January 2005 Report of the Academic Advisory Committee To Virginia Department of Environmental Quality: Freshwater Nutrient Criteria

Submitted to:

Division of Water Quality Programs
Virginia Department of Environmental Quality

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Table of Contents

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Acronyms and Abbreviations

AAC: Academic Advisory Committee
ac: acre
AFDM: ash free dry mass
cfs: cubic feet per second
Chl-a: chlorophyll-a
DCR: Virginia Department of Conservation and Recreation
Dep: depth
DEQ: Virginia Department of Environmental Quality
DO: dissolved oxygen
EPA: U.S. Environmental Protection Agency
ft: feet
ha: hectare
Int: intercept
kg: kilogram
L: liter
m: meter
μg/L: micrograms per liter (1 μg/L = 0.001 mg/L)
mg/L: milligrams per liter (1 mg/L = 1,000 μg/L)
mg/m^2: milligrams per square meter
n: number of observations in a sample (sample size)
N: nitrogen
NES: National Eutrophic Survey
NO_2^-: nitrite
NO_3^-: nitrate
P: phosphorus
r: coefficient of correlation for a sample
r^2: coefficient of determination for a sample
R^2: coefficient of multiple determination
Res: residence time
SA: surface area
SD: Secchi depth
SWCB: State Water Control Board
TN: total nitrogen
TP: total phosphorous
TSI: trophic state index
TSS: total suspended solids
USEPA: United States Environmental Protection Agency
USGS: United States Geological Survey
VDGIF: Virginia Department of Game and Inland Fisheries
Vol: volume

Introduction

This interim report of the Academic Advisory Committee (AAC) to the Virginia Department of Environmental Quality (DEQ) contains information intended to aid DEQ's development of nutrient criteria for the state of Virginia in a manner which is compliant with EPA requirements. This report builds upon an earlier report prepared by the AAC in July of 2004 (AAC 2004), which contains background and justification for the procedures employed. The report addresses issues related to freshwater nutrient criteria development for lakes and reservoirs (Section I) and rivers and streams (Section II). It includes six appendices: a summary of lake data used in this report (Appendix A), a paper comparing two reservoirs in Virginia (Appendix B), responses to DEQ questions concerning dissolved oxygen criteria for lakes (Appendix C), and three research proposals to study nutrient relationships in freshwater streams (Appendices D-F).

I. Lakes and Reservoirs

Although referred to as lakes throughout this document, the AAC analyses and recommendations in the current report apply only to Virginia's constructed impoundments. The AAC has recommended that DEQ address nutrient criteria for the state's two natural lakes (Mountain Lake and Lake Drummond) separately.

A. Preliminary Analyses

Ambient monitoring data from lakes and reservoirs were provided to the AAC by DEQ. The data included nutrient parameters (various forms of water-column nitrogen and phosphorous, Secchi depths [SD], and chlorophyll-a [Chl-a]), suspended and dissolved solids, and context variables such as location, depth, and date/time of sampling. Monitoring locations were specified as 8-digit alphanumeric monitoring location codes. DEQ personnel supplied the AAC with additional information including the lake names and ecoregion locations corresponding with DEQ monitoring location codes, and physical parameters for a limited number of lakes. Some of the lakes in the database were represented by multiple monitoring locations.

Only observations from 1 meter or less in depth were used in the data analyses. Based on recommendations by DEQ personnel following EPA practice in developing guidance criteria, only data from 1990 or later were considered in the analyses that follow. Total phosphorous (TP) values listed as equal to or less than a 0.1 mg/L detection limit were discarded; all other observations recorded as equal to or less than a detection limit were represented in the analyses as the detection-limit value, considering that detection-limit values were low compared to the bulk of the recorded observations and compared to the concentrations of concern in the current analysis. Analyses that considered water-column nutrient concentrations were conducted using total nitrogen (TN) and TP. The TN variable was calculated from measured components using the following logic:

If TN is measured, TN = measured value.
Else TN = nitrate-nitrite N (NN) + Total Kjeldahl nitrogen (TKN)

If NN is measured, NN = measured value.
Else NN = NO_2-N + NO_3-N

The TN variable was calculated for each sampling record for which all necessary components were available.

Data Structure

Although 112 lakes were represented by over 10,000 observed values of SD, Chl-a, TN, and TP (nutrient variables) in DEQ's data record since the beginning of 1990, those observations were distributed unevenly over the monitored lakes. Thirty-eight lakes averaged 10 or more observations per each nutrient variable, while another 33 averaged 5 to 9 observations per variable (Figure 1).

Those observations are distributed unevenly through time, as DEQ's approach to lake monitoring changed during the period of analysis. Prior to 1999, DEQ rarely collected monitoring data throughout the warm-weather season at individual lakes and recorded SD infrequently. SD measurements have been routinely collected by DEQ (and precursor agency State Water Control Board) at lakes since the early 1970s but only in recent years have the data been electronically recorded and readily accessible. Of Chl-a observations prior to 1999, 21% are accompanied by SD measurements. In recent years, DEQ has increased the frequency and consistency of lake monitoring procedures, and the majority of locations monitored are represented by data collected throughout the warm-weather season (Table 1). Current lakes' monitoring procedures include 7 months of data collection at each lake monitored during a given year (April – October). Since and including 1999, 76% of Chl-a observations are accompanied by SD measurements. Sixty nine percent of the total 1990-2003 observations in the database represent the 1999-2003 period (Figure 2). The fact that lake conditions in more recent years are heavily represented in the database is an asset to the current analyses.

The analyses were conducted using the EPA-recommended approach of considering each lake to be a sampling unit. Within this context, the uneven distribution of monitoring observations among lakes creates analytical difficulties. On one hand, it is desirable to conduct the analyses using the largest number of lakes possible so as to be able to derive conclusions based on water sampling data that are representative of conditions across the state and of temporal and regional variations. However, achieving such a sample size requires data from lakes with well documented conditions (i.e., with sufficient numbers of observations and a distribution through time to represent both annual and seasonal variability) be considered as equivalent to those represented by many fewer observations.

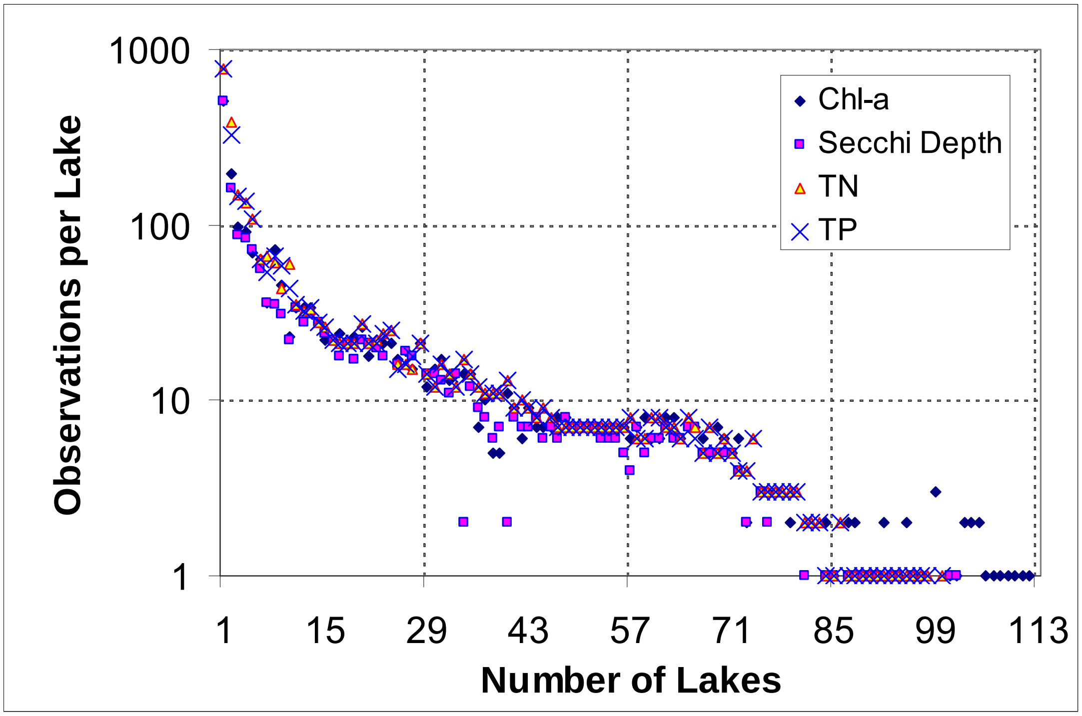


Figure 1. Number of observations per lake for the four primary nutrient variables considered for nutrient criteria development. Lakes are ordered by number of Chl-a observations

Table 1. DEQ lake monitoring data for nutrient variables available by year, 1990-2003.

Year	90	91	92	93	94	95	96	97	98	99	00	01	02	03	Sum
Lakes with Monitoring Data															
SD	1	2	3	6	9	13	16	5	8	10	10	24	31	25	163
Chl-a	29	12	13	21	13	20	20	10	12	11	15	28	32	28	264
TN	13	9	7	12	13	20	20	9	12	11	15	28	32	28	229
TP	13	10	8	12	13	19	20	8	12	11	15	28	32	28	229
Lakes with at least one observation per month, May - Sept															
SD	0	0	0	0	0	0	0	0	0	5	0	9	15	10	39
Chl-a	1	0	0	1	1	1	1	1	1	6	8	17	21	20	79
TN	0	0	0	1	1	1	1	1	1	6	8	17	18	18	73
TP	0	0	0	0	0	0	0	0	0	6	8	17	18	17	66
Total observations, all lakes															
SD	1	4	4	12	36	43	96	88	105	212	115	333	437	291	1777
Chl-a	288	57	46	68	76	101	157	144	198	252	324	503	473	366	3053
TN	122	41	24	48	76	99	155	141	143	233	308	496	466	348	2700
TP	105	45	31	38	68	90	139	129	135	228	315	496	466	350	2635

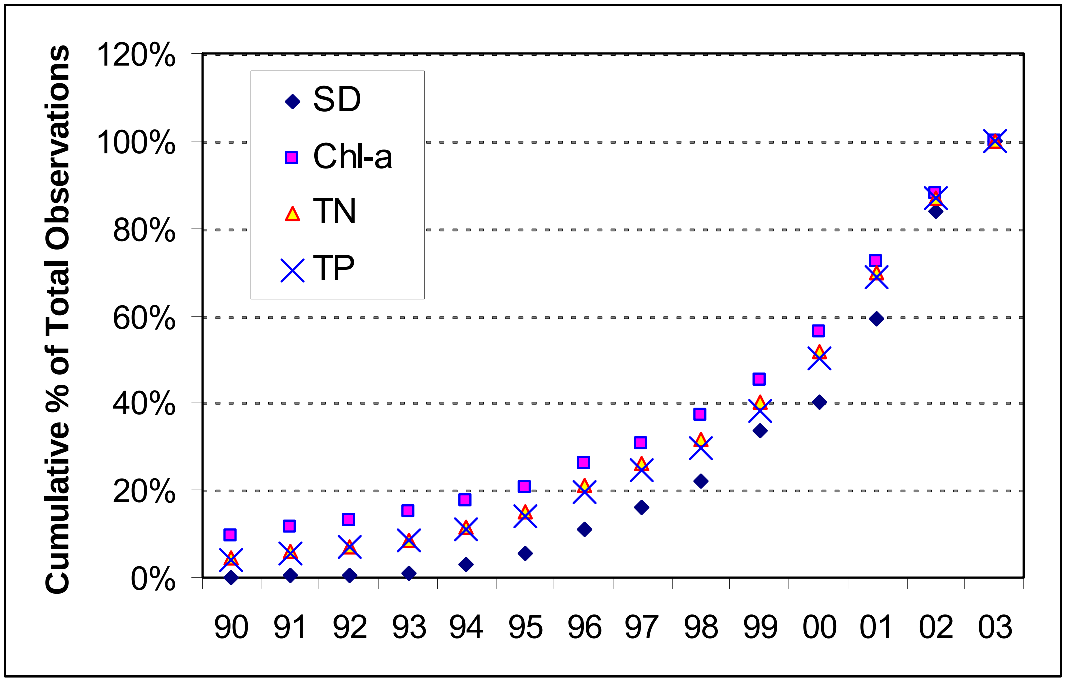


Figure 2. Cumulative frequency of observations, 1990-2003.

Seasonality

An underlying assumption of nutrient criteria development for lakes and reservoirs is that their response to nutrient inputs varies seasonally. Therefore, a preliminary analysis was conducted to characterize seasonal variations of nutrient variables in Virginia lakes and reservoirs. In addition to the four primary nutrient variables, the analysis was also conducted for total suspended solids (TSS) because TSS levels can be expected to influence measured TP concentrations, Secchi depths, and the algal biomass response to available phosphorous in the water column.

The analysis was conducted by calculating, for each of the 5 variables of interest and for each lake, a median for each month represented by 1 or more observations. For each variable, lakes were selected for inclusion in the analysis if observations were present in at least 6 of the 7 sampling months (April – October). Using this subset of the DEQ monitoring data, a monthly median was calculated and plotted for each ecoregion (Figures 3 and 4).

Results demonstrate that nutrients and related parameters in Virginia impoundments vary month-to-month and seasonally, but not necessarily in the manner expected based on scientific studies of natural lakes.

Both TN and TP appear to exhibit summer-season minima in ecoregion 14 lakes during August. A similar pattern is evident for ecoregion 9 for TP. We have no ready explanation for this pattern but can state that exploratory application of other calculation methods generated similar patterns. Thus, the pattern does not appear to be an artifact of the analysis method. Chl-a tends to exhibit summer maxima, but these occur later in the summer season than the July-August time frame that is commonly assumed and was expected. SD fails to exhibit summer minima as expected, possibly due to the influence of non-algal turbidity caused by TSS.

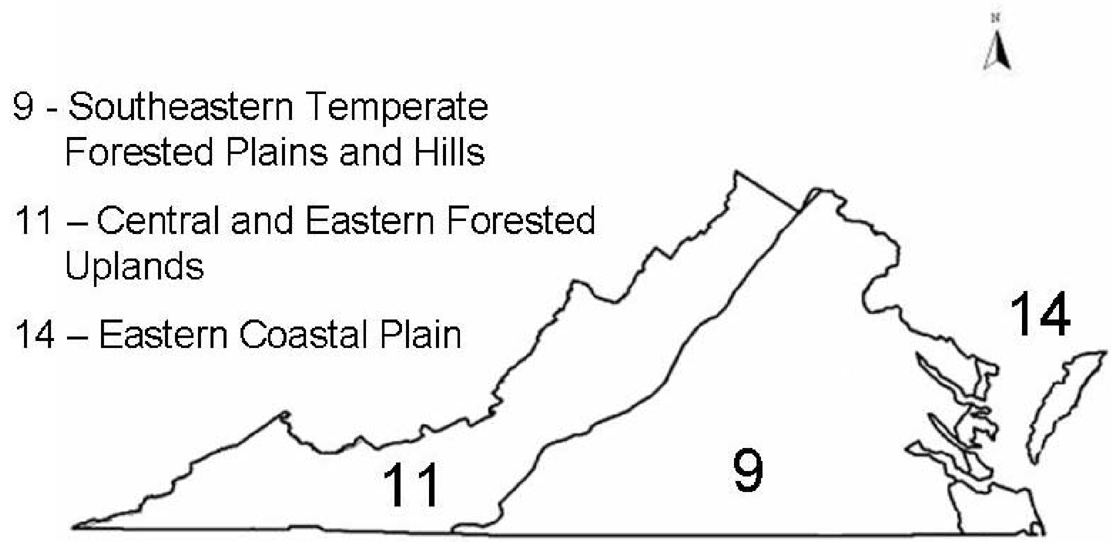


Figure 3. Level III ecoregions in Virginia

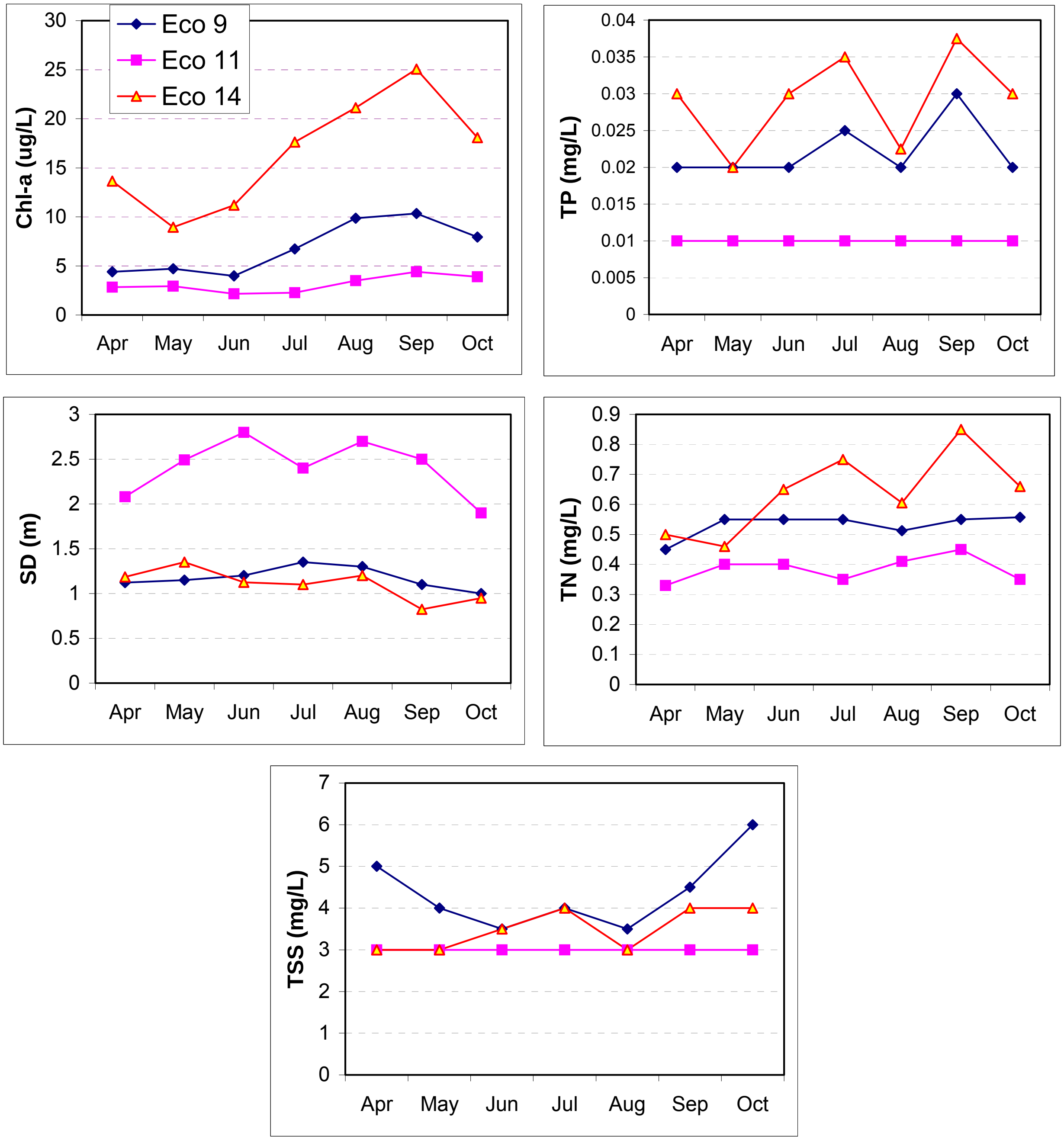


Figure 4. Seasonal variation of nutrient variables and TSS, by ecoregion. The ecoregion 9 plots represent an average of 30 lakes (range = 23 to 36); ecoregion 11 by an average of 16 lakes (range = 15 – 17); and ecoregion 14 by an average of 7 lakes (range = 5 – 8). 3 mg/L TSS and 0.01 mg/L TP represent commonly applied analytical detection limits.

B. Responses to DEQ Questions

Analysis of DEQ monitoring data, information from others sources including scientific literature, and professional judgment were applied to answer five questions relevant to nutrient criteria development.

Question 1: *What would be the implications of using the reference approach to establish nutrient criteria?*

In response to telephone discussions with DEQ personnel in November of 2004, this analysis was conducted using procedures described (USEPA 2000a, b, and c) and used by EPA to calculate the guidance criteria that were published by the agency in July of 2002 (USEPA 2002). In conducting this analysis, we applied minor modifications to the EPA method to accommodate DEQ data characteristics.

The EPA method is to calculate the 25th percentile of medians from all available lakes for Chl-a, TN, and TP, and the 75th percentile of SD medians as surrogates for reference values. We applied this approach.

EPA calculated TN 25th percentiles separately for measured and calculated TN values. We combined measured TN values and calculated TN values because measured values are sparse within DEQ's database. We then calculated a single 25th percentile for TN from the combined data.

EPA recommends that the analysis be conducted by calculating seasonal medians for each lake, and calculating a lake median for each lake from the seasonal medians. The "guidance criteria" percentiles are then calculated from the distribution of lake medians. The EPA documents suggest that a median be calculated for each of the 4 seasons that is represented by data, and a lake median be calculated only when at least 3 seasonal medians are present. We modified the concept of seasons to reflect data availability because the DEQ lake-monitoring program operates from April through October, a seven-month sampling season. We considered three separate methods for aggregating observations from this seven-month sampling period into 4 monitoring "seasons":

1. April – May, June – July, August – September, October (method S1)
2. Equal-length periods: 4/1 – 5/23, 5/24 – 7/16, 7/17 – 9/7, and 9/8 – 10/31 (method S2)
3. April, May – June, July – August, September – October (method S3).

We concluded that none of these methods was ideal, since methods S1 and S3 created seasons of unequal length, and method S2 creates seasons that do not match the DEQ monitoring schedule. Furthermore, a preliminary analysis determined that calculated lake medians and percentiles were, in some cases, influenced by the season-definition method. This influence was greatest for Chl-a and SD, with 25th/75th percentiles varying by more than 10 percent as a function of seasonal definition in some cases. Therefore, we calculated a lake-median and the desired percentiles for each nutrient variable using each of the 3 methods, and report the averages of those values (Table 2, Figure 5) for each ecoregion and for the state. Lakes with estimated residence times of fewer than 5 days were removed from the database prior to analysis (Byllesby, Nottoway Falls, Swift Creek Lake, and Banister). The procedure applied to estimate residence times and its limitations are described below (Question 4). For comparison purposes, the EPA guidance criteria, which were developed for Level III ecoregions at the national scale, are also listed.

Table 2. Results of procedure to calculate reference values for Virginia impoundments through application of EPA methods, and EPA reference values for each ecoregion that contains portions of Virginia.

	Chl-a (µg/L)	**SD** (m)	**TN** (mg/L)	**TP** (mg/L)
Statewide:				
25th percentile	3.65		0.37	0.014
75th percentile		1.78		
Count	67	63	67	67
Ecoregion 9:				
25th percentile	3.99		0.44	0.020
75th percentile		1.45		
Count	38	36	38	38
EPA Guidance	4.93	1.53	0.36	0.020
Ecoregion 11:				
25th percentile	2.50		0.29	0.010
75th percentile		3.01		
Count	19	17	19	20
EPA Guidance	2.79	2.86	0.46	0.008
Ecoregion 14:				
25th percentile	12.82		0.58	0.028
75th percentile		1.23		
Count	10	8	10	10
EPA Guidance:				
Entire Ecoregion	2.90	4.50	0.32	0.008
Subregion 63[a]	2.10	1.20	0.46	0.020

[a] The portion of Virginia contained within Ecoregion 14 is entirely within Subregion 63. Virginia segments of Ecoregions 9 and 11 are within multiple subregions.

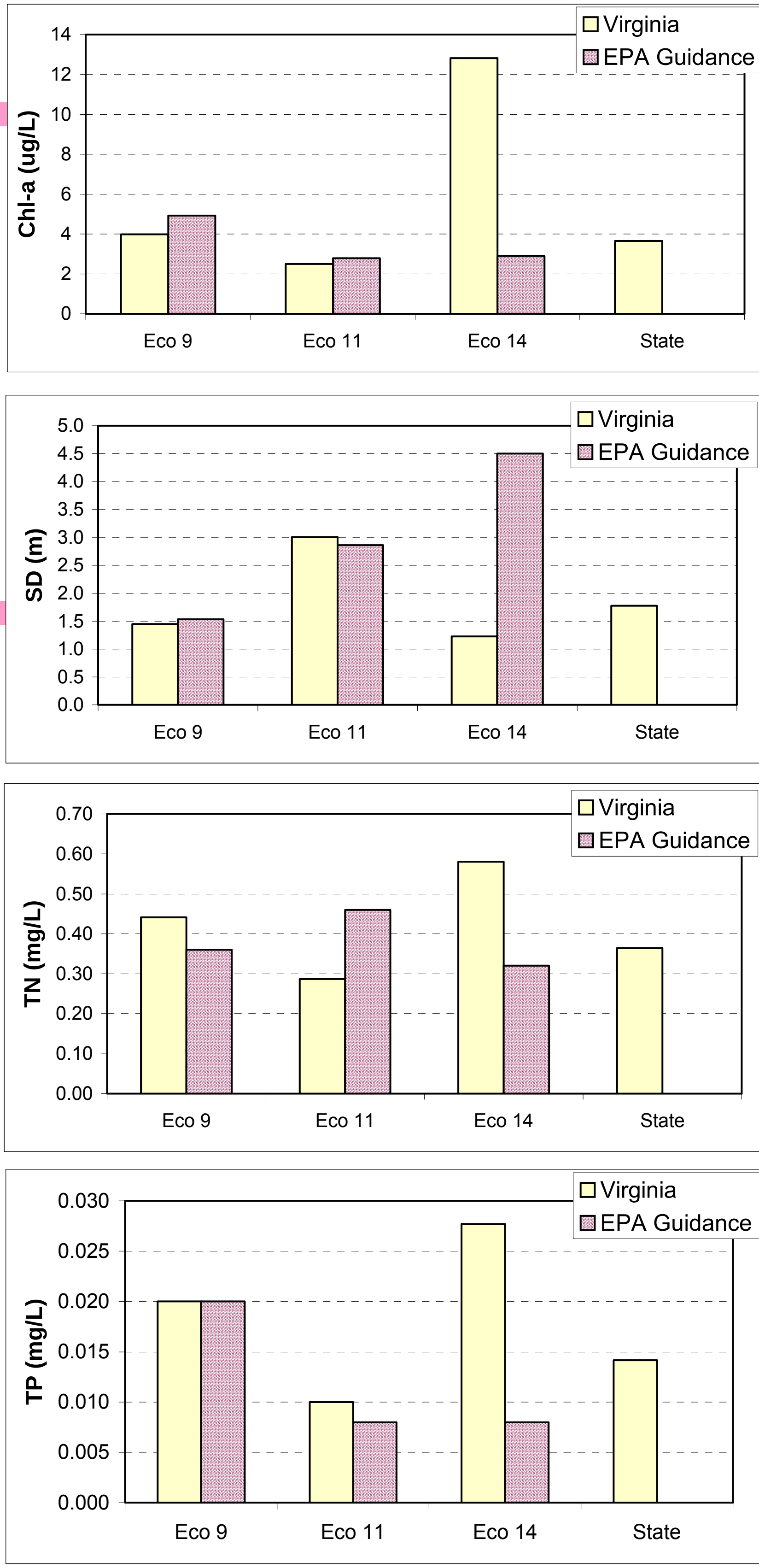


Figure 5. Virginia reference values (25th percentiles for Chl-a, TN, and TP; 75th percentiles for SD) for Virginia Level III ecoregions, and for the state as a whole, and EPA guidance for Level III ecoregions at the national level.

Question 2: *Do lakes' game fish populations vary with the lakes' nutrient status?*

An exploratory analysis was conducted following a modified version of the protocol described in the EPA lakes and reservoirs nutrient criteria guidance document (USEPA, 2000d), which considers each lake as a sampling unit. For each time period considered, the TP and Chl-a status of each lake was characterized as a mean or median value of all sampling observations from that lake.

Indicators of fishery status in Virginia reservoirs were obtained by Dr. John Ney from Virginia Department of Game and Inland Fisheries (VDGIF) biologists. Dr. Ney attended meetings of the biologists from each VDGIF region and, in a discussion format, worked with them to elicit ratings of each lake represented by 5 or more chlorophyll-a observations. The question used to evaluate reservoirs' fishery status was: How well does the water body support desirable species that achieve good growth and attain desirable size? In response to that question, VDGIF biologists rated lakes on the following scale:

1 = poor: VDGIF biologists would recommend that anglers avoid such lakes.
2 = fair: VDGIF biologists would recommend that anglers fishing such lakes not expect much in the way of fishing success.
3 = average: the lake supports an adequate fishery.
4 = good: VDGIF would recommend such a lake for fishing.
5 = excellent: VDGIF would highly recommend such a lake for fishing.

Working with the entire data set, both parametric (Pearson) and non-parametric (Kendall's) correlation analyses of fishery status with nutrient status were performed. Results are displayed in Table 3:

Table 3. Results of exploratory correlation analysis of nutrient variables vs. fishery status.

Vari-able	Aggre-gation	Seasonal Period	n	Pearson: r	Pearson: p	Kendall's: r	Kendall's: p
SD	median	June - Aug	41	0.005	0.976	0.111	0.354
TSS	median	June - Aug	48	-0.156	0.291	-0.072	0.545
TP	mean	April - May	51	0.076	0.598	0.170	0.118
TP	median	April - May	51	0.054	0.707	0.126	0.259
TP	mean	April - Sept	53	0.047	0.740	0.130	0.210
TP	median	April - Sept	53	-0.008	0.954	0.066	0.550
Chl-a	mean	June - Sept	52	0.008	0.957	0.164	0.117
Chl-a	median	June - Sept	52	0.016	0.911	0.099	0.343
Chl-a	mean	July - August	52	0.003	0.984	0.161	0.124
Chl-a	median	July - August	52	-0.009	0.951	0.099	0.343
Chl-a	mean	June - August	52	0.020	0.887	0.173	0.099
Chl-a	median	June - August	52	0.018	0.900	0.110	0.295

Notes: r = correlation coefficient; p = p-value; n = number of lakes considered in each analysis.

This preliminary analysis yielded no useful results. Analysis of data plots confirmed that (a) well defined statistical relationships between nutrient variables (Chl-a and TP) and fishery status, that would be useful in the development of nutrient criteria, are not apparent, and (b) the general form of nutrient variable-fishery status relationships is not subject to major influence by the time period selected for calculation of nutrient variable medians. Fishery nutrient requirements are addressed through an alternative procedure described later in this document (See Section I-C).

Question 3: *Do Virginia lakes demonstrate consistent relationships between water-column nutrient levels (TN and TP) and response variables (Secchi depth, and Chl-a)?*

and

Question 4: *Are there detectable influences of factors such as non-algal turbidity, suspended solids, retention time, etc. that may be used to classify lakes?*

The first step in the procedure employed to answer these two related questions was to estimate residence times for each lake, so as to remove those lakes with abnormally low residence times from the data set. As noted by USEPA (2000d. p. 3-1), "[m]any studies suggest that phytoplankton do not accumulate at retention times less than 7 days."

Data describing physical parameters for some lakes (volume, surface area, drainage area) were provided to the AAC by DEQ, but this data set was incomplete. An additional physical parameter data set for selected lakes was obtained from the Virginia Department of Conservation and Recreation (DCR), Division of Dam Safety. Drainage areas for lakes with water-quality data not represented in either of the above data sets were generated in the Virginia Tech Department of Crop and Soil Environmental Sciences GIS lab. Drainage areas, mean daily flows, latitudes, and longitudes for gaging stations located within Virginia were also obtained (from USGS) for the purposes of developing a model capable of predicting the water-volume yield of each lake's watershed. Average (1961-1990) annual rainfall for all USGS gaging and Virginia DEQ lake monitoring stations were generated in the Department of Crop and Soil Environmental Sciences GIS lab. Several water-yield prediction equations were generated and applied. One problem encountered in application concerned watershed sizes: Whereas only 3 of the gaging station watershed areas were less than 10,000 acres in size, more than 50% of Virginia lakes for which physical parameter are available have drainage areas less than 10,000 acres in size. As a result, the "best" multivariate prediction equations (i.e., highest R^2) were found to produce anomalous results for the small lakes. Therefore, we found it necessary to use a simplified procedure with drainage area as the sole predictive variable for inflow, estimating separate regression parameters for 3 watershed size ranges: less than 10,000 acres, 10,000-50,000 acres, and greater than 50,000 acres. These equations were used to estimate mean inflow to each Virginia lake, and to calculate a mean residence time, for each Virginia lake for which a volume estimate is available.

The calculated residence times are rough estimates. In addition to the inaccuracies resulting from the crudeness of the water-yield estimation procedure, the accuracy of the physical parameter estimates used in the calculation is also questionable. Where both DEQ and DCR provided estimates of physical parameters for lakes, these estimates were often in disagreement. Of the 46 lakes for which DCR and DEQ both provided volumetric estimates, for example, only 15 of these estimates were within 20 percent of one another.

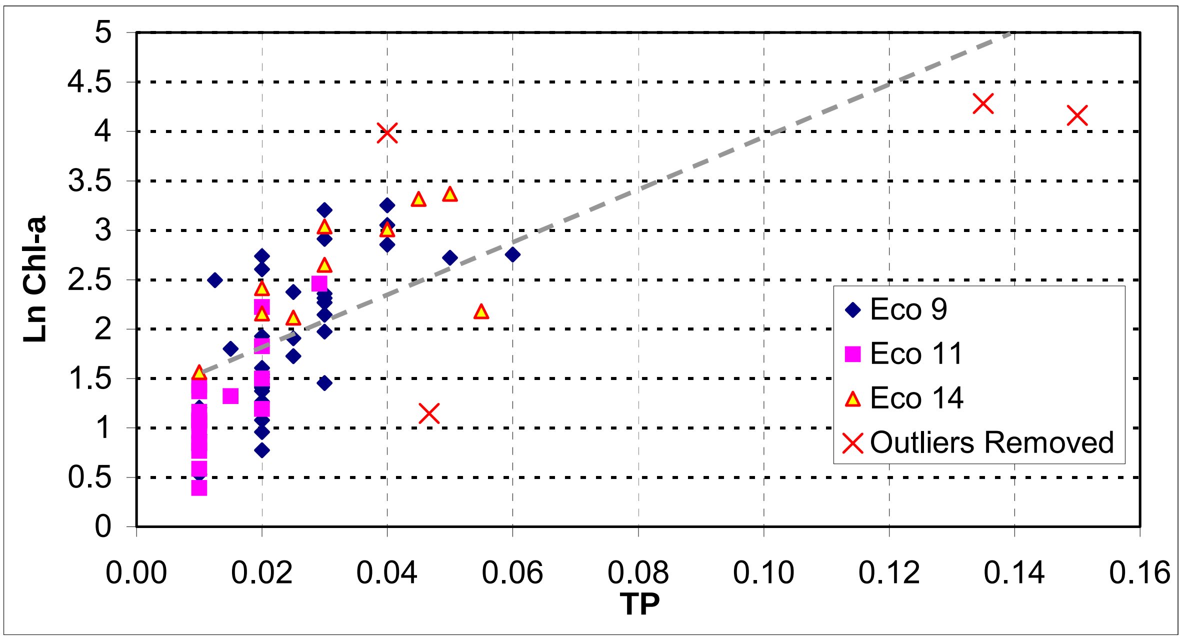
In EPA's guidance manual, it defines lakes as having a "mean water residence time of 14 or more days" and recommends that states that have not set a size limitation defining a lake, determine appropriate size limitation "to eliminate small water bodies that, because of their size (and resulting hydrology) or uses (e.g., small agricultural impoundments), do not accurately represent typical lake conditions or do not exhibit expected responses to stressors" (2000d, p. 3-1). Because of the inherent uncertainty in our calculated residence times, we decided to remove from the data set lakes with a calculated residence time of less than 5 days. Of the 95 lakes for which we were able to calculate residence times, 5 residence-time estimates were below 5 days (these were removed from the analysis), and another 8 were between 5 and 14 days.

The following analysis was performed for TP vs. Chl-a and TN vs. Chl-a, using a median value for each variable to represent each lake. The medians used were the same as those employed for the fisheries analysis below (Section I-C, Virginia DEQ Data Interpretation). Resulting relationships are represented in Figure 6.

Stepwise regressions were performed for the purpose of determining the effect of other variables on the explanatory power of the TN and TP-based Chl-a prediction models. The stepwise procedures were performed until all variables left in the model were significant at the 0.15 level. Variables considered in stepwise procedure in various combinations were TP/TN ratio, depth (ft), volume (ac-ft), surface area (ac), retention time (days), median TSS (mg/L, calculated using the same procedure as TN and TP), estimated inflow (cfs), and the natural logs of the reservoir parameters (depth, retention time, surface area, volume). Complications in the analysis occurred because the data set was poorly populated, i.e., variables were not consistently available for lakes. Therefore, as stepwise procedures considered increasing numbers of potential explanatory variables, the number of observations available to test the resultant models declined. The presence of "Outliers" (i.e., data points well outside the range established by the bulk of the data in the plots of TN and TP vs. Chl-a) also complicated the analysis due to the fact that, in least-squares regression, such points tend to exert a disproportional influence on the resultant functional form.

A number of efforts were employed to apply stepwise regression procedures as needed to overcome difficulties with the data set, including selective removal of outliers from the data set. Those procedures that yielded the most satisfactory results are summarized below (Table 4, Figure 6). As more outliers were removed, the R^2 of resultant models tended to increase. Both TN and TP proved to be useful as predictors of both Chl-a and SD, and the utility of both could be increased by adding additional variables through the stepwise regression procedures. Mean impoundment depth proved consistently useful as a predictor of both Chl-a and SD, while median TSS concentrations proved consistently useful as a predictor of SD. Residence time was not consistently useful, as expected based on previous studies, which may indicate that the residence time estimates are insufficiently accurate to aid the modeling procedure.

To summarize the committee's perspective on the results of analyses performed in response to questions 3 and 4: Although the results of these analyses do yield statistically significant relationships, we do not consider those relationships to be sufficiently robust to justify their use in criteria development. Contributing factors to this opinion include the fact that the models explain only 50 to 70 percent of the independent variables' variation, in most cases, and our lack of faith in the accuracy and precision of the input variables. Non-log plots of Chl-a vs. TN and TP show a more dispersed pattern than the log-plots of Figure 6.



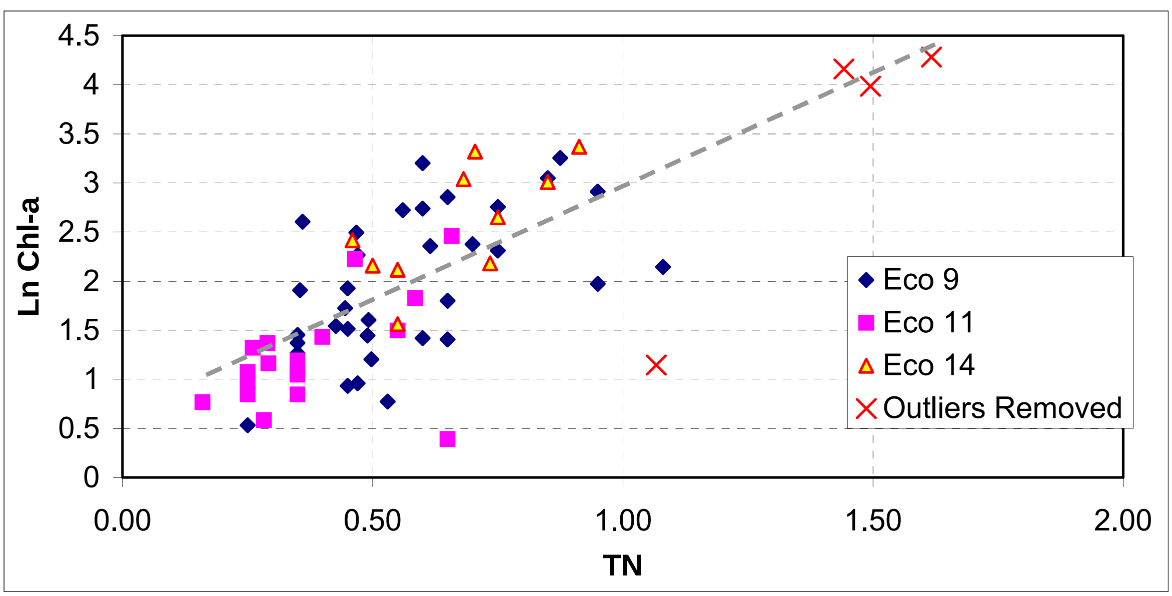


Figure 6. Ln Chl-a as univariate functions of TP and TN. Ecoregions are represented in the plots but were not considered in the regression analyses represented above.

Table 4. Results of stepwise regression procedures.

Dep-endent	- - - - - - Independent Variables / Regression Coefficients - - - - - -								n	p	Model R^2
Statewide											
	Int	TP	TN	***Dep***	***Res***	***Vol***	TSS	***SA***			
Chl-a	0.64	52.12							62	***	.5266
	0.64		2.21						62	***	.4260
Chl-a	0.52	57.27							55	***	.6176
	1.29	50.45		-.216						***	.6538
	2.84	53.11		-.318	.156					***	.6953
Chl-a	0.50		2.43						55	***	.5237
	1.60		2.08	-.321						***	.6117
	1.36		2.01	-.625		0.134				***	.6953
Chl-a	2.45	44.59		-.227	.174		.104		46	***	.7489
	0.54		2.15	-.240			.098	.070	45	***	.7506
SD	1.09						-.166		42	***	.5147
	1.40		-.973				-.118			***	.7015
	1.01		-.870	.097			-.107			***	.7211
	1.00		-.825	.263		-.062	-.095			***	.7590
	1.16		-.787	.388		-.091	-.101	11E-6		***	.7770
SD	1.10	-31.86							42	***	.5512
	1.30	-21.14					-.101			***	.6767
	.899	-18.54		.103			-.092			***	.6991
	0.86	-16.38		.250		-.053	-.085			***	.7256
	1.05	-15.99		.277		-.086	-.092	12E-6		***	.7459
Ecoregion 9											
Chl-a	.874	41.93							37	***	.3497
	.882		1.800						37	**	.3335
Ecoregion 11											
Chl-a	.290	71.64							17	***	.6932
	.182		3.048							***	.6808
Ecoregion 14											
Chl-a	1.38	42.88							7	*	.7730
	1.12		2.420						7	.06	.5495

Notes: TP, TN, and TSS = lake medians; Dep = depth (ft); Res = residence time (days); Vol = volume (acre-ft); SA = surface area (ac). All variables in italics (Chl-a, SD, Dep, Res, Vol, and SA) are expressed as natural logs. n = number of lakes used;
p-values for model: *** = p <.0001; ** = .0001< p < .001; * = .001 < p < .01

Question 5: *Should Carlson's Trophic State Index be considered as a scale to express Virginia's nutrient criteria?*

The Trophic State Index (TSI) indicator was developed for application in natural lakes (Carlson 1977). The TSI is a good tool for communicating trophic state condition to the public because it is an index. Total phosphorus, chlorophyll-a, and Secchi depth are all on a common, understandable scale. The problem with using the TSI to express nutrient criteria is the lack of spatial and temporal homogeneity among trophic state parameters in a reservoir. Suspended sediments delivered to impoundments lead to levels of non-algal turbidity that interfere with algal production, especially in the upper channel, and thus distort the assumed correspondence between the TSI components. As documented in Appendix B for Smith Mountain and Claytor Lakes, sediment-related non-algal turbidity varies spatially within reservoirs. Suspended sediment delivery from the watershed to impoundments varies temporally in response to weather conditions and seasonal cycles, as suggested by the seasonality analysis in Section I-A, Preliminary Analyses. The extent to which reservoirs vary in dissolved components that affect water clarity (such as tannins) is not known.

Virginia's impoundments are highly variable in morphometric characteristics, watershed area, retention time, and other factors that can be expected to influence both their capability to sustain designated uses at various levels of nutrient enrichment and potential correspondence between TSI measures. Given that Virginia impoundments are being treated collectively for the purpose of nutrient criteria development, the AAC recommends that nutrient criteria be implemented by monitoring nutrient variables directly and not through use of TSI, which would add yet another source of variability to criteria implementation.

C. Nutrient Requirements for Fisheries in Virginia’s Impoundments

The following analysis is conducted for the purpose of recommending candidate nutrient criteria for Virginia reservoirs that will be protective of aquatic life and of the reservoirs’ suitability for recreational fishery use. The committee believes that the status of the recreational fishery can be considered as an indicator of the impoundments’ suitability for aquatic life. Given that species of recreational fish are generally at the upper trophic level, the health of recreational fish populations can be interpreted as an indicator of ecosystem health as well as suitability for the aquatic life designated use.

The candidate criteria that follow were developed expecting that DEQ will seek to balance the nutrient requirements of recreational fisheries against those of other potential uses, including contact recreation and public water supplies, in defining nutrient criteria for implementation.

This analysis is conducted in three steps: a review of scientific literature prepared by Dr. John Ney, graphic analysis of Virginia impoundments’ fisheries and nutrient status, and synthesis of these two information sources.

Review and Interpretation of Scientific Literature: Nutrient Requirements for Virginia’s Reservoir Fisheries, by Dr. John Ney.

Community energetics dictates that the biomass of fish at or near the top of the trophic pyramid should be highly dependent on the amount of primary production at the base (Lindemann 1942). Primary production in lakes is limited by nutrients, principally phosphorus. USEPA (2000d) notes that nitrogen limitation is largely confined to subtropical and high altitude/latitude lakes). Nitrogen limited waters have TN:TP < 30 (Alam and Glecker 1994): the ratio in Virginia reservoirs is much greater.

However, the productivity of a fishery can be limited not only by insufficient energy (food) but also by inadequate habitat. High levels of algal production can cause hypolimnetic oxygen deficits to the detriment of coldwater and coolwater fishes. In shallow lakes, nutrients can stimulate excessive macrophyte growth, reducing habitat for warmwater sportfish species (Wiley et al. 1984). The influence of nutrients and resulting primary production on fisheries productivity in lakes and reservoirs should thus be parabolic, with low concentrations of nutrients constraining food supply and high concentrations limiting suitable habitat. The nutrient (phosphorus) or response (chlorophyll-a, Secchi disk water transparency) parameters that promote healthy fisheries will vary by waterbody type and the species-specific requirements of the desired fishes.

What concentrations of nutrient or response parameters will ensure the quality of Virginia’s reservoir fisheries? To address this question, we conducted a comprehensive search of relevant published literature in library data bases and interviewed fisheries-water quality experts to identify further sources. The results are summarized below. This report proceeds from a general overview of the fisheries-water quality relationship to a consideration of the particular nature of that relationship in reservoirs (vs. natural lakes), followed by analysis of water quality requirements for Virginia's three categories of reservoir fisheries: coldwater (trout), coolwater, and warmwater.

Overview

Empiric relationships between fisheries productivity (as measured by fish harvest, production, or biomass) and both primary production and phosphorus concentration have been developed and published for regional and cosmopolitan sets of lakes. Correlations between primary production and fisheries productivity are highly positive, the former explaining (r^2) 67-84% of the latter (Table 5). Correlations between total phosphorus (TP) concentration and fisheries productivity are equally strong (51-84%, Table 6).

Table 5. Predictive relationships between measures of plant and fish productivity in lakes and reservoirs, as determined from single-variable regression models.

Independent Variable	Dependent Variable	Data Set (n)	% of Variation Explained (r^2)	Source
Gross photosynthesis	Total fish yield	Indian lakes (15)	82	Melack (1976)
Phytoplankton standing stock	Total fish yield	Natural lakes, northern hemisphere (19)	84	Oglesby (1977)
Gross photosynthesis	Total fish yield	Chinese lakes and ponds (18)	76	Liang et al. (1981)
Chlorophyll-a	Sport fish yield	Midwestern U.S. lakes and reservoirs (25)	83	Jones and Hoyer (1982)
Primary production	Total fish production	Cosmopolitan lakes (19)	67	Downing et al. (1990)

Table 6. Relationship between total phosphorus concentration (μg/L) as the independent variable and various measures of fish production in lakes and reservoirs.

Dependent Variable	Data Set (n)	% of Variation Explained (r^2)	Source
Total fish yield	North American lakes (21)	84	Hanson and Leggett (1982)
Sport fish yield	Midwestern U.S. lakes and reservoirs (21)	52	Jones and Hoyer (1982)
Total standing stock	Southern Appalachian reservoirs (21)	84	Ney et al. (1990)
Piscivore standing stock	Southern Appalachian reservoirs (11)	51	Ney et al. (1990)
Total fish production	Cosmopolitan lakes (14)	67	Downing et al. (1990)

Water Quality in Reservoirs

Some of the above data sets were limited to natural lakes. Indeed, most of the analyses of trophic state (e.g., Carlson's TSI) are based on the relationships of phosphorus, chlorophyll-a, and water transparency (Secchi disk depth) in northern natural lakes (USEPA 2000d). These relationships are less robust in reservoirs, which comprise 99% of Virginia's lentic waters. Chlorophyll-a concentrations tend to be lower in reservoirs than in natural lakes (Soballe et al. 1992) because higher inorganic turbidity and flushing rates in reservoirs may limit the ability of phosphorus to stimulate phytoplankton production. In a regression analysis of 80 southeastern U.S. reservoirs, Reckhow (1988) reported a fairly strong correlation between transparency and phosphorus (r^2 =0.50), a weak relationship between chlorophyll-a and phosphorus (r^2 = 0.10), and virtually no correlation between chlorophyll-a and transparency (r^2 < 0.01). In these impoundments, inorganic turbidity largely determined water transparency, and although the suspended sediment contained phosphorus, most of the phosphorus was not biologically available. In contrast, the r^2 for phosphorus vs. chlorophyll-a has been widely reported as ~0.70 (Brown et al. 2000) for sets of natural lakes. Canfield and Bachman (1981) examined the National Eutrophic Survey (NES) data set and compared nutrient and response parameters between natural lakes and reservoirs. They also found that reservoirs usually have substantially lower chlorophyll-a than natural lakes at the same phosphorus concentrations. Interpretation of their scatter diagram indicates that to produce 10.0 mg/m^3 of chlorophyll-a (indicative of marginally eutrophic conditions) in the average natural lake would require 30 µg/L total phosphorus, whereas the average reservoir would require 40 µg/L total phosphorus.

High flushing rates (low retention times) also limit development of phytoplankton biomass. In fact, the *Technical Guidance Manual* (USEPA 2000d) recommends that reservoirs with retention times < 14 days be exempted from nutrient regulation because algal biomass buildup is minimal.

Chlorophyll-a has long been recognized as the single best metric for assessing nutrient-induced water quality of lakes because it most directly measures the parameter that affects aesthetic value and recreational use (Carlson 1977, Heiskary and Walker 1988, Bachman et al. 1996). Because water transparency is affected by inorganic turbidity and phosphorus concentration is irrelevant in low retention-time impoundments, chlorophyll-a would appear to be the parameter of choice as a criterion for nutrient standards for reservoirs.

Reservoirs also differ from natural lakes in that they characteristically exhibit a trophic gradient (Soballe et al. 1992). As dammed rivers, reservoirs lose nutrients through settling in a downstream direction. Thus a single reservoir may grade from eutrophic in its upper reaches to mesotrophic in its mid section to oligotrophic near the dam. Such systems can support good fisheries for a combination of warmwater, coolwater, and even coldwater fishes.

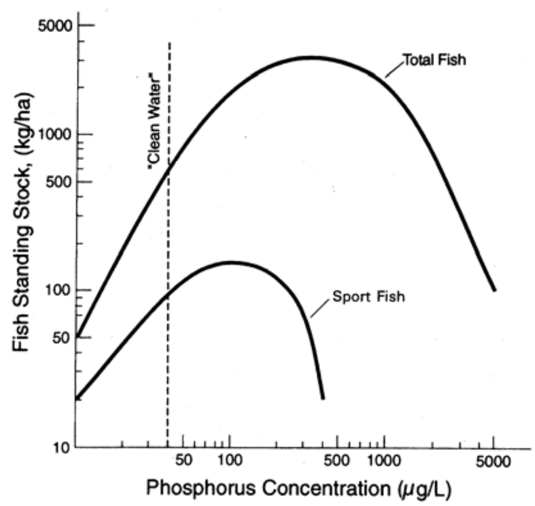
Reservoir Fisheries and Water Quality

Because inorganic turbidity and flushing can limit nutrient impacts on reservoir productivity, it might be expected that the empiric relationship between phosphorus concentration and fisheries would be relatively weak. This does not appear to be the case in the southeastern U.S. Ney et al. (1990) examined the relationship between fish standing stock and a variety of potential predictors in a set of 21 southeastern, Appalachian-region multi-purpose reservoirs for which fishery and water chemistry information was available for the same time frame (within 2 years). These reservoirs varied greatly in surface area (1,700-132,000 ha), retention time (4-438 d), and total fish standing stock (77-2,321 kg/ha). Total phosphorus was easily the best predictor of fish standing stock ($r^2 = 0.84$), followed by Secchi disk depth (negative slope, $r^2 = 0.42$) and chlorophyll-a ($r^2 = 0.31$). Fish standing stock increased linearly over the range of total phosphorus (8-81 µg/L) on a log-log scale, suggesting that maximum fish biomass would occur at higher phosphorus concentrations (Ney 1996). Fish production will ultimately be limited by habitat loss, resulting in a parabolic relationship with nutrient concentrations (Figure 7).

Total fish standing stock or total fish production may not be indicative of sportfishing potential of reservoirs because sport and food fishes usually account for less than half the total. For the southern Appalachian reservoir data set, Yurk and Ney (1989) found that piscivore (largely game fish) standing stock increased linearly over the range of total phosphorus concentrations from 8 to 81 µg/L ($r^2 = 0.51$). Jones and Hoyer (1982) reported that annual sportfish (synonym here for “gamefish”) harvest increases linearly with total phosphorus over the range 15-90 µg/L in 25 midwestern U.S. lakes (r^2

= 0.52) and with chlorophyll-a between 4 and 67 µg/L (r^2 = 0.83). In a study of 21 northern temperate natural lakes, Hanson and Leggett (1982) found that long-term sport and commercial annual harvests increased with total phosphorus concentration up to 500 µg/L (r^2 = 0.84).

Figure 7. Generalized relation of total fish and sport fish standing stock with total phosphorous concentration in temperate latitude reservoirs. Standing stock values are representative of southeastern U.S. reservoirs to 100 µg/L total P, while standing stocks at higher P concentrations are hypothetical. The vertical line labeled as "clean water" represents a TP concentration associated with water clarity that could be considered as minimally acceptable for contact recreational use and is an approximate value. The "clean water" representation is conceptual and is not reproduced here for the purpose of suggesting a specific TP criterion value (from Ney 1996).



Fisheries in Virginia Impoundments

The fisheries of Virginia's public reservoirs include several, mostly small (<100 acres) systems managed for trout (coldwater). Some are managed for a combination of coolwater (e.g., striped bass, walleye) and warmwater (sunfish, largemouth bass, catfish) species; most of these are large (> 500 acres) impoundments. Reservoirs managed solely for warmwater fisheries range from large systems (primarily in eastern Virginia) to ponds. Many of the smaller impoundments are owned by the Virginia Department of Game and Inland Fisheries (VDGIF) and managed primarily for sportfishing.

Within the overall sportfish complex, it has long been recognized that individual species respond differently to particular levels of lake fertility. The *Technical Guidance Manual* (USEPA 2000d) uses the work of Oglesby (1977) to predict that as phosphorus in natural lakes increases, fisheries will shift from coldwater (TP < 24 µg/L) to coolwater (TP = 24-48 µg/L) to warmwater (TP = 48-193 µg/L); total fisheries yield (harvest) should progressively rise over this range of phosphorus concentration. However, Oglesby's projections were based on rather limited data that has been supplemented by later studies and did not apply specifically to many of the sportfish species of Virginia's reservoirs. We use this later work, as well as water quality information from some of Virginia's best reservoir fisheries, to recommend water quality limits that will support healthy fisheries in our waters.

Coldwater Fisheries: Trout fisheries in Virginia lakes are maintained by frequent stockings from hatcheries, either on a put-and-take (adults) or put-grow-take basis (fingerlings). Rainbow, brown, and brook trout are stocked alone or in combination. Because stocked put-and-take trout fisheries are seasonal and not habitat-limited (swimming pools have been used in other states), this analysis focuses on conditions necessary for trout to grow and survive over one or more years to reach harvestable size. Essentially, this requires an oxygenated hypolimnion during thermal stratification. The relevant water quality literature is sparse. In Minnesota, natural populations of lake trout (*Salvelinus namayacush)* achieve peak abundance at TP = 6 µg/L and chlorophyll-a = 1 µg/L (Schupp and Wilson 1993). However, the lake trout requires the lowest temperatures of any salmonid and does not occur in Virginia. In Lake Windemere, UK, brown trout abundance more than doubled when TP was reduced from 30 to 11 µg/L and chlorophyll-a declined from 30 to 14 µg/L (Elliott et al. 1996). A fertilization experiment in a small mountain lake in British Columbia increased rainbow trout growth and interannual survival while raising TP from 4 to 9 µg/L and chlorophyll-a from 1 to 6 µg/L (Johnston et al. 1999).

On the basis of this literature and the concentrations reported from elsewhere for successful trout fisheries, it appears that the following concentrations are adequate to sustain habitat and promote trout growth: TP ≤ 10 µg/L and Chl-a ≤ 6 µg/L.

Coolwater Fisheries: Virginia's coolwater sportfish species are striped bass, hybrid striped bass (white bass x striped bass) and walleye. The smallmouth bass is sometimes considered a coolwater species, but it has virtually identical temperature tolerances to its congener largemouth bass, a warmwater fish considered below (Brown 1974). All three coolwater species are maintained by the stocking of hatchery-reared fingerlings on a put-grow-take basis; the single exception is the striped bass population of Kerr reservoir, which is self-sustaining.

Walleye, striped bass, and hybrid striped bass prefer water temperatures in the range of 19-28^{o}C (Coutant 1985, Hokanson 1990, Kilpatrick 2003). By late summer in Virginia reservoirs, this habitat is usually limited to the metalimnion/hypolimnion downlake region near the dam (Ney 1988, Kilpatrick 2003). However, all three species can tolerate water temperatures of >28^{o}C for extended periods without observed mortality, although growth will likely be impaired (Brown 1974, Wrenn and Forsythe 1979, Kilpatrick 2003).

The influence of water quality on walleye abundance has been examined for Minnesota lakes (the walleye is the state fish of Minnesota) and Lake Erie, which supports the most productive walleye fishery in the world. In Minnesota, walleye abundance peaks under mesotrophic conditions: TP of 15-25 µg/L and Chlorophyll-a of 7-10 µg/L (Schupp and Wilson 1993). Lake Erie's walleye populations is thriving at chlorophyll-a of 5-15 µg/L; it is actually projected to increase if phosphorus loading is doubled (Anderson et al. 2001). Walleye do well in lakes that experience occasional hypolimnetic anoxia, but poorly in lakes with Secchi disk transparency > 4 m (Schupp and Wilson 1993).

Striped bass also fare poorly under oligotrophic conditions. When Lake Mead, Nevada, became oligotrophic (TP = 10 µg/L), striped bass became stunted and emaciated (Axler et al. 1987). Smith Mountain Lake is Virginia's premier inland striped bass fishery and has a classic trophic gradient. The lower segment of Smith Mountain Lake has an oxygenated hypolimnion year-round, providing a summer thermal refuge for striped bass. However, striped bass congregate further upstream in summer, where prey fish are more abundant (Ney 1988), suggesting that food is more important than ideal habitat.

Virginia's coolwater sportfishes are fast-growing piscivores dependent on a large supply of forage fishes (e.g., gizzard shad, threadfin shad). These planktivores are most abundant in fertile systems (Bremigan and Stein 2001, Maceina 2001). In Virginia's large reservoirs, coolwater fishes appear to be more food limited than habitat limited.

The scientific literature reviewed above indicates that coolwater fisheries can prosper in systems where TP >10 µg/L and where Chl-a ≤ 15 µg/L.

Warmwater Fisheries: Principal warmwater sportfishes are primarily of the sunfish family (Centrarchidae) as well as catfishes. Catfishes have higher temperature and lower dissolved oxygen (DO) tolerances than centrarchids and are not considered further in this review. Virginia's centrarchids include sunfishes (bluegill, redear, redbreast, and pumpkinseed), black and white crappie, smallmouth bass, as well as the most-sought freshwater sportfish species, largemouth bass. Centrarchids are littoral and epilimnetic fishes that do not require an oxygenated hypolimnion as summer habitat. Nutrient-induced habitat limitations occur only in shallow lakes that become choked with aquatic macrophytes. In such systems, the cover provided by dense stands of "weeds" prevents largemouth bass from preying on sunfish; both largemouth bass and sunfish become stunted (Bennett 1962). Virginia has few macrophyte-dominated reservoirs. Where they exist, poor watershed practices (erosion) or invasive exotics (e.g., *Hydrilla)* are usually responsible.

For the most part, centarchid populations are food-limited rather than habitat-limited. Higher levels of nutrients translate to more centrarchid biomass. In fact, centrarchid lakes devoted primarily to fishing are often fertilized at least annually. Auburn University, which pioneered research on centrarchid management, recommends fertilization to achieve chlorophyll-a concentrations of 40-60 µg/L (Maceina 2001). The VDGIF frequently fertilizes its small fishing lakes to produce robust centrarchid populations for anglers. In these small (< 200 acres) lakes, chlorophyll-a in the 40-60 µg/L range commonly results.

Obviously, larger reservoirs are not subject to direct fertilization because they must accommodate aesthetic and water-contact recreation and (sometimes) coolwater fisheries. However, across reservoirs of all sizes, the pattern of higher fertility = better centrarchid fishing holds. In Minnesota, Schupp and Wilson (1993) reported that black crappie fisheries peak at TP ~60 µg/L and chlorophyll-a ~20 µg/L; white crappie do best under hypereutrophic conditions (TP ~100 µg/L; chlorophyll-a ~60 µg/L).

In a study of 30 large Alabama reservoirs, Maceina et al. (1996) found that growth of crappie and largemouth bass increased up to ~20 µg/L chlorophyll-a. In fact, the potential for an angler to catch a trophy largemouth bass (> 5 lbs.) was about 3 times greater in eutrophic than mesotrophic lakes. Bachmann et al. (1996) confirmed a similar pattern for natural Florida lakes (n = 360): trophy largemouth bass were more abundant in highly eutrophic lakes (chlorophyll-a > 40 µg/L), as were populations of redear sunfish and black crappie.

This review indicates that warmwater fisheries can thrive where TP ≤ 50 µg/L and Chl-a is 20-40 µg/L.

Virginia DEQ Data Interpretation

The above review summarizes scientific studies from throughout the USA, while the analysis that follows is focused on Virginia conditions. The purpose of this analysis is to determine the maximum nutrient concentrations (TP and Chl-a levels) that sustain good-to-excellent recreational fisheries, by fishery type and by ecoregion.

The status of the recreational fishery in each impoundment was rated on a scale of 1 (poor) to 5 (excellent) by VDGIF biologists, in response to requests advanced by Dr. John Ney. The rating scale and process are described in Section I-B, Question 2. Each reservoir was classified as one of the following types, based on the professional knowledge of Dr. John Ney and considering VDGIF biologists' comments during the rating process.

Coolwater Fisheries: Impoundments that support coolwater fishes in the deep bottom waters and warm-water fishes in shallower waters. The largest and deepest of the state's impoundments are included within this category.

Trout Fisheries: Lakes managed for support of trout, including those managed by VDGIF for this purpose. These lakes are generally small in size, and predominantly within the state's mountainous regions.

Fertilized Fisheries: Lakes managed for centrarchid species, such as sunfishes, crappies, and black basses, with fertilizers applied as a management input. These lakes are generally quite small, and fish production is the primary use. All of lakes identified as fertilized fisheries in the current analysis are owned and managed by VDGIF.

Warmwater Fisheries: The majority of the state's impoundments; all impoundments not explicitly classified as another type.

Other: Impoundments known to be affected by unique or unusual conditions and therefore considered as poorly suited to serve as indicators of how the state's lakes, in general, can be expected to respond to water-column nutrients. Conditions that cause lakes to be categorized as "other" include high levels of non-algal turbidity (including coloration of waters from watershed geology or tannins), low retention times, mechanical aeration, the presence of prolific macrophytes and vegetative structure on the lake bottom.

Impoundment classifications and the VDGIF biologists' ratings are listed in Appendix A, Table A-4.

Data analysis was conducted by plotting fishery status, represented by fishery type, against two nutrient variables – Chl-a and TP – for each lake, followed by visual interpretation of the resulting graphic plots. As discussed in the AAC July 2004 report, the AAC recommends that criteria for lakes and reservoirs not include TN criteria that could be applied independently of TP.

The initial stage of this analysis was exploratory: statewide plots were prepared of fishery status vs. a number of seasonal indicators (e.g., April – May, June – August, July – August, August – September, April – September) for both Chl-a and TP. This exercise was conducted in response to the variety of findings in the scientific literature regarding seasonal nutrient-status indicators. Visual analysis of these plots yielded no indication of any seasonal nutrient indicator being superior or qualitatively different from any other. Major differences among these plots were due to the number of lakes represented (because of varying numbers and distributions of water quality observations among lakes, the number of lakes with sufficient observations for inclusion in each representation varied). This exercise led to the conclusion that development of nutrient indicators representing the entire April – October sampling period would be the preferred approach, as it would maximize use of available water quality data.

For the second stage of analysis, Chl-a and TP medians for each lake were generated using a procedure that is analogous to the EPA protocol for calculating lake medians (see Section I-B, Question 1). However, instead of aggregating values by season, we aggregated by month (April – October) so as to generate lake-median values that better represent DEQ's lake monitoring schedule. For each lake and nutrient variable, monthly medians were calculated by aggregating all observations for each month. Then, a lake median was calculated as the median of the monthly medians for all lakes represented by 6 or 7 monthly medians (Appendix A, Table A-2, Mo values). Lake median values for lakes that had been rated by VDGIF but were represented by fewer than 6 monthly medians for any nutrient variable were calculated as the average of the S1, S2, and S3 medians (See Section I-B, Question 1. The S1, S2, and S3 medians are listed in Appendix A, Table A-2). Each rated impoundment's fishery status was plotted against its TP and Chl-a lake medians (Figure 8). The plots are interpreted by identifying those Virginia impoundments that are considered to be representative of fishery types (i.e., the fishery in that lake is not known to be influenced by conditions that are unusual throughout the ecoregion or state) and able to sustain high-quality fisheries with the highest nutrient levels. Nutrient levels in these impoundments are not necessarily at the maximum level that would be capable of sustaining such fisheries. Limited data from impoundments where fish populations have been impaired by nutrient overenrichment prevent direct interpretation of these data to indicate nutrient levels that limit fishery success.

In contrast to previous studies (Yurk and Ney 1989, Ney 1996), the plots of fishery status vs. water column TP and Chl-a generated for this report do not yield well-defined relationships. We believe that the reason for this result is size variability. Prior studies included only very large impoundments (> 2,400 acres). Lakes vary in nutrient response capability due to physical features. Generally, fish populations in small lakes are more subject to influence by non-nutrient factors than fish populations in large lakes, and relatively small lakes are heavily represented in the DEQ database. Non-nutrient factors capable of influencing fish populations include inorganic turbidity (suspended sediments) and lake physical features and structural elements.

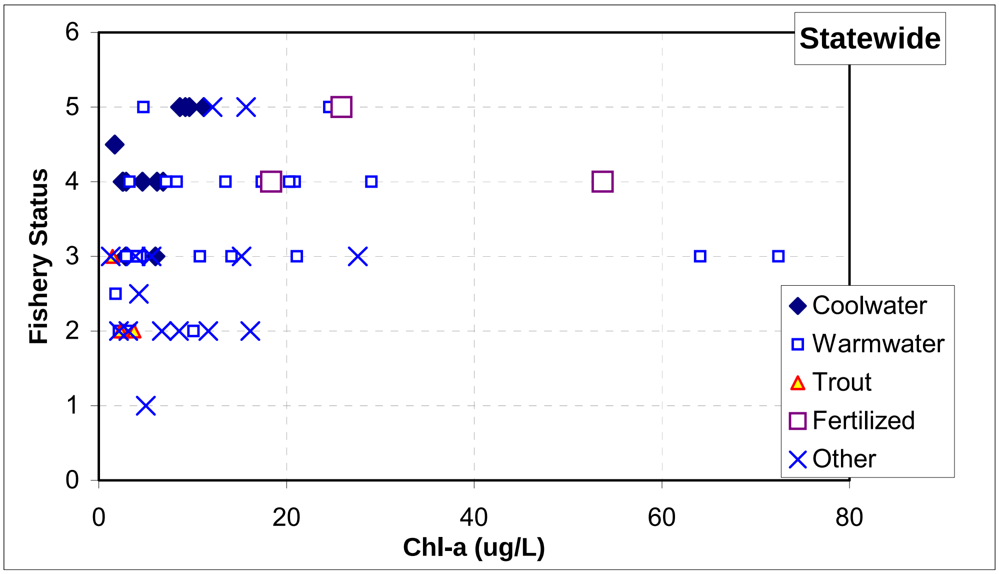
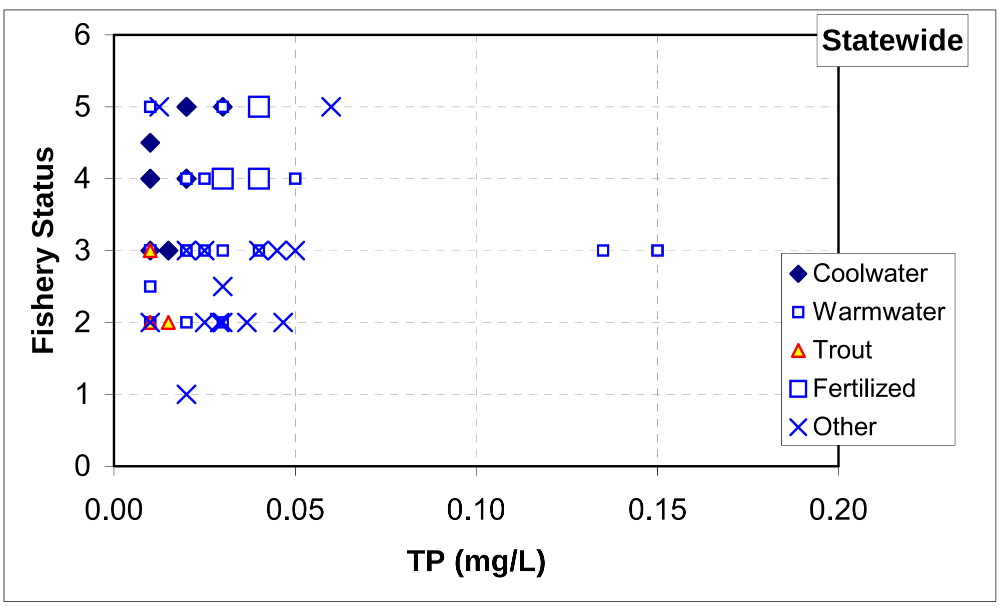
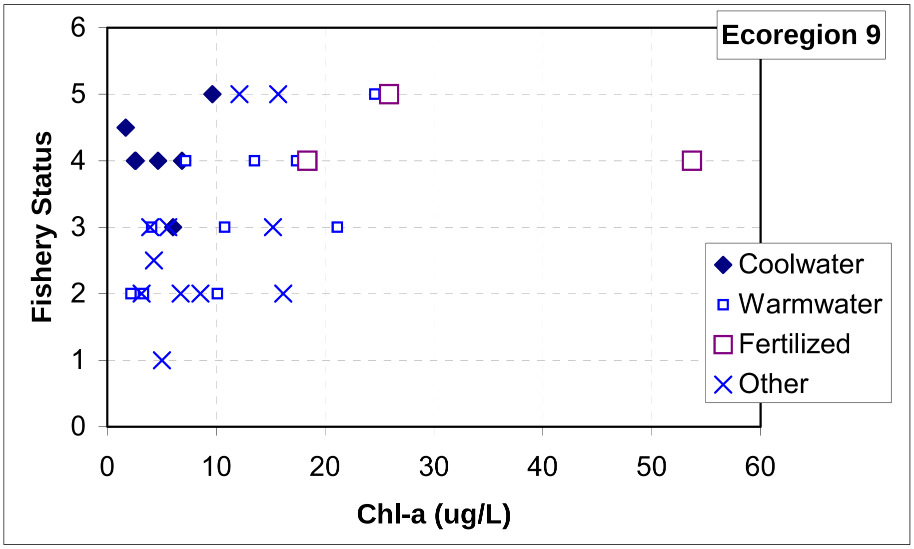
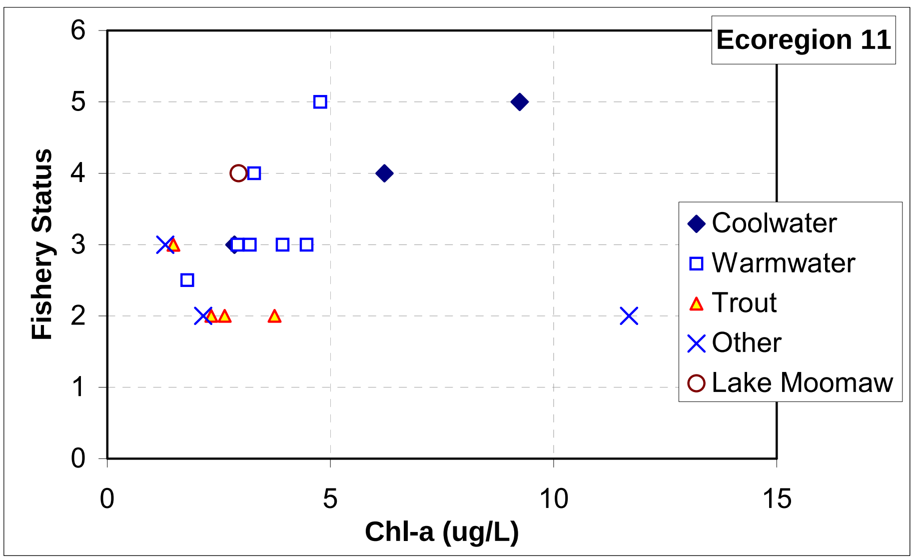
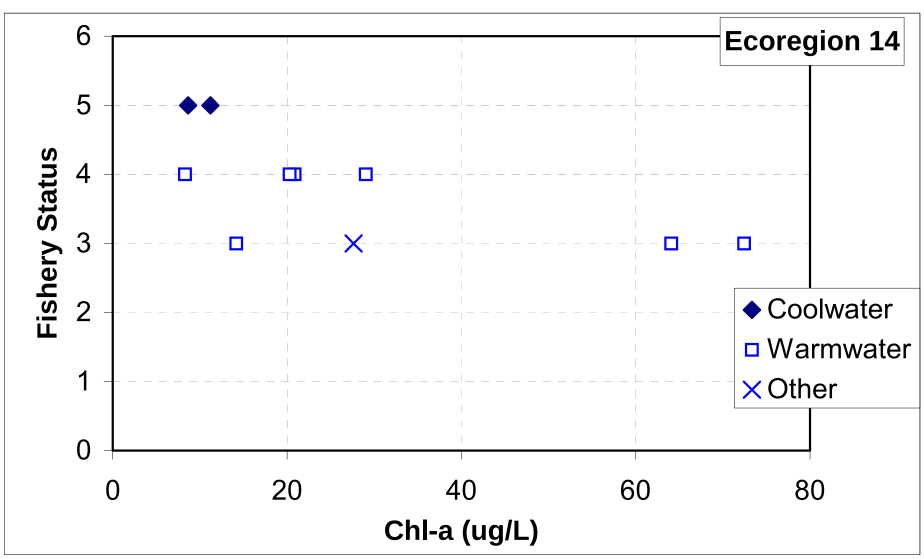


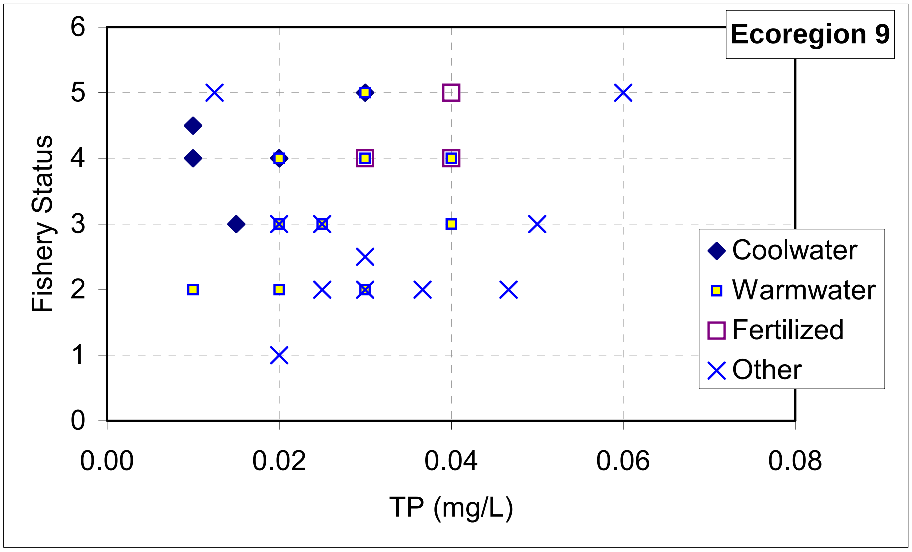
Figure 8. Fishery status vs. Chl-a median and TP median, statewide (left) and ecoregion (following pages) Lake Moomaw is a coolwater fishery that also supports trout.

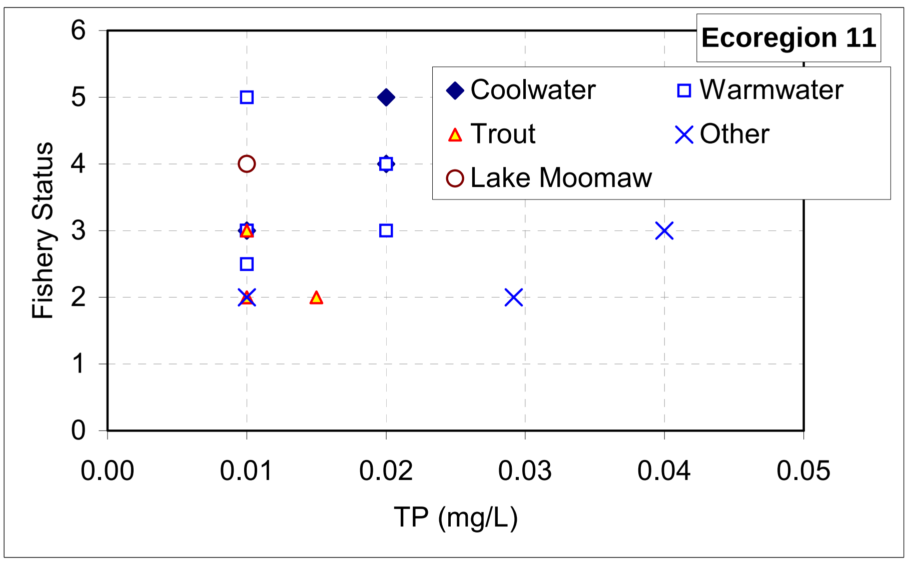



Ecoregion 9
Fishery Status
Chl-a (ug/L)
Coolwater
Warmwater
Fertilized
Other


Ecoregion 11
Fishery Status
Chl-a (ug/L)
Coolwater
Warmwater
Trout
Other
Lake Moomaw


Ecoregion 14
Fishery Status
Chl-a (ug/L)
Coolwater
Warmwater
Other


Ecoregion 9
Fishery Status
TP (mg/L)
0
1
2
3
4
5
6
0.00
0.02
0.04
0.06
0.08
Coolwater
Warmwater
Fertilized
Other


Ecoregion 11
Fishery Status
TP (mg/L)
0
1
2
3
4
5
6
0.00
0.01
0.02
0.03
0.04
0.05
Coolwater
Warmwater
Trout
Other
Lake Moomaw

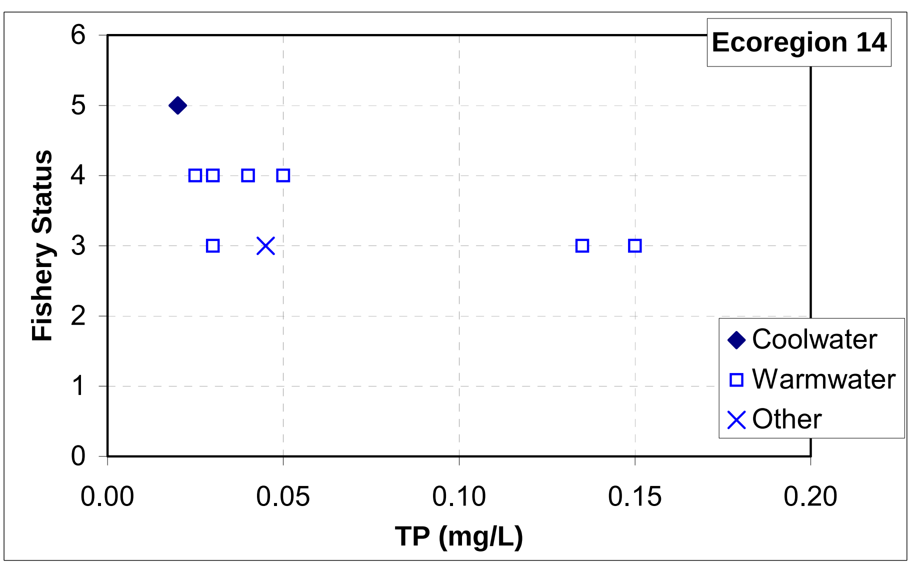

Ecoregion 14
Fishery Status
TP (mg/L)
0
1
2
3
4
5
6
0.00
0.05
0.10
0.15
0.20
Coolwater
Warmwater
Other

Table 7. Maximum TP and Chl-a lake medians (April – October, µg/L) corresponding with high-quality recreational fisheries[a] (fishery status 4 and 5, if available), by ecoregion.

Ecoregion	**Fishery Type**	**High-quality fishery maxima** (µg/L)	**Comments** (Fishery status)
9	Coolwater	TP ≤ 30	Kerr (5): TP = 30.
		Chl-a ≤ 10	Kerr (5): Chl-a = 9.66.
	Warmwater	TP ≤ 40	Lake Chesdin (4): TP = 40
		Chl-a ≤ 25	Diascond Reservoir (5): Chl-a = 25
			Chickahominy Lake (TP = 60 and Fishery Status = 5) is atypical of Virginia reservoirs due to abundant macrophytes. Despite relatively high TP, Chl-a is relatively low (16).
	Fertilized	TP ≤ 40	Curtis (4) and Stonehouse (5): TP = 40
		Chl-a ≤ 60	Curtis (4): Chl-a = 53.9
11	Warmwater, Coolwater	TP ≤ 20 Chl-a ≤ 10	South Holston Lake (5): TP = 20, Chl-a = 10. Biologically: warm water should not be any more sensitive that multipurpose.
	Trout	TP ≤ 10	Sugar Hollow (2) is said by DGIF to lose coldwater habitat in the summer; TP = 15 in Sugar Hollow; TP = 10 in all other trout lakes.
		Chl-a ≤ 4	Of the single-purpose cold-water fisheries, Switzer (3) is the best trout lake (Chl-a = 1.5). All other trout lakes rated as (2), and Chl-a > 2
			Although not a single-purpose fishery, Lake Moomaw (4) supports the state's best trout fishery (Chl-a = 3; TP = 10).
14	Warmwater	TP ≤ 50 Chl-a ≤ 30	Lake Cohoon (4) has TP = 50, Chl-a = 29. Lakes with higher TP (> 10) and Chl-a (>60) are Little Creek Res. (3) and Lake Smith (3).
	Coolwater	TP≤ 20	Lake Prince (5) and Western Branch (5): TP = 20
		Chl-a ≤ 11	Lake Prince (5): Chl-a = 11

[a] As rated by VDGIF biologists; see Section I-B, Question 2. Fishery status ratings are in parentheses after lake names; 5 = best and 1 = worst.

Synthesis and Candidate Criteria Recommendations:

The literature review provided general input for chlorophyll-a (Chl-a) and total phosphorus (TP) recommendations based on the performance of coldwater, coolwater, and warmwater fisheries. However, most of this work was conducted in other regions of the U.S. and beyond. In particular, the literature-based recommendations do not correspond to Virginia's ecoregions as defined by the USEPA. Input for ecoregion-level analysis was provided by VDGIF fisheries biologists' ratings of lake-specific fisheries as related to lake-specific nutrient parameters (preceding section, Table 7). This approach is inherently subjective and so vulnerable to potential error.

To develop candidate criteria recommendations by ecoregion, we consider both the literature synthesis and the Figure 7 plots for agreement. This exercise resulted in the following recommendations.

<u>Ecoregion 9</u>

<u>Coolwater Fisheries:</u>

Coolwater fishes require an oxygenated hypolimnion during summer stratification. The hypolimnia of virtually all Virginia reservoirs become anoxic in their upper regions by late summer; those that support good coolwater fisheries retain oxygenated hypolimnia downlake, providing thermal refuge for striped bass, hybrid striped bass (in ecoregion 11) and walleye. The striped bass is of most concern because it is the main coolwater sportfish in Virginia and its temperature preferences are slightly lower than those of hybrid striped bass and walleye. However, healthy striped bass fisheries are dependent on the supply of forage fish, which increases with nutrient concentration. This poses a habitat vs. food tradeoff. The literature review failed to identify optimum nutrient concentrations for striped bass. In ecoregion 9, good to excellent coolwater fisheries (predominantly striped bass) occur at Chl-a concentrations of 2-10 µg/L and TP of 4-40 µg/L. The premier inland striped bass fisheries in Virginia are Smith Mountain Lake and Kerr Reservoir, with median Chl-a of 2.6 and 9.7 µg/L, respectively, and median TP of 20 and 30 µg/L. Of particular interest is Kerr Reservoir because it supports the only reproducing freshwater population of striped bass in Virginia. This exceptional resource provides the hatchery supply for stocking other Virginia waters. However, higher nutrient concentrations than Kerr now experiences could reduce summer habitat for striped bass, impacting survival rates (V. DiCenzo, VDGIF, personal communication). We therefore recommend candidate criteria for coolwater fisheries in ecoregion 9 of **10 µg/L chlorophyll-a** and **30 µg/L total phosphorus**.

<u>Warmwater Fisheries:</u>

Nutrient levels in most Virginia reservoirs are not limiting to warmwater fisheries. In ecoregion 9, highly-rated warmwater fisheries occur at Chl-a up to 25 µg/L (Diascund Reservoir) and TP to 40 µg/L (Lake Chesdin). From a fisheries perspective, a TP limit below 40 µg/L would be counterproductive. Whether lower Chl-a levels would have the same result is less certain. Based on Alabama studies (Maceina et al. 1996, Maceina 2001), it appears that Chl-a of ~20 µg/L may not be detrimental to centrarchid fisheries in larger reservoirs. For ecoregion 9 warmwater fisheries, we recommend candidate criteria of **25 µg/L chlorophyll-a** and **40 µg/L total phosphorus.**

Fertilized Lakes:

The VDGIF fertilizes many of the small lakes it owns to achieve Chl-a of 40-60 µg/L, which is recommended to achieve optimum sunfish and largemouth bass (centrarchid) fisheries. In ecoregion 9, good fisheries results in fertilized lakes with chlorophyll-a up to 60 µg/L and TP of 40 µg/L. Inasmuch as these VDGIF-owned lakes are managed primarily for sportfishing by professional biologists, we recommend candidate criteria of **60 µg/L chlorophyll-a** and **40 µg/L total phosphorus.** Lakes fertilized and managed as centrarchid fisheries by VDGIF in other Virginia ecoregions should also be managed based on the same rationale.

Ecoregion 11

Coolwater Fisheries:

In western Virginia, Claytor (fishery status rating of 4), Flanagan (3) and South Holston (5) are the only reservoirs of depth and size to support coolwater fisheries. The best of these, South Holston, has median Chl-a of 9.2 µg/L and TP = 20 µg/L. Flanagan's coolwater fishery productivity is limited by low fertility (Chl-a = 2.8 µg/L, TP = 10 µg/L). Claytor is intermediate in Chl-a (6.2 µg/L) and equivalent to South Holston in TP (20 µg/L). As in ecoregion 9, a Chl-a limit of 10 µg/L appears correct to support ecoregion 11 coolwater fisheries. A TP limit of 20 µg/L is also sound; higher TP in riverine Claytor Lake could endanger summer habitat for striped bass (Kilpatrick 2003). For ecoregion 11, we recommend candidate criteria for coolwater fisheries as **10 µg/L chlorophyll-a** and **20 µg/L total phosphorus**.

Warmwater Fisheries:

Ecoregion 11 lakes that support warmwater fisheries exclusively are generally infertile. These lakes have only fair fisheries, with the exception of two small reservoirs, Lake Frederick (rating of 5) and Lake Robertson (rating of 4), which are rated more highly because they have better centrarchid fisheries than other lakes in the ecoregion. From the fisheries perspective, even these waters would benefit from greater nutrient inputs (Steve Reeser, VDGIF, personal communication). Our recommendation is the same as for ecoregion 9 warmwater fisheries; candidate criteria of **25 µg/L chlorophyll-a** and **40 µg/L total phosphorus.**

Coldwater (Trout) Fisheries:

Virginia's trout lakes are generally small (< 50 acres) and managed by either VDGIF or the U.S. Forest Service. Most support rather mediocre fisheries, either because they lose habitat in the summer (anoxic hypolimnion) or have low fertility. An example of the former is Sugar Hollow Lake (rating of 2), where median Chl-a and TP are 3.8 and 15 µg/L, respectively. The latter is represented by Switzer Lake (rating of 3), where chlorophyll-a is 1.5 and TP is < 8 µg/L. The exception to this situation is Lake Moomaw (2,600 acres; rating 4), which supports a trophy trout fishery, with stocked fingerlings growing to 5-12 lbs. over several years. Lake Moomaw has median chlorophyll-a and TP concentrations of 4 and 10 µg/L, respectively. These values concur with literature reports for productive trout fisheries. Higher levels of either parameter could impact critical summer habitat. We therefore recommend for ecoregion 11 (and all trout lakes in Virginia) candidate criteria of **4 µg/L chlorophyll-a** and **10 µg/L total phosphorus.**

Ecoregion 14

Lakes in southeastern Virginia are principally water supply reservoirs which provide some good fishing for the region's largely urban population. Warmwater fisheries predominate.

Coolwater Fisheries:

The VDGIF has endeavored to establish coolwater fisheries in ecoregion 14 by stocking striped bass in larger water-supply reservoirs. Good coolwater fisheries have been established in Lake Prince (rating of 5 for combined warmwater and coolwater fishery) and Western Branch Reservoir (5). The median TP in each of these reservoirs is 20 µg/L; median Chl-a is11 µg/L in Lake Prince and 9 µg/L in Western Branch. Nutrient parameter concentrations greater than currently experienced are likely to limit habitat in this region, which experiences the longest periods of lake thermal stratification in Virginia. For coolwater fisheries in ecoregion 11, we recommend candidate criteria of **10 µg/L chlorophyll-a** and **20 µg/L total phosphorus.**

Warmwater Fisheries:

The scatter plots for warmwater fisheries in southeastern Virginia (Figure 7) provide a rare dichotomy. Highly rated (4 or 5) lakes have Chl-a of 7-30 µg/L and TP of 20-50 µg/L, while ratings drop for more eutrophic lakes (Chl-a > 60 µg/L; TP > 100 µg/L). The nutrient concentrations to produce peak warmwater fisheries may lie between these groupings, as indicated by the literature. However, it appears that good warmwater fisheries in ecoregion 14 can be sustained with the same candidate criteria as in ecoregion 9: **chlorophyll-a = 25 µg/L** and **40 µg/L total phosphorus**.

Summary

To illustrate potential effects of candidate criteria (Table 8), we applied those criteria to the Virginia lakes data set used in the above analysis (Table 9). Available data indicate that most of the state's reservoirs satisfy the candidate criteria. Fisheries in those reservoirs that have both water quality that satisfies the candidate criteria and low fishery status ratings can be presumed to be affected by factors other than nutrient overenrichment; comments by VDGIF biologists, in many cases, document these effects (Appendix A, Table A-4). Several lakes with good (4) or excellent (5) fishery status ratings fail to satisfy the criteria, thus demonstrating the reservoir responses to nutrient inputs vary due to differences in morphometric and other factors. Lake Chickahominy, for example, supports an excellent fishery despite high phosphorous levels (median TP = 60 µg/L). Lake Chickahominy differs from other lakes in the data set due to the abundance of macrophytes and structure in the lake bottom. Lake Chickahominy also has a very low TN/TP ratio (using lake median values, TN/TP = 12, vs. the data set's mean value of 25). Lake Cohoon (4) and Lake Prince (5) also support high-quality fisheries despite marginal exceedance of candidate criteria.

Table 8. Candidate criteria to accommodate fishery recreation and protect aquatic life.[a]

Fishery Type	Warm-water	Cool-water	Cold-water (trout)	Managed / Fertilized	Warm-water	Cool-water	Cold-water (trout)	Managed / Fertilized
Eco-region	- - - - - - - - Chl-a (µg/L)- - - - - - - -				- - - - - - - - TP (µg/L)- - - - - - - -			
11	25	10	4		40	20	10	
9	25	10		60	40	30		40
14	25	10			40	20		

[a] TP and Chl-a are median values representative of the April – October period.

Table 9. Status of Virginia reservoirs used in analysis relative to candidate criteria. (> CC = median concentration higher than candidate criteria).

Lake	Eco-region	Type	Chl-a (µg/L)	TP (µg/L)	Fishery Status	Chl-a Status	TP Status
Abel Lake	9	Warm	2	20	2	ok	ok
Banister Lake	9	Warm	5	20	1	ok	ok
Big Cherry Reservoir	11	Warm	3	10	3	ok	ok
Briery Creek Lake	9	Warm	12	13	5	ok	ok
Brookneal Reservoir	9	Warm	4	30	2.5	ok	ok
Byllesby Reservoir	11	Warm	1	40	3	ok	ok
Carvin Cove Reservoir	11	Warm	4	20	3	ok	ok
Chickahominy Lake	9	Warm	16	60	5	ok	> CC
Claytor Lake	11	Cool	6	20	4	ok	ok
Curtis Lake	9	Fert	54	40	4	ok	ok
Diascund Reservoir	9	Warm	25	30	5	ok	ok
Douthat Lake	11	Cold	3	10	2	ok	ok

Elkhorn Lake	11	Cold	2	10	2	ok	ok
Emporia Lake	9	Warm	7	25	2	ok	ok
Fairy Stone Lake	11	Warm	2	10	2.5	ok	ok
Fort Pickett Reservoir	9	Warm	15	50	3	ok	> CC
Great Creek Reservoir	9	Warm	4	20	3	ok	ok
Harrison Lake	9	Warm	3	47	2	ok	> CC
Harwoods Mill Reservoir	14	Warm	8	25	4	ok	ok
Hungry Mother Lake	11	Warm	4	10	3	ok	ok
John W. Flannagan Reservoir	11	Cool	3	10	3	ok	ok
Kerr Reservoir	9	Cool	10	30	5	ok	ok
Keysville Reservoir	9	Warm	21	40	3	ok	ok
Lake Albemarle	9	Fert	18	30	4	ok	ok
Lake Anna	9	Cool	3	10	4	ok	ok
Lake Burnt Mills	14	Warm	21	30	4	ok	ok
Lake Chesdin	9	Warm	17	40	4	ok	ok
Lake Cohoon	14	Warm	29	50	4	> CC	> CC
Lake Frederick	11	Warm	5	10	5	ok	ok
Lake Gaston	9	Cool	5	20	4	ok	ok
Lake Kilby	14	Warm	28	45	3	> CC	> CC
Lake Meade	14	Warm	20	40	4	ok	ok
Lake Moomaw	11	Cool	3	10	4	ok	ok
Lake Nelson	9	Warm	7	30	4	ok	ok
Lake Pelham	9	Warm	4	20	3	ok	ok
Lake Prince	14	Cool	11	20	5	> CC	ok
Lake Robertson	11	Warm	3	20	4	ok	ok
Lake Smith	14	Warm	64	150	3	> CC	> CC
Lee Hall Reservoir	14	Warm	14	30	3	ok	ok
Little Creek Reservoir	14	Warm	72	135	3	> CC	> CC
Martinsville Reservoir	9	Warm	3	10	2	ok	ok
Modest Creek Reservoir	9	Warm	10	30	2	ok	ok
Motts Run Reservoir	9	Cool	6	15	3	ok	ok
Mountain Run Lake	9	Warm	11	25	3	ok	ok
North Fork Pound Reservoir	11	Warm	2	10	2	ok	ok
Pedlar River Reservoir	11	Warm	3	10	3	ok	ok
Philpott Reservoir	9	Cool	2	10	4.5	ok	ok
Shenandoah Lake	11	Warm	12	29	2	ok	ok
Smith Mountain Lake	9	Cool	3	20	4	ok	ok
South Fork Rivanna Reservoir	9	Warm	6	25	3	ok	ok
South Holston Lake	11	Cool	9	20	5	ok	ok
Stonehouse Creek Reservoir	9	Fert	26	40	5	ok	ok
Sugar Hollow Reservoir	11	Cold	4	15	2	ok	> CC
Swift Creek Lake	9	Warm	16	37	2	ok	ok
Switzer Lake	11	Cold	1	10	3	ok	ok
Thrashers Creek Reservoir	9	Warm	14	20	4	ok	ok
Totier Creek Reservoir	9	Warm	9	30	2	ok	ok
Waller Mill Reservoir	9	Cool	7	20	4	ok	ok
Western Branch Reservoir	14	Cool	9	20	5	ok	ok

Criteria Implementation: TP vs. Chl-a

A central issue in developing candidate criteria to protect aquatic life and recreational fisheries in impoundments is the decision whether they are intended to identify sites experiencing nutrient enrichment or the subset of these sites exhibiting symptoms of eutrophication (biological impairment arising from excess nutrients). This is a key point because it informs subsequent decisions about the types of criteria that should be adopted. The committee has adopted the position that the detection of eutrophication is the primary goal underlying the development of nutrient criteria for Virginia reservoirs. Based on this viewpoint, we recommend that secondary metrics (specifically, chlorophyll concentrations) should be the basis for establishing criteria. Our rationale is that reservoirs exhibit variable sensitivity to nutrient enrichment based on their flushing rate (residence time), critical depth (ratio of optical to mixed depth), sediment influx, and other factors (Figure 9). Given their variable response, it is not practical to apply a single standard based on nutrient concentration for the purpose of identifying impairment or to establish mitigation targets. Because only a subset of reservoirs experiencing nutrient enrichment will experience inability to serve designated use, setting standards based on nutrient concentrations would result in the classification of all nutrient-rich water bodies as impaired irrespective of their sensitivity. Prior attempts to address the issue of variable autotrophic potential have focused on the exclusion of reservoirs with very short water residence time (e.g., < 14 days). As the effects of flushing rate on autotrophic potential are continuous, there is no defensible basis for selecting an arbitrary threshold to distinguish sensitive vs. non-sensitive water-bodies. Adopting criteria based on biological attributes (chlorophyll concentration) resolves this issue by identifying lakes where the effects of nutrient enrichment have exceeded an algal-biomass threshold and avoids mitigation efforts for lakes where nutrient concentrations may be high but algal production is constrained by low autotrophic potential (fast flushing and low critical depth). Another important advantage of this approach is that chlorophyll concentrations are directly related to a number of factors that have a direct effect on the water body's capability to serve designated uses. These include: (1) taste/odor/toxicity effects arising from algal blooms in reservoirs used as drinking water sources, (2) reductions in water column transparency diminishing swimming and other recreational uses during algal blooms, and (3) effects of hypoxia on recreational fisheries and biodiversity arising from enhanced algal production.

We have expressed candidate nutrient criteria as both TP and Chl-a concentrations in response to an expectation that EPA may require that criteria be expressed as both as nutrient concentrations and as effects-based variables (SD and/or Chl-a). However, we believe that candidate criteria expressed as Chl-a concentrations of Table 8 provide a more appropriate basis for implementation than those expressed as TP concentrations.

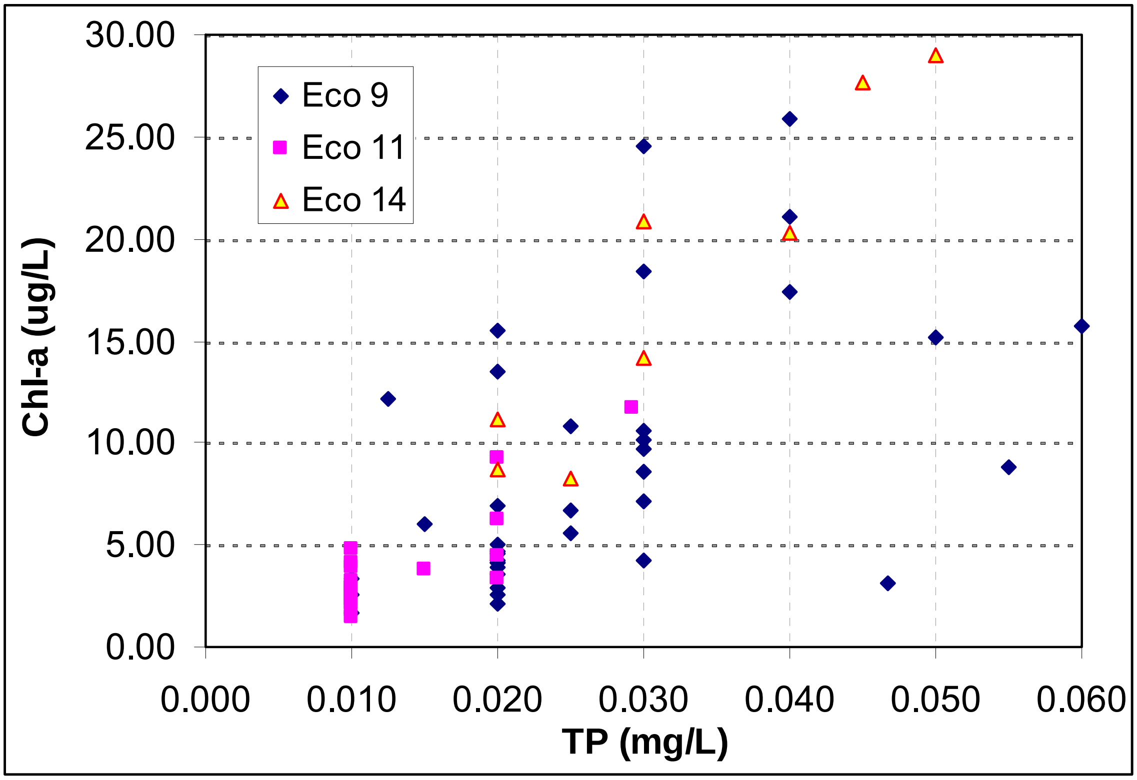


Figure 9. Lake-median (April – October) Chl-a vs. TP concentrations, by ecoregion, for the Virginia impoundments used in this study. Three lakes with Chl-a medians > 50 µg/L (outliers) are not represented.

Nutrient Requirements for Fisheries: Perspective and Recommendations

The committee is recommending candidate criteria for fishery recreation and aquatic life in recognition of DEQ's obligation to develop freshwater nutrient criteria in a manner that is consistent with EPA's requirements and timeline. Based on analyses described above, the Committee suggests candidate criteria that would be protective of fishery recreation and aquatic life in the state's impoundments (Table 8). We believe these criteria are derived from the available data via a thorough analysis using defensible methods. The candidate criteria are recommended expecting that DEQ will seek to balance the nutrient requirements of recreational fisheries against those of other potential uses, including contact recreation and public water supplies, in defining nutrient criteria for implementation, and that DEQ's implementation would include a systematic review and evaluation, as discussed below.

However, when looking at the analyses from a scientific perspective, the committee has reservations. For the following reasons and from a scientific perspective, we consider the available data to be less than an ideal basis for the analyses performed:

- VDGIF biologists' recreational fishery assessments, although based on professional knowledge of fish populations in each reservoir, are subjective. If available, data quantifying populations of recreational fishes and other aquatic species that represent a number of impoundments and are comparable across impoundments would be more desirable as a basis for conducting this task.

- Because some impoundments considered in the analysis are represented by relatively small numbers of observations, available data are not capable of characterizing water quality conditions with a high level of certainty. Most months for most lakes are represented only by one observation collected during a single year, and thus do not represent interannual variability. Lake nutrient conditions can change both throughout any given year and from year to year as a result of climatic variations and other factors.

- Because examples are few within the state's reservoirs where fisheries are known to be impaired due to nutrient overenrichment, the available data do not allow for a precise definition of the criteria.

In the committee's view, the candidate criteria expressed as Chl-a concentrations (Table 8) provide a more appropriate basis for implementation than those expressed as TP concentrations.

The committee recommends that DEQ's implementation of nutrient criteria should include a process that embodies systematic review, evaluation, and refinement as recommended by the our July 2004 report (AAC, 2004). We recommend that components of that review and evaluation process for lakes and reservoirs should include:

- Maintenance of a consistent monitoring approach and development of a more complete data record with improved utility for characterizing Virginia lakes' responses to nutrient inputs, which can be used to aid the process of criteria evaluation and refinement.
- A systematic method for developing an improved descriptive database for the state's impoundments. Availability of such a database can be expected to improve DEQ's ability to categorize impoundments based on differences in response to nutrient inputs and to understand underlying reasons for those differences. Such a database would include information on waterbody usage and morphometric/physiographic features (such as surface area, volume, mean depth, watershed areas, surface water inflows, and retention time) that influence response to nutrient inputs.
- A process of responding to numeric criteria violations that includes an evaluation of whether or not the water body in question is serving its designated use(s), combined with an associated process for making similar determinations in water bodies that are not in violation of numeric criteria.
- Review and evaluation of the number and location of monitoring points within individual lakes, including development and/or refinement of a rationale for each monitoring point's placement and documentation of that rationale so as to enable the process of criteria review, evaluation, and refinement to consider spatial variability within impoundments.

II. Rivers and Streams

Analysis of USGS and EPA Studies

Water Quality Academic Committee Report on the Utility of Ongoing Studies in Virginia and Neighboring States for Nutrient Criteria Development for Wadeable Streams, by Leonard Smock

Introduction

As part of the process of developing nutrient criteria for wadeable streams, the Virginia Department of Environmental Quality (DEQ) determined that it would be useful to identify existing or planned studies from neighboring states that might assist Virginia in the development of its nutrient criteria. Identifying data or studies focused on the relationships between nutrient concentrations and appropriate response variables from states that share nutrient ecoregions with Virginia could greatly assist and expedite DEQ's nutrient criteria development process.

The Academic Advisory Committee was requested to review several ongoing studies, identified by DEQ, to determine their potential for aiding the development of Virginia's nutrient criteria. These studies approach the problem with a focus on using periphyton as the primary response variable affected by varying nutrient concentrations in streams. The studies are reviewed here in terms of their proposed objectives, appropriateness of methodologies, data to be produced, and projected outcomes. The primary focus of this review thus is to determine the potential value and timeliness of these studies in assisting DEQ with the development of nutrient criteria for wadeable streams in Virginia.

Maryland-USGS and Pennsylvania-USGS: Efforts to Develop Response-Based Nutrient Criteria

Overview

Two of the efforts that hold promise for providing useful information are coordinated proposals to the EPA by Maryland and Pennsylvania. The initial proposal was developed jointly by the Maryland Department of the Environment and the Pennsylvania District of the US Geological Survey, titled "A Regional Approach to the Development of a Response-Based Nutrient Criterion for Wadeable Streams in Nutrient Ecoregions IX, XI, & XIV" (Appendix D). This proposal was funded, with field work having been completed during the summer 2004. Samples are presently being processed. The Pennsylvania Department of Environmental Protection and the USGS subsequently submitted a similar proposal to EPA, titled "A Response-Based Approach for Development of Nutrient Criteria in the Mid-Atlantic States" (Appendix E). That work also has been funded, with the intent of effectively doubling the sampling effort of the

Maryland-USGS project. Field work for this project is scheduled for completion during the summer of 2005. Although data from both projects could be analyzed separately, it should be the intent of the agencies to eventually pool their data to increase the statistical robustness of their analyses.

Objectives and Methodology

The overall objective of the two studies is to use an effects-based approach, rather than a reference condition approach, to develop nutrient criteria for wadeable streams in three nutrient ecoregions shared by Virginia, Maryland, Pennsylvania and West Virginia. The studies focus on the linkage of nutrient concentrations with chlorophyll-a and minimum dissolved oxygen (DO) concentrations, as well as periphyton community attributes. The projected outcome of the studies is the establishment of threshold nutrient concentrations that result in a desired minimum DO concentration for streams in each of the three nutrient ecoregions. These thresholds then could be used either to support EPA's suggested nutrient criteria based on reference conditions or as an alternative to EPA's approach and threshold concentrations.

Using information in the PA-USGS proposal, which refers to the number of streams to be sampled in both studies, there would be 24 streams sampled for each study, for a total of 48 streams across the three ecoregions. The MD-USGS work this past summer, however, resulted in only 15 streams being sampled and thus something less than the projected 48 streams will be included in the overall data base. The ecoregions that are the focus of the study are Nutrient Ecoregions IX: Southeastern temperate forested hills and plains; XI: Central and eastern forested uplands; and XIV: Eastern coastal plain. Site selection is based on a stratified random design, with the three strata being ecoregion, stream order (2nd through 4th order), and nutrient environment (low, medium and high concentrations). All sampling is conducted during the summer months in order to maximize the likely response of periphyton and DO to nutrients.

The focus of the studies is on the effect of both nitrogen and phosphorus concentrations on the response variables. Appropriate USGS and EPA sampling, sample analysis, and QA/QC protocols are being followed. Single grab samples of water are collected and analyzed from each stream to determine the concentrations of the various forms of nitrogen and phosphorus, other standard water quality parameters, and total organic carbon (TOC), the latter to provide an indication of water column DO demand. Data on DO concentrations in each stream are derived using continuous recorders over a 48-hour period, allowing the determination of nighttime, minimum DO concentrations. Benthic chlorophyll-a concentrations are used as surrogates for periphyton biomass. Data also are collected at each stream on periphyton community metrics, including species composition of the diatom community.

Analysis of projected outcomes of the studies

The three nutrient ecoregions included in these studies cover a large majority of the streams in the Commonwealth, and thus, the studies have the potential for broad utility to DEQ. One caveat to this point is that the assumption must be made that there is sufficient homogeneity within each ecoregion such that the periphyton communities of streams across these geographically rather broad ecoregions react in the same way to nutrient concentrations as they do in Virginia. These studies likely will not be sufficiently robust to test that assumption, but this probably will not be enough of a problem that it limits the usefulness of the studies to Virginia.

The general design of the studies may provide useful information that could assist in the development of nutrient criteria. One potential problem, however, concerns sampling replication. Only one sample per stream is being taken for the determination of nutrient and chlorophyll-a concentrations, raising the question of how representative a sample will be of conditions in the stream. In addition, the grab sample will only provide information on existing nutrient concentrations, with no indication of the nutrient conditions under which the periphyton grew. These limitations may impact the analysis of the relationship between nutrient concentrations and periphyton growth.

The number of streams to be sampled also will place limitations on the ability of the studies to fully reach their goals. The stratified random sampling design indicates that there will be three strata (ecoregion, stream order, and nutrient regime), each with three categories. Only when data from the two studies are pooled may there be sufficient replication of the test categories. The PA-USGS sampling effort for this coming year needs to sample as many streams as possible.

Data analysis focuses on determining the nutrient concentration (either N or P) that results in a DO concentration of 5 mg/L, the water quality standard for DO. A general problem with the approach of these studies is that they assume that the response variables, including DO, are directly reacting to nutrient concentrations. This is a tenuous assumption. The proposals do attempt to take into account in the data analysis the problem that periphyton growth may be limited by some other factor. For example, since many of the low order streams to be sampled probably have partial to full canopy cover, it is very likely that during the summer, light will be the factor limiting periphyton growth in at least some, if not many, of the streams. Unless a nutrient is the limiting factor, differences in periphyton growth and DO concentrations among streams will not be in response to differences in nutrient concentrations.

The proposed data analysis makes an attempt to alleviate this problem, but the analysis to be used seemingly employs circular reasoning. In essence, it pre-selects points by assuming that the lowest points on the plot of nutrient vs. DO concentrations are from streams that are nutrient limited and that other points are from streams where periphyton growth is limited by some other factor. Only the lowest points on the plot are then used in a regression analysis to mathematically express the nutrient-DO relationship. Thus, only those points that are presumed to define the relationship are used to quantify the relationship. Unfortunately, there will be no data to allow a determination if any of the streams are nutrient limited and thus appropriate for determining the nutrient-periphyton relationship. Defense of a nutrient criterion from this line of data analysis may be difficult.

Since light is a likely limiting factor during the summer, it could be incorporated into the data analysis to remove its effects. Categorizing the extent of canopy cover (e.g., open, partial, and full) and using that information in a multiple regression may result in a more accurate determination of the nutrient-DO relationship.

Another point to consider is that the study design and data analysis assume that the nighttime minimum DO concentration in a stream is a result of the DO demand placed on the stream by periphyton, both through respiration and their decay. Other sources of demand and reaeration are not incorporated into the study. The concentration of TOC in the water column will be determined, but there is no consideration of benthic organic matter, which in shallow streams usually accounts for a greater proportion of the DO demand than does organic carbon in the water column. In addition, variability in reaeration rates among streams will not be taken into account; differences in stream geomorphology and hydrology can have a marked effect on reaeration and hence on the minimum DO concentration in a stream.

The above real and potential problems with the proposed data analysis may limit the potential value to DEQ of this aspect of the studies. The studies will provide far better information than presently exist on the relationship of nutrients with DO and periphyton growth in wadeable streams. The data thus will provide a good next step in the development of the criteria, but the limitations of the studies must be fully recognized.

The data on periphyton community structure and species composition will be useful for the later development of a periphyton IBI that could be correlated with the general nutrient environment and eutrophication status of the streams. Much highly useful data will be made available. It is possible that this information, coupled with the information derived from The Academy of Natural Sciences-DEQ study, will provide a mechanism to classify streams based on their eutrophication status, which could lead to better establishment of a nutrient-periphyton relationship and thus nutrient criteria.

The Academy of Natural Sciences–Virginia DEQ Study on Periphyton-Nutrient Relationships

Overview

The Philadelphia Academy of Natural Sciences and DEQ collaborated on a proposal (Appendix F) to EPA's Environmental Monitoring and Assessment Program (EMAP) for funding of a proposal titled "The Development of an Algae-based Water Quality Monitoring Tool for Virginia Streams." That proposal was funded, samples were collected during September through November 2004, and the samples are presently being processed. A second year of the project, however, has not been funded, and the limited number of streams that were sampled may decrease the usefulness of this project.

Objective and Methodology

The study focuses on determining the relationship of algal biomass and species composition with nutrient conditions in wadeable streams in Virginia. The desire is to determine algal indicators of nutrient conditions that are appropriate for streams in Virginia, that can be incorporated into biomonitoring programs, and that ultimately can distinguish between different states of eutrophication.

The study uses standard EPA sampling and laboratory protocols. Some number less than the 40-70 sites that were proposed for sampling were actually sampled during the 2004 field season. Streams were chosen from DEQ's ongoing probabilistic biomonitoring sampling sites. Data will be available for each stream on chlorophyll-a, algal biomass, and species composition of the periphyton community. The proposal does not indicate that samples were collected to determine nutrient concentrations, but I assume that grab samples were taken for analysis of both N and P. Data analysis will focus on these parameters as well as periphyton community metrics such as species richness and dominance.

Analysis of Projected Outcomes of the Studies

The study takes a broad effects-based approach to determining the relationship of aspects of the periphyton community to nutrient concentrations in wadeable streams. The general approach should provide useful information that could be used in the development of nutrient criteria, although no indication is given in the proposal as to how the data will be analyzed to this effect. At this time, it appears the study is focused on data collection, and the consideration of data analysis will be made at a later time. Another point is the underlying premise of the study: the extent of periphyton growth in the streams is directly dependent on nutrient concentrations, rather than some other factor such as light. Until this connection is demonstrated, there will be uncertainty in any conclusions on a nutrient-periphyton relationship drawn from the study.

For the data to be useful in the development of nutrient criteria, DEQ will have to be able to adequately characterize the nutrient conditions in the streams or at least categorize the eutrophication status of the streams. The former may suffer unless there are more data on nutrient concentrations in the stream beyond a grab sample taken at the time of the periphyton sampling. The second approach would establish eutrophication categories defined by the extent of periphyton growth in streams. Nutrient concentrations associated with an unacceptable level of stream eutrophication, as defined by periphyton biomass or chlorophyll-a, would assist in setting nutrient criteria. The challenge here is to determine what is an acceptable vs. unacceptable level of periphyton in a stream. Data tying levels of periphyton growth to water quality parameters for which there exists a standard (e.g., DO) or to the degrading of other biological characteristics of the stream will be necessary for this approach to be of use for nutrient criteria development.

The results from this study probably can be linked to results on the periphyton community in streams being generated from the MD-USGS and PA-USGS studies.

There is sufficient similarity in the methodologies of the studies that the data could possibly be pooled, providing a larger data base for analysis. If additional sampling is conducted in the future for this or similar studies, attention should be placed on insuring compatibility with the existing data base.

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Appendix A. Lakes and Reservoirs Data Summary

Table A-1. Correspondence of DEQ monitoring stations with lake names for analysis.

Station ID	DEQ Lake Name	Station ID	DEQ Lake Name
1ALOH001.20	Abel Lake	6BLSR008.12	Corder Bottom Lake (Bark Camp L.)
1ALOH002.20	Abel Lake	6BLSR008.32	Corder Bottom Lake (Bark Camp L.)
1APOM013.02	Abel Lake	6BLSR008.52	Corder Bottom Lake (Bark Camp L.)
1APOM013.41	Abel Lake	5ALZT000.12	Crystal Lake
5ALTD005.10	Airfield Pond	1ALOM007.93	Curtis Lake
2-XLW000.60	Amelia Lake	2-DSC005.85	Diascund Reservoir
4ABAN012.46	Banister Lake	2-DSC005.91	Diascund Reservoir
2-BRC001.55	Bear Creek Lake	2-DSC006.03	Diascund Reservoir
1ABEE000.40	Beaverdam Creek Reservoir	2-DSC006.46	Diascund Reservoir
1ABEE001.40	Beaverdam Creek Reservoir	2-DSC006.65	Diascund Reservoir
7-BEA002.82	Beaverdam Reservoir (coast)	2-DSC007.09	Diascund Reservoir
7-BEA005.82	Beaverdam Reservoir (coast)	2-DSC008.12	Diascund Reservoir
7-BEE000.60	Beaverdam Reservoir (coast)	2-WLN007.36	Douthat Lake
4AXKD003.34	Beaverdam Reservoir (Bedford)	1BNTH045.36	Elkhorn Lake
4ASCB004.58	Bedford Reservoir	5AMHN053.00	Emporia Lake
6BPLL012.79	Big Cherry Reservoir	5AMHN053.29	Emporia Lake
6BPLL012.99	Big Cherry Reservoir	5AMHN057.92	Emporia Lake
6BPLL013.59	Big Cherry Reservoir	4AGOB003.86	Fairy Stone Lake
2-BRI010.78	Briery Creek Lake	2-FAC003.85	Falling Creek Reservoir
2-BRI013.12	Briery Creek Lake	2-CFK004.34	Fluvanna Ruritan Lake
4APLP000.45	Brookneal Reservoir	5ACDR000.30	Fort Pickett Reservoir
5ARDC007.30	Brunswick County Lake	5ANTW127.14	Fort Pickett Reservoir
1ASOH006.66	Burke Lake	5ANTW128.67	Fort Pickett Reservoir
1ASOH007.26	Burke Lake	5ADBS001.00	Game Refuge Lake
4ATMA004.60	Burton Lake	9-PKC016.91	Gatewood Reservoir
9-NEW129.80	Byllesby Reservoir	9-PKC017.71	Gatewood Reservoir
9-NEW132.86	Byllesby Reservoir	2-XEP000.44	Goodwin Lake
4ACRV006.19	Carvin Cove Reservoir	1AGOO003.82	Goose Creek Reservoir
4ACRR008.32	Cherrystone Lake	1AGOO004.89	Goose Creek Reservoir
2-CHK024.07	Chickahominy Lake	2-GRA000.40	Graham Reservoir
2-CHK025.15	Chickahominy Lake	5AGTC009.94	Great Creek Reservoir
2-CHK026.94	Chickahominy Lake	5AGTC011.35	Great Creek Reservoir
2-CHK029.54	Chickahominy Lake	4AGEO011.38	Gretna Lake
2-JCB000.80	Chris Green Lake	2-WER002.06	Harrison Lake
9-NEW087.14	Claytor Lake	7-POQ005.72	Harwoods Mill Reservoir
9-NEW089.34	Claytor Lake	7-POQ006.84	Harwoods Mill Reservoir
9-NEW092.66	Claytor Lake	9-HGN001.06	Hogan Lake
9-NEW098.32	Claytor Lake	9-HGN001.29	Hogan Lake
9-NEW100.54	Claytor Lake	2-HOL001.05	Holiday Lake (Appomattox)
9-PKC000.00	Claytor Lake	6CHUN004.76	Hungry Mother Lake
9-PKC004.16	Claytor Lake	6CHUN005.24	Hungry Mother Lake
4AHTA003.26	Conner Lake	6CHUN006.13	Hungry Mother Lake

Station ID	DEQ Lake Name	Station ID	DEQ Lake Name
6ACNR000.00	John W. Flannagan Reservoir	1ABRU017.58	Lake Manassas
6ACNR001.03	John W. Flannagan Reservoir	1ABRU018.78	Lake Manassas
6APNR001.82	John W. Flannagan Reservoir	2-LKM001.16	Lake Maury
6APNR007.67	John W. Flannagan Reservoir	2-LMD000.02	Lake Meade
6APNR008.15	John W. Flannagan Reservoir	2-LMD000.20	Lake Meade
4AGRA003.22	Kerr Reservoir	2-LMD000.41	Lake Meade
4AROA022.52	Kerr Reservoir	2-LMD001.41	Lake Meade
4AROA028.04	Kerr Reservoir	2-LMD002.07	Lake Meade
4AROA032.42	Kerr Reservoir	2-JKS044.60	Lake Moomaw
4AROA043.14	Kerr Reservoir	2-JKS046.40	Lake Moomaw
4ASRN005.14	Keysville Reservoir	2-JKS048.90	Lake Moomaw
2-SIN000.44	Lake Albemarle	2-JKS053.48	Lake Moomaw
8-CON002.32	Lake Anna	2-XLU000.10	Lake Nelson
8-ELK003.35	Lake Anna	8-CLC003.48	Lake Orange
8-GMC000.23	Lake Anna	8-CLC004.28	Lake Orange
8-NAR034.92	Lake Anna	3-MTN025.17	Lake Pelham
8-NAR037.22	Lake Anna	2-MIC002.44	Lake Powell
8-NAR043.00	Lake Anna	2-MIC002.84	Lake Powell
8-NAR044.68	Lake Anna	2-LPR000.02	Lake Prince
8-NAR047.17	Lake Anna	2-LPR007.55	Lake Prince
8-NAR047.69	Lake Anna	2-NWB006.56	Lake Prince
8-NAR054.17	Lake Anna	2-XMW000.72	Lake Robertson
1BDRI005.55	Lake Arrowhead	7-LAS000.06	Lake Smith
2-NWB007.04	Lake Burnt Mills	7-LAS001.03	Lake Smith
2-NWB009.48	Lake Burnt Mills	7-LAS001.44	Lake Smith
2-NWB010.54	Lake Burnt Mills	2-BRO003.55	Lake Taylor
2-APP020.23	Lake Chesdin	2-BRO003.95	Lake Taylor
2-APP023.27	Lake Chesdin	7-LCC005.40	Lake Wright
2-APP026.67	Lake Chesdin	2-SFT006.10	Lakeview Reservoir
2-APP028.58	Lake Chesdin	6CLAU001.84	Laurel Bed Lake
2-APP029.23	Lake Chesdin	6CLAU003.05	Laurel Bed Lake
2-APP061.02	Lake Chesdin	2-LHR000.96	Lee Hall Reservoir
2-LCN000.20	Lake Cohoon	2-LHR001.76	Lee Hall Reservoir
2-LMD004.35	Lake Cohoon	2-LHR002.56	Lee Hall Reservoir
2-LMD005.55	Lake Cohoon	4AROA140.66	Leesville Lake
4AROA000.00	Lake Gaston	4AROA145.34	Leesville Lake
4AROA004.54	Lake Gaston	4AROA153.59	Leesville Lake
4AROA008.66	Lake Gaston	2-LTL001.20	Little Creek Reservoir (2LTL)
4AMES007.54	Lake Gordon	2-LTL001.60	Little Creek Reservoir (2LTL)
6BPWL024.64	Lake Keokee	2-LTL002.46	Little Creek Reservoir (2LTL)
6BPWL025.20	Lake Keokee	7-LTR000.04	Little Creek Reservoir (7LTR)
6BPWL025.32	Lake Keokee	7-LTR000.95	Little Creek Reservoir (7LTR)
2-LKK000.80	Lake Kilby	9-LRV000.44	Little River Reservoir (New)
2-PKC001.84	Lake Kilby	2-LSL000.16	Lone Star Lake F
7-LAK000.34	Lake Lawson	2-LSL000.04	Lone Star Lake G
7-LAK000.41	Lake Lawson	2-LSL000.20	Lone Star Lake I
1ABRU016.28	Lake Manassas	4ABAU005.34	Martinsville Reservoir

Station ID	DEQ Lake Name	Station ID	DEQ Lake Name
5AMDT004.94	Modest Creek Reservoir	4AROA158.22	Smith Mountain Lake
3-MOT000.39	Motts Run Reservoir	4AROA163.76	Smith Mountain Lake
3-MOT001.19	Motts Run Reservoir	4AROA167.34	Smith Mountain Lake
3-MTN028.68	Mountain Run Lake	4AROA175.63	Smith Mountain Lake
7-MTL000.20	Mt. Trashmore Lake	4AROA180.21	Smith Mountain Lake
8-NIR012.99	Ni River Reservoir	4AROA183.64	Smith Mountain Lake
8-NIR016.09	Ni River Reservoir	4AROA192.94	Smith Mountain Lake
8-PNB000.05	Ni River Reservoir	4AROA196.05	Smith Mountain Lake
1BBKN001.81	North Fork Back Creek	4AWTH000.40	Smith Mountain Lake
6APNK001.26	North Fork Pound Reservoir	2-RRS003.59	South Fork Rivanna Reservoir
6APNK001.87	North Fork Pound Reservoir	2-RRS005.62	South Fork Rivanna Reservoir
6APNK002.08	North Fork Pound Reservoir	6CSFH062.93	South Holston Lake
5ANTW143.06	Nottoway Falls Lake	6CSFH066.16	South Holston Lake
5ANTW145.30	Nottoway Falls Lake	6CSFH070.80	South Holston Lake
2-LDJ000.60	Nottoway Lake	2-SPE000.17	Speights Run Lake
2-POL017.59	Pedlar River Reservoir	2-SPE001.18	Speights Run Lake
4ASRE046.90	Philpott Reservoir	2-SHS001.00	Stonehouse Creek Reservoir
4ASRE048.98	Philpott Reservoir	2-MNR014.50	Sugar Hollow Reservoir
4ASRE052.31	Philpott Reservoir	2-SFT022.14	Swift Creek Lake
4ASRE056.06	Philpott Reservoir	2-DYC000.19	Swift Creek Reservoir
2-STG000.21	Powhatan Lake - Lower	2-SFT031.08	Swift Creek Reservoir
2-STG000.91	Powhatan Lake - Upper	2-SFT031.28	Swift Creek Reservoir
2-SDY011.08	Prince Edward Lake	2-SFT032.53	Swift Creek Reservoir
4ARFK000.20	Roaring Fork Reservoir	2-SFT033.42	Swift Creek Reservoir
9-XBL000.20	Rural Retreat Lake	2-SFT034.38	Swift Creek Reservoir
9-XBL000.98	Rural Retreat Lake	1BSKD003.18	Switzer Lake
9-XBL001.02	Rural Retreat Lake	4ADAN196.09	Talbott Reservoir
2-MBN000.96	Sandy River Reservoir	2-TRO000.40	Third Branch Lake
2-SDY004.27	Sandy River Reservoir	2-TRH000.40	Thrashers Creek Reservoir
2-SDY005.85	Sandy River Reservoir	2-TOT001.01	Totier Creek Reservoir
1BCNG003.13	Shenandoah Lake	4ADAN187.94	Townes Reservoir
2-TBM000.92	Slate River Dam	4ATWT009.63	Twittys Creek
1AAUA012.15	Smith Lake	8-QEN007.02	Waller Mill Reservoir
1AAUA012.55	Smith Lake	8-QEN007.22	Waller Mill Reservoir
1ABED000.19	Smith Lake	8-QEN008.02	Waller Mill Reservoir
4ABSA000.62	Smith Mountain Lake	8-QEN008.58	Waller Mill Reservoir
4ABWR002.50	Smith Mountain Lake	2-NWB002.93	Western Branch Reservoir
4ABWR010.55	Smith Mountain Lake	2-NWB004.14	Western Branch Reservoir
4ABWR017.42	Smith Mountain Lake	2-NWB004.67	Western Branch Reservoir
4ACCK001.80	Smith Mountain Lake	2-NWB006.06	Western Branch Reservoir
4ACOA000.60	Smith Mountain Lake	6BXAR000.69	Wise Lake
4AGIL002.39	Smith Mountain Lake		

Table A-2. Lake median values derived by 4 methods[a] and ecoregion locations.

Lake	Chl-a-S1	Chl-a-S2	Chl-a-S3	Chl-a-Mo	SD-S1	SD-S2	SD-S3	SD-Mo
Abel Lake	2.56	1.93	1.93	2.17				
Banister Lake	5.75	4.66	4.66		0.93	0.90	0.90	
Beaverdam Res. (Bedford)	4.66	4.18	4.10	4.18	2.15	2.00	2.00	2.08
Big Cherry Reservoir	3.72	2.60	3.27					
Briery Creek Lake	10.71	9.54	10.65	12.13	1.38	1.40	1.40	1.35
Brookneal Reservoir	4.27	4.10	5.17	4.27	1.78	1.70	1.45	1.80
Byllesby Reservoir	0.99	1.53	1.17	1.30	0.73	0.70	0.68	0.71
Carvin Cove Reservoir	4.47	4.07	4.07	4.47	0.95	1.00	1.00	1.00
Cherrystone Lake	6.12	5.16	5.16	4.54	1.63	1.60	1.60	1.70
Chickahominy Lake	11.49	15.98	13.61	15.71	0.95	0.93	0.85	0.88
Claytor Lake	6.59	6.28	5.81	6.21	1.90	1.75	1.73	1.75
Crystal Lake	10.06	10.59	10.59	8.85	0.70	0.55	0.55	0.63
Curtis Lake	52.47	54.96			0.60	0.60		
Diascund Reservoir	19.44	19.27	21.75	24.59	0.88	0.88	1.00	0.80
Douthat Lake	2.57	2.07	2.10	2.63	3.74	3.81	3.64	3.68
Elkhorn Lake	3.32	2.20	2.20	2.33	3.11	3.24	3.24	
Emporia Lake	9.35	5.85	6.84	6.73	0.83	0.83	0.80	0.85
Fairy Stone Lake	1.80		1.80		1.90	1.90	1.40	
Falling Creek Reservoir	10.64	10.39	9.98	10.57	1.03	0.93	0.93	1.00
Fort Pickett Reservoir	15.99	14.94	15.08	15.22	0.70	0.68	0.65	
Gatewood Reservoir	2.28	2.28	2.38	2.33	2.55	2.55	2.55	2.40
Graham Reservoir	3.67	4.31	3.48	2.94	1.60	1.65	1.70	1.60
Great Creek Reservoir	4.90	8.67	3.50	3.94	1.20	1.25	1.33	1.30
Gretna Lake	5.56	4.71	4.65		0.80	0.75		
Harrison Lake	14.16	3.01	3.01	3.14	0.65	0.55	0.55	
Harwoods Mill Res.	8.68	9.22	7.69	8.29	1.30	1.23	1.25	1.20
Hungry Mother Lake	4.03	3.70	3.70	3.93	1.95	2.03	2.06	2.20
John W. Flannagan Res.	2.83	3.69	2.71	2.85	4.24	4.44	3.73	3.91
Kerr Reservoir	11.03	10.75	10.17	9.66		1.35	1.40	
Keysville Reservoir	21.12				0.95	0.95	0.95	
Lake Albemarle	29.86	24.51	24.34	18.38	1.47	1.38	1.51	1.32
Lake Anna	2.65	2.65	2.32		1.45	1.45	1.45	
Lake Burnt Mills	17.80	22.41	22.41		1.04	1.14	1.14	1.14
Lake Chesdin	17.56	17.73	17.73	17.38	0.78	0.85	0.85	0.85
Lake Cohoon	33.00	33.00	25.41	29.05	0.71	0.79	0.81	0.70
Lake Frederick	4.83	4.77	4.58	4.78	2.68	2.74	2.63	2.75
Lake Gaston	4.24	5.03	4.74			1.50	1.30	
Lake Kilby	31.41	26.83	23.09	27.63	1.03	1.10	1.08	1.05
Lake Meade	24.91	25.91	26.21	20.29	1.05	1.01	1.06	1.10
Lake Moomaw	3.46	3.13	2.66	2.94	2.68	2.45	2.50	2.75
Lake Nelson	14.68	13.07	13.07	7.19	1.62	1.65	1.65	1.40
Lake Pelham	4.36	3.89	3.98		0.88	0.60	0.60	
Lake Prince	12.10	13.33	13.40	11.19	1.25	1.38	1.45	1.50

Lake	Chl-a-S1	Chl-a-S2	Chl-a-S3	Chl-a-Mo	SD-S1	SD-S2	SD-S3	SD-Mo
Lake Robertson	10.93	2.76	3.29	3.29	2.44	3.38	3.00	2.85
Lake Smith	68.76	59.74	63.77			0.50	0.50	
Lee Hall Reservoir	17.76	12.00	12.37	14.17	0.85	0.85	0.95	0.80
Leesville Lake	4.24	3.69	3.67	4.13	1.50	1.43	1.23	1.25
Little Creek Reservoir	67.37	67.03	82.96			0.50	0.50	
Martinsville Reservoir	3.31		3.36		1.05	1.05	1.15	
Modest Creek Reservoir	16.95	6.68	6.68		1.05	1.00	1.00	
Motts Run Reservoir	8.00	7.52	7.52	6.05				
Mountain Run Lake	10.38	10.38	11.56		1.15	1.13	1.20	
North Fork Pound Res.	2.61	2.24	2.47	2.15				
Nottoway Falls Lake	7.10	12.68	12.68	6.48	0.83	0.90	0.90	0.75
Pedlar River Reservoir	8.37	4.23	3.41	2.92	2.43	2.55	2.48	2.35
Philpott Reservoir	2.51	2.33	2.35	1.70	2.60	2.63	2.60	2.70
Roaring Fork Reservoir	3.50	3.01	3.01	3.54	1.38	1.38	1.38	1.40
Shenandoah Lake	11.88	11.15	12.04			0.65	0.60	
Slate River Dam	6.45	3.88	3.88	4.24	0.61	0.65	0.65	0.60
Smith Mountain Lake	2.60	2.50	2.53	2.61	2.30	2.18	2.23	2.20
South Fork Rivanna Res.	6.25	6.25	5.63	5.62	1.46	1.46	1.35	1.53
South Holston Lake	10.44	9.53	8.26	9.24	1.70	1.64	1.49	1.64
Stonehouse Creek Res.	35.00	34.39	34.39	25.89	0.65	0.73	0.73	
Sugar Hollow Reservoir	3.79	3.77	3.78	3.75	2.63	2.61	2.60	2.63
Swift Creek Lake	14.47	17.60	16.43		0.60	0.60	0.60	
Swift Creek Reservoir	14.23	12.93	14.02	15.47	1.00	1.00	1.05	1.03
Switzer Lake	1.87	2.06	1.78	1.48	7.83	7.60	7.88	7.90
Thrashers Creek Res.	11.39	12.57	12.57	13.53	1.00	1.10	1.10	
Totier Creek Reservoir	7.19	8.54	8.54	8.55	1.08	0.93	0.93	0.90
Waller Mill Reservoir	6.49	6.88	6.88	6.86	1.40	1.53	1.50	1.40
Western Branch Res.	10.30	8.76	8.64	8.65	1.28	1.45	1.33	1.25

Lake	TN-S1	TN-S2	TN-S3	TN-Mo	TP-S1	TP-S2	TP-S3	TP-Mo
Abel Lake	0.53	0.56	0.53	0.53	0.015	0.020	0.020	0.020
Banister Lake	0.30	0.35	0.35	0.30	0.023	0.025	0.025	0.020
Beaverdam Res. (Bedford)	0.43	0.40	0.38	0.40	0.010	0.010	0.015	0.010
Big Cherry Reservoir	0.25	0.33	0.30		0.010	0.010	0.010	
Briery Creek Lake	0.47	0.45	0.45	0.47	0.015	0.010	0.010	0.013
Brookneal Reservoir	0.35	0.35	0.35	0.35	0.028	0.028	0.025	0.030
Byllesby Reservoir	0.77	0.80	0.79	0.79	0.045	0.035	0.045	0.040
Carvin Cove Reservoir	0.51	0.46	0.46	0.55	0.020	0.020	0.020	0.020
Cherrystone Lake	0.49	0.48	0.48	0.45	0.020	0.020	0.020	0.020
Chickahominy Lake	0.81	0.84	0.81	0.75	0.060	0.063	0.065	0.060
Claytor Lake	0.59	0.60	0.64	0.59	0.020	0.020	0.020	0.020
Crystal Lake	0.69	0.74	0.74	0.74	0.050	0.060	0.060	0.055
Curtis Lake	1.60	1.61	1.28		0.040	0.040	0.040	
Diascund Reservoir	0.75	0.58	0.63	0.60	0.030	0.030	0.030	0.030

Lake	TN-S1	TN-S2	TN-S3	TN-Mo	TP-S1	TP-S2	TP-S3	TP-Mo
Douthat Lake	0.29	0.26	0.28	0.25	0.010	0.010	0.010	0.010
Elkhorn Lake	0.24	0.24	0.24	0.25	0.010	0.010	0.010	0.010
Emporia Lake	0.34	0.35	0.36	0.36	0.025	0.025	0.023	0.025
Fairy Stone Lake	0.31	0.22	0.32		0.010	0.010	0.010	
Falling Creek Reservoir	0.61	0.64	0.64	0.62	0.035	0.035	0.035	0.030
Fort Pickett Reservoir	0.58	0.63	0.60	0.56	0.050	0.050	0.045	0.050
Gatewood Reservoir	0.35	0.35	0.35	0.35	0.010	0.010	0.010	0.010
Graham Reservoir	0.38	0.38	0.38	0.35	0.018	0.015	0.015	0.020
Great Creek Reservoir	0.30	0.38	0.30	0.35	0.020	0.023	0.023	0.020
Gretna Lake	0.52	0.53	0.42		0.020	0.020	0.020	
Harrison Lake	1.10	1.05	1.05		0.050	0.045	0.045	
Harwoods Mill Res.	0.58	0.55	0.53	0.55	0.025	0.025	0.025	0.025
Hungry Mother Lake	0.31	0.32	0.30	0.29	0.010	0.013	0.010	0.010
John W. Flannagan Res.	0.34	0.32	0.36	0.35	0.010	0.010	0.010	0.010
Kerr Reservoir	0.51	0.46	0.46	0.47	0.025	0.030	0.028	0.030
Keysville Reservoir	0.93	0.75	0.80	0.85	0.043	0.035	0.035	0.040
Lake Albemarle	0.95	0.92	0.90	0.95	0.028	0.028	0.028	0.030
Lake Anna	0.44	0.43	0.45	0.45	0.010	0.010	0.010	0.010
Lake Burnt Mills	0.69	0.68	0.68		0.025	0.030	0.030	0.030
Lake Chesdin	0.58	0.60	0.60	0.65	0.045	0.045	0.040	0.040
Lake Cohoon	0.92	0.95	0.95	0.91	0.048	0.045	0.050	0.050
Lake Frederick	0.55	0.55	0.55	0.55	0.013	0.010	0.010	0.010
Lake Gaston	0.42	0.43	0.43		0.020	0.020	0.020	
Lake Kilby	0.72	0.70	0.66	0.71	0.043	0.045	0.040	0.045
Lake Meade	0.80	0.80	0.75	0.85	0.035	0.040	0.040	0.040
Lake Moomaw	0.35	0.34	0.35	0.35	0.010	0.010	0.010	0.010
Lake Nelson	0.88	0.88	0.88	0.95	0.035	0.033	0.033	0.030
Lake Pelham	0.68	0.75	0.75	0.65	0.025	0.025	0.028	0.020
Lake Prince	0.46	0.46	0.47	0.46	0.025	0.028	0.030	0.020
Lake Robertson	0.45	0.38	0.35	0.35	0.018	0.015	0.015	0.020
Lake Smith	1.45	1.48	1.40		0.165	0.145	0.140	
Lee Hall Reservoir	0.70	0.70	0.65	0.75	0.030	0.033	0.033	0.030
Leesville Lake	0.58	0.58	0.60	0.60	0.020	0.020	0.020	0.020
Little Creek Reservoir	1.65	1.55	1.65		0.120	0.135	0.150	
Martinsville Reservoir	0.51	0.47	0.44	0.50	0.010	0.010	0.010	0.010
Modest Creek Reservoir	0.75	0.68	0.68	0.75	0.028	0.028	0.025	0.030
Motts Run Reservoir	0.70	0.59	0.59	0.65	0.013	0.015	0.015	0.015
Mountain Run Lake	0.65	0.80	0.80	0.70	0.025	0.025	0.023	0.025
North Fork Pound Res.	0.16	0.21	0.16	0.16	0.010	0.010	0.010	0.010
Nottoway Falls Lake	0.56	0.55	0.55	0.55	0.038	0.038	0.038	0.040
Pedlar River Reservoir	0.28	0.31	0.25	0.25	0.010	0.013	0.010	0.010
Philpott Reservoir	0.27	0.33	0.30	0.25	0.010	0.010	0.010	0.010
Roaring Fork Reservoir	0.35	0.30	0.30	0.35	0.020	0.018	0.018	0.020
Shenandoah Lake	0.65	0.68	0.65		0.030	0.028	0.030	
Slate River Dam	0.47	0.52	0.52	0.49	0.020	0.020	0.020	0.020

Lake	TN-S1	TN-S2	TN-S3	TN-Mo	TP-S1	TP-S2	TP-S3	TP-Mo
Douthat Lake	0.29	0.26	0.28	0.25	0.010	0.010	0.010	0.010
Elkhorn Lake	0.24	0.24	0.24	0.25	0.010	0.010	0.010	0.010
Emporia Lake	0.34	0.35	0.36	0.36	0.025	0.025	0.023	0.025
Fairy Stone Lake	0.31	0.22	0.32		0.010	0.010	0.010	
Falling Creek Reservoir	0.61	0.64	0.64	0.62	0.035	0.035	0.035	0.030
Fort Pickett Reservoir	0.58	0.63	0.60	0.56	0.050	0.050	0.045	0.050
Gatewood Reservoir	0.35	0.35	0.35	0.35	0.010	0.010	0.010	0.010
Graham Reservoir	0.38	0.38	0.38	0.35	0.018	0.015	0.015	0.020
Great Creek Reservoir	0.30	0.38	0.30	0.35	0.020	0.023	0.023	0.020
Gretna Lake	0.52	0.53	0.42		0.020	0.020	0.020	
Harrison Lake	1.10	1.05	1.05		0.050	0.045	0.045	
Harwoods Mill Res.	0.58	0.55	0.53	0.55	0.025	0.025	0.025	0.025
Hungry Mother Lake	0.31	0.32	0.30	0.29	0.010	0.013	0.010	0.010
John W. Flannagan Res.	0.34	0.32	0.36	0.35	0.010	0.010	0.010	0.010
Kerr Reservoir	0.51	0.46	0.46	0.47	0.025	0.030	0.028	0.030
Keysville Reservoir	0.93	0.75	0.80	0.85	0.043	0.035	0.035	0.040
Lake Albemarle	0.95	0.92	0.90	0.95	0.028	0.028	0.028	0.030
Lake Anna	0.44	0.43	0.45	0.45	0.010	0.010	0.010	0.010
Lake Burnt Mills	0.69	0.68	0.68		0.025	0.030	0.030	0.030
Lake Chesdin	0.58	0.60	0.60	0.65	0.045	0.045	0.040	0.040
Lake Cohoon	0.92	0.95	0.95	0.91	0.048	0.045	0.050	0.050
Lake Frederick	0.55	0.55	0.55	0.55	0.013	0.010	0.010	0.010
Lake Gaston	0.42	0.43	0.43		0.020	0.020	0.020	
Lake Kilby	0.72	0.70	0.66	0.71	0.043	0.045	0.040	0.045
Lake Meade	0.80	0.80	0.75	0.85	0.035	0.040	0.040	0.040
Lake Moomaw	0.35	0.34	0.35	0.35	0.010	0.010	0.010	0.010
Lake Nelson	0.88	0.88	0.88	0.95	0.035	0.033	0.033	0.030
Lake Pelham	0.68	0.75	0.75	0.65	0.025	0.025	0.028	0.020
Lake Prince	0.46	0.46	0.47	0.46	0.025	0.028	0.030	0.020
Lake Robertson	0.45	0.38	0.35	0.35	0.018	0.015	0.015	0.020
Lake Smith	1.45	1.48	1.40		0.165	0.145	0.140	
Lee Hall Reservoir	0.70	0.70	0.65	0.75	0.030	0.033	0.033	0.030
Leesville Lake	0.58	0.58	0.60	0.60	0.020	0.020	0.020	0.020
Little Creek Reservoir	1.65	1.55	1.65		0.120	0.135	0.150	
Martinsville Reservoir	0.51	0.47	0.44	0.50	0.010	0.010	0.010	0.010
Modest Creek Reservoir	0.75	0.68	0.68	0.75	0.028	0.028	0.025	0.030
Motts Run Reservoir	0.70	0.59	0.59	0.65	0.013	0.015	0.015	0.015
Mountain Run Lake	0.65	0.80	0.80	0.70	0.025	0.025	0.023	0.025
North Fork Pound Res.	0.16	0.21	0.16	0.16	0.010	0.010	0.010	0.010
Nottoway Falls Lake	0.56	0.55	0.55	0.55	0.038	0.038	0.038	0.040
Pedlar River Reservoir	0.28	0.31	0.25	0.25	0.010	0.013	0.010	0.010
Philpott Reservoir	0.27	0.33	0.30	0.25	0.010	0.010	0.010	0.010
Roaring Fork Reservoir	0.35	0.30	0.30	0.35	0.020	0.018	0.018	0.020
Shenandoah Lake	0.65	0.68	0.65		0.030	0.028	0.030	
Slate River Dam	0.47	0.52	0.52	0.49	0.020	0.020	0.020	0.020
Smith Mountain Lake	0.49	0.47	0.50	0.47	0.020	0.020	0.020	0.020
South Fork Rivanna Res.	0.44	0.44	0.51	0.45	0.023	0.023	0.030	0.025

Lake	TN-S1	TN-S2	TN-S3	TN-Mo	TP-S1	TP-S2	TP-S3	TP-Mo
South Holston Lake	0.47	0.52	0.54	0.47	0.023	0.023	0.023	0.020
Stonehouse Creek Res.	0.75	0.75	0.75	0.88	0.040	0.040	0.040	0.040
Sugar Hollow Reservoir	0.26	0.28	0.28	0.26	0.015	0.015	0.018	0.015
Swift Creek Lake	0.55	0.65	0.65		0.030	0.040	0.040	
Swift Creek Reservoir	0.65	0.63	0.58	0.60	0.025	0.023	0.028	0.020
Switzer Lake	0.67	0.63	0.62	0.65	0.010	0.010	0.010	0.010
Thrashers Creek Res.	0.34	0.35	0.35	0.36	0.028	0.035	0.035	0.020
Totier Creek Reservoir	1.07	1.05	1.05	1.08	0.030	0.033	0.033	0.030
Waller Mill Reservoir	0.50	0.48	0.45	0.45	0.020	0.020	0.020	0.020
Western Branch Res.	0.50	0.53	0.51	0.50	0.023	0.020	0.023	0.020

Lake	TSS-S1	TSS-S2	TSS-S3	TSS-Mo	Ecoregion
Abel Lake	3	3	3		9
Banister Lake	10	6	6	6	9
Beaverdam Res. (Bedford)	3	3	3	3	11
Big Cherry Reservoir	3	3	3		11
Briery Creek Lake					9
Brookneal Reservoir	3	3	4	3	9
Byllesby Reservoir	13	15	15	14	11
Carvin Cove Reservoir	4	4	3	4	11
Cherrystone Lake	4	3	3	3	9
Chickahominy Lake	4	4	4	4	9
Claytor Lake	3	4	3	3	11
Crystal Lake					9
Curtis Lake	6	6	5		9
Diascund Reservoir	7	5	6	5	9
Douthat Lake	3	3	3	3	11
Elkhorn Lake	3	3	3	3	11
Emporia Lake	7	7	7	7	9
Fairy Stone Lake					11
Falling Creek Reservoir	5	6	6	6	9
Fort Pickett Reservoir	8	8	9	8	9
Gatewood Reservoir	3	3	3	3	11
Graham Reservoir	3	3	3	3	9
Great Creek Reservoir	4	4	4	3	9
Gretna Lake					9
Harrison Lake	11	9	9		9
Harwoods Mill Res.	3	3	3	3	14
Hungry Mother Lake	3	3	3	3	11
John W. Flannagan Res.	3	3	3	3	11
Kerr Reservoir	8	6	6		9
Keysville Reservoir	7	6	7	7	9
Lake Albemarle	4	4	4	4	9
Lake Anna	3	3	3	3	9
Lake Burnt Mills					14
Lake Chesdin	8	10	10	9	9
Lake Cohoon					14

Lake	TSS-S1	TSS-S2	TSS-S3	TSS-Mo	Eco-region
Lake Frederick	3	3	3	3	11
Lake Gaston					9
Lake Kilby					14
Lake Meade	4	4	4	4	14
Lake Moomaw	3	3	3	3	11
Lake Nelson	4	4	4	3	9
Lake Pelham	5	6	6	5	9
Lake Prince	3	3	3	3	14
Lake Robertson	3	3	3	3	11
Lake Smith	12	13	15		14
Lee Hall Reservoir	7	6	6	6	14
Leesville Lake	4	4	4	5	9
Little Creek Reservoir	16	16	18		14
Martinsville Reservoir					9
Modest Creek Reservoir	5	6	6	6	9
Motts Run Reservoir		3	3		9
Mountain Run Lake	3	4	4	4	9
North Fork Pound Res.	3	3	3	3	11
Nottoway Falls Lake	7	8	8	7	9
Pedlar River Reservoir	3	3	3	3	11
Philpott Reservoir	3	3	3	3	9
Roaring Fork Reservoir	3	3	3	3	9
Shenandoah Lake	11	13	13		11
Slate River Dam					9
Smith Mountain Lake	3	3	3	3	9
South Fork Rivanna Res.					9
South Holston Lake	3	3	3	3	11
Stonehouse Creek Res.	10				9
Sugar Hollow Reservoir	3	3	3	3	11
Swift Creek Lake	10	9	9		9
Swift Creek Reservoir	5	5	5	5	9
Switzer Lake					11
Thrashers Creek Res.					9
Totier Creek Reservoir					9
Waller Mill Reservoir	4	3	3	3	9
Western Branch Res.	4	3	4	3	14

Note a:

S1: Seasons defined as April – May, June – July, August – September, October; lake medians calculated as median of seasonal medians if 3 seasonal medians are present.

S2: Seasons defined as equal-length periods: 4/1 – 5/23, 5/24 – 7/16, 7/17 – 9/7, and 9/8 – 10/31; lake medians calculated as median of seasonal medians if 3 seasonal medians are present.

S3: Seasons defined as April, May – June, July – August, September – October; lake medians calculated as median of seasonal medians if 3 seasonal medians are present.

Mo: Lake medians calculated as median of monthly medians, April – October; if at least 6 of the 7 months were represented by measured data.

Table A-3. Number of observations per lake.

Lake	Chl-a	SD	TN	TP
Abel Lake	14	2	17	17
Airfield Pond	1	1		
Amelia Lake	1		1	1
Banister Lake	8	5	6	6
Bear Creek Lake	1	1	1	1
Beaverdam Crk Res.			2	2
Beaverdam Res.	13	11	14	14
Bedford Res.		1	1	1
Big Cherry Res.	21		21	21
Briery Creek Lake	17	13	16	16
Brookneal Res.	7	7	7	7
Brunswick Cnty Lake	1	1		
Burke Lake	1			
Burton Lake			1	1
Byllesby Res.	8	6	7	7
Carvin Cove Res.	10	8	11	11
Cherrystone Lake	7	8	8	8
Chickahominy Lake	23	17	21	21
Claytor Lake	197	162	384	325
Conner Lake	1			
Corder Bottom Lake	3		3	3
Crystal Lake	8	7	7	7
Curtis Lake	7	9	12	12
Diascund Res.	17	16	16	15
Douthat Lake	7	6	7	7
Elkhorn Lake	7	5	7	7
Emporia Lake	15	14	12	12
Fairy Stone Lake	5	5	5	5
Falling Creek Res.	8	8	7	7
Fort Pickett Res.	24	18	21	21
Game Refuge Lake	2		1	1
Gatewood Res.	22	24	26	26
Goodwin Lake	2	1	1	1
Goose Creek Res.	2	2	4	4
Graham Res.	7	6	7	7
Great Creek Res.	9	8	9	9
Gretna Lake	6	5	6	6
Harrison Lake	6	5	5	5
Harwoods Mill Res.	12	14	14	14
Hogan Lake	1	1	1	1
Holiday Lake	1			
Hungry Mother Lake	6	7	10	10
J.W. Flannagan Res.	23	22	60	43
Kerr Res.	72	35	61	67
Keysville Res.	6	4	8	8
Lake Albemarle	7	7	7	7
Lake Anna	36	36	67	54
Lake Arrowhead	1			
Lake Burnt Mills	15	18	15	18
Lake Chesdin	45	31	43	58
Lake Cohoon	19	19	16	16
Lake Frederick	63	56	63	63
Lake Gaston	26	22	27	27
Lake Gordon	1			
Lake Keokee			6	6
Lake Kilby	14	14	12	12
Lake Lawson	6	4	4	4
Lake Manassas			3	3
Lake Meade	34	34	35	35
Lake Moomaw	91	84	135	136
Lake Nelson	7	7	7	7
Lake Orange	2			
Lake Pelham	5	6	11	11
Lake Powell			2	2
Lake Prince	21	21	21	21
Lake Robertson	7	7	7	7
Lake Smith	34	31	33	34
Lake Taylor	2			
Lakeview Res.	1	1	1	1
Laurel Bed lake	2		3	3
Lee Hall Res.	18	21	21	21
Leesville Lake	69	73	107	108
Little Creek Res.	22	20	22	21
Little River Res.		1	2	2
Martinsville Res.	5	5	7	7
Modest Creek Res.	7	6	9	9
Motts Run Res.	11	2	13	13
Mountain Run Lake	5	7	11	11
Ni River Res.		3	3	3
North Fork Back Crk	1			
North Fork Pound Res.	21		25	25
Nottoway Falls Lake	9	7	9	9
Nottoway Lake	1	1	1	1
Pedlar River Res.	7	7	8	8
Philpott Res.	97	87	147	145
Powhatan Lake Lower	2	1	1	1
Powhatan Lake Upper	2	1	1	1
Prince Edward Lake	2		1	1
Roaring Fork Res.	7	7	6	6
Rural Retreat Lake	3			
Sandy River Res.	3	2	3	3
Shenandoah Lake	7	6	7	7
Slate River Dam	8	6	7	7
Smith Lake			3	3

Lake	Chl-a	SD	TN	TP
Smith Mountain Lake	506	504	775	777
S. Fork Rivanna Res.	14	12	14	14
South Holston Lake	21	18	24	24
Speights Run Lake	2			
Stonehouse Creek Res.	6	6	8	8
Sugar Hollow Res.	6	6	6	6
Swift Creek Lake	7	5	5	5
Swift Creek Res.	34	28	32	32
Switzer Lake	7	7	7	6
Talbott Res.		1	1	1
Third Branch Lake	1			
Thrashers Creek Res.	6	6	8	8
Totier Creek Res.	7	7	8	8
Townes Res.			1	1
Twittys Creek	1	1	1	1
Waller Mill Res.	22	22	22	22
Western Branch Res.	28	28	28	28
Wise Lake			2	2

Table A-4. Lakes fishery status ratings and classifications for analysis.

Lake	Status	Type	VDGIF comments
Abel Lake	2	Warmwater	Infertile - Very riverine, steep-sided
Banister Lake	1	Turbid	Inorganic turbidity - Small & riverine
Big Cherry Reservoir	3	Warmwater	OK
Briery Creek Lake	5	Macrophytes & Structure	OK - VDGIF owned
Brookneal Reservoir	2.5	Very Small	OK
Burton Lake	1		Other - Impaired by inorganic turbidity;
Byllesby Reservoir	3	High flush	OK - Riverine
Carvin Cove Reservoir	3	Warmwater	OK - Limited access, no mgmt.
Chickahominy Lake	5	Macrophytes & Structure	OK - Excellent fishery; lots of wood, vegetation
Claytor Lake	4	Coolwater	OK - WW, CW; riverine
Curtis Lake	4	Fertilized	OK - VDGIF fertilizes annually
Diascund Reservoir	5	Warmwater	OK
Douthat Lake	2	Trout lake	Infertile - Put and take trout (no summer habitat)
Elkhorn Lake	2	Trout lake	Infertile - Supports trout
Emporia Lake	2	High flush	Inorganic turbidity - High flushing rate
Fairy Stone Lake	2.5	Warmwater	Infertile - Limited info
Fort Pickett Reservoir	3	Mechanically Aerated	Eutrophic
Great Creek Reservoir	3	Turbid	Inorganic turbidity - Built 1994
Harrison Lake	2	Turbid	Inorganic turbidity
Harwoods Mill Reservoir	4	Warmwater	OK - Gets CuSO4
Hungry Mother Lake	3	Warmwater	OK - Frequent drawdowns
John W. Flannagan Reservoir	3	Coolwater	OK - WW and CW
Kerr Reservoir	5	Coolwater	OK - Best crappie lake in USA
Keysville Reservoir	3	Warmwater	OK - No public access
Lake Albemarle	4	Fertilized	OK - VDGIF owned
Lake Anna	4	Big multipurpose	OK - Too warm for CW fish
Lake Burnt Mills	4	Warmwater	OK
Lake Chesdin	4	Warmwater	OK - V. good bass fishery
Lake Cohoon	4	Warmwater	OK - Dendritic, forested PWS
Lake Frederick	5	Warmwater	-
Lake Gaston	4	Coolwater	OK - Hydrilla in upper end
Lake Kilby	3	High flush	Other - High flushing rate
Lake Lawson	2	Warmwater	Eutrophic - Stunted fish

Lake Meade	4	Warmwater	OK - Supports warmwater & coolwater fishes
Lake Moomaw	4	Coolwater	OK - WW, CW and trout
Lake Nelson	4	Warmwater	OK - Vegetation controlled by grass carp; VDGIF owned
Lake Pelham	3	Warmwater	Other - May be $CuSO_4$ treated
Lake Prince	5	Coolwater	OK - Warmwater & Coolwater fish
Lake Robertson	4	Warmwater	OK - Fertilized by VDGIF in the past
Lake Smith	3	Warmwater	OK
Lee Hall Reservoir	3	Warmwater	OK - $CuSO_4$; lots of vegetation
Little Creek Reservoir (7LTR)	3	Warmwater	OK - Treated with $CuSO_4$
Martinsville Reservoir	2	Warmwater	Infertile
Modest Creek Reservoir	2	Warmwater	OK -Young, not fully developed fishery
Motts Run Reservoir	3	Coolwater	OK - WW and CW fish; deep
Mountain Run Lake	3	Warmwater	Other
North Fork Pound Reservoir	2	High flush	Infertile - Recovering from AMD
Pedlar River Reservoir	3	Warmwater	Infertile
Philpott Reservoir	4.5	Coolwater	Other
Shenandoah Lake	2	Turbid	Inorganic turbidity - VDGIF lake
Smith Mountain Lake	4	Coolwater	OK
South Fork Rivanna Reservoir	3	High flush	Eutrophic - High flushing rate
South Holston Lake	5	Coolwater	OK - WW, CW and trout
Stonehouse Creek Reservoir	5	Fertilized	OK - VDGIF lake
Sugar Hollow Reservoir	2	Trout lake	Other - Stocked with trout, but lose coldwater habitat in the summer; stunted crappie
Swift Creek Lake	2	Turbid	Inorganic turbidity
Switzer Lake	3	Trout lake	Infertile - Holds trout over summer
Thrashers Creek Reservoir	4	Warmwater	OK - VDGIF lake
Totier Creek Reservoir	2	Fluctuating	Infertile - PWS/flood control
Waller Mill Reservoir	4	Coolwater	OK - WW, CW
Western Branch Reservoir	5	Coolwater	OK

Appendix B

RESERVOIR DYNAMICS: A COMPARISON OF SMITH MOUNTAIN LAKE AND CLAYTOR LAKE

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KEY WORDS: trophic state, total phosphorus, chlorophyll-a, Secchi depth, nutrient dynamics

ABSTRACT

The dynamics and trophic states of Smith Mountain Lake and Claytor Lake are compared with each other and with other southern reservoirs studied by William Walker in his work for the Army Corps of Engineers (Walker, 1996).

The Ferrum College Water Quality Lab has collaborated with the Smith Mountain Lake Association (SMLA) since 1987 and with the Friends of Claytor Lake (FOCL) since 1996 to monitor the trophic status of Smith Mountain Lake and Claytor Lake.

Both reservoirs are hydroelectric facilities operated by American Electric Power (AEP), but are very different impoundments. Smith Mountain Lake has an average hydraulic residence time (AHRT) of about a year, while Claytor Lake's AHRT is about a month. SML receives most of its water from two rivers, the Roanoke and the Blackwater, that form the two main channels of the lake. The two channels are nearly perpendicular before their confluence produces the lake's "main basin." Claytor Lake is a "run of the river" reservoir on the New River. In addition to the differences in AHRT and geometric configuration, hydroelectric functions also produce differences in circulation patterns and water quality dynamics. Both reservoirs produce hydroelectric power, but Smith Mountain Lake is a "pump-back" facility. The Pigg River joins the Roanoke River just below the dam so that water from the Pigg River is pumped back to mix with Smith Mountain Lake water near the dam. The pump-back system also leads to more frequent variation in the water level in Smith Mountain Lake, which increases lake mixing and destabilizes the shoreline.

Smith Mountain Lake and Claytor Lake will be compared with each other and with other southeastern reservoirs in terms of trophic state parameters (total phosphorus, chlorophyll-*a*, and Secchi depth), non-algal turbidity, and trophic state index. Additional comparisons will be made between Smith Mountain Lake and Claytor Lake by considering the rate of change in trophic status and variation in water quality with distance from the dam. The presentation concludes by considering how the differences might affect strategies for managing water quality in reservoirs.

INTRODUCTION

With the assistance of citizen volunteers and student interns, scientists from the Ferrum College Water Quality Lab have been monitoring the trophic status of Smith Mountain Lake since 1987 and the trophic status of Claytor Lake since 1996. Both water bodies are reservoirs, owned and operated by American Electric Power (AEP), and were constructed for flood control, generation of hydroelectric power, and recreation. Claytor Lake, on the New River, dates back to the late 1930's and is a "run-of-the-river" reservoir with an average hydraulic residence time (AHRT) of about one month. Smith Mountain Lake dates back to the late 1960's and has an AHRT of about a year and receives most of its water from two rivers, the Roanoke and the Blackwater, that form the two main channels of the lake. The two channels are nearly perpendicular before their confluence produces the lake's "main basin." In addition to the differences in AHRT and geometric configuration, hydroelectric functions also produce differences in circulation patterns and water quality dynamics. Both reservoirs produce hydroelectric power, but Smith Mountain Lake is a "pump-back" facility. The Pigg River joins the Roanoke River just below the dam, and water from that river is pumped back to mix with SML water in the main basin. The pump-back system also leads to more frequent variation in the water level in Smith Mountain Lake, which increases lake mixing and destabilizes the shoreline.

The trophic state of a lake depends on the degree of nutrient enrichment. As nutrients accumulate in the lake, algal production increases and, in turn, water clarity decreases. The biomass produced by algae settles in the lake, causing the depletion of dissolved oxygen (DO) in the hypolimnion, even though algal photosynthesis produces oxygen in the epilimnion during the day. The diurnal DO swing becomes more severe because increased algal populations produce more oxygen during the day and consume more oxygen at night.

Trophic status is evaluated by measuring the typical suite of trophic state indicators: total phosphorus, chlorophyll-*a*, and Secchi depth. At both reservoirs, the college has worked cooperatively with the local lake association, i.e., the Smith Mountain Lake Association (SMLA) and the Friends of Claytor Lake (FOCL). Samples are collected at permanently designated stations each two weeks during the period between Memorial Day and Labor Day. Trained volunteer monitors collect the samples and measure water clarity from a boat during a one-week sampling window, and student interns analyze the samples at the Ferrum College Water Quality Lab.

Bob Carlson developed algorithms to calculate a trophic state index based on algal biomass (Carlson, 1977). However, Carlson's Trophic State Index (TSI) can be calculated from the seasonal average value of any one of the three trophic state parameters: total phosphorus concentration (TP) as the indicator of nutrient enrichment, chlorophyll-*a* concentration (CHA) as the indicator of algal biomass, or Secchi depth (SD) as the indicator of water clarity. If a lake or reservoir were functioning in classic fashion, the three TSI values (TSI-TP, TSI-CHA, and TSI-SD), calculated from each of the three trophic state parameters, would be similar. The average of the three TSI values is the combined trophic state index, TSI-C.

More recently, William Walker studied 41 southern reservoirs in his work developing a reservoir model (BATHTUB) for the Army Corps of Engineers (Walker, 1996). He found that insights into non-classical behavior could be gained by comparing relative values of TP, CHA, and SD in the study set.

The full trophic state data set from Smith Mountain Lake (1987-2004) and Claytor Lake (1996-2004) has been summarized, compared with each other, and compared with average values for the 41 southern reservoirs included in the Walker study.

METHODS

Field Procedures:

Volunteer monitors measure water clarity with a Secchi disk and collect integrated samples of the photic zone. The photic zone is operationally defined as twice the Secchi depth (~ 95% light extinction) and the integrated sample is collected with a rubber hose that has been conditioned in lake water, marked at one-meter intervals, and fitted with a rope and diver's weight. The water sample is mixed in a 4-L polyethylene bucket and an aliquot is placed in a 60-mL polyethylene bottle for total phosphorus analysis. A second 100-mL aliquot is filtered through a type-A glass filter, and the filter is analyzed for chlorophyll-*a*. The procedures used by the volunteer monitors are described in detail in the *Smith Mountain Lake/Claytor Lake Volunteer Monitoring Manual* (Thomas and Johnson, 2003).

Laboratory Procedures:

Analytical methods are adapted from *Standard Methods for the Examination of Water and Wastewater* (APHA, 1995). Total phosphorus is measured spectrophotometrically after persulfate digestion, and chlorophyll-*a* is measured fluorometrically after acetone extraction. The detailed methods are described in the *Ferrum Water Quality Lab Procedures Manual* (Johnson and Thomas, 2004).

RESULTS AND DISCUSSION

Comparison of Smith Mountain Lake and Claytor Lake to the Reservoirs in Walker's study:

Overall average values for total phosphorus, chlorophyll-*a*, and Secchi depth are displayed in Table 1 for Smith Mountain Lake (SML), Claytor Lake (CL), and the Walker study (WS). Trophic state data for SML and CL is grouped by zone, with each zone representing a 5-mile length of reservoir. Zone 1 is from 0 – 5 miles from the dam and so on; Smith Mountain Lake has 6 zones, and Claytor Lake has 4 zones. In Table 1, the average value for SML and CL is the average for all zones; the minimum value is the average value for the zone with the lowest average, and the maximum is the average value for the zone with the highest average. Both local reservoirs have lower concentrations of total phosphorus and chlorophyll-*a* and greater Secchi depths than the average of the 41 reservoirs included in the Walker study. As expected, the range of values in the 41 reservoirs in Walker's study is larger than the range found in SML and CL.

Table 1. Average values for trophic state parameters for Smith Mountain Lake, Claytor Lake, and the Walker study.

Total Phosphorus (ppb)			
	min	max	avg
Smith Mtn Lake	20	64	38
Claytor Lake	30	57	44
Walker Study	10	274	48

Chlorophyll-*a* (ppb)			
	min	max	avg
Smith Mtn Lake	1.8	11.3	5.3
Claytor Lake	1.9	8.4	6.5
Walker Study	2.0	64.0	9.4

Secchi Depth (m)			
	min	max	avg
Smith Mtn Lake	3.2	1.3	2.0
Claytor Lake	1.0	1.6	1.3
Walker Study	0.2	4.6	1.1

As part of the model development, Walker examined several relationships among the three trophic state parameters. Three of the relationships are displayed in Figure 2 with brief interpretations in the boxes below. Average values calculated for the diagnostics for Smith Mountain Lake and Claytor Lake are neither "high" nor "low," indicating classical behavior "on average." However, the minimum values of CHA*SD and CHA/TP in SML and CL indicate a low response to nutrients in some zones of SML and CL.

Table 2. Diagnostic variables used in the Walker study with values for Smith Mountain Lake and Claytor Lake.

Non-algal Turbidity (1/m)			
	min	max	avg
Smith Mtn Lake	0.27	0.52	0.42
Claytor Lake	0.40	1.00	0.60
Walker Study	0.13	5.2	0.61

NAT = 1/SD - 0.025*CHA
Inverse SD corrected for light extinction by CHA
Low: < 0.4; allocthanous PM unimportant?
high response to nutrients
High: >1; alloctanous PM important?
low response to nutrients

CHA*SD (mg/m^2)			
	min	max	avg
Smith Mtn Lake	5.6	14.0	8.7
Claytor Lake	1.9	13.6	9.2
Walker Study	1.8	31.0	10.0

mean CHA * mean SD (mg/m^2)
Light extinction; algal & non-algal turidity
Low: < 6; nonalgal turbidity dominates
expect low nutrient response
High: > 16; algal turbidity dominates
expect high nutrient response

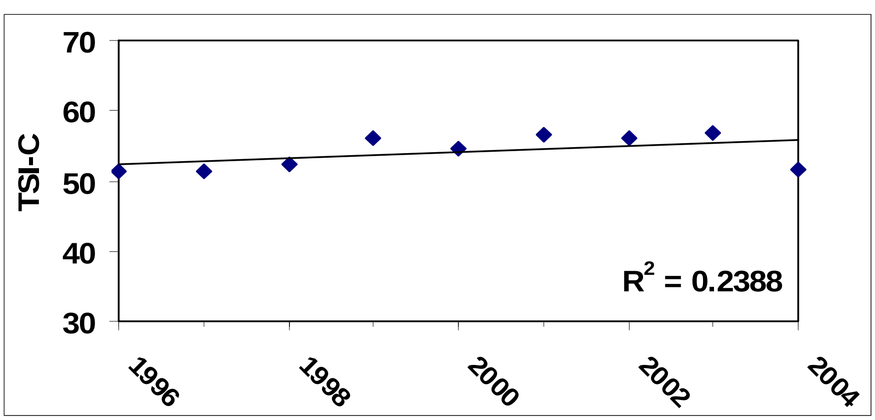
CHA/TP			
	min	max	avg
Smith Mtn Lake	0.09	0.17	0.13
Claytor Lake	0.03	0.25	0.2
Walker Study	0.04	0.6	0.2

mean CHA/mean TP
Algal use of phosphorus supply
Low: < 0.13; low phosphorus response
algae limited by N, light, or flushing rate
High: > 0.40; high phosphorus response
algae limited by phosphorus

__**Temporal Variation of trophic state parameters:**__

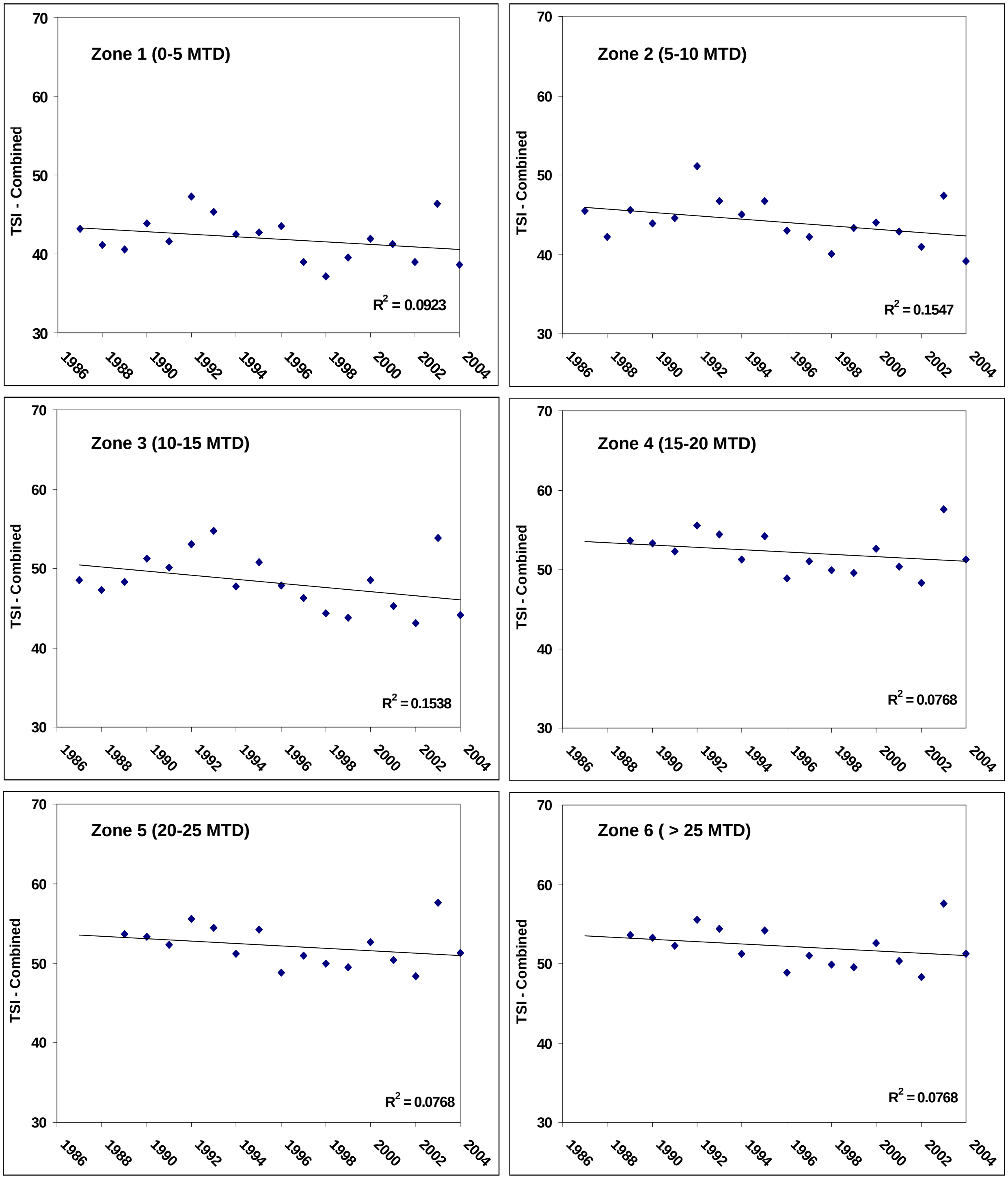
The trophic state of Claytor Lake and Smith Mountain Lake has not changed significantly since the Ferrum Water Quality Lab began the monitoring programs. Figure 1 displays the combined trophic state index for Claytor Lake.

Figure 1. The combined trophic state index for Claytor Lake (1996 – 2004).



Trophic status is evaluated by zone in Smith Mountain Lake because water quality changes significantly as it moves down the long Blackwater and Roanoke channels. Figure 2 displays the trophic state data for Smith Mountain Lake by year for each of the six zones.

Figure 2. Combined trophic state index for Smith Mountain Lake by zone (1987-2004).



<u>Spatial Variation of Trophic State Parameters:</u>

Variation of the three trophic state parameters by zone in Smith Mountain Lake is shown in figures 3, 4, and 5. In each case, the pattern in 2004 is similar to the pattern over the period from 1987 – 2004. The increase in SD towards the dam can be explained by the settling of silt in the upper channels of the lake. Phosphate strongly adsorbs to clay particles in the silt and the removal of phosphorus, in turn, leads to reduced CHA. The improved curve fit seen with the second-order regression is consistent with a settling process following first order kinetics.

Figure 3. Total Phosphorus by zone in Smith Mountain Lake.

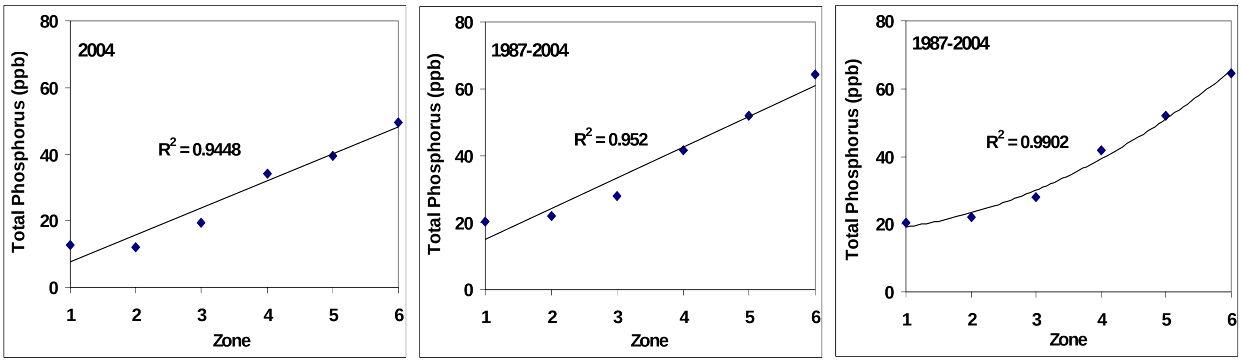


Figure 4. Chlorophyll-*a* by zone in Smith Mountain Lake.

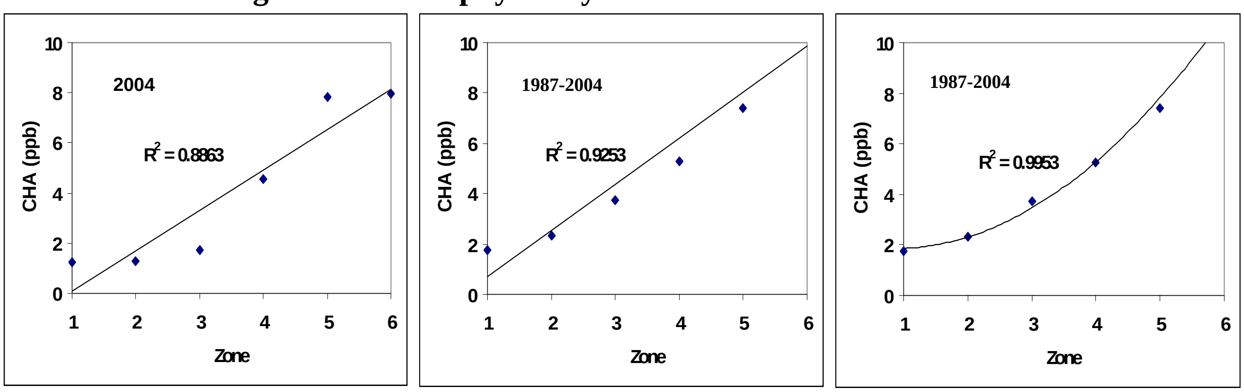


Figure 5. Secchi depth by zone in Smith Mountain Lake.

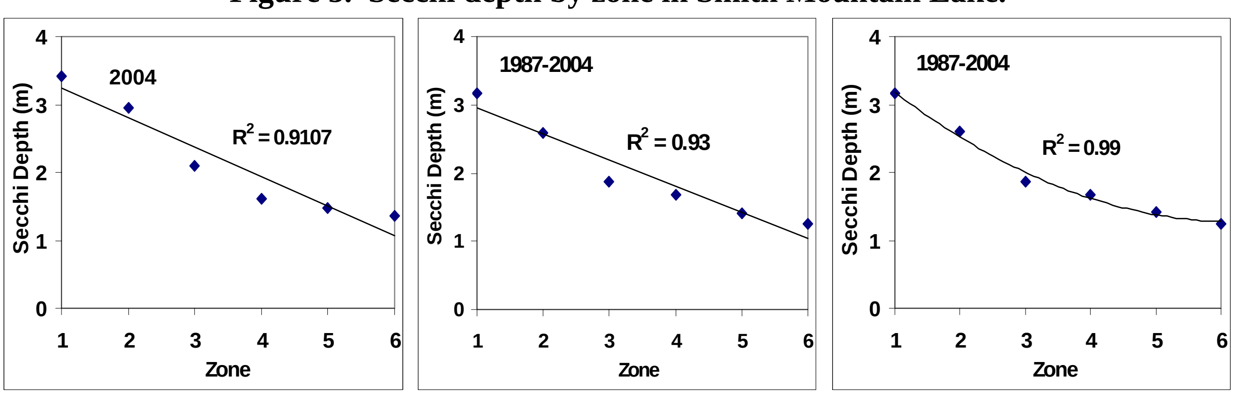
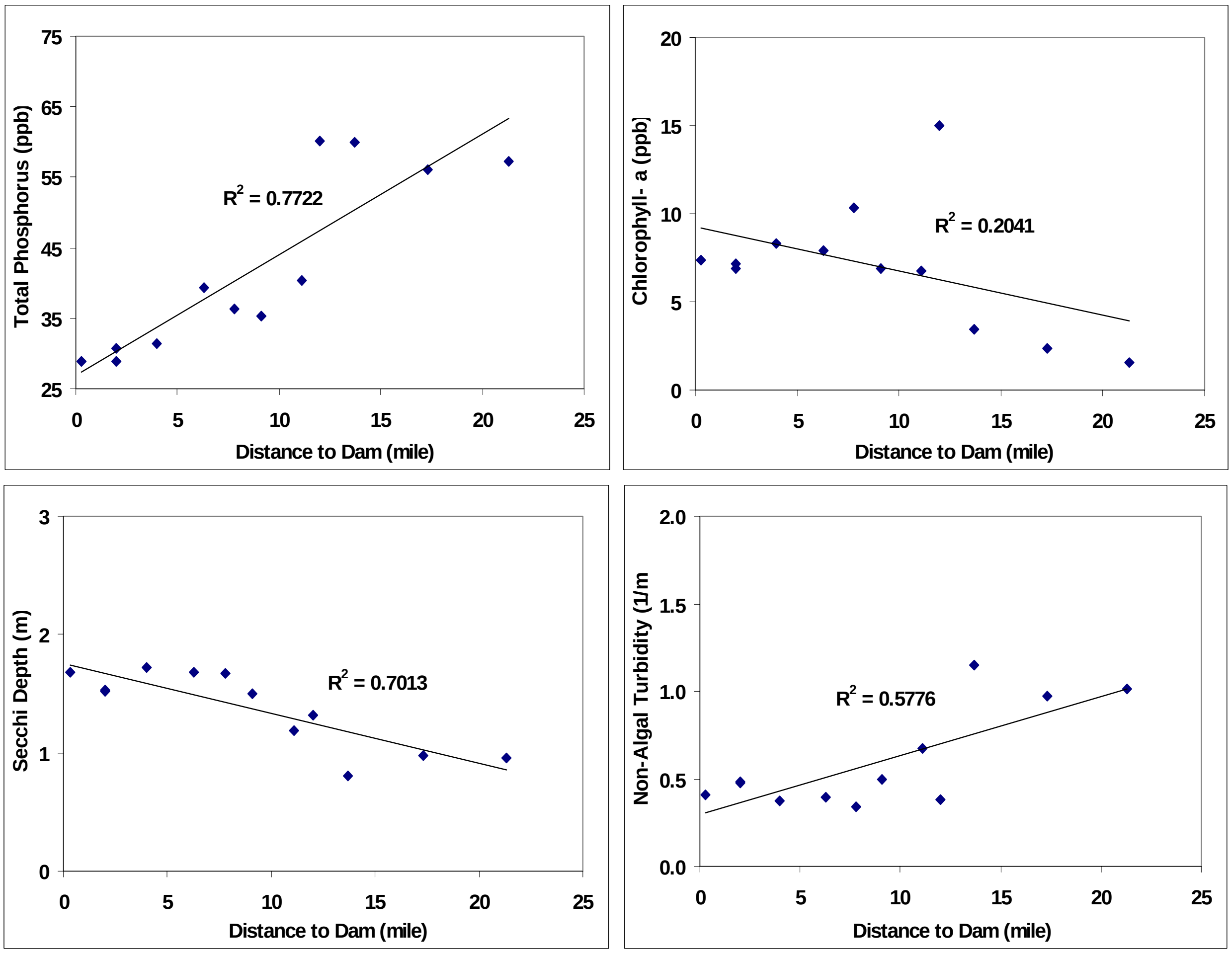


Figure 6 shows the variation of trophic state parameters with distance from the dam in Claytor Lake. Each data point in the figures below represents one of the 12 sampling sites on the lake. As in Smith Mountain Lake, settling of silt lowers the trophic status of the water near the dam. However, the extremely turbid headwaters of Claytor Lake inhibit algal growth. The three stations furthest from the dam have non-algal turbidities above 1 and much lower CHA levels than would be expected given the high TP concentration at those sites.

Figure 6. Variation of trophic state parameter with distance from dam in Claytor Lake.



CONCLUSIONS

Smith Mountain Lake and Claytor Lake have the long narrow channels typical of reservoirs. As a result, the water is not as homogeneous as found in classical lakes. As Virginia develops assessment criteria and methodologies for lakes and reservoirs, there is a need to consider the down-channel point at which the riverine channel becomes the lake and should meet state water quality criteria. AHRT of the reservoir should also be considered because “run-of-the-river” reservoirs such as Claytor Lake do not develop the internal nutrient dynamics at work in larger reservoirs such as Smith Mountain Lake.

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Ferrum College
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Bedford County
Pittsylvania County
Pulaski County
Smith Mountain Lake Association
Virginia Department of Environmental Quality
Virginia Department of Game and Inland Fisheries
Virginia Environmental Endowment

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APPENDIX C

Responses to DEQ Questions Concerning Dissolved Oxygen Criteria for Lakes

Dr. John C. Little, Vickie Singleton, Lee Bryant

1. Should the current dissolved oxygen criteria (5 ppm daily average and 4 ppm minimum) apply at all depths of a lake or only to the epilimnion of a stratified lake or reservoir or to a depth of 1 m (or 2x Secchi depth) during non-stratified conditions?

To the authors' knowledge, the United States Environmental Protection Agency (EPA) has not issued specific guidance on how states should apply the existing dissolved oxygen (DO) criteria to lakes and reservoirs. Therefore, states can interpret and apply the DO criteria for stratified water bodies as appropriate. In the absence of direction from EPA, states such as Maryland (MDE, 2004), Minnesota (MPCA, 2003), Oregon (ODEQ, 2003), and West Virginia (WV EQB, 2004) do not currently address the effects of stratification on DO concentrations in their water quality regulations. Alternatively, Colorado (CDPHE, 2005), Iowa (IDNR, 2004), and Pennsylvania (PDEP, 2000) only apply DO criteria to the epilimnion of stratified water bodies. Other states have vague references to stratification effects in their DO criteria. North Carolina's regulations state that ambient DO can be lower in lake bottom waters "if caused by natural conditions" (NC DENR, 2004). Some states specify DO concentrations for arbitrary depths in the water column. For protection of warm water aquatic life in Kentucky, DO must be measured at "mid-depth in waters 10 ft or less and at representative depth in other waters." For cold water lakes and reservoirs that support trout, the DO concentration "in waters below the epilimnion shall be kept consistent with natural water quality" (KDW, 2004). Tennessee regulations require that DO "be measured at mid-depth in waters 10 ft or less and at a depth of 5 ft for waters greater than 10 ft in depth" (TDEC, 2004).

The existing water quality standards for Virginia recognize the effects of stratification on hypolimnetic DO concentrations as referenced in Section 9 VAC 25-260-55 (VDEQ, 2004b). However, the State Water Control Board may have difficulty establishing site-specific DO criteria "that reflect the natural quality of that water body or segment," in accordance with Part E, because no natural reference conditions exist for constructed impoundments (refer to additional discussion in Response 4).

Currently, the Virginia Department of Environmental Quality (DEQ) applies existing DO criteria to the entire water column of lakes and reservoirs during stratified and non-stratified conditions (Younos, 2004). This has resulted in a number of impoundments being classified as Category 4 (does not require a TMDL) or 5 (requires a TMDL) impaired because of DO criteria violations (Table 1) (VDEQ, 2004d). Category 4 and 5 waters are those that were determined to be impaired due to natural and anthropogenic sources, respectively. DEQ applied a multi-step procedure to establish whether anthropogenic pollutants were causing hypolimnetic DO violations. The general approach involves assessment of water quality data and evaluation of anecdotal information in the watershed. Trophic State Indices (TSIs) were calculated for each impaired water body to determine if excessive nutrients are contributing to low DO concentrations in the hypolimnion.

The current methodology used by DEQ to apply existing DO criteria to constructed impoundments is sound and scientifically defensible. Until revised DO criteria that more specifically address stratification and designated uses in lakes and reservoirs are established, the current approach should be adequate. After development of revised DO criteria, reservoirs that were previously classified as Category 5 impaired may be reclassified as waters supporting one or more designated uses. Therefore, effort should be focused on determining reservoir-specific DO criteria before proceeding with TMDL development for Category 5 DO-impaired waters.

2. Should dissolved oxygen criteria be developed specifically for lakes?

We recommend that DO criteria be established specifically for lakes and reservoirs. For development of nutrient criteria for Virginia water bodies, the DEQ plans to classify state surface waters by type (estuaries, lakes and reservoirs, and rivers and streams) (VDEQ, 2004c). Additionally, the Academic Advisory Committee recommended that nutrient criteria development be based on water body types (Virginia Water Resources Research Center, 2004). Therefore, it is likely that nutrient criteria will be proposed and referenced by water type. Developing DO criteria specifically for lakes and reservoirs will provide consistency between water quality regulations. Additionally, lakes and reservoirs respond differently to nutrient inputs than estuaries and rivers and streams, which is why guidance documents for state nutrient criteria development were published by water body type (US EPA, 1998). Differing responses among surface water types will likely translate to differing DO characteristics because DO is a secondary response variable to nutrient loading (Virginia Water Resources Research Center, 2004). Typically, the primary source of oxygen into a water body is atmospheric diffusion. Diffusion of oxygen into and within water is relatively slow, so mixing is required for DO to be in equilibrium with the atmosphere. Consequently, small, turbulent streams and rivers are often near saturation with respect to DO throughout their depths. This is in contrast to the distribution of oxygen in density-stratified lakes and impoundments, which varies with depth and is controlled by hydrodynamics, photosynthetic inputs, and losses to chemical and biotic oxidations (Wetzel, 2001).

We also recommend that DO criteria development for lakes and reservoirs be based on designated uses of the water bodies. Basing DO criteria on designated uses is similar to the approach used by EPA for development of ambient DO criteria for the Chesapeake Bay and its tidal tributaries (US EPA, 2003). It is also consistent with previous recommendations of the Academic Advisory Committee (Virginia Water Resources Research Center, 2004). Basing water quality criteria on designated uses has been applied successfully by British Columbia for developing phosphorus criteria and is also used by the Canadian Federal government in specifying a number of water quality parameters (US EPA, 2000).

3. If the answer to no. 2 is yes, should dissolved oxygen criteria be developed that apply to the entire water column or to the upper layer only or should there be different criteria for different depths within a lake?

To address the effects of stratification on DO concentrations throughout the water column, we recommend that separate criteria be developed for the epilimnion and hypolimnion and that criteria development be based on designated uses of the water bodies. Application of a single DO criterion for all depths within a given lake or reservoir may be unnecessarily stringent and not required to fully support the water body's designated uses during stratification. When the water column is completely mixed, a single DO criterion that supports the water body's designated uses should be applied to all depths. If the primary cause of anoxic conditions in the lower depths of stratified impoundments is lack of reaeration by the atmosphere, then, theoretically, oxic conditions should exist when the lake is completely mixed.

Dissolved oxygen criteria for stratified water bodies should ensure that at least one layer exists in the reservoir where temperature, DO, and pH requirements are being met to support designated uses. A similar approach has been proposed for thermally stratified reservoirs in Oregon, although specific DO criteria for the hypolimnion have not been developed (ODEQ, 2004). As an example, if DO criteria are developed for protection of warm water aquatic life in a particular reservoir, specifying DO criteria for the hypolimnion may not be necessary if water quality conditions in the epilimnion can support the target species throughout the stratification period. With regard to protection of water supply use, hypolimnetic DO criteria may not be required for a given impoundment if water utility(ies) can only withdraw raw water for treatment from the epilimnion.

Specifying different DO criteria for different water column depths or regions has recently been applied by EPA to the Chesapeake Bay and its tidal tributaries (US EPA, 2003). Dissolved oxygen criteria were derived to protect estuarine species living in different habitats, also referred to as tidal water designated uses, which are influenced by natural processes in the Bay. The criteria reflect ambient oxygen dynamics, as evidenced by seasonal application of deep-water and deep-channel DO criteria that account for the effects of water column stratification. Both deep-water and deep-channel regions are below the pycnocline during periods of Bay stratification (late spring to early fall). Deep-water criteria were set at levels to protect shellfish and juvenile and adult fish, and to foster recruitment success of the bay anchovy. Deep-channel criteria were set to provide seasonal refuge and to protect the survival of bottom sediment-dwelling worms and clams. During periods of complete water column mixing, the higher DO criteria associated with open-water fish and shellfish use applies to deep-water and deep-channel designated uses (US EPA, 2003).

4. Should dissolved oxygen criteria be established by lake use (water supply, fishing, or recreation)?

Because the vast majority of lentic systems in Virginia are constructed impoundments, establishing DO criteria based on water body designated use is a reasonable methodology. This approach is a logical step considering reservoirs are artificial water bodies created for specific uses and functions. Impoundments are built and managed for various purposes including flood control, navigation, municipal or agricultural water supply, hydroelectric generation, and game fish production. Management practices often affect physical, biological, and chemical characteristics of the reservoir (US EPA, 2000). Developing DO criteria based on designated impoundment uses is recommended over specifying criteria based on a reference condition approach because the reference or undisturbed state for a reservoir is usually a lotic ecosystem. Therefore, the reference condition method is not at all applicable to constructed impoundments. Basing DO criteria on reservoir uses will avoid unnecessarily stringent criteria being applied to some water bodies while still protecting designated and existing uses. For instance, it is likely that the minimum DO criteria for protection of recreation use or water supply use is lower than that required for protection of aquatic life. For aquatic life use, minimum DO needs can vary depending on the target species (cold water or warm water).

Designated uses have already been determined for Virginia water bodies for biennial preparation of the 305(b)/303(d) integrated water quality assessment. The six existing designations are aquatic life use, fish consumption use, shellfish consumption use, swimming use, public water supply use, and wildlife use (Virginia DEQ, 2004d). Of these designated uses, only aquatic life and public water supply are directly affected by low DO concentrations in the water column of lakes reservoirs, and recreation may be considered to be indirectly affected. Compliance with fish consumption use is determined by comparison of fish tissue data with state screening values for toxic pollutants. Shellfish consumption use is not impaired if harvesting restrictions are not issued by the Virginia Department of Health. Criteria for support of wildlife use involve toxics known to be harmful to aquatic life in the water column. Currently, support of swimming use for a water body is demonstrated by compliance with bacteriological criteria such as fecal coliform and E. coli (Virginia DEQ, 2004b).

Ambient freshwater DO criteria for the protection of aquatic life, both cold and warm water species, have been determined previously by EPA (US EPA, 1986). In preparation of DO criteria specific to the Chesapeake Bay, EPA conducted a preliminary survey of the literature since the 1986 freshwater document was published and found effects data that confirmed that the DO criteria remained protective. Therefore, EPA believes that the existing freshwater criteria accurately account for the anticipated effects of low DO on freshwater aquatic species (US EPA, 2003).

To our knowledge, EPA has not developed ambient DO criteria for the support of public water supply use in lakes and reservoirs, and neither have most states. Alaska specifies that DO concentrations must be at least 4 mg L^{-1} in waters designated for drinking water supply. However, this standard does not apply to lakes or reservoirs where water is withdrawn from below the thermocline (ADEC, 2003). Colorado requires minimum DO concentrations of 3 mg L^{-1} for waters designated for domestic water supply, but the standard is intended to apply to only the epilimnion and metalimnion of stratified lakes and reservoirs (CDPHE, 2005). Florida and West Virginia have specified that surface waters used for potable water supply have DO concentrations of at least 5 mg L^{-1} (FDEP, 2002 and WV EQB, 2004).

Hypolimnetic oxygen depletion in stratified water bodies may lead to increases in hydrogen sulfide, ammonia, and phosphorus, and the release of reduced iron and manganese from the sediments. If entrained into the productive surface zone, phosphorus may stimulate algal growth, which exacerbates the problem because decaying algae ultimately fuel additional oxygen demand. Hydrogen sulfide and reduced iron and manganese are undesirable in drinking water and usually require additional treatment (Cooke and Carlson, 1989). The extra oxidant may react with natural organic matter increasing the formation of disinfection by-products.

The effects of hypolimnetic anoxia on chemical and biological parameters of concern to drinking water treatment are well documented. However, a cursory review of the scientific literature revealed little information on suggested DO criteria for protection of raw water supplies. The published studies that are most relevant to the effects of low DO concentrations on water treatment processes involve hypolimnetic aeration or oxygenation. These techniques are commonly used to add dissolved oxygen to water bodies while preserving stratification. Studies documenting the effects of hypolimnetic aeration and oxygenation have been reviewed by Fast and Lorenzen (1976), Pastorok et al. (1982), McQueen and Lean (1986), and Beutel and Horne (1999). McQueen and Lean (1986) found that for generally all installations, hypolimnetic oxygen levels increased; iron, manganese, and hydrogen sulfide levels decreased; and chlorophyll levels were not altered. The effects of hypolimnetic aeration on phosphorus were more variable. McQueen et al. (1986) attribute this to pH levels and iron availability for phosphorus sedimentation. The effects on nitrogen were not consistent either; ammonium and total nitrogen decreased in some studies but increased in others. In their review, Beutel and Horne (1999) reported that average hypolimnetic DO concentrations were maintained at greater than 4 mg L^{-1} in all cases and oxygenation decreased hypolimnetic concentrations of dissolved phosphorus, ammonia, manganese, and hydrogen sulfide by 50-100 percent.

A number of hypolimnetic oxygenation systems have been installed in potable water supply lakes or reservoirs. The City of Norfolk installed hypolimnetic aerators in Lakes Prince and Western Branch, Virginia, two water supply reservoirs. Because of the aeration system, the City has discontinued prechlorination of raw water at the treatment plant, and noticeable improvements have been observed in reservoir aesthetics (Cumbie et al., 1994). St. Mary Lake, British Columbia is a multi-use water body that supports potable water supply, a trout fishery, and recreation. An aeration system installed in 1985 has generally maintained DO at 5 mg L^{-1} in the hypolimnion and has decreased phosphorus concentrations (Nordin et al., 1995). Hypolimnetic oxygenation in Upper San Leandro Reservoir, California decreased ozone requirements by 35 percent and chlorine requirements by 14 percent at the treatment facility. Also, manganese concentrations in the raw water were decreased, resulting in decreased chlorine dosing. Consequently, the concentration of trihalomethanes in the finished water, which are regulated disinfection by-products, decreased by over 50 percent. Overall, the oxidant savings was greater than twice the cost of oxygen required to operate the hypolimnetic oxygenation system (Jung et al., 2003).

To provide some insight into the potential economic impact of remediating low-DO conditions in Virginia reservoirs, capital costs for select aeration and oxygenation systems are shown in Table 2. The primary types of devices currently in use include full-lift aerators, Speece Cones, and bubble plume diffusers. Full-lift aerators operate by injecting compressed air near the bottom of the hypolimnion. The air-water mixture travels up a vertical pipe to the lake surface where gasses are vented to the atmosphere. The aerated water is then returned through another pipe downward to the hypolimnion. In Speece Cones, oxygen is injected into an enclosed chamber that is typically located in the hypolimnion, and water is either pumped or entrained into the device (Beutel and Horne, 1999). Oxygen transfer occurs within the chamber, and oxygenated water is discharged to the hypolimnion. Pure oxygen or compressed air can also be introduced into the hypolimnion through the use of diffusers to form a rising, unconfined bubble plume. This oxygenation method is most suitable for deep lakes where the bulk of the bubbles dissolve in the hypolimnion and the momentum produced by the plume is low enough to prevent intrusion into the thermocline (Wüest et al., 1992).

It should be noted that maintenance of oxic conditions in the hypolimnion does not always result in a reduction of productivity and algal growth in lakes. Based on more than 10 years of data on hypolimnetic oxygenation and artificial mixing in two eutrophic lakes, Gächter and Wehrli (1998) found that internal cycling of phosphorus was not affected by increased hypolimnetic DO concentrations. Their research indicated that the sediment-water interface remained anoxic even in the presence of an oxic hypolimnion. The authors concluded that excessive organic matter loading and phosphorus precipitation exhausted the hypolimnetic DO supply and exceeded the phosphorus retention capacity of the sediments after diagenesis.

In summary, the information currently available regarding appropriate DO criteria for lakes and reservoirs used for drinking water supply is limited to non-existent. EPA has not developed ambient DO criteria for the support of public water supplies, and the vast majority of states do not have DO criteria specifically for this designated use. The effects of hypolimnetic anoxia on water quality parameters related to drinking water treatment are well documented, and hypolimnetic oxygenation is a proven mitigation technique. However, because of insufficient information available at this time, we can recommend only preliminary DO criteria for protection of water supply designated uses. It is suggested that the existing freshwater DO criteria for non-trout waters (5 mg L^{-1} daily average, 4 mg L^{-1} minimum) be applied to all strata used for potable water supply within a given reservoir. This is comparable to the approximate, rule-of-thumb DO value of 5 mg L^{-1} typically desired in influent raw water by treatment plant managers. It should be noted that maintaining DO at this level is commonly thought to decrease soluble iron and manganese concentrations and control the formation of hydrogen sulfide, but this has not been well established. Therefore, DO criteria for protection of water supply designated uses may need to be revised after further study by EPA or the scientific and engineering community.

Regarding primary and secondary contact recreation, we are not aware of DO criteria development by EPA for the protection these designated uses. Also, the vast majority of states have not developed DO standards for recreational uses or the aesthetic quality of lakes and reservoirs. Where such state criteria exist, they are typically part of an all-encompassing limit to be applied to the most sensitive designated water use. One exception is Alaska, which specifies that DO concentrations must be at least 4 mg L^{-1} in waters designated for primary or secondary contact recreation (ADEC, 2003). Also, Colorado requires minimum DO concentrations of 3 mg L^{-1} for primary and secondary contact recreational waters. However, the standard is intended to apply to only the epilimnion and metalimnion of stratified lakes and reservoirs (CDPHE, 2005). South Dakota specifies minimum DO levels of 5 mg L^{-1} for immersion recreation and limited contact recreation waters (SD DENR, 1997). In Virginia, if all reservoirs are designated for aquatic life and/or water supply use, the DO criteria to support these uses would more than likely be adequate to support swimming and other recreational uses. Therefore, separate DO criteria specifically for recreation and aesthetics are probably not necessary for Virginia. A similar conclusion was drawn for application of DO standards in waters of British Columbia (BC MELP, 1997).

5. Should dissolved oxygen criteria differ for natural lakes and constructed impoundments?

We recommend that separate DO criteria be developed for natural lakes and constructed impoundments. While studies of reservoir ecosystems have found functional similarities between artificial and natural lakes, natural lake ecosystems have many characteristics that are significantly different than reservoirs. The ratio of drainage basin area to water body surface area is frequently higher for reservoirs than natural lakes (Cooke and Carlson, 1989). Because reservoirs are usually formed in river valleys, their morphometry is typically dendritic, narrow, and elongated. This is in contrast to the predominantly circular or elliptical shape of natural lakes (Wetzel, 2001). Most reservoirs have asymmetrical depth distributions in the longitudinal direction, with the maximum depths occurring adjacent to the dam. Near the vertical dam wall, unusual chemical and temperature stratifications can occur, which differ dramatically from those typically present in natural lakes (Cole, 1994). Reservoirs often have higher flushing rates and lower hydraulic residence times than natural lakes. Additionally, discharges from reservoirs are not always from the surface and are frequently from deeper waters. Because reservoirs are constructed for various uses, surface levels in these water bodies typically fluctuate more than in natural lakes as water is stored and released (Cole, 1994).

Because the watershed area in relation to surface area for reservoirs is much larger than for natural lakes, inflows to reservoirs have more energy for erosion, higher sediment-load carrying capabilities, and cause increased dispersion of dissolved and particulate concentrations into the receiving water body. Runoff influent to reservoirs is usually greater and influenced more significantly by precipitation events. These characteristics induce higher but more irregular nutrient and sediment loading rates in reservoirs compared to natural lakes, which affects biological processes (Wetzel, 2001). In turn, differences in light attenuation and nutrient availability between natural and artificial lakes can result in different productivity rates and, subsequently, differing hypolimnetic dissolved oxygen concentrations. Dissolved oxygen is a secondary response variable to nutrient inputs (Virginia Water Resources Research Center, 2004).

We recommend that site-specific dissolved oxygen criteria be developed for the two natural lakes in the state, Mountain Lake and Lake Drummond. These water bodies are located in distinctly different ecological regions, and hence, each is a unique natural resource. Mountain Lake is the only notable natural lake in the unglaciated region of the southern Appalachian Highlands (Cawley et al., 2001). Lake Drummond is a blackwater lake located in the Great Dismal Swamp, which is considered to be the most northern "southern" type swamp on the east coast of the United States (Johannesson et al., 2004). In addition to dissolved oxygen data currently collected on Lake Drummond by the Virginia Department of Environmental Quality (Younos, 2004), numerous studies have been published on Mountain Lake (Simmons and Neff, 1974; Obeng-Asamoa, 1976; Parson, 1988; Beaty and Parker, 1993; Beaty and Parker, 1995; Cawley et al., 1999) and Lake Drummond (Duke et al., 1969; Anderson et al., 1977; Phillips and Marshall, 1993; Merten and Weiland, 2000). This information can facilitate development of site-specific dissolved oxygen criteria for each natural water body.

These recommendations are consistent with related recommendations of the Academic Advisory Committee regarding freshwater nutrient criteria (Virginia Water Resources Research Center, 2004).

6. Should dissolved oxygen criteria be developed specifically for the hypolimnion?

Expanding on the response to question 3, we believe that dissolved oxygen criteria should be developed specifically for the hypolimnion of constructed impoundments to address the effects of stratification. As stated previously, hypolimnetic DO criteria should take into account designated uses of the water body and what conditions will be required in the hypolimnion to achieve these uses during stratification. This is consistent with the recommendations of the Academic Advisory Committee regarding development of Virginia freshwater nutrient criteria (Virginia Water Resources Research Center, 2004). Additionally, hypolimnetic DO criteria should also consider the potential downstream effects of reduced oxygen concentrations in waters released from the lower depths of constructed impoundments. Per 9 VAC 25-260-10 of the Virginia Water Quality Standards, "in designating uses of a water body and the appropriate criteria for those uses, the board…shall ensure that its water quality standards provide for the attainment and maintenance of the water quality standards of downstream waters". Virginia streams and rivers downstream of reservoirs are currently affected by releases of hypolimnetic waters. For example, almost 6 miles of the Roanoke River have been classified as Category 5 impaired waters for DO because of hypolimnetic water discharge upstream from Lake Gaston (VDEQ, 2004d). Also, nearly 6 miles of the Meherrin River are designated Category 5 impaired for DO due to hypolimnetic releases from an upstream impoundment (VDEQ, 2004d).

The release of hypoxic or anoxic waters from stratified impoundments is currently regulated for licensure of existing and new hydropower projects. The United States Federal Energy Regulatory Commission (FERC) is increasingly specifying minimum DO concentrations in discharge waters from hydropower reservoirs (Mobley, 1997).

7. What type of Use Attainability Analysis (UAA) would be needed to demonstrate appropriate dissolved oxygen criteria for lakes?

In order to demonstrate appropriate DO criteria for lakes and reservoirs, a multi-phase Use Attainability Analysis (UAA) is recommended. In accordance with applicable UAA methodology (US EPA, 1994; OWR, 2001; VDEQ, 2004a), we feel that a comprehensive multi-phase UAA approach should be based on:

1. A review of supporting literature and historical data
2. Routine, on-site surveys performed to analyze parameters relating to DO levels (e.g., sediment loading and organic matter (OM) deposition rates, nutrient loading (especially phosphorous (P)), hydraulic input and withdrawal locations within a limnological system, stratification depths, and specific chemical analyses such as DO (via Hydrolab and modified Winkler measurements), total-P (TP), BOD, and COD)
3. Correlation of TP TSI approach with epilimnetic and hypolimnetic DO measurements to help establish overall UAA (see further discussion in Response 9)

A multi-phase UAA approach would best characterize the combined influence of the various processes impacting DO levels (in both the epilimnion and the hypolimnion) and subsequent attainable use on a site-specific basis. Epilimnetic oxygen levels are primarily controlled by photosynthesis, microbial respiration, resupply from the atmosphere, and water column demand. Hypolimnetic oxygen levels are typically governed by sediment oxygen demand (SOD). Organic or nutrient loading of thermally stratified lakes and reservoirs may lead to significant depletion of DO in the lower hypolimnetic water. Hypolimnetic oxygen depletion often results in the release of Fe, Mn, and P from sediment oxide precipitates, thereby decreasing water quality and increasing drinking-water treatment costs. Release of P can promote excessive algal growth, which stimulates eutrophication and can have detrimental effects on the health and diversity of the plant, fish, and benthic populations. The abundance of algae is directly influenced by the ratios of supplied nutrients. Even small differences in the nutrient ratios (e.g., N to P) can have significant effects on competing algal species (Gächter and Muller, 2003; Lewandowski et al. 2003). Additional oxygen is consumed as these algal blooms die, settle into the hypolimnion, and are degraded by aerobic sediment microbes. Sediment loading may also impact oxygen demand by introducing additional Fe, Mn, and P into the system and by partially controlling oxygen diffusion rates into the sediment (Muller et al., 2002). Thus, when evaluating use attainability, it is important to consider all influences on DO levels: water column demand, respiratory demand via microorganisms, SOD, and oxygen resupply. Optimal water quality and corresponding use may be established and maintained by controlling P loading or by adding oxygen to lake and reservoir systems. Hypolimnetic oxygenation systems, which preserve stratification, are increasingly used to replenish DO (refer to Response 4).

Due to the fact that complex interactions between oxygen availability and P cycling have such control on water quality and subsequent use attainability, we recommends using DO and TP as key parameters in use attainability analyses. It has been shown that DO levels may not directly correlate with soluble P levels due to benthic microbial activity and the formation of ferrous (reduced Fe) phosphate precipitates, thus supporting the need to separately quantify both DO and TP levels (Gächter and Muller, 2003). Because of the various nutrient and oxygen requirements specific to each designated use (e.g., cold-water fishery vs. drinking water supply), it seems that a UAA evaluating both DO and TP levels should be performed to address the particular attainable use criteria for a site.

8. Can historical DO/temperature depth profile data such as the 1983 EPA Clean Lakes Program funded 8 month sampling of 32 lakes in VA be used to demonstrate expected dissolved oxygen levels in undisturbed or forested watersheds?

Historical DO and temperature depth profile data may be extremely valuable resources for establishing DO reference levels and anticipated stratified zones. Historical data, such as that obtained during the 1983 EPA Clean Lakes VA sampling program, can be used to establish *expected*, base-line DO levels for watersheds with conditions similar to those sampled during this EPA study. However, this data should be used predominantly for general guideline purposes, as information obtained during the 1983 EPA Clean Lakes study was collected primarily to establish base-line data in preparation for subsequent Clean Lakes Program projects (US EPA, 1982). Base-line DO estimates should be verified by current DO measurements and modified in order to accurately characterize existing, reservoir-specific conditions. DO availability and depletion rates are very site-specific and transient as they may be significantly influenced by variables including sedimentation rates, nutrient loading, OM deposition, local sediment mineral (e.g., Fe, Mn, Ca, P) composition, and lake morphometry. Unfortunately, inadequate tributary data were obtained during the EPA sampling program due to drought conditions at the time of testing (US EPA, 1982). Thus, the transient and possibly considerable influence of nutrient and sediment loading was not included in the subsequent trophic state evaluations.

The concentration and decay of OM present at the sediment surface are typically considered to govern oxygen demand (particularly hypolimnetic) in lakes and reservoirs, with high concentrations of OM resulting in an increased oxygen demand (Kalin and Hantush 2003). However, evidence shows that organic degradation rates may not directly correlate with OM concentrations, raising the possibility that different levels of oxygen availability and differing rates of OM delivery via sediment focusing may govern SOD (Meckler et al. 2004). Thus, variations in oxygen availability, nutrient loading, and OM concentrations (all of which are highly site-specific parameters) may have significant impact on nutrient cycling, SOD, and hypolimnetic DO levels on a reservoir-specific basis.

In addition to establishing base-line DO estimates, historical data may also be very useful for determining trends in DO and temperature over time as a function of variations in anthropogenic and natural influences (Evans et al., 1996; Nishri et al., 1998; Little and Smol, 2001). It is likely that these influences have changed significantly since the early 1980's in many VA regions, resulting in altered DO and temperature conditions from those documented during the 1983 EPA Clean Lakes VA sampling program. Research has shown that temporal and spatial variations in lacustrine processes may have considerable control over subsequent SOD, DO, and TP levels (Hanson et al., 2003; House, 2003; Kalin and Hantush, 2003; Dittrich et al., 2004; Meckler et al., 2004). Transient lacustrine processes (e.g., sediment loading following storm events and intermittent accumulation of OM) can have a substantial impact on SOD in the zone-of-influence downstream of the discharge point in many systems, subsequently impacting water-column DO levels. Nishri et al. (1998) found significant variations in limnological parameters over time with epilimnetic DO concentrations increasing by ~20%, hypolimnetic H_2S concentrations increasing ~75%, and a long-term decrease in zooplankton biomass (~ 50%) from 1970 to 1991 as a result of reduced allochthonous OM loading and enhanced OM burial in the hypolimnetic sediments of Lake Kinneret (Israel). Significant variations in sediment loading and OM deposition may have occurred in numerous VA lakes and reservoirs during the last two decades. Because OM deposition and accumulation over time have been shown to have strong influence on sediment composition and trends in lake metabolism and DO levels, existing conditions may deviate considerably from DO and temperature data obtained during the 1983 EPA study (Hanson et al. 2003).

Each reservoir is impacted differently by both external (e.g., anthropogenic nutrient loading, hydraulic inputs (river, streams), local soil/mineral composition, allocthonous OM loading) and internal (bank erosion, water-withdrawal locations, autochthonous OM loading, lake morphometry) processes that have strong influence on DO levels. Using historical data from 32 of the 100+ constructed reservoirs in VA for current estimates of existing reservoir DO in undisturbed regions may therefore inadequately represent specific reservoir conditions. Nevertheless, historical DO and temperature profiles can be invaluable for establishing background information and general estimates of DO levels in undisturbed, forested areas, especially when paired with current DO measurements and site-specific data.

9. Could the TMDL program TP/DO TSI approach be used as a template for UAA demonstrations?

The Trophic State Index (TSI) total phosphorus (TP) approach is established as a predictor of algal biomass as a function of soluble TP (Carlson, 1977). A TSI value of 60 or greater for any one of the 3 indices (chlorophyll-a (CA), Secchi disk (SD), and TP) indicates that nutrient loading is negatively impacting designated uses of a particular lake or reservoir. A TSI value of 60 corresponds to a CA concentration of 20 µg/l, a SD measurement of 1 meter, and a TP concentration of 48 µg/l. TSI ratings are based on the following equations, as defined by (Carlson, 1977):

$$TSI(SD) = 10(6 - (\ln SD / \ln 2))$$
$$TSI(CA) = 10(6 - ((2.04 - 0.68 \ln CA) / (\ln 2)))$$
$$TSI(TP) = 10(6 - ((\ln 48 / TP) / (\ln 2)))$$

TP is a significant parameter for characterizing limnological trophic states and the TP TSI approach may yield a satisfactory approximation of oxygen availability/depletion with respect to certain attainable use determinations. However, while strongly indicative of potential eutrophication problems, TP analyses alone may not comprehensively indicate corresponding DO levels. Admittedly, this may or may not be problematic depending on the intended use of the lake or reservoir of concern.

Because of the complex interactions between oxygen levels and P cycling (as defined in Response 7) and the resulting impacts on water quality, it is important to evaluate both P and DO levels when estimating potential DO demand and subsequently establishing DO criteria. A combined TP/DO TSI approach may be an appropriate method for establishing UAA demonstrations as long as both TP and DO levels are quantified and correlated. While TP can be a strong indicator of DO levels and trophic states, particularly in regions of high photosynthetic activity and productivity, other biogeochemical processes may strongly impact DO in hypolimnetic regions. Conventional wisdom suggests that oxic sediments retain Fe, Mn, and P, thereby promoting improved water quality, while anoxic conditions exacerbate water quality as these chemicals and associated compounds are released into the hypolimnion. However, recent studies have suggested that benthic microbial activity and the formation of ferrous phosphate precipitates (e.g., vivianite) may have a significant influence on sediment/water cycling of chemicals and biomineral formation (Gächter and Muller, 2003), indicating that the conventional wisdom needs to be re-examined. Thus, elevated hypolimnetic DO concentrations may not necessarily result in increased P retention in the benthic sediments or reduced TP levels from the water column. Conversely, low TP concentrations in the water column may not always be indicative of relatively high levels of hypolimnetic DO, as it is possible that considerable P remains complexed in ferrous precipitates under low DO conditions.

Thus, depending on water use, TSI TP data alone may or may not be directly representative of water quality and corresponding DO criteria (Carlson, 1977). It seems that it would be highly beneficial to pair TP TSI data with supporting DO measurements. A strong UAA approach could be established by incorporating TP TSI methodology with routine DO measurements (particularly during stratification) and site-specific data to determine potential drains on oxygen demand via natural (sediment deposition, introduced Fe- and Mn-minerals, retention time) and anthropogenic (nutrient loading, hydraulic inputs and withdrawals) sources. This approach would use soluble TP and DO measurements to identify potential eutrophication problems that may exacerbate DO depletion and subsequently decrease water quality.

Conclusions and Recommendations

In summary, we recommend that DO criteria be established specifically for Virginia lakes and reservoirs and that separate criteria be developed for natural lakes and constructed impoundments. Site-specific criteria should be developed for the two natural lakes in the state, Mountain Lake and Lake Drummond. To address the effects of stratification on DO concentrations throughout the water column, separate criteria for the epilimnion and hypolimnion are recommended, and criteria development should be based on designated uses of the water bodies. Application of a single DO criterion for all depths within a given lake or reservoir may be unnecessarily stringent and not required to fully support the water body's designated uses during stratification. Dissolved oxygen criteria for stratified water bodies should ensure that at least one layer exists where temperature, DO, and pH conditions can support designated uses.

Hypolimnetic DO criteria should account for the potential downstream effects of reduced oxygen concentrations in waters released from the lower depths of constructed impoundments. Currently, almost 6 miles of the Roanoke River are classified as Category 5 impaired waters for DO because of hypolimnetic water discharge upstream from Lake Gaston (VDEQ, 2004d).

Also, nearly 6 miles of the Meherrin River are designated Category 5 impaired for DO due to hypolimnetic releases from an upstream impoundment (VDEQ, 2004d).

Because the vast majority of lentic systems in Virginia are constructed impoundments, establishing DO criteria based on water body designated use is a reasonable methodology. Designated uses have already been determined for Virginia water bodies for biennial preparation of the 305(b)/303(d) water quality assessment reports (VDEQ, 2004d). Of the six existing designated uses, only aquatic life and public water supply are directly affected by low DO concentrations in lakes reservoirs, and recreation may be considered to be indirectly affected. Ambient freshwater DO criteria for the protection of aquatic life, both cold and warm water species, have been determined previously by EPA (US EPA, 1986).

EPA has not developed ambient DO criteria for the support of public water supplies, and the vast majority of states do not have DO criteria specifically for this designated use. The effects of hypolimnetic anoxia on water quality parameters related to drinking water treatment are well documented. However, because of insufficient information available, we can recommend only preliminary DO criteria for protection of water supply uses. It is suggested that the existing freshwater DO criteria for non-trout waters (5 mg L^{-1} daily average, 4 mg L^{-1} minimum) be applied to all strata used for potable water supply within a given reservoir. This is comparable to the approximate, rule-of-thumb DO value of 5 mg L^{-1} typically desired in influent raw water by treatment plant managers. Because the direct treatment benefits of this particular DO concentration in lakes and reservoirs have not been well established, DO criteria for protection of water supply designated uses may need to be revised after further study by EPA or the scientific and engineering community.

Separate DO criteria specifically for protection of recreational uses is not recommended at this time for Virginia. If all reservoirs are designated for aquatic life and/or water supply use, then the DO criteria to support these uses would more than likely be adequate to support primary and secondary recreational uses.

Compliance with DO criteria in lakes and reservoirs will likely be determined through field data collection. Measurements are typically obtained at appropriate intervals through the water column on each sampling date. Dissolved oxygen concentrations are measured with a sensing probe or using a modified Winkler technique. The minimum frequency for characterizing mixing and the oxic status of a water body is dependent on the oxygen depletion rate. In some locations, the minimum required frequency may be monthly; in others, it may be as high as daily (US EPA, 2000). Temperature profiles will also be required to determine the onset of stratification and to delineate the density strata within water bodies. Dissolved oxygen data from most, if not all, of Virginia's significant reservoirs has been or is currently being collected, as evidenced by the biennial 305(b)/303(d) water quality assessment reports (VDEQ, 2004d). To ensure that representative DO data are being obtained to accurately characterize each reservoir's oxic status, existing sampling procedures should be reviewed. As referenced in the Nutrient Criteria Technical Guidance Manual–Lakes and Reservoirs (US EPA, 2000), there are a number of publications that provide further information on sampling designs for lakes and reservoirs (Carlson and Simpson, 1996; Gaugush, 1987; Gaugush, 1986; Reckhow, 1979; Reckhow and Chapra, 1983).

With respect to the type of Use Attainability Analysis (UAA) needed to demonstrate appropriate DO criteria for lakes and reservoirs, a multi-phase UAA is recommended, based on 1) a review of supporting literature and historical data; 2) routine, on-site surveys performed to analyze parameters relating to DO levels; and 3) correlation of TP TSI approach with epilimnetic and hypolimnetic DO measurements to help establish overall UAA. We feel that a multi-phase UAA approach would best characterize the combined influence of the various processes impacting DO levels (in both the epilimnion and the hypolimnion) and subsequent attainable use on a site-specific basis. Due to the fact that complex interactions between oxygen availability and P cycling have such control on water quality and subsequent use attainability, we recommend using DO and TP as key parameters in use attainability analyses.

Historical data, such as that obtained during the 1983 EPA Clean Lakes VA sampling program, may be very useful for establishing *expected*, base-line DO levels for watersheds with conditions similar to those sampled during the 1983 sampling program. Additionally, historical data may also be valuable for determining trends in DO and temperature over time as a function of variations in anthropogenic and natural influences. Regarding the use of historical data for estimates of current DO conditions, this data should be used predominantly for general guideline purposes, as information obtained during the 1983 EPA Clean Lakes study was collected primarily to establish base-line data in preparation for subsequent Clean Lakes Program projects (US EPA 1982). Base-line DO estimates should be verified by current DO measurements and modified with respect to existing, reservoir-specific conditions. DO availability and depletion rates are very site-specific and transient as they may be significantly influenced by variables including sedimentation rates, nutrient loading, OM deposition, local sediment mineral (e.g., Fe, Mn, Ca, P) composition, and lake morphometry. Thus, variations in oxygen availability, nutrient loading, and OM concentrations (all of which are highly site-specific parameters) may have significant impact on nutrient cycling, SOD, and hypolimnetic DO levels, emphasizing the need for current DO measurements on a reservoir-specific basis.

We feel that a combined TP/DO TSI approach may be an appropriate method for establishing UAA demonstrations as long as both TP and DO levels are quantified and correlated. Because of the complex interactions between oxygen levels and P cycling and the resulting impacts on water quality, it is important to evaluate both P and DO levels when estimating potential DO demand and subsequently establishing DO criteria. While TP may be a strong indicator of DO levels and trophic states, particularly in regions of high photosynthetic activity and productivity, other biogeochemical processes may strongly impact DO in hypolimnetic regions. A strong UAA approach could be established by incorporating TP TSI methodology with routine DO measurements and site-specific data to determine potential drains on oxygen demand via natural and anthropogenic sources. This approach would use soluble TP and DO measurements to identify potential eutrophication problems that may exacerbate DO depletion and subsequently decrease water quality.

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Table 1. Significant Reservoirs by Region as of August 2004 (VDEQ, 2004d)

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Northern Regional Office – 13 Lakes				
Able Lake	Stafford County	185	Yes	
Lake Anna	Louisa County	9,600		
Aquia Reservoir (Smith Lake)	Stafford County	219	Yes	
Beaverdam Reservoir	Loudoun County	350	Yes	
Burke Lake	Fairfax County, VDGIF	218		
Goose Creek Reservoir	Loudoun County	140	Yes	
Lake Manassas	Prince William County	741	Yes	
Motts Run Reservoir	Spotsylvania County	160	Yes	
Mountain Run Lake	Culpepper County	75	Yes	5C
Ni Reservoir	Spotsylvania County	400	Yes	
Northeast Creek Reservoir	Louisa County	49	Yes	
Occoquan Reservoir	Fairfax County	1,700	Yes	5C
Pelham Lake	Culpepper County	253	Yes	5C
Piedmont Regional Office – 11 Lakes				
Airfield Pond	Sussex County, VDGIF	105		
Amelia Lake	Amelia County, VDGIF	110		
Brunswick Lake	Brunswick County, VDGIF	150		
Lake Chesdin	Chesterfield County	3,196	Yes	5A
Chickahominy Lake	Charles City County	1,500	Yes	5A
Diascund Reservoir	New Kent County	1,700	Yes	4C
Emporia Lake	Greensville County	210	Yes	4C
Falling Creek Reservoir	Chesterfield County	110		
Great Creek Reservoir (Bannister Lake)	Lawrenceville	305		4C
Swift Creek Lake	Chesterfield County	156		
Swift Creek Reservoir	Chesterfield County	1,800	Yes	4C
South Central Regional Office – 22 Lakes				
Briery Creek Lake	Prince Edward County, VDGIF	850		
Brookneal Reservoir	Campbell County	25	Yes	
Cherrystone Lake	Pittsylvania County	105	Yes	4C
Georges Creek Reservoir	Pittsylvania County	1	Yes	
Gordon Lake	Mecklenburg County, VDGIF	157		

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Graham Creek Reservoir	Amherst County	50	Yes	4C
Halifax Reservoir	Halifax County	410	Yes	
Holiday Lake	Appomattox County	145		
Kerr Reservoir (VA portion)	Halifax County, VDGIF	35,251	Yes	5A
Keysville Lake	Charlotte County	42	Yes	
Lake Conner	Halifax County, VDGIF	111		
Lake Gaston (VA portion)	Brunswick County	5,529	Yes	5A
Lunenberg Beach Lake	Town of Victoria	13	Yes	
Modest Creek Reservoir	Town of Victoria	29	Yes	
Nottoway Falls Lake	Lunenburg County	60	Yes	5A
Nottoway Lake	Nottoway County	188		
Nottoway Pond	Nottoway County	65	Yes	
Pedlar Lake	Amherst County	75	Yes	5C
Roaring Creek	Pittsylvania County	19	Yes	
Stonehouse Creek Reservoir	Amherst County	125		
Thrashers Creek Reservoir	Amherst County	110		
Troublesome Creek Reservoir (SCS Impoundment No. 2)	Buckingham County	85	Yes	
South West Regional Office – 9 Lakes				
Appalachia Reservoir	Wise County	17	Yes	
Big Cherry Lake	Wise County	76	Yes	5A
Byllsby Reservoir	Carroll County	335		
J. W. Flannigan Reservoir	Dickenson County, ACOE	1,143	Yes	5A
Hungry Mother Lake	Smyth County	108	Yes	5A
Lake Keokee	Lee County, VDGIF	100		5A
Laurel Bed Lake	Russell County, VDGIF	300		
North Fork Pound Reservoir	Wise County, ACOE	154	Yes	5A
South Holston Reservoir	Washington County, TVA	7,580	Yes	5A
Tidewater Regional Office – 20 Lakes				
Lake Cahoon	Suffolk City	508	Yes	
Lake Burnt Mills	Isle of Wight County	711	Yes	
Harwood Mill Pond	York County	300	Yes	5A

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Lake Kilby	Suffolk City	226	Yes	
Lee Hall Reservoir	Newport News	230	Yes	5A
Little Creek Reservoir	Norfolk City	193	Yes	
Little Creek Reservoir	James City County	860	Yes	
Lake Lawson	Norfolk City	77	Yes	
Lone Star Lake F	Suffolk City	20	Yes	
Lone Star Lake G	Suffolk City	50	Yes	
Lone Star Lake I	Suffolk City	39	Yes	
Lake Meade	Suffolk City	511	Yes	
Lake Prince	Suffolk City	946	Yes	
Lake Smith	Norfolk City	193	Yes	5A
Speights Run Lake	Suffolk City	94	Yes	
Stumpy Lake	Virginia Beach	210	Yes	
Waller Mill Reservoir	York County	315	Yes	
Lake Whitehurst	Norfolk City	480	Yes	
Lake Wright	Norfolk City	49	Yes	
Western Branch Reservoir	Norfolk City	1,265	Yes	
Valley Regional Office – 12 Lakes				
Beaver Creek Reservoir	Albemarle County	104	Yes	
Mount Jackson Reservoir	Shenandoah County	0.7	Yes	
Coles Run Reservoir	Augusta County, USFS	9	Yes	
Elkhorn Lake	Augusta County, USFS	55	Yes	4C
Lake Frederick	Frederick County, VDGIF	120		4C
Ragged Mountain Reservoir	Albemarle County	54	Yes	4C
Rivanna Reservoir	Albemarle County	390	Yes	
Staunton Dam Lake	Augusta County	30	Yes	
Strasburg Reservoir	Shenandoah County	5.3	Yes	
Switzer Lake	Rockingham County, USFS	110		
Sugar Hollow Reservoir	Albemarle County	47	Yes	4C
Totier Creek Reservoir	Albemarle County	66	Yes	5A
West Central Regional Office – 15 Lakes				
Beaverdam Creek Reservoir	Bedford County	123	Yes	
Bedford Reservoir	Bedford County	28	Yes	
Carvins Cove Reservoir	Botetourt County	630	Yes	4C
Claytor Lake	Pulaski County	4,483	Yes	4C

Reservoir	Location	Surface Area (acres)	Public Water Supply?	2004 DO Impairment Category
Clifton Forge Reservoir	Alleghany County, USFS	16	Yes	
Fairystone Lake	Henry County	168		
Gatewood Reservoir	Pulaski County	162		
Hogan Lake	Pulaski County	40	Yes	
Leesville Reservoir	Bedford County	3,400	Yes	4C
Little River Reservoir	Montgomery County	113		
Martinsville Reservoir	Henry County	220	Yes	
Lake Moomaw	Bath County, USFS	2,430		4C
Philpott Reservoir	Franklin, Henry, and Patrick Counties; ACOE	2,879		4C
Smith Mountain Lake	Bedford, Franklin, and Pittsylvania Counties	19,992	Yes	4C, 5A
Talbott Reservoir	Patrick County	165		
Total 102 Lakes Statewide				

Table 2. Capital costs of representative hypolimnetic aeration and oxygenation systems.

Waterbody	Maximum Depth (m)	Volume (10^6 m^3)	Aerator or Oxygenator Type	Application	Year Installed	Oxygen Addition (kg d^{-1})	Capital Cost (2005 $)	References
Richard B. Russell Reservoir, Georgia	47	1,270	bubble plume diffuser	hydropower	1985	200,000	$1.6M	Mauldin et al. (1988), Beutel and Horne (1999), Little (2005)
Lakes Prince and Western Branch, Virginia	11	38	full-lift aerator	water supply	1991	10,700	$2.8M	Burris and Little (1998), Burris et al. (2002), Little (2005)
Camanche Reservoir, California	41	545	Speece Cone	hydropower	1993	9,000	$1.8M	Jung et al. (1999), Little (2005)
Spring Hollow Reservoir, Virginia	55	7.2	bubble plume diffuser	water supply	1998	250	$120K	Little and McGinnis (2000), Little (2005)
Upper San Leandro Reservoir, California		51	bubble plume diffuser	water supply	2002	9,000	$450K	EBMUD (2001), Jung et al. (2003), Little (2005)

Appendix D. Maryland-USGS Proposal to EPA

A REGIONAL APPROACH
TO THE DEVELOPMENT OF
A RESPONSE-BASED NUTRIENT CRITERION
FOR WADEABLE STREAMS
IN NUTRIENT ECOREGIONS IX, XI, & XIV

a proposal

Submitted to the
U.S. Environmental Protection Agency

by

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I. AGENCY OVERVIEW

Maryland Department of the Environment (MDE)

Maryland Department of the Environment (MDE) is the State government agency in charge of restoring and maintaining the quality of ground and surface waters. This requirement is accomplished through the enforcement of water quality standards and controls on point and non-point sources of pollution. To ensure that water quality standards are met, the Department monitors its waters on a rotating watershed basin system. The Department has accomplished much of its monitoring efforts through the management of grant monies awarded by EPA. Some specific monitoring initiatives include tidal and nontidal water quality assessment, monitoring in support of TMDL development and the fish and shellfish tissue-monitoring program.

United States Geological Survey

The U.S. Geological Survey (USGS), Pennsylvania District, has a long history of investigations into nutrients in streams and their relations to water quality. Staff from the Pennsylvania district have conducted long-term investigations of nutrients in the Conestoga River Basin (Lietman, 1997) as part of the Rural Clean Waters Program (RCWP). Most recently, we have completed a study of the relations of nutrients to biological indicators for lakes and streams in Pennsylvania and West Virginia (Brightbill and Koerkle, 2003). Two other studies, both long-term and involving evaluations of BMPs are nearing completion (Schreffler and others, in preparation: Galeone and Brightbill, in preparation). Capabilities within the District include macroinvertebrate identification and analysis, use of continuous water-quality monitors, field water-quality assessments, and data management and analysis. Other capabilities within the USGS include state-of-the-art laboratory analyses, macroinvertebrate identifications, development of statistical techniques for trend analysis, development of regional water-quality models, and collection and analysis of regional and nationwide environmental data.

II. BACKGROUND

Nutrients have been cited as one of the leading causes of impairment for streams in the United States. The number of waters adversely affected by nutrients is documented in the various 305(b) reports prepared by the states and submitted to the U.S. Environmental Protection Agency (EPA). Impairment from nutrients may reach as high as 50 percent of all waters surveyed in a state.

To address these problems, the EPA is in the process of helping states establish nutrient criteria. The EPA has published nutrient criteria technical guidance manuals for three aquatic environments (Lakes and Reservoirs, Rivers and Streams, and Estuarine and Coastal Marine Waters), with a fourth document (Wetlands) scheduled for publication in

December 2003. Also, EPA has published suggested nutrient criteria for all 14 nutrient ecoregions across the United States.

These suggested criteria were established based on an examination of reference conditions and levels of nutrients that lead to impairment. This approach has gained praise and acceptance from many in the scientific and regulatory community for its scientific validity. Yet, others have called for more of an effects-based approach where response variables and water uses are factored into the nutrient criteria.

The research suggested in this proposal will (1) use an effects-based approach to calculate nutrient criteria and (2) assess periphyton communities in EPA Region III streams. An effects-based approach means we look at the effects caused by nutrients to calculate a nutrient criterion level. The nutrient criteria can be used to support to EPA's reference condition approach or can be used as an alternative to the EPA approach. The periphyton community assessment can be used to evaluate the ecological health of the periphyton community for the streams studied and will provide initial data for future development of a periphyton index of biotic integrity (P-IBI).

EPA's Request for Proposals asked for a compilation and evaluation of existing data to address the proposed research. Available data are not summarized here because (1) the database contains an inadequate number of chlorophyll *a* measurements for streams and (2) the dissolved oxygen measurements residing in the current database are collected primarily during daylight hours. Critical dissolved oxygen concentrations occur at night. Further, the existing data for much of EPA Region III have recently been analyzed (Brightbill and Koerkle, 2003).

III. QUALITY ASSURANCE PROCEDURES

Quality assurance procedures will include using a written, standardized protocol for field work, training for all personnel who collect field data, and standardized field data-collection sheets for all field work. Duplicates, blanks, and reference materials will be used to assure the quality of laboratory work. Laboratory QC will include lab participation in the U.S. Geological Survey's Inter-Laboratory Evaluation Program (Woodworth and Connor, 2003).

Quality control for the data will include standardized field data-collection sheets, periodic reviews of the data sheets, spot checks of the electronic data, and both tabular and graphical displays of the data to check for anomalies.

Periphyton identifications will be done using widely accepted keys. Verification of periphyton identifications will be done by an outside lab for 5 percent of the samples.

IV. DESCRIPTION OF THE PROJECT

Purpose and Scope:

Two overall objectives are proposed:

1. Use response variables (dissolved oxygen and periphyton chlorophyll *a*) to suggest nutrient criteria for streams in EPA's Region 3. This is the primary objective. Data from the second objective will be used as input information to reach this primary objective.

2. Examine periphyton communities for streams in EPA's Region 3 to see if eutrophic conditions are associated with specific community characteristics.

Study sites would include several 2nd, 3rd, and 4th order streams in Nutrient Ecoregions IX, XI, and XIV, all in EPA's Region 3. These Ecoregions comprise most of the land area of the states in EPA's Region 3 and extend beyond Region 3 to include most of the southeastern U.S. The proposed work would involve field data collection during the critical summer months of 2004. Data evaluation and report preparation would follow through the fall and winter of 2004 and into 2005 with a final report due on September 30, 2005.

The final report for the project (page 9) will specifically address the use of periphyton community structure and chlorophyll *a* for predicting over-enrichment in streams.

Project Overview:

This proposal defines a cooperative approach to (1) defining nutrient criteria for streams in EPA Region 3 and (2) examining periphyton community structure for wadeable streams (Strahlher Order 2-4). The success of this project is based on the cooperative and collaborative efforts of EPA Region III (funding source), and National (USGS) and State agencies (MDE, WV DEP, VA DEP PA DEP) responsible for management of environmental quality. A cooperative approach is required for a region-wide effort and to pool resources for funding and personnel.

Development of Nutrient Criteria:

Other researchers have attempted to define the relations between nutrients and periphyton. These efforts have been only partly successful. One reason is that the researchers pooled all available data for the analysis, then looked for relations. But, nutrients are transient. The concentrations observed in a stream on any day will likely be different the next day or the next week. Therefore, the proposed work will examine nutrient-periphyton relationships for a short term only -- during the critical summer period of July and August. Oxygen consumption is largest at night. Thus, nighttime measurements collected during the hottest, driest period of the year are critical for establishing nutrient criteria. Measurements at other times of the year are superfluous, and even confusing.

Our approach will be to select a subset of the streams used for the periphyton community work to examine nutrient concentrations, periphyton biomass, and dissolved oxygen concentrations. For this subset of streams, we will install continuous recording dissolved oxygen monitors for a brief period (48 hours). It is important to measure the variability of dissolved oxygen for a diel cycle because the lowest dissolved oxygen concentrations will occur at night when photosynthesis is shut down, but respiration continues. (Another reason for the failure of previous nutrient studies is that routine monitoring is usually a daytime activity.) The dissolved oxygen measured during routine daytime monitoring fails to capture the lowest dissolved oxygen concentrations.

Assessment of Stream Periphyton Communities:

Examination of periphyton communities is an effects-based approach that will attempt to link nutrient conditions within a stream system to the growth of periphyton communities within that stream. Periphyton are important to stream ecology because they are the main primary producers. This means that they are one of the first links in the aquatic food chain and can ultimately affect the populations of other species as well. Periphyton are also useful indicators of stream environmental conditions because they quickly respond to changes and are sensitive to a number of disturbances, including nutrient over-enrichment. Nutrients, especially limiting nutrients, can vary in time and space in the water column, and they are transient. As a resident biotic component in streams, periphyton can quickly register and incorporate transient or episodic changes in nutrient conditions, or act as nutrient "sinks." Thus, having an understanding of the periphyton community in a stream can reveal a lot about the ecological health and the nutrient status of that stream.

In addition to nutrients, periphyton growth is controlled by available sunlight, time available to grow since the last high-flow event, streambed stability, soil type, substrate availability, water speed, and grazing by invertebrates. Finally, upstream land use (e.g., acreage and proximity of agricultural uses or publicly owned treatment works (POTWs)) and channel modification (e.g., width of the wooded riparian buffer strip) play an important role in determining nutrient additions to streams. Healthy streams typically have little obvious periphyton, because growth is cropped by invertebrate grazers and turned into invertebrate biomass. Nuisance blooms are usually a symptom of a system stressed by things like over-supply of nutrients and high temperatures (that increase algal growth rates but stress some invertebrate grazers). Analysis of periphyton coverage, biomass, and speciation (e.g. abundances of eutrophic species), as well as the aforementioned factors will be used to determine relations between nutrients and periphyton communities in Region III streams.

Approach:

Field work for the project will be done by the cooperating states (Maryland, Virginia, West Virginia, and Pennsylvania), using common protocols (mutually agreed upon) documented and distributed by the USGS. Training for all field personnel will assure uniform data collection across the Region. Data management and analysis will be handled jointly by MDE and USGS. Report preparation will primarily be the responsibility of the USGS with assistance from MDE.

Development of Nutrient Criteria:

Several streams (our goal is 12 streams for this work) will be selected for the nutrient criteria work. The streams selected will represent a range of nutrient conditions and will come from at least three Nutrient Ecoregions. At each stream, all the measurements from the periphyton component of the research (including chlorophyll *a*, nutrients, standard field measurements, and total organic carbon) described in the next section of this proposal will be recorded. In addition, continuous dissolved oxygen (DO) monitors will be deployed for at least two 24-hour periods during the hottest part of the summer. Minimum DO values are critical for aquatic life and this plan will capture those minimum DO values, or values that are near minimum for the year. Data from the continuous monitors will be downloaded in the field to a notebook computer. These data will then be transferred to computers housed at the USGS in New Cumberland, Pennsylvania for analysis. Nutrient concentrations associated with DO concentrations lower than the applicable water-quality standard (5 mg/L) will be considered to be excessive.

Assessment of Stream Periphyton Communities:

Stream locations will be selected to represent major natural and human factors that are thought to significantly influence the quality of water. The overall approach will consist of a goal-oriented, stratified random sampling design. The advantage of this approach is that fewer resources are expended since only “targeted” streams within each stratum will be sampled. Also, selection of a range of nutrient conditions will facilitate establishment of nutrient-algal (periphyton) relationships that will enable the eventual development of an index of biotic integrity based on those relationships. The goal will be to include streams that represent a wide spectrum of biotic conditions, from reference conditions to eutrophic conditions.

Because the main study objective is the development of ecoregion-specific nutrient criteria, the initial stratification will be by nutrient ecoregion. The Level III Aggregate Nutrient Ecoregions of interest in EPA Region 3 are Ecoregion IX (Southeastern Temperate Forested Hills and Plains), Ecoregion XI (Central and Eastern Forested Uplands), and Ecoregion XIV (Eastern Coastal Plain). Other Ecoregions within the EPA Region 3 boundaries represent relatively small areas and will not be sampled in the proposed research. An equal number of samples will be allocated to each ecoregion.

Next, Strahler stream order will be used to further segregate potential sampling reaches within each ecoregion. One or two Strahler orders will be selected based on availability of information in each ecoregion. Finally, a review of the existing data (EPA Nutrient database 1990-1998) will enable stratification by nutrient condition. Streams will be separated into high, moderate, and low nutrient conditions/potential based on the assessment of available in-stream nutrient data, as well as land use information.

At the completion of this stratification process, each ecoregion should have a list of potential sampling sites based on stream order and nutrient condition. Stations (sampling reaches) will be selected randomly from the entire population of streams within each stratum. The sampling reach, described by Meador and others (1993), represents the sampling unit for ecological assessments used by NAWQA, and the Maryland Biological Stream Survey (MBSS) network (Reference, date). A randomization program will be used to select "x" number of samples from the pool of available streams within each strata. Our initial goal is to sample 15 streams within each of the three Nutrient Ecoregions. The procedure will be repeated for each stratum.

A modified version of the periphyton sampling techniques and methods used in the USGS NAWQA (Moulton and others, 2002) and EPA's EMAP studies will be used. A single qualitative multi-habitat sample and duplicate quantitative single habitat samples (one for taxonomic identification, and one for biomass measurements), and a water-quality sample will be collected from each sampling reach. Riffle habitat will be used for quantitative sampling. In the Coastal Plain (Ecoregion XIV), riffle habitat may not be commonly available in all sampling reaches due to ecoregional geology. In this case, quantitative artificial substrate samplers (i.e., periphytometers) will be used in all sampling reaches in Ecoregion XIV.

Qualitative periphyton samples are intended to provide a list of species (taxa richness) present in the sampling reach. Samples of algae are collected from each periphyton microhabitat present in the sampling reach and composited into one sample. A sub-sample of the qualitative periphyton sample also can be used to assist with the identification or verification of diatom species and varieties in quantitative periphyton samples from the same location. Water quality can be assessed by interpreting autecological information, the taxon-specific physiological requirements or tolerance for defined ranges of water-quality conditions. Quantitative periphyton samples are collected to measure the relative abundance and density (algal cells per square centimeter) of each taxon present in each selected stream habitat type (riffle) in a sampling reach. Quantitative samples are collected using a variety of sampling devices (i.e., NAWQA periphyton sampling device SG-92 or the whole-rock approach); the appropriate choice of sampling equipment is dictated by the character of the dominant periphyton growth forms and microhabitats in the sampling reach. Samples are processed, stored, and transported using protocols established by EMAP studies. Habitat assessments patterned after EPA's Rapid Bioassessment Protocols (including photo documentation and geo-referencing) will complete the process for each site.

Samples for taxonomic identification will be shipped to a laboratory chosen through an open bidding process. All genera in the samples will be identified to species level to enable the development of autecological indices for the three ecoregions. A photo library will be developed for the agency for future reference purposes. A sub-sample of the quantitative sample, as well as samples for biomass determination will be retained at MDE for processing. MDE field staff are competent at periphyton identification to the genus level. This sub-sample will be used to build taxonomic expertise to species level, thus enabling the agency to develop in-house capacity for future assessment efforts.

Periphyton data will be related to corresponding physical, chemical, and biological data at each basic fixed site to evaluate taxon-specific responses to differences or changes in water chemistry, to assess the effects of algal communities on water quality, and to integrate physical, chemical, and biological characteristics into regional assessments of water quality.

Analytical Requirements:

Field water-quality samples will be sent to a contract laboratory for analysis. Analyses will be needed for a broad range of nutrients including dissolved nitrite+nitrate, dissolved ammonia nitrogen, organic nitrogen, dissolved ortho-phosphate, and total phosphorus. Total organic carbon will also be measured to provide insight into the role of organic matter in oxygen depletion in the streams. Chlorophyll *a* will be measured as a surrogate for algal biomass.

Data Management:

Initially, data from the project will be housed in electronic files at the USGS Pennsylvania District, New Cumberland, Pennsylvania. A back-up duplicate copy of all data files will be stored at MDE offices, Baltimore, Maryland. Near the end of the project, data will be placed into EPA's national database, STORET. A commercially available database management system such as Access will be used for data storage and management. Commercially available software will be used for graphical and statistical analyses.

Evaluation Plan:

The periphyton community data will be analyzed by looking for indicator species and by comparing several different community metrics. The final selected eutrophic indicators will offer the best representation of the health of the system, with attention given to simplicity. The idea is to develop a tool that is reflective of stream conditions, yet can be routinely implemented by most field biologists employed by state resource agencies. Data from the project will be examined using a variety of traditional and multivariate approaches. Non-parametric techniques are likely to be used as biological data frequently are not normally distributed. Data transformations may be needed to deal with non-linear relationships. Graphical presentation of the data will be emphasized.

For the development of nutrient criteria, graphing measured nutrient concentrations for several streams against minimum dissolved oxygen concentrations are expected to produce a relationship generalized in Figure 1. The nutrient concentration that results in meeting the water-quality standard (dissolved oxygen concentration of 5.0 mg/L) will provide the basis for the proposed nutrient criterion.

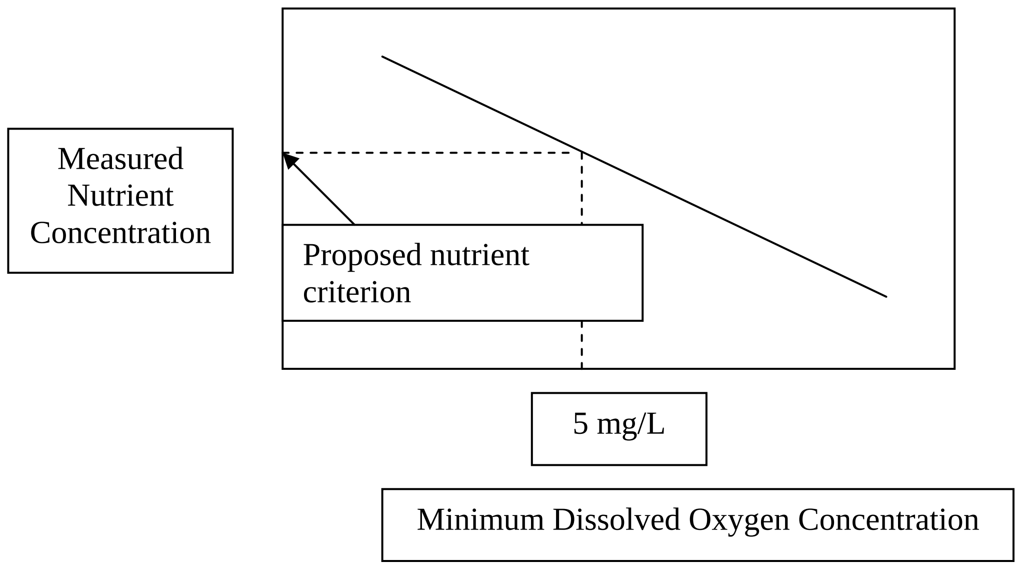

Figure 1. Expected relation between measured nutrients and minimum dissolved oxygen in Region III streams (generalized).

Data gathered to populate the graph in Figure 1 are not all expected to fall on the line depicted in Figure 1. Instead, some data points will fall above the line. However, no data points should fall below the line. Data would be expected to fall above the line when some factor other than the nutrient being considered is limiting. For example, Figure 2 shows what the data might look like for several streams, some having light as the limiting factor, and some having nitrogen as the limiting factor.

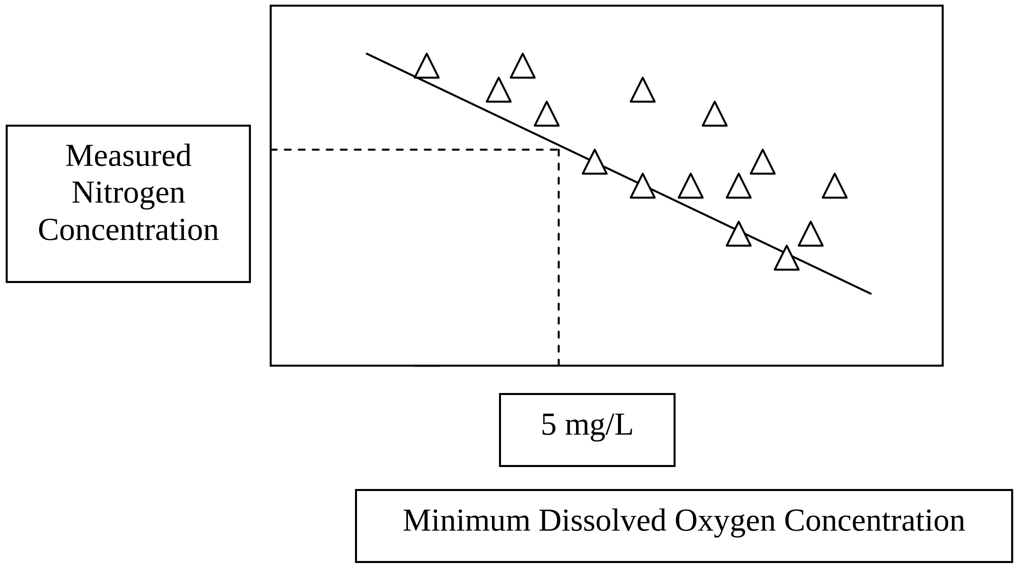

Figure 2. Hypothetical data distribution for Region III streams.

For those streams where nitrogen is limiting, the data point falls on the line. If light (or any other variable) is limiting, periphyton will not grow to their maximum potential. Minimum dissolved oxygen concentrations will be larger than the case where nitrogen is limiting. The data point will fall above the line. For those data points that fall on (or near) the line, a least squares regression, based on a General Linear Model, will be used to quantify the relation between nutrients and dissolved oxygen. This relation will be used to quantify the nutrient criterion.

We will measure dissolved organic carbon to account for oxygen-demanding organic matter in the stream. The goal is to measure relations between nutrients and minimum dissolved oxygen concentrations that are not influenced by variables other than nutrients.

This approach has a weakness that minimum dissolved oxygen concentrations are influenced by productivity of the attached algae as well as the standing crop of attached algae. We do not propose to measure algal productivity. Intuitively, algal productivity and algal standing crop are likely related, so measurement of standing crop by chlorophyll *a* concentrations should suffice.

Products:

1. Semi-annual progress reports will document progress on the project.

2. Project personnel will present a paper from the work at one scientific meeting to encourage exchange of ideas among the scientific community.

3. Project personnel will provide a seminar for one Region 3 Regional Technical Assistance Group (RTAG)[1] meeting to help disseminate the results of the work.

4. A final, published report will be provided to EPA approximately one year following completion of laboratory analyses. This report will specifically address the feasibility of using periphyton community structure and chlorophyll *a* measurements to define nutrient over-enrichment.

[1]The RTAG is a group of scientists and environmental managers that meets periodically to exchange information about nutrient criteria development and implementation and serves as an advisory body for each EPA Region on nutrient issues.

Schedule:

The following table depicts the time line to be followed for the project.

Task	Federal fiscal year 2004 (Months)												Federal fiscal year 2005 (Months)											
	O	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**
Project planning. Site selection. Meetings with partners.				■				■																
Order supplies and equipment.						■																		
Prepare sampling protocols					■																			
Write and submit QA plan, safety plan.							■																	
Field data collection										■	■	■												
Diurnal DO work										■	■	■												
Data management and analysis.													■	■										
Report preparation, review, and publication															■	■	■	■	■	■	■			
Public presentation.																					■			

Benefits:
Responding to the Clean Water Action Plan, the U.S. Environmental Protection Agency has been tasked with responding to the problem of nutrient enrichment in U.S. waterways. One of the ways the EPA is addressing this task is to provide guidance for the states to establish water-quality standards for nutrients. The results of this study will provide support for a response-based approach to establishing these nutrient standards for streams.

The results of this study and further investigations support the mission of the USGS by providing a regional pattern of water quality in the mid-Atlantic states. This knowledge and other pertinent information relating to nutrients will assist states faced with establishing water-quality standards for nutrients.

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Appendix E. Pensylvania-USGS Proposal to EPA

A RESPONSE-BASED APPROACH FOR DEVELOPMENT OF NUTRIENT CRITERIA IN THE MID-ATLANTIC STATES

a proposal

Submitted to the
U.S. Environmental Protection Agency

by

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I. ABSTRACT

An expansion of a nutrient criteria development project currently underway in Region 3 is proposed. Periphyton biomass and community structure will be evaluated in relation to nutrient concentrations. Nutrient criteria will be suggested based on the response variables, chlorophyll *a* and nighttime dissolved oxygen. Most previous studies have neglected to include nighttime dissolved oxygen. Collaboration among Region 3 states Pennsylvania, Maryland, Virginia, and West Virginia and Delaware will allow sampling in each of these states and the District of Columbia. A cooperative agreement with the USGS will add technical expertise to the project.

II. ORGANIZATIONAL OVERVIEW

Pennsylvania Department of Environmental Protection (PADEP):

The Pennsylvania Department of Environmental Protection (PADEP) is in charge of maintaining and restoring the quality of ground and surface waters. This requirement is accomplished through the enforcement of water quality standards established by the PADEP and by controls on point and non-point sources of pollution. To ensure that water quality standards are met, the Department regularly monitors the waters of Pennsylvania through the Water Quality Network which includes 123 standard stations and 26 reference stations. Monitoring and modeling in support of TMDL development is also a function of the PADEP. Most significantly for this proposal., the PADEP is charged with establishing water-quality standards, including nutrient standards, for the State.

United States Geological Survey:

The U.S. Geological Survey (USGS), Pennsylvania District, has a long history of investigations into nutrients in streams and their relations to water quality. Staff from the Pennsylvania district have conducted long-term investigations of nutrients in the Conestoga River Basin (Lietman, 1997) as part of the Rural Clean Waters Program (RCWP). Most recently, we have completed a study of the relations of nutrients to biological indicators for lakes and streams in Pennsylvania and West Virginia (Brightbill and Koerkle, 2003). Two other studies, both long-term and involving evaluations of BMPs are nearing completion (Schreffler and others, in preparation: Galeone and Brightbill, in preparation). Capabilities within the District include macroinvertebrate identification and analysis, use of continuous water-quality monitors, field water-quality assessments, and data management and analysis. Other capabilities within the USGS include state-of-the-art laboratory analyses, macroinvertebrate identifications, development of statistical techniques for trend analysis, development of regional water-quality models, and collection and analysis of regional and nationwide environmental data.

III. BACKGROUND

Nutrients have been cited as one of the leading causes of impairment for streams in the United States. The number of waters adversely affected by nutrients is documented in the various 305(b) reports prepared by the states and submitted to the U.S. Environmental Protection Agency

(EPA). Impairment from nutrients may reach as high as 50 percent of all waters surveyed in a state.

To address these problems, the EPA is in the process of helping states establish nutrient criteria. The EPA has published nutrient criteria technical guidance manuals for three aquatic environments (Lakes and Reservoirs, Rivers and Streams, and Estuarine and Coastal Marine Waters). A fourth document (Wetlands) was scheduled for publication in December 2003, but that publication has been delayed and is expected in December 2004. Also, EPA has published suggested nutrient criteria for all 14 nutrient ecoregions across the United States.

These suggested criteria were established based on an examination of reference conditions and levels of nutrients that lead to impairment. This approach has gained praise and acceptance from many in the scientific and regulatory community for its scientific validity. Yet, others have called for more of an effects-based approach where response variables and water uses are factored into the nutrient criteria.

The research suggested in this proposal will (1) use an effects-based approach to calculate nutrient criteria and (2) assess periphyton communities in EPA Region III streams. An effects-based approach means we will look at the effects caused by nutrients to calculate a nutrient criterion level. The nutrient criteria can be used to support to EPA's reference condition approach or can be used as an alternative to the EPA approach. The periphyton community assessment can be used to evaluate the ecological health of the periphyton community for the streams studied and will provide initial data for future development of a periphyton index of biotic integrity (P-IBI).

Existing data include an inadequate number of chlorophyll *a* measurements for streams. Further, the dissolved oxygen measurements residing in the current database are collected primarily during daylight hours. Critical dissolved oxygen concentrations occur at night. Further, the existing data for much of EPA Region III have recently been analyzed (Brightbill and Koerkle, 2003).

The work proposed would simply extend ongoing work which is being supported by EPA under grant number X798398201-0 awarded to the Maryland Department of the Environment.

IV. PROJECT DESCRIPTION

A. Purpose and Scope

Two overall objectives are proposed:

1. Use response variables (dissolved oxygen and periphyton chlorophyll *a*) to suggest nutrient criteria for streams in EPA's Region 3. This is the primary objective. Data from the second objective will be used as input information to reach this primary objective.

2. Examine periphyton communities for streams in EPA's Region 3 to see if eutrophic conditions are associated with specific community characteristics.

Study sites would include several 3rd and 4th order streams in Nutrient Ecoregions IX, XI, and XIV, all in EPA's Region 3. These Ecoregions comprise most of the land area of the states in EPA's Region 3 and extend beyond Region 3 to include most of the southeastern U.S. The proposed work would involve field data collection during the critical summer months of 2005. Data evaluation and report preparation would follow through the fall and winter of 2005 and into 2006 with a final report due on September 30, 2006.

B. Project Overview

This proposal defines a cooperative approach for (1) defining nutrient criteria for streams in EPA Region 3 and (2) examining periphyton community structure for wadeable streams (Strahlher Order 3 and 4). The success of this project is based on the cooperative and collaborative efforts of EPA Region III (funding source), and National (USGS) and State environmental agencies in Region 3. A cooperative approach is required for a region-wide effort, and to pool resources for funding and personnel. The work proposed is an expansion of work already in progress in Region 3 under a grant from EPA to the Maryland Department of the Environment. This proposal extends the ongoing work to additional sites. The Pennsylvania Department of Environmental Protection (PaDEP) will be the lead agency for the research. The U.S. Geological Survey will support the PaDEP in field data collection and will assume the lead role in data management, data analysis, and report preparation.

Development of Nutrient Criteria:

Other researchers have attempted to define the relations between nutrients and periphyton. These efforts have been only partly successful. One reason is that the researchers pooled all available data for the analysis, then looked for relations. But, nutrients are transient. The concentrations observed in a stream on any day will likely be different the next day or the next week. Therefore, the proposed work will examine nutrient-periphyton relationships for a short term only -- during the critical summer period of July and August. Oxygen consumption is largest at night. Thus, nighttime measurements collected during the hottest, driest period of the year are critical for establishing nutrient criteria. Oxygen measurements at other times of the year or at other times of the day are superfluous, and perhaps even confusing.

Our approach will be to select streams across the five Region 3 states and the District of Columbia to examine nutrient concentrations, periphyton biomass, and nighttime dissolved oxygen concentrations. For these streams, we will install continuous recording dissolved oxygen monitors for a 48-hour period. It is important to measure the variability of dissolved oxygen for a diel cycle because the lowest dissolved oxygen concentrations will occur at night when photosynthesis is shut down, but respiration continues. (Another reason for the failure of previous nutrient studies is that routine monitoring is usually a daytime activity.) Dissolved oxygen measured during routine daytime monitoring fails to capture the lowest dissolved oxygen concentrations.

Assessment of Stream Periphyton Communities:

Examination of periphyton communities is an effects-based approach that will attempt to link nutrient conditions within a stream system to the growth of periphyton communities within that stream. Periphyton are important to stream ecology because they are the main primary producers. This means that they are one of the first links in the aquatic food chain and can ultimately affect the populations of other species as well. Periphyton are also useful indicators of stream environmental conditions because they quickly respond to changes and are sensitive to a number of disturbances, including nutrient over-enrichment. As a resident biotic component in streams, periphyton can quickly register and incorporate transient or episodic changes in nutrient conditions, or act as nutrient "sinks". Thus, having an understanding of the periphyton community in a stream can reveal a lot about the ecological health and the nutrient status of that stream.

C. Technical Approach

Field Data Collection:

Field work for the project will be led by the Pennsylvania DEP and its cooperator, the U.S. Geological Survey. Cooperating states (Maryland, Virginia, West Virginia, and Delaware) have agreed to support the effort. We will use common protocols (mutually agreed upon), which are fully documented and distributed by the USGS. These protocols will be the same as adopted under the previous nutrient criterion grant awarded in 2004 to the Maryland Department of the Environment. Training for all field personnel will assure uniform data collection across the Region.

Several streams (our goal is 24 streams for this work which would be added to 24 streams assessed under the previous grant for a total of 48 streams) will be selected for the nutrient criteria work. The streams selected will represent a range of nutrient conditions and will come from three Nutrient Ecoregions. At each stream, periphyton biomass (chlorophyll *a* and ash free dry mass), nutrients, standard field measurements, and total organic carbon) will be measured. In addition, continuous dissolved oxygen (DO) monitors will be deployed for at least two 24-hour periods during the hottest part of the summer. Minimum DO values are critical for aquatic life and this plan will capture those minimum DO values, or values that are near minimum for the year. Data from the continuous monitors will be downloaded in the field to a notebook computer. These data will then be transferred to computers housed at the USGS in New Cumberland, Pennsylvania for analysis. Nutrient concentrations that are associated with DO concentrations lower than the applicable water-quality standard (5 mg/L) will be considered excessive.

Analytical Requirements:

Field water-quality samples will be sent to the Pennsylvania DEP laboratory for analysis. Analyses will be needed for a broad range of nutrients including dissolved nitrite+nitrate, dissolved ammonia nitrogen, organic nitrogen, dissolved ortho-phosphate, and total phosphorus. Total organic carbon will also be measured to provide insight into the role of organic matter in oxygen depletion in the streams. Chlorophyll *a* and AFDM will be measured as surrogates for algal biomass.

Data Management:

Initially, data from the project will be housed in electronic files at the USGS Pennsylvania District, New Cumberland, Pennsylvania. A back-up duplicate copy of all data files will be stored at PADEP offices, Harrisburg, Pennsylvania. Near the end of the project, data will be placed into EPA's national database, STORET. A commercially available database management system such as Access will be used for data storage and management. Commercially available software will be used for graphical and statistical analyses. All data from the project will be shared with Region 3 States and the EPA.

Assessment of Stream Periphyton Communities:

To the extent possible, stream locations will be selected to represent major natural and human factors that are thought to significantly influence the quality of water. Ideally, these the selected streams will already be monitored under the existing statewide water-quality monitoring network for each state. Also, our plan is to include streams that represent a wide spectrum of biotic conditions, from reference conditions to eutrophic conditions. Selection of a range of nutrient conditions will facilitate establishment of nutrient-algal (periphyton) relationships that will enable the eventual development of an index of biotic integrity based on those relationships.

Because the main study objective is the development of ecoregion-specific nutrient criteria, the initial stratification will be by nutrient ecoregion. The Level III Aggregate Nutrient Ecoregions of interest in EPA Region 3 are Ecoregion IX (Southeastern Temperate Forested Hills and Plains), Ecoregion XI (Central and Eastern Forested Uplands), and Ecoregion XIV (Eastern Coastal Plain). Other Ecoregions within the EPA Region 3 boundaries represent relatively small areas and will not be sampled in the proposed research.

A modified version of the periphyton sampling techniques and methods used in the USGS NAWQA (Moulton and others, 2002) and EPA's EMAP studies will be used. A quantitative sample from riffle habitat and a water-quality sample will be collected from each sampling site. Part of the periphyton sample will be used for taxonomic identification, and part for biomass measurements. In the Coastal Plain (Ecoregion XIV), riffle habitat may not be commonly available in all sampling reaches. In this case, quantitative artificial substrate samplers will be used.

Community structure of periphyton communities are intended to provide a list of species (taxa richness) present in the sampling reach. Water quality can be assessed by interpreting autecological information, the taxon-specific physiological requirements or tolerance for defined ranges of water-quality conditions. Samples for taxonomic identification will be shipped to a laboratory chosen through an open bidding process. All genera in the samples will be identified to species level to enable the development of autecological indices for the three ecoregions. A photo library will be developed for future reference purposes.

Quantitative periphyton samples are collected to measure the relative abundance and density (algal cells per square centimeter) of each taxon present in each stream. Quantitative samples are collected using a variety of sampling devices (i.e., NAWQA periphyton sampling device SG-92 or the whole-rock approach); the appropriate choice of sampling equipment is dictated by the character of the dominant periphyton growth forms and microhabitats in the sampling reach. For this study, an attempt will be made to collect all samples using the NAWQA SG-92. This will allow for consistency among samples. Samples are processed, stored, and transported using protocols established by EMAP studies.

Development of Nutrient Criteria:

The periphyton community data will be analyzed by looking for indicator species and by comparing several different community metrics (Stevenson and others, in press). The final selected eutrophic indicators will offer the best representation of the health of the system, with attention given to simplicity. The idea is to develop a tool that is reflective of stream conditions, yet can be routinely implemented by most field biologists employed by state resource agencies. Data from the project will be examined using a variety of traditional and multivariate approaches. Non-parametric techniques are likely to be used as biological data frequently are not normally distributed. Data transformations may be needed to deal with non-linear relationships. Graphical presentation of the data will be emphasized.

For the development of nutrient criteria, graphing measured nutrient concentrations for several streams against minimum dissolved oxygen concentrations is expected to produce a relationship generalized in Figure 1. The nutrient concentration that results in meeting the water-quality standard (dissolved oxygen concentration of 5.0 mg/L) will provide the basis for the proposed nutrient criterion.

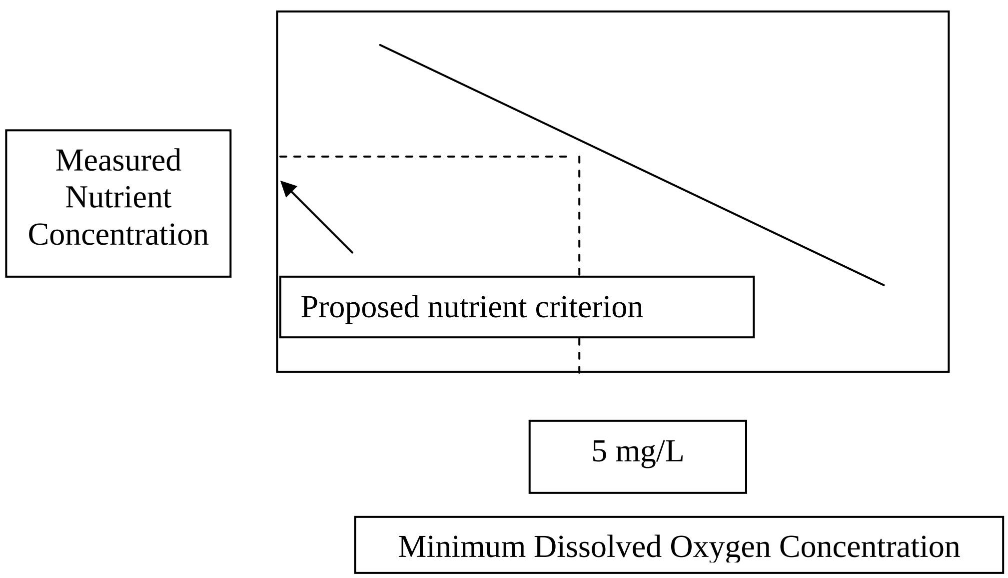

Figure 1. Expected relation between measured nutrients and minimum dissolved oxygen in Region III streams (generalized).

Data gathered to populate the graph in Figure 1 are not all expected to fall on the line depicted in Figure 1. Instead, some data points will fall above the line. However, no data points should fall below the line. Data would be expected to fall above the line when some factor other than the nutrient being considered is limiting. For example, Figure 2 shows what the data might look like for several streams, some having light as the limiting factor, and some having nitrogen as the limiting factor.

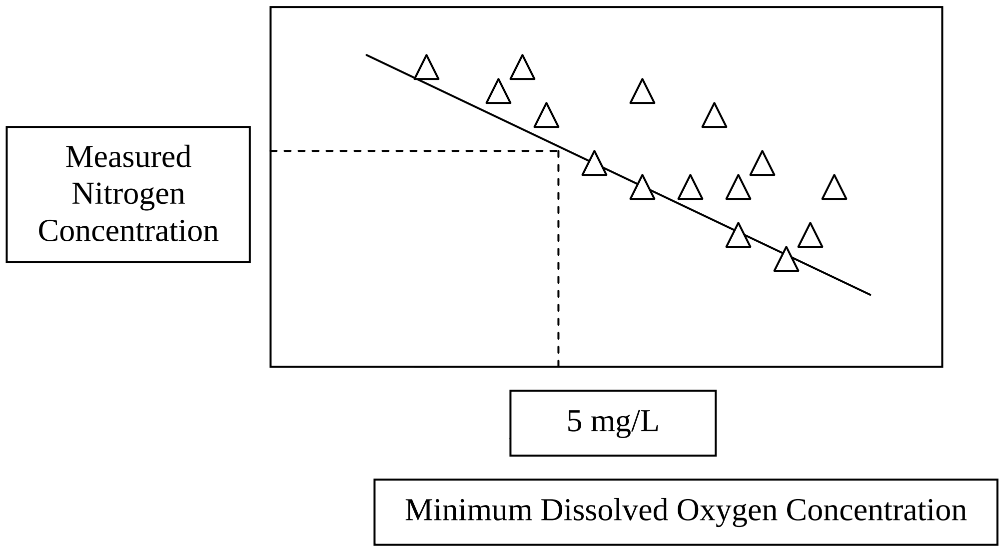

Figure 2. Hypothetical data distribution for Region III streams.

For those streams where nitrogen is limiting, the data point falls on the line. If light (or any other variable) is limiting, periphyton will not grow to their maximum potential. Minimum dissolved oxygen concentrations will be larger than in the case where nitrogen is limiting. The data point will fall above the line. For those data points that fall on (or near) the line, a least squares regression, based on a General Linear Model, will be used to quantify the relation between nutrients and dissolved oxygen. This relation will be used to quantify the nutrient criterion.

Figure 2 demonstrates the importance of using the work proposed in this proposal to extend the work from the proposal funded in 2003. Under the previous proposal, only 15 data points would be available for plotting in Figure 2. If this proposal is funded, our goal will be to populate figure 2 with as many as 48 data points, each data point representing a different Region 3 stream.

This approach has a weakness that minimum dissolved oxygen concentrations are influenced by productivity of the attached algae as well as the standing crop of attached algae. We do not propose to measure algal productivity. Intuitively, algal productivity and algal standing crop are likely related, so measurement of standing crop by chlorophyll *a* concentrations should suffice. In reality, algal standing crop is not always a good predictor of algal productivity.

Products:

This proposal will extend work funded previously (EPA grant X798398201-0). Products listed below would include data from both parts of the work, but would not be duplicated for the two phases of work.

1. Semi-annual progress reports will document progress on the project.

2. Project personnel will present a paper from the work at one scientific meeting to encourage exchange of ideas among the scientific community.

3. Project personnel will provide a seminar for one Region 3 Regional Technical Assistance Group (RTAG)[1] meeting to help disseminate the results of the work.

4. A final, published report will be provided to EPA approximately one year following completion of laboratory analyses. This report will specifically address the feasibility of using periphyton community structure and chlorophyll *a* measurements to define nutrient over-enrichment.

[1]The RTAG is a group of scientists and environmental managers that meets periodically to exchange information about nutrient criteria development and implementation and serves as an advisory body for each EPA Region on nutrient issues.

V. QUALITY-ASSRUANCE PROCEDURES

Quality assurance procedures will include using a written, standardized protocol for field work, training for all personnel who collect field data, and standardized field data-collection sheets for all field work. Duplicates, blanks, and reference materials will be used to assure the quality of laboratory work. Laboratory QC will include lab participation in the U.S. Geological Survey's Inter-Laboratory Evaluation Program (Woodworth and Connor, 2003).

Quality control for the data will include standardized field data-collection sheets, periodic reviews of the data sheets, spot checks of the electronic data, and both tabular and graphical displays of the data to check for anomalies.

Field instruments will be calibrated on site and log books will be kept for each field instrument. Separate field instruments will be used as checks for the continuous monitoring sondes and these checks will be performed at the beginning and end of the deployment period.

Periphyton identifications will be done using widely accepted keys. Duplicate periphyton identifications will be done by an outside lab for 5 percent of the samples.

VI. TRANSFERABILITY

Responding to the Clean Water Action Plan, the U.S. Environmental Protection Agency has been tasked with addressing to the problem of nutrient enrichment in U.S. waterways. One of the ways the EPA is accomplishing this task is to provide guidance for the states to establish water-quality standards for nutrients. The results of this study will provide support for a response-based approach to establishing these nutrient standards for streams.

Information from the proposed work is directly transferable to other locations within the same Nutrient Ecoregion. Techniques developed could be used for any Nutrient Ecoregion.

The results of this study and further investigations support the mission of the USGS by providing a regional pattern of water quality in the Mid-Atlantic States. This knowledge and other pertinent information relating to nutrients will assist states faced with establishing water-quality standards for nutrients.

VII. PROJECT SCHEDULE

The following table shows the time line to be followed for the project.

Task	**Federal fiscal year 2005** (Months)												**Federal fiscal year 2006** (Months)											
	O	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**
Project planning. Site selection. Meetings with partners.				■				■																
Order supplies and equipment.						■																		
Write and submit QA plan, safety plan.							■																	
Field data collection										■	■	■												
Diurnal DO work										■	■	■												
Data management and analysis.													■	■										
Report preparation, review, and publication															■	■	■	■	■	■	■			
Public presentation.																					■			

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Appendix F.
The Academy of Natural Sciences – Virginia DEQ Proposal to EPA

The Development of an Algae-based Water Quality Monitoring Tool for Virginia Streams

A Proposal Submitted To:

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May 5, 2004

The Development of an Algae-based Water Quality Monitoring Tool for Virginia Streams

Background

Nutrient enrichment is the cause of approximately half of the reported impairments in National waters. Within rivers and streams, chronic symptoms of over-enrichment include low dissolved oxygen, fish kills, increased sediment accumulation, and species and abundance shifts of flora and fauna. An often immediate effect of excess nutrients in streams is the development of nuisance levels of algae (Blum 1956, Francoeur 2001). In addition to causing water quality problems and altering ecosystem structure and function, nuisance algae growth can harm the designated use of streams and rivers in a variety of ways (Dodds and Welch 2000, U.S. EPA 2000a, U.S. EPA 2000b, ENSR 2001) and have been associated with human health problems (Oliver and Schindler 1980, Ward et al. 1996). Concerns over nutrient enrichment in the nation's water systems have led the US EPA to: a) develop water quality standards designed to protect the legally "designated uses" of the nation's waters, b) restore and maintain the chemical, physical, and biological integrity, and c) propose standards for nitrogen and phosphorus. Because chemical monitoring alone can underestimate degradation in living systems, a number of biological measurements have been developed to provide a direct assessment of resource condition. If the biota is not present at the level expected, researchers have direct confirmation of physical or chemical degradation in the stream.

Until recently, biological monitoring programs have almost exclusively focused on fish and macroinvertebrate taxa and largely excluded periphyton (benthic algae) communities. This is because the high diversity and regional differences of taxa make the initial development of an algae-based biomonitoring program a sizable undertaking. However, periphyton communities, especially those dominated by diatoms, are excellent ecological indicators of water quality. Because periphyton are directly affected by physical and chemical environmental changes, and usually have brief life cycles and rapid rates of reproduction, they are valuable indicators of short-term impacts. Periphyton assemblages are also sensitive to some pollutants which may not visibly affect other taxa or only show affects at higher concentrations. Perhaps most importantly, periphyton has specific ecological requirements that correlate strongly with environmental conditions (Pan et al. 1996, Stevenson and Pan 1999, Pan et al. 2000, Potopova and Charles 2002).

As the discussion concerning nutrient enrichment of surface waters and the establishment of nutrient limits and thresholds grows, state (Bahls 1993, Kentucky Division of Water 1993, Oklahoma Conservation Commission 1993) and national (Barbour et al. 1999) programs are being developed to examine the relationship between periphyton communities and nutrient concentrations. Six states (Florida, Idaho, Kentucky, Massachusetts, Montana, and Wyoming) currently use information from periphyton communities as a water quality management tool although several states evaluate biomass in terms of chlorophyll *a* (chl *a*) as part of their surface water monitoring program (Kroeger et al. 1999). Other states (Maryland and New Jersey) are developing relational models for using algal indices of biotic integrity and establishing nutrient limits (Ponader and Charles 2003, Beaman 2003).

Virginia currently has water quality monitoring programs in place but has not developed algal indices for freshwater bioassessment. The Virginia Department of Environmental Quality's

(VA DEQ) Freshwater Probabilistic Monitoring (ProbMon) Network (VA DEQ 2003) consists of a set of randomly chosen water quality monitoring stations (currently ~ 60/year distributed across the state) used to make statistically-based assessments of Virginia's streams. The goals of the project are to examine and assess water quality state-wide, identify and determine the extent of impairments in water quality, and identify potential threats to water quality and the types of streams that are most at risk. In addressing these objectives, the ProbMon Network will identify the water quality issues that policy makers need to address, assess the effectiveness of current management strategies at protecting resources, examine how effort can be redirected to better protect the most threatened resources, and identify where more stream protection is needed (VA DEQ 2003).

The ProbMon Network conducts macroinvertebrate surveys, records a variety of physical habitat parameters, and collects water and sediment samples for chemical analyses in the spring and fall, and uses these data to assess stream health. Although these data provide important information regarding water quality, they do not provide sufficient information to assess nutrient enrichment in Virginia streams. The development of an algal index, based on periphyton community structure as it relates to environmental conditions, will provide much-needed nutrient enrichment and water quality information on which policy-makers can base environmental decisions and will be an initial step in developing a biomonitoring tool for assessing nutrient impairment.

Virginia DEQ has secured funding from the US Environmental Protection Agency (EPA) to collect algal taxonomy and biomass samples from the ProbMon sites for the development of an algal-based tool for stream assessment. The U.S. EPA technical guidance manual for rivers and streams (U.S. EPA 2000a) recommends three approaches for development of nutrient and algal criteria: (1) the use of reference streams, (2) applying predictive relationships to select nutrient concentrations that will result in appropriate levels of algal biomass, and (3) developing criteria from thresholds established in the literature. In addition, the Ambient Water Quality recommendations for U.S. EPA Rivers and Streams Aggregate Nutrient Ecoregion IX (U.S. EPA 2000b) include establishing nutrient reference conditions in rivers and streams based on the upper 25th percentile (75th percentile) of all nutrient data from all reaches sampled, or determining the lower 25th percentile of the population of all streams within a region. A review of this approach for the New England Interstate Water Pollution Control Commission revealed that the ranges of predicted biomass production responses to nutrients, as tested for the subecoregions 59 and 84, would be below consensus threshold values (ENSR 2001). Nevertheless, the establishment of reference conditions based on percentiles will set different threshold values in different regions, depending on the range of overall water quality in the rivers of each particular region. These thresholds will be too high in ecoregions with rivers having predominantly high nutrient concentrations as compared to ecoregions with mainly low nutrient rivers, and vice versa. The applicability of this method to Virginia needs further review. In the proposed study, the VA DEQ will apply the proposed U.S. EPA percentile method to data collected from Virginia streams to:

1. explore the relationships between algal biomass as well as algal species composition and nutrients in Virginia streams,

2. develop and test algal indicators of nutrients and water quality applicable to Virginia streams and rivers,

3. develop algal indices that can be used in ongoing biomonitoring programs in Virginia, and

4. assess which indicators may be best for monitoring nutrient impairment in Virginia streams and rivers. These indicators will be based on an understanding of algal dynamics in Virginia streams, and be able to distinguish between situations where nutrient concentrations are high due to natural environmental conditions and those that result from anthropogenic influences.

The role of the Academy of Natural Sciences (ANS) in this project is to train VA DEQ biologists on algal collection methods, provide additional in-field direction and assist with algal sampling at a select subset of sites, analyze community composition of soft algae and diatom samples, and provide community composition data and basic community metrics (taxa richness, percent dominant taxa, percent taxa dominance, and siltation index). Virginia DEQ biologists will use these data to develop algal indicators of stream and river health based on predictive relationships that can be applied in a regulatory context as criteria for identifying nutrient impairment.

Study Approach

Virginia DEQ, with the assistance of an ANS biologist at some study sites (10-20), will sample periphyton for biomass and community composition in conjunction with the VA DEQ's ProbMon Network (40-70 sites). Periphyton sampling will be conducted during the fall (August-October) 2004 and will focus on algal biomass (chlorophyll *a* (chl *a*) and ash-free dry mass (AFDM)) and species composition. Field collections of algae will be conducted by ANS-trained VA DEQ biologists. Algal samples will be collected from natural rock substrates, where available, using techniques consistent with those used in ANS algal assessment protocols (Ponader and Charles 2003) and the EPA Rapid Bioassessment protocols for periphyton (Barbour et al. 1999). At each site, three sample types will be collected in triplicate: 3 composite diatom samples, 3 composite soft algae samples, and 3 quantitative composite biomass samples for chl *a* and AFDM measurement. For all samples, algae will be scraped from 4-5 randomly selected rocks, placed into containers, and preserved with formalin (soft algae and diatom samples) or by keeping samples on ice until sent to the laboratory for processing (biomass sample). The surface area from which algae was sampled will be determined for biomass samples (Ennis and Albright 1982, Moulton et al. 2002). Virginia DEQ will ship diatom and soft algae samples to ANS accompanied by sample chain of custody forms.

Chlorophyll *a* and AFDM analyses will be conducted by the VA DEQ laboratories following Standard Methods (APHA 1992) to determine algal biomass at each site. Upon receiving the taxonomy samples, an ANS biologist will compare them to the chain of custody forms and report any discrepancies to the VA DEQ. Samples will be prepared for analysis by an ANS biologist. Community composition will be determined by identifying diatom and common soft algae taxa to the lowest practical taxonomic level and counted using ANS Phycology Section protocols, common taxonomic references, and type material from the ANS Diatom Herbarium. Species identification, relative abundance, and basic community metrics (taxa richness, percent dominant taxa, percent taxa dominance, and siltation index) will be presented to the VA DEQ in the form of a letter report. Data will be provided as Access Database or Excel files, as preferred. Slides analyzed for this study will be archived in the ANS diatom herbarium.

Project Schedule

Project tasks will begin in July 2004 and continue through August 2005. A specific timeline for project tasks is outlined in Table 1.

Table 1. Timeline for specific ANS tasks in the development of an algae-based water quality monitoring tool for Virginia streams.

Project Task	**2004**						**2005**							
	J	**A**	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**
Development of a QA/QC and Field Safety Plan	■	■												
Training of VA DEQ staff	■	■												
In-field assistance with collection of algal samples		■	■	■	■									
Sample cataloguing and processing				■	■	■								
Preparation of taxonomy samples by ANS staff						■	■	■	■					
Identification and enumeration of algal taxa							■	■	■	■	■			
Data entry and QA/QC											■	■		
Writing and distribution of final project report and data													■	■

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