Total Maximum Daily Loads of
Phosphorus and Sediments to
Adkins Pond in the Pocomoke River Watershed
Wicomico County, MD

FINAL

Prepared by:

Maryland Department of the Environment

2500 Broening Highway
Baltimore, MD 21224

Submitted to:

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

1650 Arch Street
Philadelphia, PA 19103-2029

Submittal: December 7, 2001
Approval: March 27, 2002
Document version: January 25, 2002

Table of Contents

EXECUTIVE SUMMARY

On the basis of water quality problems associated with nutrients and sediments, Adkins Pond, in the Pocomoke River watershed (02-13-02-03) was identified on Maryland's 1998 list of WQLSs as being impaired. This document establishes Total Maximum Daily Loads (TMDLs) for the nutrient phosphorus and sediments entering Adkins Pond.

Adkins Pond is an impoundment located in southeastern Wicomico County, Maryland. The water overflows the dam into Adkins Race, a tributary to the Pocomoke River. Adkins Pond is used as a recreational facility for boating and fishing with an adjacent picnic area.

Adkins Pond is impacted by a high sediment load, which has resulted in excessive sedimentation and loss of the pond's volume. This threatens the ability of the water body to maintain and support fishing, and propagation of fish and other aquatic life. The pond also experiences occasional nuisance seasonal algae 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), which can result in a disruption of the pond's ecosystem balance and cause fish kills. Analysis suggests that phosphorus is the limiting nutrient for the production of algae in freshwater pond systems such as Adkins Pond. 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 Adkins Pond. 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 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 2,505 lb/yr. There are no point sources in the Adkins Pond basin. Consequently, the allocations are provided for nonpoint sources and an explicit 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 63% of the impoundment's design volume over a period of 61 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 77% reduction in phosphorus loads from nonpoint sources would be necessary to meet the TMDL.

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 body on their Section 303(d) list. A TMDL reflects the maximum pollutant loading of an impairing substance a water body can receive and still meet water quality standards. A TMDL can be expressed in mass per time, toxicity, or any other appropriate measure (40 CFR 130.2(i)). TMDLs must take into account seasonal variations and a margin of safety (MOS) to allow for uncertainty. Maryland's 1998 303(d) list, submitted to EPA by the Maryland Department of the Environment (MDE), lists Adkins Pond for nutrients and sediments. The 1998 listing was prompted by an assessment of data associated with Adkins Pond (Maryland Department of Natural Resources [DNR], 1998).

The water quality problems of Adkins Pond include over enrichment of nutrients that results in excessive algal blooms. In addition, excessive sedimentation has resulted in loss of the pond's capacity. A February 2001 bathymetry survey of Adkins Pond by MDE indicated that the pond has lost about 61% of its volume since 1940 due to sedimentation.

2.0 SETTING AND WATER QUALITY DESCRIPTION

2.1 General Setting and Source Assessment

Adkins Pond is an impoundment located in the upper Pocomoke Watershed (02-13-02-03) in Wicomico County, Maryland (Figure 1). The Pocomoke River flows into Pocomoke Sound and Chesapeake Bay at the Virginia/Maryland state line. Adkins Pond was created for agricultural water supply purposes in 1940. Currently, Adkins Pond supports a warm water fishery and is used for recreational purposes, including boating and fishing.

The Adkins Pond watershed lies in the Atlantic Coastal Plain physiographic province. The soils in the drainage area generally consist of Evesboro loamy sand, Fallsington sandy loam and Pocomoke sandy loam (Soil Conservation Service 1970). These soils are typically level to gently sloping (U.S. Department of Agriculture, Soil Survey of Wicomico County, 1970).

Inflow to the pond is primarily via two tributaries (Figure 1). Truitt Branch, Savanna Branch and Campbell Ditch merge to form the northernmost tributary, while Givens Branch forms the westernmost tributary. Under base flow conditions, the tributaries are generally shallow (about 1 foot) at their point of discharge to the pond. The pond discharges to the Pocomoke River, which flows southwesterly to Chesapeake Bay. The watershed map (Figure 2) (Maryland Department of Planning, 1997 Land Use) shows that land use in the watershed is approximately 46% forested and 54% agricultural.

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.

Several relevant statistics for Adkins Pond are provided below in Table 1. Since a large volume of the pond has been lost to sedimentation (over 60%), the TMDLs are developed under the assumption that the Pond will be dredged to restore its approximate 1940 physical dimensions.

Table 1.

Physical Characteristics of Adkins Pond

Location:	Wicomico County, MD lat. 38° 19' 59" long. 75° 22' 34"
Surface Area:	11.9 acres (current); 17.2 acres (1940)
Length:	2800 feet
Maximum Width:	600 feet
Average Pond Depth:	2.51 feet (current); 4.5 feet (1940)
Maximum Depth:	6.8 feet (current)
Volume of Pond:	29.8 acre-feet (current); 77 acre-feet (1940)
Drainage Area to Pond:	21.6 mi^2
Average Discharge:	25.5 cfs

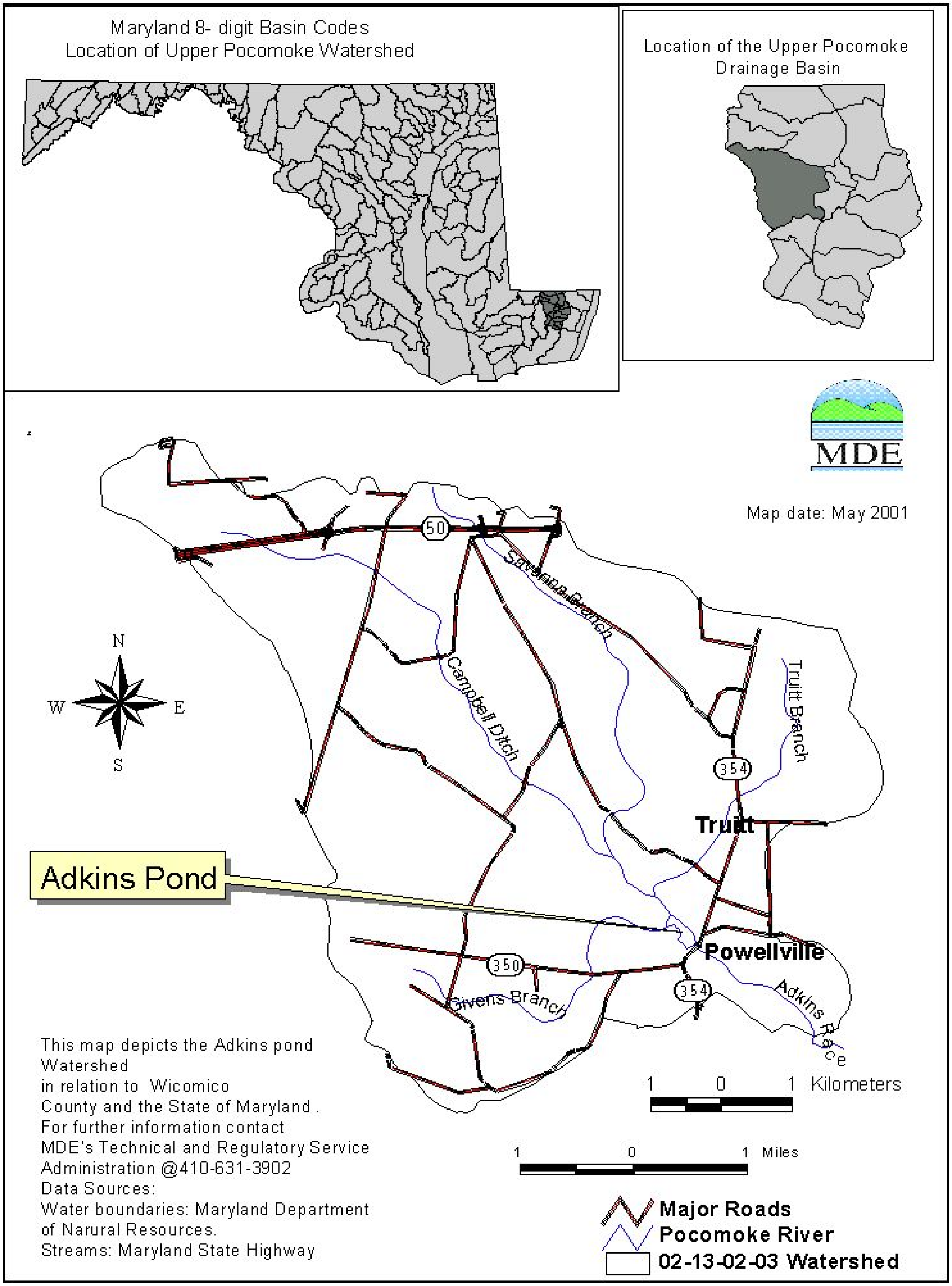


Figure 1. Location Map of Adkins Pond in Wicomico County, Maryland

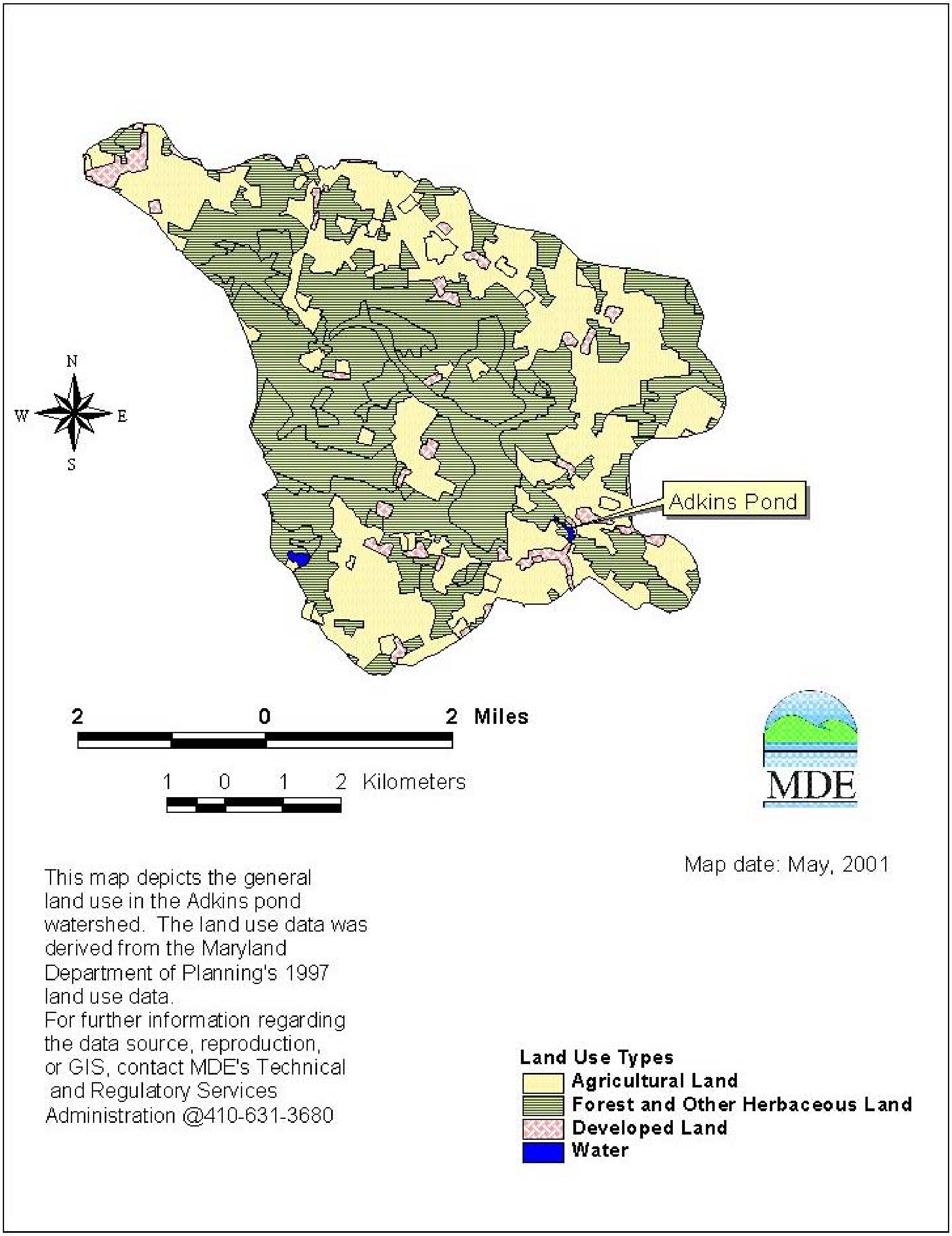


Figure 2. Predominant Land Use in the Adkins Pond Watershed

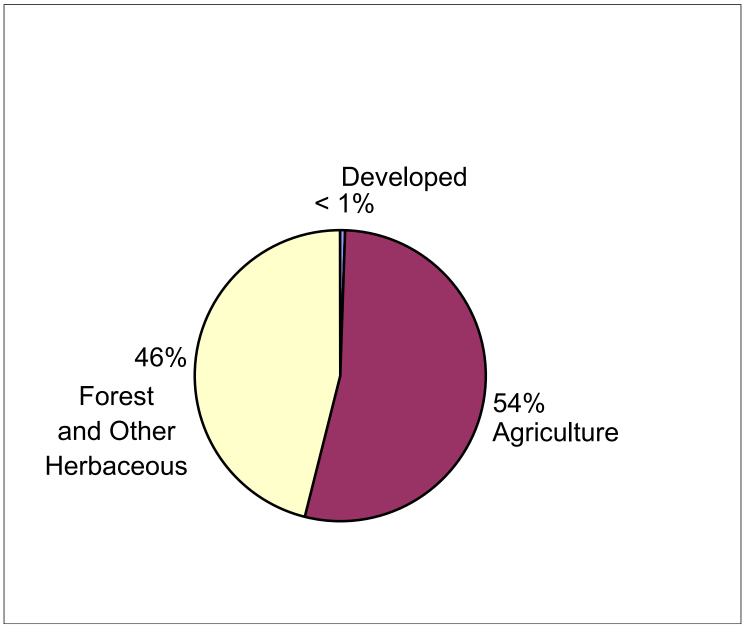


Figure 3. Land Use in Drainage Basin of Adkins Pond

2.2 Water Quality Characterization

Adkins Pond was identified as eutrophic and use impaired, utilizing a trophic classification index and data from samples collected as part of the statewide lake assessment program in 1993. The pond suffers from low oxygen levels and nuisance levels of algae based on Maryland *Lake Water Assessment Report* (1995). As a result of this evaluation, Adkins Pond was added to Maryland's 1998 303(d) list.

Adkins Pond was monitored in June and August 1993 (MDE, 1995). In addition, Maryland Department of the Environment began monthly sampling of water quality data of Adkins Pond in October 2000. Samples were collected from one station below the overflow structure and one station at each of the tributaries. Samples were analyzed for total phosphorus, soluble orthophosphorus, nitrate and nitrite N, total Kjeldahl nitrogen and chlorophyll *a*. Physical measurements of water temperatures, pH, conductivity and dissolved oxygen were recorded in the field. 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 11 to 113 µg/l have been observed in Adkins Pond. The maximum observed values in Adkins Pond, though associated with eutrophic conditions, are not extreme when compared to peak concentration of 275 mg/l in hyper-eutrophic lakes (Olem and Flock, 1990).

Dissolved oxygen (DO) concentrations in Adkins Pond during the summer months ranged from 4.0 to 8.6 mg/l. Total phosphorus concentrations ranging from 0.04 mg/l to 0.16 mg/l exceeded the range of 0.01 mg/l to 0.03 mg/l for lakes that do not exhibit signs of over-enrichment (Reid, 1961). Total nitrogen ranged from 1.5 to 5.3 mg/l in Adkins Pond.

2.3 Water Quality Impairment

The water quality impairments of Adkins Pond addressed by these TMDLs consist of violation of the applicable numeric dissolved oxygen (DO) criterion and general water quality criteria.

Adkins Pond, an impoundment on a tributary of the Pocomoke River near Powellville, 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 Adkins Pond 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 Adkins Pond are the result of over-enrichment by the nutrient phosphorus. Finally, in conjunction with excessive nutrients, Adkins Pond has experienced excessive sediment loads. In addition to carrying nutrients, the excessive sediment loads are filling the pond at a high rate. Since 1940, sediment has reduced the pond's volume from 77 acre-ft to 30 acre-ft.

3.0 TARGETED WATER QUALITY GOALS

Adkins Pond is classified as Use I – *Water Contact Recreation, and Protection of Aquatic Life*. Adkins Pond presently supports a warm water fishery. The chlorophyll *a* endpoint selected for Adkins Pond – 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).

Adkins Pond 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 ratios of watershed area to lake surface area, resulting in a relatively high degree of allochthonous nutrient loading. Thus, this type of morphometry favors eutrophy. The MACP ecoregion is topographically and functionally similar to the two agricultural ecoregions Heiskary describes in Minnesota.

The overall objectives of the TMDL established in this document are 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 improve the trophic status of Adkins Pond by reducing the total phosphorus load. This is predicted to reduce excessive algae growth, which leads to violations of the numeric DO criteria and the violation of various narrative criteria associated with nuisances (*i.e.*, odors and physical impedance of direct contact use).

Since phosphorus binds to sediments, sedimentation rates will be reduced as a result 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 the dissolved oxygen criterion of 5.0 mg/l is met in Adkins Pond;

2. Resolve violations of narrative criteria associated with phosphorus enrichment of Adkins Pond; and

3. Resolve violations of narrative criteria associated with excess sedimentation of Adkins Pond 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 Adkins Pond. The second subsection describes the analysis for determining that phosphorus is likely to be the limiting nutrient in Adkins Pond, 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 results of the Total Maximum Daily Loads and allocations for both phosphorus and sediments. 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

Adkins Pond 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 TMDL for sediments is determined based on expected sediment reduction associated with phosphorus reduction and assessed by comparison with other references for reasonableness.

The Vollenweider Relationship predicts the degree of a lake's trophic status as a function of the areal phosphorus loading. R. A. Vollenweider (1968) developed the relationship by assessing a large number of lakes. He established a linear relationship between the log of the phosphorus loading (L_p) and the log of the ratio of the lake's mean depth ($\overline{Z}$) to hydraulic residence time (τ_w) (Figure 4). This method is advantageous for a number of reasons: It is based on observed data collected from a wide range of lakes; its application is conceptually simple and does not require the assumptions of many unknown parameters; and it is recognized by the scientific community as a reasonable method of predicting the trophic status of lakes.

A frequently used biomass-related trophic state index is that developed by Carlson (1977). Carlson's trophic state 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 (ultraoligotrohic) 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):

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 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." The Vollenweider Relationship can be used only if phosphorus is the limiting nutrient. Thus, before considering the application of the Vollenweider Relationship, it is necessary to examine the ratio of nitrogen to phosphorus to establish whether phosphorus is the limiting nutrient.

In general, an N:P ratio in the range of 5:1 to 10:1 by mass is associated with plant growth being limited by neither phosphorus nor nitrogen. If the N:P ratio is greater than 10:1, phosphorus tends to be limiting, and if the N:P ratio is less than 5:1, nitrogen tends to be limiting (Chiandani et al., 1974). An N:P ratio of 10 and greater was computed based on available data, which supports the use of the Vollenweider Relationship. Supporting data are provided in Appendix A.

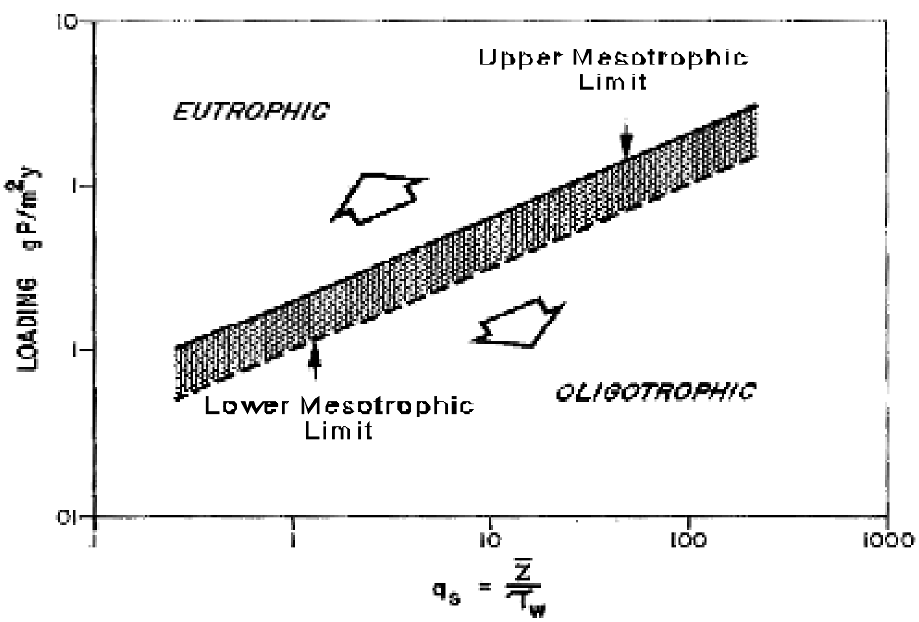


Figure 4. Vollenweider Relationship

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.

Adkins Pond Mean Depth ($\overline{Z}$):

For the present case, the Vollenweider Relationship was applied under an assumption of the pond's physical dimensions as measured during a 1940 survey. The mean pond depth was calculated using pond volume and surface area given in the "Inventory of Dams and Assessment of Hydropower Resources" (DNR 1985). The mean pond depth was calculated using pond volume and surface area. The cited surface area and volume of Adkins Pond are 17.2 acres and 77 acre-feet (3,354,120 ft^3), respectively.

The mean depth was thus calculated as follows:

- ***Adkins Pond Mean Depth ($\overline{Z}$): (Volume)/(Surface Area) = 4.5 ft = 1.37 m***
  Phosphorus Loading to Adkins Pond (Lp):

The current estimated total phosphorus loading is 9,831 lb/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 pond gives:

- ***Annual Phosphorus Load (L_p) is: 64 g/m^2 yr***. Details are provided in Appendix A.

  Adkins Pond Hydraulic Residence Time (τ_w)

The hydraulic residence time (τ_w) is computed by dividing the pond volume by average annual discharge rate; the time it would take to drain the pond. For Adkins Pond, average discharge data are unavailable. Since discharge data are unavailable, this parameter was estimated by analyzing a number of watersheds of various sizes on the Delmarva Peninsula for which long-term flow data were readily available from the U.S. Geological Survey. The average daily flow from each of these stations was plotted against watershed area. A linear regression was used to estimate the average annual discharge rate. The average discharge rate from Adkins Pond is estimated as follows (details are shown in Appendix A):

- **Flow (Q) = watershed area (21.6 mi^2) x 1.2 – 0.392 = 25.5 cfs**

Based on a volume of 77 acre-feet (3,354,120 ft^3), from above, and an average annual discharge rate of 25.5 cfs, the hydraulic residence time is calculated as follows:

- **3,354,120 $feet^3$ ÷ 25.5 $feet^3$/second = 131,534 seconds = 1.522 days = 0.0042** years

- ***Adkins Pond Hydraulic Residence Time (τ_w): 0.0042 years***

The mean depth of the pond (1.37 m) is then divided by hydraulic residence time (0.0042 years) to yield q_s, the parameter with which to compare phosphorus loading using the Vollenweider Relationship to assess the Adkins Pond's trophic status. For Adkins Pond, **q_s = 326 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 64 g/m^2-yr falls into the eutrophic range, as indicated on Figure 5 by a diamond "♦". The maximum allowable unit loading of 16.3 g/ m^2-yr for a pond with mean depth of 4.5 feet and hydraulic residence time of 0.0042 years 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 below in Section 4.5.

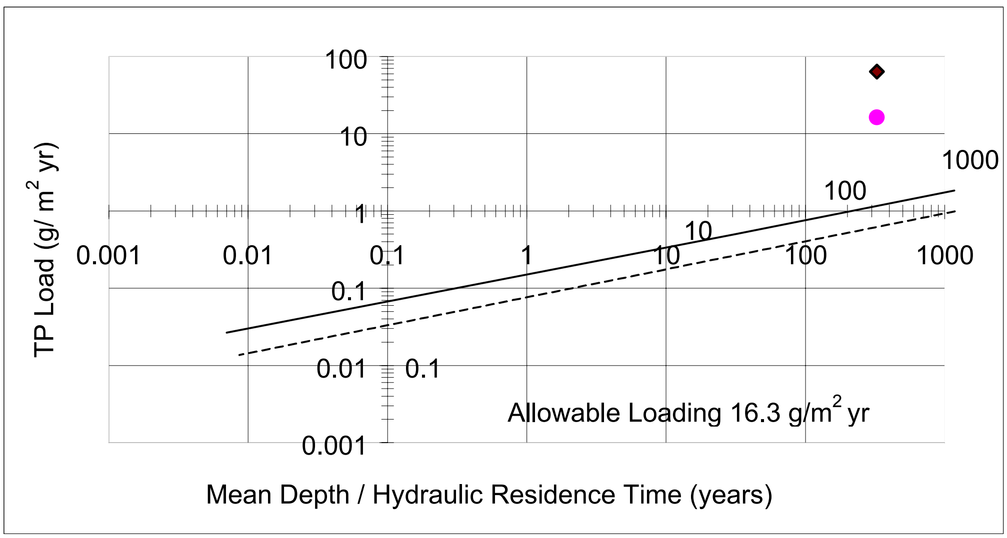


Figure 5. Vollenweider Results for Adkins Pond

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 phosphorus loading rate of 9,831 lb/yr would result in a TSI of over 80 and a chlorophyll *a* concentration greater than 150 μg/l. The TMDL water quality endpoint, which will maintain the warm water fishery and avoid nuisance algal blooms, is a chlorophyll *a* concentration of 20 μg/l. This corresponds to a maximum TSI of 60 and is associated with the lower range of eutrophic conditions. The allowable phosphorus loading rate is 2,505 lb/yr. This represents a 77% reduction in phosphorus loading.

The link between DO concentration and the pond'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 Adkins Pond (see Appendix A). These processes are outlined below:

- Dissolved oxygen saturation capacity as a function of trophic status and water temperature;
- Sediment Oxygen Demand (SOD);
- Carbonaceous Biochemical Oxygen Demand (CBOD);
- Diurnal variation of DO resulting from photosynthetic activity of algae; and
- Water reaeration.

According to calculations presented in Appendix A, it is expected that an areal phosphorus load of 16.3 g/m^2 will result in a minimum DO concentration of about 5.81 mg/l.

Excessive sedimentation negatively impacts a pond by reducing the pond's capacity to support fishery and recreational uses. Although the maximum sedimentation rates occur during wet-weather events, it is the cumulative effects of sedimentation that impact the pond. Therefore, the efforts to reduce sediment loading to the pond 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 pond.

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 1-to-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 77% NPS phosphorus reduction is about 38.5% (0.5 x 0.77 = 0.385). 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 62% of the impoundment's volume after 61 years. MDE believes that this volumetric retention will support the designated use of Adkins Pond (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	2,505 lb/yr
SEDIMENT TMDL	599 m^3/yr

4.6 TMDL Allocation

The watershed that drains to Adkins Pond contains no permitted point source discharges. Hence, in addition to an explicit 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 phosphorus loading rates for different land uses. These represent the cumulative impact from all sources—naturally-occurring and human-induced. Local contributions from different land uses are described in the technical memorandum entitled “Significant Phosphorus Nonpoint Sources in the Adkins Pond 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 the 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 explicit MOS in the form of conservative assumptions in the TMDL analysis.

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.

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°C; the highest temperature observed during monitoring was 25.8°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, 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 60 m^3/y (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
2,505	=	0	+	2,254	+	251

On average, this TMDL represents a daily phosphorus load of 6.9 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
599	=	0	+	599	+	Implicit

On average, this TMDL represents a daily sediment load of 1.6 m^3/day

5.0 ASSURANCE OF IMPLEMENTATION

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

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 77 % 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 Adkins Pond drainage basin. Second, if this goal is an over-estimation of the necessary load reductions, it can be refined using better data and analysis tools, while initial steps are taken to reduce the loads. Taking actions to meet this reduction is estimated to result in a 38% reduction in sediment loads.

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.

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.

Because the watershed is 54% 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[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: The soils in the Adkins Pond 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 be shown to capture a significant amount of sediment, by stabilizing the banks and by dissipating the energy of the surface runoff during storm events. The vegetation also helps to reduce stream bank erosion. Recent estimate of the efficiency of buffer strips in reducing sediment loads range from 70% to 90% (Qui and Prato, 1998). Such buffer strips could be established along tributaries draining to Adkins Pond.

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 Lakes. 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.

Heiskary, S. "Proposal for Listing Lakes on the 303 (d) List of Impaired Waters: Based on Nutrient Overenrichment" MPCA, St. Paul, Minnesota, January 2000

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, 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.

Rule, T. "Estimating Watershed Flow on the Delmarva Peninsula Using Linear Regression of Watershed Area versus Known Flow"' Maryland Department of Environment

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 Wicomico County, Maryland, January 1970.

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, 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.

Appendix A

Adkins Pond Water Quality

A study of Adkins pond 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, and A2, provide the underlying data from which the summaries were derived.

Assessment of the N:P Ratio for Adkins Pond

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 to 10:1 by mass is associated with plant growth being limited by neither phosphorus nor nitrogen. If the N:P ratio is greater than 10:1, phosphorus tends to be limiting, and if the N:P ratio is less than 5:1, nitrogen tends to be limiting (Chiandani, et al., 1974).

The N:P ratio was calculated using data from the October 2000 through January 2001 MDE sampling results (Table A2). The concentrations of total nitrogen (TN) and total phosphorus (TP) were used to calculate the N:P ratio. The N:P ratio ranged from 10:1 to over 20:1.

Table A1
Water Quality Data, Adkins Pond - 1993

STATION	DATE	TIME	DEPTH (m)	DO (mg/l)	Temp °C	Chl *a* (µg/l)	TKN (mg/l)	TP (mg/l)
ADK0017	6/21/93	1320	0.3	4.0	25.8	11.5	2.6	0.160
ADK0017	8/16/93	1353	0.3	8.6	24.2	113.6	1.0	0.038

Table A2
Water Quality Data—Adkins Pond, 2000-2001

STATION	DATE	Total N (mg/l)	Total P (mg/l)	WATER TEMP (°C)	TN:TP	PH FIELD	DO (mg/l)	Chloroph *a* (µg/l)
ADK0019	10/31/00	1.47	0.14	9.5	10:1	6.6	8.4	18.0
ADK0019	11/28/00	1.48	0.15	7.8	10:1	7.9	7.0	-
ADK0019	12/19/00	2.76	0.11	4.2	25:1	6.4	10.3	9.8
ADK0019	1/23/01	5.3	0.1	0.8	53:1	6.4	12.0	1.8

Supporting Calculations for the Vollenweider Analysis

Adkins Pond Mean Depth ($\overline{Z}$):

The mean pond depth was calculated using pond volume and surface area given in the Inventory of Maryland Dams and Hydropower Resources (DNR 1985). The cited surface area and volume of Adkins Pond are 17.2 acres (749,232 ft^2) and 77 acre-feet (3,354,120 ft^3), respectively.

Convert $feet^2$ to m^2 : 749,232 ft^2 x 0.09290 m^2/ft^2 = 69,604 m^2

Convert acre feet to m^3 : 77 acre feet x 1,233.5 m^3/ acre feet = 94,980 m^3

The mean depth of Adkins Pond is (Volume)/(Surface Area) is computed as:

77 acre-ft/17.2 acre = **4.5 feet**

Current Phosphorus Loading to Adkins Pond (Lp):

The total phosphorus loading from land is calculated as 9,831 lbs/year (4,453,443 g/yr) 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 = 0.02 lb/acre-yr
Land use: 54% agriculture, 46% forest
Watershed area = 21.6 $mile^2$ = 21.6 x 640 acres/$mile^2$ = 13,824 acres
P loading from agriculture source = 1.3 lb/acre-yr x 13,824 acres x 0.54= 9,704 lbs/yr
P loading from forested land =0.02 lb/acre-yr x 13,824 acres x 0.46 = 127 lbs/yr
Total P loading from nonpoint sources = 9,704+ 127= 9,831 lbs/yr = 4,453,443 g/yr

Using the estimated 1940 pond surface area (69,604 m^2), this value can be converted to grams per square meter per year as follows:

4,453,443 g/yr ÷ 69,604 m^2 = 64 g/m^2yr.

Adkins Pond Hydraulic Residence Time (τ_W):

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

Hydraulic residence time is calculated based on the pond 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 varying size on the lower Eastern Shore region of Maryland and portion of Delaware. The regression line and equation are shown in Figure A-1 below. Discharge of the pond is then estimated as a function of the watershed area. The overall

Adkins Pond watershed measures 21.6 mi^2; the estimated discharge is thus 25.5 cfs (22,788,994 m^3/yr) (18,472 acre-ft per year).

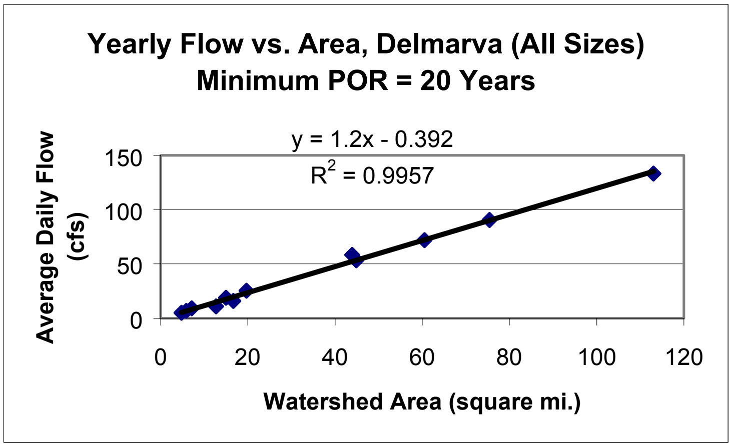


Figure A1. Discharge as function of watershed area

Hydraulic residence time (τ_w) is calculated as follows:

(77 acre feet) ÷ (18,472 acre feet per year) = **0.0042 year**.

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

From the computations above the mean depth of Adkins Pond ($\overline{Z}$) is 4.5 ft (1.37 m), and the hydraulic residence time (τ_w) is 0.0042 yr. The ratio was computed as:

1.37 m/0.0042 yr = **326 m/yr**

Graphing of Trophic Status of Adkins Pond using the Vollenweider Relationship

The intersection of the phosphorus loading rate (L_p) = 64 g/m^2yr and the ratio ($\overline{Z}/\tau_w$) = 326 m/yr was plotted on log log paper to establish the trophic status of Adkins Pond (See Figure 5).

Existing in-pond total phosphorus concentration is calculated based on total phosphorus loading divided by the total flow to the pond:

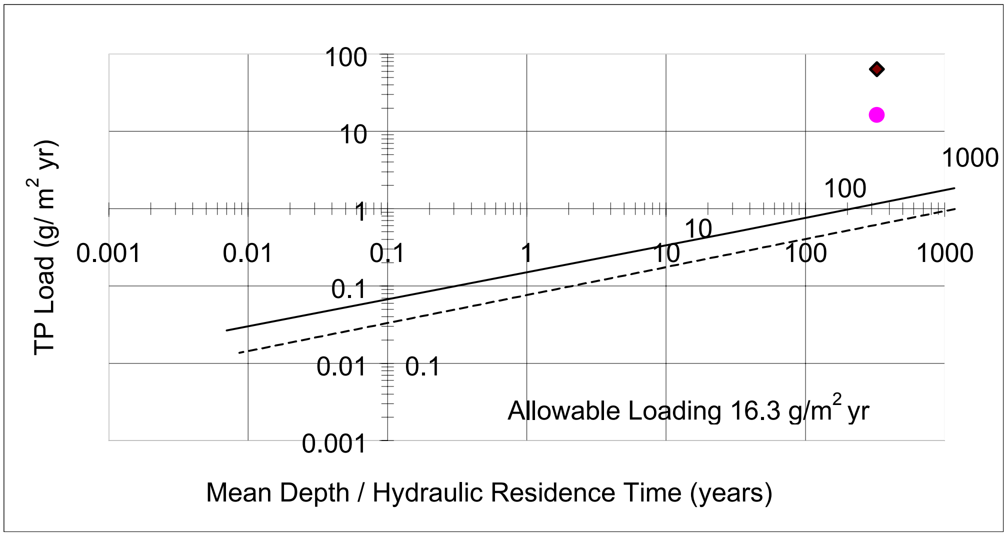
4,453,443 g/yr / 22,788,994 m^3/yr = 0.195g/m^3 = 0.000195g/l= 195 μg/l

This phosphorus concentration corresponds to Carlson's Trophic Index (TSI) greater than 80, with corresponding chlorophyll a concentration greater than 150 *u*g/l

Raschke (1994) gathered data for 17 small southeastern piedmont impoundments to establish a management relationship between algal bloom frequency and seasonal mean chlorophyll *a* concentration. Based on the bloom frequency analysis, literature values and experience, Raschke proposed a mean growing season limit of < 15 µg/l for chlorophyll *a* for attaining drinking water supply use in small southeastern impoundments. For other uses, such as fishing and swimming, a mean growing season limit of < 25 µg/l was recommended.

Adkins Pond is significantly used as a recreational warm water fishery. A reasonable management goal is to enhance or maintain support of this fishery. A possible endpoint, seeking to maintain the fishery and avoid nuisance algal blooms, is a chlorophyll *a* concentration of 20 µg/l, which is in the lower range of eutrophic conditions and corresponds to a maximum permissible TSI of 60. A TSI of 60 results in a total phosphorus concentration of approximately 50 µg/l.

Supporting Calculations for the TMDL Analysis



<u>**Estimating the Phosphorus TMDL**</u>

. **Figure A2. Vollenweider Results for Adkins Pond**

Allowable in-pond total phosphorus concentration = 50 µg/l = 0.05 mg/l = 0.05 g/m^3.

Allowable total phosphorus loading = W = (0.05 g/m^3)(326 m/yr) = 16.3 g/m^2-yr
(shown by "•" in the Figure 5 in the main report and Figure A2 above).

Annual allowable loading
= (Unit loading) x (Pond Surface Area)
= (16.3 g/m^{2}yr) x (17.2 acre x 4047 m^2) = 1,134,617 g/yr = **2,505 lb/yr**

<u>Computing the Phosphorus Margin of Safety</u>

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 (2,505 lb/yr) = **250 lb*/yr***

Computing the Percentage Phosphorus Reduction

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

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

$$\frac{(9{,}831\ \text{lb/yr}) - (2{,}254\ \text{lb/yr})}{(9{,}831\ \text{lb/yr})} = 77\%\ \text{reduction}$$

*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 pond, 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 pond;
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 chlorophyll *a* concentration of 20 µg/l in Adkins Pond, at the low end of eutrophic range. The equations used to calculate the diurnal dissolved oxygen are shown below:

Diurnal Dissolved Oxygen Calculations

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

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

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

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* (µg/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 (*langly/day*)
I_a = average solar radiation during the day (*langly/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 Adkins Pond diurnal DO swing calculations are shown below:

p_s = 0.25 P
P = 20.0 μ*g/l*
f = 0.6 day
H = 1.37 m
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):

$$G\left(I_a\right) = \frac{2.718\ (0.6d)}{1.04\ m\ (1.37\ m)}\left[e^{-0.55} - e^{-1.43}\right]$$

$$G\left(I_a\right) = 0.383$$

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

$$p_{av} = 5mg0_2 / l - d(0.383)$$

$$p_{av} = 1.92mg0_2 / l - d$$

2. Estimate of the diurnal dissolved oxygen range:

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

$$\frac{\Delta}{1.915\ mg\ 0_2 / l - d} = 0.3994$$

$$\Delta = 0.765\ mg\ 0_2 / l - d$$

For Adkins Pond, the diurnal variation in DO is calculated as a range of **0.765** mg/l—*i.e.*, **0.383** 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):

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

Where:

c = pondwide DO accounting for SOD and CBOD
Q = pond discharge = 62,388 m^3/d
K_L = DO transfer rate = 0.87 m/d
K_d = effective deoxygenation rate = 0.3/d*
L = ambient pond CBOD 2.0 mg/l (common value for Maryland waters)
A = area = 69,605 m^2
V = volume = 94,978 m^3
S_B = SOD rate = 0.94 $g/m^2/d$** (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 Adkins Pond. Mean measured in-lake DO concentrations are above 8 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 Adkins Pond (80% versus 54%), 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-pond DO computation (including SOD) is provided below:

$$c = \left(\frac{62,388\ m^3/d}{62,388,\ m^3/d + (0.87\ m/d)(69,605\ m^2)}\right)6.78\ mgO_2/l +$$
$$\left(\frac{(0.87\ m/d)(69605\ m^2)}{62,388\ m^3/d + (0.87\ m/d)(69,605\ m^2)}\right)7.559\ mgO_2/l -$$
$$\left(\frac{28494\ m^3}{62,388\ m^3/d + (0.87\ m/d)(69,605\ m^2)}\right)2.0\ mgO_2/l -$$
$$\left(\frac{0.94\ g/m^2/d(69,605\ m^2)}{62,388\ m^3/d + (0.87\ m/d)(69,605\ m^2)}\right)$$

Thus, $\boldsymbol{c} = 6.17 mgO_2/l$.

Final Estimate of Minimum DO under Critical Conditions:

Including SOD, an adjusted pond wide DO of 6.17 mg/l is estimated for Adkins Pond. Incorporating the DO depletion estimated to result from diurnal variation (0.765 mg/l), the predicted theoretical minimum DO concentration under the assumed conditions is .98-0.383 = **5.78 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 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, 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 Adkins Pond 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 Adkins Pond watershed are considered easily erodible (DNR, Oct. 1996).

To estimate the net sediment reduction associated with the 77 percent phosphorus reductions, we apply the ratio 0.5-to-1 ratio established above as follows:

100* (0.5 * 0.77) = **38.5% reduction in sediment loads**

Volume reduction between 1940 and 2001 at Adkins Pond
= 77 acre-ft – 29.8 acre-ft = 47.2 acre-ft

Volume reduction rate = 47.2 acre-ft/61 years = 0.7738 acre-ft/year = 955 m^3/year.

Applying the 38.5% reduction to the current estimation of 955m^3 of sediments per year, results in the estimated reduction = (38.5% x 955) =368 m^3/year reduction

TMDL for sediments = 955 –368= **587 m^3/year allowable sediment load**

To estimate annual accumulation associated with this loading rate, we first considered the current accumulation rate. That is, 47.2 acre-ft of 77 acre-ft, or 61% of the volume, was displaced between 1940 and 2001 (61 years). Assuming a 38.5% reduction in sediment loading, the current rate of pond volume displacement will be reduced accordingly. Thus, rather than a 61% loss of volume over 61 years, we would expect a 38% loss of volume over 61 years, computed as:

$$\frac{\text{61\% displacement in 61 years}}{\text{100\% current loading}} = \frac{\text{X\% displacement in 61 years}}{\text{61.5\% (100\%-38.5\%)}}$$

or 0.61/1 = X/0.615
X = (0.615)(0.61) = 0.375 = 37.5% (volume displacement over 61 years)
Volume retained after 61 years = 100% - 37.5% = 62.5% or 63%

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 Adkins Pond) 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).