Bear Creek Reservoir Chlorophyll-Phosphorus Relationship

The Clean Lakes Study determined that Bear Creek Reservoir had major water quality problems related to excessive nutrient loadings and the resultant high levels of algal abundance (DRCOG 1992). Problems were of sufficient magnitude that uses were impaired and a survey of Park users showed a desire for improvement. The study concluded that "water quality improvement would be necessary for both the watershed and the reservoir."

The primary water quality goal recommended in the Clean Lakes Study was "to reduce the probability that the reservoir is hypertrophic/eutrophic." Trophic status designations categorize lakes across a broad continuum of productivity, which includes oligotrophic (unproductive), mesotrophic, eutrophic, and hypertrophic (highly productive). The more productive lakes are characterized by excessive algal abundance. Bloom frequency was chosen as the metric of trophic status that could be used to register improvements in water quality. Reducing the frequency of blooms (incidence of chlorophyll concentrations in excess of 20 ug/L) by 50% was considered necessary to bring trophic status into a more desirable range close to the boundary between mesotrophic and eutrophic. From a management perspective, "reduction in bloom frequency is … the trigger for determining the percentage decrease in phosphorus loading."

By recognizing the linkage between chlorophyll and phosphorus, the Clean Lakes Study set the stage for the narrative standard and for the control regulation, which promotes attainment of the standard. The control regulation is constructed on the premise that the narrative standard, which describes the desired shift in trophic status, can be attained through management of phosphorus load from the watershed. Forecasting attainment therefore depends on a quantitative linkage between chlorophyll and phosphorus; the link is called a "concentration translator."

The general notion that phosphorus controls algal abundance has been in the scientific literature for decades (see Edmondson 1991 for a review). A recent review of 35 lake restoration case studies (Jeppesen et al. 2005) supports the view that a reduction in phosphorus load results in lower chlorophyll concentrations. The evidence has been sufficiently compelling to justify large investments to reverse eutrophication by reducing phosphorus loads. Defining the water quality benefit (reduction of chlorophyll) in terms of treatment cost (reduction in phosphorus load) relies on a quantitative linkage that is often captured through regression analysis.

Regression models showing a strong statistical linkage between chlorophyll and phosphorus are plentiful in the literature. Most were developed using data from large sets of lakes. The equation recommended in the Clean Lakes Study was "constructed" with slope and intercept from a study (Prairie et al. 1989) that used data from a large set of lakes to demonstrate the dependence of the chlorophyll-phosphorus relationship on the ratio of nitrogen to phosphorus. The recommended equation defines a line that passes through the single datum from 1988 (Figure 1). Because no numeric standard was proposed for Bear Creek Reservoir, the Clean Lakes Study equation was never used to develop a regulatory linkage between chlorophyll and phosphorus. Assuming that numeric criteria are at least a possibility for the future, a thorough evaluation of the linkage remains an important component of the technical review.

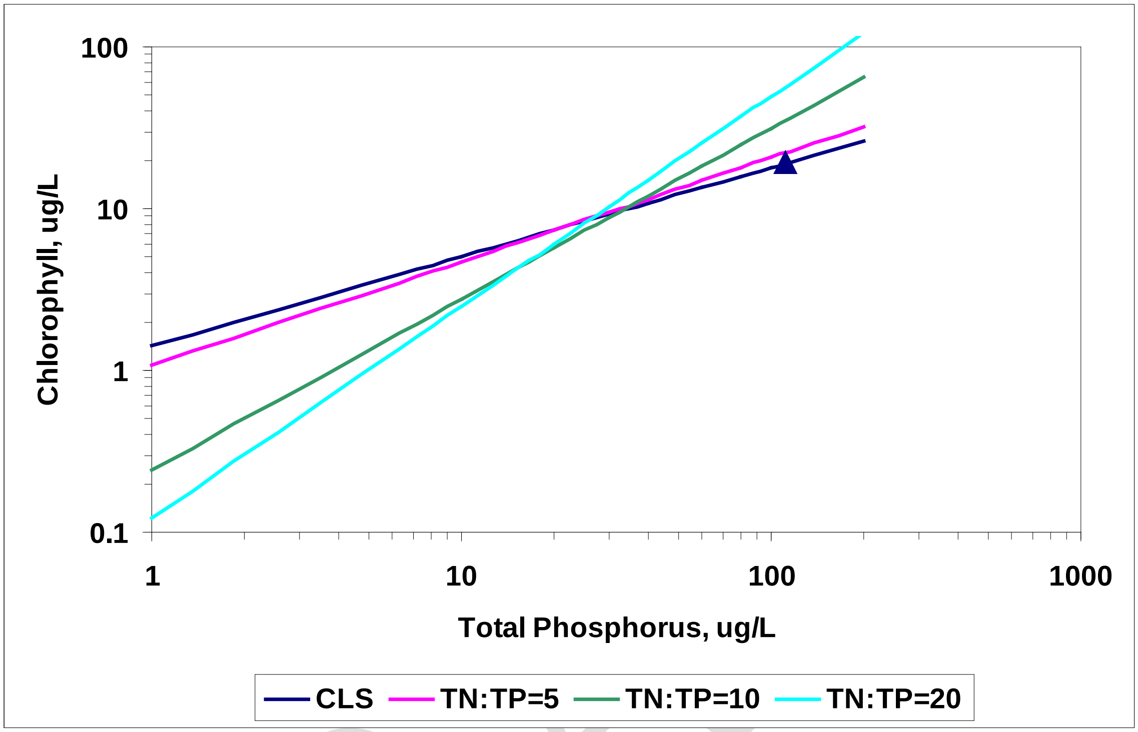

Figure 1. Power functions characterizing chlorophyll as a function of total phosphorus. Both variables are shown on log scales. The lines are based on different assumptions about the TN:TP ratio, using equations developed by Prairie et al. (1989). The equation recommended in the Clean Lakes Study (CLS) was constructed to pass through the 1988 datum (closed triangle) for Bear Creek Reservoir.

Phosphorus and chlorophyll have been measured in Bear Creek Reservoir for many years since the Clean Lakes study. Through the efforts of the Bear Creek Watershed Association, a large data set is available for investigating the linkage between chlorophyll and phosphorus. Chlorophyll and phosphorus in the mixed layer at the routine monitoring site near the dam are plotted as time series (Figures 2-3). There appear to have been changes over time in the concentrations of both constituents, although the change is more apparent in the phosphorus data. For the purpose of this technical review, attention is focused primarily on data collected after 1995.

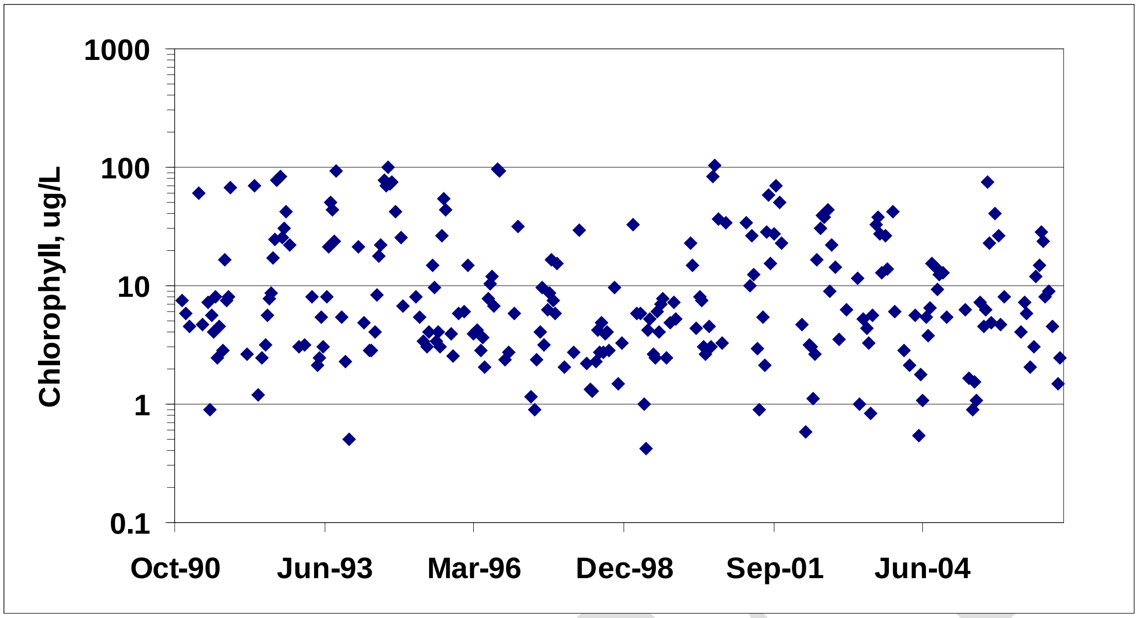

Figure 2. Chlorophyll concentrations (log scale) in Bear Creek Reservoir, 1990-2006.

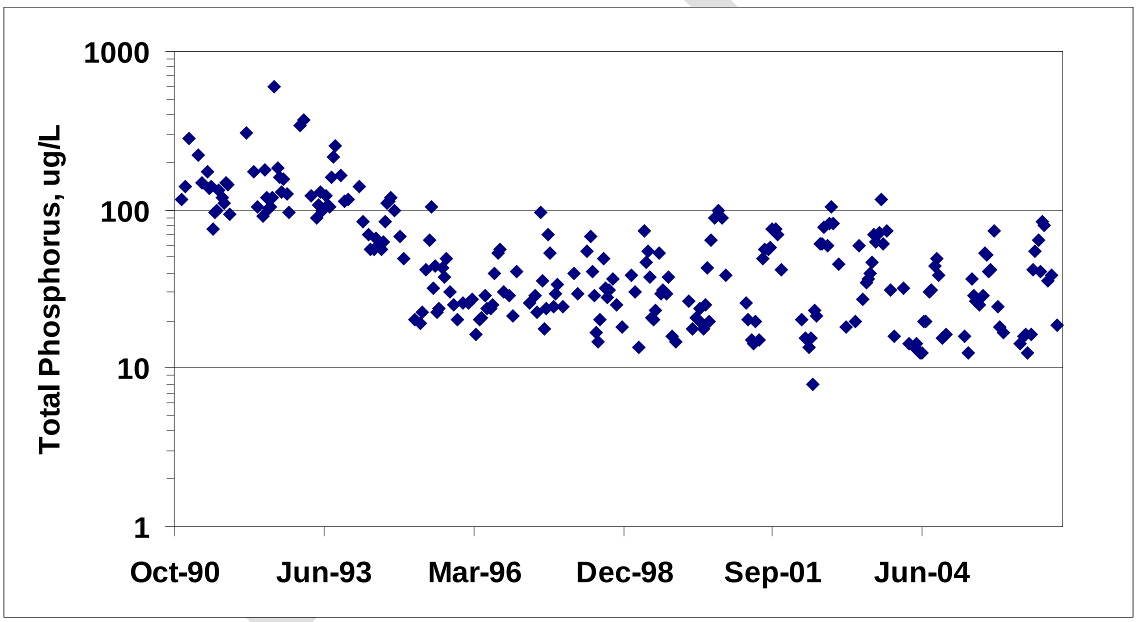

Figure 3. Total phosphorus concentrations (log scale) in Bear Creek Reservoir, 1990-2006.

Summer (Jul-Sep) median chlorophyll shows a strong correspondence to summer median phosphorus (Figure 4). Although the relationship for Bear Creek Reservoir is one of the strongest for a Colorado lake, there is still considerable scatter about the trend line. Whether or not the relationship is significant in a statistical sense, there is a substantial amount of "noise" (variability). The variability simply indicates that, in Bear Creek Reservoir, or in any other natural setting, phosphorus is not the only factor controlling the abundance of algae. (More is said about this subject in the companion document: *Creating a Concentration Translator to Link Chlorophyll and Phosphorus*.)

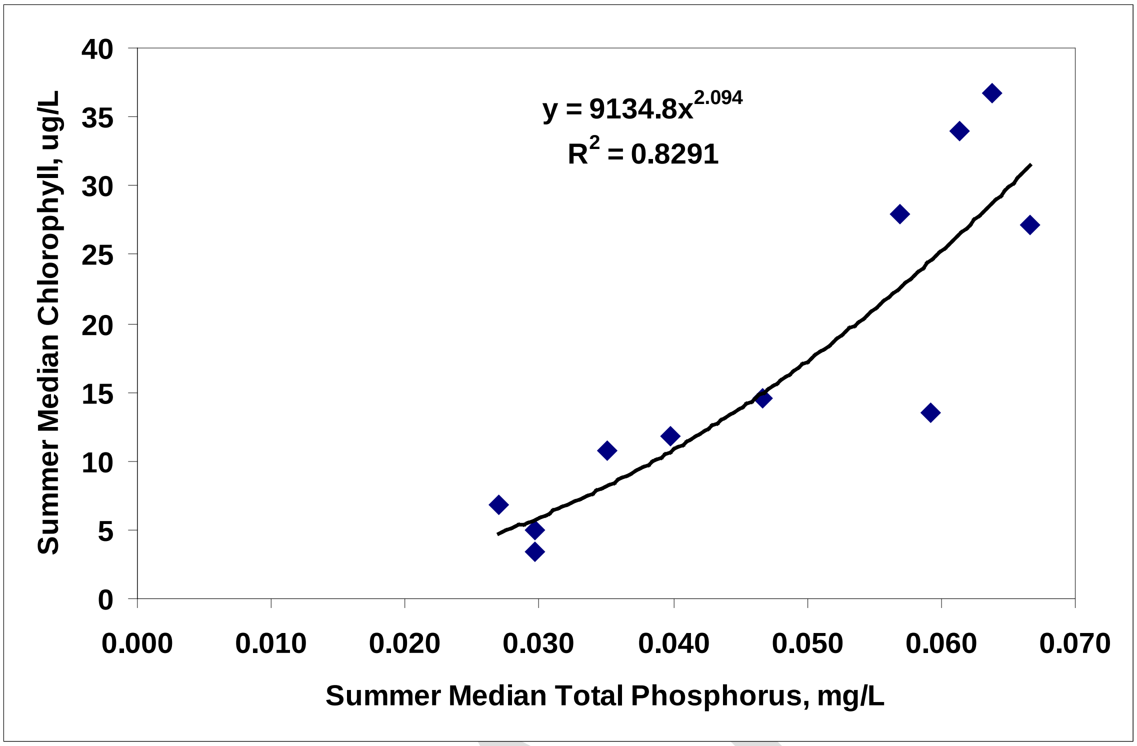

Figure 4. Relationship between summer median concentrations of chlorophyll and phosphorus in Bear Creek Reservoir, 1996-2006.

One of the problems with a regression approach is evident in Figure 4. For any concentration of phosphorus that might occur in the lake, there is a wide range of possible values for chlorophyll, about half of which are greater than the values predicted by the trend line. From a regulatory perspective, a regression approach may not be a satisfactory basis for linking chlorophyll and phosphorus.

The Division is recommending an alternative to the regression approach; it is based on a response ratio (chlorophyll:TP) that scales the responsiveness of the algae (measured as chlorophyll) to the stimulus of nutrients (phosphorus). The purpose of the response ratio approach is to develop a new concentration translator to provide the quantitative basis for predicting the potential abundance of algae (chlorophyll) for any concentration of phosphorus. Potential abundance and reasons why it may not be achieved at any particular time are discussed in the companion document (*Creating a Concentration Translator to Link Chlorophyll and Phosphorus*). It should be noted that "potential" is used in a site-specific, operational sense rather than as a theoretical maximum. Smaller ratios indicate greater suppression of abundance below the potential.

A time series for the response ratio in Bear Creek Reservoir is given in Figure 5. Each pair of chlorophyll and phosphorus values represents one estimate of the response of the resident algal community to the concentration of total phosphorus. Each ratio therefore estimates the slope of a linear relationship. The implicit assumption is that the slope is constant over the range of phosphorus values observed in one lake. The assumption seems justified insofar as the range of phosphorus concentrations observed in the mixed layer of a single lake is likely to be small.

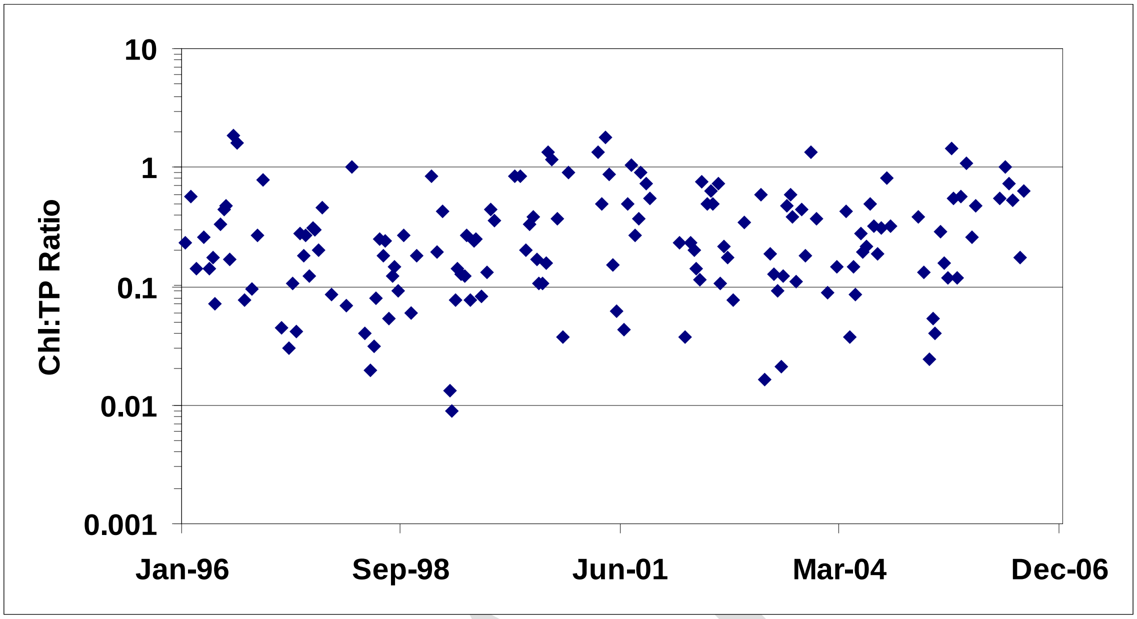

Figure 5. Chlorophyll:total phosphorus ratios observed in Bear Creek Reservoir, 1996-2006. The ratio is shown on log scale.

The responsiveness of the algal community in a lake is likely to be affected by temporal variation in the relative importance of a suite of growth and loss factors. The set of response ratios from one lake is likely to conform to some kind of frequency distribution, and the characteristics of that distribution can be used to define operationally what constitutes the potential abundance of chlorophyll for a given amount of phosphorus. In other words, a percentile can be chosen to represent potential abundance on a site-specific basis, and that percentile affects the exceedance frequency for chlorophyll at any phosphorus concentration.

The large data set available for Bear Creek Reservoir makes it well-suited for site-specific examination. The distribution of the values for the response ratio is clearly lognormal (Figure 6; based on log-transformed values of the ratio); a similar assessment of the normal distribution revealed a very poor fit. Because the distribution is lognormal rather than normal, the appropriate measure of central tendency is the median, which corresponds to a geometric mean, rather than an arithmetic mean (i.e., the average). The distinction is important from a statistical perspective, but either measure can be accommodated in a regulatory scheme. Furthermore, a conversion between average and median is possible using equations presented in a document distributed previously (*Characterizing Chlorophyll Distributions in Colorado Lakes*).

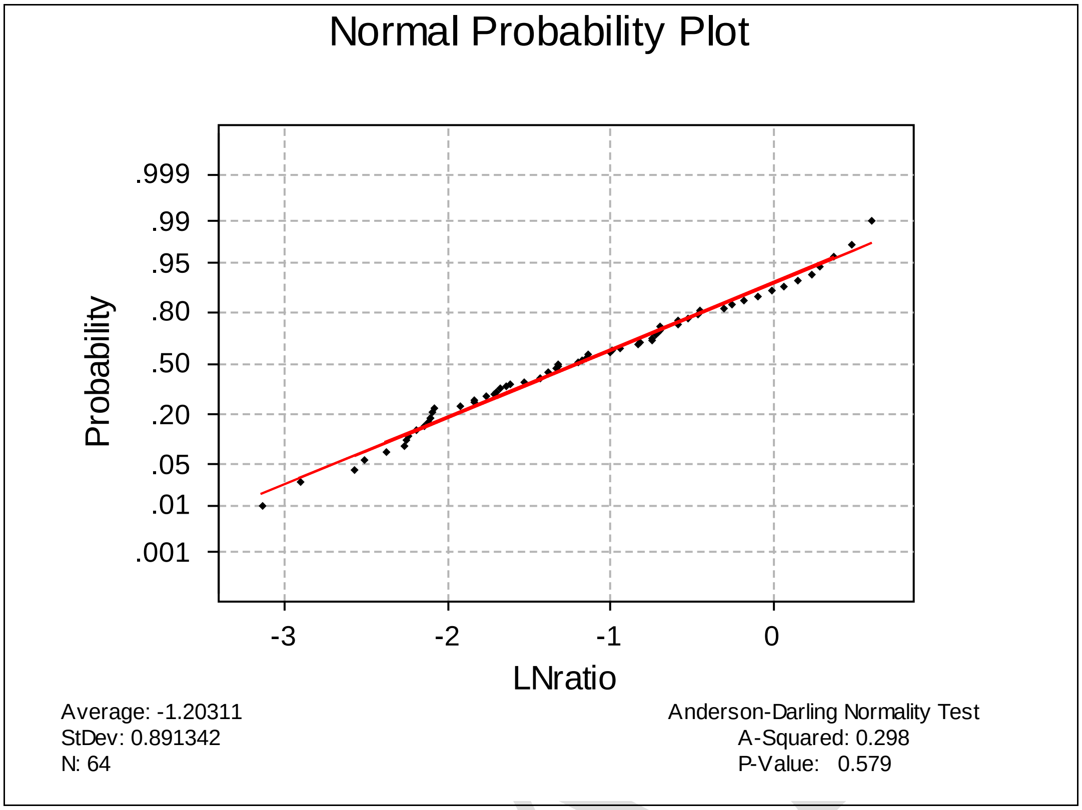

Figure 6. Normal probability plot of log-transformed summer response ratios from Bear Creek Reservoir, 1996-2006. Output from Minitab statistical software.

Percentiles from the distribution of summer response ratios can be used to define expectations for attainment of a chlorophyll goal or standard (as explained in the companion document: *Creating a Concentration Translator to Link Chlorophyll and Phosphorus*). The concept is illustrated for Bear Creek Reservoir using the 50th, 75th, and 90th percentiles of the observed summer response ratios (Figure 7). The effect of selecting a particular percentile can be explored with reference to the historical data.

A line derived from the 50th percentile response ratio shows the summer median chlorophyll that would have been expected in Bear Creek Reservoir, given the observed summer median phosphorus and assuming median responsiveness on the part of the algal community. The line is generated as the product of each observed summer median phosphorus concentration and the median response ratio (0.236). When the responsiveness of the algal community is set to the median, it means that the chlorophyll produced per unit phosphorus is considerably less than the potential for Bear Creek Reservoir. Observed values would be expected to exceed this line about half the time. The same procedure is applied to the 75th percentile response ratio (0.371), which yields predictions closer to the potential chlorophyll for Bear Creek Reservoir; observed values are less likely to exceed this line. Finally, the 90th percentile response ratio should yield predictions not often exceeded by observed chlorophyll medians (i.e., close to the potential chlorophyll for the reservoir).

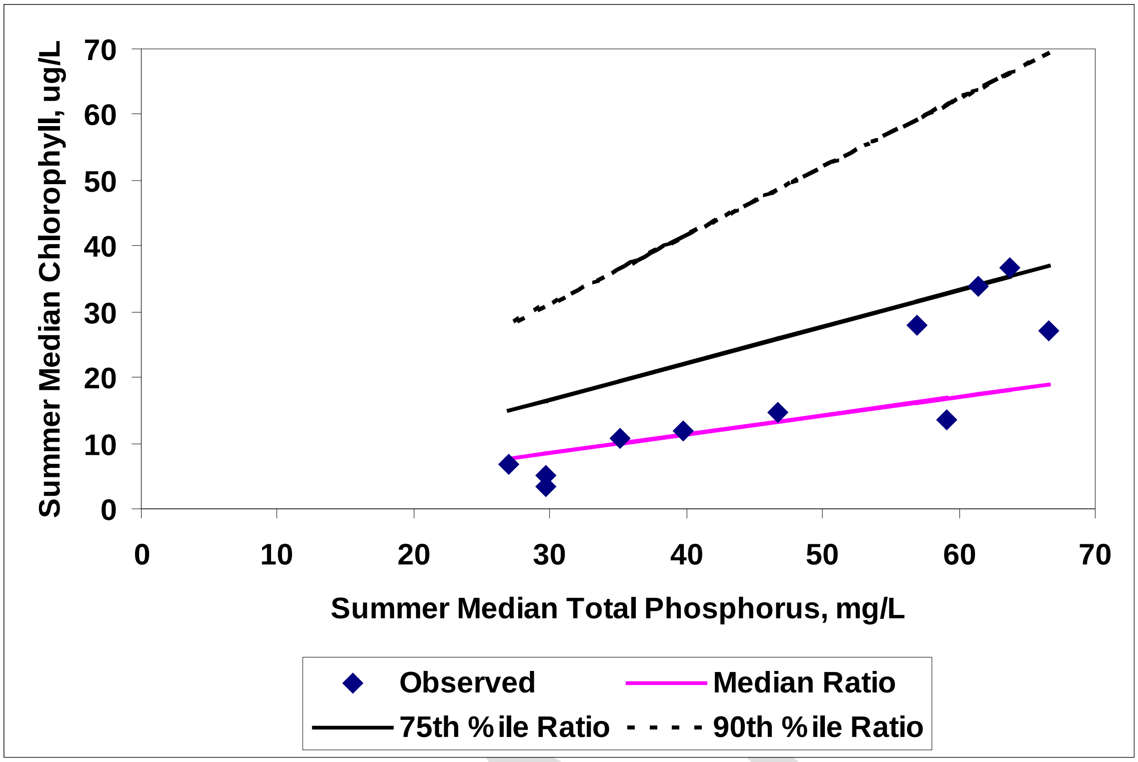

Figure 7. Relationship between summer median chlorophyll and phosphorus in Bear Creek Reservoir. Lines represent chlorophyll concentrations calculated from the median total phosphorus and three different values of the response ratio.

The Bear Creek Reservoir data set is too small a sample size from which to draw conclusions about exceedance frequencies, but a much larger set is available in the companion document (*Creating a Concentration Translator to Link Chlorophyll and Phosphorus*). In brief, the 90th percentile corresponds approximately to a one-in-20 year exceedance frequency and the 75th percentile corresponds approximately to a one-in-five year exceedance frequency. The 11-year record for Bear Creek Reservoir contains two observations at or above the one-in-five year line and none near the one-in-20 line. The 75th percentile is a suitable basis for describing how the response ratio plays a role in setting standards, but the percentile is certainly open to further discussion.

Having a concentration translator to link chlorophyll and phosphorus is a necessary component of a regulatory scheme, and it builds confidence in the assumption behind the narrative standard. If a numeric standard were proposed for chlorophyll or phosphorus in Bear Creek Reservoir, the concentration translator would be needed to link the control regulation to the underlying standard. Information in the Clean Lakes Study can be used to demonstrate application of the response ratio as a concentration translator.

The Clean Lakes Study recommended a 50% reduction in bloom frequency, which corresponded to reducing the summer mean concentration from 19 to about 12 ug/L. The translation between bloom frequency and average concentration was based on concepts and equations developed by Walker (1985). The Division has used those concepts to develop a relationship linking bloom frequency to average chlorophyll for Colorado lakes (see *Characterizing Chlorophyll Distributions in Colorado Lakes*). When the new relationship is applied to an average chlorophyll of19 ug/L, it yields a bloom frequency of 33%. Reducing bloom frequency by 50% would mean reducing the average chlorophyll to 12.7 ug/L (or a median of about 10 ug/L).

If a numeric chlorophyll standard of 10 ug/L (or average of 12.7 ug/L) were proposed, the corresponding total phosphorus concentration could be determined by site-specific application of the response ratio concept. When the 75th percentile response ratio (0.555) is applied, the corresponding summer median total phosphorus would be 0.018 mg/L (=10/0.555). If the summer median total phosphorus were held at 0.018 mg/L, the exceedance frequency for the chlorophyll standard would be about once in five years. For perspective on actual conditions, Figure 7 shows that observed concentrations for summer median total phosphorus have always been substantially higher than 0.018 mg/L.

The foregoing example should not be construed as a proposal on the part of the Division; it was simply an opportunity to demonstrate how the response ratio concept can be applied to link chlorophyll and phosphorus concentrations, as would be needed to support a TMAL for phosphorus. It is important to remember that the purpose of the response ratio approach is to ensure that standards are attained. It is not intended as a means of predicting the *most likely* concentration of chlorophyll; that would be the aim of regression analysis. Instead, the strategy involves defining a potential abundance of chlorophyll assuming that the potential could be achieved at any time.

The Division recommends the response ratio (chlorophyll:total phosphorus) as a means of defining the potential abundance of algae for any level of phosphorus. The response ratio accounts for the net effect of all growth and loss factors without attempting to quantify explicitly the role of any factor except phosphorus. Exceedance frequencies are derived empirically by applying percentiles of the response ratios to data from various Colorado lakes. The 75th percentile from the response ratio distribution yields an exceedance frequency of approximately once-in-five years.

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