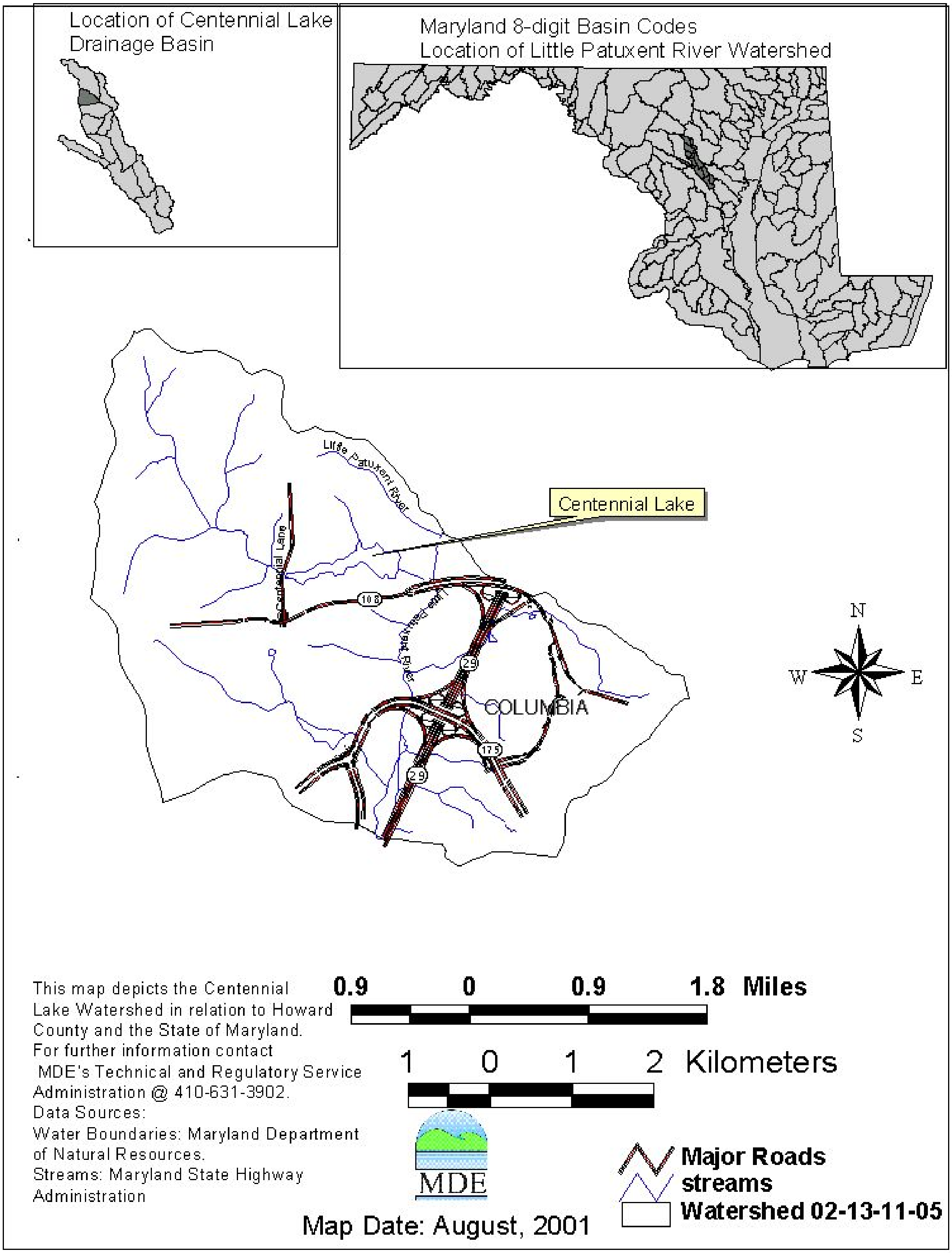

Figure 1 – Location Map of Centennial Lake in Howard County, Maryland

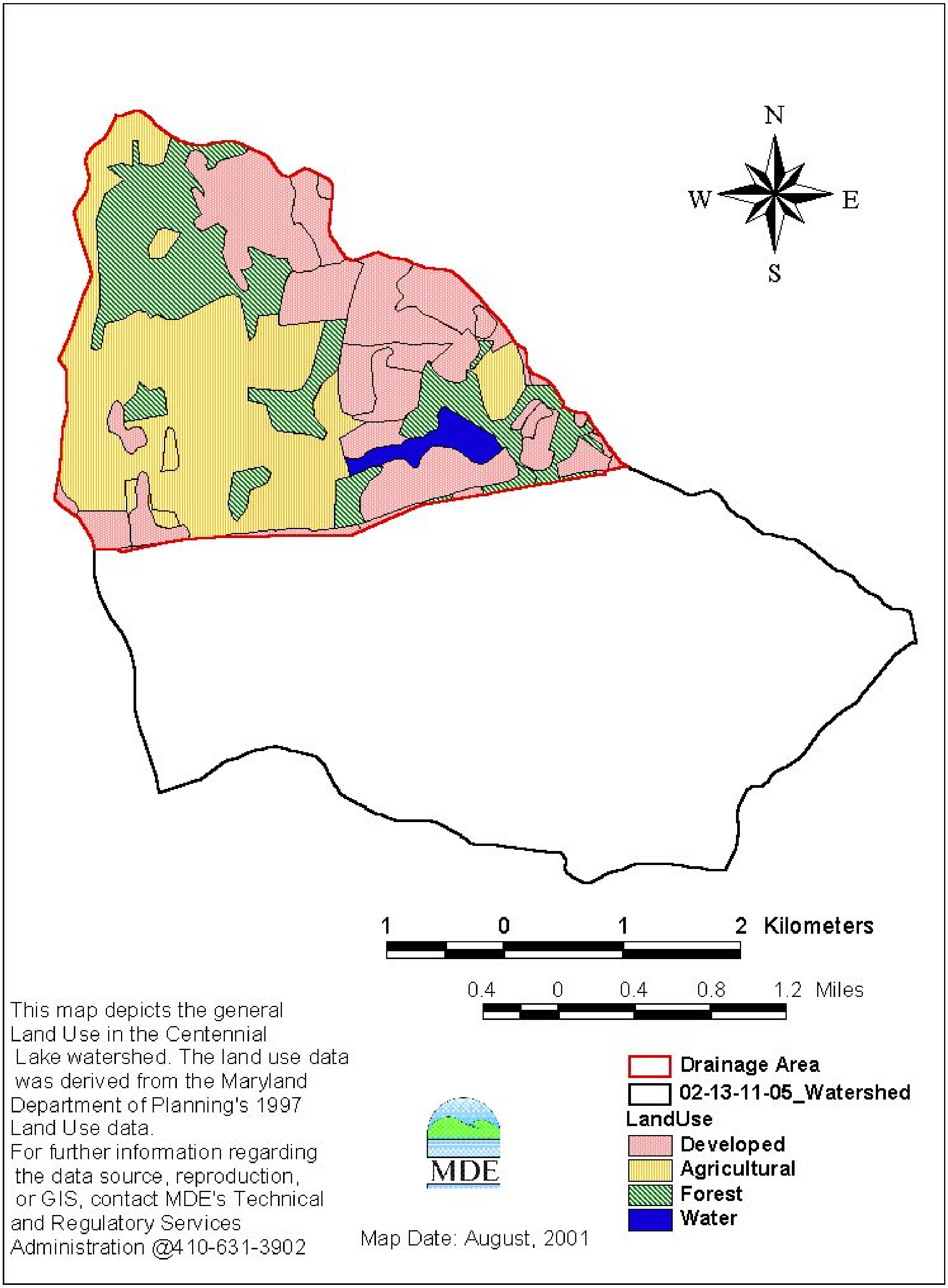

Figure 2 – Predominant Land Use in the Centennial Lake Watershed

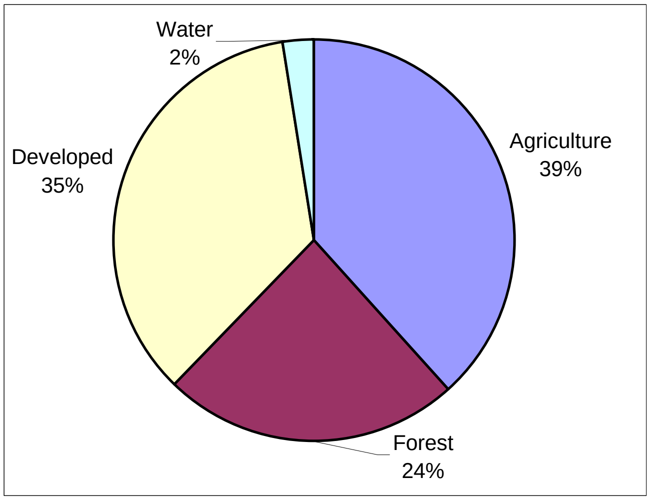

Figure 3. Land Use in the Drainage Basin of Centennial Lake

2.2 Water Quality Characterization

Centennial 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, Centennial Lake was added to Maryland's 1998 303(d) list.

Centennial Lake was monitored in August and September of 1991 (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. The Maryland Department of Health and Mental Hygiene analyzed samples for total phosphorus, soluble orthophosphorus, nitrate and nitrite, 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.

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 12 to 52.6 μg/l have been observed in Centennial Lake (Maryland Lake Water Assessment Report, 1995). The maximum observed values in Centennial Lake, 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).

Results from the 1995 Phase I Study (Coastal Environmental Services, Inc., 1995) and Centennial Lake 1996 Monitoring Program (Coastal Environmental Services, Inc., 1997) confirm that the water quality in the lake has deteriorated with severe oxygen depletion and excessive of biological productivity (see Appendix A).

MDE field office staff sampled the lake on four dates in July and August of 2001. Chlorophyll *a* concentrations ranged from 12 to 22 μg/l, and hypolimnetic anoxia was again evident. The data are presented fully in Appendix A.

Dissolved oxygen (DO) concentrations ranged from 0.1 to 11.5 mg/l along the vertical profile. Oxygen depletion occurs discontinuously, coincident with the depth at which thermal stratification was observed (*i.e*. about 4 - 5 m) during the two sampling events.

Total phosphorus concentrations ranging from 0.029 mg/l to 0.036 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 0.23 to 0.82 mg/l in Centennial Lake. Water temperatures taken during the sampling period ranged from 26.1°C to 28.6°C in the surface water depth (0.3 - 1 meter column); 23.4°C to 27.2°C in the 2 - 4 meter water column; and 14.7°C to 22.1°C in the 5-7 meter water column. This wide range of water temperatures, with an abrupt discontinuity at about 5 m, indicates that Centennial Lake is thermally stratified and not well mixed.

2.3 Water Quality Impairment

The water quality impairments of Centennial Lake addressed by these TMDLs consist of violations of the applicable numeric dissolved oxygen (DO) criterion and general water quality criteria. DO violations occur only in the hypolimnion.

Centennial Lake, an impoundment on a tributary of the Little Patuxent River near Columbia, has been designated a Use I waterbody, 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 Centennial Lake occasionally falls below the standard of 5.0 mg/l.

Maryland's General Water Quality Criteria prohibit the 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 Centennial Lake are the result of over-enrichment by the nutrient phosphorus. Finally, in conjunction with excessive nutrients, Centennial Lake has experienced excessive sediment loads.

Centennial Lake water temperatures taken during the sampling period indicate the lake is thermally stratified and not well mixed. During the 1991 sampling period (June, July and August), DO concentrations as high as 11.5 mg/l were observed at the surface (0.3 meter depth) of Centennial Lake, with DO values as low as 0.1 mg/l at a depth of 5 - 5.6 meter. Average DO at the surface was 8.8 mg/l, and 1.35 mg/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

Centennial Lake is classified as Use I—*Water Contact Recreation, and Protection of Aquatic Life*. The chlorophyll *a* endpoint selected for Centennial Lake—20 µg/l, or approximately 60 on the Carlson's Trophic 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).

Centennial Lake lies in the Piedmont ecoregion, which occurs between the Appalachian Mountains and the Atlantic Coastal Plain on the East Coast. Topography is rolling to moderately hilly, soils are varied, the land use is a mixture of forest, agricultural and developed, and there are few natural lakes (none in Maryland).

Centennial Lake 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 objective of the TMDLs established in this document is to reduce phosphorus and sediment loads to levels that are expected to result in meeting all water quality criteria that support the Use I designation. Specifically, one goal is to reduce the phosphorus load. This is predicted to reduce excessive algae growth leading 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.)

Since phosphorus binds to sediments, sedimentation rates will be reduced as a component of reducing phosphorus. It is expected that this reduction will be sufficient to prevent violations of narrative sediment criteria. 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 Centennial Lake:
   (a) 5 mg/l in the surface layer (epilimnion)
   (b) A minimum DO saturation of 10% and associated temperature-dependent DO concentration below the epilimnion (See Appendix A);

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

3. Resolve violations of narrative criteria associated with excess sedimentation of Centennial Lake by reducing sedimentation to a reasonable rate.

4.0 TOTAL MAXIMUM DAILY LOADS AND ALLOCATIONS

4.1 Overview

This subsection describes how the nutrient and sediment TMDLs and loading allocations were developed for Centennial Lake. The second subsection describes the analysis for determining that phosphorus is likely to be the limiting nutrient in Centennial 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 TMDL 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

Centennial Lake suffers from excessive nutrient enrichment and sedimentation. The TMDL for phosphorus is based on a widely accepted empirical method known as the Vollenweider Relationship (Figure 4) and Carlson's Trophic State Index. The Vollenweider Relationship allows a lake manager to predict the degree of eutrophication (nutrient enrichment) in a lake as a function of its areal phosphorus loading. Before using the Vollenweider Relationship for this purpose, the manager must determine the limiting nutrient in the lake, because the relationship only applies to phosphorus-limited lakes.

R. A. Vollenweider (1968) developed the relationship by assessing a large number of lakes. The method establishes a linear relationship between the logarithm of the areal phosphorus load to the lake (L_P g/m^2/yr) and $\mathbf{q_s}$, the logarithm of the ratio of the lake's mean depth ($\bar{z}$**)** to its hydraulic retention time **(**τ_w). Thus, the Vollenweider Relationship considers a lake's surface area, depth and flushing time in predicting the biological effect of a given phosphorus load. The relationship can be used to set targeted phosphorus loading limits to achieve a desired trophic state. 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.

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 a TSI of 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 the 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);

TSI < 35	most oligotrophic lakes
35 < TSI < 55	mesotrophic lakes
TSI > 55	eutrophic lakes
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 algal 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 (Chianudani et al., 1974). An N:P ratio of 15:1 was computed using best readily available data (MDE Lake Water Quality Assessment Project, 1995), which supports the use of the Vollenweider Relationship. Supporting data are provided in Appendix A.

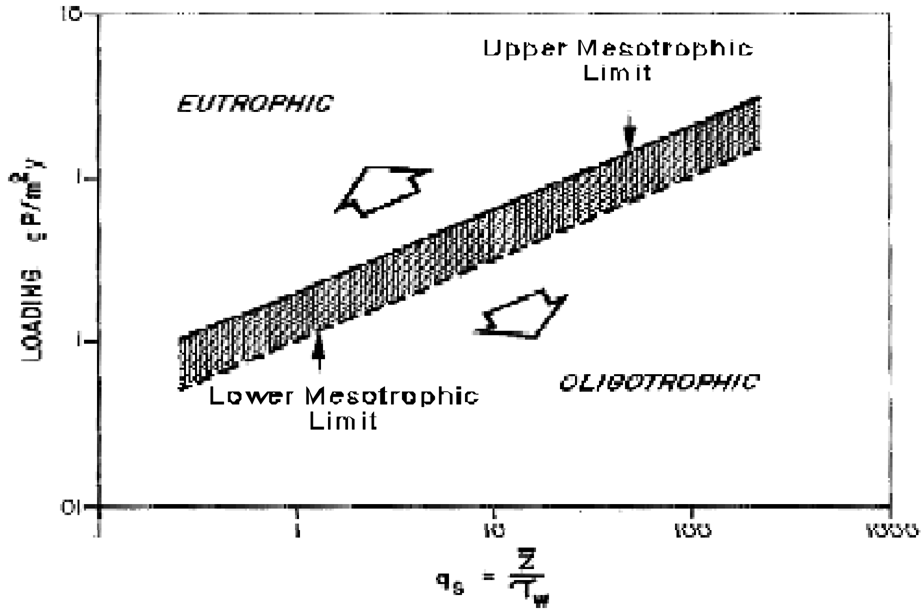

Figure 4. Vollenweider Relationship

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.

The application of the Vollenweider assumes the lake's physical dimensions when the lake and dam were constructed in 1985. 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 Centennial Lake are 50 acres (202,342.8 m^2) and 510 acre feet (629,075.7 m^3), respectively.

The mean depth was thus calculated as follows:

- ***Centennial Lake Mean Depth ($\overline{Z}$): (Volume)/(Surface Area) = 3.1 m or 10.2 ft***

Phosphorus Loading to Centennial Lake (Lp):

The current estimated total phosphorus loading is 1,230.2 lbs/year (558,009.3g/year) based on loading coefficients from the Chesapeake Bay Program, segment 340, Phase 4.3 Watershed Model and urban loading rate from MDE HSPF model. Expressing this value as a loading per surface area of the lake gives:

- ***Annual Phosphorus Load (L_p) is: 2.8 g/m^2 yr***. Details are provided in Appendix A.

Centennial Lake Hydraulic Residence Time (τ_w)

Residence time (τ_w) is computed by dividing the lake's volume by annual discharge. For Centennial Lake, average discharge data are unavailable. Since discharge data are unavailable, this parameter was estimated using the following approach (details are shown in Appendix A):

- **Flow (Q) = 6.75 cfs = 4,887 acre feet/year**

The hydraulic residence time is computed as volume/outflow; it is the time it would take to drain the lake. Assuming a volume of 510 acre feet (DNR, 1985), from above, and a discharge rate of 4,887 acre per year (see Appendix A), the hydraulic residence time is calculated as follows:

Hydraulic residence time (τ_w) is calculated as follows:

- **510 acre feet ÷ 4,887 acre feet/year = 0.1 years**

- ***Centennial Lake Hydraulic Residence Time (τ_w): 0.1 years = 38 days***

The mean depth of the lake (3.1 m) is then divided by hydraulic residence time (0.1 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 Centennial Lake, **q_s = 31 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 2.8 g/m^2-yr falls into the eutrophic range, as indicated on Figure 5 by a circle "●". The maximum allowable unit loading of 1.5 g/ m^2-yr corresponds to an estimated chlorophyll level of 20 µg/l associated with a TSI of 60 for a pond with mean depth of 3.1 m and hydraulic residence time of 0.1 years is indicated by a diamond "♦". The TMDL implications are presented below in Section 4.5.

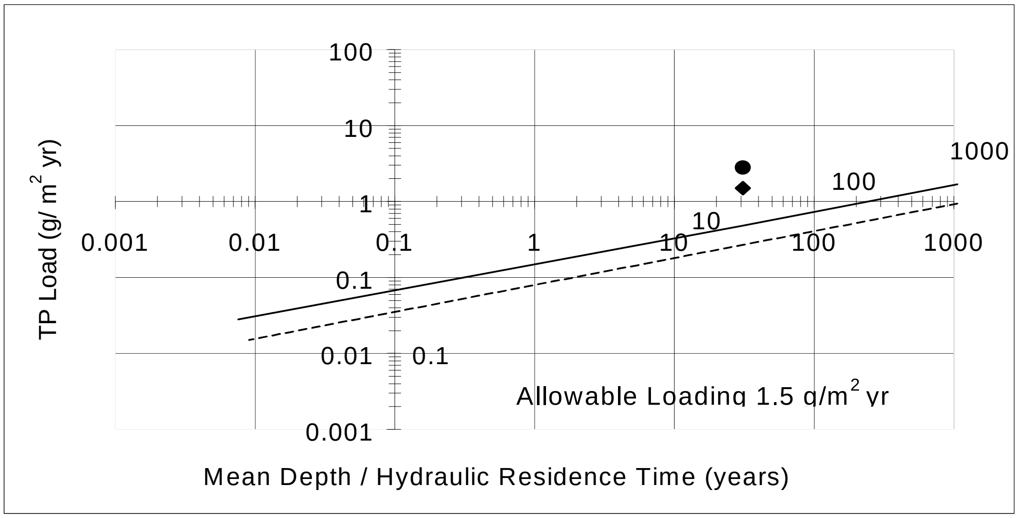

Figure 5. Vollenweider Results for Centennial Lake

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 algal 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, yielding erroneous results.

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 phosphorus loading rate of 664 lbs/yr. This represents a 51% reduction in phosphorus loading.

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 over-enrichment causes excess algal blooms, which eventually die off and decompose, consuming DO.

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

- DO 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 1.5g/m^2 will result in an increase of minimum hypolimnetic DO from the observed 0.1 mg/l to DO concentrations of about 0.5 - 0.7 mg/l. This would be consistent with Maryland's interim interpretation of the dissolved oxygen criterion as it applies to stratified lakes.

Excessive sedimentation negatively impacts a lake by reducing the lake's capacity to support fishery and recreational uses. Although the maximum sedimentation rates occur during wet weather events, it is the cumulative effect of sedimentation that impacts the lake. Therefore, the efforts to reduce sediment loading to the lake should focus on achieving effective, long-term sediment control. Since some measures to control phosphorus from agriculture sources can also effectively reduce sedimentation, the expected sediment reduction can be estimated based on the degree of phosphorus control that is needed to improve the water quality of the lake.

To quantify the sediment reduction associated with this phosphorus reduction, the EPA Chesapeake Bay Program watershed modeling assumptions were consulted. For the agricultural best management practices (BMPs) that affect both phosphorus and sediments, EPA estimates a 1:1 reduction in sediments as a result of controlling phosphorus (EPA, Chesapeake Bay Program Office [CBPO], 1998). However, this 1:1 reduction 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 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 0.5:1 ratio of sediment reduction to phosphorus reduction. The net sediment reduction associated with a 51% NPS phosphorus reduction is about 25.5% (0.5 x 0.51 = 0.255). It is assumed that this reduced sedimentation 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 20 - 69% of the lake's volume after 100 years. MDE believes that this volumetric retention will support the designated use of Centennial Lake (see Appendix A for details of this estimate).
The estimated TMDLs for phosphorus and sediment are as follows (see Appendix for detailed calculations):

PHOSPHORUS TMDL 303,514.2 g/*yr* = 664 lbs/yr

SEDIMENT TMDL 897.1 tons/yr

4.6 TMDL Allocations

The watershed that drains to Centennial Lake contains no permitted point source discharges. Hence, the entire allocation will be made to nonpoint sources. The model uses Chesapeake Bay Program, Phase 4.3 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 and Sediment Nonpoint Sources in the Centennial 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. 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, 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 45.6 tons per year.

4.8 Summary of Total Maximum Daily Loads

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

TMDL	**=**	**WLA**	**+**	**LA**	**+**	**MOS**
664	**=**	**0**	**+**	**597.6**	**+**	**66.4**

On average, this TMDL represents a daily phosphorus load of 1.8 lbs/day.

Where:

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

The annual **TMDL for Sediments (tons/yr):**

TMDL	**=**	**WLA**	**+**	**LA**	**+**	**MOS**
897.1	**=**	**0**	**+**	**897.1**	**+**	**Implicit**

On average, this TMDL represents a daily sediment load of 2.5 lbs/day.

Where:

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

5.0 ASSURANCE OF IMPLEMENTATION

Centennial 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 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), 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 BMPs that affect both phosphorus and sediments, EPA estimates a 1:1 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 WQIA 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 51 % reduction of external phosphorus loadings. Taking actions to meet this reduction is estimated to result in a 26% reduction in sediment loads from agricultural sources. Because the watershed is 39% agricultural land, meeting these reductions will entail the implementation of agricultural best management practices (BMPs). Table 2 shows estimated reduction efficiencies for individual BMPs based on the "Technical Appendix for Maryland's Tributary Strategy" (Maryland, 1996). These efficiencies, when applied in combination, can be expected to have an ultimate nutrient reduction efficiency that is greater than any single BMP, but less than the sum of the BMPs.

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	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)

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Appendix A

Centennial Lake Water Quality

A study of Centennial Lake was conducted during the 1991 MDE Lake Water Quality Assessment Project. A summary of the water quality data was provided in the main body of this report. Tables A1 through A4 provide the underlying data from which the summaries were derived.

Assessment of the N:P Ratio for Centennial 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 0.55/0.036 or 15:1. 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.

MONITORING RESULTS FROM 1996 SURVEY

A study of Centennial Lake was conducted during the 1996 monitoring program (Coastal Environmental Services, Inc) and the observed results shows dissolved oxygen concentrations were less than 0.5 mg/l at depth below 3m, chlorophyll *a* concentrations were very high in 1996, ranging from35.25µg/l in August to 52.59µg/l in July, total phosphorus ranged from 0.04mg/l to 0.18mg/l, and TSS ranged from <1mg/l to 12mg/l.

Table A1
Physical Water Quality Data—Centennial Lake, 1991

STATION	DATE	TIME	DEPTH (m)	WATER TEMP (°C)	pH FIELD	DO (mg/l)	COND (µmhos /cm)
ZAI0003	06/25/1991	1210	0.3	26.3	8.7	8.9	155
ZAI0003	06/25/1991	1210	1.0	26.1	8.6	8.9	156
ZAI0003	06/25/1991	1210	2.0	26.0	8.5	9.1	155
ZAI0003	06/25/1991	1210	3.0	25.0	8.0	9.1	155
ZAI0003	06/25/1991	1210	4.0	23.4	7.1	6.5	167
ZAI0003	06/25/1991	1210	5.0	18.9	7.3	2.5	169
ZAI0003	06/25/1991	1210	6.2	14.7	7.5	0.2	202
ZAI0009	06/25/1991	1240	0.3	26.8	9.2	11.5	156
ZAI0009	06/25/1991	1240	1.0	26.2	9.0	10.4	155
ZAI0009	06/25/1991	1240	2.2	25.0	9.0	10.5	153
ZAI0003	07/30/1991	1040	0.3	26.5	9.1	7.5	144
ZAI0003	07/30/1991	1040	1.0	26.5	9.0	7.5	148
ZAI0003	07/30/1991	1040	2.0	26.4	9.0	7.3	142
ZAI0003	07/30/1991	1040	3.0	26.3	8.9	6.4	141
ZAI0003	07/30/1991	1040	4.0	25.0	7.1	1.0	166
ZAI0003	07/30/1991	1040	5.0	21.1	7.1	0.1	178
ZAI0003	07/30/1991	1040	5.6	18.0	7.2	0.1	208
ZAI0009	07/30/1991	1100	0.3	26.4	9.0	6.8	139
ZAI0009	07/30/1991	1100	1.0	26.1	8.9	5.5	137
ZAI0009	07/30/1991	1100	2.0	25.7	8.6	4.9	135
ZAI0003	08/28/1991	1343	0.3	28.1	8.9	8.5	142
ZAI0003	08/28/1991	1343	1.0	27.9	8.9	8.5	142
ZAI0003	08/28/1991	1343	2.0	27.2	8.8	8.7	142
ZAI0003	08/28/1991	1343	3.0	26.8	7.5	4.4	145
ZAI0003	08/28/1991	1343	4.0	25.3	7.2	1.6	159
ZAI0003	08/28/1991	1343	5.0	22.1	7.1	0.1	216
ZAI0003	08/28/1991	1343	5.5	19.9	7.1	0.1	263
ZAI0009	08/28/1991	1400	0.3	28.6	9.1	9.7	139
ZAI0009	08/28/1991	1400	1.0	27.5	8.6	6.9	142
ZAI0009	08/28/1991	1400	2.0	26.9	7.3	5.2	144

Table A2
Water Quality Data—Centennial Lake, 2001

STATION	DATE	DEPTH (m)	WATER TEMP (°C)	pH FIELD	DO (mg/l)	CHLA (µg/l)
LS-10	07/19/2001	0.5	26.7	9.6	10.6	20.4344
LS-10	07/19/2001	1	26.7	9.5	10.6	21.182
LS-10	07/19/2001	2	26.5	9.3	8.2	21.182
LS-10	07/19/2001	3	24	7	0.5	21.182
LS-10	07/19/2001	4	18	7	0.2	21.182
LS-10	07/19/2001	5	13.9	7	0.2	21.182
LS-10	07/19/2001	5.5	12.4	7.1	0.3	21.182
LS-11	07/19/2001	0.5	26.7	9.3	7.8	14.7028
LS-11	07/19/2001	1	26.7	9.3	7.7	15.6996
LS-11	07/19/2001	1.8	26.4	8.6	5.4	15.6996
LSP-21	07/19/2001	0.5	26.8	9.5	9.7	
LSP-21	07/19/2001	1	26.8	9.5	9.7	
LSP-21	07/19/2001	2	26.3	8.2	5.4	
LSP-21	07/19/2001	2.9	24.5	7.1	0.3	
LS-10	07/24/2001	0.5	28.9	9.7	12	12.55968
LS-10	07/24/2001	1	28.4	9.6	12	12.55968
LS-10	07/24/2001	2	26.7	9.2	9.5	12.55968
LS-10	07/24/2001	3	24.2	7.1	1.4	12.55968
LS-10	07/24/2001	4	19	7.1	0.7	12.55968
LS-10	07/24/2001	5.1	13.3	7.3	1.7	12.55968
LS-11	07/24/2001	0.5	27.8	9.6	12.7	21.82992
LS-11	07/24/2001	1	23.3	9.4	12	23.32512
LS-11	07/24/2001	1.8	23.8	7.4	4	23.32512
LSP-21	07/24/2001	0.5	28.5	9.6	12.4	
LSP-21	07/24/2001	1	27.7	9.5	12.8	
LSP-21	07/24/2001	2.1	26.1	7.9	4.5	
LS-10	08/02/2001	0.5	25.7	9.2	10	0.7476
LS-10	08/02/2001	1	25.6	7.9	9.4	18.9392
LS-10	08/02/2001	2	25	7	4.1	18.9392
LS-10	08/02/2001	3	23.4	6.9	0.6	18.9392
LS-10	08/02/2001	4	17.9	7	0.8	18.9392
LS-10	08/02/2001	5	13.9	7	1.1	18.9392
LS-10	08/02/2001	5.4	12.8	9.2	1.5	18.9392
LS-11	08/02/2001	0.5	25.6	9.1	10	22.1788
LS-11	08/02/2001	1	25.5	9	9.5	20.4344

LS-11	08/02/2001	1.5	25.3	8.2	6.8	20.4344
LSP-21	08/02/2001	0.5	25.7	9.2	10.6	
LSP-21	08/02/2001	1	25.6	9.2	10.5	
LSP-21	08/02/2001	2	25.	7.8	5.1	
LSP-21	08/02/2001	3	22.5	7	2	
LS-10	08/07/2001	0.5	29	8.6	9.5	6.5415
LS-10	08/07/2001	1	28.8	8.6	9.7	6.5415
LS-10	08/07/2001	2	27.5	8.6	9.9	6.5415
LS-10	08/07/2001	3	23.7	6.2	0.6	6.5415
LS-10	08/07/2001	4	19	6.1	0.8	6.5415
LS-10	08/07/2001	5	15	6.2	1.3	6.5415
LS-10	08/07/2001	5.4	12	6.3	2.1	6.5415
LS-11	08/07/2001	0.5	28.6	8.6	8.8	13.4568
LS-11	08/07/2001	1	28.5	8.5	8.3	13.4568
LS-11	08/07/2001	1.5	27.2	6.8	3.4	13.4568
LSP-21	08/07/2001	0.5	28.8	8.6	9.4	
LSP-21	08/07/2001	1	28.3	8.6	9.2	
LSP-21	08/07/2001	2	25.9	8.1	8.3	

Table A3
Water Quality (Nutrient) Data Centennial Lake - 1991

STATION	DATE	TIME	DEPTH (m)	TOC (mg/l)	TN:TP	TKN (mg/l)	TP (mg/l)
ZAI0003	07/30/1991	1040	0.3	.	15:1	0.55	0.036
ZAI0003	07/30/1991	1040	0.3	.	18:1	0.55	0.030
ZAI0003	08/28/1991	1343	0.3	.	14:1	0.40	0.029

Table A4
Water Quality (Chlorophyll) Data Centennial lake - 1991

STATION	DATE	TIME	DEPTH (m)	CHLA (µg/l)	PHEA (µg/l)
ZAI0003	07/30/1991	1040	0.3	14.3	0.0
ZAI0003	07/30/1991	1040	0.3	12.0	1.6
ZAI0003	07/30/1991	1040	0.3	16.4	-3.3
ZAI0003	07/30/1991	1040	0.3	12.2	-0.2

Supporting Calculations for the Vollenweider Analysis

Centennial Lake 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 Centennial Lake are 50 acres (2,178,000 ft^2) and 510-acre feet (22,215,600 ft^3), respectively.

Convert $feet^2$ to m^2 : 2,178,000 ft^2 x 0.093 m^2/ft^2 = 202,342.8 m^2

Convert acre feet to m^3 : 510 acre feet x 1,233.5 m^3/ acre feet = 629,075.7m^3

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

629,075.7 m^3 ÷ 202,342.8 m^2 = **3.1 m or 10 ft**

Current Phosphorus Loading to Centennial Lake (Lp):

The total phosphorus loading from land is cited as 1,230.2 lbs/year based on loading rates from the Chesapeake Bay Program Phase 4.3 Model, segment 340 and Developed land loading rate from MDE's HSPF model, calculated as follows:

Land use: 35% developed land, 39% agriculture, 24% forested land
Developed land P loading rate = 0.52 lbs/acre-yr
Agriculture P loading rate = 0.94 lbs/acre-yr
Forested land P loading rate = 0.023 lbs/acre-yr
Watershed area = 3.47 $mile^2$ = 2220.8 acres
P loading from developed land = 0.52 lbs/acre-yr x 2220.8 acres x 35% = 404.2. lbs/yr
P loading from agriculture source = 0.94 lbs/acre-yr x 2220.8 acres x 39% = 814 lbs/yr
P loading from forested land = 0.023 lbs/acre-yr x 2220.8 acres x 24% = 12 lbs/yr
Total P loading from nonpoint sources = 404.2 +814 + 12 = 1,230.2 lbs/yr = 558,009.3 g/yr

Using the estimated 1985 lake surface area (202,342.8 m^2), this value can be converted to grams per square meter per year as follows: 558,009.3 g/yr ÷ 202,342.8 m^2 = **2.8 g/m^2 yr**.

Centennial 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 using the equation below. The overall Centennial Lake watershed measures 3.47 mi^2; the estimated discharge was calculated as 6.75 cfs (4,887 acre feet per year).

FLOW ESTIMATION

To conduct a Vollenweider analysis, the discharge (Q) of a lake is needed to calculate the hydraulic residence time. In the absence of accurate discharge data from lakes, it becomes necessary to estimate this parameter.

In a homogeneous area for which ample long-term USGS gages are available, linear regression has been used to estimate an annual average daily flow. In the case of smaller or more heterogeneous areas, this may not be possible. An alternate method requiring fewer observed data is to base an estimated flow on observed data from a watershed with as similar characteristics as possible. The equation below is used (Carpenter, 1983):

$$Q_{sim} = Q_{obs}\left(\frac{A_{sim}}{A_{obs}}\right)^{\exp} \quad \textbf{(1)}$$

where:

Q = discharge;
A = area
obs = observed
sim = simulated
exp = exponent (determined empirically for several geographic regions in Maryland)

For Centennial lake, gage 01591400 (in the Patuxent basin) was used as the basis. This gage, located on Cattail Creek near Glenwood, MD, drains an area of 22.9 mi^2. The gage was selected on the following bases:

- The drainage area is relatively small;
- Map observation suggests a mixture of agricultural, suburban and forest land, similar to the drainages of Centennial lake;
- The period of record is current and complete.

An average annual daily discharge (Q) was computed for a twenty-year period, October 1, 1980 through September 30, 2000 (water years 1981 through 2000). An exponent of 0.7 was used. Results appear in the table below.

SITE	**AREA (mi^2)**	**Q obs (cfs)**	**Q sim (cfs)**
01591400	22.9	25.3	NA
Centennial Lake	3.47	NA	6.75
Exponent			0.7

Hydraulic residence time (τ_w) is calculated as follows:

(510 acre feet) ÷ (13.4 acre feet per day) = **38 days**.

38 days ÷ yr /365 days = **0.1 yr**

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

From the computations above the mean depth of Centennial Lake ($\overline{Z}$) is 3.1 m, and the hydraulic residence time (τ_w) is 0.1 yr. The ratio was computed as:

3.1 m / 0.1 yr = **31 m/yr**

Graphing of Trophic Status of Centennial Lake using the Vollenweider Relationship

The intersection of the phosphorus loading rate (L_p) = 2.8 g/m^{2}yr and the ratio ($\overline{Z}$ /τ_w) = 31 m/yr was plotted on log log paper to establish the trophic status of Centennial Lake (See Figure A-1).

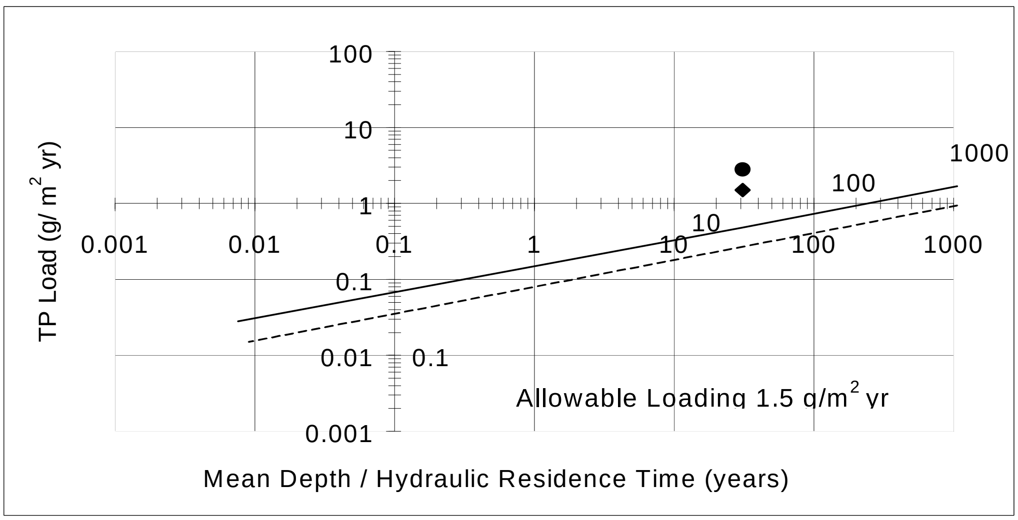


Figure A-1. Vollenweider Results for Centennial Lake

Supporting Calculations for the TMDL Analysis

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

Figure A-1 shows how the maximum allowable unit phosphorus loading can be read off of the log log paper. Point "♦" represents the maximum allowable load, which includes the load allocation and the margin of safety (1.5g/m^{2}yr).
The current trophic status associated with a loading of 2.8 g/m^2-yr falls into the eutrophic range, as indicated by a circle "●".

Computing the Phosphorus TMDL

The TMDL is computed from the maximum unit load read from Point "♦" on Figure A-1:

(Unit loading) x (Lake Surface Area) = Annual Loading
(1.5g/m^{2}yr) x (202,342.8 m^2) = 303,514.2 ***g/yr***

Converted to pounds per year:
(303,514.2 g/yr) x (0.0022 lbs/g) = **664 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 (303,514.2) = 30,351 ***g/yr***

Converted to pounds per year:
30,351 g*/yr* x (0.0022 lbs/g) **= 66.4 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:

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

$$\frac{(558{,}009.3\text{ g/yr}) - (273{,}162.8\text{ g/yr})}{(558{,}009.3\text{ g/yr})} = 51\%\text{ reduction}$$

* 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, 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-5). 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-6).

Table A-5

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-6

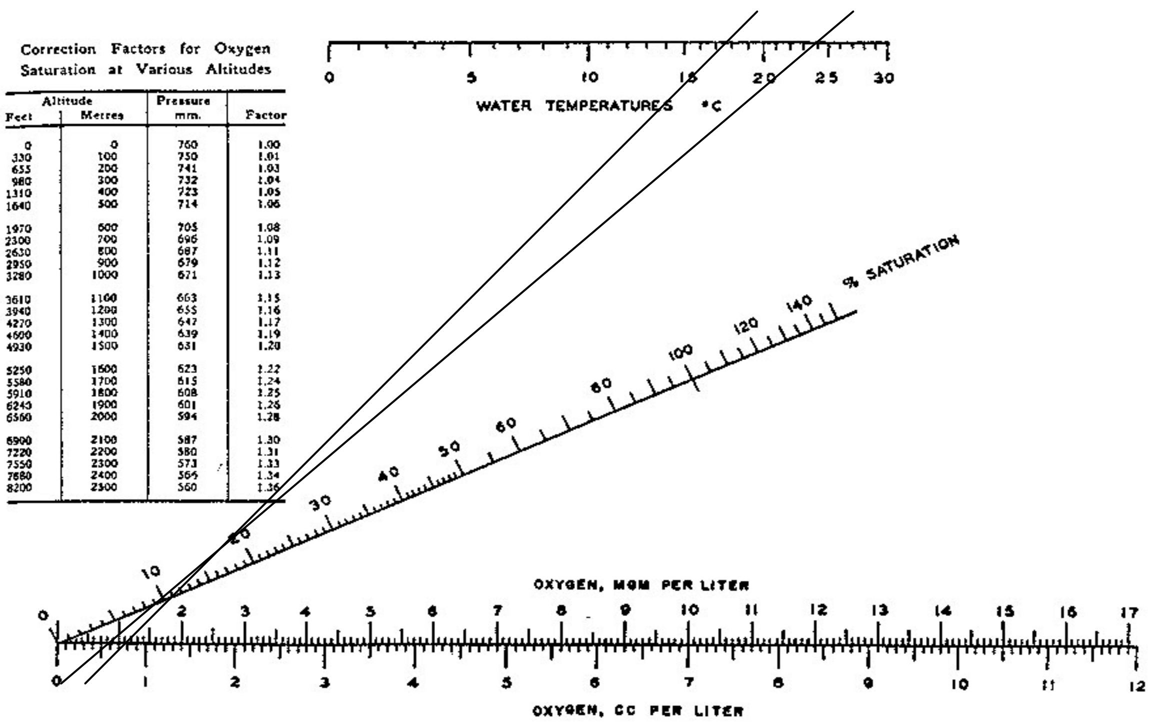
Extended Relationship between Lake Trophic Status and Dissolved Oxygen Saturation in the Sub-Epilimnetic Waters of a Thermally Stratified Lake

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 Centennial Lake at a meso-eutrophic status. Current phosphorus loading estimates place Centennial Lake 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 Centennial Lake during critical summertime conditions.

Specifically, two line segments have been drawn from the ends of the observed range of temperatures (18 – 25 °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 0.5 – 0.7 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).



Altitude Feet	Altitude Metres	Pressure mm.	Factor
0	0	760	1.00
330	100	750	1.01
655	200	741	1.03
980	300	732	1.04
1310	400	723	1.05
1640	500	714	1.06
1970	600	705	1.08
2300	700	696	1.09
2630	800	687	1.11
2950	900	679	1.12
3280	1000	671	1.13
3610	1100	663	1.15
3940	1200	655	1.16
4270	1300	647	1.17
4600	1400	639	1.19
4930	1500	631	1.20
5250	1600	623	1.22
5580	1700	615	1.24
5910	1800	608	1.25
6240	1900	601	1.26
6560	2000	594	1.28
6900	2100	587	1.30
7220	2200	580	1.31
7550	2300	573	1.33
7880	2400	565	1.34
8200	2500	560	1.36

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

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 are 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, and 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 3 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) since the sediment reduction effects of conservation tillage have not been counted.

Table 3

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	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)

To estimate the net sediment reduction associated with the 51 percent phosphorus reductions, we apply the ratio 0.5-to-1 ratio established above as follows:

100* (0.5 * 0.51) = **25.5 percent reduction in sediment loads**

Existing sediment loads were estimated using loading coefficients from the Chesapeake Bay Program Watershed Model, Phase 4.3 (segment 340). The existing sediment loads for Centennial Lake are: Forest= 35.1 tons/yr; Developed land = 160.4 tons/yr; and Agricultural source = 911.1 tons/yr.

Applying this reduction to the current estimation of 911.1 tons of sediments (agricultural sources) per year results in the estimated reduction, the converse of which is the estimated allowable load:

(0.255 * 911.1) = 232.3 tons/year reduction

Total sediment load = forest source + developed land source + agricultural source
= 35.1+ 160.4 + 911.1 = 1106.6 tons/yr
1106.6 - (0.255 * 911.1) = **874.3 tons/year allowable sediment load**

Estimation of Volumetric Preservation of Centennial Lake

No bathymetric studies have been performed to establish volume loss due to sedimentation in Centennial Lake. Since sedimentation rates (based on land use coefficients) are available, these were used to derive a range of probable volume losses due to sedimentation.

The literature was consulted to examine volume-weight measurements obtained from impoundments throughout the U.S. (Brune, 1953). The cited volume-weights (for continually submerged sediments) range from 31.6 lbs/ft^3 to 59.9 lbs/ft^3. Centennial Lake is smaller and shallower than impoundments typically used for public water supply (as are those cited), with presumably stiller waters and greater settling of fine particles. For these reasons, it is likely that the volume-weight of sediments in Centennial Lake is toward the lower end of the range.

Lower volume-weights result in a greater loss in impoundment volume from a sediment load of a specified weight. To ensure an environmentally conservative estimate, a range of low volume-weights (10 to 25 lbs/ft^3) is used. With an annual load of 874.3 tons, this range results in an annual volume loss of 1.6 acre-feet (25 lbs/ft^3) to 4.0 acre-feet (10 lbs/ft^3). Table 4 (below) expresses these annual losses in terms of preservation of the lake's volume over time.

Table 4

Expected preserved volume for Centennial Lake, assuming a sediment volume-weight ranging from 10.0 to 25.0 lbs/ft^3.

Time Period	Range Of Volumetric Preservation
50 Years	61% to 84%
100 Years	20% to 69%
200 Years	-57% to 37%