Developing Nutrient Criteria for Vermont's Lakes and Wadeable Streams

DRAFT FOR TECHNICAL REVIEW

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1. Background and Purpose

Pollution of lakes, rivers, estuaries, and wetlands by plant nutrients such as phosphorus and nitrogen is a serious water quality problem nationwide. When present in excessive amounts, these nutrients can result in algae blooms, benthic algal mats, slime layers on rocks, poor water clarity, aquatic habitat degradation for other plants and animals, and impairment of drinking water supplies. The adoption of nutrient criteria in state water quality standards is one tool states can use to control nutrient levels in state waters in order to protect the uses of those waters.

The Vermont Department of Environmental Conservation (DEC) has been working to develop nutrient criteria for possible incorporation into the Vermont Water Quality Standards as part of a national effort led by the U.S. Environmental Protection Agency (USEPA). The USEPA issued a *National Strategy for the Development of Regional Nutrient Criteria* in 1998[1]. Key elements of the strategy included the following steps:

- Publication by USEPA of technical guidance manuals for developing nutrient criteria for each of four waterbody types: lakes, rivers, estuaries, and wetlands.
- Adoption by USEPA of ecoregion-specific nutrient criteria under Section 304(a) of the Clean Water Act.
- Establishment of Regional Technical Assistance Groups (RTAGs) to guide criteria development by states in each region.
- Adoption of numeric nutrient criteria by the States, based on the technical guidance documents, published Section 304(a) ecoregional nutrient criteria, and consultation with the RTAGs.

The USEPA published nutrient criteria technical guidance documents for lakes[2] and for rivers[3] in 2000, and for estuaries (not applicable in Vermont) in 2001. There is no technical guidance document available yet for wetlands.

The USEPA has published Ecoregional Nutrient Criteria Documents containing Section 304(a) nutrient criteria for lakes, rivers, and estuaries in certain ecoregions. The published criteria include values for lakes and rivers in the three ecoregions applicable to Vermont. Each document presents recommended criteria for causal factors including total phosphorus and total nitrogen, and response variables including chlorophyll-a and either Secchi disk transparency or turbidity. The published Section 304(a) criteria are intended to serve as starting points for states and others to develop more refined nutrient criteria as appropriate, using USEPA waterbody-specific technical guidance manuals and other scientifically defensible approaches.

The Vermont DEC has been participating in the RTAG formed by the New England Region of USEPA. Vermont DEC provided monitoring data for regional and national nutrient databases assembled by USEPA to support the nutrient criteria effort. Vermont DEC staff have exchanged information and technical perspectives on nutrient criteria development with representatives of other states at RTAG meetings and national conferences.

As requested by USEPA, Vermont DEC submitted a draft *Vermont Plan for the Development of Nutrient Criteria for Lakes and Rivers* in 2002[4]. Vermont DEC has been following that plan in its technical aspects, although the schedule in the original plan is

no longer applicable. Vermont DEC received a grant from USEPA in 2004 to support the initial portion of the plan, which was to collect lake and stream data in Vermont to help quantify the relationships between nutrient variables and the support of designated water uses. The Department received a second grant from USEPA in 2005 to support the statistical analysis of the data obtained during 2004 along with other information, and to develop methods for deriving nutrient criteria appropriate for Vermont's lakes and wadeable streams.

The Water Resources Panel of the Vermont Natural Resources Board has the statutory responsibility for establishing state water quality standards in Vermont. The Water Resources Panel adopts water quality standards through a public rulemaking process conducted according to the state's Administrative Procedures Act. The Vermont DEC provides technical advice to the Panel.

The purpose of this document is to present the results of the data analysis conducted by Vermont DEC and to provide a technical basis for the development of nutrient criteria for Vermont's waters by the Water Resources Panel. The scope of this document is limited to Vermont lakes, ponds, reservoirs, and wadeable streams because of limitations in the data and statistical analyses that are currently available. Methods for deriving nutrient criteria for larger rivers and wetlands in Vermont may be developed in the future.

2. Existing Nutrient Criteria in Vermont Water Quality Standards

A. Phosphorus

The Vermont Water Quality Standards[5] contain both narrative and numeric total phosphorus criteria applicable to certain waters (Section 3-01-B-2). The general narrative criterion for phosphorus is as follows:

> *In all waters, total phosphorus loadings shall be limited so that they will not contribute to the acceleration of eutrophication or the stimulation of the growth of aquatic biota in a manner that prevents the full support of uses.*

The general policy for upland streams (all streams above 2,500 feet in elevation) is that *total phosphorus shall not exceed 0.010 mg/L at low median monthly flow.*

The Vermont Water Quality Standards include numeric total phosphorus concentration criteria for each segment of Lake Champlain and Lake Memphremagog. The phosphorus criteria range from 0.010 to 0.054 mg/L among 12 segments of Lake Champlain and two segments of Lake Memphremagog (Table 1). The criteria apply as the annual mean total phosphorus concentration in the photosynthetic depth (euphotic) zone in central, open water areas of each lake segment.

Table 1. Total phosphorus criteria for Lake Champlain and Lake Memphremagog in the Vermont Water Quality Standards.

Lake Segment		Total Phosphorus Criterion (mg/L)
Lake Champlain		0.010
	Main Lake	0.010
	Malletts Bay	0.014
	Burlington Bay	0.014
	Shelburne Bay	0.014
	Northeast Arm	0.014
	Isle LaMotte	0.014
	Otter Creek	0.014
	Port Henry	0.014
	St. Albans Bay	0.017
	Missisquoi Bay	0.025
	South Lake A	0.025
	South Lake B	0.054
Lake Memphremagog		
	Main Lake	0.014
	South Bay	0.025

The phosphorus criteria for Lake Champlain in the Vermont Water Quality Standards were endorsed by the States of Vermont and New York and the Province of Quebec in a 1993 Lake Champlain Water Quality Agreement[6] as a consistent set of management

goals for the lake. These joint criteria are incorporated into the basin plan *Opportunities for Action*[7] adopted by the Lake Champlain Basin Program. The criteria also serve as the basis for the Lake Champlain Phosphorus TMDL[8] prepared by Vermont and New York and approved by the USEPA in November 2002. Since the existing Lake Champlain phosphorus criteria are the foundation for major planning efforts and management agreements on the lake, it is essential to preserve these criteria in the Vermont Water Quality Standards as the process of further nutrient criteria development proceeds under the USEPA initiative.

Lakes, ponds, and reservoirs that have a drainage area less than 40 square miles and a drainage area to surface area ratio less than 500:1 are given special protection from phosphorus discharges in the Vermont Water Quality Standards. In these waters, *there shall be no significant increase over currently permitted phosphorus loadings.* No discharge may increase the in-stream total phosphorus concentration in a tributary by more than 0.001 mg/L at low median monthly flow, and no indirect discharge may increase the total dissolved phosphorus concentration in the groundwater 100 feet from the lake by more than 0.001 mg/L. In all Class A(1) waters, total phosphorus concentrations are not to exceed 10 μg/L at low median flows.

B. Nitrates

The general policy in the Vermont Water Quality Standards for nitrates is as follows:

> *In all waters, nitrates shall be limited so that they will not contribute to the acceleration of eutrophication or the stimulation of the growth of aquatic biota in a manner that prevents the full support of uses.*

The Vermont Water Quality Standards include the following numeric criteria for nitrates (Table 2). The nitrate criteria for flowing waters are not to be exceeded at flows exceeding low median monthly flows.

Table 2. Nitrate criteria in the Vermont Water Quality Standards.

Waterbody Type	Nitrate Criterion (mg/L NO_3-N)
Lakes, ponds, and reservoirs, not including riverine impoundments	5.0
Other Class A(1) and A(2) waters above 2,500 feet elevation	0.20
Other Class A(1) and A(2) waters at or below 2,500 feet elevation	2.0
Other Class B waters	5.0

C. Turbidity

The Vermont Water Quality Standards include the following numeric criteria for turbidity (Table 3), depending on the classification of the waterbody.

Table 3. Turbidity criteria in the Vermont Water Quality Standards.

Classification	Turbidity Criterion (NTU)
A(1) Ecological waters	10
A(2) Public water supplies	10
B Waters - cold water fish habitat	10
B Waters - warm water fish habitat	25

3. USEPA Section 304(a) Ecoregional Nutrient Criteria

Vermont lies within three aggregate ecoregions, with one Level 3 subregion within each aggregate region (Figure 1, Table 4). The Section 304(a) nutrient criteria published by the USEPA include values for lakes and rivers in each of these aggregate ecoregions and subregions.

Table 4. Aggregate ecoregions and subregions in Vermont.

Aggregate Ecoregion		Level 3 Subregion		Number of Lakes
VII	Mostly Glaciated Dairy Region	83	Eastern Great Lakes and Hudson Lowlands	87
VIII	Nutrient Poor Largely Glaciated Upper Midwest and Northeast	58	Northeastern Highlands	458
XIV	Eastern Coastal Plain	59	Northeastern Coastal Zone	13

There are 820 known lakes, ponds, and reservoirs in Vermont, including segments of Lake Champlain. A total of 558 of these lakes are included in the Vermont lake assessment database where lake impairments are tracked for Clean Water Act sections 303(d) and 305(b) reporting. These 558 waterbodies comprise over 99% of the total lake acreage in the state. Most Vermont lakes are in the Northeastern Highlands Subregion (No. 58), as indicated in Table 4.

The USEPA Section 304(a) nutrient criteria for lakes in the ecoregions applicable to Vermont are listed in Table 5. The criteria for rivers and streams are listed in Table 6.

Table 5. USEPA Section 304(a) lake nutrient criteria for Vermont ecoregions[9,10,11].

	Ecoregion VII		Ecoregion VIII		Ecoregion XIV	
Parameter	**Aggregate**	**Subregion 83**	**Aggregate**	**Subregion 58**	**Aggregate**	**Subregion 59**
TP (µg/L)	14.75	11.25	8.0	7.0	8.0	8.0
TN (mg/L)[a]	0.66	0.42	0.24	0.20	0.32	0.32
Chl-a (µg/L)[b]	2.63	2.84	2.44	2.52	2.9	4.2
Secchi (m)	3.33	4.75	4.93	5.1	4.5	4.9

[a] reported (not calculated) [b] fluorometric technique

Table 6. USEPA Section 304(a) rivers and streams nutrient criteria for Vermont ecoregions[12,13,14].

	Ecoregion VII		Ecoregion VIII		Ecoregion XIV	
Parameter	**Aggregate**	**Subregion 83**	**Aggregate**	**Subregion 58**	**Aggregate**	**Subregion 59**
TP (µg/L)	33.0	24.13	10.0	5.0	31.25	--
TN (mg/L)[a]	0.54	0.48	0.38	0.42	0.71	--
Chl-a (µg/L)[b]	1.54	1.64	0.63	–	--	--
Turbidity (NTU)	1.7	1.50	0.81	0.80	--	--

[a] reported (not calculated) [b] fluorometric technique – indicates criterion not established.

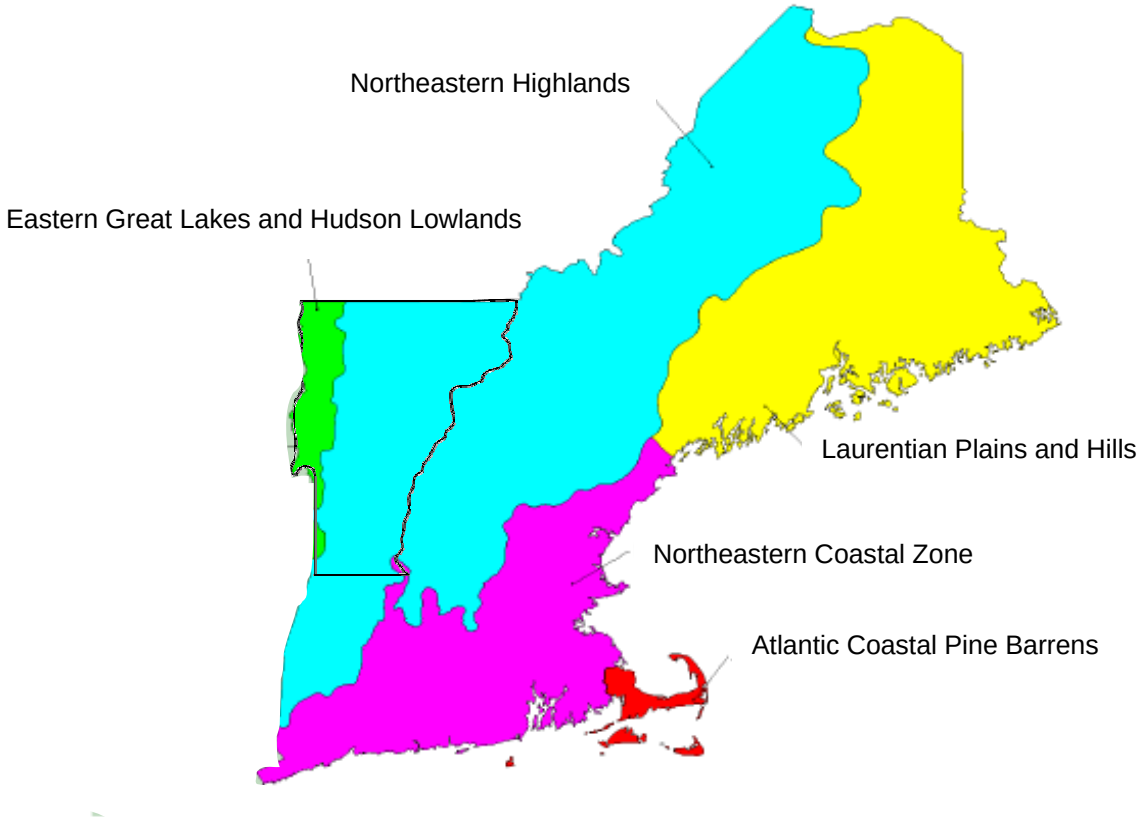

Figure 1. Ecoregions (Level 3 Subregions) in New England (modified from ENSR 2000).

As explained in the USEPA 304(a) nutrient criteria documents, the values in Tables 5 and 6 are the lower 25th percentiles for the frequency distributions of each parameter among all lakes or streams within the ecoregion, including data from all seasons during 1990-1999. This was an approximately equivalent alternative to the preferred approach described in the USEPA technical guidance manuals of selecting the upper 75th percentiles from the distributions among reference (minimally impacted) lakes in each ecoregion.

This method of deriving nutrient criteria has the serious disadvantage that the values represent somewhat arbitrarily chosen points on the frequency distributions of each parameter and have no quantified relationships with the water quality characteristics necessary to support the uses for these waters specified in the Vermont Water Quality Standards. Adoption of the EPA 304(a) criteria in state water quality standards would ensure that around 75% of the lakes and streams in these ecoregions would fail to attain the criteria, regardless of whether the uses were supported. For this reason, Vermont DEC chose to take a different approach in most cases to develop nutrient criteria for Vermont waters. Quantitative relationships were developed between nutrient criteria variables and the actual level of use support, as described in later sections of this document.

4. Classification Framework in Vermont Water Quality Standards

The Vermont Water Quality Standards currently classify waters into the following three major categories:

Class A(1)	Ecological waters
Class A(2)	Public water supplies
Class B	All other waters

The Standards also indicate that all Class B waters shall eventually be designated as one of three Water Management Types (1, 2, or 3).

The Vermont Water Quality Standards state that waters shall be managed to achieve and maintain a level of quality that fully supports specific designated uses. The designated uses that must be supported in each class of waters are listed in Table 7.

Table 7. Designated uses applicable to each major water class in the Vermont Water Quality Standards.

Designated Uses	Water Classes
Aquatic Biota, Wildlife, and Aquatic Habitat	A(1), A(2), B
Aesthetics	A(1), A(2), B
Swimming and Other Primary Contact Recreation	A(1), A(2), B
Boating, Fishing, and Other Recreational Uses	A(1), A(2), B
Public Water Supplies	A(2), B
Irrigation of Crops and Other Agricultural Uses	B

This report will focus primarily on developing nutrient criteria to protect the first two designated uses listed in Table 7 (aquatic biota, wildlife, and aquatic habitat; and aesthetics). These two designated uses have the best data available for use in linking nutrient criteria variables to the level of use support in Vermont lakes and streams. In focusing on these two designated uses, we are making the assumption that nutrient criteria that protect aquatic biota, wildlife, aquatic habitat, and aesthetics uses will also be adequately protective of the other uses listed in Table 7. For example, we are assuming that nutrient impacts on recreational uses such as swimming, boating, and fishing are related primarily to the aesthetic condition of the water (e.g., the degree of water clarity and algal growth present). We are also assuming that waters that meet their aesthetics criterion for nutrients will also be free of nutrient-related impairments to public water supplies or agricultural uses (e.g., that aesthetically acceptable water will be suitable from a nutrient standpoint for water supplies with filtration and disinfection).

The Vermont Water Quality Standards define management objectives and criteria for each of the designated uses listed in Table 7. The management objectives and criteria vary for a particular use, depending on the classification and management type. The designated uses and associated management objectives for each class of water are summarized in Table 8 for aquatic biota, wildlife, and aquatic habitat uses, and in Table 9 for aesthetics uses.

Table 8. Management objectives and criteria for aquatic biota, wildlife, and aquatic habitat uses in the Vermont Water Quality Standards (bold emphasis added).

Aquatic Biota, Wildlife, and Aquatic Habitat	
Class	**Objectives**
A(1)	Consistent with waters in their **natural condition**.
A(2)	**High quality** aquatic biota and wildlife sustained by high quality aquatic habitat necessary to support their life-cycle and reproductive requirements.
B	Aquatic biota and wildlife sustained by **high quality** aquatic habitat with additional protection in those waters where these uses are sustainable at a higher level based on Water Management Type designation.
	Criteria
A(1)	Change from the natural condition limited to **minimal impacts** from human activity. Measures of biological integrity for aquatic macroinvertebrates and fish assemblages are **within the range of the natural condition**. Uses related to either the physical, chemical, or biological integrity of the aquatic habitat or the composition or life cycle functions of aquatic biota or wildlife are fully supported. All life cycle functions, including overwintering and reproductive requirements are maintained and protected.
A(2)	Biological integrity is maintained, no change from the reference condition that would prevent the full support of aquatic biota, wildlife or aquatic habitat uses. Change from the reference condition for aquatic macroinvertebrates and fish assemblages shall not exceed **moderate changes** in the relative proportions of taxonomic, functional, tolerant and intolerant components. All expected functional groups are present in a **high quality habitat** and none shall be eliminated. All life cycle functions, including overwintering and reproductive requirements are maintained and protected. Changes in the aquatic habitat shall not exceed **moderate differences from the reference condition** consistent with full support of all aquatic biota and wildlife uses.
B(1)	Change from the reference condition for aquatic macroinvertebrate and fish assemblages shall be limited to **minor changes** in the relative proportions of taxonomic and functional components; relative proportions of tolerant and intolerant components are within the range of the reference condition. Changes in the aquatic habitat shall be limited to **minimal differences from the reference condition** consistent with the full support of all aquatic biota and wildlife uses.
B(2)	Change from the reference condition for aquatic macroinvertebrate and fish assembledges shall be limited to **moderate changes** in the relative proportions of tolerant, intolerant, taxonomic, and functional components. Changes in the aquatic habitat shall be limited to **minor differences from the reference condition** consistent with the full support of all aquatic biota and wildlife uses.
B(3)	Change from the reference condition for aquatic macroinvertebrate and fish assemblages shall be limited to **moderate changes** in the relative proportions of tolerant, intolerant, taxonomic, and functional components. Changes in the aquatic habitat shall be limited to **moderate differences from the reference condition** consistent with the full support of all aquatic biota and wildlife uses. When such habitat changes are a result of hydrological modification or water level fluctuation, compliance may be determined on the basis of aquatic habitat studies.
B(untyped)	**No change from reference conditions that would have an undue adverse effect** on the composition of the aquatic biota, the physical or chemical nature of the substrate or the species composition or propagation of fishes.

Table 9. Management objectives and criteria for aesthetics uses in the Vermont Water Quality Standards (bold emphasis added).

Aesthetics	
Class	**Objectives**
A(1)	Water character, flows, water level, bed and channel characteristics, and flowing and falling waters in their **natural condition**.
A(2)	Water character, flows, water level, and bed and channel characteristics **consistently** exhibiting **(excellent)**[a] aesthetic value.
B	Water character, flows, water level, bed and channel characteristics, exhibiting **good** aesthetic value and, where attainable, excellent aesthetic value based on Water Management Type designation.
	Criteria
B(1)	**Consistently** exhibit **excellent** aesthetic values.
B(2)	**Consistently** exhibit **very good** aesthetic values.
B(3)	Seasonal and temporal **variability** may be allowed provided that **good** aesthetic value is achieved.
B (untyped)	Water of quality that **consistently** exhibits **good** aesthetic value.

[a] The February 9, 2006 version of the Vermont Water Quality Standards omits the word "excellent" from the management objectives for aesthetics for Class A(2) waters. It will be assumed for this paper that this omission was inadvertent, and that the term "excellent" was intended here, as in previous versions of the Standards.

A major technical challenge to be addressed in this nutrient criteria document is to develop numeric values for water quality and biological variables that define the descriptive terms highlighted in Tables 8 and 9. Numeric distinctions must be made for terms such as "natural conditions," "minor" and "moderate" biological changes, and "excellent," "very good," and "good" aesthetic value.

5. Data Sources for Vermont Nutrient Criteria Development

A. Vermont Lakes

The major water quality and biological data sets available to support lake nutrient criteria development for Vermont inland lakes (i.e., lakes other than Lake Champlain and Lake Memphremagog) are derived from long-term monitoring programs such as the Spring Phosphorus Monitoring Program and the Vermont Lay Monitoring Program, and from the Lake Bioassessment Project. These programs are described in the Vermont 2004 Water Quality Assessment (305b) Report[15], and all operate according to USEPA-approved quality assurance project plans.

Under the Spring Phosphorus Program, lakes 20 acres or larger in size are sampled during spring overturn on one date per sampling year. The database contains 1,912 lake-year records on 243 different lakes sampled for spring total phosphorus during 1977-2005. Vertically-integrated, total depth (hose) samples are obtained in triplicate at one to three stations on each lake, and the sample results are averaged to produce a single spring phosphorus concentration value for that year. The program has included sampling for total nitrogen since 1998 using the same sampling methods. There are 504 lake-year records for total nitrogen on 233 different lakes.

The Vermont Lay Monitoring Program is a citizen volunteer monitoring program that has been operated by Vermont DEC continuously since 1979. Weekly summer (June-August) sampling is conducted for total phosphorus, chlorophyll-a, and Secchi disk transparency. Total phosphorus and chlorophyll-a samples are obtained as vertically-integrated (hose) composites of the photic zone (twice the Secchi depth on the day of sampling). Sample results are averaged by year to produce estimates of mean summer conditions. The Lay Monitoring Program database includes 1,143 lake-year records on 86 different Vermont inland lakes through 2005, although data for some lakes include only Secchi disk measurements.

A lake user survey was conducted in conjunction with the Vermont Lay Monitoring Program during 1987-1991[16]. The relationships between total phosphorus measurements and user perceptions of water quality were used to derive phosphorus criteria in Vermont's Water Quality Standards for portions of Lake Champlain, as described in Appendix B (Case Studies) of the USEPA (2000) *Nutrient Criteria Technical Guidance Manual for Lakes and Reservoirs*. A similar user survey was conducted on Vermont inland lakes, and the results are available to support criteria development for these lakes, as well. The user survey database includes 1,806 individual user responses paired with simultaneous measurements of one or more nutrient criteria variables (total phosphorus, chlorophyll-a, and/or Secchi depth) on 60 different inland lakes in Vermont.

The Lake Bioassessment Project was initiated in 1996 as a cooperative project with the State of New Hampshire for the purpose of developing biological criteria for Vermont lakes. The project has developed consistent protocols by which the phytoplankton and macroinvertebrate communities in lakes can be measured. A total of 12 New Hampshire and 55 Vermont lakes have been included in the project. The goal of the project is to develop numeric measurements of the biological communities listed above to assess aquatic biota use attainment. Multimetric indices have been developed for both the macroinvertebrate and phytoplankton communities, which link attainment of biota to

water quality criteria defined in Table 8. Data from the project are maintained in relational databases compatible with the water quality information.

In addition to the water quality and biological monitoring results, the Vermont DEC Lakes and Ponds Inventory database includes a variety of other information about each lake, including location, physical characteristics, and watershed land use. This information is available in database format to support lake nutrient criteria analysis.

A lake nutrient database for the entire New England region was compiled in 2000 by ENSR Corp. for the New England Interstate Water Pollution Control Commission[17]. The purpose of this database was to assemble all the relevant lake monitoring data in a consistent and comparable format for each ecoregion in New England in order to develop preliminary nutrient criteria for lakes in this region. However, data screening decisions made in compiling this database excluded all samples collected outside of the July-September period and all samples taken below five meters in depth. This resulted in the exclusion of most of the long-term monitoring data on Vermont lakes, including the entire Spring Phosphorus Program database, and most of the Lay Monitoring Program samples because these samples were collected by vertical integration methods to depths usually below five meters. The New England lake nutrient database was not used in this report because of our desire to use the extensive datasets available for Vermont lakes to develop nutrient criteria for Vermont.

B. Vermont Streams

Data from Vermont streams come from two major sources, the long-term Vermont DEC ambient biomonitoring program dataset[18], and the 2004 Vermont DEC Nutrient Criteria Project[19] database.

The Vermont DEC Ambient Biomonitoring Program collects chemical, physical and biological data from surface waters throughout the state. Wadeable streams are a prime focus of the program activities. The program is described in the state's 2004 305(b) report. All activities are conducted under the auspices of QA/QC plans approved by USEPA. Methods are well documented in the recently updated Water Quality Division Field Methods Manual[20]. Additional information on the program and the use of the data generated by the program to implement tiered aquatic life use criteria in wadeable streams is documented in: Biocriteria for Fish and Macroinvertebrate Assemblages in Vermont Wadeable Streams and Rivers–Development and Implementation[21] and in the 2006 Assessment and Listing Methodology[22].

All chemical data generated by the program are analyzed by the Department's Environmental Laboratory under the auspices of a USEPA-approved QA/QC plan, including Standard Operating Procedures (SOPs). The Ambient Biomonitoring Program has been collecting physical and biological data consistently since the early 1980s. However, it is only recently (starting in 2002) that concerted efforts to collect comprehensive chemical data in conjunction with biological samples have been initiated. Because the objectives of this nutrient criteria project are best served by evaluating concurrently-collected biological and chemical data, mining of the ambient monitoring data set has, for the most part, been limited to data obtained since 2002. Data to characterize a site consist of a single sampling event (grab sample for chemistry with concurrent physical and biological assessment) during a late summer-early fall index period (September-October) dictated by biological concerns for inter-annual consistency. Low or base-flow conditions with minimal antecedent high-flow events were targeted.

Other data are available from special projects conducted by Vermont DEC, many of which contain multiple chemical sampling events from target sites, were compiled. Some of these data were used to evaluate the representativeness of single grab samples for characterizing site nutrient status. In addition, nutrient concentration data collected in a manner consistent with the goals and objectives of this nutrient criteria project but without accompanying biological and physical data were examined for the purpose of evaluating distributions of nutrient variables in target streams and rivers (reference condition/distribution method).

ENSR Inc., under contract to USEPA and NEIWPPC, compiled and evaluated existing ambient nutrient data for rivers and streams in New England[23]. The purpose of this database was to assemble all the relevant river and stream monitoring data in a consistent and comparable format for each ecoregion in New England in order to develop preliminary nutrient criteria recommendations for rivers and streams in this region. These data were of limited value in assessing stressor/response characteristics due to lack of response variable data. Although the data compilation methods were somewhat inconsistent with the Vermont nutrient criteria project, the findings were valuable for comparative purposes.

6. Selection of Nutrient Criteria Variables

A. Vermont Lakes

USEPA technical guidance for nutrient criteria for lakes and reservoirs[2] suggests considering both causal variables such as total phosphorus (TP) and total nitrogen (TN) concentration, and response variables such as chlorophyll-a (Chl-a) concentration and Secchi disk transparency. The relationships between these variables in Vermont lakes were examined in order to select the most appropriate measures to use in developing lake nutrient criteria.

Linear regression relationships between the various causal and response variables are shown in Figure 2. The data points in Figure 2 represent the means of the annual mean values for each lake (i.e., the data were averaged by year and then the long-term means were calculated for each lake). The spring TP and TN data are from the Spring Phosphorus Monitoring Program. The summer TP, Chl-a, and Secchi data are from the Lay Monitoring Program. Linear regressions were conducted on $\log_{10}$-transformed data.

All of the relationships shown in Figure 2 were statistically significant ($p<0.001$). The R^2 values for the regression provide an indication of the strength of association between the variables. As would be expected because of concurrent sampling, summer TP is a better predictor of summer Chl-a and summer Secchi depth than spring TP, although the difference is not great. Spring TN provides a relatively poor prediction of summer Chl-a, but a better prediction of summer Secchi depth than either spring TP or summer TP.

Phosphorus vs. Nitrogen

Phosphorus is regarded as the main limiting nutrient in most freshwater lakes, although both elements are essential for algal nutrition. The ratios of TN:TP in Vermont lakes (Figure 3) are generally much higher than values of about 7.2 or less that are thought to indicate nitrogen limitation of algal biomass[24]. Phosphorus, rather than nitrogen, is the nutrient targeted for control to reduce or prevent algae blooms in Vermont lakes. Management actions to reduce phosphorus can have the effect of controlling nitrogen as well, since the two nutrients are often derived from the same sources in the watershed. For these reasons, and to avoid the creation of redundant criteria that have the same practical effect, the development of nutrient criteria for Vermont lakes will focus on phosphorus as the causal variable.

Spring vs. Summer Phosphorus

There are trade-offs involved with choosing spring vs. summer TP for the development of nutrient criteria for Vermont Lakes. The two variables are highly correlated among Vermont lakes, but summer TP values tend to be higher than spring TP values in lakes where both measures are available (Figure 4). Summer TP shows somewhat stronger predictive relationships with response variables such as summer Chl-a and summer Secchi depth (Figure 2). However, there are many more Vermont lakes having spring TP data (N=243) than summer TP data (N=63). Using spring TP data would allow a broader set of lakes to be included in the analysis and development of nutrient criteria for Vermont.

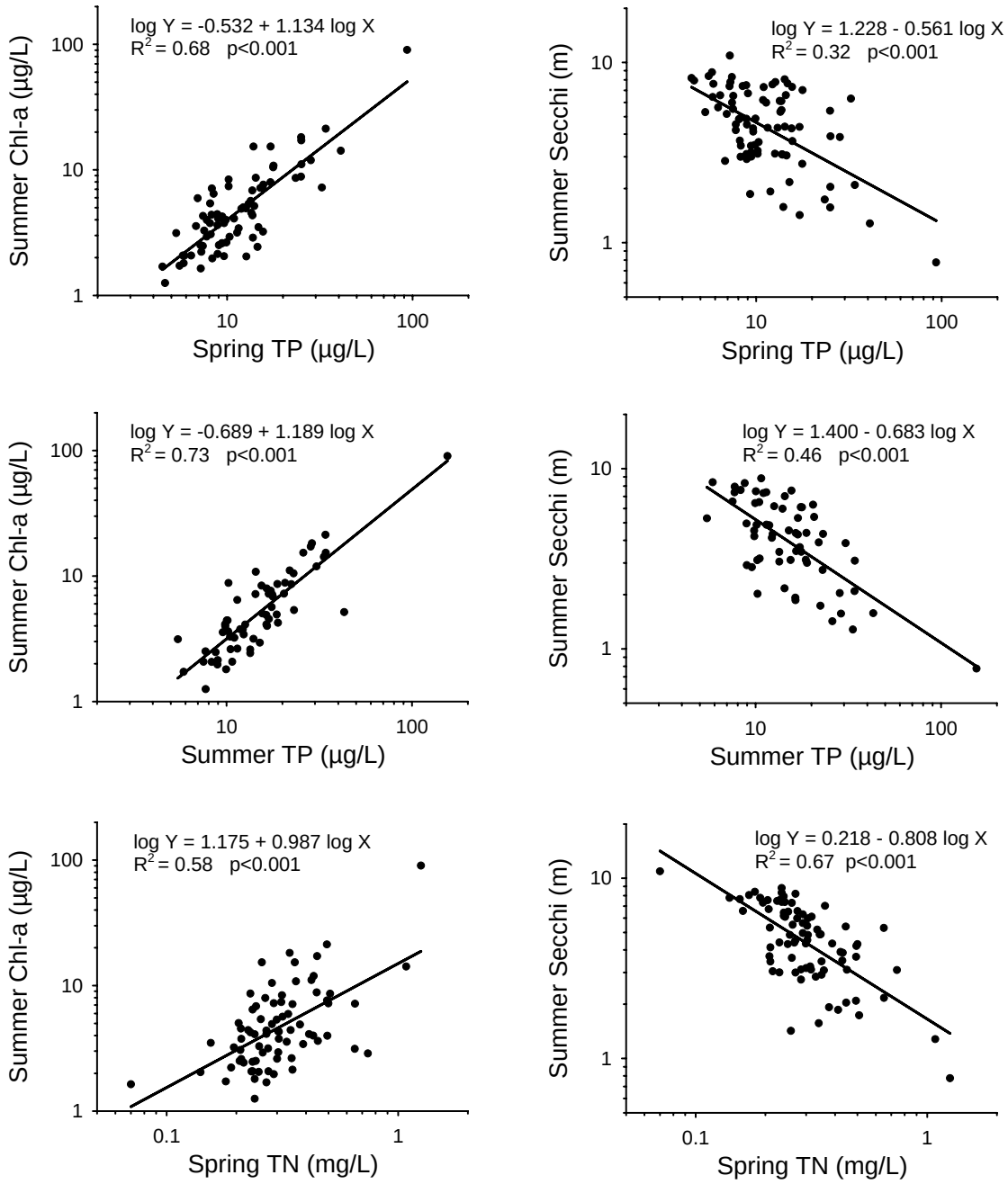

Figure 2. Regression relationships between nutrient criteria variables in Vermont lakes. Data points are long-term means of the annual mean values for each lake.

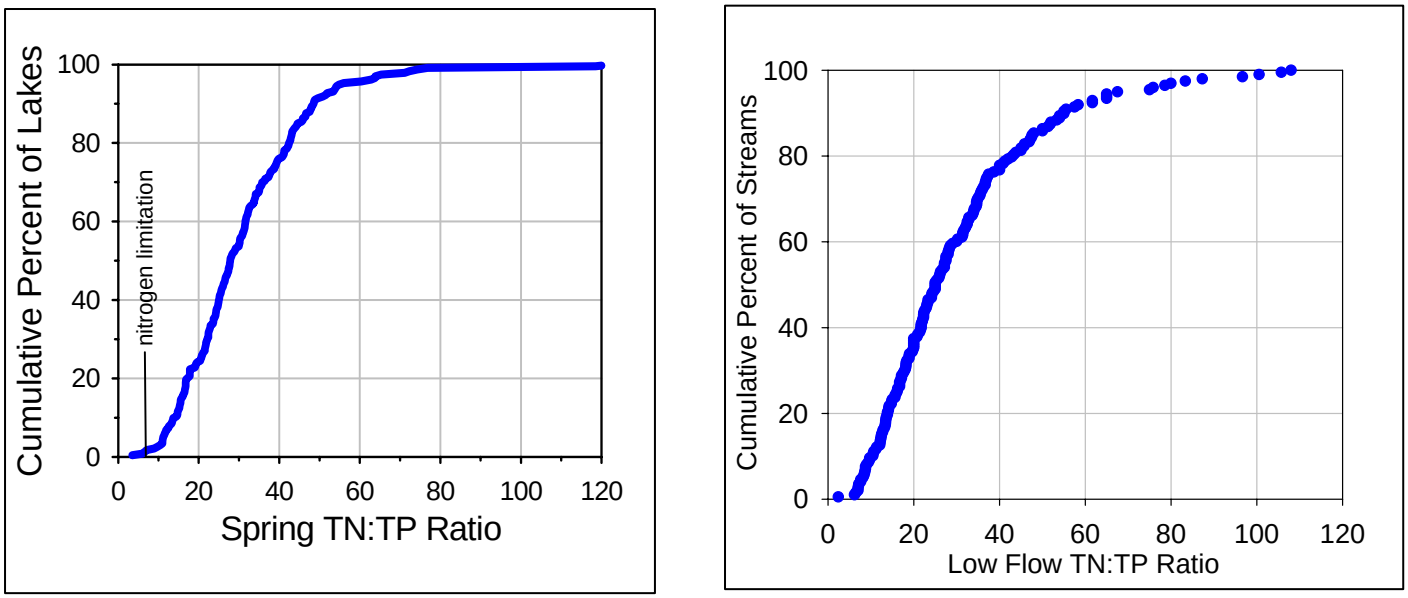

Figure 3. Cumulative frequency distribution of the spring TN:TP ratio (by mass) for Vermont lakes and streams, based on long-term annual mean values for each lake, or median low-flow values for each stream site. In lakes, TN:TP ratios below 7.2 indicate nitrogen limitation of algal growth.

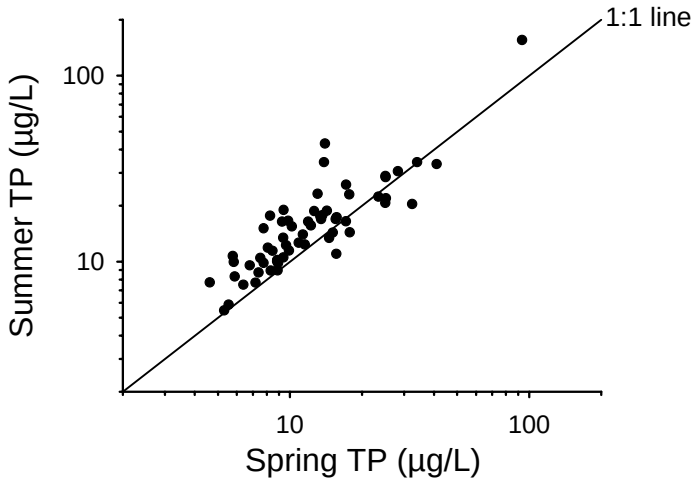

Figure 4. Relationship between summer TP and spring TP for Vermont lakes. Data points are long-term means of the annual mean values for each lake.

Spring TP measurements involve only a single lake sampling visit during each year of monitoring at a time when the water column is completely mixed vertically. Spring TP is assumed to represent the phosphorus level available to support algal production at the start of the growing season. Owing to the single sampling visit per year design of the Spring Phosphorus Program, trophic state characterizations are typically made only after four years of data are available. Of the 243 lakes monitored by the Spring Phosphorus Program, 211 lakes have four or more years data, and some have over 20 years of information. A minimum of eight weekly measurements are required by the Lay Monitoring Program procedures in order to estimate summer mean TP. To date, 46 inland lakes have four of more years of summer phosphorus data obtained at the acceptable weekly frequency.

Assessing compliance with a spring TP criterion would be more practical for a large number of lakes with limited staff resources than assessing compliance with a mean summer TP criterion. For this reason, and because of the larger spring phosphorus database available to support the development of nutrient criteria, this report will focus on spring TP, rather than summer TP, as the main causal variable for lakes.

Casual vs. Response Variables

A variety of water quality and biological response variables were considered in the development of lake nutrient criteria to protect aesthetic, recreational, and aquatic life uses, as discussed in the next section of this report. These variables included Chl-a, Secchi depth, user perceptions of water quality, and indices of biotic integrity for lake benthic macroinvertebrate and phytoplankton communities. The goal of the analysis was to quantify the relationships between these response variables and the levels of use support defined in the Vermont Water Quality Standards (Tables 8 and 9), and then derive spring TP criteria based on the relationship between spring TP and these response variables.

USEPA guidance suggests that both causal variables and response variables may be used as nutrient criteria. However, to avoid unnecessary complexity in the Vermont Water Quality Standards and possibly redundant indicators of the same cause and effect relationships, we chose to limit the derivation of the actual water quality criteria to spring TP only, based on the relationships between spring TP and the various response variables. This also ensures that the pollutant that is the fundamental cause of water quality impairments related to lake eutrophication (phosphorus) will be the focus of management actions to achieve the applicable nutrient criteria. With this approach, actions that treat only the symptoms of eutrophication (e.g., algicide applications) would not be sufficient to achieve the nutrient criteria.

Effect of Lake Physical Factors

The nutrient criteria analysis for lakes considered whether physical factors such as lake depth or drainage area affect the relationship between spring TP and water quality response variables. For example, shallow lakes might yield more algal biomass at a given phosphorus level than deep lakes because of greater light availability in the mixed layer or reduced sedimentation losses of algal cells. Rapidly flushed lakes might have lower planktonic algal biomass due to their short residence time and rapid washout of algal cells.

Residuals from the linear regressions in Figure 2 for Chl-a and Secchi depth vs. spring TP are shown in Figure 5 as a function of maximum lake depth and the ratio of drainage area to lake surface area (an indicator of flushing rate). There is no apparent pattern or trend for the Chl-a vs. spring TP residuals with either depth or drainage area to surface area ratio. This indicates that separate spring TP criteria are not needed to link phosphorus with algae levels in shallow or rapidly flushed lakes. However, lakes (generally riverine impoundments) with drainage area to surface area ratios greater than 500:1 are poorly represented in the dataset. For this reason, nutrient criteria derived from these data should be applied only to lakes with drainage area to surface area ratios less than 500:1.

Residuals for summer Secchi depth vs. spring TP show a pattern in which shallow lakes and rapidly flushed lakes have negative residuals (i.e., lower Secchi depths relative to other lakes with similar phosphorus levels). This is probably due to sediment resuspension in shallow lakes and greater sediment-derived (non-algal) turbidity in riverine impoundments. Since these factors affecting Secchi depths are not directly related to nutrient enrichment, the residuals plots indicate that Chl-a would be the better response variable to use in deriving nutrient criteria.

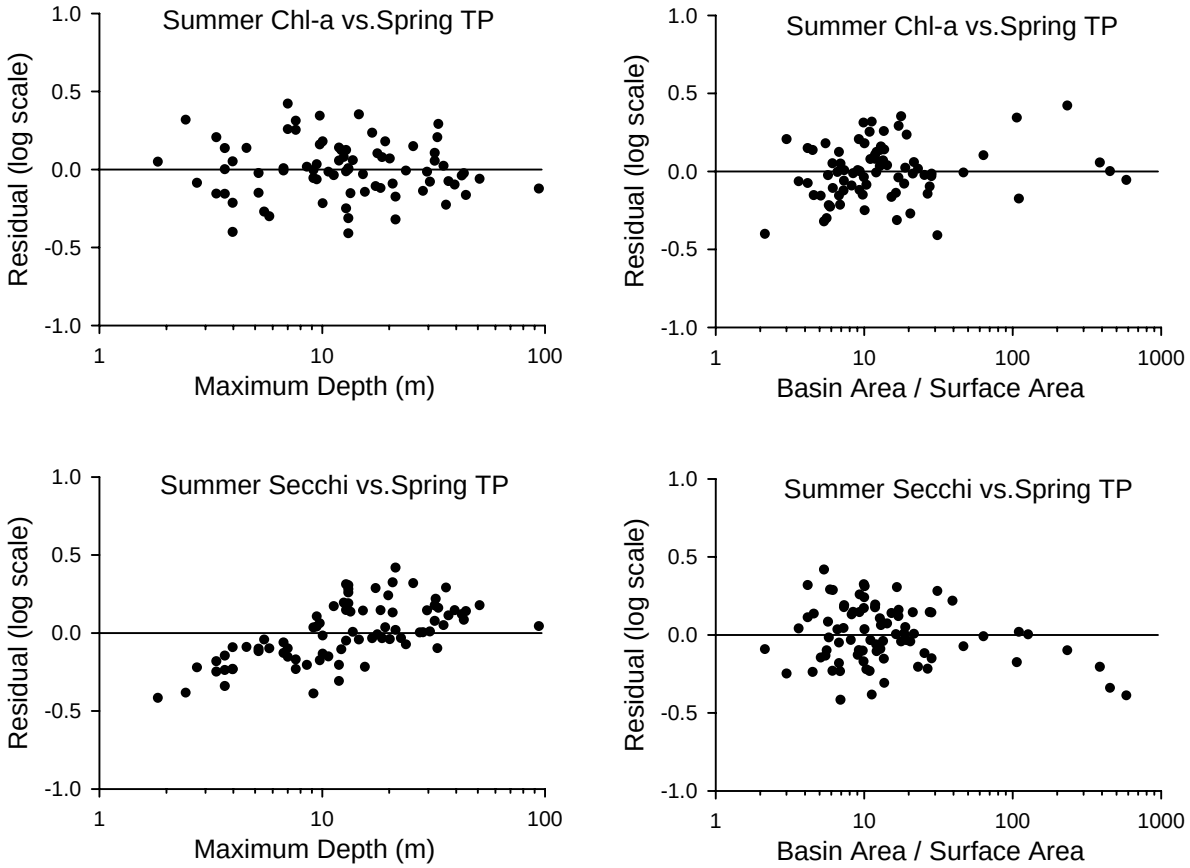

Figure 5. Residuals of the linear regression relationships (Figure 2) between log summer Chl-a, log summer Secchi depth, and log spring TP as a function of maximum lake depth and drainage basin area to lake surface area ratio.

Effect of Ecoregion

USEPA guidance recommends that nutrient criteria be specific to each ecoregion. This is because natural physical and geological factors that vary among ecoregions influence the natural or attainable trophic state of lakes and streams within each ecoregion.

The mean spring TP values among lakes in each of the three ecoregions in Vermont are shown in Figure 6. The mean spring TP value among lakes in the Eastern Great Lakes and Hudson Lowlands ecoregion (essentially the Lake Champlain Valley) was significantly higher (t-test, $p<0.05$) than the mean value for lakes in the Northeastern Highlands ecoregion. There were too few Vermont lakes having spring TP monitoring data (N=4) in the Northeastern Coastal Zone for reliable statistical analysis in that ecoregion.

There was also a significant difference in mean spring TP values between lakes in the two major Vermont ecoregions when the comparison was limited to minimally impacted reference lakes only (i.e., those lakes with less than 5% agricultural or developed land in their watersheds). This difference between reference lake populations suggests that the reason for the higher phosphorus levels in the Eastern Great Lakes and Hudson Lowlands ecoregion is due in part to natural factors such as geology or soil types. The "natural" phosphorus levels in lakes in these two ecoregions are apparently different, and this difference needs to be considered when developing nutrient criteria for lakes in these regions.

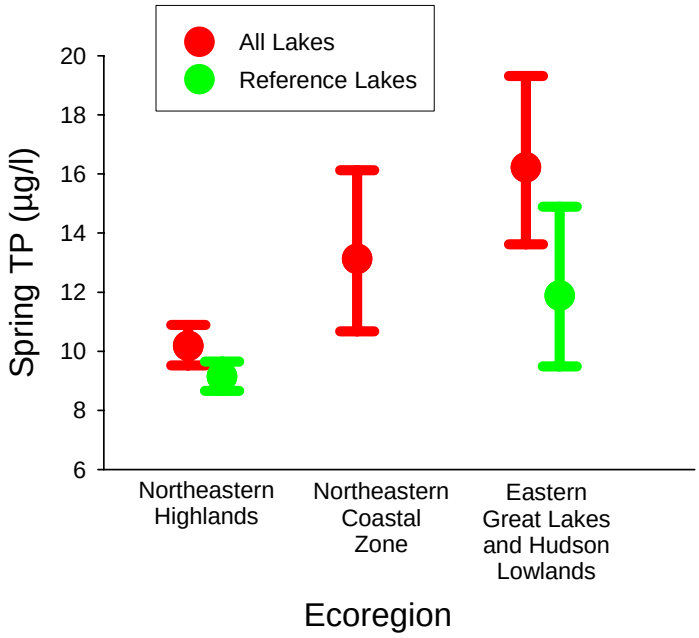

Figure 6. Mean spring TP among lakes in three ecoregions in Vermont. Errors bars are 95% confidence intervals for the ecoregion mean spring TP values, calculated from log_{10}-transformed data. Reference lakes are ones with less than 5% agricultural or developed land in their watershed.

B. Vermont Streams

Phosphorus vs. Nitrogen

As described above, Vermont Water Quality Standards include numeric criteria for total phosphorus in Class A(1) streams, and for nitrates (NO_3-N) in all waters. Total nitrogen is also a useful measure of trophic potential in streams. The data provided by the Vermont Nutrient Criteria Development Project and the Ambient Biomonitoring Program provide the basis to compare these parameters. As with lakes, total phosphorus, nitrate/nitrite (NOx-N), and TN co-vary as shown in Table 10. Based on these statistical comparisons, TP and TN are relatively independent, while NOx is highly related to TN. For this reason, the analyses carried forward through this document will focus on TP and TN.

Table 10. Linear regression results for total phosphorus, total nitrogen, and NOx-nitrogen.

Predicted variable	Independent variable	Prediction equation	Variance explained (R^2)	*p*-value / N paired samples
LogTN =	LogTP	0.509 LogTP -1.049	42.4%	<0.0001 / 198
LogNOx =	LogTP	0.325 LogTP – 0.971	13.4%	<0.0001 / 145
LogNOx =	LogTN	0.974 LogTN – 0.193	72.7%	<0.0001 / 145

Hydrologic Considerations: Spring Flow vs. Base Flow

Instantaneous concentrations of nutrients and other constituents in rivers and streams are highly reliant on flow. The positive flow-dependence of phosphorus is well documented, and must be accounted for where total loadings to downstream waters are of interest. In the current analysis, however, it is the in-stream trophic condition that results from in-situ concentrations of nutrients and the relationship of that trophic condition to designated use support that is of primary interest. Nutrients that are transported during relatively short term high flow-events are minimally available for biological uptake at a given site, although it is recognized that high flow nutrient loads are important to downstream lakes and lentic systems and that resource spiraling will render some component of the transported nutrients available to other downstream segments. In addition, physical stress on attached algae resulting from high flows (scour) minimizes the potential for the accrual of algae during those high flows, even in the presence of elevated nutrient concentration. Nutrients emanating from steady-state point sources are most likely to exert maximum influence on receiving waters during extended periods of summer base flow when in-stream waste concentrations are maximized.

Instantaneous concentrations of nutrients collected during a representative base flow period are used in this analysis to characterize the concentration of nutrients available to the primary producer community over the duration of the growing season and thus represent the potential for periphyton accrual at the test site. There is some uncertainty associated with using an instantaneous value to characterize a mean concentration that should be considered when assessing the precision of the cause and effect relationships observed in this data set. Multiple instantaneous observations of nutrient concentrations collected at discrete sites during base flow conditions in the same year and season suggest that estimates of the base flow mean seasonal concentration are subject to an average percent standard error in the range of 15-20%. Table 11 summarizes some multiple sampling event data assessed for this analysis.

Table 11. Percent standard error summary statistics for mean TP values derived from multiple sampling events at the same site at base flow conditions during the same season. Values represent the potential uncertainty introduced by using a single sample to characterize mean or median seasonal concentrations of TP in streams

	TP Percent Standard Error of the Mean		
	Mean of the %SE's	**Median of the %SE's**	**Range of the %SE's**
Paired samples (N=52)	18	13	0-71
24 multiple (N=2-8) samples	14	9.5	3.5-42

In-stream TP and TN samples collected by Vermont DEC volunteer partners show the importance of stream order, watershed position, and land-use patterns on the relationship of spring to summer nutrient concentrations. Five regularly-scheduled weekly samples collected during the spring snowmelt/high-flow period in 2005 were compared to five biweekly samples collected during the following summer. Sites shown in this comparison were within upper portions of the respective streams watersheds, and were not affected by point source discharges (Table 12). TP was considerably higher in spring than summer for the mixed-use and forested watershed, and increased with increasing land use disturbance. There was no clear pattern in the ratios of spring to summer TN. These complexities highlight why the Vermont Water Quality Standards base in-situ criteria on a low median monthly flow basis. The analyses provided below rely on summer low-flow measurements to document measurable impacts to in-stream aesthetic and biological conditions.

Table 12. Ratios of spring to summer mean total phosphorus and total nitrogen concentrations for three streams in west-central Vermont.

Stream and dominant land-use	Ratio of mean spring:summer TP	Ratio of mean spring:summer TN
Little Otter Creek, agricultural watershed	1.08	1.25
Lewis Creek, mixed-land use watershed	2.55	0.87
New Haven River, forested watershed	5.91	1.72

Response Variables

There are numerous possible response variables to document impacts to the aesthetic quality and biological integrity of wadeable streams. For the purpose of evaluating aesthetic quality, we considered the use of response variables including chlorophyll-a, periphyton abundance, and observational ratings. For the purpose of evaluating biologic integrity and aquatic life use support, we used assessments of the structure and function of aquatic macroinvertebrate communities made in conjunction with the Vermont Nutrient Criteria Development project and the Ambient Biomonitoring Program.

Chlorophyll-a: Instantaneous water-column chlorophyll-a concentrations were quantified as relative fluorescence units using an in-situ fluorometry for sites measured by the Vermont Nutrient Criteria Development Project. For wadeable moving streams, water column concentrations of chlorophyll-a are not expected to relate to instantaneous

measurements for nutrients, since for these systems, periphyton, and not pelagic phytoplankton, is the prevalent primary producer. This is quite evident in the measured chlorophyll-a results. First, there is no significant relationship between total nitrogen or NOx-nitrogen and chlorophyll-a. Second, the relationship between total phosphorus and chlorophyll-a is weak as compared to the relationship noted for lakes ($p<0.001$ and $R^2 = 0.260$ for streams, while $p<0.001$ and $R^2 = 0.73$ for lakes; Figure 2). Finally, the range of measured chlorophyll-a is very low in streams, with the 90th percentile value at 2.7 µg/L as measured by the fluorometer. For these reasons, water-column chlorophyll-a is not considered further as a suitable response variable.

Periphyton abundance: In-situ macro and micro-algal cover and filament length were categorized using a modified pebble-count approach. This measurement provides a semi-quantitative estimate of periphyton cover of the stream bottom. At each sampled location, up to 100 observations of macro and micro-algal filament length were recorded from randomly identified riverbed stones within the target reach. These data were reduced to two metrics: weighted mean value for macro-algal cover, and micro-algal filament length (i.e., micro-algal film thickness).

Aesthetic, trophic, swimming, and siltation observational ratings: The overall aesthetic appearance, swimming desirability, siltation, and magnitude of visually apparent trophic enrichment were categorized by field technicians during the implementation of the Vermont Nutrient Criteria Development Project, and as a routine element of the Ambient Biomonitoring Program. These evaluations were made by staff only after all other sampling activities were completed, and provide a set of "rating factors" for each site, based on the consensus of the team carrying out the sampling.

As would be predicted, these measurements were somewhat interrelated (Figure 7). The aesthetic and trophic ratings were most closely related, although significant additional unexplained variance was evident. The siltation rating evaluates the general "looseness" and preponderance of fine bed sediment at a site, and is a complementary evaluation of the standard embeddedness metric. The degree to which siltation at a location is a result of upstream particulate-derived nutrient supply versus nutrients at a site causing in-situ production of fine organic sediments is difficult to decipher. The swimming rating of a site takes into consideration the aesthetic, trophic, and siltation ratings of a location, along with other external factors such as setting. Owing to the variability inherent in the swimming measure, and the causal indeterminacy of the siltation rating, only the aesthetic and trophic ratings were be employed for the analyses described below.

Aquatic macroinvertebrates: While periphyton is presumed to be the primary response variable to nutrient enrichment in streams, the relationships between measures of periphyton and aquatic life designated use support have not been developed in Vermont. In addition, establishing precise relationships between nutrient concentrations and periphyton biomass is notoriously difficult. Biggs[25] cites the following as contributing to the difficulties: "*1) the dynamic nature of biomass accrual and loss processes; 2) the concentrations of dissolved nutrients measured in solution mainly reflecting nutrients that are left over after the periphyton have removed what they need and not the supply concentration; 3) the difficulty of isolating seepage and groundwater upwelling zones to quantify the local supply of nutrients on the stream bed.*"

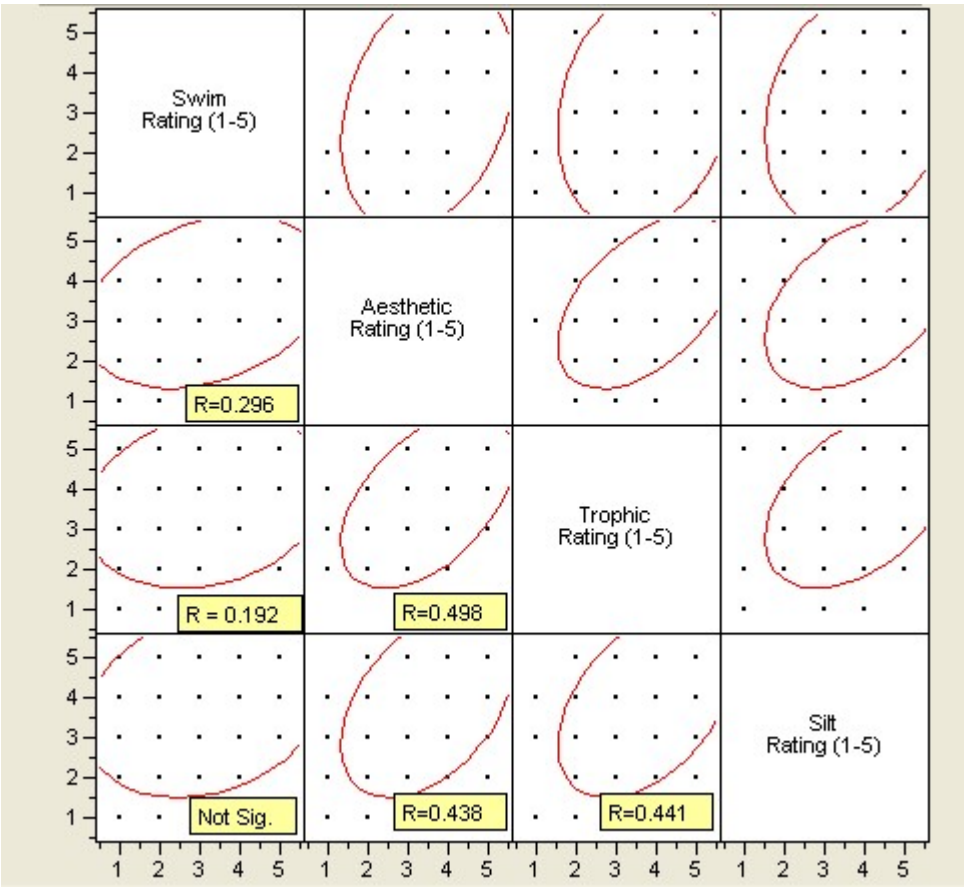

Figure 7. Scatterplot matrix of swimming, aesthetic, trophic, and siltation ratings for 151 Vermont wadeable stream sites. Correlations are calculated as Spearman R-values, and are statistically significant at p<0.05 unless otherwise noted. Ellipses represent 90 percent confidence around the correlation.

In contrast to periphyton, the relationships between the secondary response variable, macroinvertebrate community structure and function, and aquatic life designated use support are very well developed for the target stream population in Vermont. This analysis presumes the presence of measurable signals of nutrient enrichment and trophic status within the structure and function of the macroinvertebrate community. The existence of strong connections to aquatic life use support evaluations is a dominant consideration in the selection macroinvertebrates as the response variable.

This analysis addresses a class of stream nominally referred to as wadeable streams. For the purpose of aquatic life use assessments, Vermont DEC has further identified four biologically unique sub-classes of wadeable streams, or wadeable stream ecotypes, based on macroinvertebrate community characteristics. Vermont DEC has developed biological criteria for the following three of those wadeable stream ecotypes in Vermont.

- Small, high-gradient (SHG) streams
- Medium, high-gradient (MHG) streams
- Warm-water, medium-gradient (WWMG) streams

These ecotypes are discriminated by the structural and functional characteristics of macroinvertebrate communities residing in the least disturbed, or reference, reaches of

wadeable streams in Vermont. The primary geophysical gradients that separate the stream ecotypes include slope, elevation, drainage area, temperature and to some extent, ecoregion. Biocriteria have not yet been developed for the fourth ecotype, low gradient soft bottom streams.

The vast majority of sites located in the Eastern Great Lakes and Hudson Lowlands ecoregion (essentially the Lake Champlain Valley) are captured as WWMG streams in the ecotype classification. The SHG and MHG streams occur almost exclusively in the Northeastern Highlands ecoregion. All three ecotypes are predominantly hard-bottom streams with biocriteria developed from riffle-community characteristics. Biological response to nutrient stressors was examined in each of these three steam ecotypes for this nutrient criteria analysis.

The Macroinvertebrate Trophic Condition Index: Vermont rivers and streams are impacted by a wide range of chemical, physical and biological stressors in addition to nutrients. The overall macroinvertebrate community assessment designation used by Vermont DEC does not discriminate between stressors but represents an overall biologic condition rating resulting from the cumulative effects of all stressors impacting the site. The Macroinvertebrate Trophic Condition Index (MTCI) was developed specifically for this nutrient criteria development project in order to discriminate the component of designated use attainment related to trophic condition stressors from non-trophic drivers of non- attainment such as sedimentation and toxicity.

The MTCI was developed independently for each of the three wadeable stream ecotypes listed above. For each stream ecotype, relationships between biological response variables indicative of nutrient enrichment and nutrient concentrations were examined. A subset of biological metrics showing positive dose-response relationships to nutrient concentrations was selected. Regression analysis was used to evaluate the strength of the dose-response relationships. The selected variables were standardized to a common range of 0-1. To calculate the MTCI, the normalized variables were summed and divided by the number of variables making up the index, to derive an MTCI value in the range of 0-1. The variables used for deriving the MTCI for each stream ecotype are shown in Table 13.

Table 13. Variables used to derive the macroinvertebrate trophic community index for Vermont wadeable stream ecotypes (PPCS=Pinkham Pearson Coefficient of Similarity; PMAO-Percent Model Affinity-Order; EPT=Percent abundance of mayfly, stonefly and caddisfly taxa)

	Stream Ecotype		
Variable	**SHG**	**MHG**	**WWMG**
Biotic Index (BI)	X	X	X
% Hydropsychid caddis	X		X
Macroinvertebrate community functional similarity (PPCS)	X	X	
Ratio of sensitive organisms to tolerant dipterans (ept/ept + chiro)	X	X	X
Weighted mean macro-periphyton (WMMacro)	X		
Macroinvertebrate community taxonomic similarity (PMAO)			X
Trophy (observational assessment)		X	

Effect of Canopy Cover and Light

One important attribute of stream aesthetic quality is that of light penetration through the overlying canopy. In wadeable streams, primary production is regulated by a number of factors including the availability of light and nutrients, disturbance frequency, and grazing pressure. Primary production by periphyton or phytoplankton of wadeable streams can be minimized by low levels of light, even at extraordinarily high nutrient concentrations.

Canopy cover was controlled for in the design of the Vermont Nutrient Criteria Development project, and was measured empirically using spherical densiometers under the assumption that variation in canopy cover (and therefore light) would be an important covariate of periphyton expression. However, Spearman correlations between percent canopy and weighted mean macroalgae, microalgae, and trophic ratings were very low (maximum R = -0.22), and multiple regression modeling indicated that canopy cover did not significantly affect the primary response variables, once the effect of nutrient concentration was accounted for. Therefore, with the exception of macroinvertebrate response analyses, canopy cover was not included as a covariate in the analyses described below.

Sites with measured percent canopy cover greater than 75% were deleted from the data set used to assess macroinvertebrate response in order to minimize the potential for light limitation to confound the results. Linear regression analyses were used to verify the potential for canopied sites to effect the precision of stressor/response analyses based on secondary response variables – e.g., macroinvertebrate community structure and function. When TP and TN were regressed against the Macroinvertebrate Trophic Condition Index (MTCI) for streams with greater than 75% canopy and those with less than 75% canopy, R^2 values were not significant at the p=0.05 level in the shaded streams but were significant (p=0.001) in the streams with canopy less than 75%. The shaded stream regressions were affected by a number of sites with high nutrient concentrations and minimal trophic response as measured by the MTCI.

Effect of Ecoregion

Stream TP and TN vary significantly by ecoregion, although the differences in means are limited in magnitude (Figure 8). Streams sampled in the Great Lakes and Eastern Hudson Lowlands were higher in nutrient concentration on average than streams in the other ecoregions (TP: $F_{2, 197} = 8.48$, $p=0.003$; TN: $F_{2, 196} = 10.21$, $p<0.0001$). There was no statistically significant difference in N:P ratios across ecoregions. Since biological stream classifications used in this analysis account for any potential ecoregional differences in biological condition, it was determined that there was no need to account for the effect of ecoregion in this analysis.

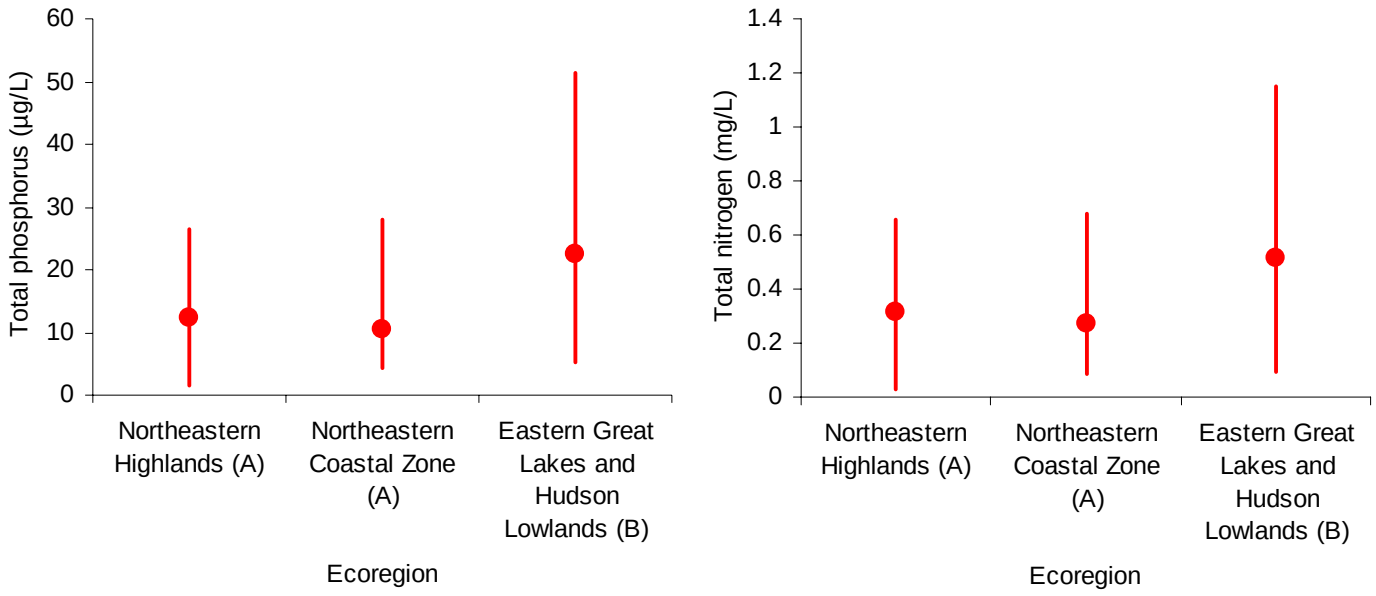

Figure 8. Mean TP and TN concentrations among streams in three ecoregions in Vermont. Errors bars are 95% confidence intervals for the ecoregion mean concentrations, calculated from $\log_{10}$-transformed data. Statistically significant differences between ecoregions are noted by differing letters.

7. Nutrient Criteria for Vermont Lakes

The Vermont lake data were analyzed in order to establish quantitative relationships between spring TP concentrations and the management objectives for the various water uses defined in the Vermont Water Quality Standards (Tables 8 and 9). In the case of aesthetics and recreational uses, the goal was to identify spring TP values supporting "natural," "excellent," "very good," and "good" aesthetic value. For aquatic life uses, the goal was to define spring TP levels corresponding to the natural biological condition, and to "minor" or "moderate" biotic community changes from the reference condition.

A. Aesthetics and Recreational Uses

Defining "Natural Condition"

The management objectives for aesthetics for Class A(1) waters in the Vermont Water Quality Standards are to maintain water character and other features in their natural condition (Table 9). This is one case where the application of the USEPA approach of defining a phosphorus criterion from the frequency distribution for minimally impacted reference lakes may be appropriate, since the use to be protected is specifically defined as the "natural condition."

The natural phosphorus concentrations tend to be different on average between the two major ecoregions in Vermont (Figure 6). For this reason, separate spring TP criteria for the "natural condition" were considered for each ecoregion.

Frequency distributions for spring TP in Vermont lakes with mostly natural watersheds (less than 5% agricultural or developed land within the watershed) are shown in Figure 9. The long-term mean spring TP values among these lakes were log-normally distributed, so the values were $\log_{10}$-transformed in order to calculate the parameters (mean, standard deviation) for the distributions. There were no data available for lakes with natural watersheds in the Northeastern Coastal Zone ecoregion. Lakes in this ecoregion should be included with lakes in the Northeastern Highlands ecoregion for the purposes of ecoregional nutrient criteria development in Vermont.

The 50th percentile of the spring TP distribution in the Northeastern Highlands ecoregion (i.e., the geometric mean value for reference lakes in this region) is just over 9 μg/L (Figure 9). Using the 75th percentile as recommended by the USEPA would result in a criterion of about 11 μg/L. The upper 90th percentile for natural lakes in the Northeastern Highlands ecoregion is about 14 μg/L. The 50th percentile of the spring TP distribution for natural lakes in the Eastern Great Lakes and Hudson Lowlands ecoregion is about 12 μg/L, with the 75th percentile at 16 μg/L and the 90th percentile at 21 μg/L.

Figure 9 illustrates that there is a large variation in phosphorus concentrations within each ecoregion, even among lakes with minimal human impact in their watersheds. It may be possible to select an appropriate percentile to use in defining a spring TP criterion for "natural condition" in these ecoregions, but there will still be many individual lakes having naturally occurring phosphorus levels that are above the general criterion chosen in this manner.

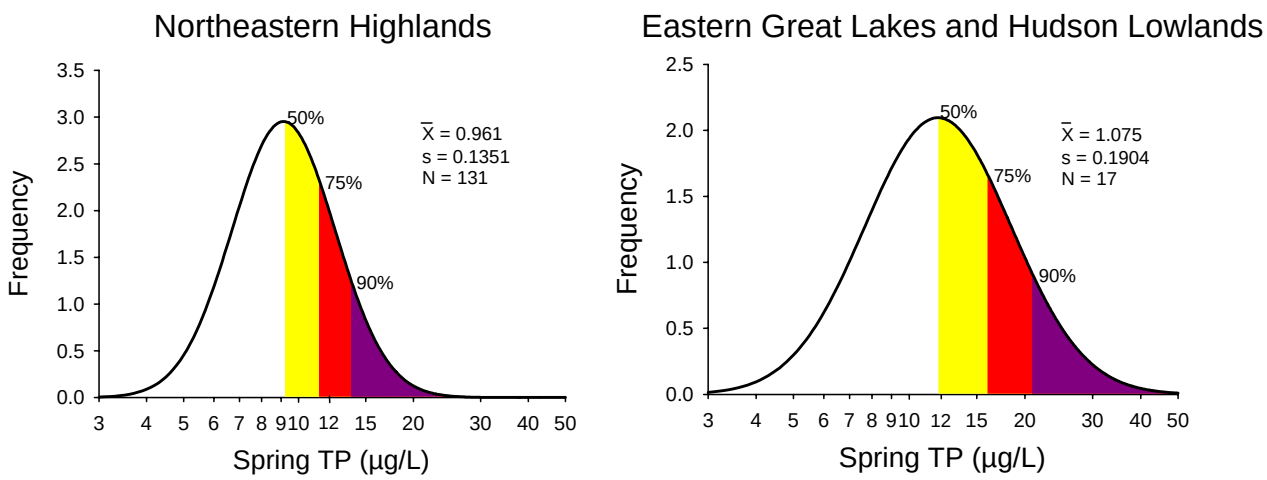

Figure 9. Frequency distributions of spring TP in Vermont ecoregions for lakes with natural watersheds (less than 5% agricultural or developed land). The statistics shown for the distributions were calculated on $\log_{10}$-transformed data.

Defining "Excellent," "Very Good," and "Good"

The lake user form that was used during 1987-1991 in conjunction with the Vermont Lay Monitoring Program was structured in a way so that the results can now be used to help define the water quality conditions corresponding to the aesthetics-based management objectives for the various water classes, as listed in Table 9. The user survey form consisted of two parts. Part A sought a description of the physical condition of the lake water, while Part B (shown below) sought an opinion on the suitability of the lake water for recreation and aesthetic enjoyment. The responses to Part B were used for this analysis because they related more closely to the management objectives defined in the Water Quality Standards. The lay monitors were asked to provide an evaluation using this form each time they obtained measurements of TP, Chl-a, or Secchi depth.

Vermont Lake User Survey Form (Part B)

Please circle the one number that best describes your opinion on how suitable the lake water is for recreation and aesthetic enjoyment today.

1. Beautiful, could not be any nicer.
2. Very minor aesthetic problems; excellent for swimming, boating, enjoyment.
3. Swimming and aesthetic enjoyment slightly impaired because of algae levels.
4. Desire to swim and level of enjoyment of the lake substantially reduced because of algae levels.
5. Swimming and aesthetic enjoyment of the lake nearly impossible because of algae levels.

The Lay Monitoring and user survey data were analyzed for the inland lake dataset in order to define the relationship between user survey responses and the Chl-a concentration present at the time of observation (Figure 10). The frequency of each user

survey response (1, 2, 3, 4, or 5) was tabulated for intervals of Chl-a. The mid-points of each Chl-a interval were used to plot the curves in Figure 10. Chl-a was chosen for this analysis because it was the water quality response variable that had the most consistent relationship with Spring TP for lakes with different depths and drainage areas (Figure 5).

As would be expected, the proportion of responses indicating "beautiful" or "excellent" conditions declines and the proportion of responses indicating some degree of use impairment increases as Chl-a levels increase (Figure 10). The relationship is not entirely smooth due to variations in how individual lake users perceive water quality. However, the curves in Figure 10 provide a basis for selecting instantaneous Chl-a concentrations that correspond to specific levels of use support. Instantaneous Chl-a criteria that could be derived in this manner are shown in Table 14.

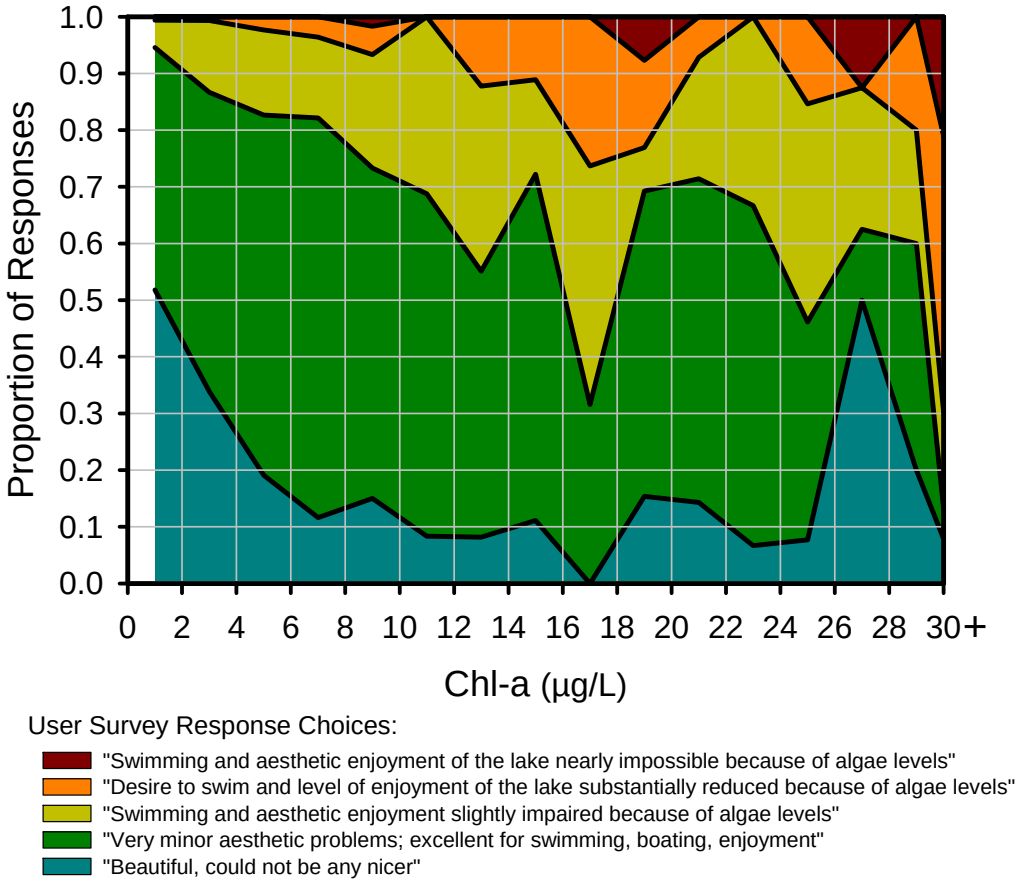

Figure 10. Distribution of responses to the Vermont inland lake user survey as a function of the Chl-a concentration measured at the time response was provided.

Table 14. Instantaneous Chl-a criteria derived from the Vermont lake user survey analysis (Figure 10).

Class	Management Objectives and Criteria for Aesthetics and Recreational Uses	User Response Corresponding to Management Objective	Instantaneous Chl-a value
A(1)	Natural condition.	User survey data were not used to define this objective.	--
A(2) B(1)	Excellent aesthetic value.	75% of lake users indicate "beautiful" or "excellent" conditions.	9 µg/L
B(2)	Very good aesthetic value.	50% of lake users indicate "beautiful" or "excellent" conditions.	16 µg/L
B(3)	Good aesthetic value.	90% of users report no more than slight impairment due to algae levels.	24 µg/L
B (untyped)	Good aesthetic value.	90% of users report no more than slight impairment due to algae levels.	24 µg/L

Defining "Consistently" and "Variability"

The Vermont Water Quality Standards indicate that excellent, very good, or good aesthetic value should be achieved "consistently" for Class A(2), B(1), B(2), and B(untyped) waters (Table 9). The term "consistently" implies a high time frequency of attainment (i.e., nearly all the time). The criterion for Class B(3) waters indicates that "variability may be allowed" provided that good aesthetic value is achieved. However, it will be assumed for this analysis that the provision of "variability may be allowed" was intended to apply to water level and flow manipulations in rivers affected by hydropower operations, and not to lake aesthetics. Nutrient criteria were therefore developed to achieve the standard of "consistently good aesthetic value" for both B(3) and B(untyped) waters.

Since the ultimate goal of this analysis was to derive lake nutrient criteria expressed in terms of spring TP values (see earlier discussion), the monitoring data were analyzed in order to quantify the frequencies with which these aesthetic conditions are obtained as a function of spring TP. All the available summer Chl-a data (N=7,946) were pooled for all lakes, and the frequencies at which the instantaneous Chl-a criteria in Table 14 were actually attained were tabulated for various intervals of spring TP concentration. The mid-points of each spring TP interval were used for plotting purposes (Figure 11). Figure 11 shows how the frequency of attainment declines as spring TP increases, and provides a basis for selecting spring TP criteria that correspond to appropriately high frequencies of attainment.

A 100% frequency of attainment of the Chl-a values in Table 14 would not be a realistic standard to achieve for most lakes, even those with mostly natural watersheds, because of the large natural variability in algae levels and Chl-a concentrations during the summer season. If a 90% frequency of attaining the instantaneous Chl-a criteria in Table 14 is accepted instead as an appropriate way to apply the term "consistently," then Figure 11 would indicate spring TP criteria of 11 µg/L for Class A(2) and B(1) waters (excellent), a criterion of 16 µg/L for Class B(2) waters (very good), and a criterion of 24 µg/L for Class B(3) and B(untyped) waters (good).

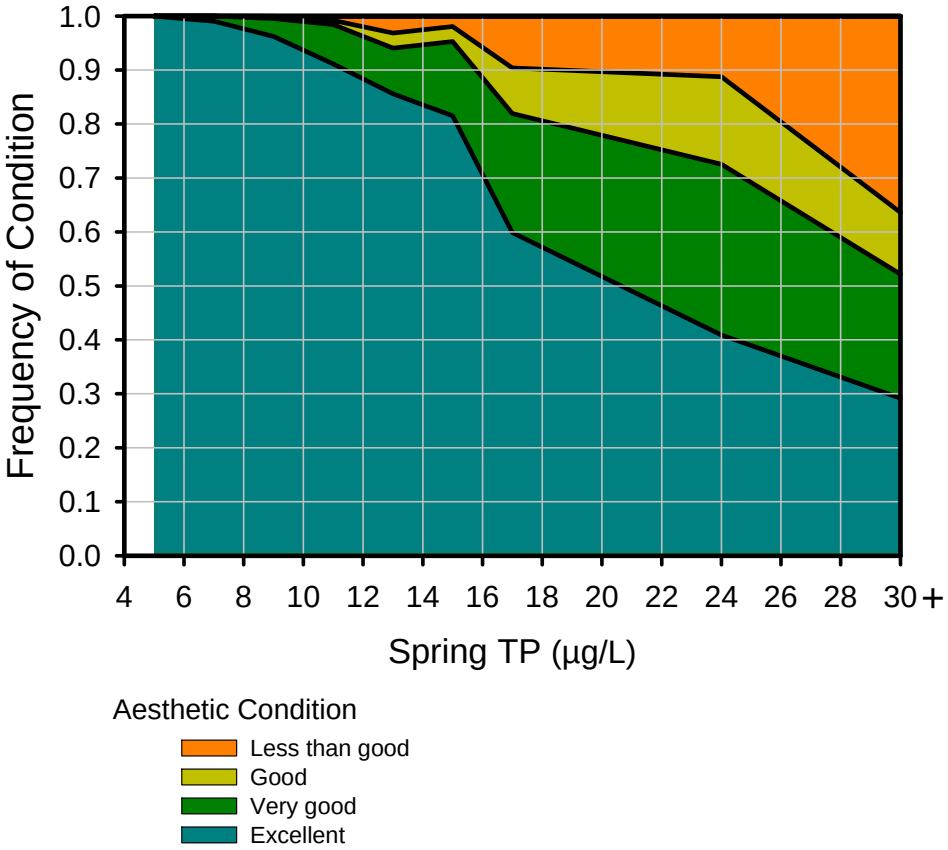

Figure 11. Temporal frequencies of "excellent," "very good," and "good" aesthetic and recreational conditions as a function of spring TP concentration in lakes. Aesthetic conditions were defined in this example based on Chl-a concentrations as follows (from Table 10).

Less than good: Chl-a >24 µg/L
Good: Chl-a >16 µg/L and ≤24 µg/L
Very Good: Chl-a >9 µg/L and ≤16 µg/L
Excellent: Chl-a ≤9 µg/L

Summary of Proposed Criteria

The spring TP criteria proposed in the preceding discussion to protect aesthetics and recreational uses in the various classes of waters were presented as examples of how the Vermont lake user survey and long-term lake monitoring data could be used to derive such criteria. These criteria are summarized in Table 15. The Vermont Water Resources Panel may choose through public discussion and further deliberation to make different choices regarding natural phosphorus levels and acceptable frequencies of attaining various aesthetic conditions. The analysis presented here is intended to provide technical assistance for these ultimate policy decisions.

Table 15. Summary of spring TP criteria to protect aesthetic and recreational uses of Vermont lakes.

Class	Management Objectives and Criteria	Spring TP Criterion (µg/L)	Ecoregion
A(1)	Natural condition	11[a] 11[a] 16[a]	Northeastern Highlands Northeastern Coastal Zone Eastern Great Lakes and Hudson Lowlands
A(2)	Consistently excellent value	11	All
B(1)	Consistently excellent value	11	All
B(2)	Consistently very good value	16	All
B(3)	Consistently good value	24	All
B(untyped)	Consistently good value	24	All

[a] Applies upper 75th percentile of the distributions in Figure 9.

B. Aquatic Life Uses

The Vermont Lake Condition Index

In this section, we relate biological conditions to stated objectives in the Vermont Water Quality Standards, and to observed levels of phosphorus. Since 1996, the Lake Bioassessment Project has developed indicators of aquatic life use attainment for lakes. Initially, the project sought to develop indices of biotic integrity for three biological guilds: macroinvertebrates; phytoplankton; and macrophytes. Over the course of the project period, a continually increasing number of assessed lakes has provided an expanding dataset. This dataset has been periodically re-analyzed with the goal of developing multimetric biological indices for each guild.

The ability to develop useful indices for each biological guild is predicated on the ability to define an appropriate reference condition and identify a suite of consistently measurable metrics that can discriminate known-impacted lakes from lakes that are of reference quality. Commonly, aggregations of biometrics known as multimetric indices are constructed to account for natural variation expected across groupings, or classes, within which waterbodies express similar biological characteristics. To date, class-specific multimetric indices assessing the phytoplankton[26] and macroinvertebrate guilds

have been developed. Efforts to develop an index for aquatic plants have not been successful.

The indices, known as the Vermont Lake Condition BioIndex (VLCBI) for macroinvertebrates and phytoplankton, are specific to one of three defined waterbody classes: small low-alkalinity lakes; small well-buffered lakes; and, large lakes. A statistical approach known as a discriminant classification analysis was used to a-priori classify lakes before the biological communities were assessed in the field.

The VLCBI assesses biological condition in relation to the criteria expressed in Table 8. Specifically, the indices are constructed to provide numeric interpretations of the terms "natural condition," "minor changes," and, "moderate changes." The VLCBI does not address criteria for habitat.

Defining "Natural Condition," "Minor," and "Moderate"

For the purpose of biological or nutrient criteria derivation, the reference lake set used in for the multimetric indices provides the starting point for characterizing biota "within the range of the natural condition" (Table 8). However, unforeseen historical effects on waters that appear least-impacted can carry lasting impacts on aquatic biota, which are only identified during sampling or analysis. For this reason, we propose that the natural condition be defined as the biological attributes measured from reference lakes for which resulting VLCBI scores are in the upper 75% of the distribution[27] (Figure 12, Table 16).

The ranges of multimetric index scores equating to minor or moderate changes from the reference condition are as much a matter of policy judgment as of technical or scientific analysis. The decision as to where to draw distinctions in deviations from the reference condition essentially define the level of protection afforded under the varying water management type criteria described in Vermont Water Quality Standards. Any number of different "cutpoints" might be defined, which in turn will affect the ultimate nutrient criteria that would apply to maintain aquatic biota within the desired range of deviation from reference.

We propose a simple approach to determining minor and moderate deviations from reference, based on VLCBI scores. Specifically, any lakes with scores falling below the "natural condition," but within the upper third of the range of scores for all assessed lakes would be identified as exhibiting biota with no more than "minor changes in the relative proportions of taxonomic and functional components." Lakes with index scores below this threshold, but above the lower third of the range of scores for all assessed lakes, would be identified as exhibiting biota with no more than "moderate changes in the relative proportions of tolerant, intolerant, taxonomic, and functional components" (Figure 12).

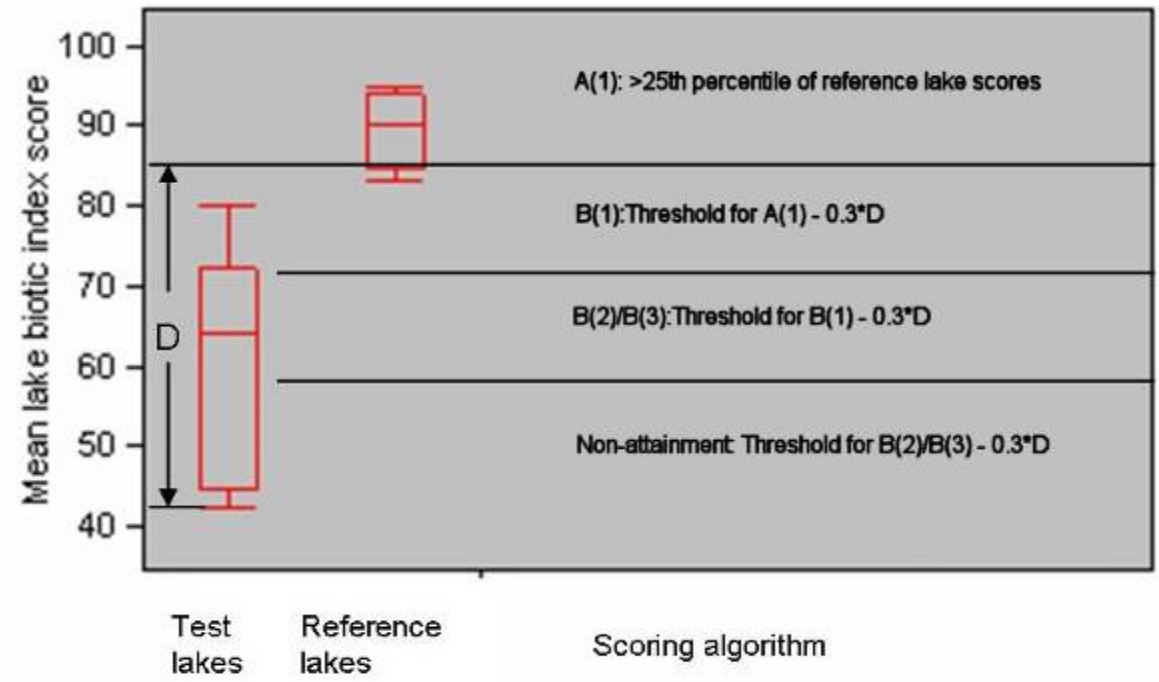

Figure 12. Proposed algorithm to determine threshold Vermont Lake Condition Index scores in relation to Vermont water management type criteria for Class A and B waters. Data shown are for the macroinvertebrate index, for large lakes. Adapted from Vermont DEC (2006) Error! Bookmark not defined.**.**

Table 16. Proposed overall Vermont Lake Condition Index score threshold values in relation to deviation from reference. Scores are expressed as the percent of the maximum attainable.

VT Lake Condition index	Lake class→ / Water Management type ↓	Well buffered	Low alkalinity	Large
Macroinvertebrates	Natural condition	>85	>75	>85
	Minor change from reference	≥74	≥65	≥71
	Moderate change from reference	≥63	≥55	≥57
	Non-attainment	<63	<55	<57
Phytoplankton	Natural condition	≥57	≥73	≥86
	Minor change from reference	≥45	≥60	≥64
	Moderate change from reference	≥33	≥47	≥42
	Non-attainment	<33	<47	<42

Relating Vermont Lake Condition Index Scores to Phosphorus Concentrations

As described above, phosphorus is the limiting nutrient influencing primary productivity in north-temperate lakes. As such, it is intuitive that increases in total phosphorus will ultimately cause excessive or even runaway primary production, leading to cascading changes in aquatic food webs[28]. However, multiple stressors are known to impact Vermont lakes, and the VLCBI is not designed to detect the biological response to eutrophication in exclusion of these other stressors (e.g., cumulative development and associated habitat modification, sedimentation, water level fluctuation, acidification).

Accordingly, as a first step to determining threshold nutrient concentration that will protect aquatic biota, we used analysis of variance to test the hypotheses that spring and/or summer total phosphorus concentrations are elevated at lower levels of aquatic life use attainment. This analysis was run separately using the phytoplankton and macroinvertebrate index scores. Lakes were placed into one of four groups based on VLCBI scores: natural condition; minor change; moderate change; and, non-attainment. For phytoplankton, both summer and spring TP concentrations varied significantly with these groups (Figure 13, summer: $F_{3, 19} = 4.59$, $p = 0.0168$; spring: $F_{3,44} = 7.93$, $p = 0.0003$). Expressing "natural condition" as the control group, spring total phosphorus was significantly elevated in non-attaining lakes ($p < 0.05$), and was modestly elevated ($p = 0.078$) in lakes identified as exhibiting minor changes from the reference. For macroinvertebrates, total phosphorus did not vary significantly across the groups ($p > 0.1$), indicating that the macroinvertebrate index as currently constructed is not sensitive to eutrophication stress in exclusion of other stresses.

The phytoplankton dataset was used to determine the proportion of lakes meeting each biological attainment category, along the gradient of measured spring TP. It is not realistic to expect that all lakes falling within a given TP concentration range will have the same biological condition. An area plot relating the probability of attaining the various biological conditions to spring TP concentration (Figure 14) indicates that at low TP concentrations, a high proportion of sampled lakes demonstrate attainment of Class B(1) criteria (minor change) or better. Non-attainment of biological standards for any water classification is probable only at the most elevated TP concentrations.

The distribution of naturally occurring TP concentrations shown in Figure 9 can be used for the Class A(1) objective of keeping waters in their "natural condition." This basis for deriving criteria corresponding to natural TP levels is independent of the biological data.

Given the statistical overlap in phosphorus concentrations among lakes exhibiting minor vs. moderate changes from reference, only a single TP concentration value should be established to protect waters across these biological conditions. Based on the lakes sampled, a phosphorus concentration of 17 µg/L would ensure that 90% of lakes sampled exhibit no more than a moderate change from reference, while keeping 80% of these lakes at no more than a minor change from reference (Figure 14). At a phosphorus concentration of 22 µg/L, most lakes continue to exhibit no more than moderate changes from the reference condition. However, above this value the proportion of lakes exhibiting non-attainment (i.e., an undue adverse effect on aquatic biota) increases dramatically, indicating that a value of 22 µg/L may be a suitable threshold for establishing a Class B (untyped) criterion.

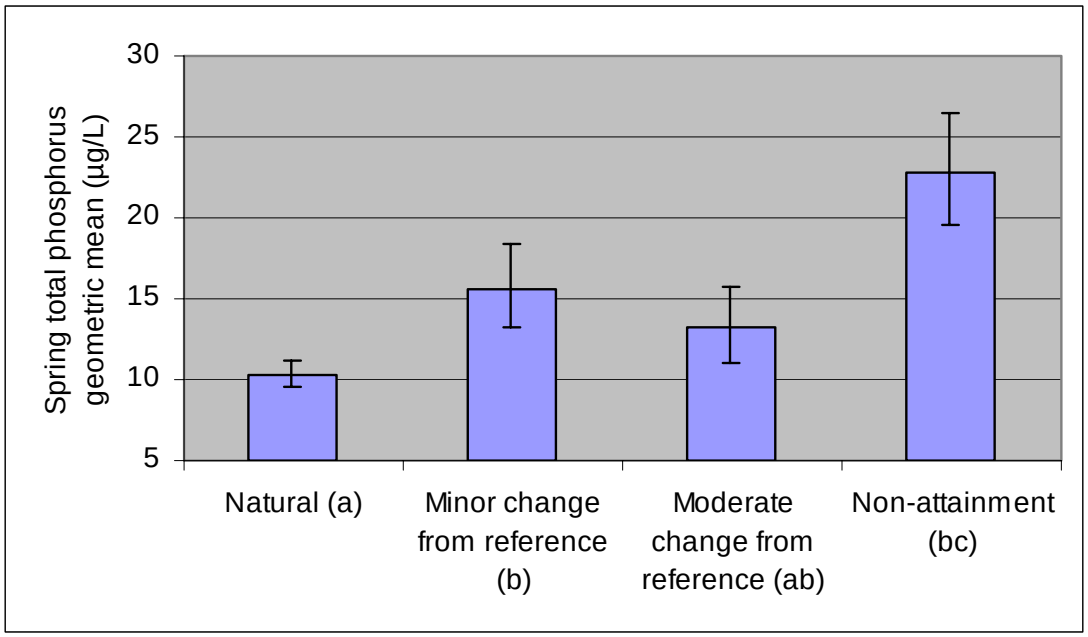

Figure 13. Analysis of variance of natural-log spring phosphorus concentrations by biological assessment category assessed by the Vermont Lake Condition Index for phytoplankton. Statistically significant differences between categories are noted by differing letters.

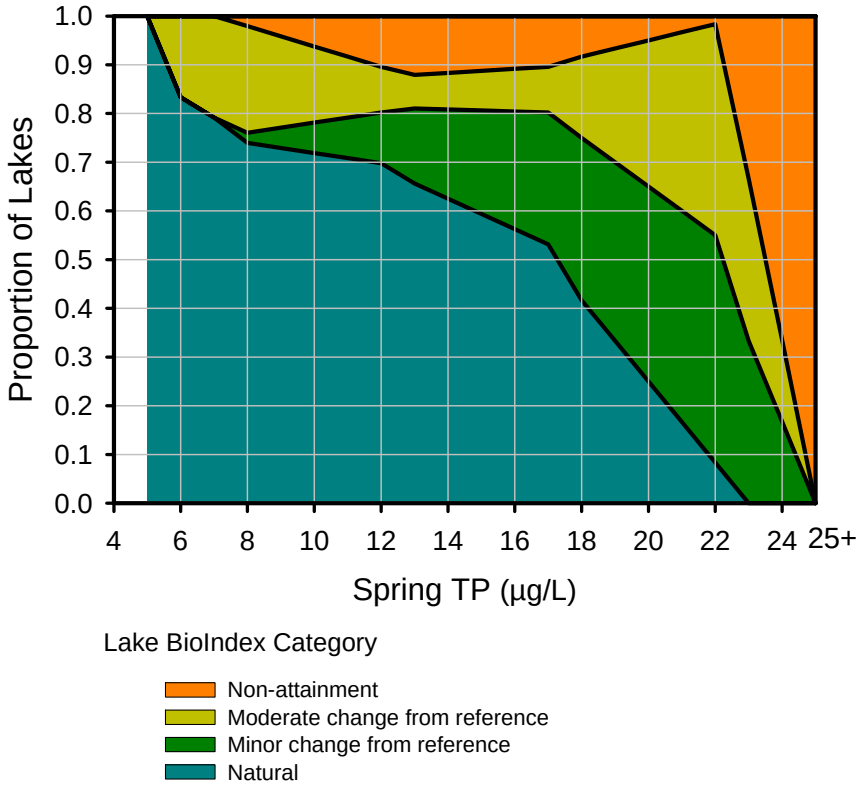

Figure 14. Proportion of lakes attaining biological assessment categories based on Vermont Lake Condition Index scores for phytoplankton, in relation to spring total phosphorus.

Summary of Proposed Criteria

The spring TP criteria discussed in the previous section are presented as examples of how the VLCBI for phytoplankton, in concert with long-term lake monitoring data, could be used to derive criteria, which are summarized in Table 17. The Vermont Water Resources Panel may choose through public discussion and further deliberation to make different choices regarding natural phosphorus levels, the VLCBI "cutpoints" corresponding to biological condition, and acceptable proportions of lakes attaining various biological conditions. The analysis presented here is intended to provide technical assistance for what are ultimately policy decisions.

Table 17. Summary of spring TP criteria to protect aquatic life uses of Vermont lakes.

Class	Management Objectives and Criteria	Spring TP Criterion (µg/L)	Ecoregion
A(1)	Natural condition	11[a] 11[a] 16[a]	Northeastern Highlands Northeastern Coastal Zone Eastern Great Lakes and Hudson Lowlands
B(1)	Minor change from reference condition	17	All
A(2), B(2), B(3)	Moderate change from reference condition	17	All
B (untyped)	No change from reference conditions that would have an undue adverse effect	22	All

[a] Applies upper 75th percentile of the distributions in Figure 9.

8. Nutrient Criteria for Vermont Wadeable Streams

A. Aesthetics and Recreational Uses

Defining "Natural Condition"

The management objective of maintaining the aesthetic characteristics of waters in their natural condition applies to Class A(1) waters (Table 9). The Vermont Water Quality Standards specify a TP criterion of 10 µg/L for all streams above 2,500 feet in elevation, and classify all waters above this elevation as A(1) unless specifically classified as A(2). Therefore a TP criterion of 10 µg/L currently applies to Class A(1) streams.

In the case of nitrates, the current criterion is 0.20 mg/L NO_3-N for Class A(1) and A(2) streams above 2,500 feet in elevation, and 2.0 mg/L NO_3-N for Class A(1) and A(2) streams below 2,500 feet elevation. To date however, there are few streams below 2,500 feet that have been classified as A(1).

Since total nitrogen, rather than nitrate, is the preferred causal variable for further stream nutrient criteria development in Vermont, the monitoring data were analyzed to establish a relationship between the two variables. Under the reasonable assumption that NOx concentrations approximate NO_3 for sites without oxygen depletion, TN concentrations can be predicted from measured NOx values using linear regression ($TN = 0.103 + 1.139*NOx$, $F_{1,135} = 387$, $p<0.001$, $R^2 = 0.74$). Using this relationship, the 0.2 mg/L NO_3-N criterion corresponds to a TN concentration of 0.33 mg/L, and the 2.0 mg/L NO_3-N criterion corresponds to a TN concentration of 2.4 mg/L.

The Vermont Nutrient Criteria Project data (Figure 15) provide context for these previously established criteria values for phosphorus and nitrogen. For TP, between 22% and 45% of sampled sites fall at or below the upland stream criterion value of 10 µg/L, depending on ecoregion. For TN, 30% of sampled sites the Eastern Great Lakes and Hudson Lowlands ecoregion fall at or below the Class A(1) derived TN criterion value of 0.33 mg/L, while for the other ecoregions, 65% to 70% of sites fall at or below the criterion. The USEPA population distribution approach to nutrient criteria derivation suggests the 25th percentile of all locations assessed can be taken as a suitable criterion to protect reference conditions (e.g., "natural condition"). The observed percentiles are sufficiently consistent with the USEPA approach that no change is indicated for the existing phosphorus and nitrate criteria for upland streams that are classified as A(1). However, the 2.0 mg/L nitrate criterion for lower elevation A(1) streams (corresponding to a TN value of 2.4 mg/L) may not be sufficiently protective of natural conditions since all assessed sites have TN concentrations below this value.

Defining "Consistently Excellent" and "Consistently Good" Aesthetic Value

Vermont Water Quality Standards establish the objectives of consistently excellent aesthetic value for Class A(2) and B(1) waters, consistently very good value for Class B(2) waters, and consistently good value for other Class B waters (Table 9). The aesthetic value (e.g., excellence or goodness) of waters was evaluated using the distributions of aesthetic and trophic ratings across sites visited by the Vermont Nutrient Criteria Development Project.

The trophic and aesthetic ratings are shown in relation to TP and TN in Figure 16. These data show a fairly clear gradient whereby aesthetic value declines with increasing nutrient levels. However, the use of this gradient alone to select potential thresholds for criteria

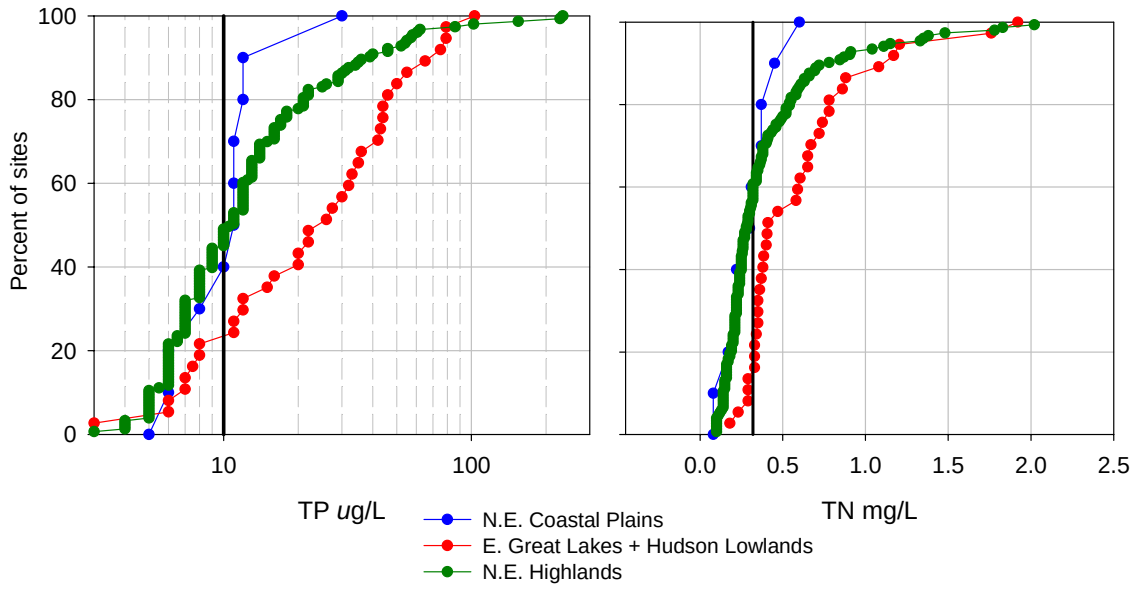

Figure 15. Cumulative distributions of total phosphorus and total nitrogen in wadeable Vermont streams, by ecoregion. The lines inscribed identify the Class A(1) criterion for total phosphorus and total nitrogen. The total nitrogen criterion limit of 0.33 mg/L was derived by linear regression from the existing Vermont criterion of 0.2 mg/L NO_3-N.

limits should be treated cautiously as there is considerable overlap in nutrient concentrations among sites of different aesthetic condition.

The results are displayed as area plots in Figure 17 showing the proportion of sites attaining the various aesthetic conditions as a function of TP. The TP range across all sites was divided into intervals, and the midpoints of each interval were used for plotting purposes. For example, at a total phosphorus concentration of 10 µg/L, all sites displayed good or better aesthetic value, 95% of sites displayed very good or better aesthetic value, and 80% of sites displayed excellent aesthetic value. By contrast, at 60 µg/L TP, 87% of sites displayed good or better aesthetic value, 39% of sites displayed very good aesthetic value, and 13% of sites displayed excellent aesthetic value.

In the case of TN, while there was a gradient whereby aesthetic quality declined with increasing TN (see Fig 16), there were numerous sites where aesthetic value was less than good, even at relatively low nitrogen concentrations, implying aesthetic value at these sites in only weakly controlled by nitrogen. Owing to this overlap, we determined that for wadeable streams, the proportion of sites meeting various aesthetic quality thresholds could only be established with confidence using TP.

The plots shown in Figure 17 were used to define TP criteria corresponding to a reasonably high probability that sites having a particular TP concentration would meet the various aesthetics conditions. For the purposes of this analysis, we applied a probability of 75%, *where possible*. However, this level of protection was not achievable in the highest quality waters, and the realities of the data necessitated the use of probabilities as low as 61% in some cases. Table 18 shows threshold concentrations determined using this approach.

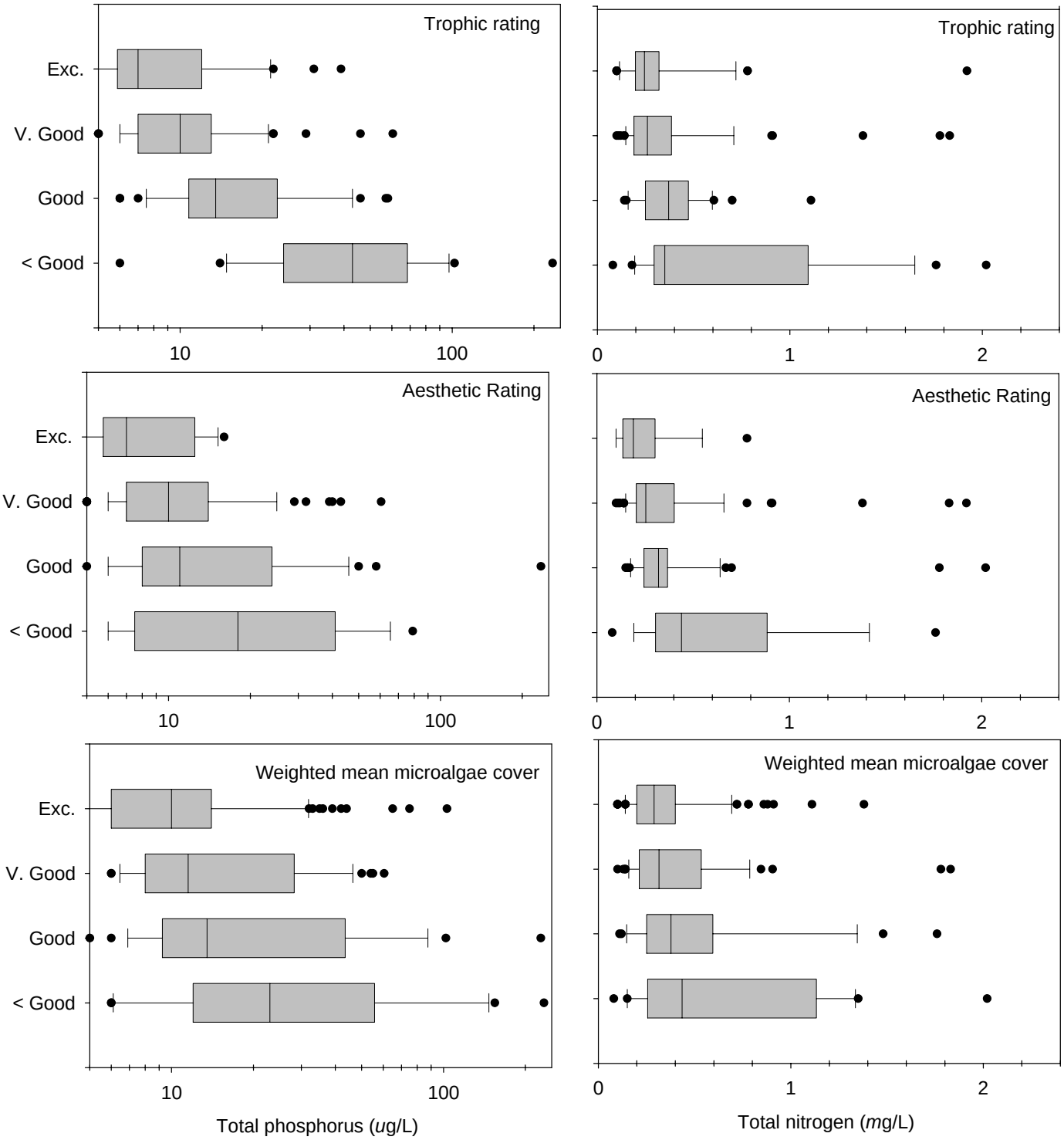

Figure 16. Total phosphorus and total nitrogen ranges by trophic and aesthetic ratings, and for percentile ranges of weighted mean microalgae, for wadeable Vermont streams. Whisker caps are 5th / 95th percentiles, and points show outlier data.

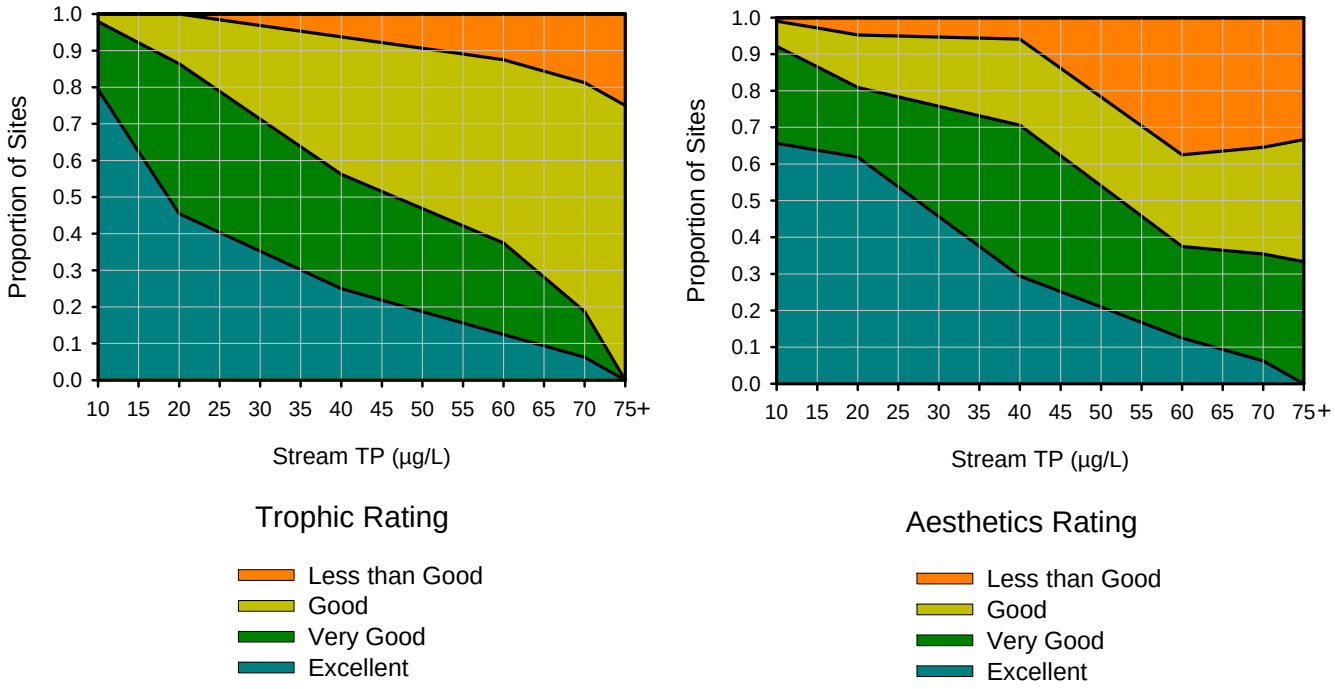

Figure 17. Proportion of sites attaining trophic and aesthetic rating categories based on total phosphorus.

Table 18. Threshold concentrations of total phosphorus derived from aesthetic, trophic, and microalgae abundance ratings.

Rating Type	Excellent aesthetic quality Class A(1), A(2), B(1)		Very good aesthetic quality Class B(2)		Good aesthetic quality Class B(3) and B(untyped)	
	TP Criterion (µg/L)	% of sites attaining condition	TP Criterion (µg/L)	% of sites attaining condition	TP Criterion (µg/L)	% of sites attaining condition
Aesthetic	10	65%	32	75%	53	75%
Trophic	12	75%	28	75%	75	75%
Microalgae	10	61%	18	75%	57	75%
Mean	10	67%	26	75%	62	75%

The aesthetic value of waters was also evaluated using the distributions of periphyton abundance across sites visited by the Vermont Nutrient Criteria Development Project. For this analysis, we examined two metrics: weighted mean macroalgal percent cover; and weighted mean microalgal filament length.

The results indicated that periphyton cover is typically quite low in Vermont streams. The weighted mean cover for macroalgae was skewed towards low values indicating at most the presence of a detectable biofilm. Zero cover was evident at ≤10% of sites, while 5% or less cover was evident for 75% of sites, and 25% or less cover was present at 90% of sites. Only ten percent of sites sampled approached a weighted mean percent cover

score equivalent to greater than 25% cover of macroalgae. The weighted mean filament length for microalgae was more evenly distributed. Few sites displayed no biofilm, while 80% of sites displayed at most 0.5 mm mean filament length. The remaining sites had weighted mean filament lengths in excess of 0.5 mm.

The ranges of these metrics were divided by the percentiles of their distributions into excellent (≤50th %), very good (51-75th %), good (76-90th %), and "less than good" (91th %-maximum) aesthetic categories. These periphyton-based aesthetic ratings were then related to TP and TN concentrations at each site (Figure 16).

When the relationships between nutrients and macroalgal cover or microalgal filament length were compared, two findings were evident. First, as with the aesthetic and trophic ratings, there was considerable overlap in the ranges of total nitrogen concentrations across the classified periphyton metrics, and this precluded the use of TN in establishing potential criteria thresholds based on periphyton metrics. Second, weighted mean microalgal filament length was observed to be more sensitive to total phosphorus concentrations than was mean macroalgal cover (i.e., filament length yielded more conservative threshold concentrations). For this reason, weighted mean microalgal filament length was chosen as the periphyton response variable for use in deriving TP criteria, using where possible the same 75% probability level employed for the aesthetic and trophic ratings (Figure 18, Table 18).

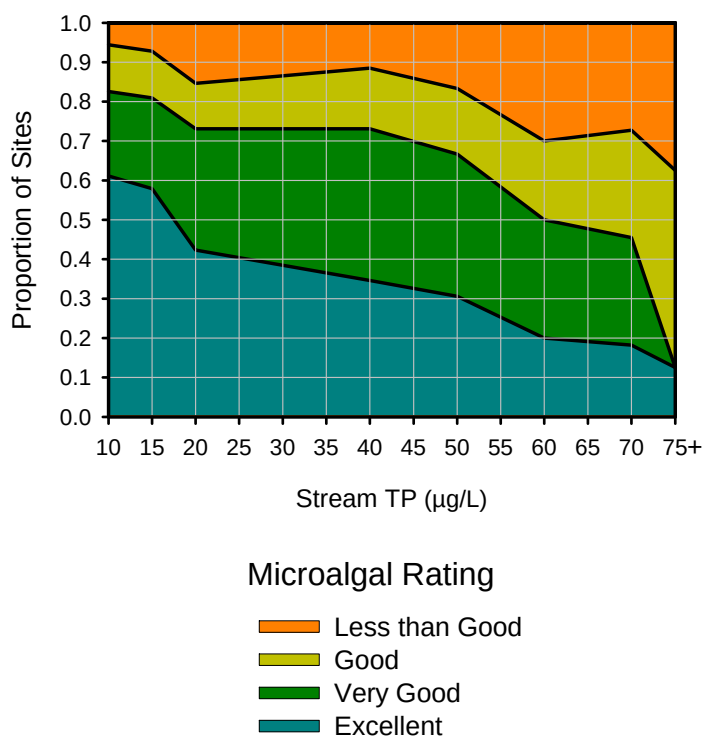

Figure 18. Proportion of sites attaining microalgal filament length rating categories based on total phosphorus. Rating categories are defined by percentiles of the distributions in Figure 16

Summary of Proposed Criteria

The nutrient thresholds shown in the preceding discussion protect aesthetics and recreational uses in the various classes of waters, and were presented as examples of how the Vermont Nutrient Criteria Development Project data could be used to derive criteria. Owing to the design of the project, the thresholds represent values derived at low flow, and as water quality criteria should be applied under low flow conditions. The mean of the thresholds provided in Table 18 are used in the criteria summary in Table 19. The Vermont Water Resources Panel may choose through public discussion and further deliberation to make different choices regarding natural phosphorus levels and acceptable frequencies of attaining various aesthetic conditions. The analysis presented here is intended to provide technical assistance for these ultimate policy decisions.

Table 19. Summary of phosphorus and nitrogen criteria to protect aesthetic and recreational uses of Vermont wadeable streams, for all ecoregions.

Class	Management Objectives and Criteria	TP Criterion (µg/L)	TN criterion (mg/L)	Notes
A(1)	Natural condition	10	0.33	TN criterion corresponds to existing nitrate criterion of 0.20 mg/L NO_3-N
A(2), B(1)	Consistently excellent value	10		
B(2)	Consistently very good value	26		
B(3)	Good value, variability allowed	62		
B(other)	Consistently good value	62		

B. Aquatic Life Uses

The Vermont wadeable stream macroinvertebrate biocriteria have been calibrated to identify distinctions between natural or "reference" conditions (Class A1), and deviations from reference conditions consistent with the descriptors "minor" (Class B1), and "moderate" (Classes A2, B2, and B3) found in the Vermont Water Quality Standards (Table 8). Eight metrics of macroinvertebrate community structure and function were used to derive an overall community assessment of natural (Class A1), minor change from reference condition (Class B1), moderate change from reference condition (Classes B2/B3), or non-attainment (NA). Metric thresholds have been derived independently for SHG, MHG, and WWMG ecotypes.

An overall community assessment does not discriminate stressors, and reflects a condition resulting from all chemical, physical and biological stressors operative in the stream system. For this reason, the macroinvertebrate trophic community index (MTCI) was developed as described previously and used to differentiate sites where nutrient enrichment may be the primary stressor affecting the macroinvertebrate community. The distribution of MTCI scores within overall community assessment categories (natural, minor, moderate, NA) was used to identify similar trophic categories. Box and whisker

plots were used to identify thresholds of MTCI values consistent with the overall community categorical rankings.

Figure 19 shows the distribution of MTCI scores with overall macroinvertebrate community scores for Medium High Gradient (MHG) streams, with MTCI scores on the Y-axis. Medians, quartiles, and 90th percentiles are indicated. These plots were used to visually select MTCI thresholds. The intent of the threshold selection was, using the "natural/minor" threshold for example, to balance the inclusion of as many of the "natural" sites as possible while excluding as many of the "minor" sites as possible. For MHG streams, those thresholds were MTCI scores of 0.3, 0.4, and 0.5 for the natural/minor, minor/moderate and moderate/non-attainment (NA) threshold respectively. Thus, sites with MTCI scores of less than 0.3 would be categorized as "natural", 0.31-0.4 as "minor change", 0.41-0.5 as "moderate change", and greater than 0.5 as "NA". A similar exercise was conducted with Small High Gradient and Warm Water Medium Gradient streams. For all three stream types, community assessment and MTCI were highly correlated ($p<0.001$, Spearman Rank Correlation).

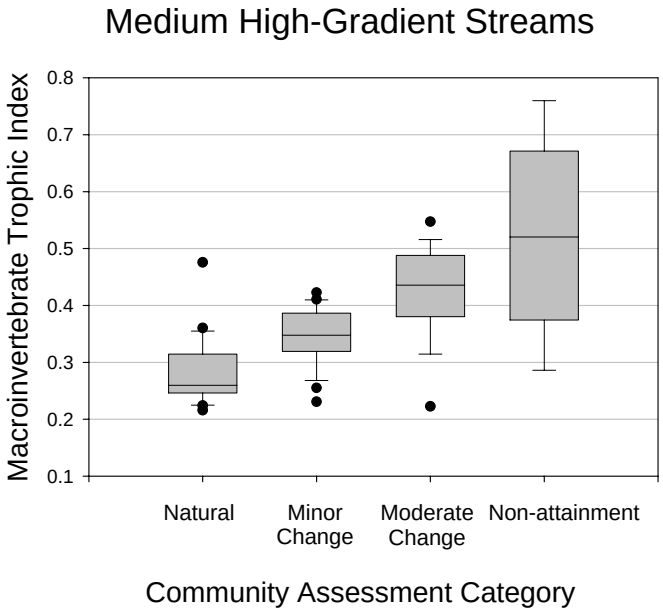

Figure 19. Medium High Gradient Streams - Distribution of Macroinvertebrate Tropic Condiditon Index scores within overall macroinvertebrate community assessment categories. Trophic condition categories were established by identifying trohic index scores differntiating community assessment categories.

Mean phosphorus and nitrogen concentrations were significantly ($p<0.05$, Kruskal-Wallis Rank ANOVA) higher in WWMG streams than in SHG and MHG streams but were not significantly different between SHG and MHG streams. Median TP concentrations in SHG, MHG and WWMG streams were 9 μg/L, 9 μg/L, and 22 μg/L respectively. Median TN concentrations were 0.240 mg/L, 0.285 mg/L and 0.535 mg/L in SHG, MHG and WWMG streams respectively.

The distributions of TP and TN within trophic categories (natural through NA) for each of the three stream eco-types were examined for the purpose of evaluating TP and TN concentrations in relation to trophic condition as measured by the MTCI (Figures 20-22). With the exception of TP in Warm Water Medium Gradient streams, there is a fairly clear distinction between nutrient concentrations between moderate or better and non-attainment trophic condition. Although the upper range of nutrient concentrations tends to expand with trophic category, mean concentrations of TN and TP were not significantly different between trophic categories natural, minor and moderate for any stream type.

Area plots that allow a visual examination of the probability of attaining a certain trophic condition at any given nutrient concentration provide a means for assessing and identifying acceptable thresholds. The data used to derive the box and whisker plots (Figures 20-22) were used to develop the area plots depicted in Figure 23.

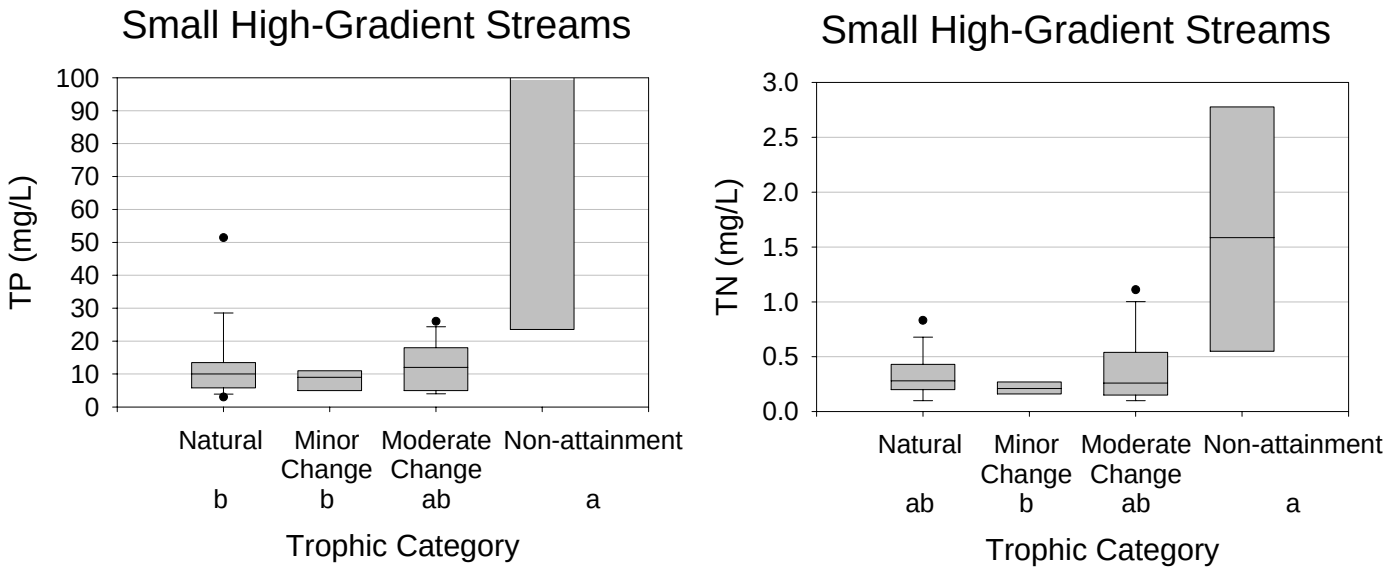

Figure 20. Distribution of TP and TN within trophic categories for Small High Gradient streams. Linear regression R^2 of TP and TN vs. MTCI were 0.247 (p=0.001) and 0.338 (p<0.001) respectively. Mean concentrations within trophic categories with the same letter are not significantly different.

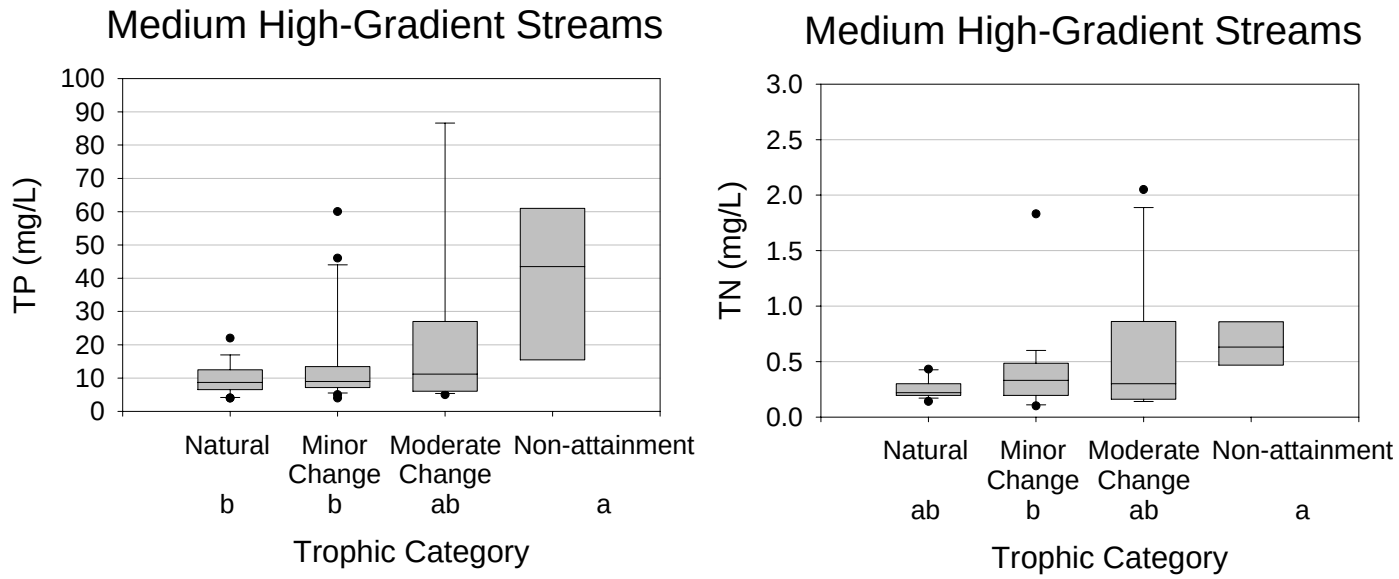

Figure 21. Distribution of TP and TN within trophic categories for Medium High Gradient streams. Linear regression R^2 of TP and TN vs. MTCI were 0.293 (p<0.001) and 0.198 (p<0.001) respectively. Mean concentrations within trophic categories with the same letter are not significantly different.

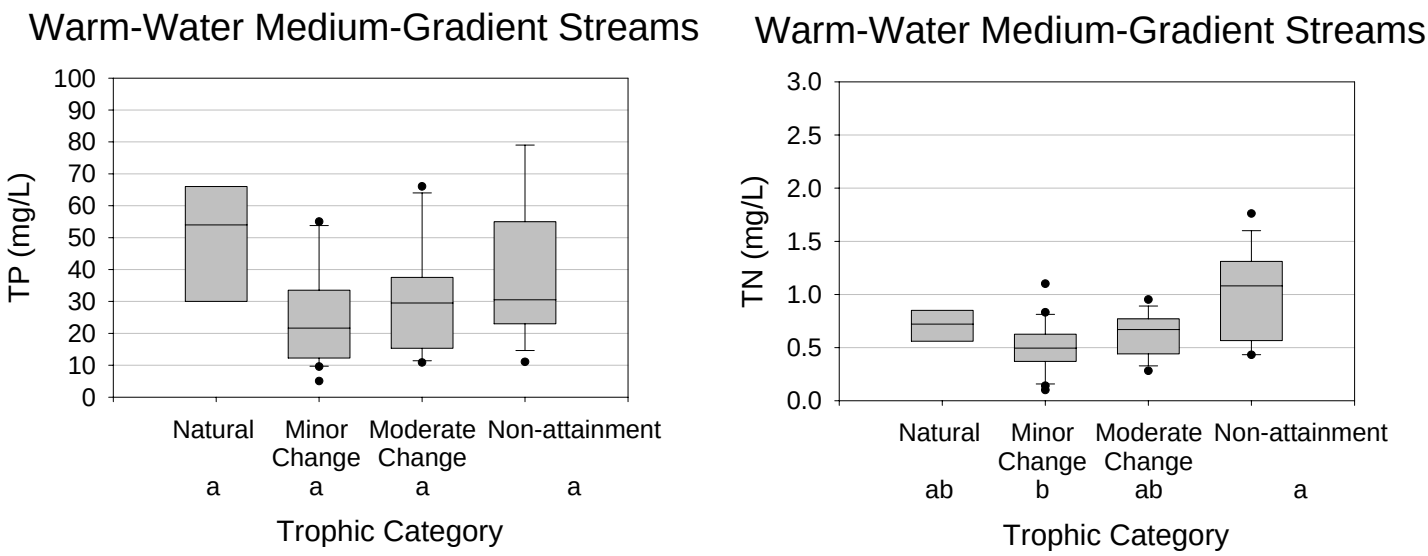

Figure 22. Distribution of TP and TN within trophic categories for Warm Water Medium Gradient streams. Linear regression R^2 of TP and TN vs. MTCI were 0.0002 (p=0.921) and 0.144 (=0.017) respectively. Mean concentrations within trophic categories with the same letter are not significantly different.

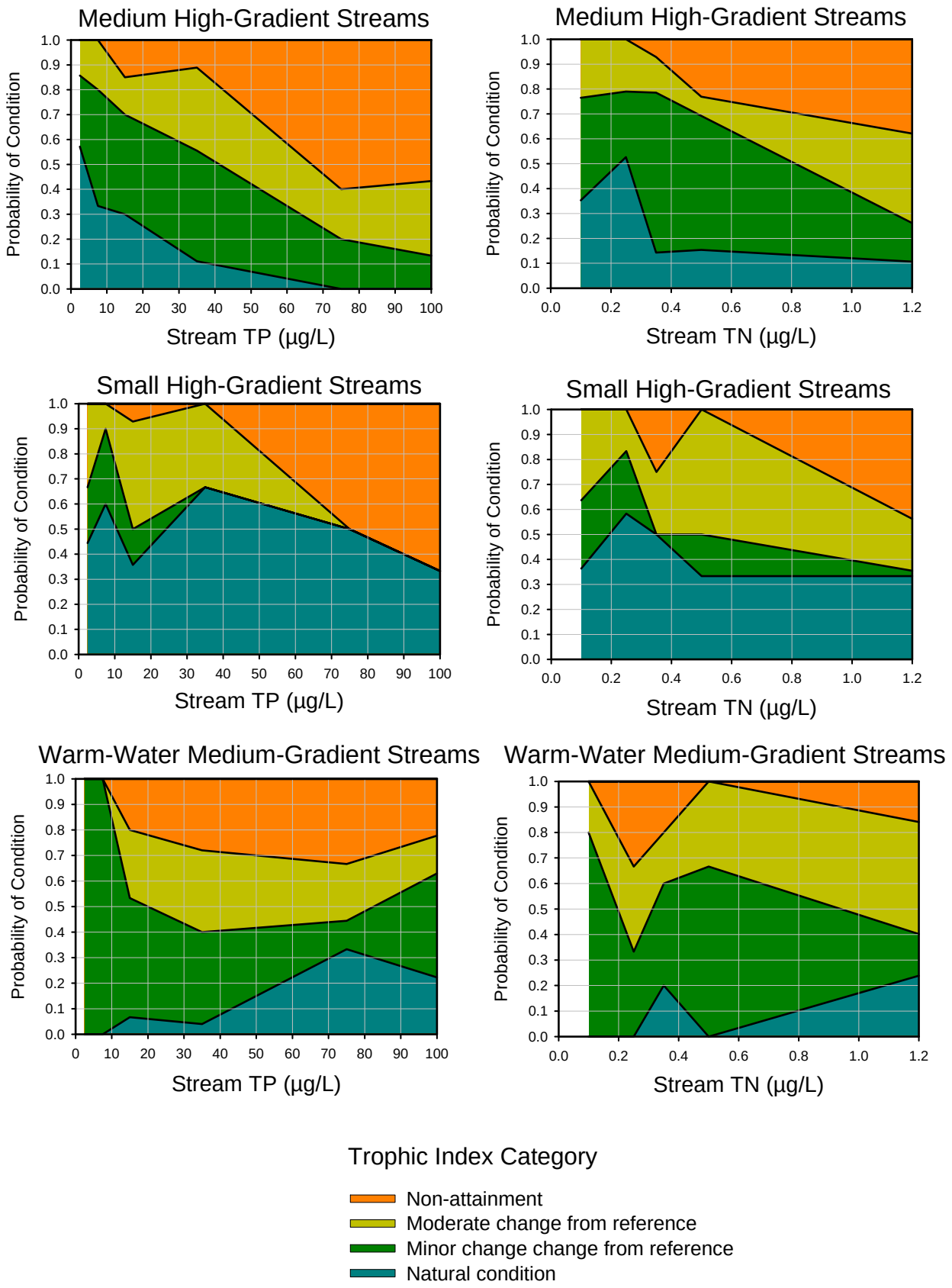

Figure 23. Proportion of sites attaining trophic condition at varying TP and TN concentrations for three wadeable stream types. Plots are used to identify potential nutrient impact thresholds.

For each stream type a plot was developed depicting the probability of a site's inclusion in a trophic category based on its observed TP or TN concentration. The plots above show quite different patterns of trophic response to TP concentrations for the three stream types.

- The MHG streams show a fairly consistent response to increasing TP and TN. As TP and TN increase, the probability of attaining natural condition decreases while the probability of a condition not supporting aquatic life use increases.
- The SHG data show a less consistent response but there is a clear threshold beyond which condition dramatically degrades.
- The WWMG plots are generally inconclusive as even at the highest TP and TN concentrations there is an equal probability of attaining natural trophic condition or of failing to support aquatic life uses. There is no consistent response of trophic condition to TP or TN concentrations.

The lack of distinction between nutrient concentration and Class A and B attainment conditions (trophic condition moderate or better) precludes the defensible derivation of meaningful trophic condition thresholds between these classes using this dataset. Therefore, the data were evaluated for the purpose of deriving a meaningful and defensible threshold for determining the probability of attainment of Class B or better aquatic life use. The area plots can be used to generate a table showing the relationship between TP and TN concentrations and the probability of use attainment. Table 20 below shows the TP and TN concentrations for SHG and MHG streams in relation to 60, 70, 80, and 90 percent probability that Class B aquatic life use will be supported if these concentrations are not exceeded. For example, in a SHG stream, if the summer base flow average TP concentration exceeded 25 µg/L, there would be a 10% probability of non-attainment of aquatic life use.

Table 20. TN and TP concentrations associated with varying probabilities of attaining Class B aquatic life use. Exceedence of a concentration would indicate an inverse probability of impairment (e.g., a concentration associated with a 90% probability of use attainment would indicate a 10% probability of impairment if exceeded).

Probability of Class B Aquatic Life Use Attainment	Small High Gradient Streams		Medium High Gradient Streams	
	TP (µg/L)	TN (mg/L)	TP (µg/L)	TN (mg/L)
90%	<25	<0.4	<15	<0.4
80%	<50	<0.8	<40	<0.8
70%	<60	<1.0	<50	<1.0
60%	<70	<1.2	<60	<1.2

An alternative way to evaluate the same data focuses less on establishing thresholds between Class and Water Management Types and more on evaluating degrees of potential impact. Sediment criteria for toxic pollutants are developed based on co-occurrence analyses similar to the data generated for this project. Pollutant concentrations indicating initial dose/response observations, or "threshold effects," are determined from observations of distributions along the dose/response continuum. At the threshold effect concentration, initial response of the biologic community to the pollutant is likely to be

observed. The response may not be adverse and may not result in an impairment, but is nonetheless evident as a response to pollutant concentrations and can serve as an early warning signal. An examination of the box and whisker plots is amenable to this analysis. As with the area plot analysis, there is no predictable relationship between nutrients and trophic condition in the WWMG streams and no further analysis will be done at this time.

The 75th percentile of TP and TN concentrations within the natural (or reference) trophic condition category can serve as an arbitrary but reasonable early response indicator. An examination of the distribution plots identifies the natural condition thresholds as follows:

- TP in SHG streams – 14 μg/L
- TP in MHG streams – 13 μg/L
- TN in SHG streams – 0.4 mg/L
- TN in MHG streams – 0.3 mg/L

In an effort to generate some meaningful dose/response within the WWMG stream type, several data stratifications were evaluated.

- Drainage area: The data plotting trophic index vs. drainage area showed very little variation for WWMG streams with a drainage area of greater than 100 km^2, but extreme variability for streams with a smaller drainage area. The data were divided into two groups – drainage area greater than 100 km^2 and drainage area less than 100 km^2. No statistically significant differences were found for median TP and TN median values between trophic categories for either group.
- Stormwater impact: Many of the stream with drainage areas less than 100 km^2 are highly impacted by stormwater, possibly confounding nutrient/trophic condition relationships. This set of small streams was divided into two groups: Chloride (indicator of urbanization and stormwater influence) greater and less than 50 mg/L. Again, no statistically significant differences were found for median TP and TN values between trophic categories for either group.
- The data do suggest that most WWMG sites that are not heavily impacted by stormwater attain moderate or better trophic condition at TP concentrations less than 70 μg/L and that most sites not attaining at least a moderate condition have TP concentrations greater than 70 μg/L. A similar observation for TN identifies an attainment threshold of 1.0 mg/L for TN.

Summary of Proposed Criteria – Aquatic Life Use

Class	Management Objectives and Criteria	TP Criterion (µg/L)	TN criterion (mg/L)	Notes
A(1)	Natural condition	SHG: 14 MHG: 14 WWMG: --	SHG: 0.4 MHG: 0.4 WWMG: --	Based on 75th percentile of "natural" trophic category.
B(1)	Minor change from reference	SHG: -- MHG: -- WWMG: --	SHG: -- MHG: -- WWMG: --	No relationships strong enough to discriminate between B(1) and B(2)
A(2), B(2), B(3), B(untyped)	Moderate change from reference	SHG: 40 MHG: 40 WWMG: 70	SHG: 0.8 MHG: 0.8 WWMG: 0.8	Based on 80% probability of attainment for SHG and MHG

9. Summary of Proposed Nutrient Criteria

Throughout the preceding sections, separate analyses have been carried out to propose criteria limits to protect aesthetics and aquatic life uses for lakes and streams. Table 21 summarizes these proposed limits in a single table, and identifies the "functional criterion" (i.e., the most stringent value) that would apply for lakes and wadeable streams in each water class.

The Vermont Water Resources Panel may choose through public discussion and further deliberation to make different choices regarding natural nutrient levels and acceptable frequencies of attaining various aesthetic and aquatic life conditions. The analyses and proposed criteria presented in this report are intended to provide technical assistance for these ultimate policy decisions.

Table 21. Summary of proposed TP and TN criteria for lakes and wadeable streams in Vermont. The "functional criterion" is defined as the most stringent criterion value for each lake and stream water class.

Water Class/Type	Lakes TP (µg/l)			Wadeable Streams TP (µg/L) / TN (mg/L)		
	Criteria to protect aesthetic uses	Criteria to protect aquatic life uses	Functional criterion	Criteria to protect aesthetic uses	Criteria to protect aquatic life uses[3]	Functional criterion
A(1)	11[1] 16[2]	11[1] 16[2]	11[1] 16[2]	10 / 0.33	SHG 14 / 0.4 MHG 14 / 0.4	10 / 0.33 10 / 0.3
A(2)	11	17	11	10	SHG 40 / 0.8 MHG 40 / 0.8 WWMG 70 / 0.8	10 / 0.8 10 / 0.8 10 / 0.8
B(1)	11	17	11	10		10
B(2)	16	17	16	26	SHG 40 / 0.8 MHG 40 / 0.8 WWMG 70 / 0.8	26 / 0.8 26 / 0.8 26 / 0.8
B(3)	24	17	17	62	SHG 40 / 0.8 MHG 40 / 0.8 WWMG 70 / 0.8	40 / .8 40 / 0.8 62 / 0.8
B(untyped)	24	22	22	62	SHG 50 / 0.8 MHG 40 / 0.8 WWMG 70 / 0.8	40 / 0.8 40 / 0.8 62 / 0.8

[1] Lakes in the Northeastern Coastal Zone and Northeastern Highlands Ecoregions, defined in Figure 9.

[2] Lakes in the Eastern Great Lakes and Hudson Lowlands Ecoregions, defined in Figure 9.

[3] SHG: Small, high gradient streams; MHG: medium, high gradient streams; WWMG: warm-water medium gradient streams.

10. Nutrient Criteria Implementation Considerations

A. Considerations for Lakes

Compliance Locations

Where numeric nutrient criteria for lakes are currently defined in the Vermont Water Quality Standards (e.g., Lakes Champlain and Memphremagog), these criteria are to be achieved in centrally-located, openwater areas, specific to geographically-identified lake segments. Vermont DEC recommends that a similar approach be adopted for nutrient criteria that are promulgated for other lakes and ponds statewide, with the exception that the criteria in general apply to individual lakes as opposed to lake segments.

Lake Size Threshold

Vermont DEC recommends for practical reasons that a size cutoff be established for application of nutrient criteria for lakes and ponds. The monitoring programs (Spring Phosphorus Program, Lay Monitoring Program, Lake Biocriteria Development Project) providing the data from which criteria were derived have always targeted lakes of 20 acres in size or larger (290 lakes plus 11 Champlain segments). There are few data from which to assess spring phosphorus concentrations for lakes smaller than this size, and lakes 20 acres or larger represent 95% of all lake acres statewide. For reasons discussed earlier in this report, spring TP criteria for Vermont inland lakes should apply only to lakes with drainage area to surface area ratios less than 500:1.

Temporal Considerations

Phosphorus criteria currently defined in the Vermont Water Quality Standards for Lakes Champlain and Memphremagog are expressed as annual average concentrations in the photic zone of each lake segment. As explained in Sections 5 and 7 (above), the criteria proposed in Table 21 were derived using spring total phosphorus concentrations, which are whole water column measurements. The use of an annual mean photic-zone concentration is therefore not appropriate. These new phosphorus criteria should be defined in the Standards as values to be measured as water column averages between the time of ice-out and the onset of thermal stratification in the spring.

Owing to the considerable year-to-year variability in spring TP concentrations, Vermont DEC requires a minimum of four years of monitoring data in order to report a mean spring total phosphorus concentration with known confidence. The confidence in the mean is expressed by Vermont DEC as a standardized coefficient of variation (standard error as a proportion of the mean). The Vermont DEC will assess attainment of any new nutrient criteria for lakes to be based on the mean spring TP concentration derived from four or more years of data, where the coefficient of variation of the mean is 10% or less.

Criteria as Screening Values

As described in Section 7, the criteria that are expressed as mean spring phosphorus concentrations are selected to protect a large proportion of lakes from exhibiting occurrences of nuisance algal growth or alteration of the phytoplankton community. Accordingly, mean spring total phosphorus concentrations should be viewed as surrogates of actual impairment of aesthetic values or biotic integrity. In terms of identifying waters for placement on the Vermont 303(d) List of Impaired Waters[29], Vermont DEC recommends that apparent violations of any nutrient criteria for inland lakes (e.g., not Champlain nor Memphremagog) be used not as sole grounds for declaring

a lake impaired, but rather as a triggers to require: 1) an assessment of the summer seasonal mean chlorophyll-a concentrations; and, 2) an assessment of the phytoplankton community using the VLCBI.. Following this assessment, mean spring phosphorus concentrations in excess of promulgated criteria limits, in conjunction with *either* chlorophyll-a resulting in less than consistently excellent, very good, or good aesthetic value, *or* VLCBI levels sufficient to cause more than a minor or moderate change from reference conditions, would indicate the need for a formal impairment listing. Once such a listing is established, the phosphorus criteria should serve as goals for total maximum daily load analyses or other pollution control initiatives.

Implications for Impairment Listing

A list of Vermont inland lakes and their average spring phosphorus concentrations (sorted from high to low) is provided in Section 11. This list may be used to evaluate the compliance and impairment listing implications of the lake phosphorus criteria proposed in this report or other phosphorus criteria values considered by the Water Resources Panel.

Implications for Permitting

Adopting numeric phosphorus criteria for Vermont inland lakes with drainage area to surface area ratios greater less than 500:1 is not likely to have major implications for wastewater discharges. At present, only a very few such Vermont lakes (e.g., Harriman Reservoir in Whitingham, Crystal Lake in Barton) serve as a receiving water for a permitted direct wastewater discharge in its watershed.

Phosphorus Criteria for Lake Champlain and Lake Memphremagog

The phosphorus criteria proposed in this report are not intended to be applied to Lake Champlain or Lake Memphremagog. No data from these two large lakes were used in the analyses presented in this report. The existing phosphorus criteria for these lakes in the Vermont Water Quality Standards were derived from a previous analysis using a separate dataset. The existing phosphorus criteria for Lake Champlain are serving as the basis for water quality agreements between Vermont, New York, and Quebec, the comprehensive basin plan adopted by the Lake Champlain Basin Program, and the Lake Champlain Phosphorus TMDL. For these reasons, the criteria for Lake Champlain and Lake Memphremagog should not be altered as a result of this analysis.

B. Considerations for Wadeable Streams

Compliance Locations

Measurements to determine exceedences of the threshold criteria should be made in a section of the stream representative of well-mixed flow. Standard sample collection procedures should be followed. Below permitted discharges, compliance should be determined at the edge of the mixing zone.

Flow Conditions

The threshold values identified in this document for wadeable streams are based on the presumption that maximum periphyton accrual potential occurs during periods of extended low summer flow. The threshold values are intended to represent mean nutrient concentrations maintained during those low flow periods. Therefore, any assessment of potential threshold value exceedence should be done in the context of assessing mean concentrations at low flows, either through modeling (e.g., determining permit limits for a point discharge) or through analysis of multiple samples collected during periods of low

flow. We recommend that the lowest median monthly flow that occurs during the summer growing season (generally the August median flow) be used to assess compliance with the nutrient thresholds. Recommendations for the number of samples required to determine a mean concentration may be determined on a site-specific basis but should in no case be less than three samples collected at low flows.

Criteria as Screening Values

As discussed in previous sections, threshold or screening values do not provide a conclusive indication of impairment of aquatic life designated uses, but rather provide an indication of the probability that aquatic life uses are adversely impacted. Exceedence of these threshold values should be used to trigger a more rigorous assessment of the aquatic biota. Actual impairment of aquatic life uses must be determined through an assessment of the aquatic macroinvertebrate or fish communities using standard Vermont DEC protocols for determining aquatic life use impairments.

Implications for Permitting and Impairment Listing

If numeric criteria for TP and TN were adopted for Vermont wadeable streams, then all existing NPDES discharges would need to be screened for their potential to cause or contribute to exceedences of these threshold criteria at design flows during critical seasons. Site-specific aesthetic and biologic assessments would be required at sites where dilution analysis indicated thresholds were exceeded to determine use support status.

A rough estimate based on existing NPDES information suggests that if a TP effluent concentration of 1.0 mg/L were discharged at design discharge rates at low median monthly flow, approximately 17 permitted discharges would show a potential to exceed the Class B (WMT2-3) aquatic life use TP threshold value of 0.040 mg/L. Similarly, for TN discharged at 4.0 mg/L under the same conditions, approximately three permitted discharges would show a potential to exceed the Class B (WMT2-3) threshold value of 0.8 mg/L. Aesthetic use thresholds for TP in Class B1 waters (0.026 mg/l) would be exceeded at 29 permitted discharges. Future permitting decisions would have to include an assessment of the potential for TP and TN exceedences of these threshold values.

11. List of Spring Phosphorus Concentrations in Vermont Lakes

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
HALFMOON	B	Fletcher	58	375	21
JEROME	B	Addison	83	220	18
SHELBURNE	B	Shelburne	83	92	452
COGGMAN	B	West Haven	83	76	20
RICHVILLE	B	Shoreham	83	62	129
MUD (CRAFBY)	B	Craftsbury	58	49	35
TICKLENAKED	B	Ryegate	58	41	54
LILY (POULTY)	B	Poultney	83	36	22
COLCHESTER	A2	Colchester	83	35	186
VALLEY	B	Woodbury	58	32	88
HOUGH	B	Sudbury	83	29	16
IROQUOIS	B	Hinesburg	83	28	243
LONG (MILTON)	B	Milton	83	27	47
FAIRFIELD	B	Fairfield	58	25	446
CARMI	B	Franklin	58	25	1402
PINNEO	B	Hartford	58	25	50
GREAT HOSMER	B	Craftsbury	58	25	140
ROUND (MILTON)	B	Milton	83	24	22
MILL (BENSON)	B	Benson	83	23	39
WINONA	B	Bristol	83	23	248
HARRIMAN (NEWBRY)	B	Newbury	58	22	20
BAKER (BARTON)	B	Barton	58	22	51
LOWER	B	Hinesburg	83	21	58
INDIAN BROOK (ESSEX)	A2	Essex	83	21	50
TILDYS	B	Glover	58	21	33
INMAN	A2	Fair Haven	83	21	85
WATERBURY	B	Waterbury	58	19	839
N.E. DEVELOPERS	B	Wells	83	18	27
SPRING (SHRWBY)	B	Shrewsbury	58	18	66
SILVER (GEORGA)	A2	Georgia	83	18	27
RICHMOND	B	Richmond	58	18	24
TOAD (CHARTN)	B	Charleston	58	18	22
MOLLYS	B	Cabot	58	18	38

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
BLISS	B	Calais	58	18	46
CURTIS	B	Calais	58	17	72
STAR	B	Mount Holly	58	17	63
HIGH (SUDBRY)	B	Sudbury	58	17	20
CHITTENDEN	B	Chittenden	58	17	702
MILTON	B	Milton	83	17	24
NORTH ST. ALBANS	B	Fairfax	83	17	35
MUD (MORGAN)-N	B	Morgan	58	17	35
PARKER	B	Glover	58	16	250
BEEBE (HUBDTN)	B	Hubbardton	83	16	111
ELFIN	B	Wallingford	58	16	16
BROWNINGTON	B	Brownington	58	15	139
BLACK (HUBDTN)	B	Hubbardton	83	15	20
CEDAR	B	Monkton	83	15	123
WOLCOTT	B	Wolcott	58	15	74
MCALLISTER	B	Lowell	58	15	25
BLUEBERRY	B	Warren	58	15	48
STEVENS	B	Maidstone	58	15	26
MILL (WINDSR)	B	Windsor	59	15	77
ECHO (HUBDTN)	B	Hubbardton	83	15	54
HARDWOOD	B	Elmore	58	15	44
GLEN	B	Castleton	83	15	206
RUNNEMEDE	B	Windsor	59	15	62
SILVER (BARNRD)	B	Barnard	58	14	84
BOMOSEEN	B	Castleton	83	14	2360
LONG (GRNSBO)	B	Greensboro	58	14	100
ARROWHEAD MOUNTAIN	B	Milton	83	14	760
LAUREL	B	Whitingham	58	14	16
PARAN	B	Bennington	83	14	40
HORTONIA	B	Hubbardton	83	14	479
DERBY	B	Derby	58	14	207
FORESTER	B	Jamaica	58	14	9
ST. CATHERINE	BC	Wells	83	14	904
CRANBERRY MEADOW	B	Woodbury	58	14	28
HALLS	B	Newbury	58	13	85

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
GREENWOOD	B	Woodbury	58	13	96
LOWER WORCESTER	B	Worcester	58	13	35
FERN	B	Leicester	83	13	69
CLYDE	B	Derby	58	13	186
GATES	B	Whitingham	58	13	30
ROOT	B	Benson	83	13	18
LOVES MARSH	B	Castleton	83	13	62
MOLLYS FALLS	B	Cabot	58	13	397
ZACK WOODS	B	Hyde Park	58	13	23
LOWER SYMES	B	Ryegate	58	13	57
SUNRISE	B	Benson	83	13	57
ELMORE	B	Elmore	58	13	219
LONG (EDEN)	B	Eden	58	13	97
ROUND (NEWBRY)	B	Newbury	58	12	30
TURTLEHEAD	B	Marshfield	58	12	69
EWELL	B	Peacham	58	12	51
LITTLE (WELLS)	B	Wells	83	12	162
SOUTH ST. ALBANS	B	Fairfax	83	12	27
MOREY	B	Fairlee	58	12	547
MUD (PEACHM)	B	Peacham	58	12	34
OLD MARSH	B	Fair Haven	83	12	131
NEAL	B	Lunenburg	58	12	185
STOUGHTON	B	Weathersfield	58	12	56
NORTH MONTPELIER	B	East Montpelier	58	12	72
MCCONNELL	B	Brighton	58	12	87
LILY (VERNON)	B	Vernon	59	12	41
COLTON	B	Killington	58	12	27
NORTH HARTLAND	B	Hartland	59	12	215
GALE MEADOWS	B	Londonderry	58	12	195
HOWE	A2	Readsboro	58	12	52
GREEN RIVER	B	Hyde Park	58	12	554
SADAWGA	B	Whitingham	58	12	194
DANIELS	B	Glover	58	11	66
MUD (THETFD)	B	Thetford	58	11	20
UPPER SYMES	B	Ryegate	58	11	20

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
HARVEYS	B	Barnet	58	11	351
HINKUM	B	Sudbury	83	11	60
FOREST (AVERLL)	B	Averill	58	11	62
FAIRLEE	B	Thetford	58	11	457
MIRROR	B	Calais	58	11	85
WHEELER (BRUNWK)	B	Brunswick	58	11	66
MAY	A2	Barton	58	11	116
PAUL STREAM	B	Brunswick	58	11	20
BAKER (BRKFLD)	B	Brookfield	58	11	35
SODOM	B	East Montpelier	58	11	21
NORTH SPRINGFIELD	B	Springfield	58	11	290
JOHNSON (ORWELL)	B	Orwell	83	11	20
ROOD	B	Williamstown	58	11	23
LITTLE HOSMER	B	Craftsbury	58	11	180
BARBER	B	Pownal	58	11	19
DENNIS	B	Brunswick	58	11	49
BRANCH	A1	Sunderland	58	11	34
METCALF	B	Fletcher	58	10	81
CHARLESTON	B	Charleston	58	10	40
WARDEN	B	Barnet	58	10	46
KENT	B	Killington	58	10	99
COLBY	B	Plymouth	58	10	20
LOWELL	B	Londonderry	58	10	109
MARTINS	B	Peacham	58	10	82
WAPANACKI	B	Wolcott	58	10	21
NOYES	B	Groton	58	10	39
WEST MOUNTAIN	B	Maidstone	58	10	60
AUSTIN	B	Hubbardton	83	10	28
WRIGHTSVILLE	B	East Montpelier	58	10	190
ADAMS (WOODFD)	B	Woodford	58	10	21
KNAPP BROOK #2	B	Cavendish	58	10	35
PENSIONER	B	Charleston	58	10	173
SALEM	B	Derby	58	10	764
LYFORD	B	Walden	58	10	33
WALLACE	B	Canaan	58	10	532

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
KENNY	B	Newfane	58	10	26
JACKSONVILLE	B	Whitingham	58	10	20
BURR (SUDBRY)	B	Sudbury	83	10	85
ABENAKI	B	Thetford	58	10	44
RAPONDA	B	Wilmington	58	9	121
LEVI	B	Groton	58	9	22
CHIPMAN	B	Tinmouth	58	9	79
HORSE	B	Greensboro	58	9	32
WANTASTIQUET	B	Weston	58	9	44
DANBY	B	Danby	58	9	56
LAKOTA	B	Barnard	58	9	20
COLE	B	Jamaica	58	9	41
BERLIN	A2	Berlin	58	9	293
SABIN	B	Calais	58	9	142
OSMORE	B	Peacham	58	9	48
PERCH (BENSON)	B	Benson	83	9	24
MUD (GRANBY)	B	Granby	58	9	55
SHIPPEE	B	Whitingham	58	9	24
SPECTACLE	B	Brighton	58	9	103
SUNSET (BRKFLD)	B	Brookfield	58	9	25
SOUTH (EDEN)	B	Eden	58	9	103
CRESCENT	B	Sharon	58	9	20
BIG	B	Woodford	58	9	31
KNAPP BROOK #1	B	Cavendish	58	9	25
KETTLE	B	Groton	58	9	109
EAST LONG	B	Woodbury	58	9	188
ATHENS	B	Athens	58	9	21
LEFFERTS	B	Chittenden	58	9	55
COLLINS	B	Hyde Park	58	9	16
FLAGG	B	Wheelock	58	9	111
GILLETT	B	Richmond	58	9	30
KEISER	B	Danville	58	9	33
COLES	B	Walden	58	9	125
SHADOW (CONCRD)	B	Concord	58	9	128
DEER PARK	B	Halifax	58	9	22

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
SILVER (LEICTR)	B	Leicester	58	9	101
EMERALD	B	Dorset	58	9	28
PIGEON	B	Groton	58	9	69
COITS	B	Cabot	58	9	40
RICKER	B	Groton	58	9	95
NULHEGAN	B	Brighton	58	9	37
GROUT	B	Stratton	58	9	84
BLACK (PLYMTH)	B	Plymouth	58	9	20
BUCK	B	Woodbury	58	8	39
NICHOLS	B	Woodbury	58	8	171
CHANDLER	A2	Wheelock	58	8	68
GROTON	B	Groton	58	8	422
SHAFTSBURY	B	Shaftsbury	83	8	27
NINEVAH	B	Mount Holly	58	8	171
THURMAN W. DIX	A2	Orange	58	8	123
LILY (LONDRY)	B	Londonderry	58	8	21
MILES	B	Concord	58	8	215
PEACHAM	B	Peacham	58	8	340
WEST HILL	B	Cabot	58	8	46
MANSFIELD	B	Stowe	58	8	38
RUTLAND CITY	A2	Rutland Town	58	8	13
JOES (DANVLL)	B	Danville	58	8	396
EDEN	B	Eden	58	8	194
AMHERST	B	Plymouth	58	8	81
WEATHERHEAD HOLLOW	B	Guilford	58	8	33
SEYMOUR	B	Morgan	58	8	1769
DUNMORE	B	Salisbury	83	8	985
HARTWELL	B	Albany	58	8	16
RESCUE	B	Ludlow	58	7	180
MCINTOSH	B	Royalton	58	7	23
ECHO (CHARTN)	B	Charleston	58	7	550
HALF MOON	B	Hubbardton	83	7	23
ISLAND	B	Brighton	58	7	626
MUD (LEICTR)	B	Leicester	83	7	23
NORTON	B	Norton	58	7	583

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
BANCROFT	B	Plainfield		7	14
FOSTERS	B	Peacham	58	7	61
SHADOW (GLOVER)	B	Glover	58	7	210
SOUTH (BRKFLD)	B	Brookfield	58	7	16
SUNSET (BENSON)	B	Benson	83	7	202
HIDDEN	B	Marlboro	58	7	17
ECHO (PLYMTH)	B	Plymouth	58	7	104
TURTLE	B	Holland	58	7	27
WOODWARD	B	Plymouth	58	7	106
SOUTH (MARLBR)	B	Marlboro	58	7	68
BEAVER (HOLLND)	B	Holland	58	7	40
HOLLAND	B	Holland	58	7	325
BALD HILL	B	Westmore	58	7	108
BEAN (LYNDON)	B	Lyndon	58	7	24
NEWARK	B	Newark	58	7	153
ROACH	B	Hubbardton	83	7	20
PLEASANT VALLEY	A2	Brattleboro	58	7	25
LONG (WESTMR)	B	Westmore	58	6	90
SUNSET (MARLBR)	A2	Marlboro	58	6	96
BEAN (SUTTON)	B	Sutton	58	6	30
MITCHELL	B	Sharon	58	6	28
MILLER	B	Strafford	58	6	64
ELLIGO	B	Craftsbury	58	6	174
NORFORD	B	Thetford	58	6	21
CASPIAN	B	Greensboro	58	6	789
JOBS	B	Westmore	58	6	39
FOREST (CALAIS)	B	Calais	58	6	133
SWEET	B	Guilford	58	6	20
RESERVOIR	B	Ludlow	58	6	32
CENTER	B	Newark	58	6	79
MAIDSTONE	B	Maidstone	58	6	745
GREAT AVERILL	B	Norton	58	6	828
DUCK (WATRFD)	B	Waterford	58	5	16
WILLOUGHBY	B	Westmore	58	5	1687
CRYSTAL (BARTON)	B	Barton	58	5	763

Lake name	Class	Town	Ecoregion*	Mean Spring TP (µg/L)	Lake Area (acres)
LITTLE AVERILL	B	Averill	58	4	467

* 58) Northeastern Highlands; 59) Northeastern Coastal Zone; 83) Eastern Great Lakes and Hudson Lowlands

12. References

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