3. Select variables for monitoring nutrients. Variables, in the context of this document, are measurable attributes that can be used to evaluate or predict the condition or degree of eutrophication in a water body. Four primary water quality variables that must be addressed are TN, TP, chl *a* as an estimate of algal biomass, and turbidity (see Section 3.2). Measurement of these variables provides a means to evaluate nutrient enrichment and can form the basis for establishing regional and waterbody-specific nutrient criteria. Additional secondary variables may also be monitored.

4. Design a sampling program for monitoring nutrients and algal biomass in rivers and streams. New monitoring programs should be designed to identify statistically significant differences in nutrient and algal conditions while maximizing available management resources (see Section 4.2). Initial monitoring efforts should focus on targeting reference stream reaches that can be used to assess impairment by nutrients and algae.

5. Collect data and build database. Potential sources of additional data for nutrient criteria development include current and historical water quality monitoring data from Federal, State, and local water quality agencies; university studies; and volunteer monitoring information. Databases can be used to organize existing data, store newly gathered monitoring data, and manipulate data as criteria are being developed. The USEPA is developing a national relational database for State/Tribal users to store, screen, and manipulate nutrient-related data.

6. Analyze data. Statistical analyses are used to interpret monitoring data for criteria development. Nutrient criteria development should relate nutrient concentrations in streams, algal biomass, and changes in ecological condition (e.g., nuisance algal accrual rate and deoxygenation). In addition, the relative magnitude of an enrichment problem can be determined by examining total nutrient concentration and chl *a* frequency distributions for stream classes. These analyses provide water quality managers with a tool for measuring the potential extent of overenrichment.

7. Develop criteria based on reference conditions and data analyses. Criteria selected must first meet the optimal nutrient condition for that stream class and second be reviewed to ensure that the level proposed does not result in adverse nutrient loadings to downstream waterbodies.

Three general approaches for criteria setting are discussed in this manual: (1) identification of reference reaches for each stream class based on best professional judgement (BPJ) or percentile selections of data plotted as frequency distributions, (2) use of predictive relationships (e.g., trophic state classifications, models, biocriteria), and (3) application and/or modification of established nutrient/algal thresholds (e.g., nutrient concentration thresholds or algal limits from published literature).

Initial criteria should be verified and calibrated by comparing criteria in the system of study to nutrients, chl *a*, and turbidity values in waterbodies of known condition to ensure that the system of interest operates as expected. **A weight of evidence approach that combines any or all of the three approaches above will produce criteria of greater scientific validity.** Selected criteria and the data analyzed to identify these criteria will be comprehensively reviewed by a panel of specialists in each USEPA Region. Calibration and review of criteria may lead to refinements of either derivation techniques or the criteria themselves. In some instances empirical and simulation modeling, or data sets from adjacent States/Tribes with similar systems may assist in criteria derivation and calibration.

8. Implement nutrient control strategies. Much of the management work done by USEPA and the States and Tribes is regulatory. Nutrient criteria can be incorporated into State/Tribal standards as enforceable tools to preserve water quality. As an example, nutrient criteria values can be included as limits in NPDES permits for point source discharges. The permit limits for N, P and other trace nutrients emitted from wastewater treatment plants, factories, food processors and other dischargers can be appropriately adjusted and enforced in accordance with the criteria.

In addition, watershed source reduction responsibilities, especially with respect to nonpoint sources, can be established on the basis of nutrient criteria. Resource managers can use nutrient criteria to help define source load allocations for a watershed. Once sources have been identified, resource managers can begin land use improvements and other activities necessary to maintain or improve the system. System improvements from a watershed perspective must proceed on a reasonable scale so that protection and restoration can be achieved.

9. Monitor effectiveness of nutrient control strategies and reassess the validity of nutrient criteria. Nutrient criteria can be applied to evaluate the relative success of management activities. Measurements of nutrient enrichment variables in the receiving waters preceding, during, and following specific management activities, when compared to criteria, provide an objective and direct assessment of the success of the management project.

Throughout the continuing process of problem identification, response and remediation, and evaluation to protect and enhance our water resources, States, Tribes, and the USEPA are called upon by the U.S. Congress to periodically report on the status of the Nation's waters (Section 305 [b] of the Clean Water Act as amended). Establishment of nutrient criteria will add two causal and two response parameters (see Sections 3.2 - 3.3) to the measurement process required for the biannual Report to Congress. These measurements can be used to document change and monitor the progress of nutrient reduction activities.

The chapters that follow present detailed information that elaborates upon this outline of nutrient criteria development. For some water quality managers, components of certain criteria development steps may already be completed for existing stream monitoring programs (e.g., sampling design for specific stream systems). Thus, some steps can be excluded as the manager advances further through the process. However, should new or revised monitoring programs be envisioned, review by the water quality manager of each of the steps outlined in this guidance is recommended.

Although this document is meant to provide the best available scientific procedures and approaches for collecting and analyzing nutrient-related data, including examination of nutrient and algal relationships, a comprehensive understanding of nutrient and algal dynamics within all types of stream systems is beyond the current state of scientific knowledge. The National Nutrient Program represents a new effort and approach to criteria development that, in conjunction with efforts made by State and Tribal water quality managers, will ultimately result in a heightened understanding of nutrient/algal relationships. As the proposed process is put into use to set criteria, program success will be gauged over time through evaluation of management and monitoring efforts. A more comprehensive knowledge base pertaining to nutrient and algal relationships will be expanded as new information is gained and obstacles overcome, justifying potential refinements to the criteria development process described here.

1.6 IDENTIFY NEEDS AND GOALS

The overarching goal of developing nutrient criteria is to ensure the quality of our national waters. Ensuring water quality may include restoration of impaired systems, conservation of high quality waters, and protection of systems at high risk for future impairment. The goals of a State or Tribal water quality program will be defined differently based on the needs of each State or Tribe, but should, at a minimum, protect established designated uses for the waterbodies within State or Tribal lands. Once goals and objectives are defined, they should be revisited regularly to evaluate progress and assess the need for refinements or revisions.

The first task of a water quality manager is to set a water quality goal, such as “no nuisance algal blooms such that swimming is restricted during summer months.” After such a goal is established, managers must develop a timeline, budget, and plan of action for accomplishing this goal. Needs of the program, such as funding, acquiring relevant data, and assigning employee responsibilities must be addressed. Well-defined needs and goals will help in assessing the success of the criteria development process and will identify attainable water quality goals.

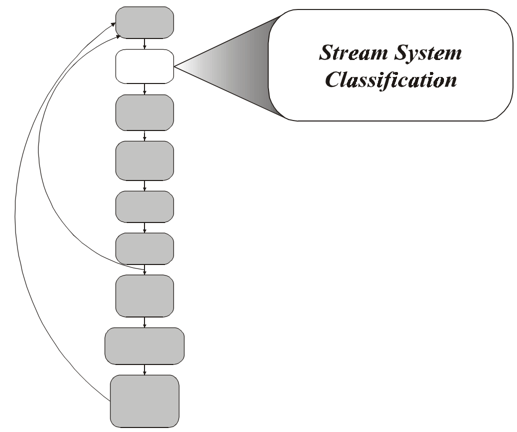
1.7 DOCUMENT STRUCTURE

This manual comprises nine chapters that formulate the steps recommended for nutrient criteria development. The first step of the process, identifying goals and objectives, is unique to each water quality manager and should be revisited regularly to evaluate progress and assess the need for goal and/or objective refinements or revisions. The next step entails stream classification based on physical and nutrient gradient factors (Chapter 2). Sampling variables, including primary and appropriate secondary variables (Chapter 3), should be selected for monitoring efforts. Once these variables are determined, sampling designs for new monitoring programs can be developed (Chapter 4). Chapter 5 discusses potential data sources that can be used by water quality managers to develop criteria and addresses the usefulness of databases in compiling, storing, and analyzing data. A variety of data analysis methods and techniques used to derive criteria are presented in Chapters 6 and 7, respectively. These two chapters are meant to provide water quality managers with a range of options that may be useful for deriving criteria. Nutrient management programs (including nutrient control strategies for point and nonpoint sources) and points of contact or references that may be useful to water quality managers are provided in Chapter 8. Chapter 9 concludes the criteria development process with a brief discussion of continued monitoring and reassessment of goals and the established criteria.

It should be noted that completion of *each* previously described step may *not* be required by all water quality managers. Many State or Tribal water quality agencies already have established stream classes, monitoring programs, and/or databases for their programs and therefore can bypass those steps. This manual is meant to be comprehensive in the sense that all of the criteria development steps are described; however, the process can be adapted to suit existing water quality programs.

Appendix A of the manual contains five case studies: (1) Tennessee ecoregion streams (southeastern U.S.), (2) Clark Fork River (western forested mountains), (3) upper Midwest river basins (prairie-agricultural river systems), (4) Bow River (northern Rockies), and (5) desert streams (arid western U.S.). These case studies are meant to characterize some of the variability observed within North American stream systems and region-specific issues that should be considered when developing nutrient criteria. Appendices B and C provide water quality managers with information and additional references for laboratory/field methods and statistical tests/modeling tools, respectively. Appendix D defines frequently used acronyms and technical terms found throughout the document.

Chapter 2. Stream System Classification



2.1 INTRODUCTION

This chapter discusses classification of streams for water quality assessment and nutrient criteria development. The purpose of classification is to identify groups of rivers or streams that have comparable characteristics (i.e., similar biological, ecological, physical, and/or chemical features) so that data may be compared or extrapolated within stream types. This chapter focuses on providing water quality managers with a menu of tools that can be used to classify the stream system of interest, resulting in different aggregations of physical parameters that correlate with water quality variables.

Classifying rivers and streams reduces the variability of stream-related measures (e.g., physical, biological, or water quality variables) within identified classes and maximizes inter-class variability. Classification schemes based on non-anthropogenic factors such as parent geology, hydrology, and other physical and chemical attributes help identify variables that affect nutrient/algal interactions. Classification can also include factors that are useful when creating nutrient control strategies such as land use characteristics, bedrock geology, and identification of specific point and nonpoint nutrient sources. Grouping streams with similar properties will aid in setting criteria for specific regions and stream system types, and can provide information used in developing management and restoration strategies.

A two-phased approach to system classification is prescribed here. Initially, stream classification is based primarily (though not exclusively) on physical parameters associated with regional and site-specific characteristics, including climate, geology, substrate features, slope, canopy cover, retention time of water, discharge and flow continuity, system size, and channel morphology. The second phase involves further classifying stream systems by nutrient gradient (based upon measured nutrient concentrations and algal biomass). Trophic state classification, in contrast, focuses primarily on chemical and biological parameters including concentrations of nutrients, algal biomass as chlorophyll *a*, and turbidity, and may also include land use and other human disturbance parameters. The additional sub-classification of streams by nutrient condition, in conjunction with an understanding of dose-response relationships between algae and nutrients, helps define the goals for establishing nutrient criteria.

The physical and nutrient characterization discussed above can often be complemented by designated use classifications. These are socially-based classifications developed in accordance with EPA policy and based on the predominant human uses that a State or Tribe has concluded are appropriate for a particular stream or river. Water quality standards, predicated on criteria, are applied to these designated use classifications and are enforceable to protect specified uses. Uses are designated in accordance with relative water quality condition and trophic state. For more information on designated use classifications and their relationship to water quality criteria and standards, see the USEPA Water Quality Standards Handbook (USEPA 1994).

Stream classification requires consideration of stream types at different spatial scales. Drainage basins can be delineated and classified at multiple spatial scales ranging from the size of the Mississippi River basin to the few square meters draining into a headwater stream. The general approach is to establish divisions at the largest spatial scale (river basins of the continent), and then to continue stratification at smaller scales to the point at which variability of algal-nutrient relationships is limited within specific stream classes.

The highest level of classification at the national level is based on geographic considerations. The Nation has been divided into 14 nutrient ecoregions (Omernik 2000) based on landscape-level geographic features including climate, topography, regional geology and soils, biogeography, and broad land use patterns (Figure 4). The process of identifying geographic divisions (i.e., regionalization) is part of a hierarchical classification procedure that aggregates similar stream systems together to prevent grouping of unlike streams. The process of subdividing the 14 national ecoregions should be undertaken by the State(s) or Tribe(s) within each of those ecoregions. Classification of State/Tribal lands invariably involves the professional judgement of regional experts. Experts familiar with the range of conditions in a region can help define a workable system that clearly separates different ecosystem types, yet does not consider each system a special case.

The usefulness of classification is determined by its practicality within the region, State, or Tribal lands in which it will be applied; local conditions determine the appropriate classes. In this Chapter, a regionalization system derived at the national level is presented. This system provides the framework from which State and Tribal water resource management agencies can work to establish appropriate subdivisions. In addition, different classification schemes are presented to provide resource managers with information to use in choosing a stream classification system. It is the intent of this document to provide adequate flexibility to States and Tribes in identifying State and Tribal-specific subregions.

The following sections describe specific examples of first-phase physical classification based on variation in natural characteristics and secondly, nutrient gradient classification schemes for identifying similarities within stream system types. Each classification method is presented and the rationale for its use is provided.

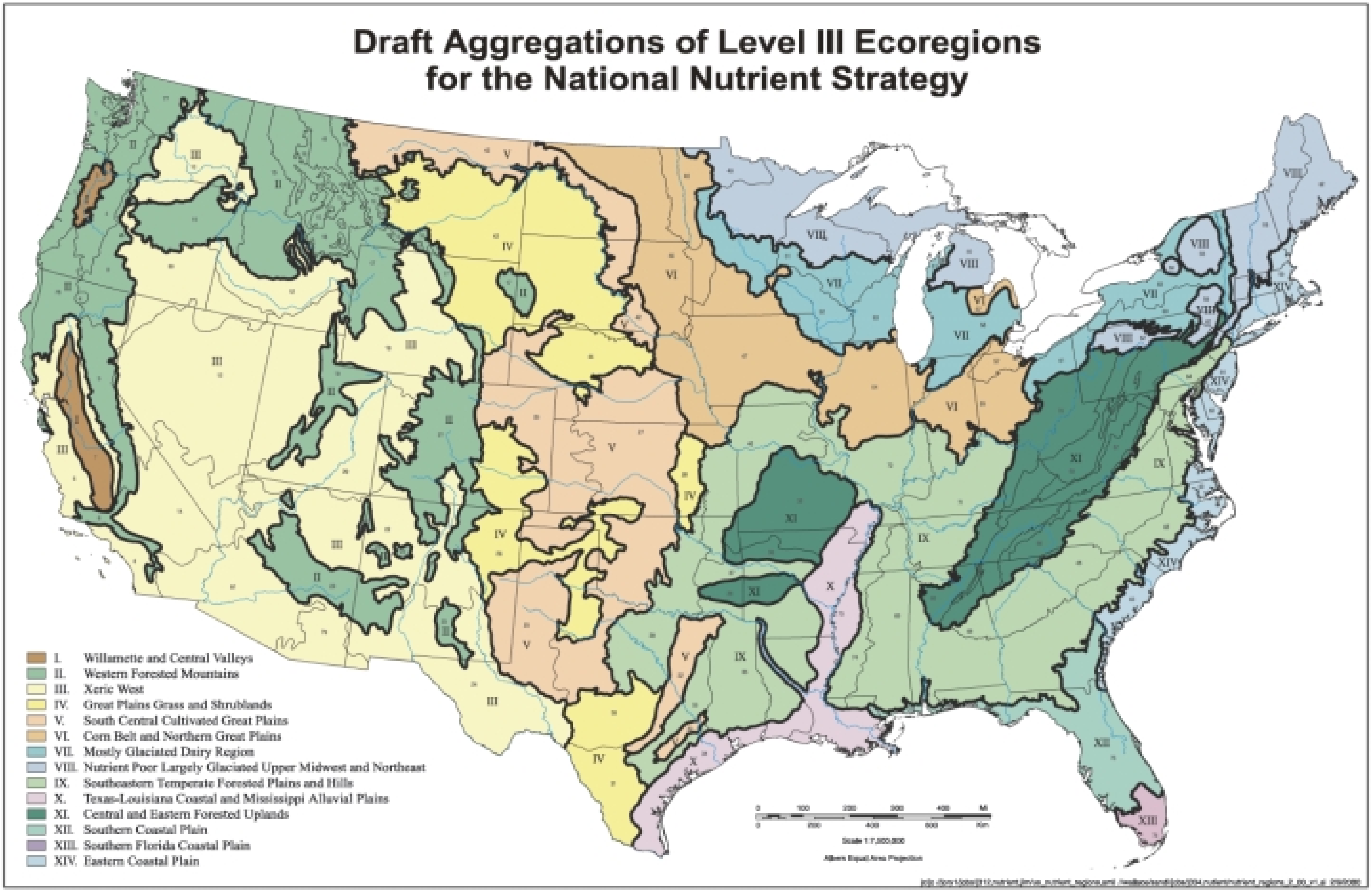


Figure 4. Fourteen nutrient ecoregions as delineated by Omernik (2000). Ecoregions were based on geology, land use, ecosystem type, and nutrient conditions.

2.2 CLASSIFICATION SCHEMES BASED ON PHYSICAL FACTORS

The classification systems described in the following sections (including ecoregional, fluvial geomorphological, and stream order classification schemes) are based on physical stream and watershed characteristics. Stream systems are characterized by the continual downstream movement of water, dissolved substances, and suspended particles. These components are derived primarily from the land area draining into a given channel or the drainage basin (watershed). The climate, geology, and vegetational cover of the watershed are reflected in the hydrological, biological, and chemical characteristics of the stream. Therefore, factors such as general land use, climate, geology and general hydrological properties must be considered regardless of the method of classification used. As described above, the initial classification should be based on physical characteristics of parent geology, elevation, slope, hydrology and channel morphology. Hydrologic disturbance frequency and magnitude are also important when classifying stream systems.

In addition to classification of stream systems, factors contributing to trophic state and macrophyte and algal growth should be considered. Table 1 presents several factors that affect periphyton and plankton biomass levels in stream systems. Macrophyte-dominated systems could occur under conditions similar to those favorable for high periphyton biomass (Table 1), if the velocity is low and the substrate includes organic sediment. Macrophytes are generally unlikely to develop in systems where the stream bottom is composed primarily of gravel or other large substrata (Wong and Clark 1979). The following section specifically addresses the potential effects of hydrology and channel morphology, flow, and parent geology on algal and macrophyte growth within stream systems.

River and stream types (and reaches within these waterbodies) are too diverse to set one criterion for all stream/river types. However, it is not necessarily feasible or recommended to develop site-specific criteria for every stream reach within the U.S. Morphological and fluvial characteristics of a stream influence many facets of its behavior. Streams with similar morphologies may have similar nutrient capacities or similar responses to nutrient loadings. Rivers and streams are very diverse within ecoregions. Reaches within one stream can have a distinct morphology. The geomorphology of a river or stream – its shape, depth, channel materials – affects the way that waterbody receives, processes, and distributes nutrients. Nutrient cycling processes that occur upstream affect communities and processes downstream by altering the form and concentration of nutrients and organic matter in transport (nutrient spiraling); these effects can be further intensified by patch dynamics (Mulholland et al. 1995). The spatial scales which most influence upstream-downstream linkages are the geomorphology-controlled patterns observed at the landscape scale and the nutrient-cycling-controlled patterns observed at the stream reach scale (Mulholland et al. 1995). Therefore, to set appropriate criteria for rivers and streams in an ecoregion, streams must be classified by their morphological characteristics at both the landscape and stream reach scale, with an emphasis on those characteristics most likely to affect nutrient cycling.

ECOREGIONAL CLASSIFICATION

Ecoregions are based on geology, soils, geomorphology, dominant land uses, and natural vegetation (Omernik 1987; Hughes and Larsen 1988) and have been shown to account for variability of water quality and aquatic biota in several areas of the United States (e.g., Heiskary et al. 1987; Barbour et al. 1996). On a national basis, individual streams and rivers are affected by varying degrees of development, and user perceptions of acceptable water quality can differ even over small distances.

Table 1. Geological, physical, and biological habitat factors that affect periphyton and phytoplankton biomass levels in rivers and streams given adequate to high nutrient supply and non-toxic conditions. Note that only one factor is sufficient to limit either phytoplankton or periphyton biomass.

Phytoplankton-Dominated Systems	**Periphyton-Dominated Systems**
High Phytoplankton Biomass · low current velocity(< 10 cm/s)/long detention time (>10 days) and · low turbidity/color and · open canopy and · greater stream depth and · greater depth to width ratio	High Periphyton Biomass · high current velocity (>10 cm/s) and · low turbidity/color and · open canopy and · shallow stream depth and · minimal scouring and · limited macroinvertebrate grazing and · gravel or larger substrata and · smaller depth to width ratio
Low Phytoplankton Biomass · high current velocity (>10 cm/s)/short detention time (<10 days) and/or · high turbidity/color and/or · closed canopy and/or · shallow stream depth	Low Periphyton Biomass · low current velocity (< 10 cm/s) and/or · high turbidity/color and/or · closed canopy and/or · greater stream depth and/or · high scouring and/or · high macroinvertebrate grazing and/or · sand or smaller substrata

Ecoregions are generally defined as relatively homogeneous areas with respect to ecological systems and the interrelationships among organisms and their environment (Omernik 1995). Ecoregions can occur at various scales; broad-scale ecoregions may include the glaciated corn belt of the central and upper Midwest or the arid to semi-arid basin and desert regions of the southwest. At more refined scales, regions within the broader regions can be identified.

Ecoregions serve as a framework for evaluating and managing natural resources. The ecoregional classification system developed by Omernik (1987) is based on multiple geographic characteristics (e.g., soils, climate, vegetation, geology, land use) that are believed to cause or reflect the differences in the mosaic of ecosystems. Omernik's original compilation of national ecoregions was based on a fairly coarse (1:7,500,000) scale that has subsequently been refined for portions of the southeast, mid-Atlantic, and northwest regions, among others (Omernik 1995). The process of defining subregions within an ecoregion requires collaboration with State/Tribal scientists and resource managers. Once appropriate subregions are delineated, reference sites can be identified (see Section 4.2). Similar to the process described for ecoregion refinement, reference site selection involves interactions with scientists and water quality managers that understand local conditions. Field verification techniques, methods for selecting reference sites for small and/or disjunct subregions can be found in Omernik (1995).

FLUVIAL GEOMORPHOLOGY

Fluvial geomorphology mechanistically describes river and slope processes on specific types of landforms, i.e., the explanation of river and slope processes through the application of physical and chemical principles. The morphology of the present-day channel is governed by the laws of physics through observable stream channel features and related fluvial processes. Stream pattern morphology is directly influenced by eight major variables including channel width, depth, velocity, discharge, channel slope, roughness of channel materials, sediment load and sediment size (Leopold et al. 1964). A change in one variable causes a series of channel adjustments which lead to changes in the other variables, resulting in channel pattern alterations. Many stream classification systems, have a fluvial geomorphologic component.

ROSGEN

The stream classification method devised by David Rosgen is a comprehensive guide to river and stream classification (see Rosgen 1994 or 1996). The Rosgen classification system is currently utilized by several States. This system integrates fluvial geomorphology with other stream characteristics. Specifically, Rosgen combines several methods of stream classification into one complete, multi-tiered approach. Rosgen's method has four levels of detail: broad morphological (geomorphic) characterization, morphological description (stream types), stream "state" or condition, and verification. Level I classification, geomorphic characterization, takes into account channel slope (longitudinal profile), shape (plan view morphology, cross-sectional geometry), and patterns. Level I streams are divided into seven major categories and labeled A-G. The Level II morphological delineative criteria include landform/soils, entrenchment ratio, width/depth ratio, sinuosity, channel slope, and channel materials. The 42 subcategories of Level II streams are labeled with a letter and a number, A1-G6 (see Rosgen 1994, 1996). Level III designations are primarily used in specific studies or in restoration projects to assess the quality and/or progress of a specific reach. Level IV classifications may be used to verify results of specific analyses used to develop empirical relationships (such as a roughness coefficient) (Rosgen 1996).

Rivers and streams are complicated systems. A classification scheme is an extreme simplification of the geomorphic and fluvial processes. However, the Rosgen system of classification is a useful frame of reference to :

1. Predict a river's behavior from its appearance;
2. Develop specific hydraulic and sediment relations for a given morphological channel type and state;
3. Provide a mechanism to extrapolate site-specific data collected on a given stream reach to those of similar character; and
4. Provide a consistent and reproducible frame of reference of communication for those working with river systems in a variety of professional disciplines (Rosgen 1994).

Classification of streams and rivers allows comparisons and extrapolation of data from different streams or rivers in an ecoregion. Comparing similar streams may help to predict the behavior of one stream based data and observations from another. *Applied River Morphology* (Rosgen 1996) contains in-depth descriptions of each Level II stream type (A1-G6) and includes photographs and illustrations. Rosgen discusses theoretical characterizations and variables and provides field methods for delineating stream types. The Rosgen classification system may be more detailed than needed for many States and Tribes. For more information on the Rosgen classification system, see Rosgen (1996).

STREAM ORDER

Identifying stream orders in a given delineated watershed can provide a classification system for monitoring streams. A variety of methods have been proposed for ordering drainage networks for stream classification and monitoring. The Horton-Strahler method (Horton 1945; Strahler 1952) is most widely used in the US. Each headwater stream is designated as a first order stream. Two first order streams combine to produce a second order stream, two second order streams combine to produce a third order stream and so on (Figure 5). Only when two streams of the same order are combined does the stream order increase. Numerous lower order streams may enter a main stream without changing the stream order. As a result, utilizing this method for classification may lead to problems of disparity in hydrological and ecological conditions among same order streams even within the same region. Resource managers using stream order as a classification system should ensure that topographic maps used to identify watershed boundaries all utilize the same scale. The inclusion or exclusion of perennial headwater streams should be decided before ordering drainage networks of interest.

Stream order (Strahler 1952) is used to classify streams in the EPA Environmental Monitoring and Assessment Program (EMAP). Sample sites were selected using a randomized sampling design with a systematic spatial component. The survey in the mid-Atlantic region was restricted to wadeable streams defined as 1^{st}, 2^{nd}, or 3^{rd} order as delineated using USGS 1:100,000 scale USGS hydrologic maps that were incorporated into EPA's River Reach File (Version 3). Sample probabilities were set so that approximately equal numbers of 1^{st}, 2^{nd}, and 3^{rd} order stream sites would appear in the sample population. Data were collected at 368 different sites representing 182,000 km of wadeable streams in the mid-Atlantic region (Herlihy et al. 1998).

PHYSICAL FACTORS USED TO CLASSIFY STREAMS AND ANALYZE TROPHIC STATE

The following sections focus on physical characteristics of streams that can be used to sub-classify stream systems. Physical characteristics that can be used for stream classification include system hydrology and morphology, flow conditions, and underlying geology.

Hydrology and Morphology

Hydrologic and channel morphological characteristics are often important determinants of algal biomass. Unidirectional flow of water sets up longitudinal patterns in physical and chemical factors that may also affect macrophyte growth when light and substrate conditions are adequate. Channel morphology or shape of a river or stream channel at any given location is a result of the flow, the quantity and character of the sediment moving through the channel, and the composition of the streambed and banks of the channel including riparian vegetation characteristics (Leopold et al. 1964). Frequent disturbance from floods (monthly or more frequently) and associated movement of bed materials can scour algae from the surface rapidly and often enough to prevent attainment of high biomass (Peterson 1996). In areas with less stable substrata, such as sandy bottomed streams, only slight increases in flow may lead to bed movement and scouring. Scouring by movement of rocks has been directly linked to reduction in algal biomass and subsequent recovery from floods (Power and Stewart 1987). Larger, more stable rocks can have higher periphyton biomass (Dodds 1991; Cattaneo et al. 1997). Thus, in cases where

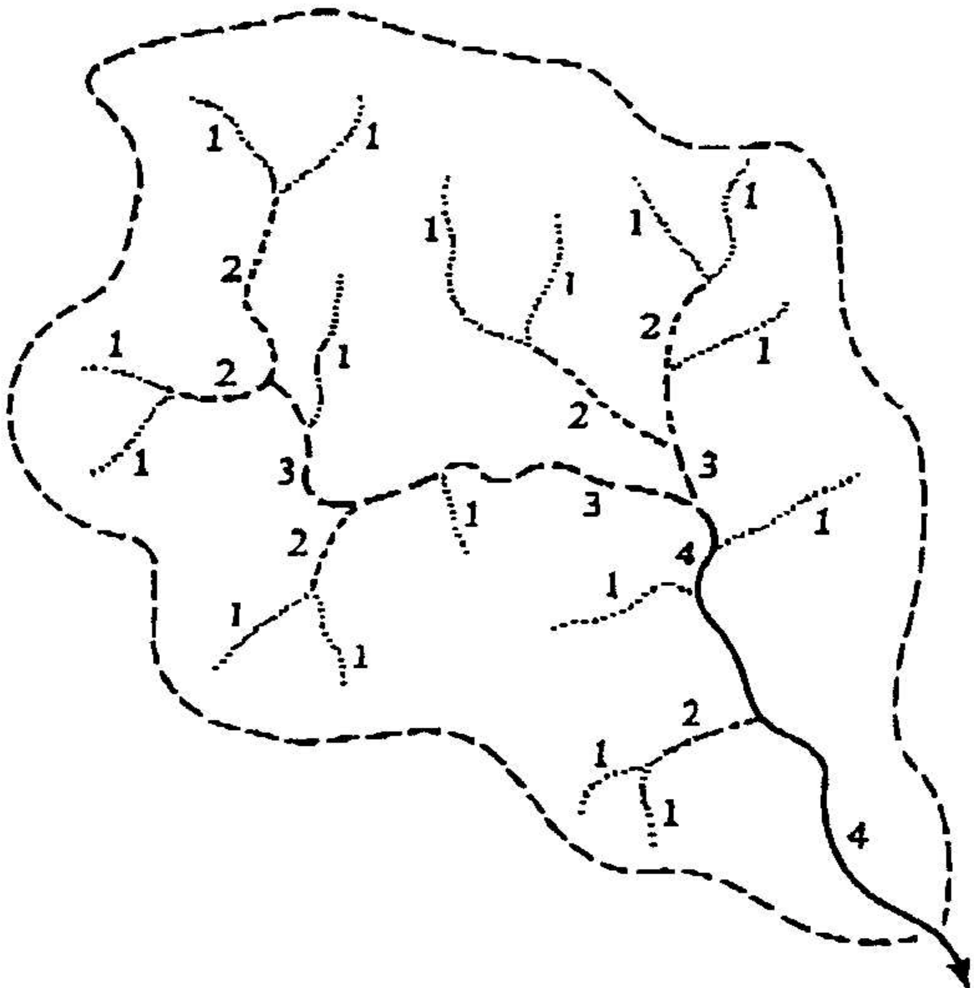


Figure 5. Stream ordering of a watershed basin network using the Strahler method. (Adapted from Strahler [1964]).

there is frequent movement of substrata, high nutrients may not necessarily translate into excessive algal biomass (Biggs et al. 1998a,b).

Consideration of both geology and hydrologic disturbance can provide important insights into factors influencing algal biomass. Research done in New Zealand identified geology, land use patterns, and stream conductivity (as a surrogate for total nutrients) as important determinants of algal biomass because these factors affected nutrient inputs and flood disturbance (Biggs 1995). The effects of disturbance by floods can be complex and complicated by biological factors; very stable stream beds may be associated with an active grazing community and have less biomass than more unstable systems. This notwithstanding, flow regime, channel morphology and bed composition (such as sand versus large boulders) appear to be major controlling factors and should be considered when managing eutrophication in a particular watershed.

Flow Conditions
Low and stable flow conditions should be considered in addition to frequency and timing of floods when physically classifying stream systems. Flood frequency and scouring may be greater in steep-gradient (steep slope) and/or channelized streams and in watersheds subject to intense precipitation events or rapid snow melt. Periods of drying can also reduce algal biomass to low levels (Dodds et al. 1996). A stream may flood frequently during certain seasons, but also remain stable for several months at a time. The effects of eutrophication may be evident during stable low flows. Also, stable flow periods are generally associated with low flow conditions, resulting in the highest nutrient concentration from point source loading. Hence, low-flow periods often present ideal conditions for achieving maximum algal biomass. For these reasons, nutrient control plans may require strategies that vary seasonally (e.g., criteria for a specific system may differ with season or index period).

Underlying Geology
Streams draining watersheds with phosphorus-rich rocks (such as from sedimentary or volcanic origin) may be naturally enriched and the control of algal biomass by nutrient reduction in such systems may be difficult. Bedrock composition has been related to algal biomass in some systems (e.g., Biggs 1995). In addition, nutrient content, and hence algal biomass, often naturally increases as elevation decreases, especially in mountainous areas (Welch et al. 1998). Some naturally phosphorus-rich areas include watersheds draining some volcanic soils, and other areas have high weathering of nitrate from bedrock (Halloway et al. 1998). Review of geologic maps and consultation with a local Natural Resources Conservation Service (NRCS) agent or soil scientist may reveal such problems.

2.3 CLASSIFICATION SCHEMES BASED ON NUTRIENT GRADIENTS

Nutrient loading is the factor most likely to be controlled by humans, but the ability to control algal biomass within the stream itself may be influenced by additional factors. Factors that may control algal biomass in streams include bedrock type and elevation (because they determine the natural or background nutrient supply), physical disturbance (flooding and drying), light, sediment load, and grazing. Many of these factors will be accounted for in the physical classification of stream systems. However, characterization of nutrient gradients in stream systems will be influenced by land use practices as well as point source discharges (Carpenter et al. 1998). The nutrient ecoregions defined by Omernik (2000) separate the country into large ecoregions with common land use characteristics. These ecoregions should be further subdivided for use at the State, Tribal, or local scale.

Changes in the natural processes that control algal production and biomass in a stream or river as one moves downstream through a watershed are obviously an important consideration. The River Continuum Concept (RCC) (Vannote et al. 1980) provides one general model for predictions of stream size effects on algal-nutrient relations. The RCC predicts, among other things, that benthic algal biomass will increase with stream size to a maximum for intermediate stream orders (i.e., third and fourth order stream reaches) as stream width increases and canopy cover consequently decreases. The RCC also suggests that (1) sestonic (suspended) chlorophyll will become more important in larger, slow-moving rivers and (2) turbidity in deep, high order streams causes light attenuation, which tends to prohibit high benthic algal biomass. The RCC may not hold for unforested watersheds (e.g., Dodds et al. 1996) or those with excessive human impacts such as impoundments or severe sediment input from logging. For example, Rosenfield and Roff (1991) observed that stream primary productivity in Ontario streams was largely independent of stream size. However, the RCC is valuable for identifying variables that change with stream size and affect algal-nutrient relations.

CLASSIFICATION BY NUTRIENT ECOREGIONS

The draft nutrient aggregations map of level III ecoregions for the conterminous United States (Figure 4; Omernik 2000) defines broad areas that have general similarities in the quantity and types of ecosystems as well as natural and anthropogenic characteristics of nutrients. As such, ecoregions are intended to provide a spatial framework for the National Nutrient Criteria Program. In general, the variability in nutrient concentrations in streams, lakes, and soils should be less in those ecoregions having higher hierarchical levels, i.e., nutrient concentrations found in level III ecoregions (84 ecoregions delineated for the mainland U.S.) (Omernik 1987), than those of waterbodies located in draft aggregations of Level III ecoregions.

CLASSIFICATION BY TROPHIC STATE

The primary response variable of interest for stream trophic state characterization is algal biomass. Algal biomass is usually concentrated in the benthos of fast-flowing, gravel/cobble bed streams (i.e., periphyton dominated) and measured as benthic chl *a* per unit area of stream substrate. In slow-moving, sediment-depositing rivers (i.e., plankton dominated), algal biomass is suspended in the water column and measured as sestonic chl *a* per unit water volume. Trophic classifications for lakes and reservoirs may be appropriately applied to seston in slow-moving rivers as these classifications are based primarily on chl *a* per unit volume (e.g., OECD 1982). However, lake classification schemes have limited value for fast-flowing streams dominated by benthic periphyton because the limited areal planktonic chlorophyll data available for lakes reveal little differentiation between oligotrophic and eutrophic systems (Dodds et al. 1998).

Nitrogen and phosphorus are important variables for classification of trophic state because they are the nutrients most likely to limit aquatic primary producers and are expressed per unit volume in both fast-flowing streams and slow-flowing rivers. Concentrations of total nutrients and suspended algal biomass are well-correlated in lakes and reservoirs (Dillon and Rigler 1974; Jones and Bachmann 1976; Carlson 1977). Developing predictive relationships between nutrient and algal levels in fast-flowing streams may be difficult considering that most available nutrients are in the water column and most chl *a* is in the benthos. Therefore, trophic state classification for periphyton-dominated stream systems is more appropriately based on benthic or areal algal biomass (e.g., mg/m^2 chl *a*) than on concentrations of N and P.

As stated above, classification of trophic state in stream systems is most appropriately based on algal biomass and secondarily on nutrients. When trophic state classification is based upon nutrients, total water column concentrations (TP and TN) are more appropriate than dissolved inorganic nitrogen (DIN) or soluble reactive phosphorus (SRP). Inorganic nutrient pools are depleted and recycled rapidly. Most monitoring programs will not be able to closely track soluble nutrients in a stream system and should therefore focus on total water column concentration rather than soluble nutrient species.

Additional factors also confound the interpretation of dissolved nutrient data. Algae are able to directly utilize inorganic nutrient pools (DIN and SRP) and deplete these pools if algal biomass is high enough relative to stream size and nutrient load. Thus, moderately low levels of DIN and SRP do not necessarily result in low algal biomass. This seeming contradiction is because the supply rate of inorganic nutrients may still be high even if a large biomass of algae has removed a significant portion of the DIN or SRP from the water column. Algal growth rate (including diatoms and filamentous greens) can be saturated at low dissolved inorganic nutrient concentrations (Bothwell 1985, 1989; Watson et al. 1990; Walton et al. 1995). Total phosphorus and TN may better reflect stream trophic status compared to inorganic P and N because algal drift increases with benthic algal biomass. Thus, as soluble nutrient depletion increases with benthic algal biomass, that depletion can be partially compensated for by increases in particulate fractions of TP and TN resulting from benthic algal drift and suspension in the water column.

A trophic classification scheme for streams and rivers, based on chlorophyll *a* and nutrients, was recently developed by Dodds et al. (1998). The approach used by Dodds et al. was based upon establishing statistical distributions of trophic state-related variables. The data were viewed in two ways: 1) three trophic state categories were constructed based on the lower, middle, and upper thirds of the distributions and were assigned to oligotrophic, mesotrophic and eutrophic categories respectively; and 2) the actual distributions (Table 2) were used to determine the proportion of streams in each trophic category. It should be stressed that this approach proposes

Table 2. Suggested boundaries for trophic classification of streams from cumulative frequency distributions. The boundary between oligotrophic and mesotrophic systems represents the lowest third of the distribution and the boundary between mesotrophic and eutrophic marks the top third of the distribution.

Variable (units)	Oligotrophic-mesotrophic boundary	Mesotrophic-eutrophic boundary	Sample size (N)
mean benthic chlorophyll (mg m^{-2})$^{+}$	20	70	286
maximum benthic chlorophyll (mg m^{-2})$^{+}$	60	200	176
sestonic chlorophyll (μg L^{-1})$^{++}$	10	30	292
TN (μg L^{-1})$^{+,+++}$	700	1500	1070
TP (μg L^{-1})$^{+,++,+++}$	25	75	1366

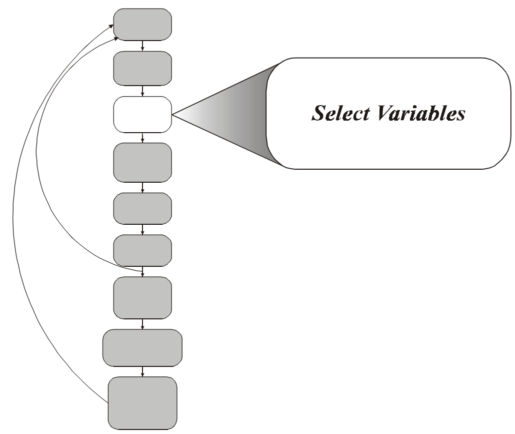
$^{+}$Data from Dodds et al. (1998); $^{++}$data from Van Nieuwenhuyse and Jones (1996); $^{+++}$data from Omernik (1977).

trophic state categories based on the current distribution of algal biomass and nutrient concentrations which may be greatly changed from pre-human settlement levels. These distributions were determined using data for benthic and sestonic chlorophyll and water column TN and TP from a wide variety of previously published studies. The data were gathered from temperate stream sites located in North America and New Zealand. The data for TN and TP used in this analysis were not taken from the same sources as the data for benthic and sestonic chlorophyll *a*. Hence, the distributions should only be used to link nutrient concentrations and algal biomass in a very general sense.

Management Applications

Classifying streams by trophic state can assist water quality managers in setting criteria and identifying those systems most at risk for impairment by nutrient enrichment. For example, an understanding of stream trophic state and ambient nutrient concentrations allows the manager to determine if the system of interest is eutrophic due to nutrient inputs that are natural or cultural. Comparisons with streams in the same local area that have similar physical characteristics will help clarify this issue prior to making management decisions. Management options may be limited if the condition of the stream is caused by high background levels of nutrient enrichment. However, if nutrient sources are largely cultural, establishing nutrient control strategies may realistically result in improvements in stream trophic state and therefore be useful in managing the stream system.

Chapter 3.
Select Variables



3.1 INTRODUCTION

Candidate variables, in the context of this document, are measurable water quality variables that can be used to evaluate or predict the condition or degree of eutrophication in a water body. Data that are most useful in determining river and stream trophic status are water column nutrient concentrations and algal biomass. Benthic and/or planktonic biomass can reach nuisance levels in many stream systems. Measurement of these variables provides a means to evaluate the current degree of nutrient enrichment, and can form the basis for establishing regional and waterbody-specific nutrient criteria. Numerous variables can potentially be used as part of nutrient surveys or eutrophication assessments including measures of water column nutrient concentrations (e.g., TP, SRP, orthophosphate, TN, total Kjeldahl nitrogen [TKN], NO_3^-, ammonia [NH_3]); dissolved organic carbon (DOC); water column and algal/macrophyte tissue N:P nutrient ratios; and algal biomass surrogates (e.g., chl *a*, ash-free dry mass [AFDM], turbidity, percent of benthic algal coverage, species composition).

Criteria development at the EPA Regional and National level will begin with nutrient data gleaned from EPA's STORET (STOrage and RETrieval) database. Primary nutrient parameters to be considered include water column concentrations of TN, TP, algal biomass as chl *a*, and turbidity or transparency. These four variables are considered a starting point for criteria development and their efficacy in controlling nutrient enrichment will be re-evaluated over time. Inorganic nutrient species (PO_4 and NO_3) are usually more biologically available, and may need to be considered in instances where small scale effects from specific sources are an important issue (e.g., point source impacts from outfall pipes, and non-point source impacts during rain events immediately following inorganic fertilizer application). STORET data on the primary parameters are the foundation of the dataset used at National and Regional levels for developing nutrient criteria. Supplemental data from other Federal agencies, State/Tribal agencies, and university studies will also be included as available. Sources of available data, the parameters included in the primary datasets, and the minimum data requirements for criteria development are discussed in Chapter 5.

Interpretation of parameter values and their cause-and-effect relationships depends on whether the data are from stream segments that are slow-moving with a depository substratum and plankton-dominated, or that are fast-moving with an eroding (gravel/cobble) substratum and periphyton-dominated. Criteria for streams with intermediate characteristics, i.e., in which the bottom is not generally visible in slow-moving segments and is not likely to have algal biomass problems, may need to be developed primarily for fast moving stream segments. Hence, significance of each individual or group of variables is discussed for each extreme stream/river type; the reader, of course, realizes that flowing waters can be found along all points on the trophic continuum and parameter values can vary even within a stream reach. This chapter lists and describes (1) primary response variables that will be used by EPA to set default criteria and (2) secondary response variables (including sensitive variables, i.e., those likely to be most sensitive to enrichment as influenced by increased primary producer biomass and metabolic activity) that can be used to predict the enrichment status of stream systems.

3.2 PRIMARY VARIABLES

The primary variables considered for nutrient criteria development are water column concentrations of TN, TP, benthic and planktonic algal biomass as chl *a*, and turbidity or transparency. These variables will be used to set criteria ranges for each EPA ecoregion at the National level (see section 1.5). The primary causal variables, TN and TP, are closely related to the response variables, algal biomass as chl *a* and turbidity or transparency, although the relationships between these variables are not as tightly coupled in rivers and streams as they are in lakes. Concentrations of nutrients and algal biomass and measures of turbidity/transparency are more highly variable in rivers and streams because of fluctuating flow conditions. Therefore, knowledge of the flow conditions in the waterbody of concern will be used to help define the nutrient condition of that waterbody, and will be used in criteria development. Criteria will not be established for flow as a variable. Stream sampling should be conducted during periods of peak algal biomass or periods when problems related to algae may be greatest (e.g., low-flow or following rain events with high nonpoint source nutrient inputs). Subsequent sections of the chapter discuss other potential variables that may be useful in developing nutrient criteria. Methods for measuring and analyzing many of the variables discussed in this Chapter can be found in Appendix B.

NUTRIENTS

Nitrogen and phosphorus are the primary macro-nutrients that enrich streams and rivers and cause nuisance levels of algae. Conditions that allow periphyton/plankton biomass to accumulate (i.e., adequate light, optimum current velocity [periphyton], sufficient water detention time [plankton], as well as low loss to grazing) will not result in high biomass without sufficient nutrient supply. Nutrients, especially P, are frequently the key stimulus to increased and high algal biomass.

Phosphorus is the key nutrient controlling productivity and causing excess algal biomass in many freshwaters worldwide. However, nitrogen can become important in waters receiving agricultural runoff and/or wastewater with a low N/P ratio and in waters with naturally phosphorus-rich bedrock (Welch 1992). Nitrogen may have more importance as a limiting element of biomass in streams than in lakes (Grimm and Fisher 1986; Hill and Knight 1988; Lohman et al. 1991; Chessman et al. 1992; Biggs 1995; Smith et al. 1999). Lohman et al. (1991) reported low NO_3-N causing N limitation at sixteen sites in ten Ozark Mountain streams and cited sources for N limitation in northern California and the Pacific Northwest. Nitrogen was clearly the limiting nutrient in the upper Spokane River, Washington (Welch et al. 1989). Chessman et al. (1992) observed that N was more often limiting than P in Australian streams.

Analyses of data from 200 rivers suggests that TN is more closely correlated to mean benthic algal biomass than TP, and DIN is more closely correlated to biomass than SRP (Dodds et al. unpublished).

The directly available forms of N and P are mainly inorganic (NO_3^-, NH_4^+ and PO_4^{3-}), although many algae are able to use organic forms (Darley 1982). Total N and TP include these soluble fractions, as well as the particulate and dissolved organic fractions. Particulate and dissolved organic fractions are not immediately available and portions may be relatively refractory. Because soluble inorganic fractions are directly available, soluble inorganic N, P, or both may be low during active growth periods when demand is high and, therefore, may not be good predictors of biomass (Welch et al. 1988). Total N and TP are often good predictors of algal biomass in lakes and reservoirs, to a large extent because much of the particulate fraction is live algal biomass. That is not the case in fast-flowing, gravel/cobble bed streams where the total nutrient concentration includes detritus but not the living periphytic algae where biomass measurements are taken. In fast-flowing systems, water column nutrients flow past the living periphyton biomass before they can be completely assimilated. Therefore, the relationship between benthic chlorophyll and water column nutrients is weaker in fast-flowing versus standing water systems (Dodds et al. 1998).

ALGAL BIOMASS AS CHLOROPHYLL *a*

Algae are either the direct or indirect cause of most problems related to excessive nutrient enrichment; e.g., algae are directly responsible for excessive, unsightly periphyton mats or surface plankton scums, and may cause high turbidity, and algae are indirectly responsible for diurnal changes in DO and pH. Chl *a* is a photosynthetic pigment and sensitive indicator of algal biomass. It can be considered the most important biological response variable for nutrient-related problems. The following discussion of chl *a* as a primary variable includes information for both benthic and planktonic chl *a*. Benthic chl *a* can be difficult to measure reliably due to its patchy distribution and occurrence on non-uniform stream bottoms. Periphyton is often analyzed for AFDM, which includes non-algal organisms. Additional factors that can be used to determine which type of chlorophyll (benthic or planktonic) is most important in the system of interest can be found in Table 1, Section 2.2.

Unenriched, light-limited, or scour-dominated stream systems typically have benthic chl *a* values much less than 50 mg/m^2. Biggs (1995) reported the following range of chl *a* values from monthly observations over a one year period in 16 New Zealand streams: 1) unenriched streams in forested catchment (0.5-3 mg/m^2), 2) moderately enriched streams in catchments with moderate agricultural use (3-60 mg/m^2), and 3) enriched streams in catchments highly developed for agriculture and/or underlain with nutrient-rich bedrock (25-260 mg/m^2). Lohman et al. (1992) reported a range of 42 to 678 mg/m^2 chl *a* from over two years of spring to fall biweekly observations at 22 sites on 12 Missouri Ozark Mountain streams, with higher levels occurring at more enriched sites. Unenriched sites exhibited mean biomass values that did not exceed 75 mg/m^2. However, highly and moderately enriched sites exceeded a nuisance level mean biomass (150 mg/m^2) within 3 or 4 weeks, respectively, following flood-scour events. The highest maximum value observed at ten sites in late summer 1987 in the Clark Fork River, Montana, was approximately 600 mg/m^2 (Watson and Gestring 1996). Furthermore, values for benthic chl *a* as high as 1200 mg/m^2 have been observed in gravel/cobble bottom bed streams (Welch et al. 1992).

Planktonic chl *a* in deep, slow-moving rivers will have an upper limit determined by light attenuation, which increases with the suspended chl *a* concentration. Maximum chl *a* can be low (<10 μg/L) even if slow-moving systems are nutrient enriched because most flowing systems disperse phytoplankton before high algal biomass develops. However, under low flow conditions (accompanied by low mixing and shallow depth), large planktonic algal blooms often develop in slow-moving, nutrient enriched rivers. The theoretical maximum attainable before light limits photosynthesis in lakes (assuming light is attenuated by algae only) is about 250 mg/m^2. This theoretical maximum is equivalent to 25 mg/m^3 (μg/L) in a 10-m depth water column or 125 μg/L in a 2 m deep lake. Van Nieuwenhuyse and Jones (1996) compiled summer mean suspended chl *a* values for rivers, and found no values greater than 180 μg/L. Mixing and light attenuation from non-algal particulate matter, which are typical in deep, slow-moving rivers, may further limit light availability for photosynthesis.

A conceptual distribution of algal biomass in the euphotic zone over a range of water detention times was suggested by Rickert et al. (1977) (see Welch 1992). For example, the lower Duwamish River, Washington estuary typically contained around 2 μg/L chl *a* during summer, even though it was heavily enriched with secondary treated sewage effluent. However, when the water detention time increased and mixing decreased as a combined result of minimum range tidal conditions and low river flow in August, chl *a* reached a maximum of 70 μg/L (Welch 1992).

Algal biomass data in fast-flowing, gravel/cobble bed streams and deep, slow-moving, turbid rivers must be interpreted in light of the physical constraints that determine the potential for nutrient utilization (see Chapter 2). Relatively low biomass can be observed in highly enriched waters, if physical (light, temperature, current) or grazing constraints are severe. Relatively high algal biomass can occur with low enrichment if physical constraints approach the optima for algal growth. However, chl *a* concentrations near the maximum values cited above will not occur without nutrient enrichment.

TOTAL SUSPENDED SOLIDS, TRANSPARENCY, AND TURBIDITY

Total suspended solids (particulate matter suspended in the water column) attenuate light and reduce transparency, whether the source is algae, algal detritus or inorganic sediment. Streams may also have high concentrations of light-absorbing dissolved compounds (e.g., blackwater streams). The concentration of total suspended solids can be determined directly or as an effect on light transmission or scattering. Quantitative relationships have been developed for individual and/or groups of waters to predict transparency from particulate matter and/or chl *a* (Reckhow and Chapra 1983; Welch 1992). However, relationships of chl *a* and transparency (as an effect of nutrients) are not prevalent in fast-moving streams systems; most likely because of interference from time- and flow-variable inorganics and large diameter suspended solids. Total suspended solids may increase due to algae and detritus sloughed from large algal mats, but caution should be exercised in interpreting these data. During high flow, the concentration of suspended solids (and water clarity) will likely be more strongly influenced by inputs of inorganic sediment or channel erosion in streams, especially in urbanized and agricultural watersheds.

Turbidity, as NTUs (Nephelometric Turbidity Units), measures suspended matter in the water column whether of organic (i.e., chl *a*) or inorganic origin. Turbidity correlated with rain-event sampling may help identify non-point source loadings. Although turbidity is not commonly used as an index of eutrophication in either lakes or streams, it nonetheless should increase in streams with increasing algal biomass due to nutrient enrichment.

Periphyton are directly affected by suspended solids (as turbidity) due to light attenuation. Quinn et al. (1992) found that waters with turbidity measurements that range between 7-23 NTUs have reduced abundance and diversity of benthic invertebrates. They attributed the reduction in benthic invertebrates to turbidity, largely because of its adverse effect on periphyton production as an invertebrate food source (Quinn et al. 1992). In Illinois, the turbidity of agricultural streams (NTU 10-19) had more effect on periphyton accrual than did nutrient enrichment (Munn et al. 1989). Total suspended solids ranging from about 22 to 30 mg/L increased the loss rate of periphyton (mixture of filamentous blue-green and diatoms) tenfold, although increased velocity with and without solids caused more loss (Horner et al. 1990).

The vertical water column in relatively clear-water, gravel/cobble bed streams/rivers is usually insufficient to determine Secchi disk depth. However, the white Secchi disk routinely used in lakes and reservoirs to determine transparency is appropriate for slow-moving streams and rivers (Welch 1992). Transparency, as influenced by low concentrations of particulate matter in shallow, fast-flowing streams systems, can also be determined with a black disk (Davies-Colley 1988). The path length for transparency is measured horizontally in such shallow streams, as opposed to vertically in lakes, reservoirs and deep rivers/estuaries. As periphyton biomass increases, particulate matter sloughed and/or eroded from the substratum also increases, reducing transparency.

FLOW AND VELOCITY

The rate of discharge or flow in a stream system can be separated into two primary components, baseflow and storm or direct runoff. Baseflow comprises the regular groundwater inputs to a stream. This water typically reaches the stream through longer flow paths than direct runoff and sustains streamflow during rainless periods. Direct runoff is hillslope or overland flow runoff that reaches a stream channel during or shortly after a precipitation event. Both components of flow are reflected in a hydrograph (a graph of the rate of discharge plotted against time) of the stream segment. Runoff processes (including stream discharge and groundwater recharge), seasonal variation of flow, and methods to calculate average stream velocity, the annual probability hydrograph and flow duration curves are discussed at length in Dunne and Leopold (1978).

The flow of a river or stream affects the concentration and distribution of nutrients. Generally, point source concentrations are higher during low flow conditions due to reduced water volumes; in contrast, nutrients from non-point sources may be more highly concentrated during high flow conditions due to increased flow paths through the upper soil horizons and overland flow. There is also a rough correlation of total dissolved solids concentration with climate and hydrology. Streams in arid regions tend to have high concentrations of total dissolved solids (though the total annual solute transport is low because of low runoff), whereas in humid regions, concentrations tend to be lower with higher total annual solute transport (Dunne and Leopold 1978). However, the complexity of the interactions of nutrient concentration and flow make it important to examine both point sources and non-point sources of nutrients and wet weather (high flow) and dry weather (low flow) stream conditions to verify nutrient sources and concentrations in multiple flow conditions (Dunne and Leopold 1978).

Brandywine Creek, Pennsylvania, provides an example of how stream flow can affect nutrient concentrations in a stream system (Dunne and Leopold 1978). The Brandywine Creek watershed drains portions of the Piedmont plateau and Atlantic coastal plain into the Delaware River. The watershed land use is a mix of urban, agricultural and suburban uses, and includes both point and non-point pollution sources. Brandywine Creek was sampled during periods of storm runoff and dry-weather flow for P and stream discharge. Point discharges of P were diluted as stream discharge increased following storm events. As storm runoff occurred, concentrations of P increased dramatically at sampling sites not dominated by point discharges. At sites not dominated by point discharges, runoff from forested and cultivated hillslopes washed large amounts of P into the Brandywine Creek in both solid organic form and sorbed to soil particles.

Hydrologic variability is an important consideration in the development of nutrient and algal criteria for all streams; nonetheless, there is often a higher degree of variability for specific types of regional stream systems. In particular, the spatial and temporal heterogeneity found in arid regions, the stark contrast between wet and dry, can be dramatic (see Desert Streams Case Study, Appendix A). When viewing desert catchments from above, the observer is often presented with a dry landscape of high relief bisected by the string of glistening beads that is the spatially intermittent stream. The dry arroyos or quiet, disconnected pools and short reaches of wetted stream that characterize desert streams during dry periods are in complete contrast to the raging torrents that they can become at flood stage. This hydrologic variability and the unique chemical and biological characteristics of arid lands aquatic ecosystems make the use of broad generalizations to explain nutrient regimes difficult.

In arid landscapes, stream ecosystems are dynamically linked with the surrounding upland ecosystem. In addition, surface discharge regimes may vary from completely dry, to flows as much as three to five orders of magnitude greater than mean annual flow, all within a period of hours or days. In comparison to streams in more mesic regions, the coefficient of variation of annual flow is 467% greater in arid lands streams (Davies et al. 1994). The aquatic ecosystems structured by these chaotic flow regimes (Thoms and Sheldon 1996) may require different techniques for nutrient criteria development than those used in more homogeneous environments.

Drying disturbance, or more specifically the contraction and fragmentation of a stream ecosystem, is a critical component of the hydrologic regime of desert streams. Drying occurs as a spatially or temporally intermittent stream recedes after a wet period. In streams where the dry period and extent may be greater than the wet, drying is likely to be an important determinant of biological pattern and process (Stanley et al. 1997; Stanley and Boulton 1995).

In order to properly characterize the nutrient regime of a stream ecosystem, the flow of water, surface and subsurface, flood or base flow, wet or dry must be considered at ecologically significant temporal and spatial scales. It is also important that the manager address this hydrologic regime at the scale of the question to be answered. If a stream is dry for 75% of the average year, or for 75% of its length, is it correct to characterize it from surface water data alone? If 50% of the entire annual load of a limiting nutrient passes through a stream ecosystem in three discrete storm events, what is the effect of that nutrient on the stream ecosystem itself? What is the effect to downstream ecosystems? Due to the spatial and temporal variability of flow patterns, the characterization of desert stream nutrient dynamics is an intricate undertaking. However, stream complexities will only be understood through appropriate assessment and evaluation.

3.3 SECONDARY RESPONSE VARIABLES

The following sections describe additional variables that may be useful in criteria development. These variables comprise chemical, physical, and biological parameters, some of which exhibit heightened response to nutrient enrichment.

SENSITIVE RESPONSE VARIABLES

The variables discussed below that are apt to be most sensitive to nutrient enrichment, via increased algal productivity and biomass are: 1) DO and pH, 2) benthic community metabolism, and 3) autotrophic index. These variables should vary directly with algal productivity and detect relatively small changes in nutrient condition. While other variables such as total suspended solids, macroinvertebrate indices, dissolved organic matter, and secondary production may be directly affected by algal productivity and biomass, they may also be strongly dependent on other natural factors and/or sources/types of pollutants.

Dissolved Oxygen and pH

Periphyton algal biomass above nuisance levels often produces large diurnal fluctuations in DO and pH. Photosynthesis/respiration by dense periphyton mats commonly causes water quality violations (Anderson et al. 1994; Watson et al. 1990; Wong and Clark 1976). These water quality impairments occur in stream systems as a result of nutrient-produced excessive algal biomass in fast-flowing, gravel/cobble bed streams as well as sluggish stream systems. Excessive macrophyte biomass can produce similar swings in DO and pH (Wong and Clark 1979; Wong et al. 1979).

The extent of diurnal swings in DO and pH will depend on several factors, such as turbulence (which affects reaeration), light, temperature, buffering capacity, and the amount and health of algal and/or macrophyte biomass. Sluggish streams and rivers may show a greater range in DO and pH per unit biomass compared to faster streams due to less turbulence and associated atmospheric exchange of CO_2 and O_2 (Odum 1956; Welch 1992). Light limitation may also be a common feature of algae in enriched streams, and therefore, light is likely an important control on diurnal DO and pH swings (Jasper and Bothwell 1986; Boston and Hill 1991; Hill 1996). Higher temperatures tend to enhance algal growth in many streams and may increase photosynthesis and respiration in many systems resulting in greater variation in diurnal DO and pH values. Streams with low buffering capacity will show greater diurnal swings in pH. Furthermore, biomass-specific metabolic rate (especially respiration–see photosynthesis/respiration discussion) tends to be greater in fast-flowing waters because periphytic growth is stimulated by velocity. The influence of the above factors on DO concentration and pH value reduce the specificity and potentially reduce the reliability of these variables to indicate response from nutrient enrichment. Therefore, direct measures of algal biomass, such as chl *a*, are preferred response variables.

Aquatic animals are affected most by maximum pH and minimum DO, rather than by the daily means for these variables (Welch 1992). Hence, monitoring for water quality should include pre-dawn hours to observe the diurnal minimum DO and afternoon hours for maximum pH. Routine grab samples in monitoring programs usually do not include such strict protocols. It may be possible to estimate minimum DO from equilibrated average and maximum DO (Slack 1971) which occurs during mid-day to afternoon, along with maximum pH.

Metabolism

Photosynthetic rate, or primary productivity, is often considered a more sensitive variable of response to nutrients than algal biomass. Biomass is a net result of gains (productivity) minus losses (algae lost due to death, scour, etc.) (see discussion in Stevenson 1996). Productivity is essentially growth, and therefore is a more direct measure of nutrient effects. Productivity can be determined for whole stream reaches by monitoring diurnal DO concentrations (see methods section, Appendix B) or alternatively, productivity and respiration may be measured using light/dark chambers. Whole-stream metabolism measurements are integrative over all components of the stream system and eliminate artifacts of enclosure that commonly confound results in chamber experiments. Marzolf et al. (1994, 1998) detail the methods for measuring whole-stream metabolism. Productivity and respiration in light/dark chambers may vary on an hourly and daily basis with temperature, light, and nutrients; short-term measurements must be corrected for those factors (Welch et al. 1992). The necessity of normalizing measurements and the greater analytical difficulty of productivity, has made algal biomass the preferred variable to indicate nutrient effects on periphyton and phytoplankton as evidenced by the generally established trophic state criteria for lakes and reservoirs (Welch 1992), and proposed for streams/rivers (Dodds et al. 1998). The rate at which maximum biomass is attained is dependent mostly on nutrient availability, minus losses to grazing and scouring, or washout in the case of phytoplankton. While integrated daily productivity is usually directly related to biomass as chl *a* (Boston and Hill 1991), there can be considerable variability in the relationship due to the variables discussed above, as shown by the ratio of productivity to biomass as chl *a* (Figure 6). The ratio of productivity to biomass as chl *a* is an index of growth rate. If there is no variability in productivity:biomass, the relationship will be constant and will not vary on a day-to-day basis.

Gross photosynthesis/respiration ratios (P/R ratios) can be useful indicators of trophic characteristics. P/R ratios have long been recognized to indicate the relative autotrophic (P/R >1) or heterotrophic (P/R <1) character of streams and rivers. Measurement of P/R and interpretation of results is dependent on the scale at which the measurements are made, and the point in the annual cycle when the measurements are taken. For example, low-order streams that flow through forested watersheds tend to be heterotrophic with photosynthesis limited by light due to shading; mid-order streams and rivers flowing through areas with minimal riparian vegetation, or largely unshaded due to width, are usually autotrophic (unless organic waste inputs are significant); high order rivers tend to return to a heterotrophic character due to light limitation brought on by increased depth and turbidity (Vannote et al. 1980; Bott et al. 1985). Furthermore, the P/R ratio for a short-term measurement (24-72 hours) in the spring may indicate an autotrophic stream, while on an annual basis the stream is heterotrophic (Hall and Moll 1975; Wetzel 1975; Wetzel and Ward 1992).

There are problems with interpreting P/R ratios, however. Photosynthesis/respiration ratios can vary seasonally and could actually reflect a temporary heterotrophic condition during a period of low periphyton biomass, due to scouring or low light, while otherwise it would be autotrophic. Decreased velocity can also decrease stream/river P/R, because mat thickness of periphytic diatoms can increase while the depth of active photosynthesis remains relatively constant (Biggs and Hickey 1994). Thus, photosynthesis is limited by light attenuation in the mat, but respiration is stimulated by movement of organic materials to heterotrophic organisms in the mat.

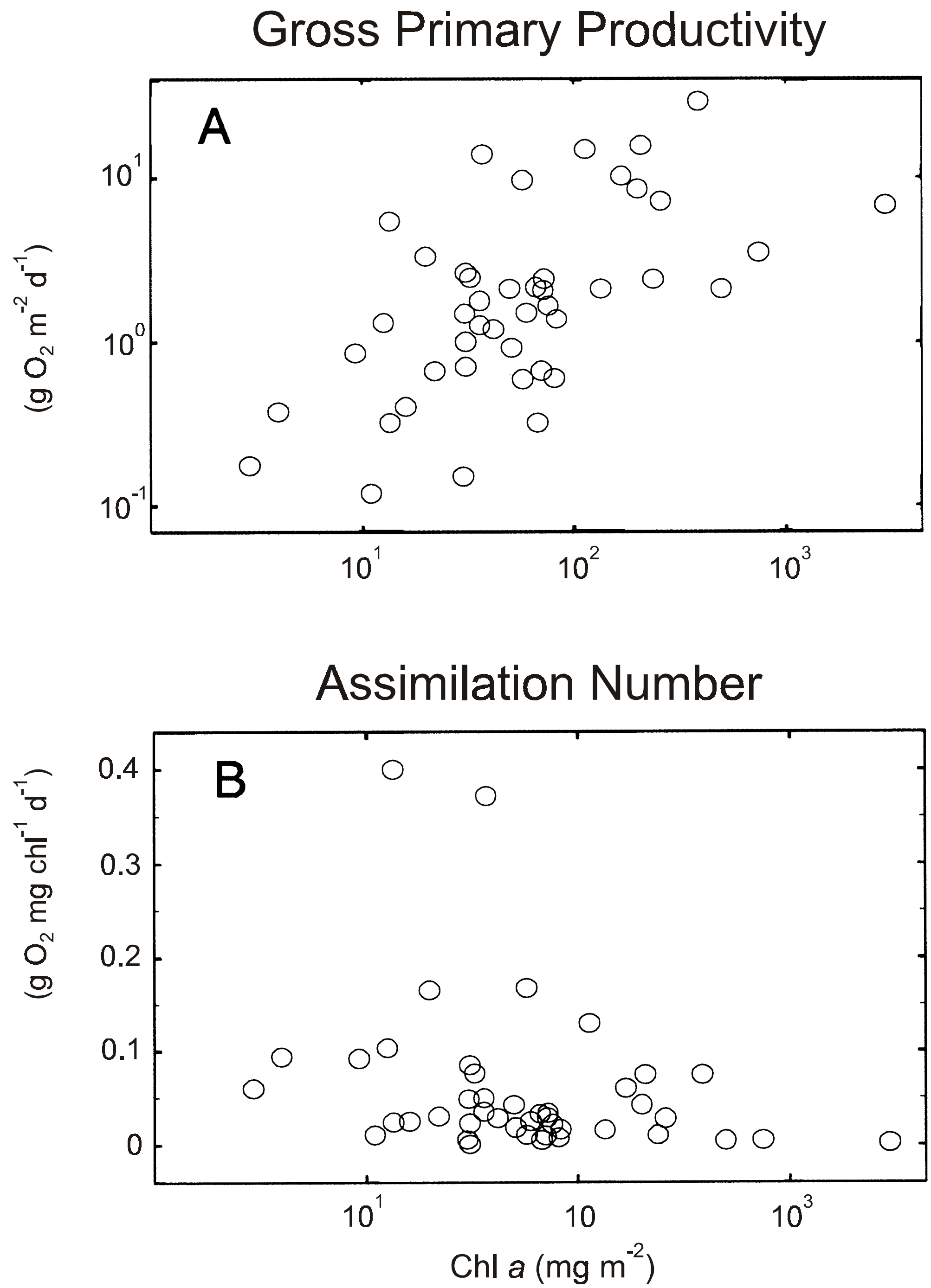


Figure 6. Integrated daily productivity related to biomass as chlorophyll *a* (data compiled by Dodds from published literature; many of the data from Bott et al. 1985).