Bear Creek Reservoir Technical Review Part 3: Site-Specific Criteria

Existing Narrative Standard

The Clean Lakes Study determined that the trophic status of Bear Creek Reservoir was eutrophic or even hyper-eutrophic in 1988 and concluded that "existing water quality data [show] use impairment." The study recommended improving water quality by reducing chlorophyll concentrations substantially. The intent to improve water quality is clear in the narrative standard adopted for Bear Creek Reservoir:

> *Concentrations of total phosphorus in Bear Creek Reservoir shall be limited to the extent necessary to prevent stimulation of algal growth to protect beneficial uses. Sufficient dissolved oxygen shall be present in the upper half of the reservoir hypolimnion layer to provide for the survival and growth of cold water aquatic life species. Attainment of this standard shall, at a minimum, require shifting the reservoir trophic state from a eutrophic and hypertrophic condition to a eutrophic and mesotrophic condition.*

The substance of the narrative can be distilled into three simple statements. Algal abundance in Bear Creek Reservoir is too high and should be reduced. Phosphorus is the basis for controlling algal abundance (and thus the justification for the Control Regulation). Excessive algal abundance causes decreases in oxygen concentrations in the hypolimnion, with potential to impair conditions for cold-water aquatic life. Although the substance of the narrative is clear, it lacks a specific basis for determining attainment. Nevertheless, thresholds can be inferred for chlorophyll and dissolved oxygen.

Interpreting the Chlorophyll Goal
Trophic state is clearly the primary focus of the narrative standard because it is used to frame both the existing condition and the goal for biological productivity in the reservoir. Indicators of productivity include the causative agents (e.g., nutrient concentrations), which determine potential, or response factors (e.g., algal productivity or abundance), which reflect the outcome. In practice, chlorophyll concentration is commonly used because it is easy to measure and there is usually a good correspondence between algal abundance (chlorophyll) and algal productivity.

Different schemes exist for defining the trophic state of a lake, and they rely on static indicators like chlorophyll, phosphorus, or water transparency. Some are based directly on the underlying variables and others are based on indices (Trophic State Index, or TSI) that "normalize" variables on a comparative scale. Unfortunately, the standard offers no guidance concerning the metric that should be used to evaluate trophic state, or the precision with which the attainment threshold should be defined. The

Division interprets the trophic state narrative as a long-term average chlorophyll concentration corresponding to the OECD boundary[1] between mesotrophic and eutrophic conditions, which is 8 ug/L.

Chlorophyll concentrations vary considerably over time, but trophic state should be interpreted based on typical conditions. The typical trophic state of Bear Creek Reservoir remains well above the threshold of attainment (mesotrophic-eutrophic boundary) defined in the narrative standard (Figure 1). Even after external phosphorus loads were reduced in 1994-1995, the reservoir has remained too productive to be considered in attainment of the standard. From 1996 to 2008, the median summer average chlorophyll concentration was 24 ug/L, indicating that the reservoir has remained at the eutrophic-hypertrophic boundary considered unacceptable when the narrative standard was adopted.

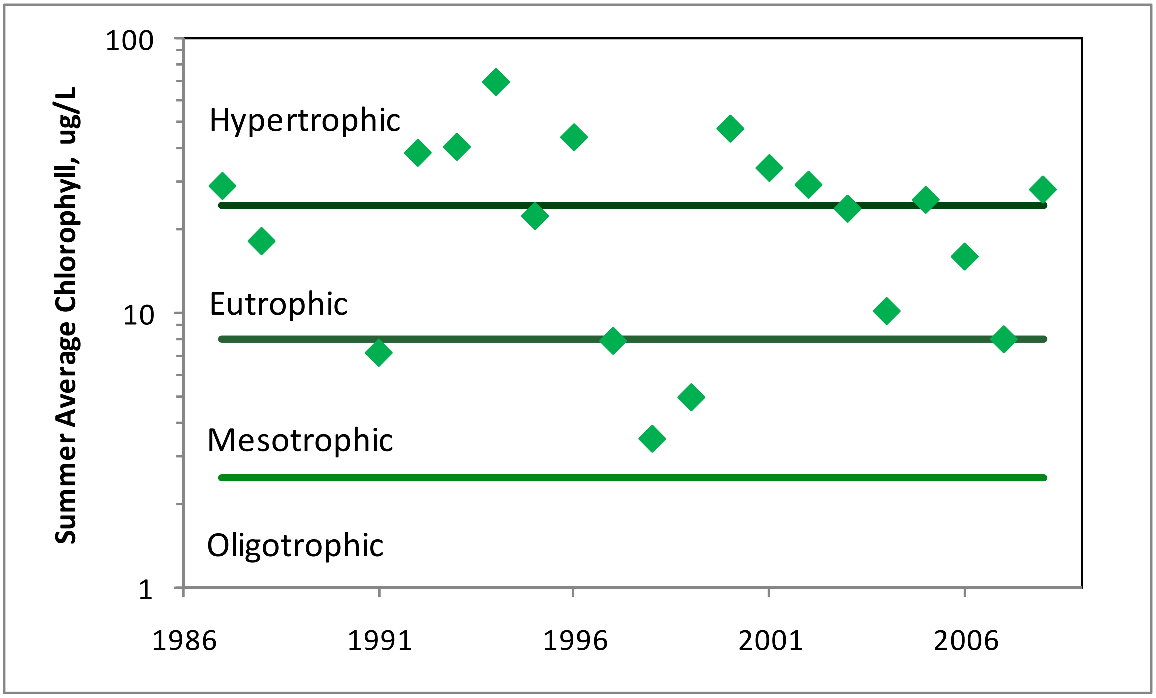

Figure 1. Summer average chlorophyll concentrations in Bear Creek Reservoir, 1987-2008. The OECD classification scheme is used to locate boundaries between trophic state categories. The narrative standard defines attainment at the mesotrophic-eutrophic boundary.

There can be little doubt that Bear Creek Reservoir is more productive than intended by the narrative standard. It has remained productive despite a significant reduction in external phosphorus load. Continuing failure to attain the standard is now understood to be due mainly to the persistence of internal phosphorus release, which should dissipate over a period of years (see Exhibit 2). In anticipation of improving conditions, the Division believes it is important to develop a numeric standard for chlorophyll. That task, which involves translating the long-term average chlorophyll concentration into a standard with exceedance frequency, is presented in the next section.

[1] The "fixed boundary" scheme of the Organisation for Economic Co-operation and Development (OECD: *Eutrophication of Waters*, Paris 1982) is widely-cited for definitions of trophic state. Boundaries are given separately for chlorophyll, phosphorus, and transparency (Secchi disk depth).

Interpreting the Dissolved Oxygen Goal
The narrative standard also defines a goal for dissolved oxygen that is based on protecting coldwater aquatic life in the upper half of the hypolimnion. Attainment of this goal would mean that the concentration of dissolved oxygen would have to be at least 6 mg/L. Dissolved oxygen concentrations in Bear Creek Reservoir did not meet this goal at the time of the Clean Lakes study, and they would not meet it now if aerators were not operated throughout the summer. Furthermore, it is debatable if this goal could be achieved in any mesotrophic lake (see http://dipin.kent.edu/tsi.htm, for the implications of trophic state on fisheries and recreation).

The Division believes the dissolved oxygen goal is inconsistent with the general intent of the narrative standard, which is clearly focused on achieving a particular trophic state. Imposing such a strict dissolved oxygen standard would effectively supersede the trophic state goal. The Division recommends retaining the focus on trophic state and removing what is, in effect, a site-specific dissolved oxygen standard that is unnecessarily strict.

Developing a Numeric Chlorophyll Standard

If the trophic state goal of the narrative standard is taken literally, it calls for typical chlorophyll concentrations of about 8 ug/L. A numeric standard can be derived from the typical value once variability is defined and the allowable frequency of exceedances is specified. Summer average chlorophyll concentration varies from year to year, and the variability around the long-term average determines how often a particular concentration might be exceeded. The goal is to define the standard as the concentration not to be exceeded more than once in a specified period of time.

It has been the practice in the control regulation lakes to assess chlorophyll concentrations on the basis of a "growing season" average. Growing season is assumed to correspond to summer months. The Division proposes July through September as the averaging period for Bear Creek Reservoir. Within that period, the average chlorophyll concentration is determined from samples taken within the mixed layer.

Exceedance frequencies were not defined when standards and control regulations first were adopted. The Division recommends once in five years as the allowable frequency of exceedance, in part because it matches the typical cycle of assessments performed for basin hearings. The Commission recently adopted the same exceedance frequency for Chatfield Reservoir. A once-in-five year exceedance frequency corresponds to the 80^{th} percentile of the distribution characterizing all summer average concentrations for a particular lake.

Chlorophyll concentrations vary from year to year in every reservoir, and, if suitable data exist, the set of measured values can be used to develop a site-specific characterization of the statistical distribution. Unfortunately, a site-specific characterization is problematic for Bear Creek Reservoir because chlorophyll concentrations have been inflated by internal phosphorus release. An alternative approach can be developed using data from other lakes and by making some assumptions. Several Colorado reservoirs have been studied sufficiently to provide some useful generalizations.

In most lakes, the set of summer average chlorophyll concentrations tends to fit a lognormal, rather than a normal, distribution. The distinction is important because central tendency for a lognormal distribution is a geometric mean rather than an arithmetic mean (or average); alternatively, the median can be used. In addition, the variance of a lognormally distributed variable tends to increase as the mean increases. This second attribute of the distribution is important because the 80th percentile will be farther from the mean when chlorophyll concentrations are high than when they are low.

Chlorophyll has been monitored in many Colorado lakes, and twelve lakes have a sufficient data record to define year-to-year variation in the seasonal average chlorophyll (Table 1). The relationship between the 80th percentile and the median of the summer averages is quite strong (Figure 2), and it can be used to define the 80th percentile expected for any particular chlorophyll concentration. For example, given a typical seasonal average of 8 ug/L, which is the goal for Bear Creek Reservoir, the corresponding 80th percentile would be about 10 ug/L.

Lake	Years	Seasonal Average Chlorophyll, ug/L	
		Median (50th Percentile)	**80th Percentile**
Arvada	9	3.6	3.7
Aurora	9	2.2	2.4
Barker	7	4.1	5.0
Barr	6	80.6	104.1
Bear Creek	18	24.9	39.4
Cherry Creek	17	17.4	23.1
Dillon	19	4.4	5.6
Green Mountain	13	2.7	3.8
Milton	6	47.6	67.8
Quincy	8	7.0	8.0
Seaman	7	10.1	13.3
Standley	12	2.8	3.8

Table 1. Seasonal average chlorophyll concentrations in Colorado lakes with at least five years of data and at least four measured values in each summer (Jul-Sep). For each lake, the typical (median) seasonal average and the 80th percentile are derived from the set of yearly values.

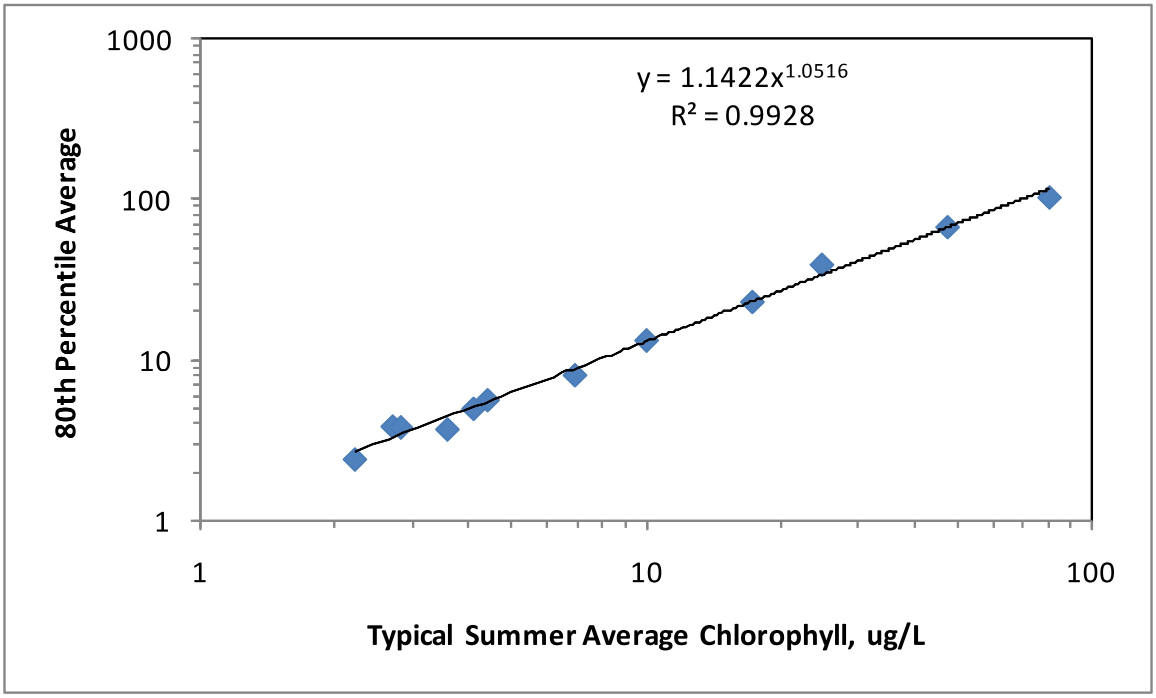

Figure 2. Relationship between the 80th percentile and the typical summer average concentration of chlorophyll in a set of Colorado lakes (see Table 1). Both variables are plotted on log scale. A power function was fit to the points using the Excel® trend line function.

Developing a Numeric Phosphorus Standard

The narrative standard assumes that chlorophyll concentrations are best controlled by managing the release of phosphorus from the watershed. Consequently, it is important to establish a link between chlorophyll and phosphorus concentrations in the reservoir. The responsiveness of the resident algal community (i.e., the chlorophyll supported per unit phosphorus in the mixed layer) tends to be site-specific. The approach taken for development of standards for Chatfield Reservoir was based on the typical responsiveness.

Summer average chlorophyll and phosphorus concentrations are available from 20 years of monitoring (1987-88, 1999-2008). The ratio of chlorophyll to phosphorus was calculated for each year, and the results were fit to a lognormal distribution. The median of the distribution is 0.3176. Applying the median ratio to the proposed chlorophyll standard of 10 ug/L yields an associated phosphorus concentration of 32 ug/L, which the Division proposes as a standard. Development of numeric standards for chlorophyll and phosphorus translates the trophic status component of the narrative standard into a site-specific characterization of the boundary between mesotrophic and eutrophic conditions.

Developing an Allowable Phosphorus Load

Control regulations were established in the 1980s and 1990s to ensure implementation of the phosphorus controls necessary for attaining the underlying standards in each reservoir. They were adopted prior to the advent of TMDLs, and served the dual purpose of defining the pollutant load allocations and describing the actions required for implementation. A key component of the Control Regulation is the maximum annual load of phosphorus (lbs/y) that is consistent with attainment of the standard. Three of the four control regulations specify the total maximum annual load (TMAL), but the Bear Creek Reservoir Control Regulation does not.

The TMAL, where it exists, is allocated among point and non-point sources, and it includes a margin of safety (MOS). The allocation step is beyond the scope of the present review, but an estimation of phosphorus load is still needed. The load estimate developed in this document is called an *allowable load*, and it represents the maximum load of phosphorus consistent with attainment of the proposed standards. It does not qualify as a TMAL because there has been no allocation among sources and no formal basis for establishing the MOS.

There are two components to the estimation of allowable load – 1) a general linkage between phosphorus load and the resulting concentration in the lake, and 2) the critical flow scenario used for implementing controls. The link between load and concentration is affected by retention of phosphorus, presumably through sedimentation, that reduces the amount available for algae in the summer. The critical flow scenario is determined by the hydrologic conditions under which the risk of non-attainment is greatest.

Linking Phosphorus Load and Concentration

The linkage between the annual load of phosphorus and the seasonal average concentration is the basis for ensuring that the phosphorus standard is attained. Historically, mass balance models have been used to predict in-lake concentrations as a function of external load and hydraulic properties of the reservoir. The key component of the relationship is the proportion of the phosphorus load that is retained in the reservoir; it is usually presented as an empirical function of hydraulic residence time or water load.

The mass-balance modeling approach runs into two obstacles for Bear Creek Reservoir – not all load is from external sources, and there is no apparent connection between retention and residence time (see Exhibit 3). Internal phosphorus release affects in-lake concentrations independently of external load, and the effect occurs primarily during the summer months when the seasonal average is determined. As long as it persists, internal load has the potential to undermine benefits expected from controlling external load.

The year-to-year variability in phosphorus retention in Bear Creek Reservoir is not explained by the hydraulic factors that have been used in developing empirical relationships based on large sets of lakes. The apparent absence of a relationship between retention and residence time in this reservoir is similar to what has been observed in other control regulation lakes. The lack of a predictive equation for the phosphorus retention value is not a handicap, however. The existing set of measured values is very strong and can be used to define a single characteristic value for phosphorus retention, which is about 40% in Bear Creek Reservoir.

The phosphorus retention value is used to derive the input concentration from the standard. With a phosphorus standard of 32 ug/L and a retention value of about 40%, the corresponding input concentration is 53 ug/L.[2]

Critical Flow Condition
Selection of the critical flow regime can be guided by the nature of the relationship, if any, between load and flow. A plot of annual values for total external load against annual inflow yields a strong linear relationship (Figure 3), which suggests that input concentration is essentially constant across a wide range of flow conditions. When input concentration is unaffected by flow, the threat to attainment should be no greater at high flow than at low flow. Consequently, there is no obvious rationale for selecting a critical flow condition.

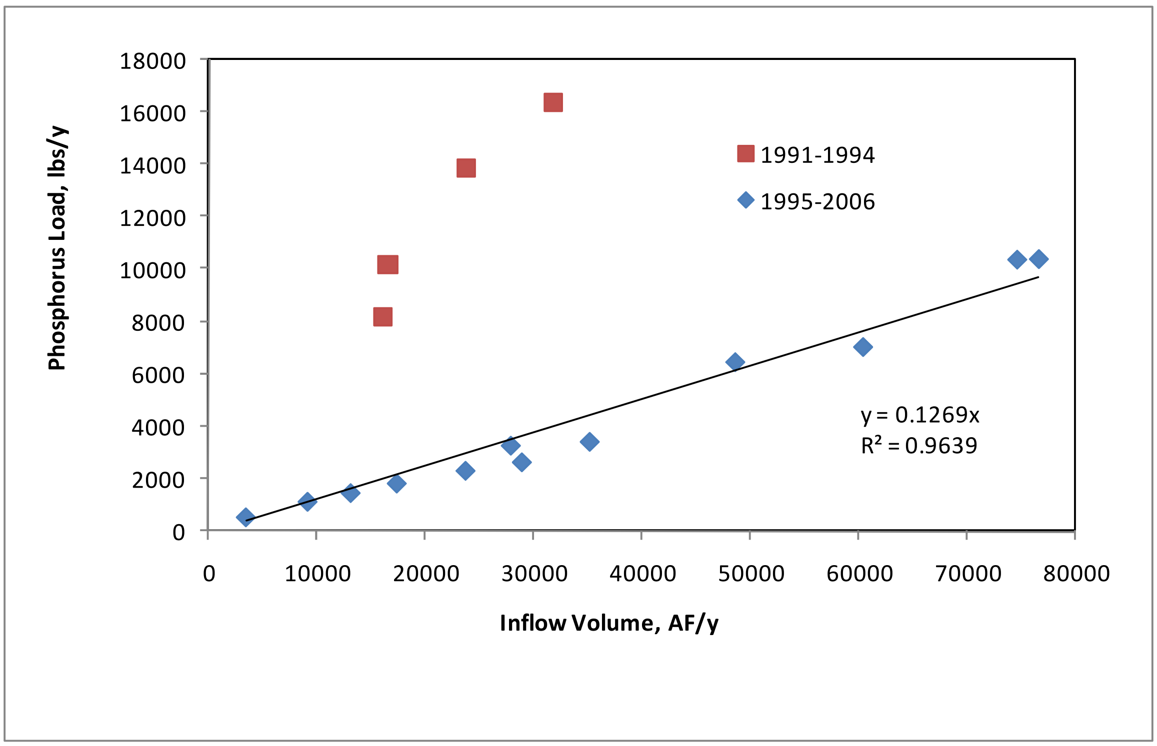

Figure 3. External load from all sources as a function of inflow volume to Bear Creek Reservoir, 1991-2006. A linear trend line is shown for 1995-2006; 1991-1994 are excluded from the line because phosphorus controls were not yet fully operational. The line is forced through the origin because there can be no external load when there is no inflow. The slope has units of lbs/AF and corresponds to a concentration of 47 ug/L.

[2] The input concentration is equal to the standard (32) divided by apparent retention (40%). An input concentration of 53 ug/L is slightly higher than the concentration in the notice (49 ug/L) because the retention value was revised upward in preparing documents for the Pre-Hearing Statement. The implicit assumption is that the input concentration, which is a flow-weighted annual average, is correlated with the in-lake concentration, which is a summer average in the mixed layer. This assumption cannot be tested with data from Bear Creek Reservoir as long as internal load remains a potent source or phosphorus.

Median annual inflow (28,891 AF/y; period of record, 1978-2006) is a logical choice for the critical flow condition when there is no compelling reason to select a low flow or a high flow scenario. Median flow is also the Division's flow of choice in development of TMDLs for streams that demonstrate no significant seasonal patterns in concentrations. There is, however, a caveat regarding internal phosphorus load. Selection of the median inflow is driven by expectations for external load, and it contains the tacit assumption that internal load will become negligible in the future.

Allowable Load Estimation

The allowable load of phosphorus from external sources is derived from the critical flow condition and the input concentration (53 ug/L) associated with attainment of the phosphorus standard. At the median inflow of 28,891 AF/y, an external load of 4127 lbs is consistent with attainment of the proposed nutrient standards. This determination of allowable load assumes that internal load becomes negligible in the future, which is a reasonable expectation when external loads are curtailed as they were for Bear Creek Reservoir.

Defining allowable load for a single, critical flow condition is correct procedure, but it seems to cause confusion among stakeholders. Confusion arises in part from a desire to interpret loads at flows other than the median. Logically, larger loads are expected at higher flows, and smaller loads are expected at lower flows. Loads at either extreme may be equally consistent with attainment of the standards, but neither is defined explicitly in the Control Regulation. Direct comparison of observed loads to the allowable load is simply not appropriate. Moreover, it is not necessary for regulatory purposes because there is no compliance requirement for annual loads. The allowable load provides a target for implementing controls (to the extent that they are necessary), and it is regarded as appropriate as long as the standards are being attained. Failure to attain the standard would be justification for reviewing the allowable load.

The interest in tracking changes in phosphorus yields from the watershed is not misplaced, but annual loads must be scaled for flow before they are useful for this purpose. Trends in phosphorus yield can be examined by plotting a time series for input concentration, which is simply the annual load divided by the annual flow. Because the input concentration for Bear Creek Reservoir seems to be constant across a wide range of flows, a trend for increasing input concentration would be a reason to evaluate the effectiveness of existing control measures.

Proposing an allowable load that is smaller than the existing wasteload allocation (5,255 lbs/y) is likely to cause consternation until some additional explanation is provided. Little is known about the technical rationale for determining the existing wasteload allocation. Moreover, the problem is exacerbated by the absence of information about other components of the TMAL.

Actual loads from point sources are much less than the present allocation (1543 lbs, or about 30% of the allocation, in 2006). Furthermore, input concentrations, which are based on actual loads from point and non-point sources, are routinely less than the 53 ug/L on which the allowable load estimate is based. The typical input concentration since 1996 has been almost 20% lower at 43 ug/L (Figure 4). Although the appropriateness of existing allocations is not the subject of the present technical review, it will be part of the process that would follow adoption of the proposed regulatory changes.

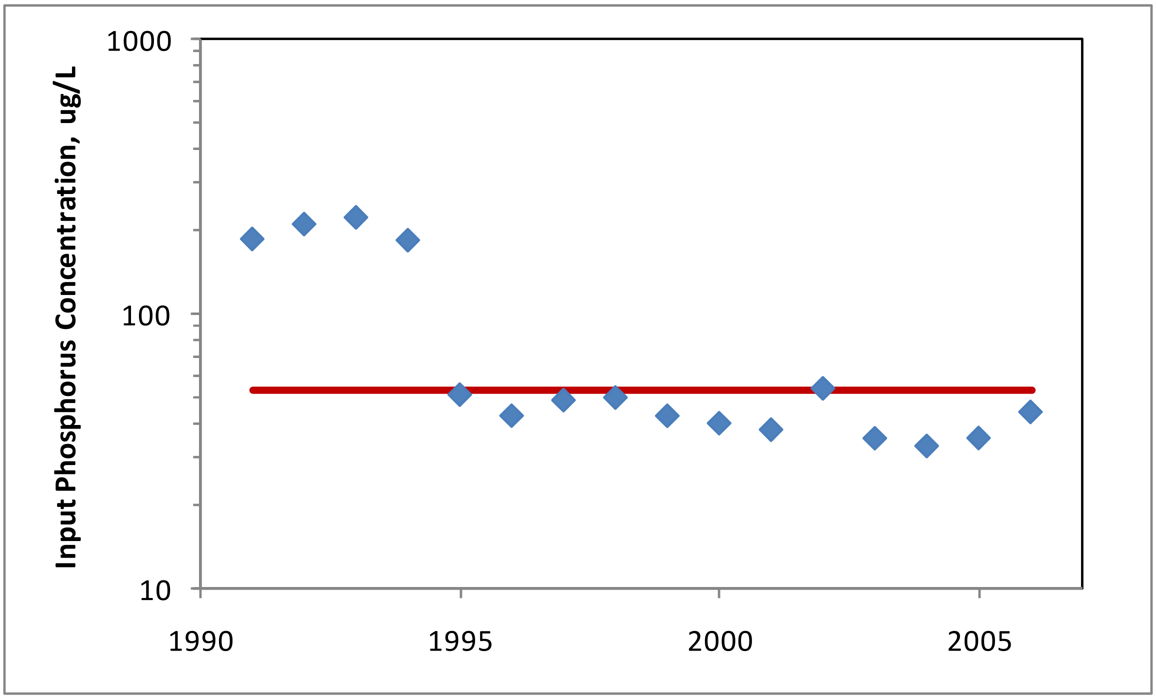

Figure 4. Time course of input phosphorus concentrations to Bear Creek Reservoir, 1991-2006. Point source controls were operational by the end of 1994. The horizontal line shows the concentration (53 ug/L) associated with the allowable load.

Caveat

The lake is not now in attainment of either the existing narrative standard or the proposed chlorophyll and phosphorus standards. However, attainment is expected when internal phosphorus load is exhausted because existing external loads appear to be consistent with the allowable load estimated for the reservoir. Internal load can be expected to dissipate over time, but the process may take many years. What should be done about non-attainment while internal load remains a potent factor?

The Division recommends a patient approach wherein the proposed standards are adopted with the expectation that internal load will dissipate over time. The alternative – of trying to offset internal load by imposing more severe restrictions on external sources – seems unnecessarily draconian and may not even be feasible. The internal load is not large relative to typical external loads, but it is disproportionately effective because it is delivered chiefly during the growing season. Moreover, it is delivered at a time when there may be very little inflow, and thus little external load. Consequently, it may be virtually impossible (or at least very expensive) to negate the effect of internal load by manipulating concentrations of the external sources.

The Division recommends adopting a temporary modification for the chlorophyll and phosphorus, to be applied until the internal load becomes negligible. It would be a type iii temporary modification because there is uncertainty about the standard; if internal load does not dissipate completely, the approach to development of standards may have to be changed. Furthermore, it is important to dispel any notion that external load could be manipulated to offset present internal load without imposing an unreasonable burden on dischargers.

Recommendations

1) Validate the original water quality goal of trophic status at the eutrophic-mesotrophic boundary by establishing appropriate numeric standards for chlorophyll and phosphorus. The Division believes the goal is achievable with existing external loads, but success depends ultimately on the assumption that internal load will dissipate over time.
2) *Regulation 38*: Adopt a chlorophyll standard of 10 ug/L to be assessed as the average concentration in the mixed layer during the summer (Jul-Sep). One exceedance is allowed in any five-year period. This standard represents the once-in-five-year exceedance threshold for a lake at the boundary between mesotrophic and eutrophic conditions.
3) *Regulation 38*: Adopt a phosphorus standard of 32 ug/L to be consistent with attainment of the chlorophyll standard proposed for Bear Creek Reservoir. The proposed phosphorus standard reflects the site-specific responsiveness of the resident algal community to phosphorus. The typical ratio of seasonal average chlorophyll to seasonal average phosphorus is 0.318.
4) *Regulation 38*: Adopt a temporary modification for existing conditions to expire 12/31/2014. The proposed standards are not currently attainable due to internal phosphorus release. The temporary modification allows time for internal load to dissipate.
5) *Regulation 74*: Adopt an allowable phosphorus load of 4127 lbs/y at the median inflow of 28,891 AF/y. This load scenario corresponds to an input concentration of 53 ug/L. The input concentration is discounted by phosphorus retention (40% retained) to yield an in-lake concentration of 32 ug/L.