CHAPTER 3

A. Defining the Resource of Concern
B. Classification

Preliminary Steps for Criteria Development

A. Defining the Resource of Concern

Defining the resource of concern begins the overall process of establishing nutrient criteria. Resources of concern here are lakes and reservoirs, and managers must decide which water bodies are to be included in the population to which criteria will be relevant and applicable. Many States define jurisdictional lakes (“waters of the State”) as those above a size threshold. For example, the inclusion of farm ponds and other similar small ponds can potentially result in an inordinately large population of lakes that would be required to be considered during the criteria establishing process. These practical considerations often make it desirable to eliminate small water bodies from the resource population.

States may have already established a regulatory size threshold that specifies what should be considered a lake from the State management perspective. For example, the Florida Department of Environmental Protection routinely samples only lakes larger than 10 acres, because there are more than 7,000 lakes of 10 acres or more in Florida (Huber et al., 1982) and lakes under 10 acres are thought to number 10,000 or more. Florida surface water quality criteria apply to all lakes not wholly owned by a single person other than the State (Florida Amended Code, 62-340). States are encouraged to determine if the established threshold is appropriate for the nutrient criteria setting procedure described in this document and to adjust it as necessary. If States have not set size limitations that define a lake, State water resource agencies should evaluate the lake resources in the State to determine appropriate size limitations. The goal of such an exercise is to eliminate small water bodies that, because of their size (and resulting hydrology) or uses (e.g., small agricultural impoundments), do not accurately represent typical lake conditions or do not exhibit expected responses to stressors.

For the purpose of this document, lakes are defined as natural and artificial impoundments with a surface area greater than 10 acres and a mean water residence time of 14 or more days. Man-made lakes (i.e., artificial lakes) with the same characteristics may be viewed as part of the same system. Reservoirs are man-made lakes for which the primary purpose of the impoundment is other than recreation (e.g., boating, swimming) or fishing, and the water retention time and water body depth and volume vary widely. Hydroelectric power generation, drinking water supply, and flood control are examples of typical uses of reservoirs.

Impoundments on rivers, especially ones on larger rivers, also require specific definition. Impoundments behind low-head dams for navigation, as on the Ohio and Mississippi Rivers, are hardly lakelike in their characteristics; in fact, they are called navigational pools. At what point does a pool on a river become a lake? Limnologists generally consider lakelike characteristics to increase with water mean residence time. Many studies suggest that phytoplankton do not accumulate at retention times less than 7 days (e.g., Kimmel et al., 1990).

These definitions are provided for the purpose of illustration and consistency. States with legal definitions of their lakes or reservoirs should obviously adhere to their own terms and interpret this guidance accordingly.

B. Classification

1. Geographic Divisions

The establishment of a single, national nutrient criteria for lakes is not a realistic goal because of the significant variability of water bodies that exist across the country in a variety of climates, geographic locations, and ecosystems. On a national basis, individual lakes and reservoirs are affected by varying degrees of development, and user perceptions of water quality can differ even over small distances. As a result, the nutrient criteria development process discussed in this document is based on an approach that acknowledges geographic differences in lakes across the country and within States and that uses a classification system to clarify those differences. The initial classification scheme used in this manual is the ecoregion approach (Omernick, 1987, 1988, 1995). However, many viable regionalization techniques exist for delineating geographic regions.

The process of identifying geographic divisions (i.e., regionalization) is part of a hierarchical classification procedure with the purpose of grouping similar lakes together (i.e., to prevent comparison of unlike lakes). Classifying lakes reduces the variability of lake-related measures (e.g., physical, biological, or water quality variables) within classes and maximizes the variability among classes. Classification invariably involves professional judgment to arrive at a workable system that separates clearly different ecosystems, yet does not consider each lake a special case. The intent of classification is to identify groups of lakes that under ideal conditions would have comparable characteristics (e.g., biological, ecological, physical). To the extent possible, classification should be restricted to those characteristics of lakes that are intrinsic, or natural, and are not the result of human activities. These characteristics include size, maximum or mean depth, detention time, and shape.

The general approach to the regionalization process is to establish divisions at the broadest level and then to continue to stratify to a reasonable point. In this section, a regionalization system for the national scale is presented to provide a framework for developing nutrient criteria. EPA encourages States to identify State-specific subregions, if appropriate, and to use the national regionalization scheme discussed below as the basis for further subdivisions.

■ National Nutrient Ecoregions

Ecoregions are a mapped classification system of ecological regions, that is, regions with assumed relative homogeneity of ecological characteristics (Omernik, 1987). EPA has developed maps of ecoregions of the United States at various levels of resolution and aggregation (Omernik, 1987). The most commonly used is the Level III ecoregions, consisting of 79 ecoregions in the conterminous United States. Ecoregions were based on interpretations of the spatial coincidence in all geographic phenomena that cause or reflect differences in ecosystem patterns. These phenomena include geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. The relative importance of each characteristic varies from one ecoregion to another regardless of the hierarchical level.

For the National Nutrient Criteria Program, a map of aggregations of the Level III ecoregions was developed to define broad areas, within which there are general similarities in the quality and types of ecosystems as well as in natural and anthropogenic characteristics that affect nutrients (see Figure 1.1).

The regions are intended to provide a spatial framework for general guidance and reporting for the National Nutrient Criteria Program.

These nutrient regions and their component Level III ecoregions are described more fully in Appendix A. The nutrient regions delineated in Figure 1.3 are not intended to be homogeneous. They are aggregations of ecoregions where expectations within a nutrient region are more similar than expectations among nutrient regions. Some regions may be characterized by relative homogeneity; other regions may be characterized by extreme heterogeneity. An example of a heterogeneous region is Region XII, the Southern Coastal Plain, which has lakes ranging from ultra-oligotrophic lakes in sandy ridges and hills to highly eutrophic solution lakes in areas with phosphatic soils (Griffith et al., 1997). By comparison, Region VI, the Corn Belt and Northern Great Plains, is more homogeneous and is expected to be dominated by mesotrophic to eutrophic lakes, owing to the fertile plains soils and extensive agriculture. Region VIII, the Nutrient Poor Largely Glaciated Upper Midwest and Northeast, is dominated by oligotrophic lakes, but it also has small subregions with higher nutrient concentrations and mesotrophic lakes (Omernik et al., 1988; Rohm et al., 1995).

The nutrient regions can form the basis for initial development of nutrient criteria. Expectations can be developed for nutrient concentrations and loadings in each of the regions and criteria derived from those expectations.

■ Further Subregionalization

The heterogeneity within many of the nutrient regions will require further subregionalization or subclassification to implement nutrient criteria. Using the ecoregion concept as a basis, EPA has developed lake regions based on phosphorus and other considerations for three areas: the Upper Midwest, comprising parts of nutrient regions VI, VII, and VIII in Minnesota, Wisconsin, and Michigan (Omernik et al., 1988); the Northeast, comprising nutrient regions VII, VIII, and XIV ranging from northern Pennsylvania and New Jersey through New York and the New England States (Rohm et al., 1995); and Florida, comprising a small part of nutrient region IX, most of Region XII, and all of Region XIII (Griffith et al., 1997). The regionalizations for the Upper Midwest and Northeast are based on total phosphorus concentration because of the dominance of phosphorus as the principal limiting nutrient in cool temperate lakes of the world (e.g., Schindler, 1978). The regionalization for Florida also takes into account total nitrogen concentration, algal chlorophyll, pH, color, Secchi depth, lake origin, and lake hydrology. In warm temperate and subtropical lakes, nitrogen concentration is often the principal limiting nutrient (e.g., Shannon and Brezonik, 1972; Carlson, 1992).

These subregionalizations were developed from data on nutrient concentrations of sampled lakes in the regions, soils, and land use (Omernik et al., 1988; Rohm et al., 1995; Griffith et al., 1997). The distributions of nutrient concentrations of each subregion were characterized (usually with a histogram) if data were available. In subregions where no data were available, the nutrient distributions were estimated based on similarity of soils and land use to regions where data were sufficient to characterize. It is expected that as more data are developed through the National Nutrient Criteria Program, more nutrient ecoregions will be similarly subdivided.

2. Nongeographic Classifications

Many lake classifications have been proposed in addition to trophic state and geography (Hutchinson, 1957). Lake classification can be further complicated by natural or human- induced conditions that can intrinsically affect the state of a lake and, therefore, how it can be classified. For example, acidic lakes (whether naturally acidic or from acid deposition) are commonly found in the Adirondacks of New York, Pennsylvania, and West Virginia and in sand ridges of Florida. High mineral turbidity is found in reservoirs where streams have a high load of suspended fine sediment, typically in arid and semiarid regions.

Although lake types can be explained to greater or lesser extent on geographic considerations, it may be more convenient to classify lakes by nongeographic variables, which may yield more explanatory power than geographic locations. Discussed below are certain factors that potentially can affect the classification process but that generally fit the geographic-oriented focus of the above geographic approaches (e.g., ecoregional, water quality characteristic).

■ Lake Origin

Hutchinson (1957) lists 76 different types of lakes based solely on their origins. Although we often think of a lake simply as a hole in the ground with water in it, the number of different lake types should make us pause to consider how many ways the origin shapes the area, the volume, and the shape of the lake basin. Lakes of volcanic origin are probably very deep, with virtually no littoral zone and small watersheds. Crater Lake (lake type 10), for example, is extremely deep and very clear and has only the crater walls for a watershed. However, it is susceptible to nutrients introduced by septic leakage because of the very small water load.

Lakes of tectonic origin such as those found in faults (lake type 9; e.g., Lake Baikal) might behave similarly. Other lakes may be extremely shallow such as oxbow lakes (lake type 55) or maritime coastal lakes (lake type 64). In these instances, there may be extensive shallow areas and considerable interaction of the sediments with the overlying water. The shape of the basin and watershed help determine the controlling variables of surface area, depth, volume, and retention time. Rather than use discrete classes (e.g., large lakes, small lakes), it may be more effective to treat the shape-related variables as a continuous characteristic. This is discussed in more detail in Section 3.

■ Reservoirs

Reservoirs and impoundments, created by the damming of a stream, have characteristics of both rivers and lakes (Thornton, 1990). Reservoirs are divided into three zones—riverine, transitional, and lacustrine—which correspond to (1) flowing, riverlike conditions, (2) transition to lake conditions, and (3) nonflowing lakelike conditions near the dam, respectively. With expected life spans ranging from several decades to a century or more, reservoirs are more ephemeral than most natural lakes and have several physical characteristics unique to reservoirs and natural reservoirs formed by natural dams (e.g., beaver dams, terminal moraines, landslides).

Reservoirs vary widely in physical characteristics of shape, size, and hydrology. They can range from small, shallow impoundments (farm ponds) to deep storage reservoirs to “run of the river” flowthrough navigational pools and hydroelectric reservoirs on large rivers. They are built and managed for widely different purposes, including flood control, navigation, municipal or agricultural water storage, hydroelectric generation, and gamefish production. Many dams are constructed to allow discharge from the epilimnion, metalimnion, and/or hypolimnion, depending on management goals of the water bodies. This must be known before understanding the limnology of the reservoir. The management practices in turn affect physical, chemical, and biological characteristics of the reservoir.

Although no natural reservoir reference conditions exist, the operational determination of nutrient reference conditions for reservoirs is the same as for natural lakes. Reservoirs can be classified according to hydrology, morphometry, management objectives, and other factors. Age of the reservoir may be important in determining expectations. Several considerations affect the classification of reservoirs as opposed to natural lakes:

- *Distribution*. Reservoirs and impoundments are most numerous in regions with few or no natural lakes. The nonglaciated parts of North America have the largest number of reservoirs (except Florida, which is a Karst landscape).

- *Form*. The form or shape of a basin and watershed may be the most important distinction between natural and artificial lakes. Shape substantially influences hydrology and water quality of impoundments. Large reservoirs are drowned river valleys and tend to be long and deep with numerous embayments of tributary streams. The watersheds of reservoirs are relatively much larger than those of natural lakes and contribute relatively greater sediment loads.

- *Longitudinal gradient*. Reservoirs have characteristics typical of both lakes and streams. They are streamlike at the head where major tributaries enter and are more lakelike near the dam (Thornton, 1990).

- *Turbidity and loading*. Many reservoirs are more turbid than natural lakes, and they receive more nutrients and organic matter from their tributary streams than do natural lakes. This is partly related to the greater relative size of reservoir watersheds.

- *Management*. Reservoirs were built and are managed for specific purposes: hydropower, water supply, and flood control. Fisheries and other uses are usually secondary. Management might include extreme water level fluctuations and discharge depth controls, effects not present in most natural lakes.

Most of the differences between reservoirs and natural lakes are resolved in the classification of the lake resource. The needs for which they were designed dictate many of the attributes of artificial water bodies. Operational strategies can influence reservoir characteristics and resultant water quality (Kennedy and Walker, 1990; Kennedy et al., 1985). The release of water from deep in the water column (hypolimnetic release) increases heat gain and the dissipation of materials accumulated in bottom waters (Martin and Arneson, 1978; Wright, 1967). Surface releases dissipate heat and retain materials. These and other operational differences can provide a basis for grouping reservoirs within and among regions.

Relationships between why a dam is built, how and where it is built, how it is subsequently operated, and the characteristics of the resulting reservoir are reasonably well defined (Kennedy, 1999a). With regard to the establishment of nutrient criteria, can we utilize these relationships to define appropriate groups within which to identify reference conditions? Three categories of reservoir characteristics seem germane for this purpose: location within a drainage basin; structural and operational characteristics of the dam; and hydraulic residence time.

Location in Drainage Basin

Decisions about where dams are located broadly define physical attributes of the resulting reservoir, which, in turn, strongly influence its limnological character (Kennedy, 1999a). For example, tributary storage reservoirs are located on lower order rivers in the upland areas of drainage basins and, thus, often reside in steeply sloping and dendritic basins with long, complex shorelines. Such reservoirs are frequently relatively deep and strongly stratified. Inflows are often lower for suspended sediment concentrations and may exhibit great seasonal or short-term variability. Changes in storage can result in marked changes in pool elevation, and water residence times are often long.

By contrast, run-of-the-river and mainstem storage reservoirs, frequently operated to meet navigation and hydropower objectives, are located on higher order river reaches. Run-of-the-river reservoirs often are limited in lateral extent to the areas immediately adjacent to the original river channel and seldom experience frequent or extensive changes in pool depth. Because they are commonly located at the downstream extent of large drainage basins, they receive high suspended sediment loads, are turbid, and flush rapidly. Dams for mainstem storage reservoirs, on the other hand, generally inundate broad river flood plains, offering extensive storage volumes. Despite relatively high inflow rates, water residence times can be long because of the large potential storage volume. Moderate changes in pool depth occur, and in-reservoir inorganic turbidity levels, while initially relatively high due to riverine influences, often are reduced because of long water residence times.

Dam Structure and Operation

The purpose or purposes for which dams are built determine, in general, their structural design and their mode of operation. The location of outlet structures relative to the depth of the water column, as well as the thermal structure of the water column, determine the depth strata from which water is released. As discussed previously, withdrawal depth can have significant implications for reservoir thermal cycles and the expression of trophic responses to changing nutrient levels. Thus, interactions between reservoir depth, depth from which water is released, the volume of water released, and thermal structure of the water column must be considered when assessing relative similarities between reservoirs and lakes or among reservoirs.

As engineered systems designed to accomplish specific and often narrowly defined water control objectives, dams and the reservoirs they impound exhibit prescribed characteristics dictated by functional requirements. The scheduling of changes in reservoir volume (and, therefore, depth), for example, is determined by basin capacity, hydrology, and water uses. From an operational standpoint, this often involves the development and application of “rule curves,” or predetermined changes in reservoir surface elevation. For tributary storage reservoirs, particularly those operated for flood control, rule curves frequently require the lowering of surface elevations as a means to allow storage of subsequent flood waters, which may be retained for extended periods of time before their release downstream. The result is marked seasonal fluctuations in water column depth, reservoir volume, and water retention time.

Operational requirements for run-of-the-river reservoirs offer a contrasting example. Because the primary purpose of such reservoirs is navigation, reservoir surface elevations must be controlled within narrow limits. Thus, despite larger inflow volumes, rule curves for run-of-the-river reservoirs dictate minimal fluctuations in water column depth. In the absence of changes in water storage volume, water residence times are determined by hydrologic conditions and are uncoupled from dam operation.

From the above discussion and examples, it is obvious that dam structure and operation need to be considered when evaluating factors that influence the limnological attributes of reservoirs and the expression of trophic responses. In addition to their importance to the development of nutrient criteria, these relationships also describe potential management opportunities unique to reservoirs.

Hydraulic Retention Time

Hydraulic retention time, defined as lake or reservoir volume divided by outflow rate and expressed as days or years, strongly influences limnological processes in lakes and reservoirs (e.g., Straškraba et al., 1993). These influences include changes in material retention rates (Straškraba et al., 1995; Kennedy, 1998), modifications to thermal structure, and impacts on the size and composition of planktonic communities (Straškraba and Straškrabova, 1975; Soballe and Threlkeld, 1985; Soballe and Bachmann, 1984).

Residence times vary widely between natural lakes and reservoirs and among reservoirs. Thornton et al. (1980) evaluated data for selected U.S. Army Corps of Engineers reservoirs and lakes contained in the National Eutrophication Survey database, and the authors reported significantly higher geometric mean values for lakes (270 days) than for reservoirs (135 days). A similar assessment of data included in the National Inventory of Dams (U.S. Army Corps of Engineers, 1998) indicates a broad range in water residence time for reservoirs impounded by U.S. dams (Kennedy, 1999b). Values for the nearly 65,000 reservoirs ranged from less than 1 day to more than 750 days; a similar range was observed for those operated by the Corps of Engineers. Many of those with short residence times are operated as run-of-the-river reservoirs for the purpose of navigation.

Ryding and Rast (1989) suggest that impoundment-related changes in water quality will occur when doubling times for algae are less than water residence times. Since Reynolds (1997) suggests that algal doubling rates are in the range of ½ to 1½ per day, it is clear that nutrient-related influences on trophic state are possible at relatively short water residence times. For reservoirs with longer residence times, anticipated differences in trophic responses between natural lakes and reservoirs will be minimized. In such cases, it may be possible to include both natural lakes and reservoirs with similar water residence times, assuming broad similarities in other attributes, in the same group when establishing reference conditions or developing nutrient criteria. In regions with a limited number of reservoirs, this will allow increased sample size for statistical treatments of the data.

On the basis of the above considerations, a reasonable and defendable approach to the identification of appropriate groups of reservoirs would employ multiple descriptors based on operational and physical attributes. Suggested measurement variables for each attribute are presented in Table 3.1. Taken together, this suite of physical and operational characteristics attempts to define factors influencing the expression of trophic responses to changing nutrient levels relative to reservoirs.

Therefore, reservoirs having short detention times should be considered separately from natural and man-made lakes because of their different origins, morphometry, and hydrodynamics. Reservoir studies have shown that the nutrient loading paradigm fits with some modifications (Canfield and Bachmann, 1981). The rapid flushing rates and longitudinal gradients that typify most mainstem reservoirs require modifications of the models to account for down-reservoir changes in water from sedimentation and dilution with passage through the system. Also, nutrient loading models that work well to explain in-lake concentrations in natural lakes overestimate values measured in reservoirs (Jones and Bachmann, 1978); for a given external load, reservoirs appeared to have lower in-lake phosphorus values than natural lakes. Differences between reservoirs and natural lakes were thought to be tied to the fact that reservoirs are constructed in erosional topography and receive much larger inputs of suspended solids than most natural lakes. With greater sediment input, it follows that reservoirs would have greater sedimentation rates and that more phosphorus would be lost from the water column as compared with natural lakes.

Table 3.1. Categories and attributes for a Composite Classification Approach for CE Reservoirs and Suggested Measurement Variables (Kennedy, 1999b)

Category	Attribute	Measured Variable
Location and size	Watershed dimension Reservoir dimension	Drainage area Location of dam in hydrologic continuum Surface area Volume Length Mean and maximum depth Shoreline development ratio
Hydrology	Hydraulic loading Storage dynamics	Inflow and outflow rates Annual/seasonal hydraulic retention time Pool elevation/volume Change in pool elevation
Structure and operation	Dam design Dam operation	Dam height Outlet depth (relative to water column depth) Quantity and seasonality of release volumes Depth of release
Other response effects	Light regime Mixing regime	Nonalgal turbidity Photic depth to mixed depth ratio Thermal stability Mixed layer depth

Another factor contributing to apparent differences in water column nutrient values is that reservoirs typically have large watersheds (Canfield and Bachmann, 1981). As a result, inflow enters from a parent river that, during stratified periods, forms a density flow below the warm surface water but above the colder bottom waters (tropholytic zone) that does not mix or contribute nutrients to the photic zone (Ford, 1990). Timing of nutrient-laden inflows relative to seasonal stratification can be as important as their volume in controlling nutrient values within the water column. Water bodies with density currents do not always show a response to external inputs. In these water bodies, loading models need to take into account the effects of inflow timing and flow stratification. The relative timing of flow and stratification will vary from year to year and could make nutrient content of the surface layer unpredictable except as a long-term average.

■ Water Chemistry (nonnutrient)

Intrinsic water chemistry (not including nutrients) can be used to classify lakes. The most likely variables include acid-base chemistry (any of alkalinity, pH, conductivity) and dissolved organic matter (water color). Color and pH are cheaply and easily measured in the field and are therefore highly cost-effective.

Lake water chemistry is largely determined by the hydrologic pathways of water entering the lake and the material the water contacts along its path. Lakes with large inputs of water from shallow ground water, including wetlands, tend to be stained yellow or brown with dissolved humic compounds. Water entering a lake as deeper ground water tends to be clear but will contain the cations of the soils and aquifer. Highly colored lakes have been termed dystrophic because they often are observed to have low productivity in spite of moderate to high nutrient concentrations (Wetzel, 1975). Colored water not only reduces light penetration, but the dissolved organic matter also can chelate nutrients, making them unavailable for algal uptake. Therefore, water color is an important classification variable (or covariate; see below) for lake nutrient criteria.

Alkalinity also influences lake productivity, in part because alkaline soils are richer in several nutrients (especially phosphorus and potassium) than are acid soils, and because the nutrients are more readily available to plants. The world's most productive agricultural regions are in alkaline soils. Alkalinity, or its related variables pH and conductivity, are important classification variables for nutrient criteria. As an example, Florida lakes were characterized as acidic or alkaline and as colored or clear, resulting in four lake types (Shannon and Brezonik, 1972). Although pH and as color are continuous variables, it was more convenient to cluster the Florida lakes into four groups because response to nutrient enrichment and macroinvertebrate communities also clustered according to the four groups (Gerritsen et al., 1999).

■ Nonalgal Turbidity (suspended sediments)

High concentrations of nonalgal suspended materials are prevalent in lakes in many regions of the world and can inhibit growth of phytoplankton, causing light limitation. Nonalgal turbidity from suspended clay or organic matter is also strongly regional, depending on soil characteristics, vegetation, and hydrology. It is a prominent characteristic of many impoundments in Midwestern and arid Western States. Nonalgal turbidity can produce low algal chlorophyll-to-nutrient ratios and cause a lack of relationship between chlorophyll and phosphorus in some regions (Jones and Novak, 1981; Hoyer and Jones, 1983; Carlson, 1991; Jones and Knowlton, 1993). Light limitation of algal biomass in the mixed zone of lakes occurs when irradiance absorbed by the phytoplankton community is less than is required for net growth of biomass over time. Light limitation extended over periods of a week or longer is common in deep or turbid lakes during winter because of low incident light, but it is less common in summer when incoming irradiance is maximal and when mixing depth is reduced by thermal stratification.

The Carlson trophic state index (TSI) (1977) can be used to identify certain conditions in the lake or reservoir in which algal biomass is not related to phosphorus or nitrogen. When more than one of the three variables are measured, it is probable that different index values will be obtained. Because the relationships between the variables were originally derived from regression relationships and the correlations were not perfect, some variability between the index values is to be expected. However, in some situations the variation is not random, and factors interfering with the empirical relationship can be identified. These deviations of the total phosphorus or the Secchi depth index from the chlorophyll index can be used to identify errors in collection or analysis of real deviations from the "standard" expected values (Carlson, 1980b). Some possible interpretations of deviations of the index values are given in Table 3.2 (Carlson, 1983, 1992).

In turbid lakes, it is common to see a close relationship between the total phosphorus TSI and the Secchi depth TSI, while the chlorophyll index falls 10 or 20 units below the others. Clay particles contain phosphorus, and therefore, lakes with heavy clay turbidity will have the phosphorus correlated with the clay turbidity while the algae may neither utilize all the phosphorus nor contribute significantly to the light attenuation. This relationship of the variables does not necessarily mean that the algae is limited by light, only that the measured phosphorus is not all being utilized by the algae.

3. Covariates

Several of the above factors have strong influences on lake trophic state and may be expected to vary widely within nutrient regions. Whether a given factor needs to be considered separately in lake classification within regions depends on its variability in the region and its regional relevance in affecting trophic state. Additional classification factors may be treated as additional classes (e.g., as classes of large and small lakes) or as continuous covariates (e.g., a regression model to predict natural trophic state of lakes according to lake size). State and regional experts can use their knowledge of lake characteristics to determine if any of the modifying factors should be considered as part of a State-level classification scheme.

Lake morphometry and lake hydrology affect trophic state through the influence of water movement, retention time, and stratification. In-lake phosphorus dynamics in mixed and stratified lakes can complicate the relationship between external loading and measurements of lake trophic state, making model-based predictions uncertain in some cases. In mixed lakes, phosphorus has been shown to increase during the spring to summer period (Riley and Prepas, 1985), presumably because of recycling due to mixing of the water column and internal loading from the sediments (Osgood, 1988; Welch and Cooke, 1995). In contrast, it is typical for phosphorus to decrease somewhat in stratified lakes because of sedimentation processes, with the metalimnion acting as a barrier to upward transport into the photic zone.

Shallow lakes can efficiently cycle phosphorus and, under favorable light conditions, convert phosphorus into phytoplankton biomass. As a consequence of these internal loading mechanisms, shallow lakes do not always readily respond to reductions in external nutrient loading. Among large stratified lakes, evidence exists that the efficiency of nutrient recycling increases with lake size; mixed layers in large lakes are more turbulent and thicker than in small lakes, and these processes increase the probability of nutrient regeneration within the mixed layer rather than loss to the sediments. The response to greater nutrient regeneration is greater phytoplankton photosynthesis. These findings suggest that external nutrient loads should be converted into biological production more efficiently in stratified lakes than in small lakes.

Water residence time can have a significant effect on the amount of algae in the water. The water must remain in the basin for a period longer than the doubling time of the algae or the algae will wash

Table 3.2. Conditions Associated with Various Trophic State Index Variable Relationships

Relationship Between TSI Variables	Conditions
TSI (CHL) = TSI(CHL) = TSI(SD)	Algae dominate light attenuation
TSI(CHL) > TSI(SD)	Large particulates, such as Aphanizomenon flakes, dominate
TSI(TP) = TSI(SD) > TSI(CHL)	Nonalgal particulates or color dominate light attenuation
TSI(SD) = TSI(CHL) > TSI(TP)	Phosphorus limits algal biomass (TN/TP ratio greater than 33:1)
TSI(TP) > TSI(CHL) = TSI(SD)	Zooplankton grazing, nitrogen, or some factor other than phosphorus limits algal biomass

out of the basin. This means that for faster growing algae such as *Chlorella*, the water residence time would have to be at least 2 days. For slower growing species, the residence times would have to be much longer. In reservoirs with short residence times, the algae would not necessarily reach densities in which nutrients were limiting to their growth. However, residence time may vary seasonally, and there may be times when the algae do become nutrient limited. Another consideration would be that in short residence time situations, attached plants (both macrophytes and attached algae) may proliferate, and criteria would have to be set in reference to attached rather than planktonic forms.

Any continuous variable, such as pH, color, lake depth, or lake area, can be treated as a covariate in a classification. Often, it may be more convenient to treat them as discrete classes (large and small; acid and alkaline). Whether to treat an important classification variable as discrete classes or as a continuous covariate may depend on the size of the database, the distribution of lakes across the gradient, and whether the trophic response to the gradient is linear. For example, a uniform or unimodal distribution across a gradient would suggest treating the variable as a covariate (e.g., lake surface area), while a bimodal distribution would suggest dividing into classes (e.g., pH classes of acidic and nonacidic lakes). If a relationship is found between measures of lake size or hydrology and trophic state, then additional classes reflecting these factors, or treating them as a covariate, must be considered. Because relationships with morphometric variables are often linear, the covariate approach usually is preferred for those variables (area, depth, retention time). Conversely, water chemistry variables (pH, color, hardness) may cluster naturally due to geology, soils, and vegetation, so the class approach may be preferred for those variables.

Case Study: Ecoregional Classification of Minnesota Lakes

Minnesota has over 12,000 lakes spread across diverse geographic areas. Previous studies had shown distinct regional patterns in lake productivity associated with regional differences in geology, vegetation, hydrology and land use (Heiskary and Wilson, 1989). Minnesota contains seven ecoregions (Omernik, 1987), and four of the ecoregions contain 98 percent of the lakes. These four ecoregions are the Northern Lakes and Forest (NLF), North Central Hardwood Forest (NCHF), Northern Glaciated Plains (NGP), and Western Corn Belt Plains (WCBP) (Figure, p. B-4). Minnesota uses these ecoregions as the framework for analyzing data, developing monitoring strategies, assessing use patterns, and developing phosphorus goals and criteria for lakes (Heiskary, 1989).

The Minnesota Pollution Control Agency (MPCA) and several other groups collected data on chlorophyll *a* concentrations and several water quality parameters (total phosphorus, total nitrogen, and Secchi transparency) in 90 reference lakes between 1985 and 1987. Secchi transparency data were collected mostly by volunteer participants in the Citizen Lake Monitoring Program. Reference lakes were chosen to represent minimally impacted sites within each ecoregion. Criteria used in selecting reference lakes included maximum depth, surface area, fishery classification, and recommendations from the Minnesota Department of Natural Resources (Heiskary and Wilson, 1989). Lake morphometry had previously been examined. In addition to the reference lake database, MPCA examined a statewide database containing data collected by these same groups on approximately 1,400 lakes form 1977 to 1987.

Differences in morphology, chlorophyll *a* concentrations, total phosphorus, total nitrogen, and Secchi transparency were found among lakes in the four ecoregions in both studies. Lakes in the two forested ecoregions (NLF and NCHF) are deeper (median maximum depth of 11 meters) with slightly smaller surface areas (40 to 280 ha) than those in the plains ecoregions (NGP and WCBP). Lakes in the two plains ecoregions were typically shallow (median maximum depth of 3 meters) with larger surface areas (60 to 300 ha).

Box-and-whisker plots for chlorophyll a and water quality measurements in the reference lake study paralleled the morphological differences seen among the ecoregions (Heiskary and Wilson, 1989). The two plains ecoregions had significantly higher chlorophyll *a* levels than either of the two forested ecoregions. Results of the statewide database analysis showed these same trends. The results of these two database analyses support the use of ecoregions in developing frameworks for data analysis, monitoring strategies, assessing use patterns, and developing phosphorus goals and criteria for lakes.