pennsylvania
DEPARTMENT OF ENVIRONMENTAL PROTECTION

BUREAU OF CLEAN WATER

EVALUATIONS OF PHOSPHORUS DISCHARGES TO LAKES, PONDS, AND IMPOUNDMENTS

JULY 2013

EVALUATIONS OF PHOSPHORUS DISCHARGES TO LAKES, PONDS, AND IMPOUNDMENTS

APPENDIX A

LAKE SURVEY PROTOCOL AND METHODOLOGY

INTRODUCTION

This section sets forth the protocol and methodology for the implementation of Section 96.3 and 96.5(b). The protocol relies on calculated Trophic State Indices (TSI) to identify the lake trophic status (i.e., lake quality as defined by productivity) and an empirical model to predict lake trophic quality at various phosphorus (P) loading levels. The data requirements, sampling protocols and interpretive guidance to conduct surveys are detailed below.

A. Lake Survey Protocol

The annual water quality response in a lake is determined by a number of factors. A major factor is the amount of nutrients and sediments which enter the lake directly and via the tributaries. These loads are determined to a large extent by the amount and distribution of rainfall over a given period, watershed characteristics, and point and nonpoint sources of nutrients. The biological response to these nutrients is affected by several factors, the two most important being ambient water temperature and incident sunlight. The nature of the biological response influences other water quality parameters such as dissolved oxygen (DO), water transparency, chlorophyll-a, and pH. Thus, the required data parameters are: nutrients (phosphorus (P) and nitrogen (N)), chlorophyll-a, and water transparency (Secchi depth), as well as vertical profiles for temperature, DO and pH. Sampling procedures for each of these parameters are discussed below and summarized in Table A-1.

Nutrients - The two major nutrients which affect lake productivity are phosphorus (P) and nitrogen (N). In the majority of Pennsylvania lakes, P is the limiting nutrient - that is, P is the nutrient in least supply, so it limits productivity. The limiting nutrient can be determined by calculating the N/P ratios. An N/P ratio of greater than 15:1 indicates a phosphorus limitation; less than 7:1 indicates nitrogen limitation. Ratios between 7:1 and 15:1 indicate co-nutrient limitation.

B. Selection of Recommended Lake Model(s)

Selection of one model that can be applied to the various bodies of water throughout Pennsylvania is difficult. This is partly due to the limitations under which these models were developed, the variety of point and nonpoint loads that contribute P loads, and a wide spectrum of a lake's physical, chemical and biological characteristics. It now appears that the most applicable of these empirical models for impounded waters in Pennsylvania are those by: Vollenweider; Jones and Bachman; Larsen and Merceir; and Reckhow.

In 1981, EPA proposed a "draft simplified methodology" for evaluating the phosphorus effluent limitations on point source discharges. The recommended methodology used the Carlson TSI in developing Lake Trophic State classification and the Reckhow empirical models. These models will be used until changed (in writing) by the Division of Water Quality Standards. Currently, three of the four Reckhow empirical models have been programmed for personal computers and they are illustrated in Appendix B, Table B-1.

C. Documentation of Model Computer Program

Two Oxic Lake Models and one Anoxic Lake Model, all developed by Reckhow, were selected as the most representative models applicable for lakes in Pennsylvania. The anoxic model should be used if DO depletion (DO <1.0 mg/l) occurs in the hypolimnion during the summer stratification of the lake. In cases where DO depletion does not occur, the appropriate oxic model should be selected. The input and output routines for all models are essentially the same. The user will select the correct oxic model for use based on Z/T value (see below). The user will determine use of anoxic model based on DO in the hypolimnion.

D. Minimum Data Required for the Model

The following lake/impoundment-related data are necessary to run the lake evaluation models: (1) existing in-lake P concentration (mg/l); (2) mean depth of lake in meters; (3) mean detention time in days; and (4) surface area in acres.

Wastewater discharger data should be recorded and used in the calculations. Information needed includes: total number of discharges; for each discharge, record (a) discharger name; (b) permit #; (c) existing flow (mgd); (d) permitted design flow (mgd); (e) existing permit P limits (mg/l); and (f) average P limits (mg/l) actually met.

Refer to the formulas in Table B-1. The logic of the calculations follows: calculate existing total loads on the impoundment from both point and NPS based upon the in-lake P concentration.
(1) Calculate load contributions from existing point sources based on total existing flows and weighted average of existing facility performance. For any impoundment with no existing discharges, set this load to be zero;
(2) Subtract the existing point source load contribution from the total in-lake load to determine existing NPS load contributions. This NPS load is converted to a P concentration and a corresponding TSI for the NPS;
(3) Evaluate a nutrient loading scenario, assuming existing point sources at design flow and no P controls. The model assumes that all of the existing (and proposed) discharges will discharge 8 mg/l of P in their effluents. This load is converted into P concentration and a corresponding TSI with no point source controls;
(4) Finally, compare the NPS TSI (from Step 2) and the "no P.S. Control TSI (from Step 3)" with the P control decision matrix (see tables of Appendix C). Determine the appropriate P control levels and/or any other action such as diagnostic studies or ecosystem monitoring, based on Tables C-1 and C-2.

LAKE EVALUATION MODEL

This section provides a summary of available impoundment water quality evaluations models, and discusses the lake models selected for use in Pennsylvania.

A. Summary of Available Lake Models

There are basically two types of predictive models: dynamic and empirical. Dynamic models are waterbody specific and have extensive data requirements for development, calibration and verifications. These are complex models that consist of a series of interrelated differential equations which attempt to define the chemical, physical, and biological reactions and inter-reactions governing algae growth, including nutrient loads, light and temperature. The use of dynamic models has in the past been limited to site-specific situations.

Empirical models, on the other hand, are derived from available data. They are statistical regressions that quantify a basic cause and effect relationship. They do not attempt to account for or describe every component of the eutrophication process. They are generally “black box” type approaches to relating nutrient (P) inputs to the resultant trophic water quality response.

Empirical models are more generally applicable than dynamic models and they have less extensive data requirements. There are several prominent empirical models in use, all of which are similar in principal. Variables used in most empirical models include surface P loading rates, mean lake depth, hydraulic retention time, and surface hydraulic loading rate. Mahannah and Bhagut and Mueller have evaluated prediction performance of six commonly used empirical models. Reckhow also compared eight empirical models relating to developmental data base, known constraints, known basis and considerations of uncertainty.

The following N and P species should be analyzed in performing lake surveys: Total phosphorus, total nitrogen and ammonia. Water samples should be collected at depths of 1 meter below the surface and 1 meter above the bottom with a Kemmerer or VanDorn sampler and immediately placed on ice.

Note: If sampling data indicate that the lake is nitrogen limited throughout the growing season, this procedure (protocol) is not applicable. These cases should be referred to the Water Quality Monitoring and Assessment Section of the Division of Water Quality Assessment and Standards for additional review and consideration.

<u>Chlorophyll-a</u> - Chlorophyll-a is an indicator of primary productivity. The higher the values, the more productive the ecosystem. Lake water for measurement of chlorophyll pigments should be filtered through a 47 mm diameter glass fiber filter (Gelman type A/E). The filters should then be placed in individual vials, covered with aluminum foil, double-bagged in clear plastic zipseal bags, packed in ice (dry ice if available) and held in the dark until delivery to the lab. The filters are then frozen until extraction and quantitative measurements are performed.

Water Transparency - The transparency of the water column can be used as an indicator of lake productivity, with some exceptions (e.g., naturally turbid lakes, or lakes with dense macrophyte growth). Generally, the more productive a lake, the more algae in the water column, and the lower the transparency. A Secchi disk is a common method of evaluating such transparency. The disk should be lowered through the water column until it is no longer visible and then raised until it reappears. This averaged depth should be recorded in tenths of a meter.

TABLE A- 1: SUMMARY OF DATA REQUIREMENTS AND SAMPLING METHODOLOGIES FOR THE LAKE TROPHIC STATE ANALYSES

Parameter	Symbol	Collection Method	Collection Area	Filtration	Storage or Special Handling
Total Alkalinity	TAlk	Kemmerer or Van Dorn sampler	1 meter below surface and 1 meter above bottom	No	Cool, 4°C
Total Phosphorus	TP	Kemmerer or Van Dorn sampler	1 meter below surface and 1 meter above bottom	No	Cool, 4°C Field fix to pH <2 with H_2SO_4
Total Nitrogen	TN	Kemmerer or Van Dorn sampler	1 meter below surface and 1 meter above bottom	No	Cool, 4°C
Ammonia	TNH_3	Kemmerer or Van Dorn sampler	1 meter below surface and 1 meter above bottom	No	Cool, 4°C Field fix to pH <2 with H_2SO_4
Chlorophyll-a	Chl-a	Kemmerer or Van Dorn sampler	1 m below surface	47 mm diameter glass fiber filter (Gelman Type A/E)	Pack in ice or dry ice, shield from light; freeze in laboratory until analyzed
Transparency	Tr	Secchi disk	Until no longer visible in water column	N.A.	N.A.
pH	pH	pH meter, HydroLab or equivalent	Thru water column at 1 meter intervals	N.A.	N.A.
Specific Conductivity	SC	Specific conductivity meter, HydroLab or equivalent	Thru water column at 1 meter intervals	N.A.	N.A.
Dissolved Oxygen	DO	DO meter, HydroLab or equivalent	Thru water column at 1 meter intervals	N.A.	N.A.
Temperature	Temp	Field thermometer, HydroLab or equivalent	Thru water column at 1 meter intervals	N.A.	N.A.

N.A. - Not Applicable

Water Temperature, DO, pH and Specific Conductance - Although these parameters are not directly used in calculating the TSI determination, they are useful in further defining and clarifying the quality and condition of a lake based on lake stratification characteristics. Most deeper Pennsylvania lakes will thermally stratify during the summer months. The lighter, warmer water will float on top of the heavier, cooler water. The different densities of the warmer and cooler waters prevent mixing of the two layers. During this time, a eutrophic lake will experience total (or near total) DO depletion of the lower layers (hypolimnion) due to the oxygen demand of decomposing organic materials. At the same time, specific conductance will increase due to the release of ions from the sediments under these anaerobic conditions, and pH will decrease due to the formation of carbon dioxide. These parameters should be measured in the deepest part of the lake at 1 meter vertical intervals, and the data so recorded.

Sampling Frequency - It is, of course, desirable to have as much data as possible in developing a lake trophic profile. Weekly sampling throughout a growing season would be ideal. However, in most cases this is not practical. Therefore, a minimum of three sampling periods is required. These should be during or as close as possible to spring overturn, during peak growing season (July or August), and during or as close as possible to autumn overturn. This sampling regime is consistent with those which were used during the EPA National Eutrophication Survey in Pennsylvania (1972) and Trophic Classification of Twenty-Six Publicly Owned Pennsylvania Lakes (1981).

Sampling Locations - A minimum of two sampling stations is required: one in the deepest part of the lake (usually near the outfall) and one near the lake inlet. Additional stations may be needed on larger lakes or on those with unique morphological characteristics, such as a lake with many embayments. In some cases, the Trophic Status of an embayment may differ significantly from the main body of the lake. In these cases, if the discharge being evaluated is to the embayment, the embayment TSI should be used in calculating P treatment requirements.

b. Document and Evaluate Survey Findings

Documenting Survey Data - A necessary requirement for any scientific study is to accurately organize record data and observations in a logical and consistent format. Appendix D contains the suggested Field Data Collection Sheet which should be utilized for all Section 96.3 and/or 96.5(b) Lake and Impoundment Studies. Any specific observation or finding not on the data sheet should be described in the remarks section.

The Lake Trophic classification system is a direct function of available data and is only as good as these data. The water quality variables that are used to assign a TSI are dynamic and are influenced by many variables, both biotic and abiotic. The data used to make a Trophic State assessment should be as comprehensive and diverse as practical.

Determining Lake TSI - Once the samples have been collected and the data analyzed, the trophic state of the lake should be determined using the following formulas:

Secchi TSI = 10(6 - (ln SD/ln2)) where SD is the measured Secchi Depth in meters and ln is natural log.

Chlorophyll-a TSI = 10(6 – ((2.04 – 0.68*ln CHL))/ln2) where CHL is the measured chlorophyll-a concentration in ug/L (or mg/m3) and ln is natural log.

Total Phosphorus TSI = 10(6 – (ln(48/TP))/ln 2), where TP is the total phosphorus concentration in ug/L and ln is natural log.

TSI calculations on total nitrogen are a fairly new development and are used in conjunction with the other three.

Total Nitrogen = 54.45 + 14.43 ln(TN), where TN is the total nitrogen concentration in mg/L and ln is natural log.

The Carlson TSI is shown with its related parameters below in Table A-2. For the phosphorus TSI, the average of three sample readings of total P 1 meter below surface will be used to determine in-lake P for the model. TSIs can also be calculated from average Secchi readings and chl-a levels. This Index does not specifically label a lake as to trophic state, but instead provides a relative numerical ranking according to the measured values of three parameters (total P, chlorophyll-a, Secchi depth).

A comparison of this index to other ranking systems indicates that lakes with a TSI value of less than 40 are oligotrophic, and those with a value of greater than 50 are eutrophic.

TABLE A-2: CARLSON'S TROPHIC STATE INDEX

TSI	Secchi Disk (m)	Near Surface phosphorus (µg/l)	Surface chlorophyll (µg/l)
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.34
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1,183

c. Interpretation Survey Data

Although the relationships among the water quality variables used in TSI determinations have been developed through extensive statistical correlations, in some cases significant deviation from expected values or range of values arises. For example, a lack of increased chlorophyll-a in response to measured high phosphorus concentrations could be indicative of several possibilities including analytical error, nitrogen limitation, micro-nutrient limitation, luxuriant macrophyte growth, or even a toxic substance such as in acid mine drainage. If disparities are observed throughout all sampling periods (spring overturn, summer, fall overturn), additional field studies and laboratory algal assays may be needed in order to establish definitive cause/effect relationships.

The profiles of temperature, DO, pH and conductivity should be used to support and clarify TSI determinations. For example, in a stratified eutrophic lake, oxygen depletion generally occurs in the bottom layer (hypolimnion) with concurrent increases in conductivity and decreases in pH.

d. Prepare Survey Report

The regional biologist who conducted or helped to conduct the survey and evaluate the data should draft a report summarizing the major findings, conclusions and recommendations of the survey. A suggested report outline and format is provided below.

e. Lake Survey Report Format

<u>Introduction</u> - Include a general statement relating to the purpose of the survey (in accordance with Section 96.3 and/or 96.5(b)), dates of data collection, and a description of the location that includes latitude, longitude and the county and quadrangle names.

<u>Drainage Basin Characteristics</u> - Provide details on size, geology, soils and land use: (percent urban, suburban, agricultural, forest, lake surface).

<u>Hydrology</u> - Provide details on inflows, outflows and mean retention time.

<u>Major Point Source Waste Discharges in Watershed</u> - Note all discharges, NPDES permit numbers, type of waterbody (tributary or directly to the lake) and waterflow volume.

<u>Nonpoint Sources (NPS) of Pollution</u> - NPS concerns, such as agricultural runoff, malfunctioning septic systems and urban runoff should be described.

<u>Discussion</u> - Reference historical data, if any, which relates to water quality in the lake (e.g., reported nuisance algal blooms, excessive macrophyte growth which required chemical treatment, or impaired designated water uses).

Provide a detailed evaluation of the current data and its relationship to lake water quality and the TSI (i.e., the use of the P, chlorophyll-a, and Secchi disk data in the Carlson TSI). Reference the pH, temperature, DO and specific conductivity vertical profile data in the lake quality characterization. Based on these data, provide materials for the chosen model (oxic or anoxic) and discuss the results of the modeling exercise in developing P treatment requirements.

These Appendices should be attached to the Lake Survey Report:

A. Data Tabulation

B. Profiles for Temperature, DO, pH and Specific Conductivity

C. Lake Model Results

References

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APPENDIX B

LAKE PHOSPHORUS LOADING
EUTROPHICATION RESPONSE MODEL

TABLE B-1
RECKHOW MODELS

The Reckhow models listed below are used consistent with appropriate physical and/or stratification characteristics of the lake. These have been computer programmed.

1. Oxic lakes with z/t < 50 m/yr

$$P = \frac{L}{\frac{18z}{10+z} + 1.05\left(\frac{z}{t}\right)^{0.012z/t}}$$

2. Oxic lakes with z/t > 50 m/yr

$$P = \frac{L}{2.77z + 1.05(z/t)^{0.0011z/t}}$$

3. Anoxic Lakes

$$P = \frac{L}{0.17z + 1.13\left(\frac{z}{t}\right)}$$

Where :

P = lake phosphorus concentration (mg/l).
z = lake mean depth (m).
t = Hydraulic retention time (yr).
L = annual areal phosphorus loading rate ($g/m^2/yr$).

APPENDIX C

PHOSPHORUS CONTROL
DECISION MATRIX

Phosphorus Control Decision Process

The model for establishing the TSI of an impoundment and determining the P control requirements for wastewater discharges calculates the existing total loads to the impoundment from both point and nonpoint sources based upon the in-lake P concentration. Then the program:

(1) Calculates load contributions from existing point sources based on total existing flows and the weighted average of existing facility performance. For any impoundment with no existing discharges, the model calculates this load to be zero.

(2) Subtracts the existing point source load contribution from the total in-lake load to determine existing NPS load contributions. This NPS load is converted to a P concentration and a corresponding TSI for the NPS.

(3) Evaluates a nutrient loading scenario, assuming existing point sources at design flow without any P controls. The model assumes that all of the existing (and proposed) facilities will discharge 8 mg/l of P in their effluents. Again, this load is converted into P concentration and a corresponding TSI with no point source controls.

(4) Compares the NPS TSI from Step 2 and the "no P.S. Control TSI" from Step 3 with a built-in P control decision matrix, (shown in tables C-1, C-2 and C-3). Tables C-1 thru C-3 show appropriate P control levels for all discharges and/or recommends other appropriate actions, such as diagnostic studies or ecosystem monitoring.

Nonpoint Source Assessment

The regulation for controlling P discharges to lakes, ponds and impoundments, and the corresponding implementation procedures are intended primarily to determine the need for and levels of point source controls. In making such determinations, it is assumed that Best Management Practices (BMPs) for NPS are in place. However, recognizing that BMPs for NPS may not, in fact, be in place, the model can also be used to estimate the extent of NPS P loading to an impounded body of water. As specified in item (2) above, the model "---subtracts the existing point source load contribution from the total in-lake load to determine existing NPS load contributions. Then NPS load is converted to a P concentration and a corresponding TSI for NPS."

Although the model does not differentiate between the individual loadings due to various NPS (e.g., runoff from agriculture, pastures, urban or forest areas, atmospheric deposition, septic system infiltration, groundwater or in-lake recycling), some gross interpretation of NPS contribution may be possible from general land use information. This information could then be used to estimate the lake trophic status improvement that could be expected if controls were implemented for the significant NPS.

Diagnostic-feasibility studies are necessary to determine specific NPS contributions. The implementation guidance, as currently written, requires such studies only when a lake is determined to be hypereutrophic and the imposition of point source P controls would not result in any significant improvement in lake trophic status (i.e., the impoundment would remain hypereutrophic even if stringent point source P controls were imposed). However, diagnostic-feasibility studies could also be required for any lake for which NPS are determined to be the dominant source of P loading, especially in those cases when the TSI is greater than 60.

TABLES C-1 & C-2
P-CTRL DECISION MATRIX

Table C-1

Present (or adjusted) TSI*	Estimated TSI W/PS Discharge(s) With No PS Controls		
	<45	45-80	>80
<45	1	See Table C-2	2
45-80	______		3
>80	______	______	4

*From NPS only, for impoundment with no existing PS discharges, the adjusted TSI is equivalent to the present TSI.

1,2,3,4 - See Table C-3

Table C-2

Estimated TSI w/PS Discharge(s) and No Controls	Required Level of PS Controls	Commentary
<45	No P Control Needed (*)	______
46-59	No P Control Needed (*)	______
60-65	2 mg/l	Ecosystem response should be monitored
66-80	1 mg/l	Ecosystem response should be monitored

* Secondary treatment or equivalent is considered adequate. For evaluation purposes, this is interpreted as 8 mg/l of P in the effluent.

TABLE C-3
RECOMMENDED POINT SOURCE PHOSPHORUS CONTROLS

Scenario #	Present/Predicted Trophic State	Recommended PS P-Controls
1	Lake is presently Oligotrophic and is expected to remain in this state following the introduction of PS discharge(s).	No PS P-Controls necessary.
2	Lake is presently Oligotrophic, but is expected to become Hypereutrophic with the introduction of PS discharge(s).	PS P-Controls of 1 mg/l should be implemented immediately; more stringent controls may be needed depending on observed ecosystem response.
3	Lake is presently Mesotrophic/Eutrophic, but is expected to become Hypereutrophic with the introduction of PS discharge(s).	Same as 2.
4	Lake is presently Hypereutrophic, and will remain in this state with introduction of PS discharge(s).	Any determination on PS P-Controls should be deferred until a lake diagnostic study is performed.

APPENDIX D

LAKE/RESERVOIR FIELD DATA SHEET

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pennsylvania
DEPARTMENT OF ENVIRONMENTAL PROTECTION

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL PROTECTION
BUREAU OF POINT AND NON-POINT SOURCE MANAGEMENT

LAKE/RESERVOIR FIELD DATA SHEET

Lake Name ______________________ County ______________________

Station ______________________ Lat. __________ Long __________

Date __________ Time __________ Collectors ______________________

Weather ____

Cloud Cover (%) 0 25 50 75 100 Comments (Hazy/Foggy) __________

Wind Conditions: None Light Moderate Heavy Direction ______________________

Rain Conditions: None Drizzle Light Moderate Heavy

Surface Turbulence ______________________ Air Temperature (ºC) ______________________

Station Depth (meters) ______________________

SECCHI DISK READING (TENTHS OF A METER) __________

FIELD MEASUREMENTS

DEPTH (meter)	TEMP (ºC)	D.O. (ppm)	pH	Sp. Cond. (Umhos)	DEPTH (meter)	TEMP (ºC)	D.O. (ppm)	pH	Sp. Cond. (Umhos)
surface					11M				
1M					12M				
2M					13M				
3M					14M				
4M					15M				
5M					16M				
6M					17M				
7M					18M				
8M					19M				
9M					20M				
10M									

SAMPLES COLLECTED

TYPE/DEPTH	SAC	VOLUME FILTERED	TIME COLL.	COLLECTION NUMBER
WATER QUALITY (Top)				
WATER QUALITY (Bottom) Depth of Sample:				
CHLOROPHYLL A				
OTHER (blank/dup.)				
PLANKTON TOW (2x _____m net diameter = _____")				

COMMENTS: ____

____

____

____