Regional Patterns of Total Phosphorus in Lakes of the Northeastern United States

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ABSTRACT

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A map of total phosphorus regions has been compiled for lakes in the glaciated portion of the northeastern United States. Total phosphorus data from over 2,600 of the approximately 22,000 lakes larger than 1 hectare in the study area were used for the analysis. Many of the lake regions delineated include lakes with widely differing phosphorus levels. The distinguishing feature of each region is the distribution, or mosaic, of lake phosphorus values. The pattern of values is determined by, or associated with, the particular landscape characteristics of that region and differs in comparison to patterns of lake phosphorus values in adjacent regions. Characteristics examined included: physiography, land cover/land use, vegetation (both potential and existing), soil type, and bedrock and surficial geology. For some regions, where summer lake phosphorus data were sparse, increased emphasis was placed on using combinations of landscape characteristics to refine boundaries. This method comprised using those characteristics most strongly associated with patterns of summer phosphorus data elsewhere in the region and/or patterns developed and qualitatively adjusted from lakes sampled during other seasons. Accompanying the map are descriptions of the distinctive attributes of each region, the reliability of the data used for analysis, and frequency distributions of known and estimated summer total phosphorus concentrations in lakes. The predictive power of similar regionalizations (Omernik 1987, Omernik et al. 1988) has been evaluated using independent data sets (Larsen et al. 1986, Omernik et al. 1991) and the regionalizations have proven useful for managing lakes in the Midwest (Heiskary et al. 1987, Heiskary and Walker 1988, Fulmer and Cooke 1990, Omernik et al. 1991, Lillie et al. 1993). This regionalization is offered as a framework for further verification and application to lake management decisions and the setting of regionally appropriate goals for attainable water quality in lakes of the northeastern United States.

Key Words: regionalization, total phosphorus, trophic state, attainable quality, lake management, lake restoration.

The thousands of lakes, ponds, and reservoirs in the northeastern United States comprise an invaluable resource. Reports from the northeastern states to Congress, mandated by section 305(b) of the 1972 Federal Water Pollution Control Act, indicate that the water quality of many lakes within the region is threatened. Although lakes undergo natural changes in trophic state, activities within their watersheds can increase loads of sediment and nutrients and lead to accelerated rates of eutrophication and water quality degradation. Because the types and natural characteristics of lakes, and resiliencies of lakes to human perturbations, vary considerably among regions, spatial frameworks are useful for evaluating and protecting water quality within realistic social and economic constraints. These frameworks can be used to effectively prioritize lakes for conducting research and monitoring, extrapolating site-specific results to other lakes, and determining what level of quality is realistically attainable in preservation and restoration efforts.

Like many natural phenomena, no two lakes are exactly alike; however, regions can be identified that contain lakes of similar type, water quality or distinctive combination of types and quality. The regional patterns in lakes are associated with patterns in landscape characteristics, including surficial geology, bedrock geology, soils, vegetation, land surface form, and land use (Moyle 1956, Omernik 1987, Canfield and Hoyer 1988, Jones and Knowlton 1993). These regional patterns in lake types, characteristics, and quality are hierarchical. North America can be broken into several large, generally distinct lake regions based on climate, on the effects of continental or alpine glaciation, on the presence of karst topography, etc. Within some of these regions, such as the regions of continental glaciation in the northeastern United States and Upper Midwest, there are lake sub-regions that, regarding lake trophic state, are recognizable at a larger map scale (smaller area) (Omernik et al. 1988). Even within these sub-regions, the trophic state of lakes varies due to individual differences in lake hydrology, morphometry, and the amount of internal nutrient loading (Fulmer and Cooke 1990, Omernik et al. 1991).

Grouping lakes into regions within which similar factors affect trophic state provides a sound basis for identifying representative lakes to structure lake management. The combination of landscape characteristics important in defining regions of similarity in trophic state, and the relative importance of each characteristic, differ from area to area. Identifying which characteristics may be limiting lake quality, and whether they can be controlled, will yield a better understanding of what level of quality is realistically attainable for lakes in each region.

Much of the work of defining natural regions, evaluating their predictive power, and applying results to lake management has centered on the midwestern United States. Regional frameworks have been developed (Omernik 1987, Omernik et al. 1988) and effectively implemented there for such lake management purposes as: monitoring trends in water quality (MPCA 1986), establishing realistically attainable protection and restoration goals (Heiskary et al. 1988, Heiskary 1989*a*, Heiskary and Wilson 1989, and Fulmer and Cooke 1990), and refining predictive equations for lake trophic state (Lillie et al. 1993).

Similar work with regional frameworks in the northeastern United States is lacking. Correlation between patterns in lake water chemistry and physiographic regions has been noted in Connecticut (Deevey 1940) and has been used to partition variability in physical/chemical lake relationships for areas of the Northeast (Linthurst et al. 1986). However, the trophic state of lakes within physiographic regions is generally far too heterogeneous for lake management decisions to be based on physiographic region alone. Moreover, classification by physiographic region fails to account for visible patterns that are sometimes associated with specific combinations of other landscape characteristics such as soils, surficial geology, and land use/land cover.

The goal of this study was to identify regional patterns in the trophic state of lakes in the glaciated portion of the northeastern United States and to describe the landscape factors associated with those patterns. It is important to note that regional descriptions represent existing conditions, and that characterizations were not based on strictly pristine or best quality lakes in an area. However, natural and anthropogenic causes of variability within apparent regions were examined. Total phosphorus was used as the indicator of lake trophic condition, based on its role in controlling the fertility of most lakes, because it is sampled with standard methods, and because total phosphorus data are widely available. The correlation of total phosphorus with trophic condition may be weaker in lakes dominated by macrophytes rather than algae (Welch and Kelly 1990). Summer (mid-June to mid-September) concentration patterns were shown because of the relative availability of data and proportionately high rate of lake use during this period. The relevant landscape processes related to trophic state were evaluated using maps of physiography, soil type, land use/land cover, vegetation (both potential and existing), and bedrock and surficial geology.

Methods

Source Materials

The 2,691 lakes used to define phosphorus regions represent about 12% of the approximately 22,000 lakes, ponds, and reservoirs larger than 1 hectare found in the area. These data were acquired from federal and state agencies and universities. We used the most recent data available for coverage of the area and did not use data collected prior to 1975. Data sets of potential use in this analysis were inspected along with their documentation to determine the degree to which the sampling, analysis, and reporting methods employed were consistent and monitored for quality. Although sampling methodology and laboratory analysis techniques were not identical for all data sets selected for use, they are generally comparable and adequate for analysis at a regional scale (Table 1). Maps of landscape characteristics and environmental data were assembled with the assistance of participating state personnel. Many sources and maps of varying scales were used during the regionalization process (Table 2). The use of multiple source materials to obtain information on the distribution of landscape characteristics helped to compensate for gaps in the data at particular scales and for differences in the quality of the data compiled in thematic maps (Omernik, in press).

Preliminary Variability Analysis

The bulk of phosphorus values available represented summer lake samples, and in order to

Table 1.—Lake total phosphorus data used in map compilation, listed by contributing agency, with sampling year, and laboratory analysis method and quality.

State Source	Years Sampled	Number of Lakes	Total Phosphorus Analysis Method	Quality Assurance
Connecticut - CT				
CT Agric Exp Sta[a]	1978-80	47	persulfate[b] single solution[c]	analytical uncertainty= +/-4 µg/l[d]
CT-DEP[e]	1989-90	49	colorimetric phosphomolybdate[f]	detection = 1µg/l[g] precision = 10.7%[h] accuracy = 88.5% w/in 2 SD
USEPA-NLS[i]	1984	24	persulfate digestion automated color- imetric phospho- molybdate[j]	detection = 2µg/l prec. = 8.6 @100 µg/l[k] accur. = 18.5 @ 27 µg/l[l]
Maine - ME				
ME-DEP[m]	1980-90	479	modified[n] single reagent[o]	detection = 0.5 µg/l precision = 16.3% accuracy = 99.5%
USEPA-NLS	1984	234	see CT entry	see CT entry
Massachusetts - MA				
MA-DEP[p]	1978-92	13	not available	not available
USEPA-NLS	1984	98	see CT entry	see CT entry
New Hampshire - NH				
NH-DES[q]	1976-90	503	ammonium persul- fate single agent ascorbic acid[r]	detection = 5µg/l prec.=1.3@50 µg/l[s] accur.=104.8 +/-4.1[s]
USEPA-NLS	1984	87	see CT entry	see CT entry
New Jersey - NJ				
NJ-DEP[t]	1988-92	57	manual ascorbic acid reduction[u]	detection = 20 µg/l precision = +/-20[v] accur.= 100% +/- 25[w]
USEPA-NLS	1984	19	see CT entry	see CT entry
New York - NY				
NY-DEC[x]	1982-89	320	manual ascorbic acid reduction[u]	detection = 2 µg/l prec.=6.4@30 µg/l[s] accuracy = 103%[s]
Adirondack Lake Survey Corp[y]	1984-87	928	modified[z] of auto. single reagent[aa]	detection = 5 µg/l QC compare to

Table 1 continued.

				control limits; triplicates every 20 samples [z]
USEPA-NLS	1984	240	see CT entry	see CT entry
Pennsylvania-PA				
PA-DER[bb]	1978-92	62	automated method (Technicon) 365.3[cc]	detection = 5 μg/l prec.=1.5 @ 30 μg/l accur. = 93.8%
USEPA-NLS	1984	106	see CT entry	see CT entry
Rhode Island-RI				
Univ. of RI[dd]	1988-91	35	persulfate oxidation Technicon Anal.[ee]	detection = 5ug/l prec.=3 @ 150 μg/l[s] accur.= 98.7% +/- 2.9
USEPA-NLS	1984	15	see CT entry	see CT entry
Vermont-VT				
VT-DEC[ff]	1978-89	198	auto. persulfate digestion[gg]	detection = 3 μg/l[s] prec. = 10%[hh] accur.=100% +/- 20[s]
USEPA-NLS	1984	61	see CT entry	see CT entry

Footnotes

a. Frink and Norvell 1984
b. Gales et al. 1966
c. Murphy and Riley 1962
d. Norvell and Frink 1975
e. CT-DEP 1991
f. Fishman and Friedman 1989
g. Friedman and Erdman 1989
h. relative standard deviation
i. kanciruk et al. 1986
j. Kanciruk et al. 1986
k. root mean square of relative standard deviation
l. relative error calculated from subsequent survey Best et al. 1987
m. ME-DEP unpub. data
n. ME-DPH 1980
o. Method 424G in APHA 1981
p. MA-DEP unpub. data
q. NH-DES unpub. data
r. NH-DES 1991 based on 365.2 in US-EPA 1983, and 424f in APHA 1985
s. best estimate based on subsequent analysis
t. NJ-DEP unpub. data, NJ-DEP 1989; NJ-DEP 1991
u. Method 355.2 in US-EPA 1979
v. relative percent difference; control 1974
w. % recovery; control limits
x. NY-DEC unpub. data
y. ALSC unpub. data
aa. US-EPA 1971
bb. PA-DER unpub. data
cc. Method 365.3 in US-EPA 1974
dd. Green et al. 1989-92
ee. Nowicki 1986
ff. VT-DEC unpub. data
gg. US-EPA 1983
hh. mean relative percent difference

maximize comparability, we chose to use only summer values wherever possible. Epilimnetic, mid-lake samples collected during the growing season (mid-June to mid-September) were screened to exclude obvious outliers and reported as a mean for all summer values recorded per lake. For Vermont, which collected primarily spring values, and Pennsylvania, which reported phosphorus as a yearly average, this was not possible (adjustments made to these data are described in the following two paragraphs). We also used fall values generated by the National Lake Survey (NLS; Linthurst et al. 1986), conducted in the Northeast in 1984, to confirm apparent patterns based on data from other sources. While absolute values might display differences between seasons, general patterns in the high-quality, independent NLS data and associated landscape characteristics were used to verify regions and assess comparability of data from other sources, particularly at state lines where different sources were used on either side of the line.

Because phosphorus concentrations can differ seasonally, we needed to determine how patterns developed from data sampled in the spring in Vermont could be used in conjunction with data sampled in summer in the surrounding states. To achieve this, we examined the magnitude of variation between those Vermont lakes for which there existed both spring and summer values. Average spring total phosphorus values were regressed against average summer values measured in the same lake for all but one outlying hyper-eutrophic lake. Regression results were poor but showed spring values were generally lower than summer values (spring = 0.48 summer + 7.61; r^2=0.32; n=17 stratified lakes only).

Because our approach to spatial analysis of the phosphorus values entailed placing each lake into one of eight classes, (from less than 5 µg/L, to greater than 50 µg/L of total phosphorus), it seemed appropriate to examine the degree to which Vermont lakes shift classes between spring and summer sampling, rather than use a poor linear model. Approximately 50% of the lakes with spring total phosphorus values less than 15 µg/L shifted one to four classes upward (Table 3). The two lakes that shifted the most were close to areas of high total phosphorus values relative to others in the state. While spring values for these two lakes were low, their summer values were consistent with regional central tendencies. In the more enriched lakes (spring total phosphorus between 15 and 30 µg/L), summer values shifted two to three classes either higher or lower with no distinct pattern.

We qualitatively adjusted the Vermont spring values for the regionalization by comparing them with patterns of summer values in similar regions with similar landscape associations in adjacent states. We assumed the distribution and central tendency of summer phosphorus values associated with the combination of landscape characteristics defining a region adjacent to the Vermont state line would be exhibited in the portion of that or similar regions within Vermont. Spring values from Vermont were therefore subjectively rescaled to correspond with distributions of summer total phosphorus found in the appropriate regions contiguous to Vermont.

The degree of similarity between available summer phosphorus values and yearly reported averages in Pennsylvania lakes was much greater than the relationship between spring and summer values in Vermont (average yearly total phosphorus = 0.66 summer + 14.42; r^2 = 0.79; n = 37). Further analysis revealed that 76% of the lakes stayed in the same phosphorus class regardless of whether the summer or

Table 2.—Landscape information used in the regionalization process.

State Specific Resource	Geology	Soils	Land Use/ Land Cover	Vegetation
Maine	Osberg et al. 1985	Rourke et al. 1978	Adamus 1978, Day 1950, Me. DIFG 1974, Trefethen 1938	Ferguson 1974
New Hampshire	Billings 1980	Pilgrim & Peterson 1979		Reiners & Stone 1979
Vermont	Doll 1970		Meeks 1975	Post & Curtis 1970
Massachusetts	Zen 1983		Brownlow 1979	Egler 1940
Rhode Island	Quinn 1965	Wright & Sautter 1979	MacConnell 1974	MacConnell 1974
Connecticut	Rodgers 1985	Hill et al. 1980	CCOPM 1985	Dowhan & Craig 1976
New Jersey	Johnson 1950			
New York	Craft 1979, Fisher et al.1970	Cline & Marshall 1977	Stout 1952, NY-APA 1982	NY-DEC 1983
Pennsylvania	Berg et al. 1984	Higbee 1967	Higbee 1967	Lull 1968
General Area Resource	**Physiography/ Geomorphology**	**Soils**	**Land Use/ Land Cover**	**Vegetation**
Northeastern United States	Denny 1982 Fenneman 1938 Hammond 1970 Hunt 1979 Larson & Stone 1982 Thornbury 1965	Ciolkosz et al. 1989 Melvin et al. 1992 Smith 1984 Soil Cons. Serv. 1991	Anderson 1970 Loveland et al. 1991 USDA 1981 Wright 1933	Kingsley 1974 Kuchler 1970 Leak 1982 US For. Serv. 1970 Westveld 1956

yearly average total phosphorus value was used to classify the lake. Of the remaining 24% of the lakes, none shifted more than one class either way; six had summer values one class lower than average yearly value and three had summer values one class higher. Because of the close correspondence between yearly and summer values, no seasonal adjustment was necessary for Pennsylvania lakes.

Summer phosphorus values were also expected to vary from year to year. For this reason, as much summer epilimnetic data as possible was gathered and summarized as a mean value for each lake. We did not use phosphorus data collected prior to 1975 because of concern that some laboratory analysis methods in use at that time were not as accurate or sensitive as current methods. Smeltzer et al. (1989) have documented variation in the multi-year mean for lakes extensively monitored for spring total phosphorus in Vermont. Expressing precision as a multi-year coefficient of variation (CVm), they found most lakes sampled for between 4 and 10 years yielded a value of 0.15 or less and recommended this criterion for inclusion of long-term means in empirical models. As an example of the lakes used in this study, the median coefficient of variation of the multi-year mean for lakes sampled between 2 and 4 years in Rhode Island was 0.10. On a year-to-year basis, seventy-one percent of the lakes stayed within the same phosphorus class or bounced between two classes. The tendency to shift between classes did not seem to be associated with either lake depth or mean total phosphorus concentration. Year-to-year variability in total phosphorus values throughout the region did not appear to deviate substantially from a CVm of 0.15, or result in shifts of more than several classes for each lake.

Table 3.—Shift in phosphorus classes for ordered spring (V) and summer (S) values collected from 18 Vermont lakes.

VT-DEC*	TOTAL PHOSPHORUS (μg/l)							
Lake ID #	<5	5-9	10-14	15-19	20-24	25-29	30-50	>50
0079		VS						
1285		VS						
0274		V	S					
0866		V			S			
0386			VS					
1485			VS					
0576			V	S				
0010			V				S	
1074				VS				
1040				V			S	
1409				V	S			
0145					V		S	
0526			S			V		
0430							VS	
0663							VS	
0926						S	V	
1180						S	V	
1353								VS

*Vermont Department of Environmental Conservation

Summer phosphorus values were also expected to differ among lakes based strictly on differing morphology. Generally, deeper lakes that stratify have different phosphorus regimes than those that do not (Cole 1975). Although factors other than depth influence whether a lake will stratify, lake depth is probably a fairly reliable indicator. In order to estimate the depth at which lakes are likely to stratify in the northeastern United States, mean and maximum lake depth from 93 lakes from the Maine data set with stratification information were examined. Each lake was plotted by depth and coded by whether it stratified. Bounds of 9 m maximum and 5.25 m mean depth contained 73% of all nonstratified lakes (Fig. 1). In all subsequent analyses, lakes deeper than 9m were coded to indicate probable stratification.

Data Analysis

Mean epilimnetic total phosphorus values were included in a database with accompanying geographic coordinates, probable lake stratification code information, and a flag indicating whether the lake's watershed was greater than 129.5 km^2 (50 mi^2). Omernik et al. (1988) found that lakes with large watersheds typically contain land from more than one region and reflect characteristics of more than one region. This tends to mask the relationship between patterns in landscape and lake water chemistry. Lakes with larger watersheds were examined with this phenomenon in mind.

Each lake was classified into one of eight categories based on its total phosphorus value. Cut-points for phosphorus classes were subjectively determined using frequency distributions of average summer phosphorus values from 2,101 lakes sampled across the same area in a pilot study performed in 1986. Classes were constructed to contain similar numbers of lakes and provide a sufficient number of classes to differentiate lakes along the continuum from nutrient poor to enriched, hence the upper categories cover broader ranges than the lower categories.

A Geographic Information System (GIS; ARC/INFO) was used to plot the location of each lake, color-coded by its phosphorus class. Different symbols were used to indicate probable presence or absence of stratification. Lakes with watersheds greater than 129.5 km^2 (50 mi^2) were flagged. Using a random process covering about 10% of the lakes, locational accuracy was verified by registering overlays to appropriate USGS 1:250,000-scale topographic maps and comparing plotted lake position to USGS map position. Maintaining the database as a GIS coverage accommodated the display and overlay of lake data at the various scales of available mapped landscape information.

Maps from the USGS 1:250,000 series were used as base maps to overlay lake data and to delineate lake region boundaries. Although spatial patterns of lake phosphorus data are apparent at varying scales, we found the 1:250,000 scale most appropriate for interpreting associations with landscape characteristics displayed on state-level maps (commonly compiled at this scale). With smaller (larger area) map scales (i.e. 1:1,000,000 or smaller) landscape-level information tends to coalesce and salient detail is lost. Maps of data at a larger scale (e.g. 1:100,000 or 1:24,000), when available, produce a cumbersome number of maps across which regional interpolations must be made. The 1:250,000-scale map series also provides accurate locational control and relatively consistent portrayal of topographic information across the series.

Map Compilation

The lake regions depicted on the final map (Fig. 2) were delineated using a qualitative regionalization approach. The color-coded maps of lake phosphorus values were examined subjectively to identify regional patterns of existing lake phosphorus data comprising areas of similar lake phosphorus values, or similar distributions of values, relative to adjacent areas. These patterns were then compared with maps of landscape characteristics known to influence the quality of lakes on a regional basis. Boundary delineations required interpretation of changes or breaks in the combination of factors associated with apparent regions. Care was taken to involve scientists and resource managers with local and regional expertise in lake trophic state in the interpretation and delineation process. Regional patterns in lake phosphorus levels and associated landscape factors are evident at various scales. We chose to define the lake regions at a scale that would be conducive to lake management at the state level (several regions per state). More extensive analysis of patterns in variability within each of the lake regions remains and may be of considerable utility in some areas.

Map analyses revealed that the combination of landscape and lake characteristics most useful in the delineation process were not the same across all regions. Particular combinations of factors seemed to explain patterns of phosphorus well in some regions but not in others. Several factors, however, were commonly associated with differences in lake phosphorus levels regardless of the region. Lakes in areas with high percentages of urban or agricultural land use tended to have high phosphorus values, particularly when underlain by substrates of carbonate rock such as limestone. Lakes low in phosphorus were frequently associated with areas of low agricultural potential, which tended to be mostly forested, underlain by acidic bedrock such as granite, phylite, and schist, and had soils derived from this bedrock or associated glacial till.

Areas of lakes with similar morphometry (i.e. lake size, depth, and density) were also sometimes correlated with particular patterns of lake quality and indicated the presence of a distinct region. For example, a small area in the extreme southeastern part of New Hampshire has a considerably higher percentage of lakes with low phosphorus values than the surrounding region, and is also characterized by a higher concentration of lakes and deeper lakes (Map; region 59-05). Pitted morainal outwash characterizes the region and probably influenced formation of the numerous small, deep lakes found there. Although patterns in morphometry and phosphorus values in this area are distinctly different from those in the surrounding area, corresponding differences between the areas were not evident on maps of soil type and surficial geology. Basically, southeastern New Hampshire and northeastern Massachusetts are underlain by complex melanges of metamorphosed igneous rock whose form and derivative soils were extensively altered by glacial activity. This homogenized mixture of bedrock, glacial till, and soils apparently is not strongly related to patterns in lake total phosphorus. Differences in lake abundance and, to a lesser extent, land surface form (USGS 1:250,000-scale topographic maps) were more useful in defining the region.

The availability of lake phosphorus data and reliable mapped landscape information was generally good for the northeastern United States. However, there is considerable variability in the quality of phosphorus data and mapped environmental data within the nine-state area. Therefore, the confidence with which the regions were defined, and the estimated distribution of lakes in each phosphorus class, also varied spatially. A subjective indicator of this reliability is given with each region's description on the back of the folded color map enclosed in the envelope on the back cover of this issue. In regions where many lakes were monitored with even spatial coverage, reliability was qualitatively rated as "good". Regions where there were few lakes but where the patterns of lake phosphorus and associations with the landscape characteristics were obvious, were also designated as "good." At the other end of the reliability/confidence scale, a number of regions were classified as "poor," generally because of a lack of monitored lakes or because the regional mosaic of landscape characteristics did not appear to correspond well with patterns in the phosphorus concentration in lakes. Regions where some lakes were monitored and some association between patterns in phosphorus content and landscape characteristics were evident were labeled as "fair," (Fig. 3.)

After the lake region boundaries were defined, phosphorus values were analyzed to establish the central tendency of the range of phosphorus concentrations within each region. The regions then were coded to the color scheme displayed on the map. Each lake region has been identified based on the format produced for the national ecoregions map (Omernik 1987). The first two numbers refer to the ecoregion that all or most of the mapped lake region occupies. For the glaciated portion of the northeastern United States the ecoregions are: the Northeastern Highlands (58), the Northeastern Coastal Zone (59), the Northern Appalachian Plateau (60), the Erie/Ontario Lake Plain (61), and the North Central Appalachians (62). The second set of numbers serves as a designator of lake regions within the ecoregion. Histograms of the monitored distribution of total phosphorus by class

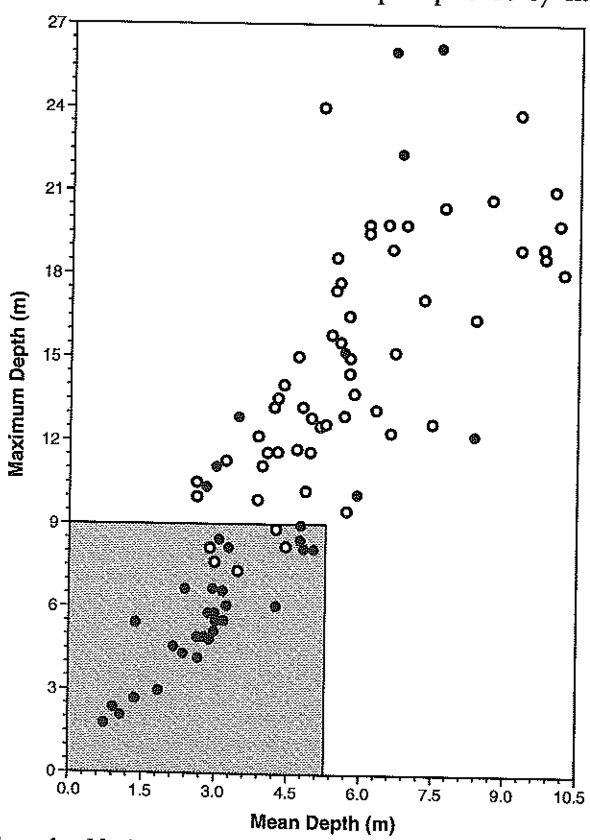


Figure 1.—Maximum versus mean depth for 93 lakes in Maine; 73% of nonstratified lakes are within the bounds of < 9 m maximum depth and < 5.25 m mean depth. Solid circles represent nonstratified lakes, open circles stratified.

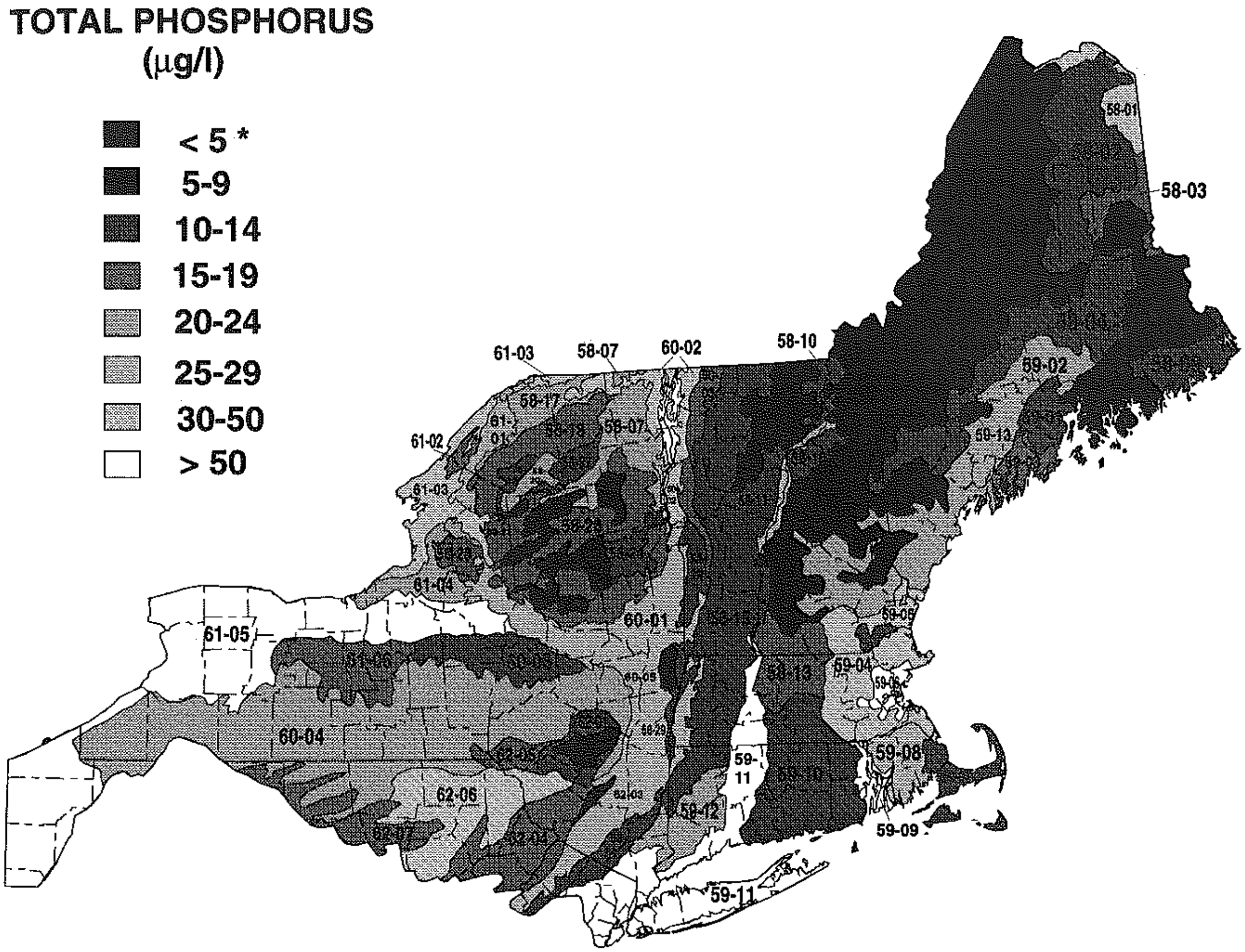
(example in Fig. 4) are displayed with the narrative description of each region on the back of the map sheet attached to the back cover of this issue.

Frequency curves were developed (Fig. 4) and portrayed on the front and back of the map to indicate the probable distributions of phosphorus values in each region. They should not be thought of as exact depictions of existing phosphorus values in lakes in the region, but rather as reasonable approximations of the likely phosphorus distribution, based on sampling data and the strength of association between landscape characteristics within a region. Those frequency curves appearing in gray, rather than in color, represent regions where there were a paucity of available lake phosphorus data or where the associations between phosphorus and landscape characteristics were less evident. For these regions we therefore judged the reliability of our estimated probable distribution curves as "poor".

Applications

Recognition of lake regions provides a first step in explaining variation and estimating the range of quality in lakes in any given area. In this study, the grouping of lakes by region resulted in a reduction in variance; within-region variance was an average of 18.3% of total variance, in 52 of the 61 regions. In the remaining 9 regions, where patterns in total phosphorus values were more heterogeneous, they were nonetheless distinct from patterns in adjacent regions. Moreover, the association of patterns in total phosphorus with various landscape characteristics helped to explain possible reasons for the elevated variance in lake phosphorus values in these regions.

The ecoregions developed by Omernik (1987) have already been used to partition variation and enhance the effectiveness of resource management processes such as reporting monitoring results and tracking trends in water quality (MPCA 1986, Wilson and Walker 1989, Omernik et al. 1991, Lillie et al. 1993;). The USEPA Science Advisory Board (1991) has found the ecoregion concept defensible and has judged it as superior to most resource classification methods currently in use. Like the multi-purpose ecoregions, the special-purpose lake phosphorus regions provide a more effective framework for grouping monitoring sites than using political or hydrologic units, which typically do not correspond to factors associated with regional differences in resource quality (Omernik and Griffith 1991). By plotting median values of selected water quality parameters by ecoregion across time, investigators detected significant trends that might



* Not represented on phosphorus region map.

Figure 2.—Total Phosphorus Regions for Lakes in the Northeastern United States. This figure is an abbreviated, smaller scale version of the two-sided color map enclosed in the envelope in the back cover of this issue of Lake and Reservoir Management[1].
[1]If the larger scale, color map has been removed or otherwise separated from the Journal, single copies may be obtained from James Omernik (USEPA, Environmental Research Laboratory, 200 SW 35th St., Corvallis, OR 97333) while the supply lasts.

otherwise have been masked in the state of Minnesota (MPCA 1986). Ecoregions have also been incorporated as a component of Minnesota's predictive models for total phosphorus, chlorophyll *a*, and Secchi disk transparency in lakes (Wilson and Walker 1989). Aggregations of lake phosphorus regions (Omernik et al. 1988) have been used in a similar fashion in Wisconsin (Lillie et al. 1993). In areas characterized by extreme heterogeneity, spatial analysis at a finer scale can be utilized to further partition variation and improve predictive power. The Wisconsin Department of Natural Resources initiated a study in such an area in northwestern Wisconsin at the behest of concerned lake property owners. Results of this study revealed some strong spatial associations between both landscape and morphometric characteristics and variations in lake quality within regions, but the combinations of characteristics and strength of association differed from region to region (Omernik et al. 1991). Statistical correlations between landscape and morphometric characteristics and phosphorus levels across an area of several regions as diverse as those in the northwestern

Wisconsin study would not be likely to yield results as pronounced or insightful without regional partitioning.

A regional framework also provides a logical basis for selecting areas where waters might be expected to have similar quality. Hughes et al. (1986) outline a method of choosing relatively unimpacted streams typical of each region, to serve as regional reference sites. These reference sites would then represent the level of water quality realistically attainable in the region. Larsen et al. (1988) demonstrated how this might be done, suggesting the use of measures of quality at the best 25% of the regional reference sites as a goal for attainable quality. The Minnesota Pollution Control Agency applied such a method to set regionally appropriate standards for total phosphorus in Minnesota lakes (Heiskary et al. 1987, Heiskary and Walker 1988) and is using the ecoregions to set protection and restoration goals for summer lake nutrient concentrations, algal bloom frequency, and Secchi disk transparency (Heiskary 1989*a*).

Identifying the landscape influences that are characteristic of each region aids in understanding and clarifying which factors might be limiting quality. For example, in region 61-05 in western New York and

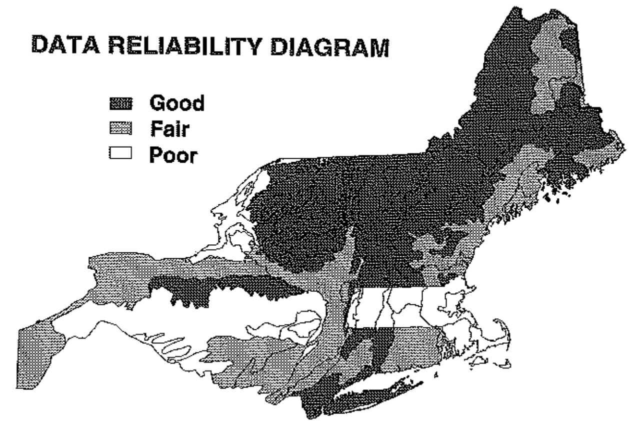


Figure 3.—Rated reliability of information used to define lake phosphorus regions and estimate probable frequency of lakes in each phosphorus class.

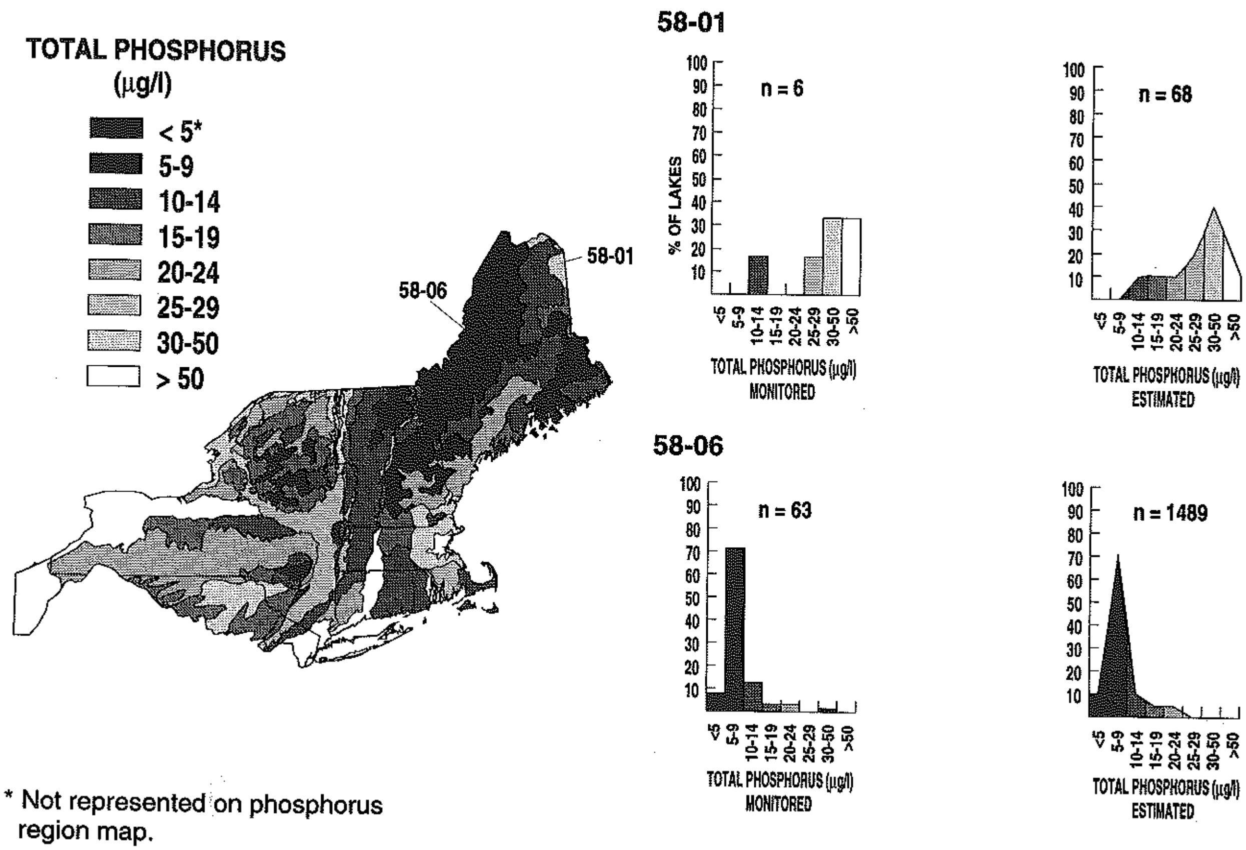


Figure 4.—Examples of histograms and frequency curves for two of the 61 lake phosphorus regions depicted on the map attached in the back cover of this issue. The histograms illustrate the range of variation for the lakes for which phosphorus values were available in each region and the frequency curves reflect the probable distribution of lake total phosphorus that would be expected based on the sampled data and apparent associations with landscape characteristics. The "n" in the monitored histogram represents the number of lakes from which data were obtained and used in determining the regions. The "n" in the estimated curve is the number of lakes in each region detectable on 1:100,000 scale maps through an automated process (Bondelid et al. 1990).

Pennsylvania, surficial geologic deposits are a mix of glacial till and lacustrine sediments. Both the underlying bedrock and the mix of land uses differ from east to west across the region, yet the nutrient rich calcareous soils probably have a dominant influence on the trophic state of lakes in the region. In region 61-06, directly to the southeast, bedrock and soils are similar to those of 61-05 but heterogeneity in lake quality appears to be determined primarily by lake morphology. The few deep trench lakes of valley-head glacial moraine origin are much lower in total phosphorus than the more numerous small shallow human-made lakes sprinkled throughout the region.

A map of regions is an effective mechanism for communicating these ideas and limitations to the general public and explaining the allocation of resources and the course of management scenarios. Heiskary (1989*b*) found citizen complaints about water quality to be spatially aggregated. The highest density of complaints occurred in areas where lakes were relatively more variable in quality and the reasons for the variability were not immediately intuitive (e.g. areas characterized by complex mixes of forest, soil, and land use types). Lillie (1990) used a map of ecoregions to illustrate general differences in the potential quality of lakes across the state of Wisconsin for the Wisconsin Department of Natural Resources' popular magazine.

The regional framework provides a rational basis for prioritizing restoration efforts and planning realistic methods and goals. Fulmer and Cooke (1990) demonstrated how using the ecoregion framework to set regionally attainable goals for reservoir restoration leads to more appropriate management and restoration decisions. They showed how using a single standard, based on the statewide median phosphorus concentration, would have led to allocating resources for restoring eutrophic reservoirs where quality could not realistically be improved to meet the standard due to limitation by landscape factors. No action for a third of the reservoirs that naturally had phosphorus levels less than the maximum allowable standard would possibly result in continued declines in water quality.

The nutrient levels of a water body strongly reflect the capacity of locally important landscape characteristics to influence trophic condition. Moreover, the relationships between water quality and landscape characteristics can be viewed in regional terms. The development of realistically attainable phosphorus standards should reflect regional differences in the types and strengths of association between landscape characteristics and nutrient levels in lakes.

Phosphorus levels vary widely among the lakes of the northeast, and sampling data are available on only 12% of them. We offer this regionalization as a guide for using the approach to structure and modify management plans for improved efficacy in the Northeastern United States. The regions and explanatory material depicted on the map may be used to help clarify regional patterns, partition variability for improved monitoring sensitivity and predictive power in modeling, and to plan preservation and restoration activities with realistically attainable goals.

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