

Colorado Lake Nutrient Criteria
A Rationale for Development

Water Quality Control Division
October 2006

Executive Summary

The Water Quality Control Division is in the process of developing nutrient criteria for lakes and reservoirs. The current proposal protects uses by setting thresholds for algal abundance, as measured by chlorophyll concentration. There are two types of chlorophyll thresholds – an average for the growing season and a bloom frequency. The growing season (Jul-Sep) average targets a balance between support for fishery productivity and the high transparency of water favored by other uses. A healthy fishery is assumed to be indicative of support for the aquatic life use.

Thresholds for growing season chlorophyll are suggested for each of three fishery types – cold water (6 ug/L), cool water (15 ug/L), and warm water (25 ug/L). The threshold suggested for cold water fisheries is consistent with values observed in Blue Mesa Reservoir, which is managed as a premier cold water fishery. A concentration threshold of 40 ug/L, not to be exceeded more than 20% of the time, is suggested for algal blooms.

Phosphorus is considered the causal component of nutrient criteria for lakes. The linkage between chlorophyll and phosphorus is defined by a site-specific response ratio that establishes the potential response of algae to chlorophyll in each lake. The response ratio provides an implicit accounting of contribution that factors other than phosphorus make in regulating algal abundance, without having to model that role explicitly. The response ratio is used to compute the average growing season phosphorus concentrations consistent with attainment of the chlorophyll threshold. Data from several Colorado lakes are evaluated on the basis of the suggested thresholds.

Introduction

States are required to Enrichment of surface waters with nutrients of anthropogenic origin is the fundamental problem to be addressed by nutrient criteria. There is little doubt that anthropogenic enrichment, which is called cultural eutrophication, holds considerable potential for impairing water quality. The threat has been recognized for decades, and many lakes and streams in the US have experienced the detrimental effects of eutrophication, the most obvious of which is excessive growth of algae. The remedy to impairment is deceptively simple: reduction of nutrient loads will curtail excessive algal growth. The difficulty is in determining an acceptable level for algal abundance or for the nutrients that promote algal growth; there is no bright line of toxicity that signals impairment.

The Water Quality Control Division (WQCD) has initiated an incremental approach to the development of nutrient criteria, consistent with EPA's waterbody-specific strategy. This document sets forth a proposal for nutrient criteria applicable to Colorado's lakes and reservoirs (henceforth, all are referred as lakes). The purpose of the proposal is to provide interested parties with a focal point for further discussions, with the aim of shaping a plan that will meet regulatory needs in a timely and defensible manner.

The WQCD concept is based on the premise that excessive algal abundance, which is the most obvious manifestation of cultural eutrophication, is the principal agent of

impairment. Thresholds for the concentration of chlorophyll, which is a practical measure of algal abundance, can be used to identify potential threats to uses. Where threats are perceived, a site-specific linkage between chlorophyll and phosphorus can be used to implement controls. This document develops a rationale for nutrient criteria and examines the potential ramifications for several Colorado lakes.

Background

States are required to adopt nutrient criteria. EPA has developed recommended criteria that acknowledge differences among water body types (streams, lakes, wetlands) and geography. Regional differences are addressed by aggregating lakes according to ecoregions. On a nationwide scale, the aggregation approach taken by EPA results in a high degree of spatial resolution that precedes efforts to define reference conditions.

Colorado is divided into 5 ecoregions (Level III) that reflect the geographic diversity of the state. All of the higher elevation areas are grouped in the Southern Rockies ecoregion (21). The eastern plains are divided into the Western High Plains (25; chiefly the lower South Platte basin) and the Southwestern Tablelands (26; chiefly the lower Arkansas basin). Most of the western part of the state falls within the Colorado Plateaus ecoregion (20; lower Colorado and Dolores basins); a portion of the Yampa River basin in the northwest lies within the Wyoming basin (18). In the southern part of the state, some valleys are within the Arizona/New Mexico Plateau ecoregion (22; chiefly the lower Rio Grande and San Juan basins). Reservoirs are found within all of the ecoregions.

Table 1. Summary of EPA recommendations for nutrient criteria in Colorado’s ecoregions. The number of lakes in each ecoregion applies only to the chlorophyll data; other constituents may be represented by a different number of lakes. In all cases, the recommendations are based on the 25th percentile values. See EPA Ecoregional Nutrient Criteria documents for lakes at <http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/lakes/index.html>

Ecoregion	Basin	Lakes	TP	NO3	Chl	Secchi
Southern Rockies	All; high elevation	7	14.8	10	1.7	4.2
Wyoming Basin	Yampa	5	10.0	50	1.4	3.0
Colorado Plateau	Colorado	34	3.0	10	1.4	3.2
AZ/NM Plateau	San Juan, Rio Grande	5	15.0	20	2.0	2.9
Western High Plains	South Platte, Arkansas	12	24.0	10	2.4	1.5
SW Tablelands	Arkansas	11	20.0	10	1.2	1.7

From a national perspective, EPA’s recommendations represent a valiant effort to produce a comprehensive, uniform approach to nutrient criteria development. At the local scale, however, states have rarely adopted those recommendations without at least minor changes. In some cases, states have been content to make refinements on the basis of finer geographic resolution (Level IV ecoregions, for example).

Colorado is among the states that have declined to adopt EPA’s recommendations for nutrient criteria. The decision is based in large part on concerns about key assumptions in EPA’s methodology. The first problematic assumption concerns the appropriateness of defining reference conditions for reservoirs. There is no pre-development condition

for reservoirs, as there would be for natural lakes. The statistical basis for the recommendations (25th percentile) relies on the implicit assumption that, within any geographically homogeneous region, the least productive lakes are the most “desirable” ones. Management for fishery production might justify maintaining higher productivity, provided that higher productivity does not impair other uses. The purpose for the reservoir and the classification that has been adopted should be considered when defining the water quality conditions necessary to protect designated uses.

The second problematic assumption concerns the linkage between the reservoir and the surrounding landscape. Eco-regions are defined chiefly on the basis of terrestrial ecological conditions. Nutrient export from a watershed is influenced by geology (including soils) and hydrology, and the resulting load to a lake within that watershed exerts strong control over the growth of resident algae. The concept applies well to natural lakes and to reservoirs where all water comes solely from the surrounding watershed. In Colorado, and in many western states, reservoirs often store water diverted from other drainages, which may be characterized by entirely different ecological conditions. The linkage between water quality and the local eco-region type is of uncertain usefulness in defining expectations for many Colorado reservoirs.

Boulder Reservoir provides an excellent illustration of the point. The natural watershed is less than 10 mi² of relatively low elevation land at the western edge of the plains. Only a small fraction of water entering the reservoir is from the natural watershed, however. More than 90% of the annual inflow comes from the Colorado-Big Thompson project, which derives most of its water from high elevation watersheds west of the Continental Divide. Many more examples could be described, but the point is clear – in highly managed water supply systems, there is no reason to expect the kind of linkage between water quality and land use that would typify natural lakes. When that linkage is removed, it undermines the rationale for aggregating lakes by ecoregion.

A third problematic assumption concerns the derivation of individual criteria in EPA’s methodology. The EPA methodology defines reference conditions independently for each factor based on 25th percentiles. It fails to preserve the linkages between cause and response variables that characterize the biological processes in individual lakes, and thus as an amalgam of 25th percentiles, it does not define a reference lake. It is well known that algae in different lakes respond differently to nutrient concentrations. The abundance of algae may be governed by phosphorus, or nitrogen, or grazers, or light, and the role of each factor differs among lakes as well as over time within one lake.

Finally, by specifying independently the concentrations acceptable for each constituent, the criteria are not amenable to site-specific application. This is contrary to what one would expect for biological systems and to the history of control regulations in Colorado. Each control regulation that addresses concerns about eutrophication has a different set of conditions regarded as acceptable for protecting water quality. The WQCD would like to preserve that flexibility.

It is neither surprising nor disturbing that Colorado might have objections to EPA's recommended criteria. Those objections, as well as additional objections by other states, do not invalidate a nationwide set of recommendations, but they do underscore the wisdom of EPA's encouragement for states to develop their own criteria. States can choose to assume the burden and apply local knowledge to the development of more satisfactory criteria. Given what is at stake in terms of protecting uses, there is considerable incentive for the WQCD to develop nutrient criteria suitable for Colorado.

In September, 2002, EPA approved the WQCD's plan for nutrient criteria development. The plan, which called for linking criteria to uses, involved two concurrent efforts, one focused on "high priority" water bodies and the other aimed at developing a regionalized approach. Further consideration of the connection between algal abundance and designated uses, as outlined in this document, has been facilitated by having a number of lakes with a strong data record (e.g., Bear Creek Reservoir, Lake Dillon, Cherry Creek Reservoir, Chatfield Reservoir). An empirical approach with a strong data record also will benefit the approach to regionalization.

Protection of uses is complicated in Colorado, as in most states of the arid west, by the fact that virtually all of the "lakes" are really multipurpose reservoirs. These are managed systems, and the existing management objectives may legitimately influence development of nutrient criteria. *The challenge for Colorado is to develop criteria that protect uses in managed systems.*

Protecting Uses

By choosing chlorophyll concentration as the focal point for development of nutrient criteria, Colorado has incurred an obligation to define the thresholds above which excessive algal abundance has an adverse impact on uses. There is little argument that adverse impacts can occur, but there may be little agreement about the specific chlorophyll concentrations that should trigger action. With the possible exception of algal toxins, there are no sharp thresholds of algal abundance associated with acute or chronic effects.

Most of the adverse impacts of excessive algal abundance are either qualitative or indirect. Blooms of algae, for example, can be detrimental to recreational use (e.g., swimming) by making the recreational experience unpleasant, or to water treatment by decreasing filter runs. The assessment of "how much is too much" is largely qualitative, however. The indirect role of algal abundance in contributing to increased pH and loss of hypolimnetic dissolved oxygen is well-known, but the amount of chlorophyll corresponding to an impact depends on conditions within each lake. Production of toxins by certain algal species represents a potentially important human health risk, but even here, the linkage to chlorophyll depends on the composition of the algal community. It would be easy to conclude that adverse impacts are minimized by keeping chlorophyll concentrations as low as possible, if it were not for the interests served by sustaining productivity in a lake.

Most reservoirs in Colorado support managed fisheries, and the yield of the fishery is sustained by the productivity of the lake. For support of a sport fishery, higher algal abundance (more chlorophyll) is better, up to a point, although the optimal chlorophyll for high fishery productivity may be higher than would be desirable for swimming. Maintenance of species diversity or richness is probably optimal at an intermediate level of chlorophyll (see Ludsin et al. 2001). In view of the positive role that nutrients play in sustaining productivity, it is useful to consider nutrient criteria in the context of optimizing the “level of use support” (see: <http://www.trinityra.org/BasinPlan/BHR2003/NutrientvsUsesStudyFinalReport.pdf>)

Development of lake nutrient criteria in Colorado begins with the premise that a healthy productive fishery is consistent with support of aquatic life use. Most visitors expect to be able to catch fish, and a productive fishery depends on a supply of nutrients. Although an over-abundance of nutrients is undesirable, the nutrient supply must be adequate to sustain the fishery. In fact, there is justifiable concern that overzealous control of nutrients can undermine fisheries. Research over the last decade has explored the possibility that reversal of cultural eutrophication, if carried to extremes, could have significant adverse impacts on the productivity of recreational fisheries (Jeppesen et al. 2005). The term “oligotrophication” has been coined to identify that process (Ney 1996).

Nutrient Criteria and Support for Fisheries: Virginia’s Experience

The State of Virginia has taken an innovative approach in which chlorophyll standards are applied to lakes classified according to fishery type. Three of those categories (cold, cool or warm) are appropriate for Colorado. Chlorophyll is a practical target for this purpose because it is a more direct indicator of actual productivity. Nutrient supply is more indicative of potential productivity, which may not be realized in a given setting.

Virginia’s procedure for setting criteria included a literature review aimed at determining the chlorophyll and total phosphorus levels that would optimize fish productivity (Zipper et al. 2005). In parallel, fisheries across the state were ranked, and those rankings were compared with chlorophyll and phosphorus concentrations. The correspondence between fishery ratings and prospective nutrient criteria was inconsistent, prompting consideration of an alternative approach. Within each of three ecoregions (9, 11, and 14) in Virginia, the quintessential fishery of each type was identified, and the chlorophyll and phosphorus in those lakes became the standards. A relatively small number of reservoirs with high quality fisheries became very influential in determining the criteria that would be applied statewide. There was general consistency across the three ecoregions.

Virginia cold water fisheries: A few small reservoirs in ecoregion 11 are managed for trout (rainbow, brown, or brook). All are sustained by stocking (put-and-take or put-and-grow), and most are marginal insofar as hypolimnetic anoxia constrains habitat. Lake Moomaw is relatively large and is judged to have a good cold water fishery. The levels of chlorophyll (4 ug/L) and total phosphorus (10 ug/L) characteristic of Lake Moomaw were adopted for all cold water fisheries in the state. These criteria are consistent with the literature review that recommended setting chlorophyll less than or equal to 6 ug/L and total phosphorus less than or equal to 10 ug/L for cold water fisheries.

Virginia cool water fisheries: All three ecoregions in Virginia have cool water fisheries, most of which are managed as put-and-grow systems for striped bass, wiper, or walleye. Only Kerr Reservoir has a self-sustaining population of striped bass. Temperature preferences of these fish can be met only in the metalimnion or hypolimnion of larger reservoirs where some deep water habitat remains oxygenated. Success with striped bass in Kerr Reservoir made it the basis for setting criteria applicable to all cool water fisheries in ecoregion 9 (10 ug/L for chlorophyll and 30 ug/L for total phosphorus). In ecoregion 11 the quality of the fishery in South Holston Reservoir made it the basis for the proposed criteria: 10 ug/L for chlorophyll and 20 ug/L for total phosphorus. In ecoregion 14, there are two reservoirs that support good cool water fisheries, and they match the criteria proposed for ecoregion 11. The proposed criteria for cool water fisheries are consistent with literature recommendations of chlorophyll ≤ 15 and total phosphorus > 10 .

Virginia warm water fisheries: Most reservoirs in Virginia are managed for warm water fish, chiefly centrarchids or catfish. Because the centrarchids are generally more sensitive to oxygen and temperature than are catfish, nutrient criteria are based on sustaining centrarchid fisheries. In ecoregion 9, there are two high quality warm water fisheries. The chlorophyll criterion is set to 25 ug/L on the basis of Diascond Reservoir, and the total phosphorus criterion is set to 40 ug/L on the basis of Lake Chesdin. Warm water fisheries in ecoregion 11 are not regarded as good enough to be used to derive criteria. Ecoregion 14 has a number of good warm water fisheries for which the criteria from ecoregion 9 seem consistent, and were thus applied. The criteria proposed for warm water fisheries are consistent with literature recommendations of chlorophyll in the range of 20-40 ug/L and total phosphorus ≤ 50 ug/L.

The applicability of Virginia's nutrient criteria to Colorado's lakes deserves comment. On the basis of geography alone, the states have little in common. Much of Virginia is near sea level and very little of the state reaches the minimum elevation in Colorado (3350 ft). Thus, nearly all of Colorado's lakes lie at elevations greater than those of any Virginia lakes. Consistent differences also extend to temperature and precipitation. On the other hand, almost all "lakes" in Virginia are reservoirs managed for water supply and recreation (chiefly fishing). The two states have in common a need for standards applicable to lakes that are man-made and intensively managed, two features that argue for an optimization approach to setting criteria. Thus, it seems reasonable to explore the application of Virginia criteria, or at least the methodology, to Colorado.

Fisheries and Chlorophyll in High-Elevation Lakes of Colorado

The Colorado Division of Wildlife (DOW) manages fisheries statewide, and has supplied evaluations for a selection of high elevation lakes (Table 2). The DOW assessments have been supplemented with water quality data drawn from a variety of sources. One of the premier cold water lake fisheries in Colorado is in Blue Mesa Reservoir. There is also a good record of water quality data summarized in a recent report (Bauch and Malick 2003). In the Iola Basin, which is the upstream end of the reservoir, the typical chlorophyll concentration during the growing season is about 6 ug/L. Much lower

chlorophyll concentrations (typically 1-1.5 ug/L) are found in the other two basins through which the water moves with no significant addition of nutrients.

Table 2. Fishery evaluations for selected high elevation (>7500 ft) lakes.

Lake	Elevation	Fishery evaluation
Island	10290	Meeting goal: catchable trout
Eggleston	10140	Meeting goal: catchable trout
Platoro	10034	Seems unproductive
Trickle Park	9928	Meeting goal: catchable trout and fingerling plants
Overland	9900	Meeting goal: catchable trout and fingerling plants
Turquoise	9869	Unproductive
Trout Lake	9714	Mgt goals met: put and take catchable
La Jara	9698	Chemical reclamation
Mt Elbert Forebay	9646	Unproductive
Rio Grande	9400	Limited productivity
Taylor Park	9330	Mysis is a problem.
Road Canyon	9275	Highly productive; winterkill
Twin Lakes	9200	Unproductive
Chambers	9200	Relatively unproductive
Big Meadows	9200	Goals are being met
Dome	9017	Good fishery
Antero	8940	High harvest
Silver Jack	8926	Meeting goal: subcatchable plants
Clear Creek	8875	More productive than Twin, but not by much
Tarryall	8860	High harvest
Beaver Creek	8850	Growth rates below average
Groundhog	8728	Mgt goals met: put and grow fingerling
Spinney	8686	Moderate harvest
Eleven Mile	8597	Moderate harvest
North	8583	Relatively sterile
Terrace	8571	Metal pollution; drained in 2004
Sanchez	8272	Very productive
Williams Creek	8241	Mgt goals met: put and grow fingerling
Lemon	8148	Mgt goals met: put and take catchable. Growth rates below average
Delaney Butte	8145	Goals being met
Mountain Home	8145	Goals are met
Dowdy	8135	Goals being met
Jackson Gulch	7825	Mgt goals met: put and take catchable; mixed warmwater
John	7800	Not meeting catch rate expectations. Need to reduce suckers and eliminate winterkill
Smith	7721	Very productive
Miramonte	7700	Mgt goals met: put and grow fingerling
Vallecito	7665	Mgt goals met: catchable and subcatchable
De Weese	7665	Algal blooms; historically productive
San Luis	7525	Chemical reclamation
Blue Mesa	7519	Managed as a premier fishery. Seems to be performing well

The DOW also has rated some lakes as unproductive on account of low nutrient concentrations; Turquoise and Twin Lakes are cited as examples. In those lakes, the WQCD has measured chlorophyll concentrations that average about 1 ug/L during the growing season. Another perspective is available from water quality data (but no fishery

survey) for Dillon Reservoir, which is highly regarded as a recreational amenity. Average chlorophyll concentration in Dillon during the growing season is usually in the range of 3-6 ug/L, and there is ample oxygen in the hypolimnion. A selection of high elevation lakes shows the range of chlorophyll concentrations observed in cold water fisheries (Figure 1). Lakes with high chlorophyll concentrations are more likely to experience significant depletions of dissolved oxygen in the hypolimnion, resulting in a significant constriction of habitat available for cold water species. In Stagecoach Reservoir, for example, where chlorophyll concentrations of 100 and 200 ug/L have been recorded, there is virtually no oxygen below the mixed layer and the lake is on the 303(d) list.

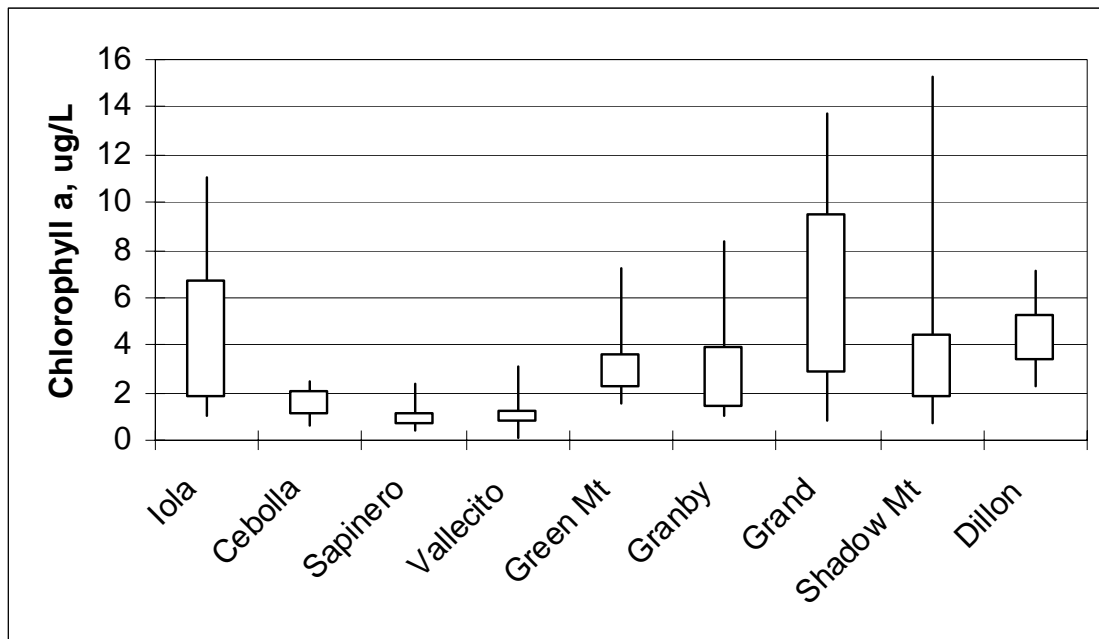


Figure 1. Distributions of chlorophyll concentrations from the growing season (Jul-Sep) in several high-elevation reservoirs. Distributions are represented by box-and-whisker plots where the box represents the central 50% of the distribution and the tips of the whiskers represent 5th and 95th percentiles. Data are from various sources.

Algal Blooms and Impairment

The foregoing discussion developed a rationale for protecting aquatic life based on average chlorophyll concentrations during the growing season. Other uses also must be considered. Algal populations can grow very rapidly when conditions are favorable, leading to the formation of “blooms” that may impair recreational or water supply uses. The active growth leading to blooms tend to be short-lived, ending when nutrients are exhausted, although a legacy of decaying biomass may persist for some time.

Thresholds of impairment are difficult to define for blooms. World Health Organization has issued guidelines for recreational use in terms of chlorophyll concentrations, based on worst-case assumptions that make chlorophyll a surrogate for toxins produced by blue-green algae. If all algae were toxin-forming blue-greens, a chlorophyll concentration of

50 ug/L would pose a “moderate risk” for recreational use. Swimmers might consider the recreational experience undesirable at considerably lower chlorophyll concentrations.

The State of Texas has undertaken surveys of recreational use in several reservoirs and concluded that it is hard to quantify what is objectionable in terms of chlorophyll concentration. Expectations appear to influence the chlorophyll concentration that affects the recreational experience. Users become accustomed to conditions in particular lakes. Nevertheless, a threshold of 27 ug/L was set based on those surveys. Other states have reached different conclusions about what constitutes a bloom. Minnesota defines a nuisance bloom at 20 ug/L and a severe nuisance bloom at 30 ug/L, whereas Florida sets the threshold for a bloom at 40 ug/L. Colorado has not reached a conclusion about the threshold for blooms, but a concentration in the range of 30-40 ug/L is a good basis for discussion.

From a regulatory perspective, it is desirable to cast the definition of a bloom in terms of both magnitude and frequency. A single bloom once in 10 years may not be cause for concern, but a more regular occurrence – e.g., 20% of the time – might be sufficient to trigger action to control nutrients. Fortunately, a statistical approach can be applied to gain a better understanding of the practical implications of particular strategies. Walker (1985) demonstrated the statistical linkage between average chlorophyll concentration and the frequency of exceedance for specified bloom thresholds. It is based on the assumptions that the frequency distribution for chlorophyll concentrations is log-normal and the standard deviation can be predicted from the average concentration. He developed an example based on data from Vermont lakes. The same procedures can be applied to data from Colorado lakes.

There is a strong relationship between the average and the standard deviation for chlorophyll concentrations measured in Colorado lakes (Figure 2). The relationship is similar to that derived from Vermont lakes. For any average chlorophyll concentration, the expected frequency of exceedance can be forecast for any bloom threshold. For example, if the growing season average were 6 ug/L, there would be little or no chance that chlorophyll concentrations would exceed a bloom threshold (Figure 3). In fact, the average concentration would have to be at least 15 ug/L before a bloom threshold of 30 ug/L would be exceeded at least 10% of the time. The comparable concentration from the Vermont equation would be about 18 ug/L, and results from Florida LakeWatch data (Bachmann et al. 2003) place the concentration at about 20 ug/L. The salient point is that there is almost no chance of significant blooms for the range of average concentrations being considered for cold water fisheries in Colorado.

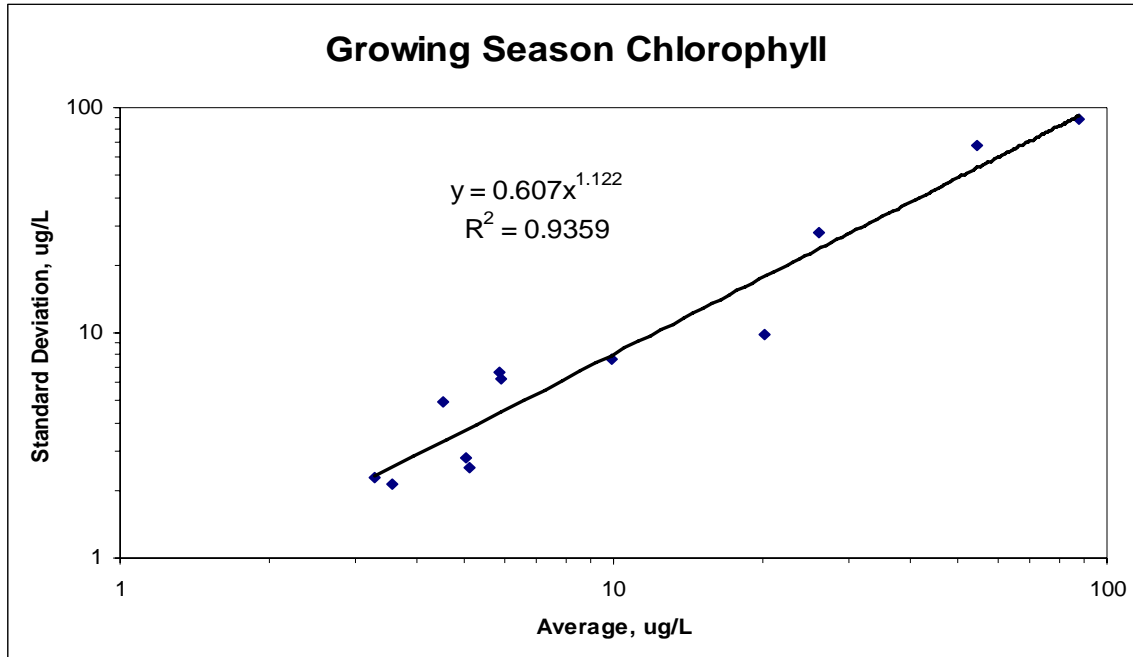


Figure 2. Standard deviation as a function of average chlorophyll concentrations measured during the growing season. Each point represents all data available for one Colorado lake.

Statistical forecasts of bloom frequency also can be used to assess the high end of average concentrations that might be adopted for warm water lakes in Colorado. For example, if the bloom threshold were 40 ug/L, and an exceedance frequency were set to 20%, the average concentration acceptable for the growing season would be about 28 ug/L. It is important to emphasize that thresholds, frequencies, and growing season average are mentioned here expressly for the purpose of stimulating discussion; no decisions have been reached yet about the role that blooms might play in nutrient criteria.

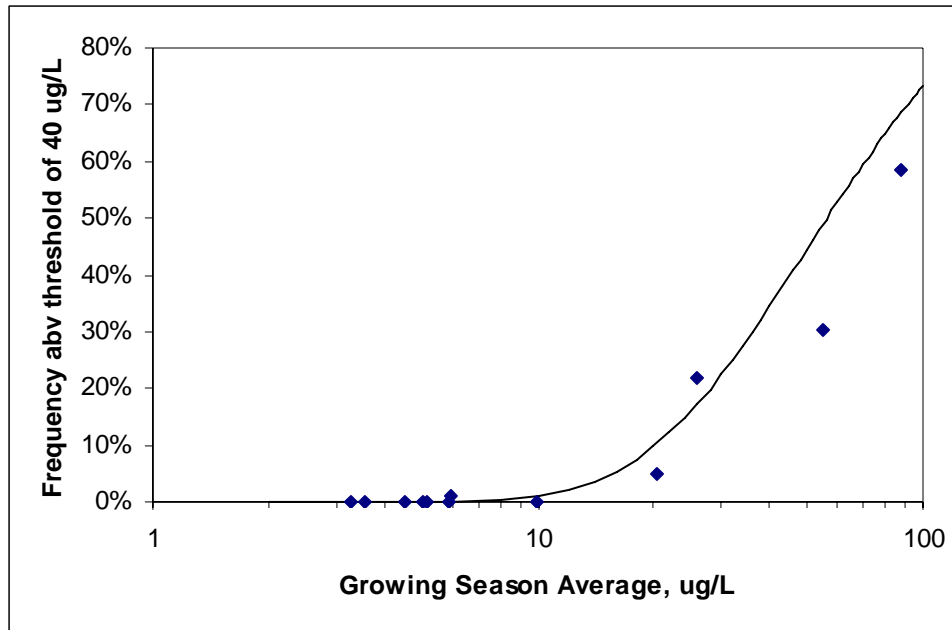


Figure 3. Observed and predicted exceedance frequency when the bloom threshold is set to 40 ug/L for Colorado lakes.

Control of Algal Abundance

When chlorophyll thresholds are exceeded, attention will be drawn to the factors that regulate algal abundance. In each lake, algal abundance is controlled by a suite of physical, chemical, and biological factors. The principal physical factors – light and temperature – regulate growth rates, influencing the accumulation of biomass during the growing season. Although many chemical factors have potential to limit algal abundance, the primary nutrients – phosphorus and nitrogen – attract the most attention. Finally, there are biological factors, the most important of which is grazing, whereby algal biomass is removed.

The relative importance of each control factor varies among lakes and over time within each lake. Interplay of the control factors shapes seasonal patterns in the abundance of the algal community. Temporal changes in the relative importance of the factors also can hinder efforts to develop predictive relationships on the basis of a single factor (e.g., explaining chlorophyll solely as a function of phosphorus concentration).

Algal growth rates are dependent on temperature, which varies seasonally and with depth in each lake. For simplicity, this document focuses on conditions in the mixed layer where temperature tends to be uniform over depth. Seasonal patterns of temperature within the mixed layer are reasonably consistent from year to year within each lake. Elevation is a strong correlate of temperature in the mixed layer (Figure 4), as would be expected from the influence of elevation on climate. The relevance to algal communities is that the potential growth rate at mid-summer in the lowest elevation lakes is about twice that of the highest elevation lakes (assuming Q_{10} of 2.0).

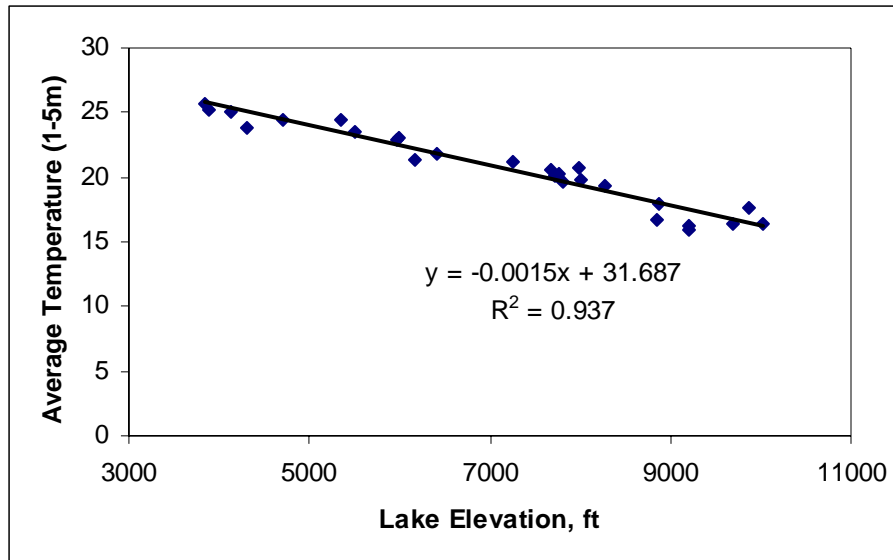


Figure 4. Average temperature in the mixed layer of several Colorado reservoirs sampled during a 17-d period centered on 1-Aug-2006. Surface temperatures were excluded to avoid bias from undistributed daytime heat gain.

Algal growth also depends on light, both in terms of day length and intensity. The instantaneous growth rate of each algal cell is affected by the intensity of light it receives, which is a function of time of day, depth of water above the cell, and transparency of the water. A steep gradient of light intensity exists within the mixed layer. The light reaching the bottom of the mixed layer is much less than the light available at the surface. If the secchi depth (a common measure of water clarity) is 2.0m, a typical growing season value for Chatfield Reservoir, and assuming that the secchi depth corresponds to 10% transmittance, light intensity at 4m would be only 1% of the surface value. The thickness of the mixed layer and the clarity of the water combine to control the light climate for the average algal cell circulating in the mixed layer. Because the mixing depth and water clarity may change frequently during the growing season, the growth potential for the algal community in each lake is subject to change.

Nutrient concentrations in each lake are determined by the mix of natural and anthropogenic sources within the watershed. The higher the concentration of nutrients, the greater is the potential for algal abundance, other things being equal. At any given moment, however, only one nutrient can truly be said to limit to algal growth. This idea is embodied in Liebig's Law:

“Under conditions of equal temperature and light, the nutrient available in the smallest quantity relative to the requirement of the plant will limit productivity.”

The concept of a limiting nutrient is useful from a theoretical perspective and it has implications for lake management, but some caution is appropriate when drawing

conclusions about *the* limiting nutrient in a lake, especially in view of the potential for changes over the course of the growing season.

Phosphorus has long been identified as the principal limiting nutrient for lakes, but nitrogen limitation also occurs. Even in a single lake, the distinction may not be unambiguous. In Dillon Reservoir, for example, nitrogen is depleted in the mixed layer by the end of the growing season in some years, but not all. In Cherry Creek Reservoir, in contrast, nitrogen typically is undetectable in the mixed layer during the growing season; occasionally, the supply of nitrogen is renewed briefly when stratification is disrupted by a storm event. The importance of seasonal shifts in nutrient limitation has been documented for a number of Colorado lakes (Morris and Lewis 1988). Efforts to predict algal abundance on the basis of a single factor may be hindered by seasonal variation in the relative importance of control factors like nutrients.

From a practical perspective, even though nitrogen can be limiting at times, or even throughout most of the growing season, phosphorus is usually considered the better choice when implementing controls on nutrient loads. When there is excessive algal abundance in a nitrogen-limited lake, phosphorus concentrations can be reduced to the point that phosphorus limitation supersedes nitrogen limitation.

The suite of physical and chemical control factors in a particular lake establishes an upper bound on algal abundance at any point in the growing season. The abundance expected in the basis of these factors may not be realized, however, due to grazing pressure. Where zooplankton are abundant, they may consume a significant portion of the algal biomass. The capacity of grazers to consume algal biomass may be quite variable during the growing season, further confounding efforts to discern a simple determinant of algal abundance within a lake.

Defining the relationship between algal abundance and control factors is the key to implementation when uses are not being attained. This is often attempted with simple regressions equations, as is reviewed in more detail below. A multivariate approach might be tempting, but information on all factors – including light climate, mixing depth and grazing pressure – is not often available. A complex mechanistic model capable of predicting temporal change in each factor is even less feasible.

The WQCD's proposal is based on defining total phosphorus concentrations consistent with chlorophyll standards, as mentioned previously. The chlorophyll standards are applied statewide, but the phosphorus concentrations are developed for each lake or for regional sets of lakes. Before outlining the Division's approach, it is helpful to examine the predominant approach, based on regression analysis.

Prediction of Chlorophyll Concentration

Many regression equations have been developed to predict chlorophyll concentration as a function of one or more control factors. Only a small selection is shown here for illustrative purposes. One widely cited equation was derived by Jones and Bachmann (1976), and it has been applied in the development of control regulations in Colorado. It

predicts growing season chlorophyll as a function of total phosphorus, and it performs reasonably well when applied to a cross section of Colorado lakes (Figure 5). The chief problem with this predictive relationship is that it is much more useful for explaining variance in a cross section of lakes than it is for interannual variability within any one lake. Data from Colorado lakes make this point clearly (Figure 6).

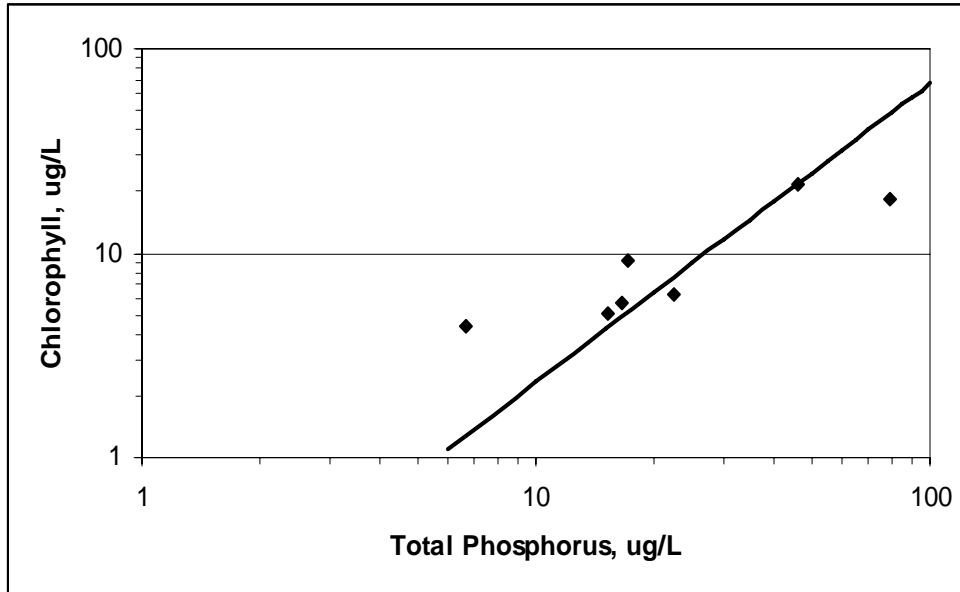


Figure 5. Relationship between phosphorus and chlorophyll for several Colorado lakes (symbols) and as defined by the Jones-Bachman relationship. Each point represents the average of growing season averages from 6-11 years.

Much effort has been devoted to improving the prediction of chlorophyll by adding other causal variables, such as nitrogen, total suspended solids (TSS), and zooplankton abundance (Figures 7-10). Some success has been achieved for particular sets of lakes, but most of the relationships still include phosphorus.

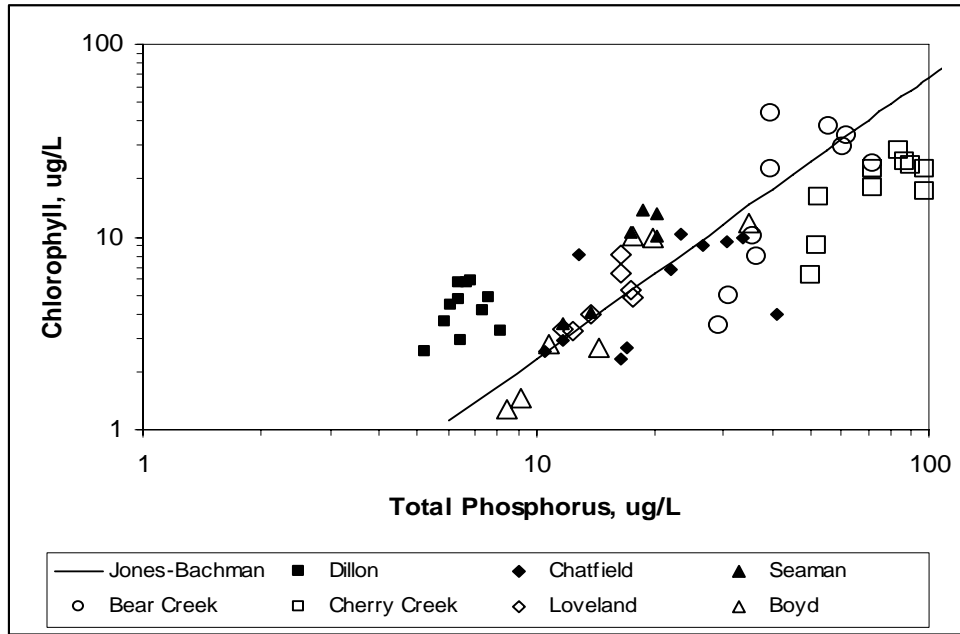


Figure 6. Relationship between phosphorus and chlorophyll for several Colorado lakes (symbols) and as defined by the Jones-Bachman relationship. Each point represents a growing season average from one lake.

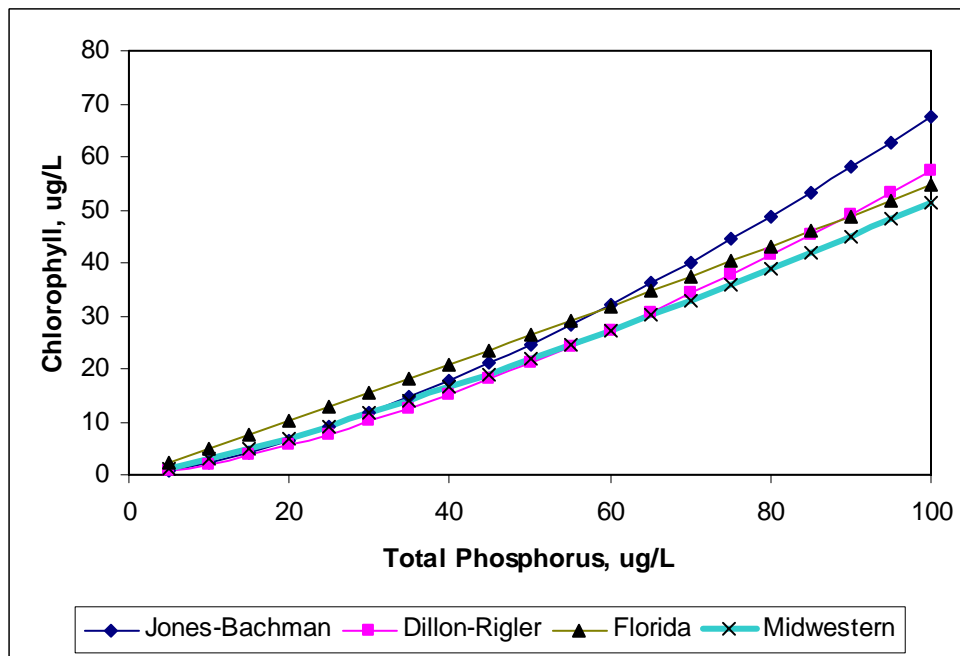


Figure 7. A selection of equations predicting chlorophyll as a function of phosphorus. Sources include Jones and Bachman (1976), Dillon and Rigler (1974), Hoyer and Jones (1983), and Brown et al. (2000).

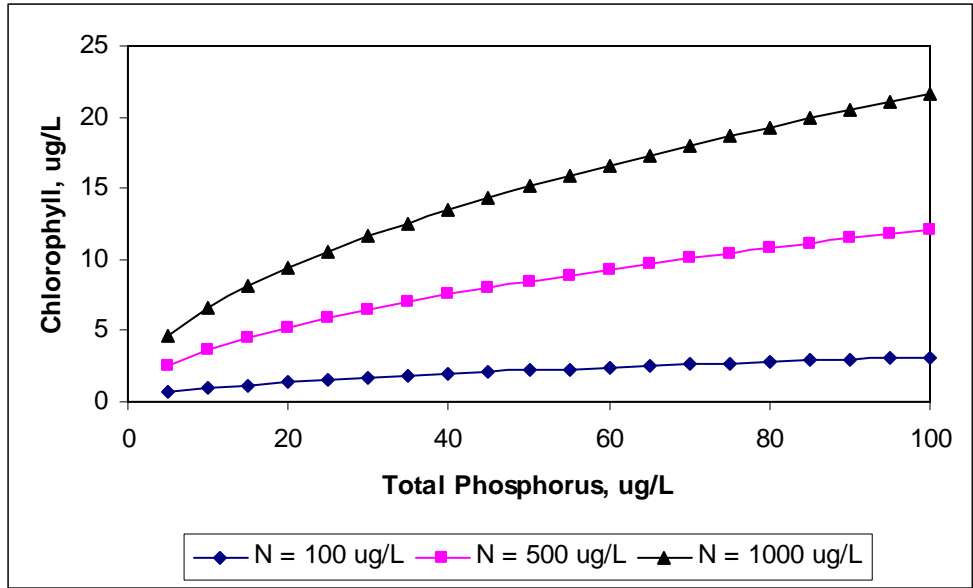


Figure 8. Predictions of chlorophyll as a function of phosphorus, at three levels of nitrogen. From Prairie et al. (1989).

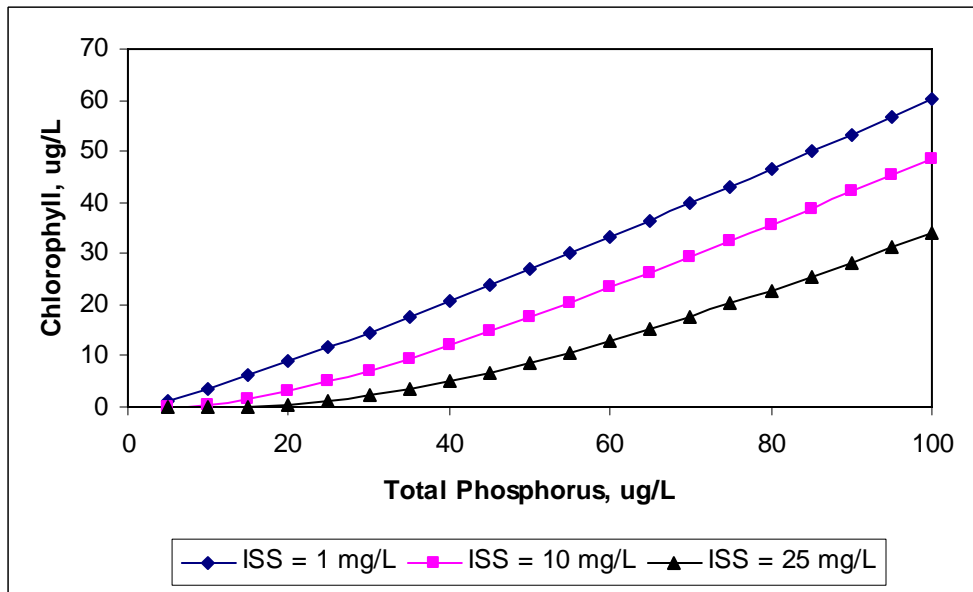


Figure 9. Predictions of chlorophyll as a function of phosphorus, at three levels of inorganic suspended solids (ISS). From Hoyer and Jones (1983).

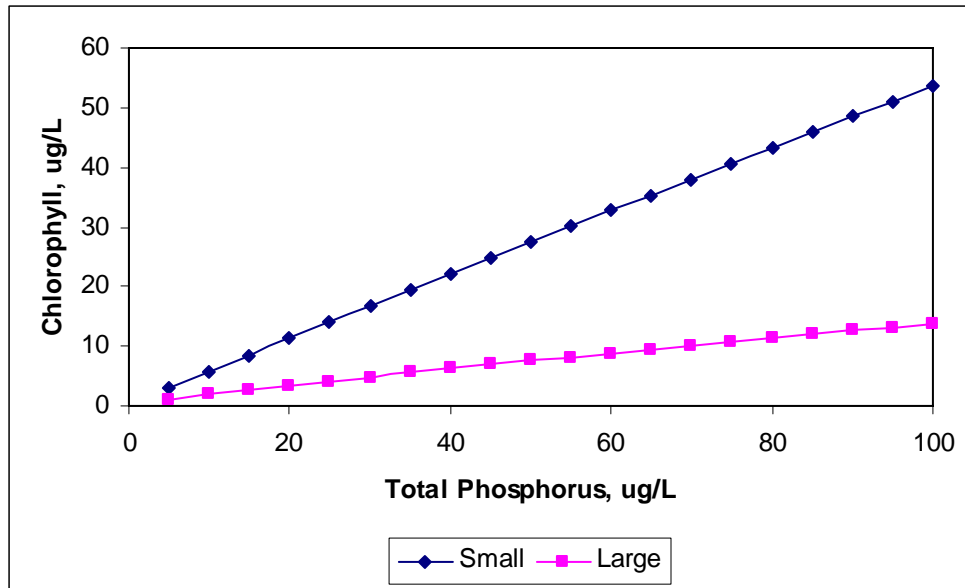


Figure 10. Predictions of chlorophyll as a function of phosphorus, in the presence of large or small herbivores. From Mazumder and Havens (1998).

Simple regression models may not be well-suited to the regulatory task of defining thresholds. Regression lines typically predict average chlorophyll concentration as a function of average phosphorus concentration, but regulatory standards define exceedance thresholds. In concept, confidence limits for the regression line can be used to associate the regulatory threshold with an average phosphorus concentration. In practice, it may not be feasible to do so because within-lake relationships tend to show a high degree of uncertainty, leading to very broad confidence intervals.

Poor performance of simple regression models also poses problems when restoration efforts are needed. If the relationship does not explain most of the variation in chlorophyll on the basis of changes in phosphorus concentration, it undermines confidence in the notion that reduction of phosphorus load will result in a reduction in algal abundance. Whatever shortcomings might be perceived for phosphorus as a predictor of chlorophyll concentration, it remains the single best predictor of chlorophyll.

An Alternative Approach to Defining Algal Response

Dissatisfaction with regression analyses has spurred consideration of an alternative approach for linking chlorophyll and phosphorus by means of a response ratio, which is simply the chlorophyll concentration divided by the total phosphorus concentration (see Hern et al. 1981). The concept is not new, but it offers advantages over a standard regression approach. It begins with the premise that phosphorus is the most effective tool for preventing exceedances of chlorophyll standards. It assumes that, for a given lake, the optimal response of the algal community is a constant. The observed response ratio may be suppressed at any point in time by operation of other control factors. By examining the distribution of response ratios for a lake, conclusions can be drawn about the phosphorus concentration consistent with the regulatory threshold for chlorophyll.

Proposing reliance on site-specific response ratios departs from typical regression approaches in two ways. First, it assumes, in effect, that the response of the algal community (as chlorophyll) to phosphorus is better characterized by a linear relationship than a power function, at least for the range of concentrations typical of a single lake. (There are statistical reasons why the log-transformations underlying a power function are desirable, but the power function yields a different response ratio for every phosphorus concentration.) Second, it means that each paired measurement of chlorophyll and phosphorus is an equally valid estimate of the response ratio for the lake.

The motivating interest from a regulatory perspective is in associating the exceedance threshold for chlorophyll with a particular phosphorus concentration. For each lake, there is an optimal response ratio that reflects the capacity of the algal community to produce chlorophyll given a particular phosphorus concentration. The optimal conditions vary among lakes and represent a baseline contribution from the other control factors characteristic of that lake. Not all values of the response ratio represent optimal conditions because seasonal variations in other control factors (e.g., grazing by zooplankton) will depress the response ratio. The properties of the distribution of response ratios from each lake can be used to define the ratio appropriate for preventing exceedances of the chlorophyll standard. For example, the ratio might be selected to be consistent with a chlorophyll standard that cannot be exceeded more than once in ten years, assuming that the growing season average is based on 6 measurements.

Defining the Response Ratio

The linkage between chlorophyll and phosphorus has been explored extensively in the scientific literature. There is little doubt that phosphorus is essential for algal growth, but there is considerable unexplained variation in most relationships between chlorophyll and phosphorus. The connection is affected by the physiology of algal species, the species composition of the phytoplankton community, and by the aggregate effect of other control factors on the algal community in each lake. The WQCD strategy involves site-specific evaluation of chlorophyll:total phosphorus response ratios, with the goal of identifying regional values applicable to lakes for which sufficient data may not be available. It is especially important for predicting the benefit expected from incremental reduction of phosphorus concentration.

Chlorophyll is a convenient measure of algal biomass, but the amount of chlorophyll per unit biomass varies across species and according to the physiology of each species. In a study of batch cultures, Riemann et al. (1989) found that chlorophyll was 1-6% of phytoplankton carbon content. (Carbon is a common frame of reference for studies reporting the chemical composition of plankton.) The same study also reported that, in eutrophic environments, chlorophyll typically was in the range of 1.5-3.7% of phytoplankton carbon. There is considerable latitude in the relationship between chlorophyll and carbon, but a value in the vicinity of 3% is probably reasonable under ideal conditions (see Chapra 1997).

Phosphorus constitutes about 2.4% (by weight) of the carbon content of algae, based on the Redfield ratio ($C_{106}H_{263}O_{110}N_{16}P_1$), which is often taken as a guide to the chemical composition of plankton. Thus, under ideal conditions, the ratio of chlorophyll to total phosphorus should be slightly greater than 1 (3.0:2.4). A ratio of 1:1 is consistent with the upper bound of most observations from lakes in the National Eutrophication Survey (Figure 11), although the average response ratio in the summer was considerably less: 0.29 (Hern et al. 1981). If nothing else were known, a ratio of 1:1 might be a good starting point for control measures, but it could be unnecessarily stringent for many lakes.

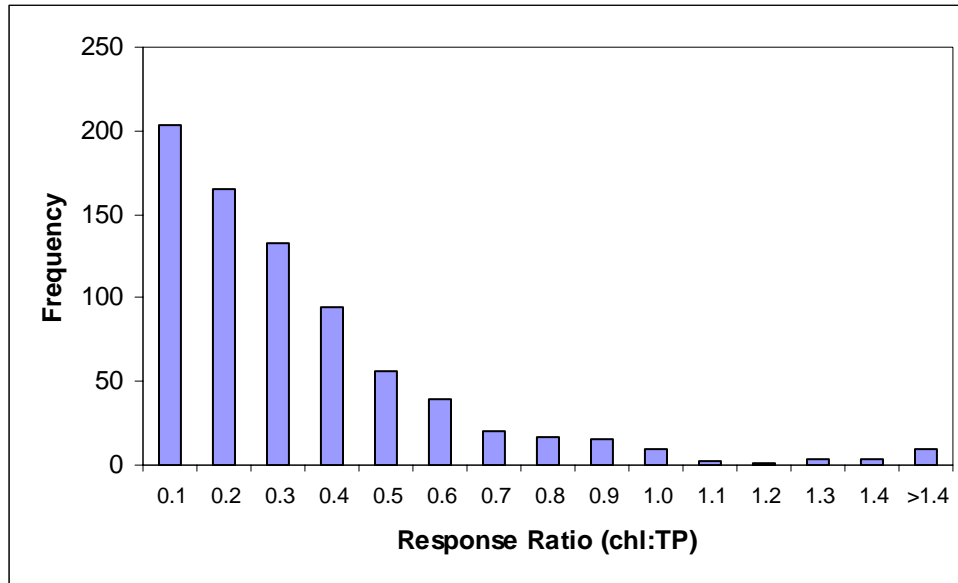


Figure 11. Frequency histogram of response ratios recorded during the National Eutrophication Survey (Hern et al. 1981).

There is a rich legacy of empirical relationships documenting the strong general dependence of chlorophyll on phosphorus. Most were developed from a cross section of lakes, often from broad geographic areas. Regression analysis is used to define the response (chlorophyll) as a function of one or more causal variables (almost always including total phosphorus). For simple linear regression, the slope defines the average increase in chlorophyll to an increase in total phosphorus. From the standpoint of implementing controls, the equation can be used to predict the reduction in chlorophyll that can be expected in response to a specific reduction in total phosphorus. This approach can work well as long as phosphorus remains the limiting factor throughout the growing season. Unfortunately, other factors may supersede phosphorus for some part of the growing season.

The response ratio observed in a particular lake on a particular date reflects the recent aggregate response of the phytoplankton community to the available phosphorus; it represents the realized potential for algal growth. For a cross section of lakes, typical ratios can be extracted from regression equations characterizing chlorophyll as a function of phosphorus. Published equations can therefore yield a preview of regional variability in responses. One of the best-known equations relating chlorophyll to phosphorus was

developed by Jones and Bachmann (1976). When the response ratio is calculated from the equation, it suggests that the response ratio was strongly suppressed at low phosphorus concentrations, but moved closer to an optimal value at higher phosphorus concentrations (Figure 12). Similar patterns appear in relationships defined for northern lakes (Dillon-Rigler 1974) and Midwestern lakes (Hoyer and Jones 1983). Florida lakes, in contrast, show a relatively consistent ratio across a wide range of phosphorus concentrations (Brown et al. 2000).

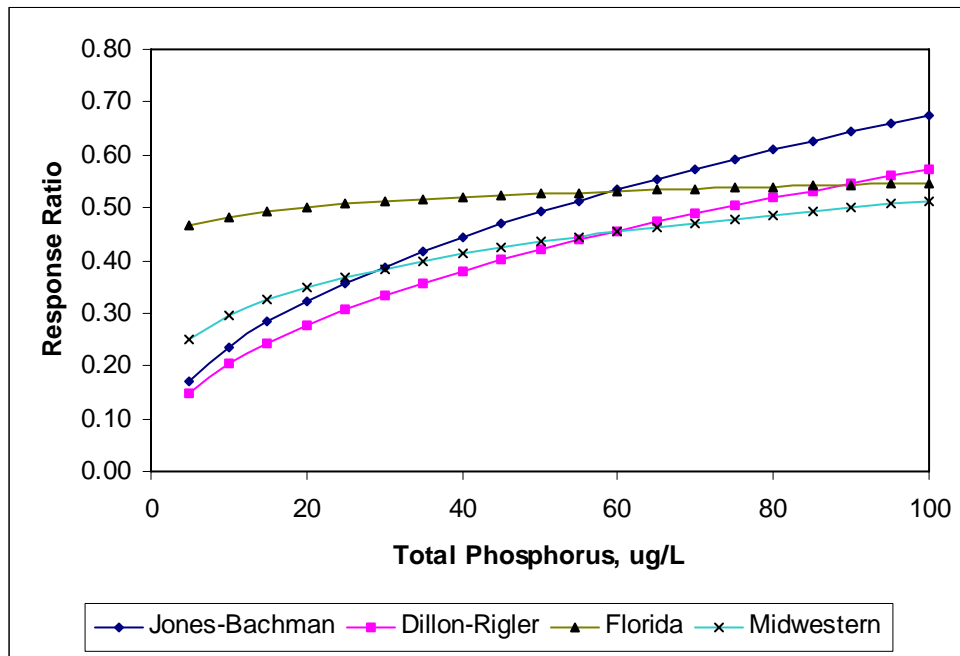


Figure 12. Response ratios implied by chlorophyll-phosphorus regression analyses developed for lakes in different regions.

Many studies have addressed the role that factors other than phosphorus may play in the control of algal growth. Nitrogen is frequently found to be important in limiting algal growth, although the interplay of phosphorus and nitrogen may be complex (Morris and Lewis 1988). Several authors have incorporated nitrogen in predictive equations for chlorophyll, and one such equation, from Brown et al. (2000) can be used to show the effect of nitrogen limitation on the response ratio (Figure 13). Clearly, there is potential for low nitrogen concentrations to suppress the response ratio, and the influence is strong enough that it could produce seasonal variation in the response ratio for a given lake.

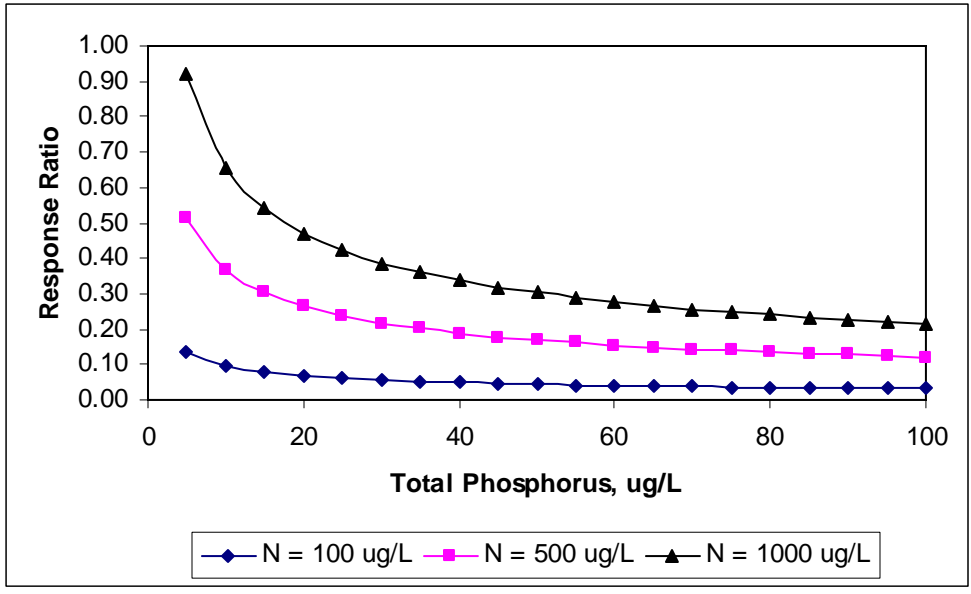


Figure 13. Response ratios implied by an equation that predicts chlorophyll as a function of phosphorus and nitrogen. Each line represents predictions for a fixed nitrogen concentration.

Similar graphs show the influence of inorganic suspended solids (Figure 14) and grazing as indicated by the presence of large or small herbivores (Figure 15). Presumably, the difference occurs because large herbivores are much more efficient grazers, and are therefore able to suppress the response ratio by removing evidence of algal growth.

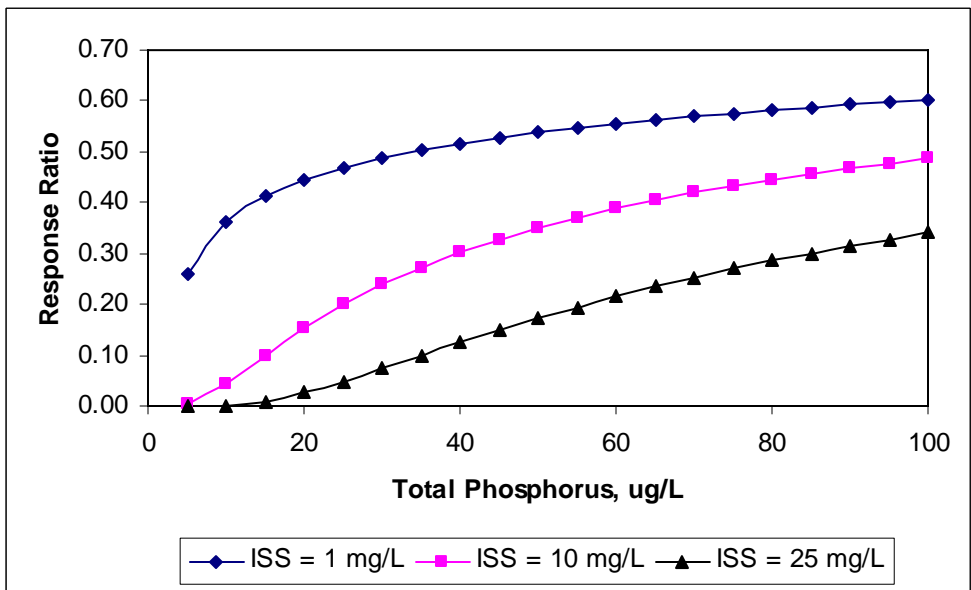


Figure 14. Response ratios implied by an equation that predicts chlorophyll as a function of phosphorus and inorganic suspended solids (from Hoyer and Jones 1983). Each line represents predictions where inorganic suspended solids is held constant at 1, 10, or 25 mg/L.

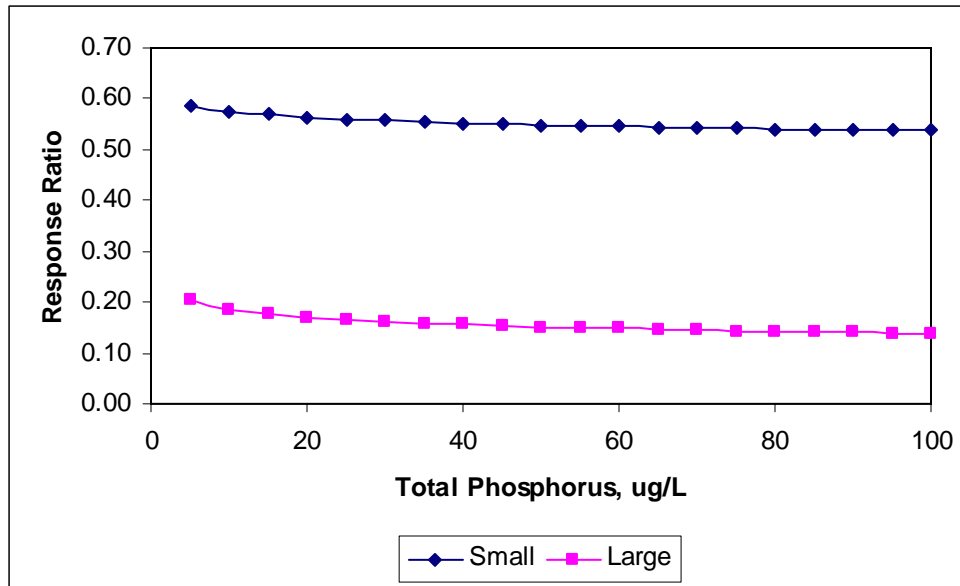


Figure 15. Response ratios implied by equations that predict chlorophyll as a function of phosphorus. Each line represents predictions for lakes where the zooplankton community is comprised of small or large herbivores (from Mazumder and Havens 1998).

In each case where phosphorus is supplemented with another control factor, more variance in chlorophyll concentration can be explained. Each time another factor becomes important relative to phosphorus, the response ratio is depressed. This was evident for decreasing nitrogen concentration, increasing suspended solids, and increasing grazing pressure. It is not difficult to imagine a sequence of events in a lake where variations in nitrogen concentrations, or the wax and wane of grazer populations, could alter the response of algal populations to phosphorus concentration at any point in time. It would be difficult to incorporate all relevant variables in a predictive equation, but it is relatively easy to capture the aggregate effect on algal growth by means of the response ratio.

As attractive as the concept of the response ratio might be, it must also be shown to be practical in terms of data requirements and implementable in terms of applicability to lakes with lesser data sets. Several lakes in Colorado have very extensive data records that can be evaluated on the basis of phosphorus and chlorophyll data. The four lakes with eutrophication-related control regulations – Bear Creek, Chatfield, Cherry Creek, and Dillon – are especially useful. Coverage is relatively good for montane and Front Range sites, but weak for low elevation sites in the eastern and western parts of the state.

Potential Implications for Colorado Lakes

Proposal of standards leads logically to questions about prospects for compliance. Anticipating this natural curiosity, the Division has assembled data from lakes with suitable monitoring records. Before embarking on this exploration, it is important to emphasize that standards have not been formally proposed. Furthermore, the existing classifications for aquatic life (cold and warm) are not aligned well with the fishery categories (cold, cool, and warm) that might provide a framework for nutrient criteria.

Chlorophyll thresholds are applied as follows, based on growing season averages: 6 ug/L for cold water fisheries, 15 ug/L for cool water fisheries, and 25 ug/L for warm water fisheries. In addition, a threshold of 40 ug/L is proposed for blooms. Graphs for lakes with an aquatic life classification of Cold (Figures 16-19) include reference lines at 6 (cold water fishery threshold), 15 (cool water fishery threshold), and 40 ug/L (bloom threshold). Graphs for lakes with aquatic life classification of Warm (Figures 20-25) include reference lines at 15 (cool water fishery threshold), 25 (warm water fishery threshold), and 40 ug/L (bloom threshold). The reference lines provide context for chlorophyll concentrations that have been measured during the growing season. The four lakes with control regulations (Chatfield, Cherry Creek, Bear Creek, and Dillon) are included because they offer the best data sets; there are no plans to alter the chlorophyll targets now in the control regulations.

The four reservoirs with a Cold classification for aquatic life represent very different situations regarding the likelihood that chlorophyll concentrations will exceed regulatory thresholds. In Dillon Reservoir, the average chlorophyll concentration has approached the 6 ug/L threshold in the past, but not on a regular basis (Figure 16). It should be noted that the growing season defined in this document (Jul-Sep) differs from that used in the Control Regulation for Dillon (Jul-Oct). Seaman Reservoir and Chatfield Reservoir have higher chlorophyll concentrations than Dillon, but growing season averages are below the threshold for cool water fisheries and there have been no exceedances of the bloom threshold (Figures 17-18). In Bear Creek Reservoir, chlorophyll concentrations have been high enough to exceed the bloom threshold several times, and growing season averages have routinely exceeded the cool water fishery threshold (Figure 19). Recent changes in lake aeration strategy may have an impact on chlorophyll.

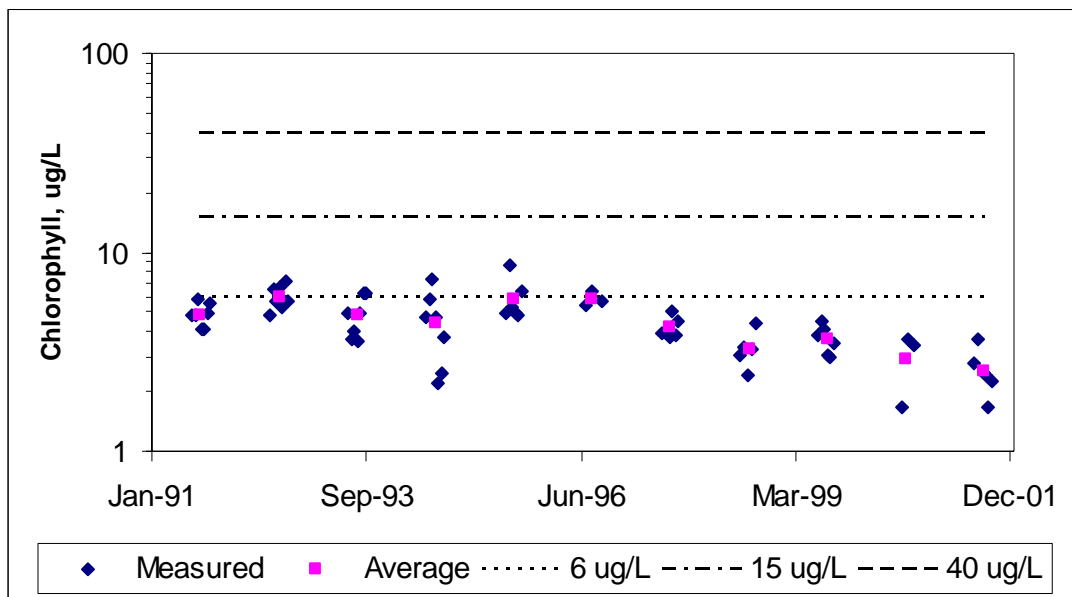


Figure 16. Chlorophyll concentrations and growing season averages for Dillon Reservoir. Thresholds are shown for cold water fisheries (6 ug/L), cool water fisheries (15 ug/L), and blooms (40 ug/L).

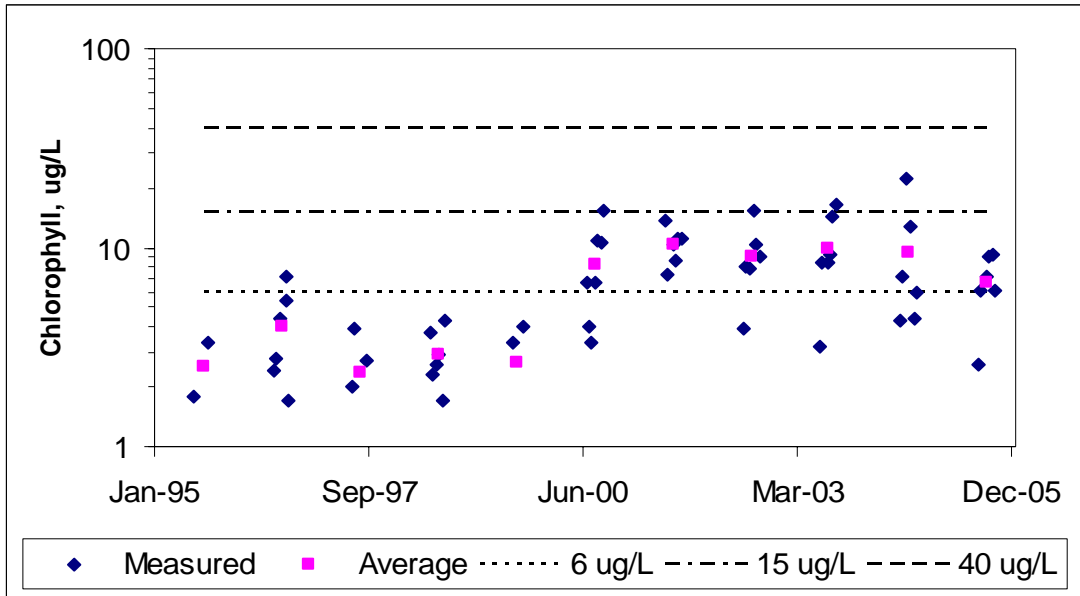


Figure 17. Chlorophyll concentrations and growing season averages for Chatfield Reservoir. Thresholds are shown for cold water fisheries (6 ug/L), cool water fisheries (15 ug/L), and blooms (40 ug/L).

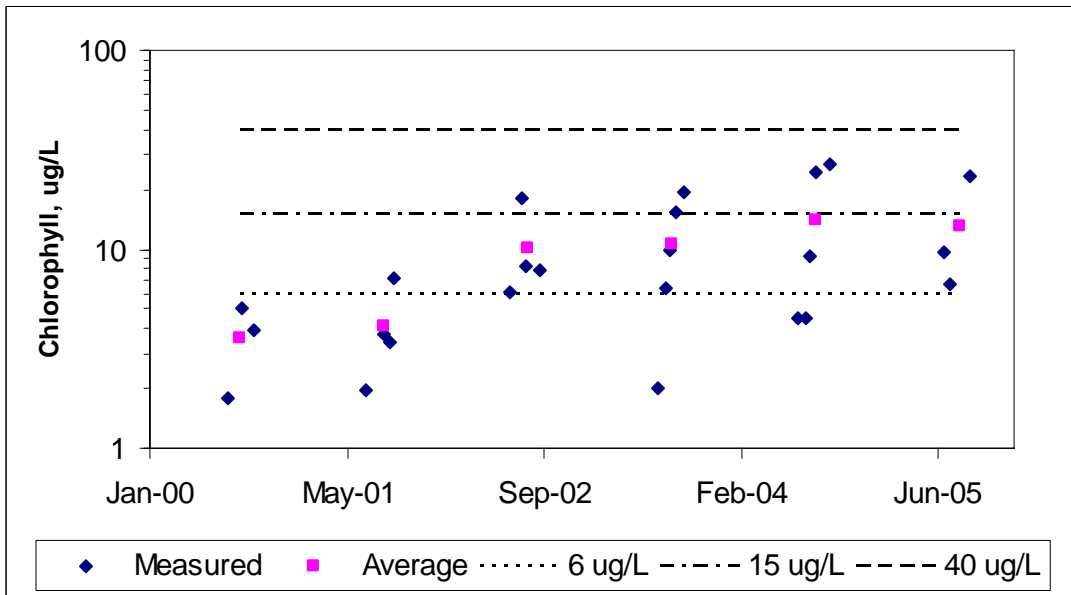


Figure 18. Chlorophyll concentrations and growing season averages for Seaman Reservoir. Thresholds are shown for cold water fisheries (6 ug/L), cool water fisheries (15 ug/L), and blooms (40 ug/L).

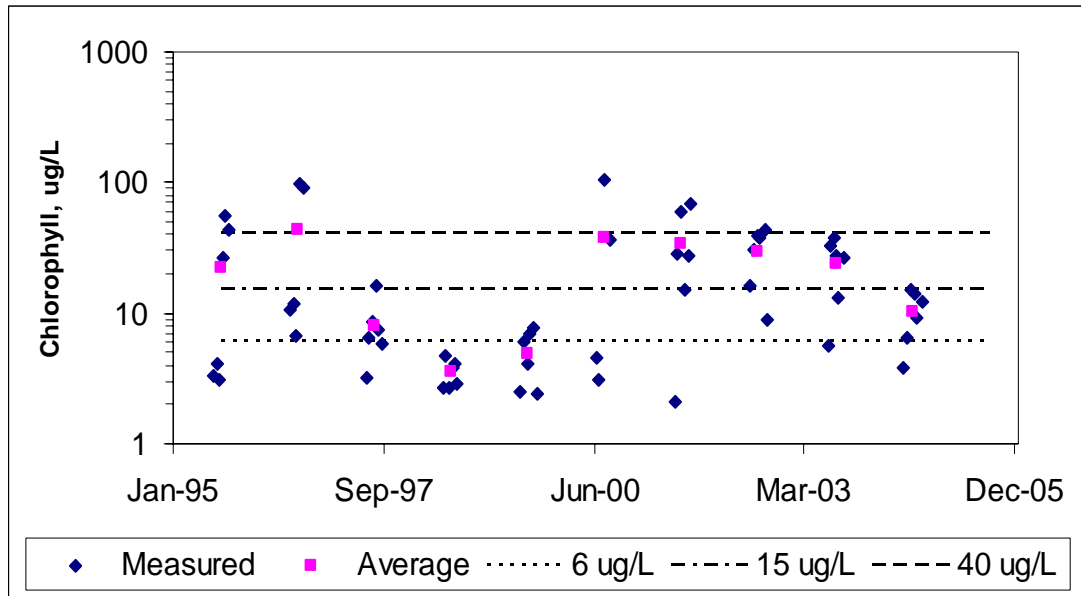


Figure 19. Chlorophyll concentrations and growing season averages for Bear Creek Reservoir. Thresholds are shown for cold water fisheries (6 ug/L), cool water fisheries (15 ug/L), and blooms (40 ug/L).

A similar set of graphs is shown for lakes with a Warm classification for aquatic life. The frame of reference for growing season averages is created by the cool water (15 ug/L) and warm water (25 ug/L) thresholds for chlorophyll, as well as the bloom threshold (40 ug/L). For Cherry Creek Reservoir, chlorophyll concentrations are typically within the thresholds set for blooms and for warm water fisheries, although the growing season average routinely exceeds the standard (15 ug/L) set in the control regulation. Growing season averages for Boyd and Loveland lakes remain below the threshold set for cool water fisheries. Barr and Milton reservoirs typically have chlorophyll concentrations exceeding the bloom threshold and growing season averages above that suggested for warm water fisheries.

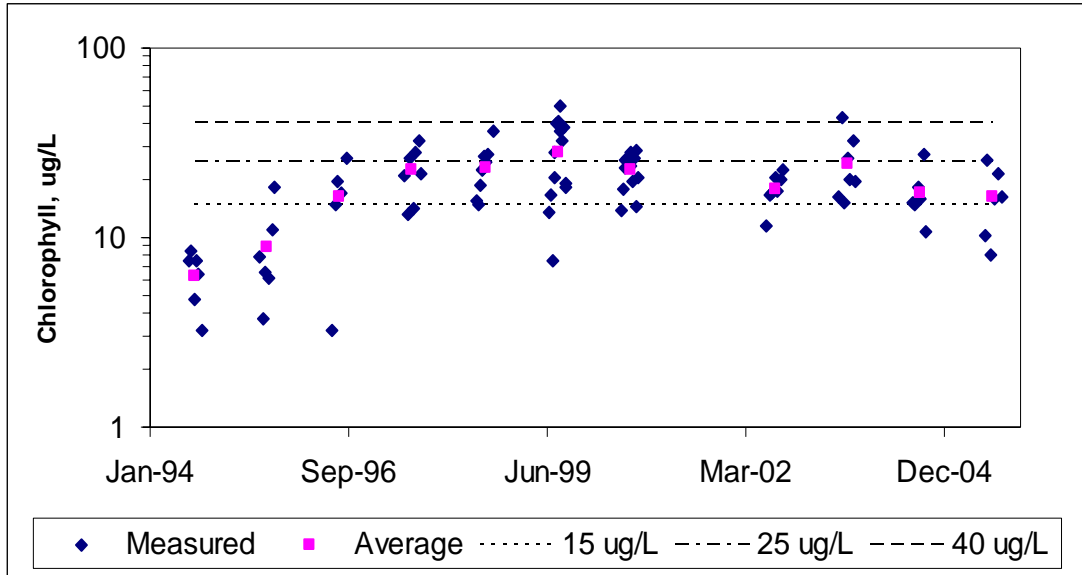


Figure 20. Chlorophyll concentrations and growing season averages for Cherry Creek Reservoir. Thresholds are shown for cool water fisheries (15 ug/L), warm water fisheries (25 ug/L), and blooms (40 ug/L).

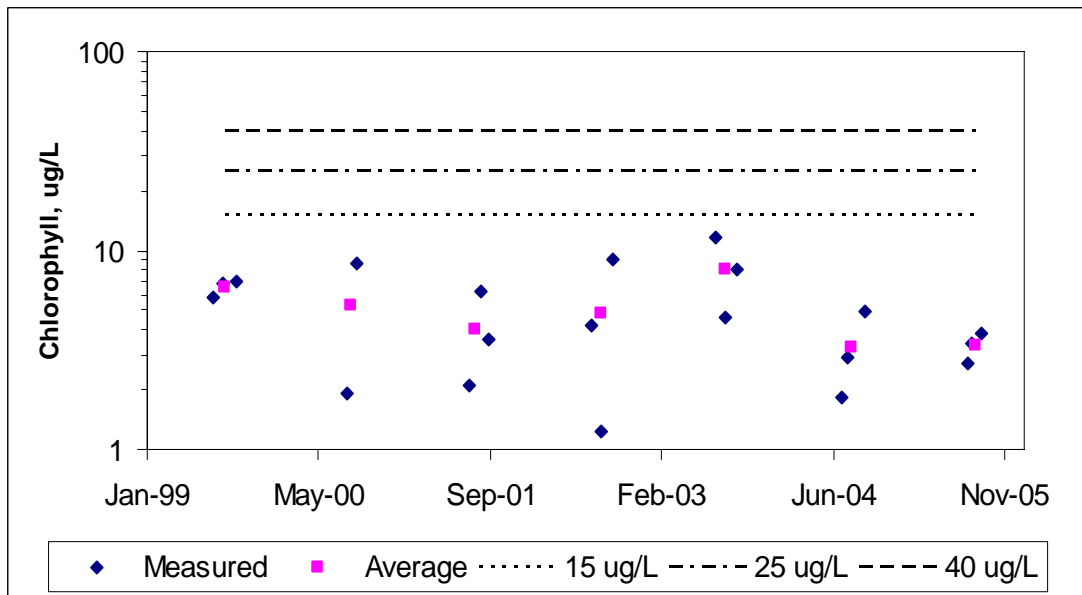


Figure 21. Chlorophyll concentrations and growing season averages for Loveland Lake. Thresholds are shown for cool water fisheries (15 ug/L), warm water fisheries (25 ug/L), and blooms (40 ug/L).

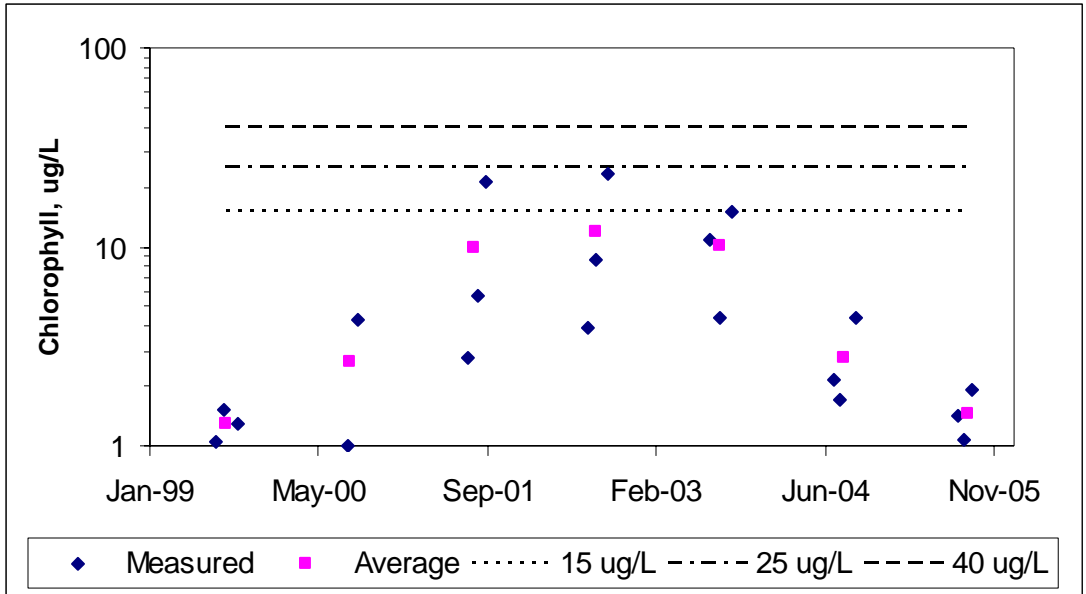


Figure 22. Chlorophyll concentrations and growing season averages for Boyd Lake. Thresholds are shown for cool water fisheries (15 ug/L), warm water fisheries (25 ug/L), and blooms (40 ug/L).

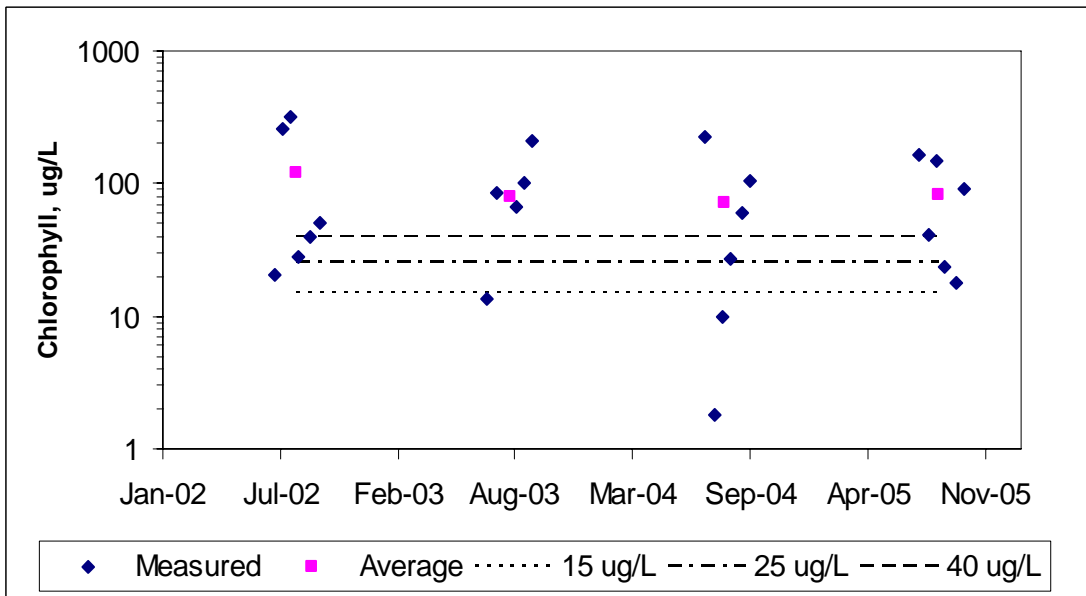


Figure 23. Chlorophyll concentrations and growing season averages for Barr Lake. Thresholds are shown for cool water fisheries (15 ug/L), warm water fisheries (25 ug/L), and blooms (40 ug/L).

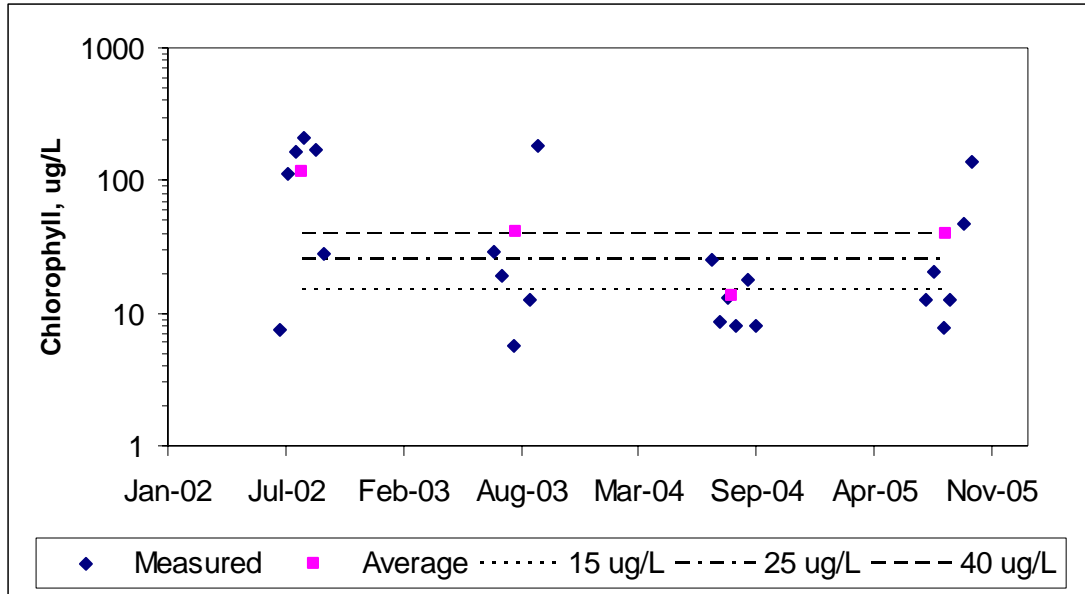


Figure 24. Chlorophyll concentrations and growing season averages for Milton Reservoir. Thresholds are shown for cool water fisheries (15 ug/L), warm water fisheries (25 ug/L), and blooms (40 ug/L).

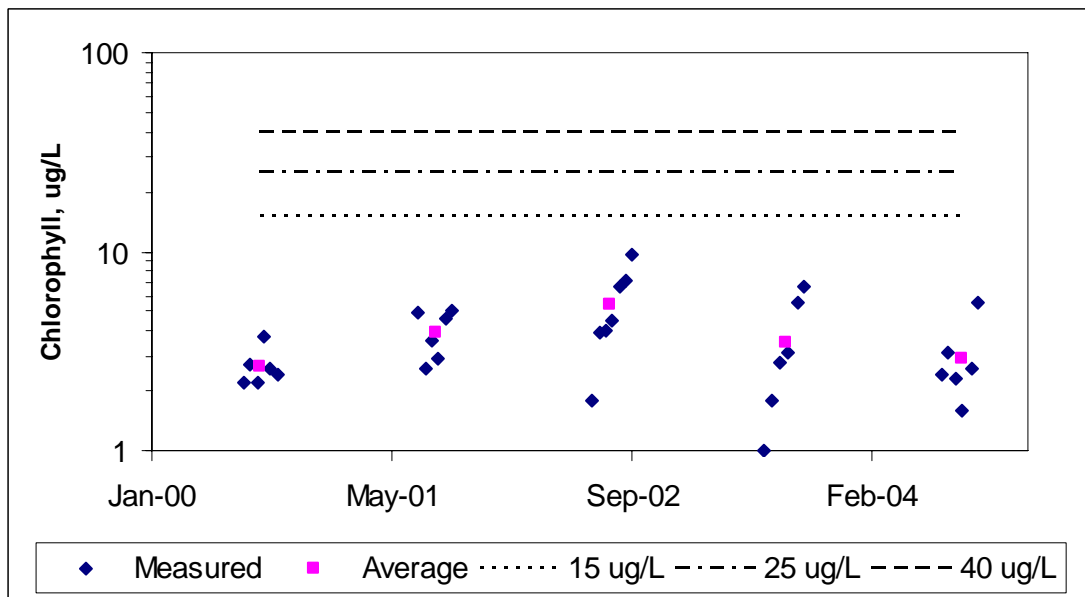


Figure 25. Chlorophyll concentrations and growing season averages for Standley Lake. Thresholds are shown for cool water fisheries (15 ug/L), warm water fisheries (25 ug/L), and blooms (40 ug/L).

The comparison of observed chlorophyll concentrations with prospective thresholds leads to questions about classification and compliance, but it is premature to address either issue at this time. Standards are still a subject for discussion and compliance issues depend both on standards and on classification (i.e., the mismatch of fishery type and aquatic life classification must be resolved). Nevertheless, it is useful to proceed to the

next step in the scheme for nutrient criteria, and that is the formulation of site-specific phosphorus thresholds that can be applied when chlorophyll thresholds have been exceeded.

The strategy for setting a site-specific phosphorus threshold involves the chlorophyll threshold and the response ratio (chlorophyll:total phosphorus). The response ratio is chosen such that it represents near-optimal growth for the resident algal community. For the purpose of illustrating implementation of the strategy, a short-cut method is presented here; it is the 90th percentile of the response ratios computed from the growing season average concentrations of chlorophyll and phosphorus. A more elaborate procedure, involving consideration of the distributions of individual data pairs and a specified number of samples from the growing season, would be applied in formal development of phosphorus thresholds. The difference in outcomes between the elaborate procedure and the short-cut is not likely to be large, but the conceptual differences are important.

The allowable total phosphorus concentration is computed by dividing the chlorophyll threshold by the 90th percentile value of the response ratio. This procedure is not applied to the bloom threshold because growing season averages have been chosen to limit potential for bloom formation. Response ratios and resulting phosphorus thresholds are shown in Table 3. Graphs for all lakes are shown in Figures 26-35.

Table 3. Response ratios for selected Colorado lakes. Total phosphorus thresholds have been calculated from cold or cool water fishery thresholds for the four lakes with aquatic life classification of Cold; for the other lakes, the cool and warm water fishery thresholds were calculated.

Lake	Elevation	Response Ratio	Cold	Cool	Warm
Dillon	9000	0.870	6.9	17.2	
Chatfield	5430	0.446	13.4	33.6	
Seaman		0.698	8.6	21.5	
Bear Creek	5560	0.716	8.4	21.0	
Cherry Creek	5550	0.314		47.7	79.5
Loveland	5010	0.433		34.7	57.8
Boyd	4958	0.527		28.5	47.5
Standley	5500	0.411		36.5	60.9
Barr	5100	0.191		78.7	131.1
Milton	4800	0.132		113.6	189.4

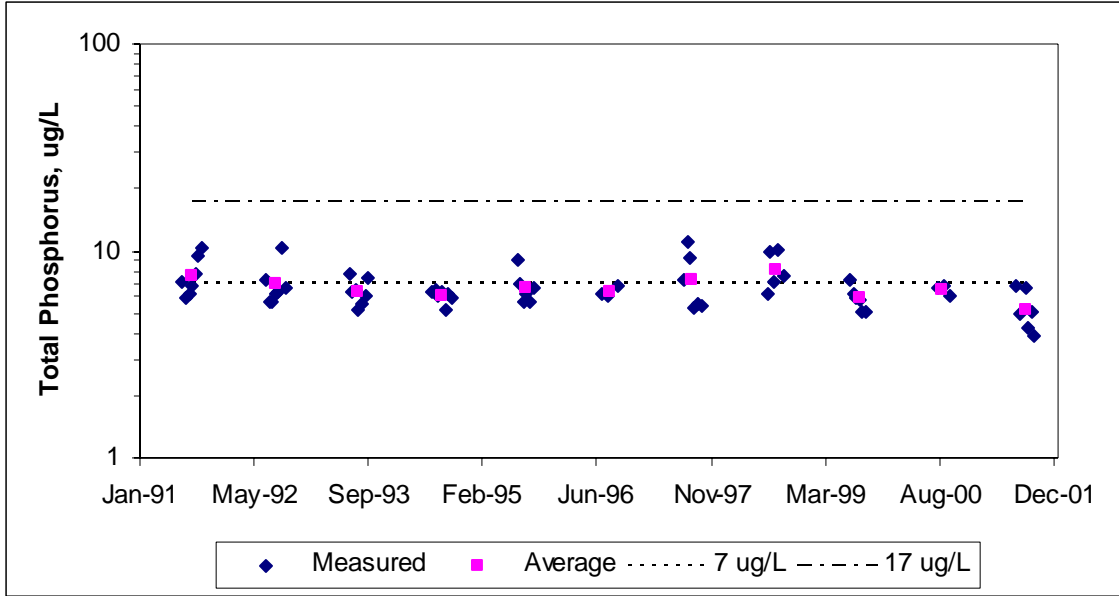


Figure 26. Threshold concentrations for total phosphorus in Dillon Reservoir, based on cold water and cool water thresholds for chlorophyll and a response ratio of 0.87.

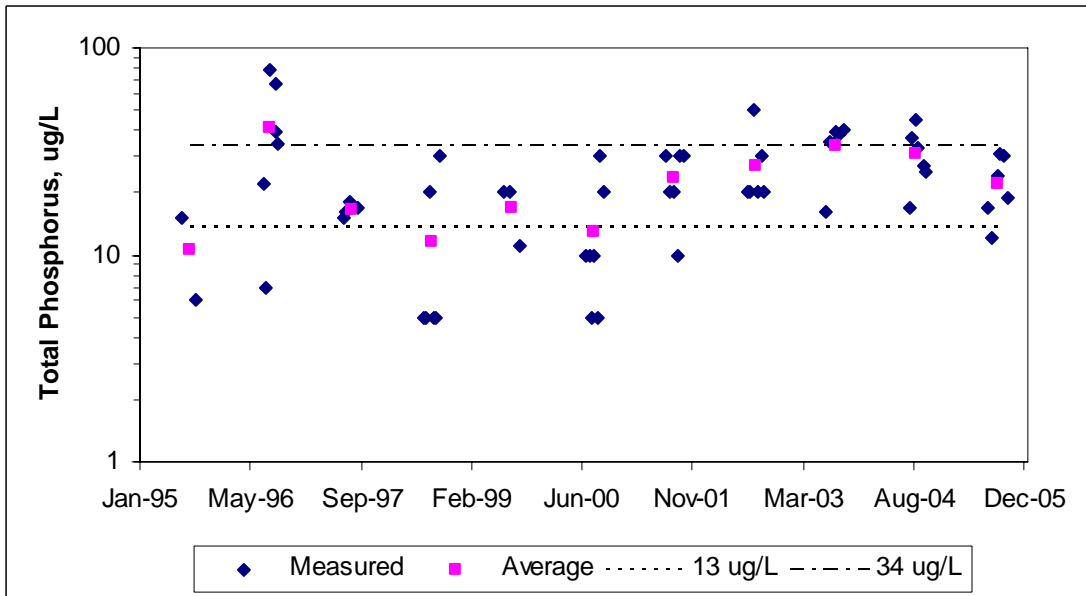


Figure 27. Threshold concentrations for total phosphorus in Chatfield Reservoir, based on cold water and cool water thresholds for chlorophyll and a response ratio of 0.45.

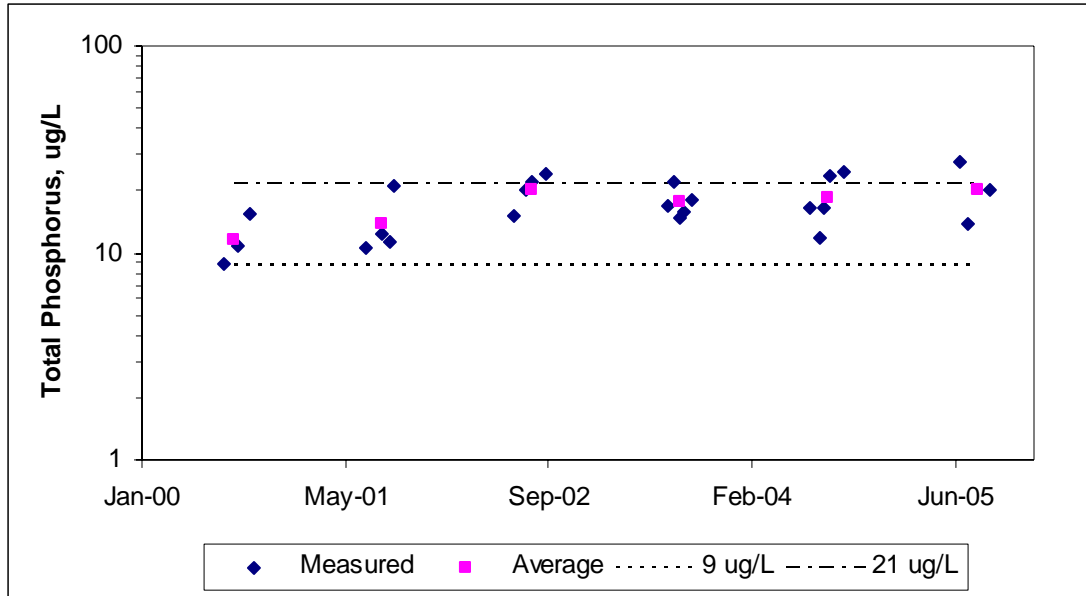


Figure 28. Threshold concentrations for total phosphorus in Seaman Reservoir, based on cold water and cool water thresholds for chlorophyll and a response ratio of 0.70.

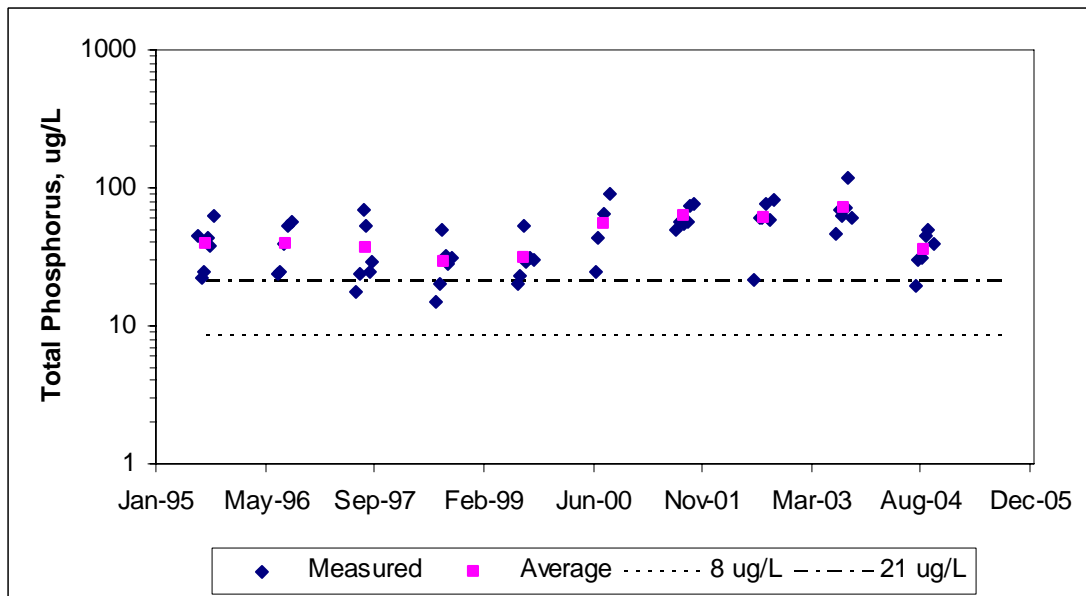


Figure 29. Threshold concentrations for total phosphorus in Bear Creek Reservoir, based on cold water and cool water thresholds for chlorophyll and a response ratio of 0.72.

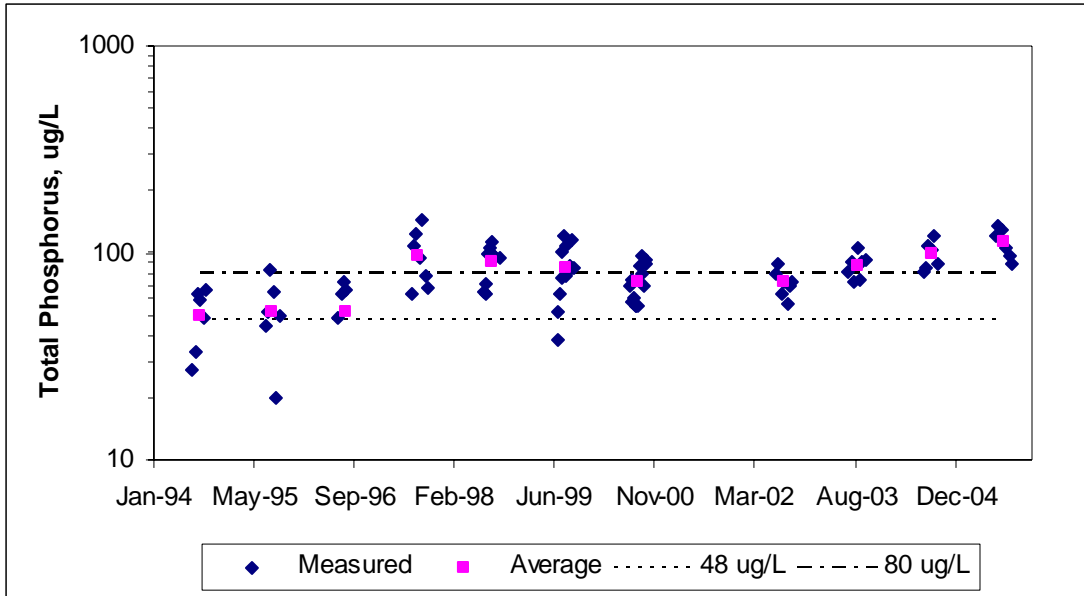


Figure 30. Threshold concentrations for total phosphorus in Cherry Creek Reservoir, based on cool water and warm water thresholds for chlorophyll and a response ratio of 0.31.

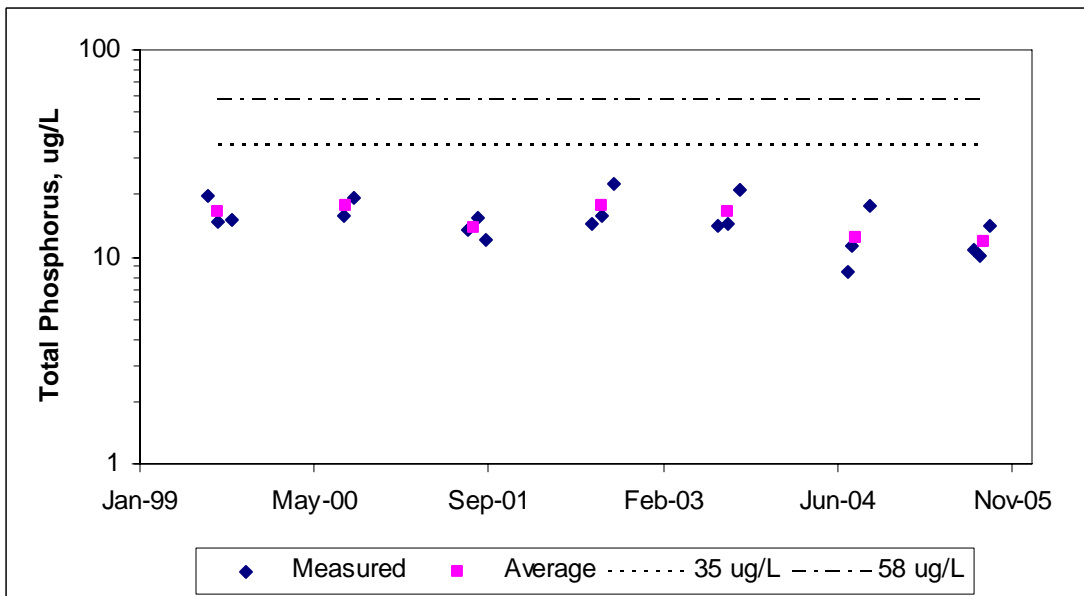


Figure 31. Threshold concentrations for total phosphorus in Loveland Lake, based on cool water and warm water thresholds for chlorophyll and a response ratio of 0.43.

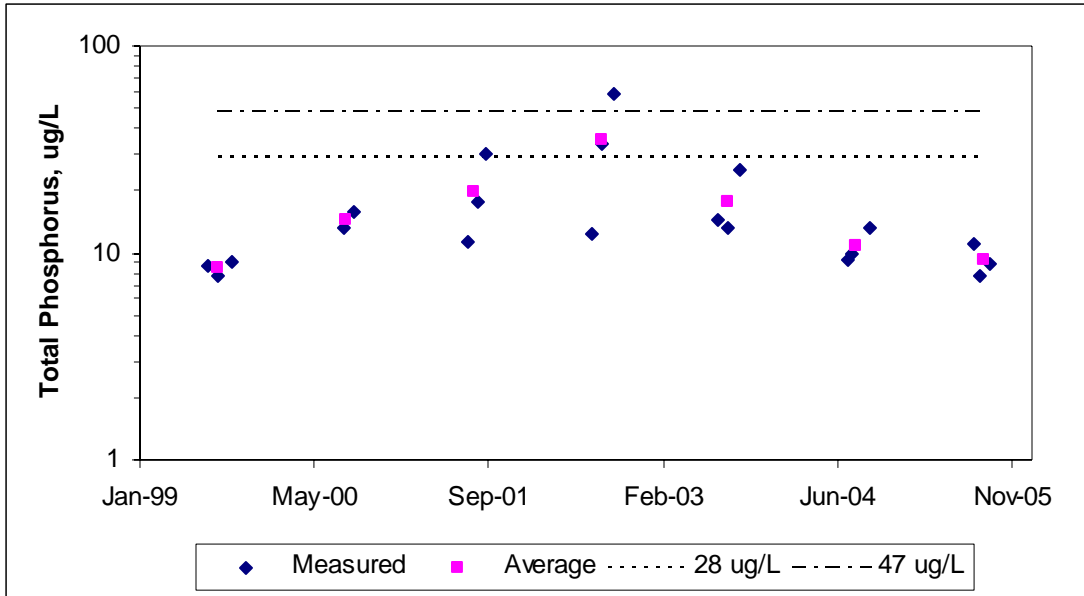


Figure 32. Threshold concentrations for total phosphorus in Boyd Lake, based on cool water and warm water thresholds for chlorophyll and a response ratio of 0.53.

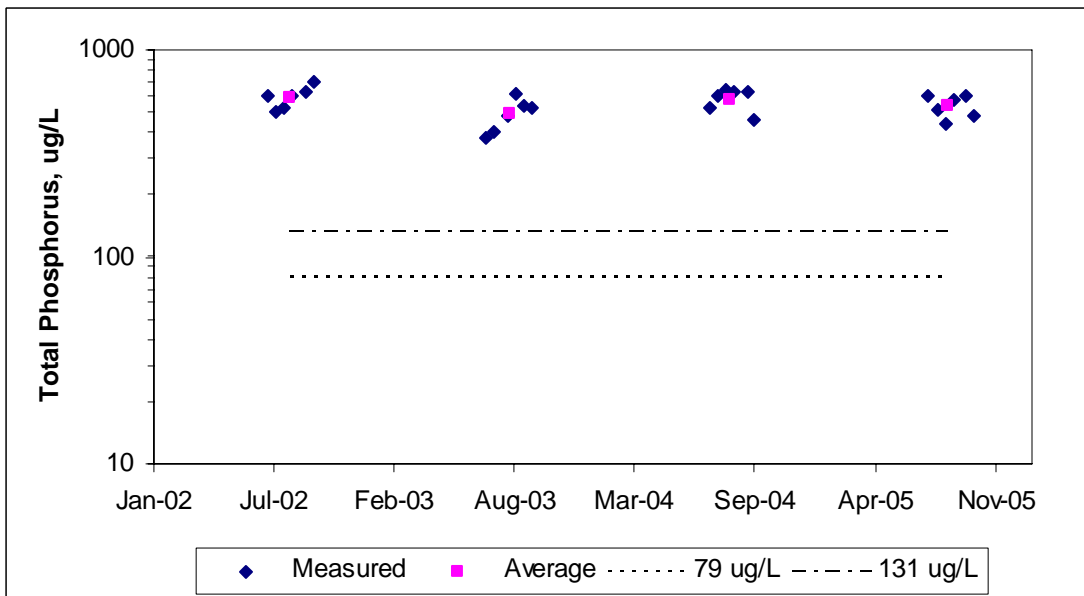


Figure 33. Threshold concentrations for total phosphorus in Barr Lake, based on cool water and warm water thresholds for chlorophyll and a response ratio of 0.19.

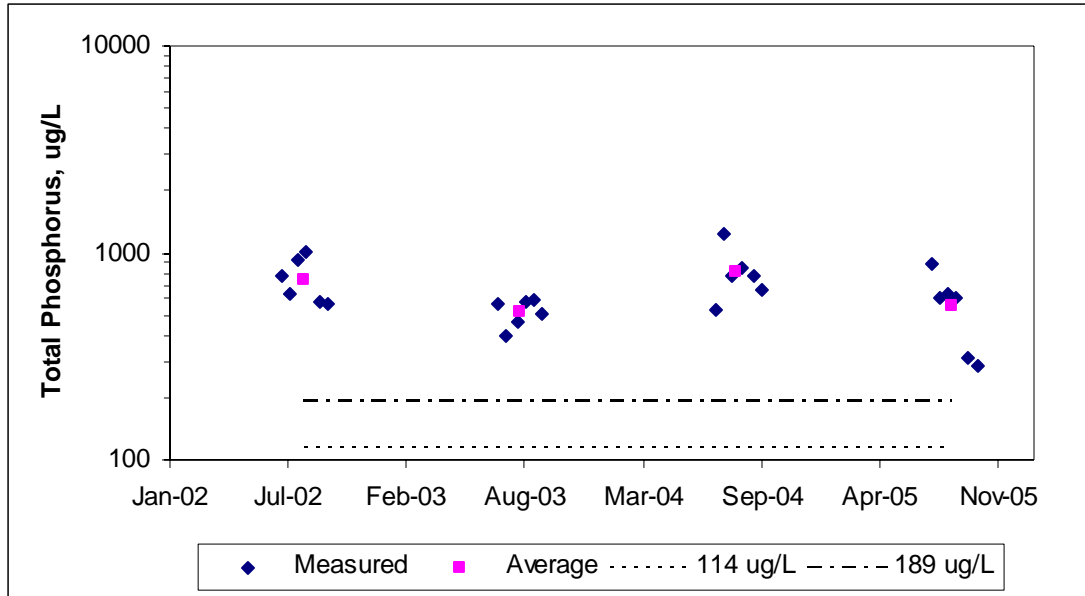


Figure 34. Threshold concentrations for total phosphorus in Milton Reservoir, based on cool water and warm water thresholds for chlorophyll and a response ratio of 0.13.

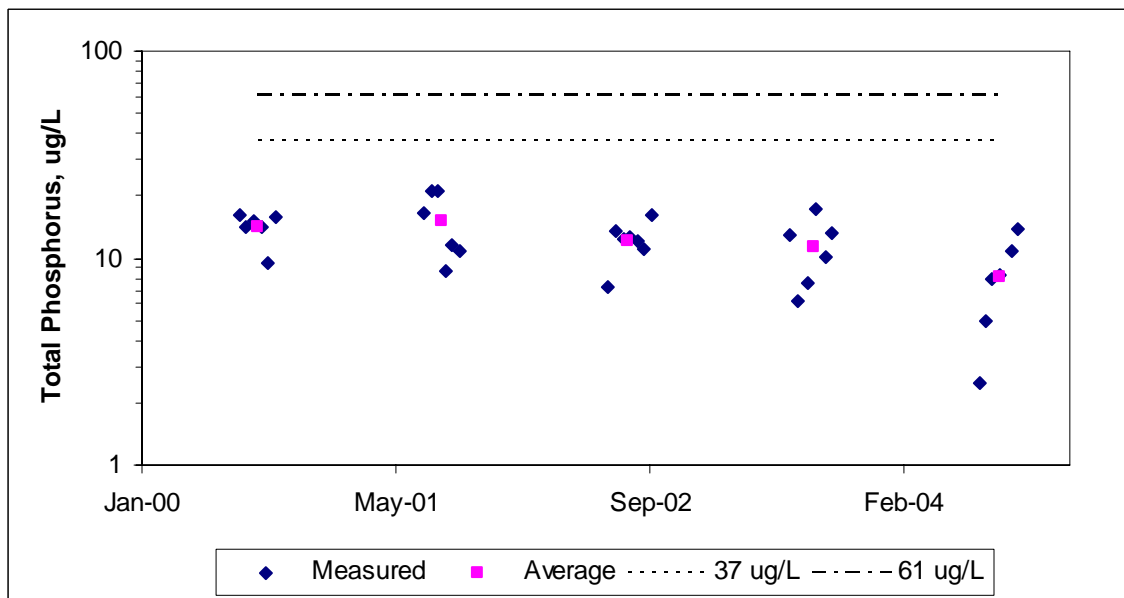


Figure 35. Threshold concentrations for total phosphorus in Standley Lake, based on cool water and warm water thresholds for chlorophyll and a response ratio of 0.41.

The phosphorus concentration observed during the growing season in Dillon Reservoir hovers very close to the threshold calculated by the Division’s procedure; at the same time, the concentration remains within the bounds set by the control regulation (7.4 ug/L for Jul-Oct). The response ratio for Dillon (0.87) is the highest among the Colorado lakes that have been examined. The phosphorus concentrations observed in Chatfield Reservoir and Seaman Reservoir are usually higher than the site-specific cold water

fishery threshold, but usually less than that computed for the cool water fishery threshold. Phosphorus concentrations in Bear Creek Reservoir are consistently above the cool water fishery threshold. Among the reservoirs classified Warm for aquatic life, Loveland and Boyd have phosphorus concentrations below the cool water threshold; Barr and Milton are consistently above the warm water threshold, and Cherry Creek Reservoir is in between.

For several of the lakes, the potential for concern about chlorophyll concentrations depends on how fishery types are integrated into existing classifications for aquatic life. If all lakes classified Cold for aquatic life must meet a chlorophyll threshold for cold water fisheries, many will exceed that threshold.

Discussion Items

The basic framework proposed for nutrient criteria in Colorado lakes contains one response variable (chlorophyll) and one causal variable (phosphorus), and an unconventional method (response ratio) is used to define a site-specific link between the two. Any part of the criteria is open to discussion; a few possibilities for discussion include the following:

- 1) Is algal abundance (chlorophyll concentration) a suitable basis for protecting uses?
- 2) Should phosphorus thresholds be set independent of the chlorophyll concentration? If not, Is the response ratio an appropriate tool?
- 3) Are there suggestions for alternative (and defensible) chlorophyll thresholds?
- 4) The current regulatory classification scheme recognizes only two aquatic life categories – cold and warm, but chlorophyll thresholds would be proposed for three fishery types. What is the best way to reconcile this difference?

Acknowledgements

Barb Horn of the DOW was instrumental in gathering the information on fisheries in high elevation lakes. Water quality data were supplied by City of Westminster, City of Greeley, Cherry Creek Basin Water Quality Authority, Chatfield Watershed Authority, Bear Creek Watershed Authority, Northwest Colorado Council of Governments, and the Metro Wastewater Reclamation District.

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