Bear Creek Reservoir Site-Specific Standards

Introduction

Bear Creek Reservoir was constructed by the US Army Corps of Engineers (USACE) to provide flood-control for the Denver area. The reservoir began filling in 1979 and was completed in 1982. The reservoir itself is relatively small – 110 surface acres and 2000 acre-feet (AF) of storage at multi-purpose pool elevation. It is located within a park operated by the City of Lakewood and is a heavily used recreational amenity. Two tributaries – Bear Creek and Turkey Creek – drain most of the watershed for the reservoir. The Bear Creek basin, which comprises about 75% of the reservoir's drainage area, begins at the Continental Divide in the Mount Evans Wilderness Area. The Turkey Creek basin has its headwaters near Conifer at about 9000 ft and includes about 22% of the reservoir's drainage area.

The first concerted effort to evaluate water quality in Bear Creek Reservoir began with a Clean Lakes Study[1], which was carried out in 1988 and 1989. The study concluded that the reservoir was enriched with nutrients and supported excessive growth of algae. Algal abundance was excessive to the point of causing degradation of water quality and impairment of the use. The study recommended that limits be placed on the phosphorus supply to the reservoir in order to reduce algal abundance.

The findings and recommendations of the Clean Lakes study led to adoption of a site-specific narrative standard[2] in May 1992. The narrative standard provided the regulatory basis for development of Watershed Control Regulation No. 74, which was adopted in July 1992. The narrative standard recognized explicitly that the reservoir was too productive – too "green" due to excessive algal abundance – and that the level of productivity needed to be reduced. The control regulation set limits on point sources in order to control the phosphorus supply to the reservoir. Adoption of site-specific nutrient criteria placed Bear Creek, along with Dillon, Cherry Creek, and Chatfield reservoirs, in the forefront of efforts to prevent or reverse eutrophication in Colorado, and decades ahead of statewide efforts to develop nutrient criteria[3].

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[1] DRCOG. 1992. Bear Creek Reservoir Clean Lake Study. Denver Regional Council of Governments, Denver. 133p.

[2] "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 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."

[3] Although the Division developed proposals for *nutrient criteria*, the proposals were adopted as "interim numeric values" in Section 31.17.

The Commission's adoption of regulations to prevent further nutrient enrichment (eutrophication) in Bear Creek Reservoir was timely in view of the potential threats from development. Imposition of point source controls through the Control Regulation soon resulted in significant reductions of external phosphorus loads to the reservoir. However, the narrative standard did not provide a quantitative basis for deciding if the water quality goal had been achieved.

The Division conducted a technical review for the purpose of understanding the current trophic condition of the reservoir and the adequacy of existing regulations for supporting attainment of the narrative standard. The technical review, which included numerous presentations to stakeholders in 2008, recommended that the narrative be replaced with numeric standards for chlorophyll and phosphorus. No changes were recommended for the control regulation because more time was needed to develop revisions that would include the phosphorus allocations. The standards proposed for chlorophyll and phosphorus were adopted by the Commission in 2009. In 2011, after a lengthy review, EPA approved the chlorophyll standard, but disapproved the phosphorus standard, arguing that it was not sufficiently protective of the chlorophyll standard.

Following EPA's disapproval of the phosphorus standard, the Division developed a plan for resolving technical issues and presented the plan to the Commission at the December 2013 Temporary Modifications hearing. The plan involves analysis of data that have been obtained subsequent to the 2009 hearing, and it takes advantage of insights gained in developing a statewide approach to nutrients in preparation for the 2012 nutrients hearing. At its foundation, the plan remains true to the Commission's original intent of setting a water quality goal in terms of "trophic condition", which characterizes the abundance and productivity of algae. Specifically, the goal is to "bring the reservoir to a trophic status of mesotrophic to eutrophic"[4].

The lake does not meet the trophic condition goal now, and it has not met the goal for as long as studies have been conducted. Algal abundance is too high in most years, and this is a manifestation of a nutrient enrichment. Algal abundance will remain excessive until the nutrient supply is reduced sufficiently. Although the solution is superficially simple, successful implementation will depend on defining critical conditions and correctly identifying the nutrient source(s) responsible for excessive algal abundance.

In broad terms, the Division's primary aim is to propose revised numeric standards for chlorophyll and phosphorus that will be consistent with the Commission's original goal of shifting the trophic condition of Bear Creek Reservoir to the mesotrophic-eutrophic boundary. Development of revised standards is facilitated by having data from additional years of monitoring and by having an improved methodology for defining threshold concentrations. It will also be necessary to investigate in detail the reasons why the trophic condition goal has not been met.

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[4] As stated in section 74.10 of the control regulation.

Failure to attain the goal, despite having reduced nutrient loads significantly via point source controls, creates uncertainty about the basis for standards and their attainability. In the previous hearing, this uncertainty prompted the Division to propose, and the Commission to adopt, temporary modifications. Such a step may also be necessary in this hearing, but not without also proposing a plan for action to resolve the uncertainty.

A key element of the analysis will address the relative importance of nutrient sources, with particular attention to those sources contributing the most to excessive algal abundance in the summer months. The focus on summer months is appropriate because that is when algae have been most abundant historically, and it is necessary because that is the time when attainment is assessed. Ultimately, this part of the analysis will guide future actions by providing a better understanding of the extent to which the key nutrient sources are amenable to control.

Background on Trophic Condition

Colorado lakes exhibit a wide range of productivity, which has important implications not only for fisheries, but also for water quality. In most lakes, productivity, including growth and reproduction of fish populations, is supported ultimately by algae. Nutrient supplies enable the growth of algae, and it is the growth of algae that has potential to cause, directly and indirectly, water quality problems in lakes.

The relationships between nutrients and algal productivity, and between algal abundance and water quality, are continuous in the sense that they cover a broad spectrum of low to high productivity and good to bad water quality. To simplify characterization of lakes according to productivity, limnologists have developed a classification scheme with four categories each accompanied by a set of water quality generalizations (Table 1). The generalizations are given for perspective and should not be considered the defining factors for trophic condition; the best indicator of trophic condition is algal abundance (chlorophyll concentration).

Table 1. Trophic condition categories with fixed boundary concentrations for phosphorus and chlorophyll as defined by OECD[5]. Common water quality attributes for each trophic condition are shown in the final column.

Trophic Condition	Total Phosphorus, ug/L	Chlorophyll, ug/L	Common Water Quality Attributes
Oligotrophic	<10	<2.5	Low algal abundance, clear water, ample D.O.
Mesotrophic	10-35	2.5-8	Intermediate conditions of algal abundance, clarity and D.O.
Eutrophic	35-100	8-25	High algal abundance, turbid water, D.O. depletion in hypolimnion
Hypertrophic	>100	>25	Dense algae, light limitation, possible summer-kill conditions

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[5] OECD. 1982. Eutrophication of Waters: Monitoring, Assessment and Control. Organisation for Economic Co-operation and Development, Paris. 154 p.

The four categories characterize "trophic condition" across a spectrum of increasing algal abundance, beginning with oligotrophic. Oligotrophic lakes tend to be deep and, in Colorado, are generally associated with undeveloped watersheds, such as those at higher elevations. These lakes have low nutrient supplies, low algal abundance, and few, if any, water quality problems related to algae. Lakes with mid-range productivity ("mesotrophic") can support productive fisheries without risk of water quality problems; this is the target trophic condition that was used to develop the interim numeric values that were adopted for nutrients in Colorado's Cold Lakes.

More productive lakes can support more productive fisheries, up to a point. "Eutrophic" lakes tend to be shallower. They provide good support for warmwater fisheries and do not experience serious water quality problems related to algal abundance except at the high end of the productivity range. In slightly abbreviated form[6], eutrophic is the target trophic condition established to develop interim numeric values for Colorado's Warm Lakes. There is also a category of highly productive ("hypertrophic") lakes in which algal abundance is so high that serious water quality problems are the norm.

The primary water quality indicator of trophic condition is chlorophyll concentration, which is a measure of algal abundance. High chlorophyll concentrations are generally associated with a more productive lake. Nutrient concentrations also are indicative of trophic condition because the availability of nutrients places an upper bound on algal abundance. However, high nutrient concentrations cannot compel algae to grow; other factors may limit algal growth seasonally or consistently.

The relationship between nutrient concentrations and chlorophyll is strong in a general sense, but it also reflects considerable variability due to interactions with other limiting factors (e.g., light, temperature, grazing, or washout) to be considered in more detail later. The variability is important in two ways. First, algal abundance rarely reaches the potential expected on the basis of nutrient concentrations, in theory (e.g., 1 ug chlorophyll per ug phosphorus). Second, although typical nutrient concentration is a pretty good predictor of typical chlorophyll concentration, the variability among years is sufficient that phosphorus concentration, for example, would have to be set very low if the intent was to "guarantee" attainment of a chlorophyll standard in every year. Given the variability inherent in the relationship between nutrients and chlorophyll, it is more effective to consider attainment issues independently rather than as a dependent relationship.

The classification scheme sets arbitrary boundaries between the trophic conditions, but it is important to mention that these are based on what is typical for a lake. Chlorophyll concentrations vary from year to year, and the range of concentrations may cross one or more boundaries. Nevertheless, unless the nutrient supply is fundamentally altered (e.g., increased

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[6] The upper bound for chlorophyll in eutrophic lakes is 25 ug/L according to the OECD classification scheme, but the upper bound set for Warm lakes in Colorado is 20 ug/L. Setting a threshold lower than the upper bound of eutrophic was necessary to avoid water quality problems.

by additional wastewater discharge), trophic condition is stable and best classified on the basis of central tendency.

Characterization of Trophic Condition in Bear Creek Reservoir

Chlorophyll and nutrient concentrations have been measured in Bear Creek Reservoir since 1987. The data set is one of the best available from Colorado lakes. As such, there is a firm basis for characterizing trophic condition based on chlorophyll concentration (Figure 1). Bear Creek Reservoir was clearly very productive when the first studies were undertaken, and it has remained so despite significant intervention to control point sources of nutrients. The typical condition for the lake is on the boundary between eutrophic and hypertrophic.
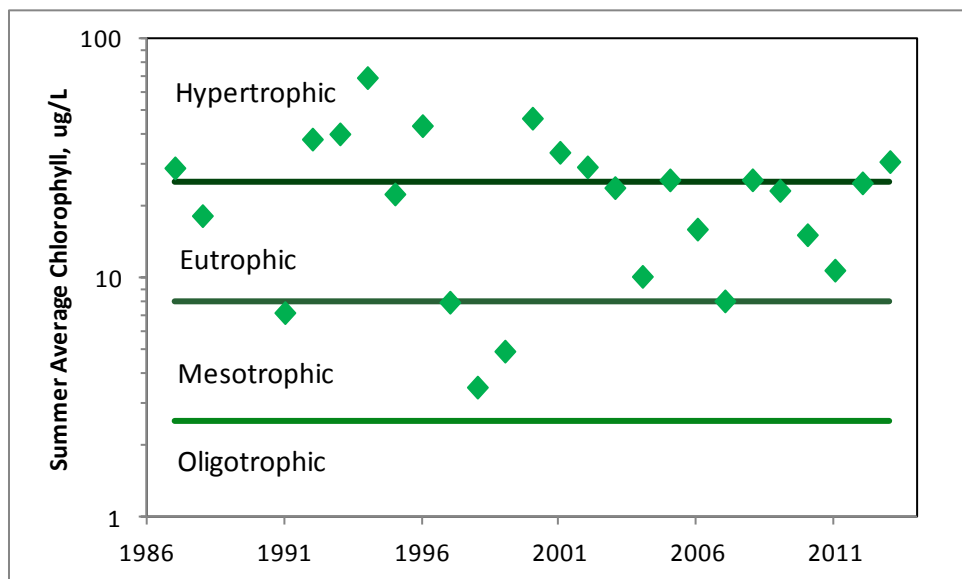

Figure 1. Trophic condition in Bear Creek Reservoir based on average chlorophyll concentration during the summer (Jul-Sep), 1987-2013. The average for 2013 excludes the last sampling date in September, which was influenced by a significant flood event.

Highly productive conditions in the reservoir and the attendant water quality problems stimulated regulatory efforts to reduce the level of algal abundance. The cornerstone of the effort was captured in a narrative standard that sought to shift "reservoir trophic state from a eutrophic and hypertrophic condition to a eutrophic and mesotrophic condition." The control regulation launched the effort by setting limits for phosphorus in wastewater effluent. Imposition of point source controls was quite successful in reducing the phosphorus concentrations reaching the reservoir, but less successful in reducing the average summer phosphorus concentrations that support algal growth at the time attainment of the standard is assessed (more about this later in the context of phosphorus recycling).

It is plain that the trophic condition of Bear Creek Reservoir has not yet been shifted to the goal set by the Commission even though point source control measures have been in place for 20 years. In fact, it would be hard to demonstrate that there has been any substantive change

in trophic condition. The failure of point source controls to shift trophic condition raises a question about the feasibility of attaining the goal for the reservoir.

There are three elements to the feasibility issue – defining the thresholds that characterize attainment of the target trophic condition, assessing prospects for controlling the main nutrient sources, and determining if eutrophication is reversible in Bear Creek Reservoir. Consideration of the first two elements will benefit from additional data and a new methodological approach. The third element is largely theoretical and based on recent scientific literature.

Attainment Thresholds for the Target Trophic Condition

In 1992, the Commission established "mesotrophic to eutrophic" as the target trophic condition for Bear Creek Reservoir. The target was described in a narrative standard that applied to the reservoir until numeric standards were adopted in 2009. Adoption of numeric standards was an effort to facilitate assessment the Commission's original intent regarding the target trophic condition.

After the Commission adopted numeric standards for chlorophyll and phosphorus, EPA disapproved the phosphorus standard. Disapproval was based on a number of factors, including the method by which the phosphorus number was derived. Although the chlorophyll number was approved by EPA, the Division chose to review numeric values for both chlorophyll and phosphorus in order to ensure that both proposals for new thresholds will be consistent with the Commission's original intent. It is also an opportunity to incorporate a substantial amount of new data and to apply a methodology developed for the nutrient rulemaking hearing in 2012. It is important to emphasize that the proposed chlorophyll and phosphorus standards represent a package that is internally consistent; one cannot be changed independently of the other.

The methodology developed by the Division for nutrient criteria in Colorado defines attainment thresholds with linkages and translators that are tied to the target trophic condition, which is the mesotrophic-eutrophic boundary. The chlorophyll concentration at this boundary – 8 ug/L – defines typical condition, but does not locate the corresponding phosphorus concentration or define an attainment threshold for either parameter. Both tasks can be accomplished entirely with data from Bear Creek Reservoir.

Linking Phosphorus to Chlorophyll at the Target Trophic Condition

Algae cannot grow without a supply of phosphorus, and the concentration of phosphorus often imposes the primary limitation on algal abundance in a lake. The concept of phosphorus limitation was central to development of the Bear Creek Watershed Control Regulation (Regulation No. 74), and it has guided development of the phosphorus standard.

General relationships between chlorophyll and phosphorus have been developed for many different groupings of lakes[7], and we have done the same for Colorado lakes (Figure 2). Many papers have been published explaining aspects of the variability in those relationships. They underscore the complexity of the issue and make it plain that variability in the relationship is a feature common to most, if not all, lakes.

The figure shows a scatter plot with the fitted equation:
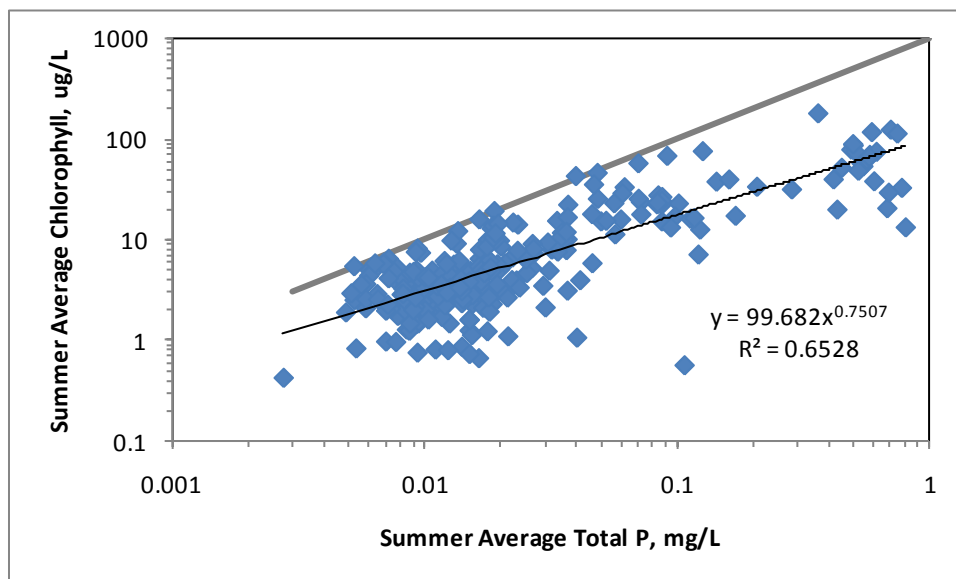
$$y = 99.682x^{0.7507}$$
$$R^2 = 0.6528$$

Figure 2. Relationship between summer average concentrations for chlorophyll and total phosphorus for Colorado lakes. Each point represents both constituents from one summer in one lake (i.e., one lake-year). The thick, solid line at the top indicates the theoretical limit (1:1) where algal abundance has reached the capacity defined by the corresponding phosphorus concentration. A power function is fitted to the data (thin, solid line), and the equation is inset at the lower right of the figure.

The relationship between chlorophyll and phosphorus shows considerable variability in Bear Creek Reservoir (Figure 3), as it does in most lakes. The slope of the relationship is essentially the same for the entire period of record (1987-2013) and the recent record (2000-2013) when aerators have assured destratification by thorough mixing. Furthermore, the slope is almost identical to that derived for lakes throughout Colorado (Figure 2). However, algal abundance has become more responsive to phosphorus (about 18% larger coefficient) in recent years, apparently due to mixing. Assuming that mixing continues indefinitely into the future (i.e., that the relationship shown in Figure 3 for 2000-2013 applies), the phosphorus concentration corresponding to the target chlorophyll value (8 ug/L) would be 16 ug/L. If mixing is discontinued, the relationship is likely to be different and perhaps more like the one characterizing all years (as shown in Figure 3); if so, the corresponding phosphorus concentration would be about 19 ug/L.

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[7] Chow-Fraser, P, DO Trew, D Findlay, and M Stainton. 1994. A test of hypotheses to explain the sigmoidal relationship between total phosphorus and chlorophyll a concentrations in Canadian lakes. Canadian Journal of Fisheries and Aquatic Science 51: 2052-2065.
Dillon, PJ and FH Rigler. 1974. The phosphorus-chlorophyll relationship in lakes. Limnology and Oceanography 19: 767-773.
Jones, JR and RW Bachmann. 1976. Prediction of phosphorus and chlorophyll levels in lakes. Journal of the Water Pollution Control Federation 48(9): 2176-2182.

The plot shows Summer Average Chlorophyll (ug/L) on the y-axis (log scale from 1 to 100) versus Summer Average Total Phosphorus, mg/L on the x-axis (log scale from 0.02 to 0.2), with two fitted equations:

$$y = 186.96x^{0.7618}$$
$$R^2 = 0.3351$$

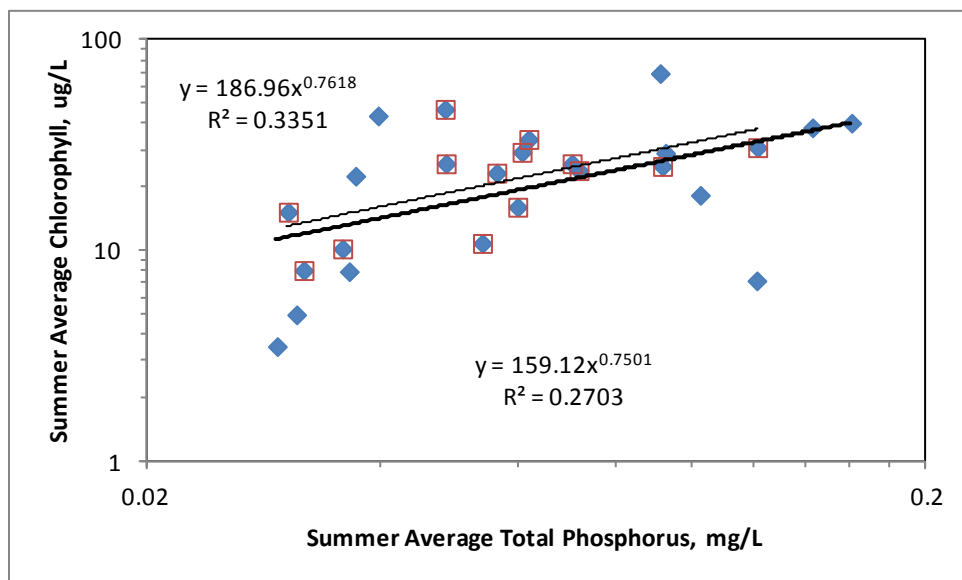$$y = 159.12x^{0.7501}$$
$$R^2 = 0.2703$$

Figure 3. Relationship between average concentrations of chlorophyll and phosphorus for the summer months of 1987-2013. The lower trend line includes all years (diamonds), and the upper trend line applies to the subset of recent years (2000-2013) when the lake was destratified (box enclosing diamond).

Assuming that mixing affects the relationship between chlorophyll and phosphorus creates some uncertainty regarding the development of standards. As long as the aerators continue to be operated as they have been since 2000, it is reasonable to expect that the relationship between chlorophyll and phosphorus will remain stable. If the aerators are not operated and the lake is allowed to stratify, the response of the algae to phosphorus is likely to change.

Defining Attainment Thresholds

Application of the target trophic condition concept to Bear Creek Reservoir makes it possible to define the typical concentrations of chlorophyll and phosphorus that support the use, but it does not define the attainment thresholds, which incorporate the allowable frequency of exceedance (once in five years). Locating the attainment thresholds as a function of typical values is accomplished with translator functions. These translators are based on the observed frequency distributions[8] of summer average concentrations in Bear Creek Reservoir.

Probability plots of average summer concentrations of chlorophyll (Figure 4) and phosphorus (Figure 5) show that both conform to lognormal distributions. The analysis shows the parameters of each distribution, but the historical median is not consistent with target trophic condition. The distribution can be "translated" by substituting the target trophic

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[8] Using an observed frequency distribution departs somewhat from the statewide methodology where relationships between 50th (i.e., typical) and 80th percentile (once in five year exceedance frequency) concentrations were derived from a set of well-studied lakes. However, the concept is consistent and the use of a frequency distribution makes it possible to rely entirely on data from Bear Creek Reservoir.

condition for the historical median, if we assume that the variance is unchanged[9]. To illustrate, the general equation for the 80th percentile of the distribution of chlorophyll values is shown below; it is based on the mean (μ) and the standard deviation (σ) of the log-transformed values and the 80th percentile of the standard normal distribution ($z_{0.80}$). It is followed by the same equation with substitutions for the parameters of the chlorophyll distribution shown in Figure 4. The final equation substitutes the target median of 8 ug/L (the natural log of 8 is 2.079) completes the translation.

$$Chl_{0.80} = EXP(\mu + \sigma * z_{0.80})$$

$$Chl_{0.80} = EXP(3.036 + 0.5058 * 0.8416)$$

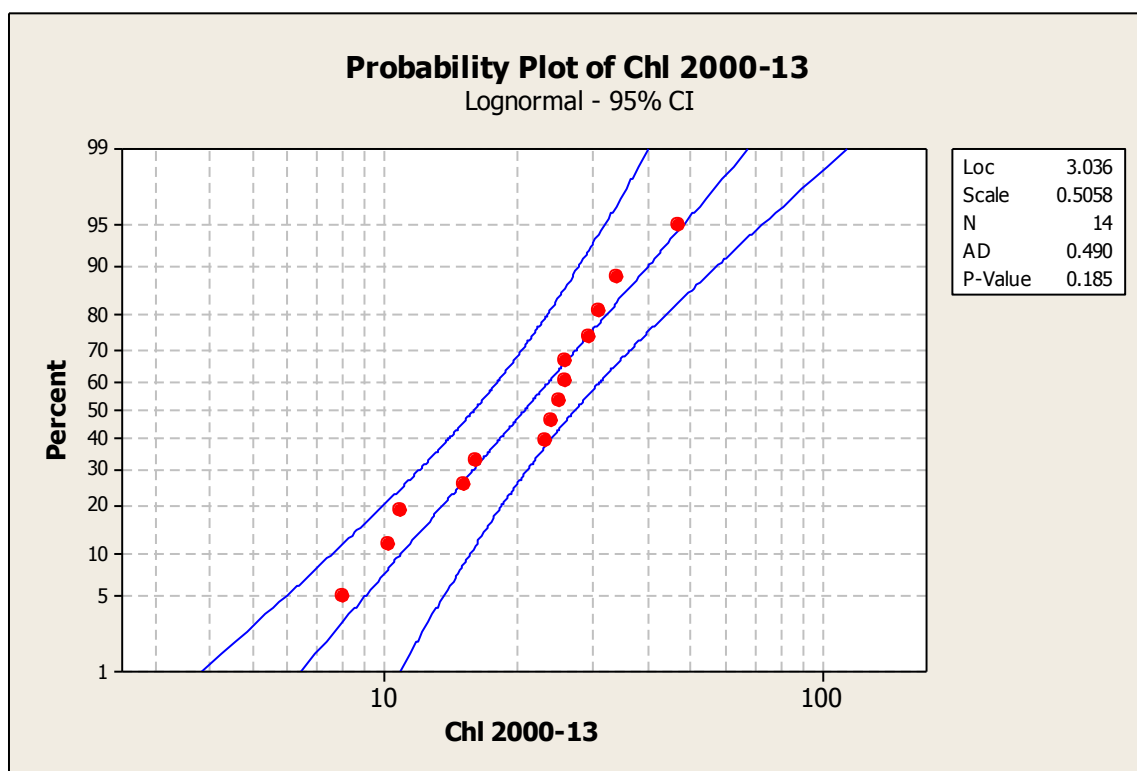$$Chl_{0.80} = EXP(2.079 + 0.5058 * 0.8416)$$

Figure 4. Probability plot of average summer concentrations of chlorophyll, 2000-2013. (from Minitab)

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[9] The assumption is necessary because the variance tends to be proportional to the mean in positively skewed distributions (e.g., lognormal). Precedent for the translation is found in the Biotic Ligand Model.
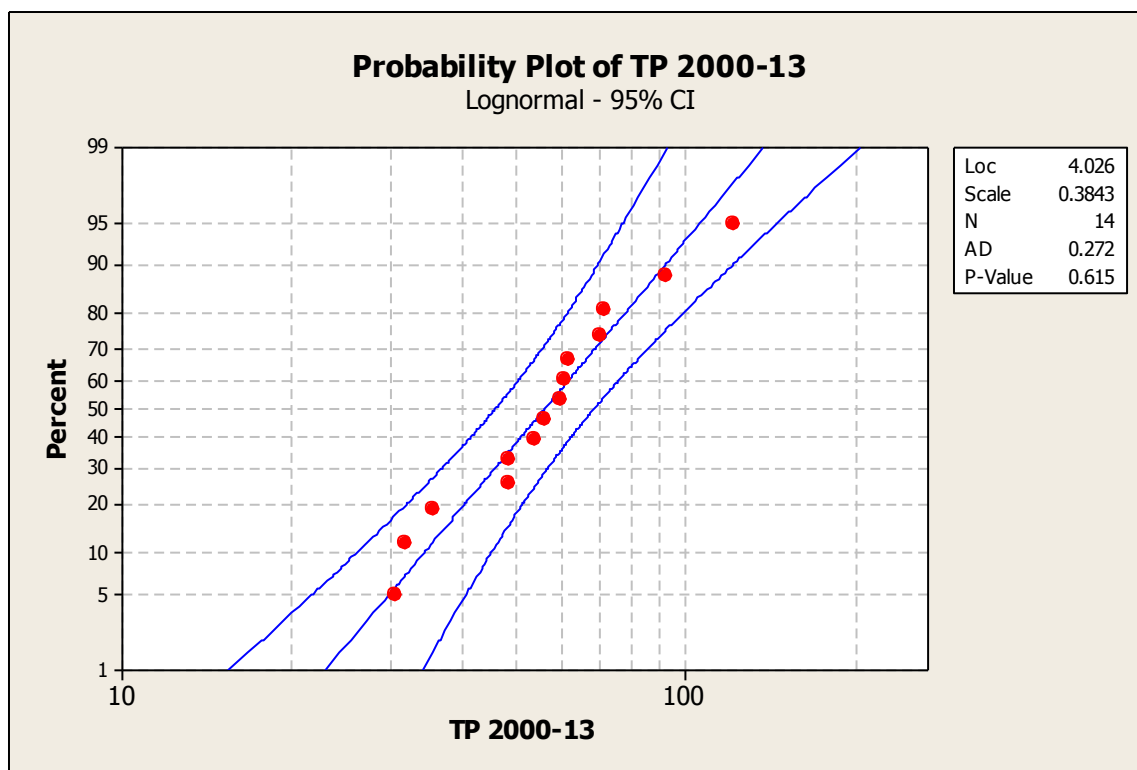
Figure 5. Probability plot of average summer concentrations of total phosphorus, 2000-2013. (from Minitab)

After translating the chlorophyll distribution so that the median is 8 ug/L, the attainment threshold (80th percentile) would be 12.2 ug/L. Applying the comparable translation to the phosphorus distribution yields an attainment threshold of 22 ug/L. Both numbers differ from those adopted previously, in large part because additional data have expanded the basis for defining thresholds under current operating conditions. Once again, however, the caveat about mixing applies. These attainment thresholds characterize expectations with aerators operating as they have in the past; the magnitude would be uncertain if aerators were shut off.

Implementation of Standards

The Division is not proposing any change to the duration and frequency elements of the standards. The phosphorus and chlorophyll standards are defined as seasonal averages. Samples are to be collected at a site in deep water near the dam and should be representative of conditions in the mixed layer. Past monitoring has included 5 or 6 samples during the summer months (July, August, and September), and it is anticipated that the same level of effort will be applied in the future. For assessment, the average (arithmetic mean) is calculated for the summer samples in each year. The standard is considered to be attained as long as summer average concentrations do not exceed the standard more than once in five years on average.

The chlorophyll and phosphorus standards are considered to be independently applicable. That is, impairment can be determined with either parameter without confirmation by the

other parameter. The parameters are linked biologically because algae require phosphorus to grow, but the linkage is "noisy" in a statistical sense because phosphorus cannot compel algae to grow (i.e., other limiting factors complicate the relationship). Independent applicability establishes a more sensitive basis for assessing departures from the target trophic condition, and it is a practical way to adapt regulation to a complex natural relationship where neither constituent is toxic (at least not at the target levels).

Attaining Target Trophic Condition

Bear Creek Reservoir is more productive than the target trophic condition (Figure 6). Over the last decade, trophic condition has been firmly within the eutrophic range and probably closer to the upper end. When the data are re-cast in terms of attainment, the benefits of independent applicability are evident (Figure 7). If the phosphorus data were used only to confirm a result based on chlorophyll, there would be seven years in which the lake might seem to be in attainment. Yet, such a conclusion would be contrary to the trophic state characterization presented in Figure 6.
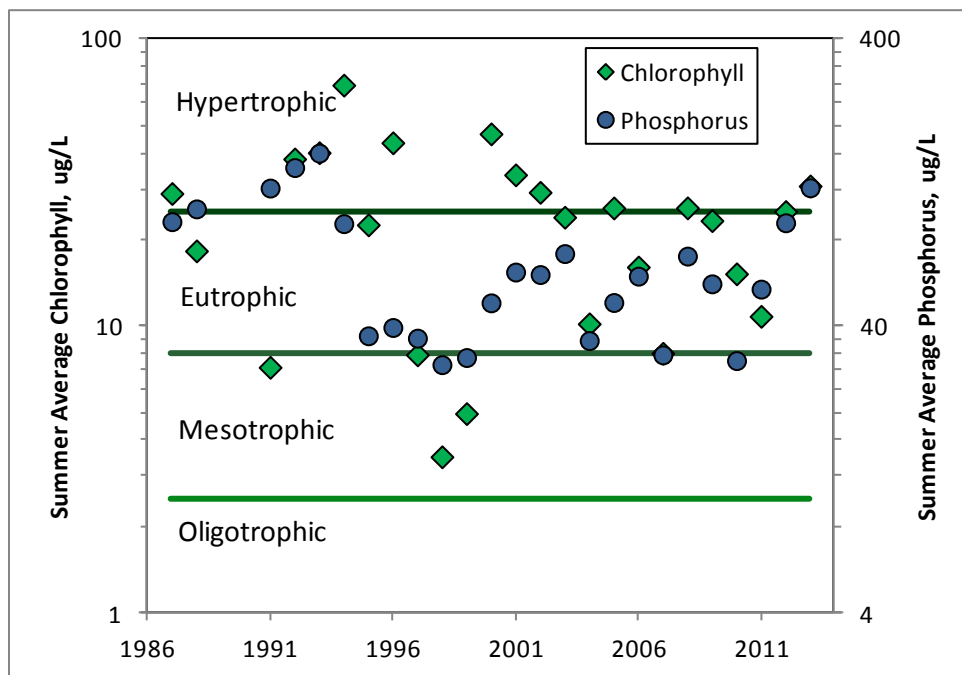

Figure 6. Average chlorophyll and phosphorus concentrations in Bear Creek Reservoir during the summer (Jul-Sep), 1987-2013. Horizontal lines indicate boundaries for trophic condition.
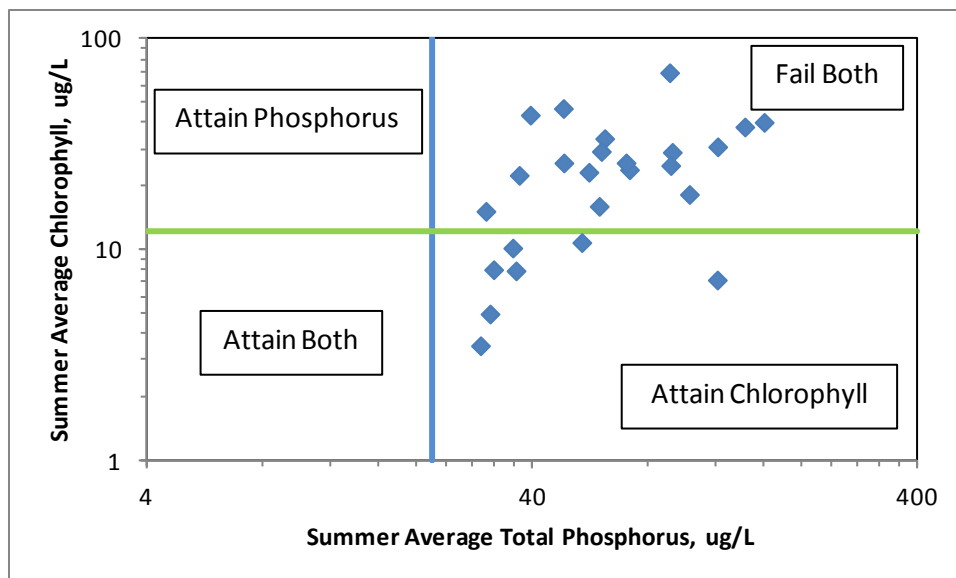
Figure 7. Attainment characterization with independent applicability. Each point shows paired summer averages for chlorophyll and phosphorus for the period of record (1987-2013). The vertical line (proposed phosphorus standard) and the horizontal line (proposed chlorophyll standard) divide the region into quadrants with different attainment conditions.

Phosphorus concentrations consistently have been too high for the target trophic condition and too high to attain the standard. Prospects for attaining the target trophic condition in the future depend largely on successful reduction of the phosphorus sources that support the development of algal abundance during the summer. A detailed treatment of phosphorus sources is presented in the attached Appendix; a brief synopsis is given here.

Most of the external phosphorus load to the reservoir is from anthropogenic sources. This remains true even though point source loads have been reduced significantly. Phosphorus concentrations in effluent, which were probably 4-5 mg/L before point source controls were imposed, had been reduced to about 0.25 mg/L by 2010. Thus, point source loads are now about 5 or 10% of what they were in the early 1990s before controls were imposed. Septic systems (OWTS) now appear to be about twice as large a source as point sources are. Opportunities clearly remain for additional control of anthropogenic sources, but it is doubtful that imposing more controls on external sources would yield any benefit today because of the dominant role currently played by internal recycling of phosphorus.

Internal recycling of phosphorus is the reason that previous point source controls have resulted in no apparent reduction in the productivity of the lake. The origin of phosphorus that is being recycled today is the external load from previous years, and this legacy effect drives algal growth in a way that is largely independent of current external loads. Recycling becomes increasingly important for algal growth as external loads decrease (i.e., as inflows are reduced). In fact, it is the reason that low flow (or no flow) conditions yield the highest phosphorus and chlorophyll concentrations (Figure 8). Inflows do not contain enough phosphorus to elevate concentrations to the levels that occur in the lake; only recycling can do that.
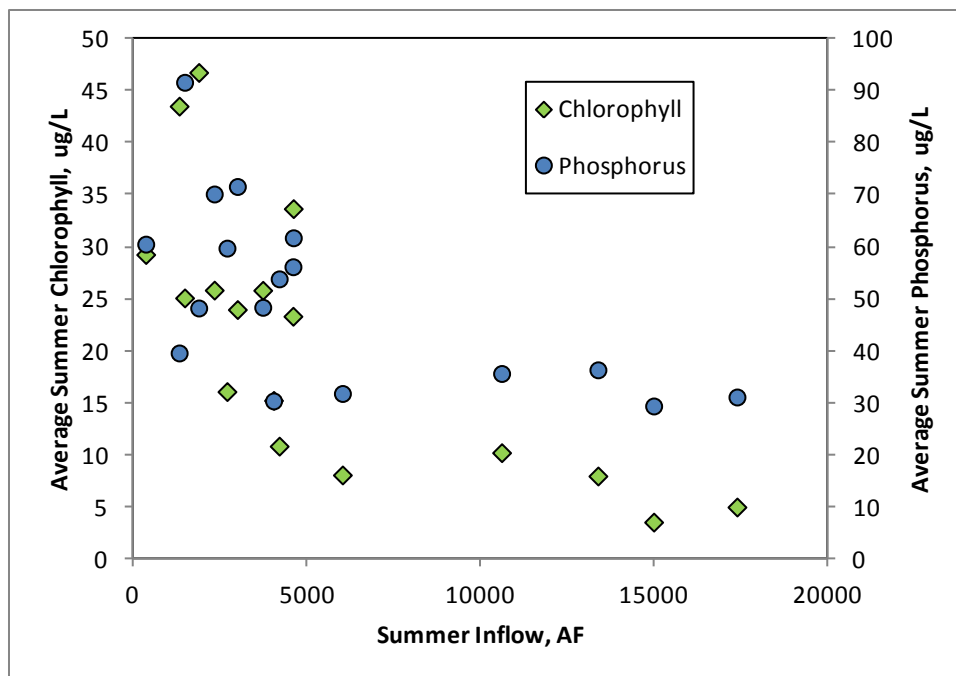
Figure 8. Average summer concentrations of chlorophyll and phosphorus in Bear Creek Reservoir as a function of total summer inflow, 1996-2012.

Identifying the lowest inflow as the critical condition is important for understanding dynamics, but does little to advance the understanding of prospects for attaining the target trophic condition in Bear Creek Reservoir. However, it does place the focus squarely on internal recycling as the problem that must be resolved before it is clear what additional steps, if any, are required for attaining chlorophyll and phosphorus standards. Prospects for success depend entirely on the persistence of recycling in the years to come, but it is nevertheless worth considering what trophic conditions to expect if internal recycling is eliminated.

We are making predictions about a future in which recycling ceases to be an important source of phosphorus. There will still be external load, some portion of which will be deposited and retained in the sediment. Firm estimates of phosphorus retention are difficult to make while recycling remains important. Moreover, it is not clear to what extent aeration alters the potential for retention. However, it is possible to estimate how much retention would be required to reduce typical inflow concentrations to the concentration of the standard. The typical inflow concentrations (flow-weighted means) are about 40 ug/L, which implies that retention would have to be about 50% to meet the proposed standard. Retention on this scale is not unusual in reservoirs, but it would be speculative to say that it could happen in Bear Creek Reservoir.

Sources of Uncertainty

The site-specific standards proposed for Bear Creek Reservoir are derived from existing conditions, but are not intended as ambient-based standards. Instead, relationships and

distributions defined with existing conditions are used to forecast standards protective of improved water quality. The concept is sound, but it introduces uncertainty.

The distributions of chlorophyll and phosphorus concentrations and the linkage between chlorophyll and phosphorus have been characterized on the basis of historical data. While this represents a reasonable characterization, it comes with a disclaimer familiar to investors: "Past performance does not guarantee future results." A few examples will give a sense of the implications for magnitude and variance.

Variability in phosphorus and chlorophyll concentrations may be different with and without aeration. For example, the consistent mixing provided by aerators might decrease variance in concentrations. For much of the monitoring record, especially for the period following imposition of point source controls, aerators have been in operation. Will those data provide a realistic estimate of variance if aeration were to be stopped?

The linkage between chlorophyll and phosphorus is based on a long data record that spans a wide range of concentrations. This is beneficial from a statistical perspective, but contains the implicit assumption that the responsiveness of the algal community to phosphorus supply is a characteristic of the reservoir. Will responsiveness, and thus the chlorophyll-phosphorus linkage, be altered if the trophic condition is shifted significantly?

The most likely pathway for altering trophic condition is to curtail or eliminate internal recycling. A change of this nature would reduce the phosphorus supply, but might also alter the availability of the remaining phosphorus. Phosphorus released from lake sediments tends to be almost entirely dissolved and available, whereas phosphorus from external sources tends to be less available. Will a reduction in internal recycling affect the responsiveness of the algae in a manner that would change the chlorophyll-phosphorus linkage?

The proposed standards assume that internal recycling can be reduced or eliminated, but there is no assurance that the assumption is valid. If it is true, will additional control measures be needed? If it is not true, what trophic condition is feasible?

The goal for trophic condition in Bear Creek Reservoir is more ambitious than anyone realized at the time it was proposed. Serious efforts have been made to achieve the goal, and the results of those efforts have been documented through persistent monitoring. It is fair to say that there is an undesirable level of uncertainty regarding the attainability of the goal. That same uncertainty extends to attainability of the proposed standards, but is not the sole source of uncertainty. The threshold values for both chlorophyll and phosphorus have additional uncertainty because existing conditions have been used to extrapolate values defining a trophic condition that does not exist today. Given the unusual amount of uncertainty, albeit largely unavoidable, it is appropriate to propose temporary modifications to be in effect until plans to resolve the uncertainty have been carried out.

Plan to Resolve Uncertainty

At the previous hearing, the Commission adopted temporary modifications for the chlorophyll and phosphorus standards. EPA disapproved both. In retrospect, there were two weaknesses in the Division's approach to the question of uncertainty about the standards. The first was a vague description of that uncertainty, and the second was in having only a passive approach to resolving the uncertainty. We believe that there is now a solid technical basis for characterizing the sources of uncertainty as outlined in the preceding section. In addition, the Division is now recommending an active approach for resolving uncertainty.

The plan for resolving uncertainty involves three elements – diminishing the influence of recycling under present conditions, investigating the feasibility of phosphorus inactivation strategies, and reaching a conclusion about the reversibility of eutrophication in Bear Creek Reservoir. Before describing the elements of the plan, it is important to emphasize that any action on the plan requires coordination with and participation of stakeholders. The Bear Creek Watershed Association has been the key stakeholder group in the past, and the Division anticipates the association will continue to play a key role in working to improve water quality in Bear Creek Reservoir.

Internal recycling does not appear to have diminished in the years since point source controls were imposed even though external loads were reduced significantly. It was originally thought that aeration might be helpful for reducing internal recycling by making chemical conditions less favorable for phosphorus release. At the time (1992), the proposal was logical, but it has become clear that the strategy has not worked in Bear Creek Reservoir; the technical literature is now full of similar observations (e.g., Cooke et al. 2005). What benefits, other than saving operational costs, might be had by ceasing aeration?

If Bear Creek Reservoir is allowed to stratify, as it did before aerators were installed, recycled phosphorus would be trapped in the hypolimnion for most of the summer. Recycled phosphorus would thus be unavailable for algal growth as long as stratification persisted. At the same time, there would be some settling of algal cells that would take chlorophyll and phosphorus out of the mixed layer. The net result would be lower concentrations of chlorophyll and phosphorus in the mixed layer during most of the summer. Of course, when stratification breaks down in the fall – probably during September – the phosphorus-enriched waters of the hypolimnion would be mixed throughout the water column, which would stimulate algal growth. One other advantage of allowing stratification to occur is that the colder temperatures in the hypolimnion could slow recycling of phosphorus.

The hope is that allowing the lake to stratify would diminish the importance of recycling under present conditions. How much and for how long cannot be specified with certainty. Nevertheless, it is an action that has little downside risk for the trophic state of the reservoir, and it can be ended at any time.

The second element of the plan involves consideration of strategies that might bind some of the phosphorus in the sediment in a way that would make it unavailable for recycling. Careful investigation of these strategies is warranted because it involves the addition of chemicals

(e.g., alum or a patented product like "Phoslock") and would require a discharge permit. Nevertheless, it would be worth considering in this case because external loads have already been reduced significantly. If this kind of intervention is successful in curtailing phosphorus recycling, it would remove uncertainty about the feasibility of attaining the target trophic state. At that point, it would be reasonable to consider what additional external control measures, if any, would be needed to attain the target trophic condition.

The first two elements set up consideration of the third element, which concerns the reversibility of eutrophication in Bear Creek Reservoir. Lakes in which eutrophication reversal has failed are sufficiently common to have given rise to a theoretical explanation involving alternative stable states[10]. The gist of the theory is that the supply of phosphorus in the sediment is sufficient to sustain recycling for many years. Reducing external load (as has already happened in Bear Creek Reservoir) does not have any practical benefit in terms of altering trophic condition in these lakes.

Recommendations

1) Adopt the following standards
    a. Chlorophyll – 12.2 ug/L
    b. Total phosphorus – 22.2 ug/L
    c. Assess as summer average concentration based on at least three samples representative of the mixed layer
    d. Allow one exceedance in five years on average
2) Adopt temporary modifications for both standards
    a. Basis: uncertainty about the underlying standards
    b. Set expiration for 2020

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[10] Carpenter et al. 1999. Management of eutrophication for lakes subject to potentially irreversible change. Ecological Applications 9(3): 751-771.
Carpenter. 2005. Eutrophication of aquatic ecosystems: Bistability and soil phosphorus. PNAS 102(29): 10002-10005.
Scheffer and van Nes. 2007. Shallow lakes theory revisited: Various alternative regimes driven by climate, nutrients, depth, and lake size. Hydrobiologia 585: 455-466.

Appendix: Sources of Phosphorus

Bear Creek Reservoir receives phosphorus from its watershed and, to a lesser extent, from direct precipitation. Phosphorus exported from the watershed includes a natural, or background, component that is supplemented with phosphorus of anthropogenic origin. The anthropogenic component is comprised of point sources and nonpoint sources that reflect population growth and development.

In addition to the external phosphorus sources, there is seasonal recycling of phosphorus previously deposited in the sediment of the lake. Internal release of phosphorus augments the external supply, and the amount and timing of the internal release has a large impact on trophic condition. Although the internal release is not fundamentally a new source of phosphorus, the methods for controlling it are completely different than those that can be applied to external sources. Moreover, internal release may not be responsive to reduction of external phosphorus load.

Assessing the relative importance of background, anthropogenic, and recycled phosphorus will help guide decisions about what can or should be done to shift Bear Creek Reservoir closer to the water quality goal, which is the boundary between mesotrophic and eutrophic conditions. Each of the three major phosphorus sources is considered on the basis of the very extensive data set that has been assembled by the Bear Creek Watershed Association (BCWA). The data record spans many years and includes many sites throughout the watershed and in the reservoir. The Division's intent is to develop the technical basis for understanding how trophic condition might be altered by manipulating phosphorus contributions from one or more of the identified sources.

In the following analysis, we develop an understanding of phosphorus sources and their relative importance from two perspectives. The first is to predict the contributions based on the best available information; these predictions represent the export of phosphorus expected from each source. The second perspective involves estimates of the load delivered to the reservoir based on observed flows and concentrations; these are estimates of actual load. Anticipating that the two approaches may not agree perfectly, we expect to reconcile differences and reach conclusions about relative importance.

Predicted Contributions

Background Phosphorus

Separating the background phosphorus contribution from anthropogenic sources establishes the nutrient supply that would have been available to sustain algal growth in the absence of development. The purpose is to provide context for the role of development. However, the

task of isolating the background contribution is hampered to some extent because development preceded construction of the reservoir

The background phosphorus contribution is affected by local conditions including geology, hydrology, and vegetation. In the Bear Creek watershed, these factors vary considerably across an elevation gradient of more than 8,000 ft. In addition, the landscape, especially at lower elevations, has been altered by development. Nevertheless, an estimate can be derived with phosphorus concentrations from the BCWA monitoring program and hydrologic data from USGS gages.

Phosphorus concentrations are low in Bear Creek at sites in or near the National Forest boundary that are representative of background conditions. There are no comparable sites at lower elevation. Even those sites in areas with little development have markedly higher phosphorus concentrations than background (Table 2). While it may be reasonable to assume that background concentrations may be higher at low elevations in the watershed, it is not possible at present to separate low elevation background from anthropogenic contributions related to development. Consequently, we will apply one background concentration – 13 ug/L – throughout the watershed.

Table 2. Flow-weighted mean concentrations of phosphorus in sites selected for characterization of background phosphorus yields in the Bear Creek Reservoir watershed. Low development sites in the lower basin of Bear Creek are included for comparison.

Site	Type	Approx. Elevation, ft	Area, sq mi	Total P, ug/L
Below Summit Lake (site 38)	Background, high elevation	12,800		8.9
Abv Singing River Ranch (sites 1a & 58)	Background, high elevation	7,650		12.9
Vance Creek (site 25)	Background, high elevation	7,800		16.9
Upper Bear Creek Basin	**Background**		**106**	**13**
North Turkey Creek (site 19)	Low Development, low elevation	8,000		28.8
Cub Creek (site 35)	Low Development, low elevation	8,050		32.6
Lower Basin	**Low Development**		**130**	**30**

Phosphorus concentrations are paired with flow to determine phosphorus export from the watershed. USGS gages in the watershed (Table 3) are used to derive annual runoff values (Table 4). Runoff varies with elevation, and the effect of elevation can be can be incorporated by dividing the Bear Creek basin into upper and lower sections at the Evergreen gage (USGS 06710385). The upper Bear Creek basin includes about 60% of the area drained by Bear Creek above the reservoir. There is little consumptive use in this region and no transfer of flow out of the basin. Runoff values from this location will be used in conjunction with the background concentration of 13 ug/L to calculate annual phosphorus export from the watershed above Evergreen Lake.

Table 3. Gaging stations with daily flow records within the study period. The full period of record is available on CDSS. Gage 06710605 has been operated seasonally since 2009.

USGS Gage	Location	Area, sq mi	Period of Record
06710385	Bear Cr abv Evergreen	103	1984-2014
06710500	Bear Creek at Morrison	164	1900-2014
06710605	Bear Creek abv Bear Cr Lake nr Morrison	176	1986-2014
06710992	Turkey Creek nr Indian Hills	45.9	2001-2006
06710995	Turkey Creek nr mouth of Canyon	47.4	1998-2001
06711040	Turkey Creek abv Bear Creek Lake nr Morrison	50.6	1987-1989

Table 4. Annual (calendar year) runoff values (mm/y) for sections of the Bear Creek Reservoir watershed. The Evergreen gage represents the upper basin of Bear Creek. Runoff for the lower basin of Bear Creek is estimated from the difference in flows between the Evergreen (06710385) and Morrison (06710500) gages. Runoff for the remainder of the basin (Turkey Creek, Coyote Gulch, Bear Creek below diversions, and direct runoff) is calculated as the difference between the USACE computed inflow and the flow left in Bear Creek after diversions below the Morrison gage. A limited set of values is available Turkey Creek; they are shown for comparison.

Year	Upper Bear Creek Basin	Lower Bear Creek Basin	Turkey Creek	Residual
1991	143.0	33.8		14.8
1992	102.3	27.9		39.0
1993	76.8	25.4		26.1
1994	80.0	18.3		21.9
1995	224.9	209.3		9.7
1996	97.1	8.2		86.1
1997	172.5	53.9		71.8
1998	230.5	84.7		151.5
1999	212.4	71.7	82.1	84.5
2000	78.2	0.4	22.4	23.4
2001	86.5	18.4	24.1	23.3
2002	30.9	6.6	5.8	7.4
2003	120.9	70.0	76.8	76.4
2004	118.3	43.1	46.1	47.3
2005	118.9	59.0	74.1	56.1
2006	68.0	3.2	12.0	0.0
2007	190.7	97.8		54.7
2008	83.5	7.4		39.7
2009	83.7	32.7		84.6
2010	94.5	35.5		95.0
2011	69.6	2.0		45.3
2012	51.9	0		19.3

The watershed draining the lower basin of Bear Creek (below Evergreen gage) yields much less runoff than the upper basin. In part this is because less precipitation falls at lower elevation, but there also is some consumptive use downstream and some evaporation from the surface of Evergreen Lake. This runoff value is not adjusted for the major diversions that are between the Morrison gage and the reservoir.

Runoff from the remainder of the reservoir watershed – including Turkey Creek, Coyote Gulch, Bear Creek below the diversions, and direct runoff – is calculated based on the difference between the USACE computed inflow to the reservoir and the flow remaining in Bear Creek after diversions by the Harriman and Ward ditches. Water yields for the Turkey Creek basin can be estimated only for those few years that coincide with operation of gages. Those yields generally agree well with those derived for the residual portion of the basin, which is similar with respect to area and general land cover.

Background phosphorus export is the product of background concentration (treated as a flow-weighted mean concentration) and water yield in each year. Annual export is calculated separately for three portions of the reservoir watershed. Phosphorus export from the upper basin of Bear Creek is based on flow at the Evergreen gage and a flow-weighted mean concentration of 13 ug/L (Table 5). Export from the upper basin is reduced by about 22% through sedimentation when Bear Creek passes through Evergreen Lake. Export from the lower basin of Bear Creek is based on the flow increase registered at the Morrison gage and a background concentration of 13 ug/L. Annual phosphorus transport in Bear Creek is reduced significantly (median of 29%) by the Harriman and Ward ditches. Export from residual areas is not affected by sedimentation or diversion. The phosphorus load to the reservoir typically is less than export by about 35% due to the aforementioned sedimentation and diversion processes.

Table 5. Transport of background phosphorus from the watershed of Bear Creek Reservoir. Export from the upper basin of Bear Creek passes through Evergreen Lake where about 22% of the phosphorus is lost to sedimentation. Export from the lower basin of Bear Creek is added to the net export from the upper basin, and the total is adjusted for diversions. The residual area includes contributions from Turkey Creek, Bear Creek below the diversions, and direct drainage areas. Background load to the reservoir is less than export from the watershed due to sedimentation in Evergreen Lake and diversion of phosphorus transported in Bear Creek.

Year	Upper Basin Export, lbs	Upper Basin Adjusted for Sedimentation, lbs	Lower Basin Export, lbs	Total Export Adjusted for Diversions, lbs	Residual Area, lbs	Total Export, lbs	Background Load, lbs
1991	1093	853	178	856	68	1340	924
1992	782	610	147	539	179	1108	718
1993	587	458	134	381	120	841	501
1994	611	477	96	379	101	808	480
1995	1719	1341	1103	2244	45	2867	2289
1996	743	579	43	449	396	1182	846
1997	1319	1029	284	1136	330	1934	1466

Year	Upper Basin Export, lbs	Upper Basin Adjusted for Sedimentation, lbs	Lower Basin Export, lbs	Total Export Adjusted for Diversions, lbs	Residual Area, lbs	Total Export, lbs	Background Load, lbs
1998	1762	1374	447	1657	697	2906	2354
1999	1624	1267	378	1433	389	2391	1822
2000	598	466	2	278	108	707	385
2001	661	516	97	409	107	865	516
2002	236	184	35	71	34	305	105
2003	925	721	369	409	352	1646	761
2004	904	705	227	663	217	1349	880
2005	909	709	311	823	258	1478	1081
2006	520	405	17	268	0	537	268
2007	1458	1137	516	1430	252	2225	1682
2008	638	498	39	318	183	860	501
2009	640	499	172	473	389	1202	862
2010	722	563	187	587	437	1347	1024
2011	532	415	10	157	208	751	365
2012	397	309	0	132	89	486	221

Point Source Phosphorus

Seventeen point sources have phosphorus allocations defined in the control regulation. Most of these are on or near the mainstem of Bear Creek. Because these dischargers are covered under the control regulation, they are obliged to monitor phosphorus concentrations and report loads in Discharge Monitoring Reports (DMRs).

The history of point source phosphorus contributions is important in two ways. The first is that concentrations were reduced significantly when facilities were upgraded after adoption of the control regulation. Most facilities now discharge phosphorus at concentrations less than 0.5 mg/L rather than 4 or 5 mg/L as expected with only secondary treatment. The second point is that concentrations at most facilities have declined over the last decade as operators gain more experience with the phosphorus removal processes. At the same time, wastewater flows have not increased much. Taken together, treatment improvements have probably reduced export to less than 10% of the level that was being discharged in the early 1990s.

Table 6. Point source export of phosphorus and net load reaching the reservoir, 2003-13. Calculations of diverted phosphorus are based on monthly totals for flows and monthly DMRs for phosphorus. Diversions for Oct-Dec 2013 are estimated.

Year	Discharge of TP, lbs/y	Flow, MG/y	TP, mg/L	Diverted, lbs/y	Load to Reservoir, lbs/y
2003	2131	559	0.457	1355	776
2004	1739	491	0.424	453	1286
2005	1801	520	0.415	448	1353

Year	Discharge of TP, lbs/y	Flow, MG/y	TP, mg/L	Diverted, lbs/y	Load to Reservoir, lbs/y
2006	1532	499	0.368	431	1101
2007	1869	571	0.392	386	1482
2008	1224	502	0.292	424	800
2009	1242	525	0.284	392	850
2010	1052	517	0.244	192	860
2011	996	477	0.250	515	481
2012	970	455	0.255	449	521
2013	1130	496	0.273	386	745

Most of the wastewater enters Bear Creek above the major diversion points (except Morrison), so that some portion of the point source load is diverted before reaching the reservoir. The diversions are seasonal and have the greatest effect when stream flows are low.

Phosphorus from On-site Wastewater Treatment Systems (OWTS)

Wastewater produced by the population of the reservoir watershed is treated either by municipal WWTFs or by OWTSs. In order to estimate the phosphorus contribution from OWTSs, we need a good estimate of the number of systems in the watershed. In the absence of a direct count, we must estimate the number of systems based on population.

The population from census blocks within the watershed was 43,345 in 2010. Resolution at the spatial scale of census blocks is not available for earlier years, which is unfortunate because information on growth may be important. However, because most of the people live in the Jefferson County portion of the watershed, data from census tracts can be used to assess growth (Table 7). It is evident that the population changed little over the decade from 2000 to 2010.

Table 7. Population estimates for the Bear Creek Reservoir watershed based on census tract data for 2000 and 2010.

Census Tract	Description	2000 Census	2010 Census
98.46	Conifer/285 Corridor	4129	4786
98.47	Conifer/285 Corridor	3235	3269
98.48	Conifer/285 Corridor	2524	2519
120.26	Conifer/285 Corridor	3459	3368
120.30	Conifer/285 Corridor	3854	3719
120.31	Conifer/285 Corridor	3847	3739
120.32	Conifer/285 Corridor	2471	2574
120.33	Conifer/285 Corridor	2871	2860
120.37	Conifer/285 Corridor	3458	3331
98.45	Central Mountains	4097	4010
120.27	South-Central Mtns/Indian Hills	2846	2952

Census Tract	Description	2000 Census	2010 Census
	Total	40141	40586

The population data are parsed in two ways in order to estimate phosphorus contributions from OWTSs. The first is to estimate the population served by OWTS and the second is to determine what portion of the population on OWTS is located in the upper and lower basins of Bear Creek upstream of the Harriman and Ward ditches. By parsing the population in this manner, it is possible to apply the appropriate "discount" for OWTS phosphorus that is diverted out of Bear Creek before it reaches the reservoir. The BCWA has prepared a map that shows population estimates for eight sub-basins in the reservoir watershed (Table 8). Although the total is slightly larger than that presented in Table 7, it is close enough to provide a sound basis for estimating phosphorus contributions.

Table 8. Population of the Bear Creek Reservoir watershed partitioned by sub-basins as shown in BCWA Map Series 26.

Sub-basin	2010 Population Estimate
Headwaters of Bear Creek	163
Vance Creek	81
Evergreen Lake - Bear Creek	4514
Cub Creek	5448
Troublesome Creek - Bear Creek	9812
Mount Vernon Creek - Bear Creek	5457
Turkey Creek	8227
Bear Creek Lake	8047
Total	41749
Subtotal for Bear Creek above diversions	25475
Subtotal for residual areas, excluding "Bear Creek Lake" sub-basin	8227

In the portion of the Bear Creek watershed that is upstream of the Harriman and Ward ditches, the total population is estimated to be 25,475. According to the BCWA, about 19,400 are served by municipal WWTFs. The balance (6,083) is assumed to be reliant on OWTSs.

In the rest of the reservoir watershed (residual areas), the entire population is relatively large (16,274), but few homes are served by the WWTFs identified in the control regulation. Although the initial assumption might be that most of these homes are on OWTS, closer inspection suggests otherwise. Most of the homes in the "Bear Creek Lake" sub-basin are in developments that are served by WWTFs discharging outside of the reservoir watershed. These appear to include the Green Mountain, Lakehurst, and Willowbrook W&S districts. The population of the residual areas on OWTS is probably best represented by the total for the "Turkey Creek" sub-basin (8227), which includes the Indian Hills area.

The amount of phosphorus that an OWTS contributes to a stream is difficult to estimate directly, and it is likely to vary among locations. The best we can do is to rely on a general set of assumptions from which per capita phosphorus yield can be estimated. There are three components to the calculation – per capita daily volume of water, phosphorus concentration, and the fraction of phosphorus retained in the soil.

Indoor residential water use is assumed to be 171 liters per person per day, which is the median of values presented in a recent study (Lowe et al 2009). The same study reported that the median phosphorus concentration was 9.8 mg/L. Thus the per capita phosphorus load to the OWTS would be 1.7 g/d. The load from the OWTS to the stream will be less because the soil will retain much of the phosphorus. Many factors may affect the fraction that is retained before the phosphorus reaches the stream, but a reasonable estimate of retention is 90% (MT DEQ). Net delivery to the stream would be about 61 g/year for each person on OWTS.

For the portion of the Bear Creek basin upstream of the major ditches, the export of phosphorus all OWTSs would be 820 lbs/y. This amount would have to be discounted for the mass removed via diverted flows. For the rest of the basin, which is not affected by those diversions, the export from all OWTSs would be 1109 lbs/y. Once diversions are accounted for (median = 237 lbs/y), the median load to the reservoir is 1692 lbs/y.

Precipitation

Precipitation falling directly on water surface of the reservoir adds phosphorus to the lake, and the amount can be estimated from the volume of water and a constant concentration. The volume of water is based on monthly precipitation recorded at a gage in Lakewood (Coop station 054762) and the monthly median lake surface area (usually about 100 acres). A constant phosphorus concentration[11] of 87.5 ug/L is applied to the monthly water volume contributed from precipitation. The concentration is taken from the Chatfield Reservoir Clean Lakes study because no comparable data are available at Bear Creek Reservoir. In view of the small contribution (ca. 30-50 lbs/y) to the total phosphorus load, use of a constant concentration is acceptable. The annual estimates are shown in Table 9 when all sources are compared.

Summary of Predicted External Phosphorus Loads

External phosphorus loads were predicted for four sources – background, point source, OWTS, and precipitation. Loads from background and precipitation are strongly connected to hydrologic conditions, which show considerable variation among years. Loads from point sources have responded to improvements in treatment. Loads from OWTS are assumed to be constant on a per capita basis. Additional variability is introduced into loads delivered in Bear Creek due to variability in the proportion of flow diverted annually at the Harriman and Ward

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[11] The concentration is taken from the Chatfield Reservoir Clean Lakes study; no comparable data are available for the Bear Creek watershed.

ditches. Net contributions of the four external sources are compared in those years for which all contributions could be calculated (Table 9).

Table 9. Summary of net phosphorus loads from external sources, 2003-2012. For each source, the load is shown as lbs/y and percent of total net load for the year.

Year	Background		Point Source		OWTS		Direct Precipitation		Total
2003	761	25.4%	776	25.9%	1417	47.4%	37	1.2%	2992
2004	880	22.5%	1286	32.9%	1692	43.3%	49	1.3%	3908
2005	1081	25.5%	1353	31.9%	1771	41.8%	35	0.8%	4241
2006	268	8.8%	1101	36.4%	1629	53.8%	30	1.0%	3027
2007	1682	33.5%	1482	29.5%	1819	36.2%	37	0.7%	5021
2008	501	17.2%	800	27.4%	1596	54.6%	24	0.8%	2921
2009	862	25.0%	850	24.7%	1687	48.9%	49	1.4%	3449
2010	1024	28.0%	860	23.5%	1751	47.8%	29	0.8%	3664
2011	365	15.9%	481	20.9%	1412	61.5%	39	1.7%	2298
2012	221	9.9%	521	23.3%	1460	65.5%	29	1.3%	2231
Median	812	23.8%	855	26.7%	1658	48.4%	36	1.1%	3238

The loads predicted for the four external sources suggest that OWTSs contribute about half of the net amount reaching the reservoir, and the rest is split about equally between background and point sources. Direct precipitation is an insignificant source. Two points should be emphasized regarding these predictions. The first is that accuracy is likely to vary among sources; the point source predictions are probably the most accurate, and the OWTS predictions are the most uncertain (and are not verifiable). The second, and related, point is that these predictions are intended mainly to provide a sense of relative magnitude; the actual load is estimated where the tributaries enter the reservoir.

Estimates of Actual Load

The actual phosphorus load to the reservoir consists primarily of phosphorus delivered via the two main tributaries – Bear Creek and Turkey – as well as some phosphorus from direct runoff and minor tributaries. Because load is the product of concentration and flow, measured values of concentration and flow must be available concurrently for each tributary. On each sampling date, of which there are generally 15 to 17 per year, grab samples are taken for phosphorus analysis and flow is determined by instantaneous measurement or by reference to a gage. In addition, daily flows are available for Bear Creek just above the reservoir for most of the period of record, and the USACE has provided a record of daily computed inflows to the reservoir from all sources.

Although flows are measured daily, phosphorus concentrations are measured on only about 5% of the days in each year. Consequently, an assumption must be made about the best way to assign a concentration to every day in each year. The nature of the assumption depends on

the underlying relations, if any, between flow and concentration. If flow is a very good predictor of concentration, a regression model could be the best approach. On the other hand, if there is no relationship between flow and concentration, then it might be best to apply an average concentration to an annual flow.

In Bear Creek, phosphorus concentrations are elevated at the lowest flows, but show no relationship over a wide range of flows (Figure 9). In contrast, phosphorus concentrations in Turkey Creek show a weak positive relationship to flow (Figure 10). Both relationships are weak in a statistical sense and would not be helpful for assigning concentrations to days when phosphorus was not measured.
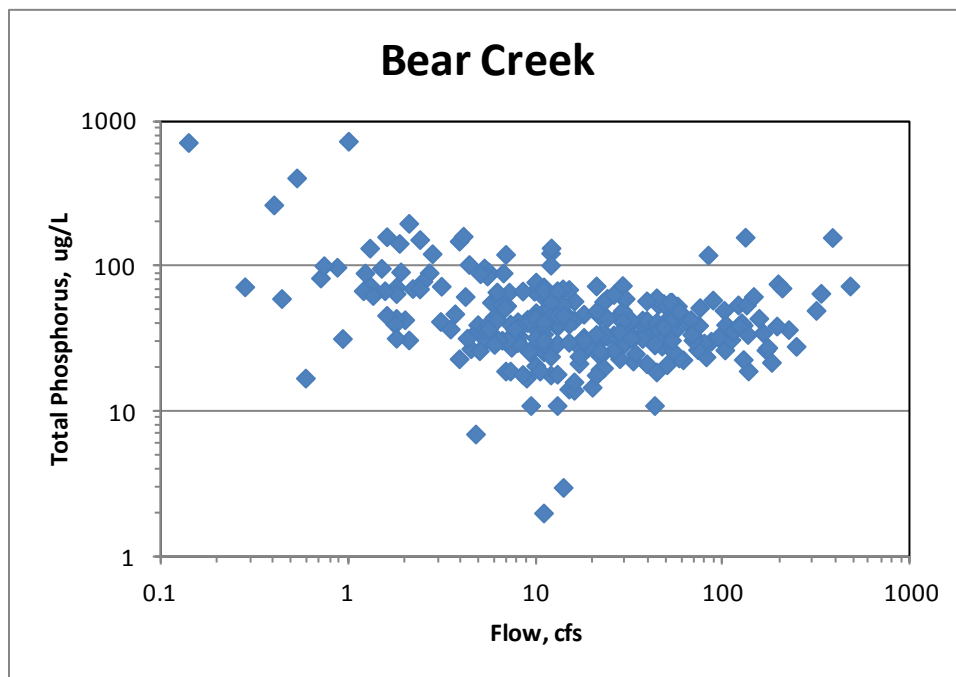
Figure 9. Relationship between phosphorus concentration and stream flow in Bear Creek just above the reservoir, 1996-2013.
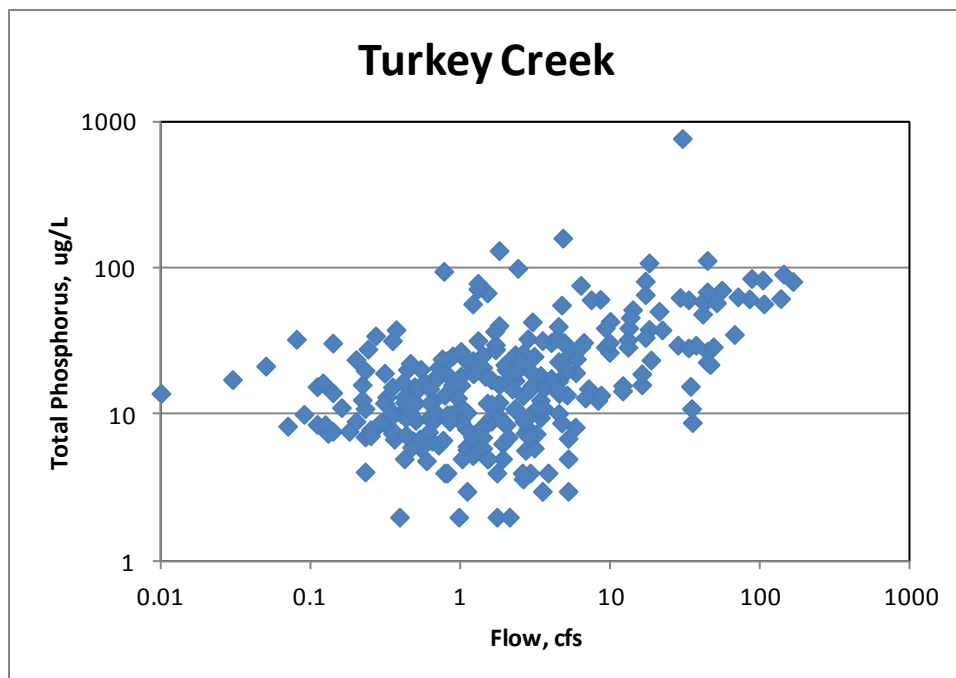
Figure 10. Relationship between phosphorus concentration and stream flow in Turkey Creek just above the reservoir, 1996-2013.

Although the relationship between concentration and flow is weak, it is not absent. Rather than having to rely on a poor predictive equation, we chose to calculate flow-weighted mean concentration (FWMC) on an annual basis. This approach acknowledges a role for flow while recognizing that the nature of the relationship is imprecise and may vary from year to year.

It is evident that phosphorus concentrations have declined significantly over time in both streams (Figure 11). Current values are about 25% of those recorded at the beginning of studies. The decline is attributed to controls on point sources. Stream concentrations appear to have been relatively stable since the late 1990s.
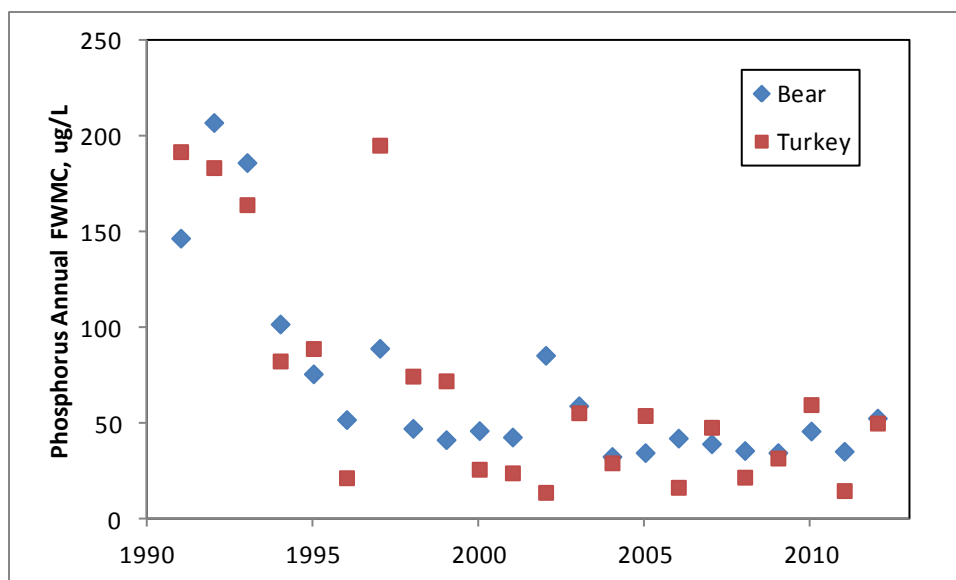
Figure 11. Annual flow-weighted mean concentrations (FWMC) of total phosphorus in Bear Creek and Turkey Creek near the reservoir.

The FWMC concentrations can be paired with annual flows to provide annual load estimates (Table 10). Contributions from Bear Creek comprise about 70% of the typical annual phosphorus load to the reservoir. Concentrations are very similar in Bear Creek and Turkey Creek even though the two tributaries differ substantially in the relative importance of point and OWTS sources.

Table 10. Flow-weighted mean concentrations (FWMC) of total phosphorus in Bear Creek and Turkey Creek. These annual concentrations are paired with annual inflow to derive phosphorus load for Bear Creek and for all other inflows (remainder). The FWMC for Turkey Creek is applied to the Remainder flows as described in the text.

	Bear Creek		Remainder		Total
Year	FWMC (ug/L)	TP Load (lbs)	FWMC (ug/L)	TP Load (lbs)	TP Load (lbs)
1991	146.9	9930	192.2	3628	13558
1992	207.4	9670	183.8	3316	12986
1993	186.4	5838	164.5	2238	8076
1994	102.1	3489	82.7	792	4281
1995	76.0	15196	89.3	256	15452
1996	52.1	2765	21.7	457	3222
1997	89.4	10507	195.5	2838	13345
1998	47.5	8596	74.8	2041	10637
1999	41.6	5934	72.4	1552	7487
2000	46.3	1287	26.2	205	1493
2001	43.0	1542	24.3	275	1817
2002	85.7	541	14.1	43	584
2003	59.3	2423	55.7	1314	3736
2004	32.8	1907	29.5	604	2511
2005	34.8	2460	54.2	1354	3814

Year	Bear Creek FWMC (ug/L)	Bear Creek TP Load (lbs)	Remainder FWMC (ug/L)	Remainder TP Load (lbs)	Total TP Load (lbs)
2006	42.4	843	16.7	83	926
2007	35.8	4628	48.1	1034	5662
2008	35.9	1162	22.0	277	1439
2009	34.8	1536	32.0	955	2491
2010	46.1	3003	59.8	1391	4394
2011	35.5	974	15.0	60	1033
2012	52.9	632	50.3	400	1032
Median	46.9	2613	52.3	874	3775
Median 03'-'13	35.9	1722	40.0	780	2501

Phosphorus Recycling in the Reservoir

The phosphorus supply available to algae may include phosphorus that is recycled within the lake. Under the right conditions, phosphorus may be released from the lake sediments (internal release or internal load) and added to the supply delivered by external sources. The phosphorus in the sediments is an accumulation of external load from previous years that settled out of the water column rather than being transported downstream. By origin, it represents a legacy effect, but it is also an augmentation of the annual external load in terms of its availability to algae.

When Bear Creek Reservoir was first studied more than 20 years ago, the reservoir was thermally stratified into upper (epilimnion) and lower (hypolimnion) layers. Stratification was stable and persisted through the summer months. The existence of stable stratification made it easy to detect internal recycling of phosphorus because concentrations would increase in the hypolimnion as long as stratification remained (Figure 12). In the early 1990s, before point source controls were imposed, concentrations in the hypolimnion were 5 or 6 times greater than concentrations in the epilimnion.
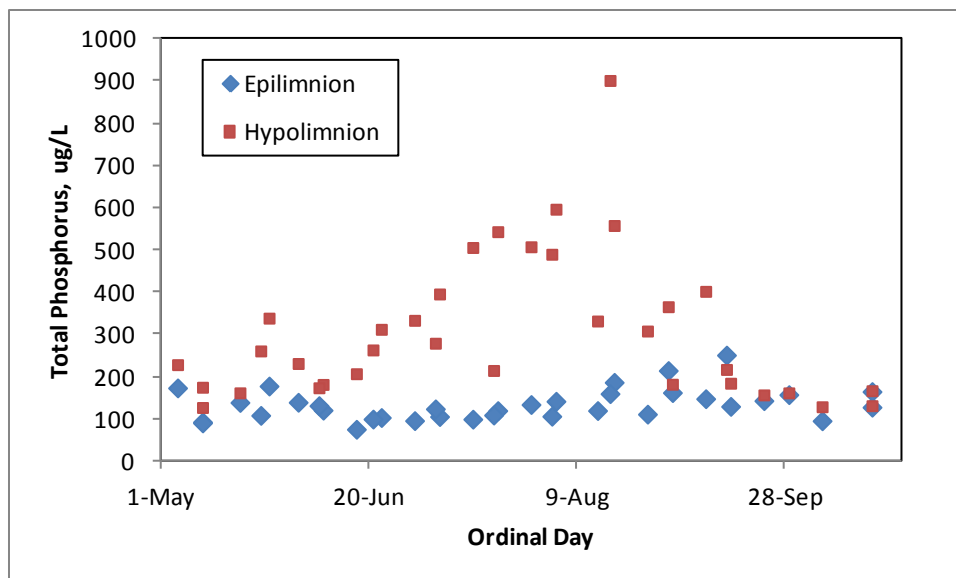
Figure 12. Phosphorus concentrations in the epilimnion and hypolimnion of Bear Creek Reservoir, 1991-1993. The months of May-Oct were chosen to highlight the effect of summer stratification. The years were chosen because they preceded phosphorus controls and aeration.

The accumulation of phosphorus in the hypolimnion is no longer available as a marker for recycled phosphorus because aerators now disrupt and prevent stratification. However, it is still possible to estimate the rate of recycling by determining the phosphorus content of the whole reservoir. This task is facilitated by aeration because it ensures that the reservoir remains relatively well-mixed.

The phosphorus content of the reservoir can be determined on each sampling date based on the volume, which is available daily from the USACE, and the depth at which phosphorus concentrations were measured in the water column. For most of the period of record, samples were taken from top, middle, and bottom depths that correspond to 56%, 33%, and 11% of lake volume respectively. For the last few years, the middle sample has been omitted, making it necessary to assume a different partitioning. Fortunately, aerators have been delivering more effective mixing that reduces the likelihood of vertical variation in concentration.

The concept for estimating internal release is to determine the rate of change in the phosphorus content of the lake during the window of time when temperature is suitable for the key biological processes. The rate is obtained from the slope of the line relating phosphorus content to sampling dates. An example is drawn from data collected in 2012 (Figure 13). The regression analysis is restricted to those dates on which the bottom temperature was near or above 15°C. The slope shows the phosphorus concentration in the lake increasing at a rate of about 0.9 ug/L/d at a time when there was very little inflow (i.e., very little external phosphorus load).
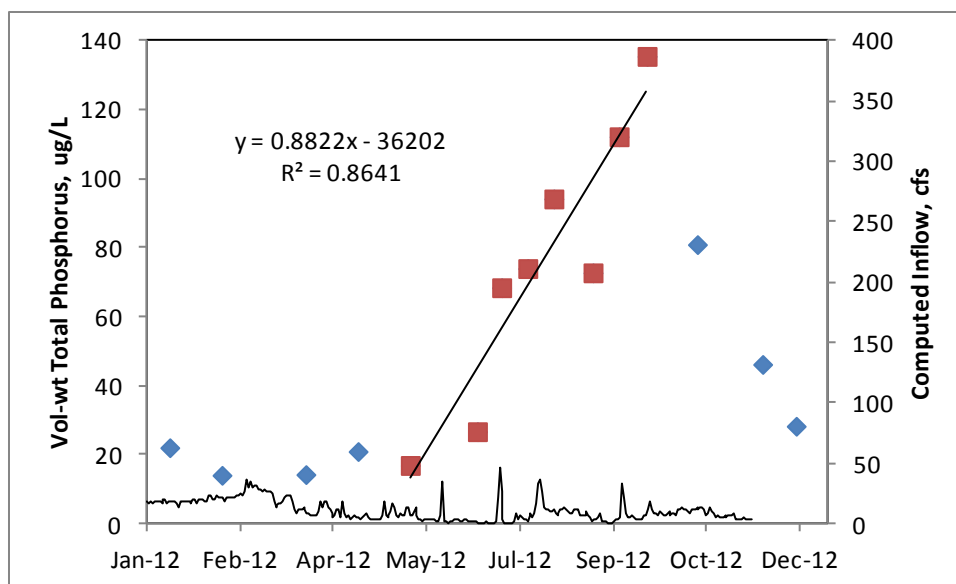
Figure 13. Phosphorus content (closed symbols) and computed inflow (solid line) of Bear Creek Reservoir in 2012. Phosphorus content is calculated from observed concentrations and sampling depths. The closed squares indicate phosphorus content during the period of internal recycling; these points are included in the regression equation. Computed inflow was provided by the USACE.

The observed rate of phosphorus increase is variable across years, but most of the variability can be attributed to hydrologic factors (Table 11). The highest rates are observed when inflows are lowest for the corresponding period of time. Conversely, when inflows are high, phosphorus concentrations show little increase.

Table 11. Net release rates for phosphorus during the growing season in Bear Creek Reservoir. The record begins with 1996 to focus on years after phosphorus controls were in place. 2013 is excluded due to the flood in late September. Computed inflows are from the USACE and correspond to the time period over which the release rate was assessed.

Year	Computed Inflow, AF	Net Release, ugP/L/d	Aeration Technique
1996	8313	0.27	Hypolimnetic aeration
1997	11012	0.04	Hypolimnetic aeration
1998	13049	0.07	Hypolimnetic aeration
1999	16185	0.18	De-stratified, part season
2000	2319	0.70	De-stratified
2001	5326	0.46	De-stratified
2002	641	0.61	De-stratified
2003	4437	0.37	De-stratified
2004	12210	0.23	De-stratified
2005	4953	0.18	De-stratified
2006	2886	0.63	De-stratified
2007	8095	0.06	De-stratified
2008	2620	0.26	De-stratified
2009	6296	0.23	De-stratified
2010	4169	0.10	De-stratified
2011	4310	0.47	De-stratified

Year	Computed Inflow, AF	Net Release, ugP/L/d	Aeration Technique
2012	1638	0.88	De-stratified

The relationship is immediately comprehensible when the inflow is scaled by the volume of the reservoir (Figure 14). As inflows increase, the net effect of internal phosphorus release is diminished by dilution. At the lowest inflows, the net rate of increase is in the range of 0.7-0.8 ugP/L/d, which corresponds to 400-450 lbs of phosphorus during the growing season[12]. Although increasing flow depresses the apparent rate of increase, this is simply a dilution effect. The net addition of phosphorus is likely to be about 400 lbs/y, regardless of the flow regime.
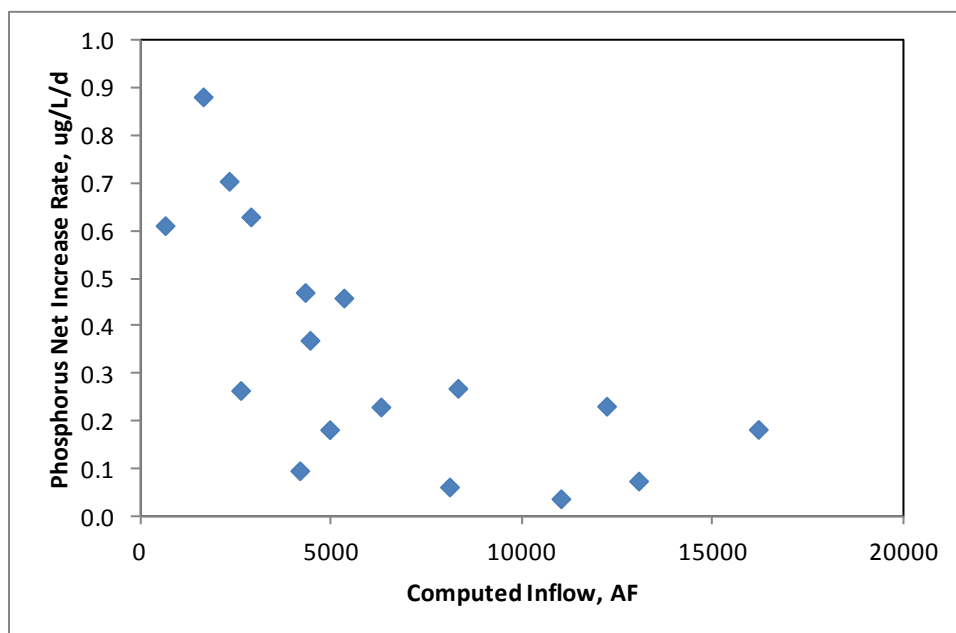
Figure 14. Observed net rate of phosphorus increase in Bear Creek Reservoir as a function of the computed inflow for the corresponding period of time (generally June-September).

The estimate of 400 lbs/y for internally recycled phosphorus is based on the observed net rate of increase. The actual rate is certain to be higher. Phosphorus released from the sediment is quickly distributed throughout the water column by the aerators, and algae will make use of the available phosphorus. Throughout the summer, as algae grow and die, algal cells settle to the bottom taking with them the accumulated phosphorus. Some of this phosphorus was recycled from the sediment, but then is re-deposited in the sediment. In other words, it is a dynamic exchange in which the net rate of phosphorus increase will underestimate the actual rate.

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[12] The phosphorus release rate can be converted to pounds added by assuming a constant storage of about 1900 AF and a fixed time interval of 110 days (June through mid-September).

At first glance, the net addition of 400 lbs of recycled phosphorus each year would seem to be small compared to a typical external load of about 2500 lbs/y. However, direct comparison is not apt for reasons related to the seasonality of flows, algal growth, and assessment. The reservoir is small, and the average residence time is short (typically about a month). Nevertheless, the residence time is longer in the summer, when algae are growing and when the chlorophyll standard applies.

Inflows during the summer months are typically low, in part because of seasonal diversions from Bear Creek. The median residence time based on flows for Jul-Sep is about 150 days. Reduced inflows during the summer means that external loads are less important than would be expected from the annual totals and there is less flushing to dilute the influence of recycled phosphorus. The interplay of flows, nutrients, and chlorophyll can be seen in graphs of concentration vs. flow (Figure 15 to Figure 17). Phosphorus concentration is highest at low flows, when there is little inflow to dilute recycled phosphorus. Nitrate concentrations, in contrast, are lowest at low flow; nitrate is not augmented by recycling, and it is taken up by actively growing algae. Finally, chlorophyll is highest at low flow because the nutrient supply is good, and growth rates exceed what is needed to replace algae lost to the outflow.
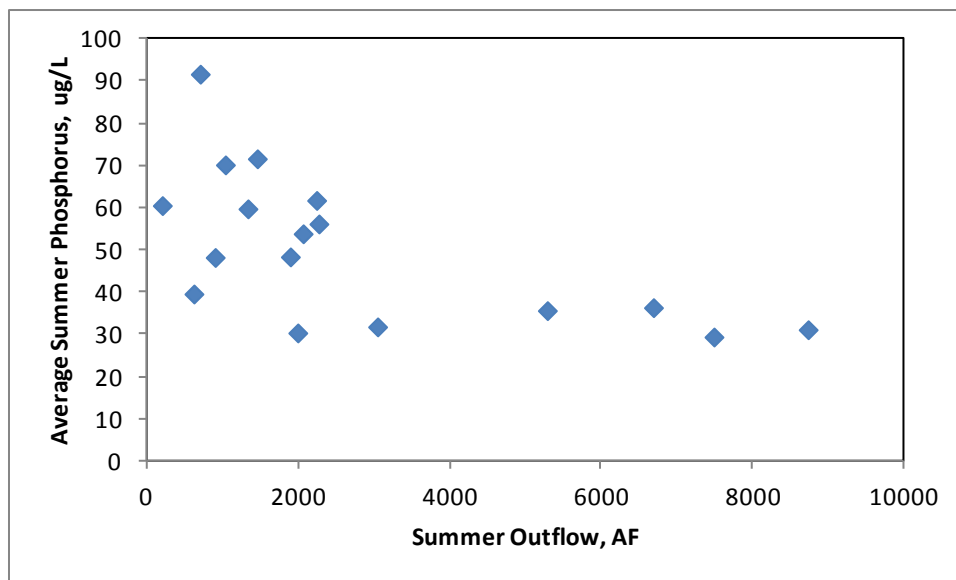

Figure 15. Relationship between the average concentration of phosphorus in the summer (Jul-Sep) and the volume of water flowing out of the reservoir, 1996-2012. The volume of the reservoir is approximately 2000 AF.
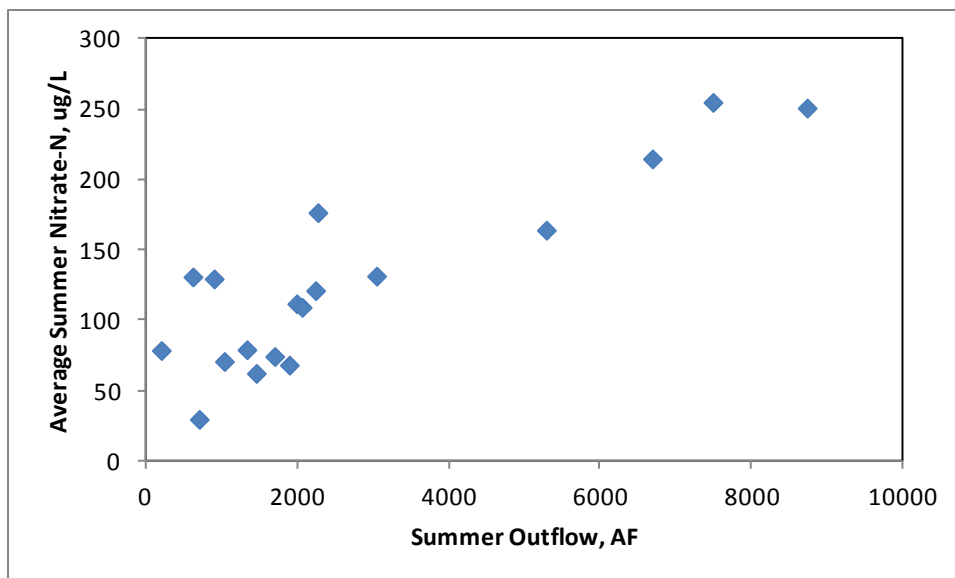
Figure 16. Relationship between the average concentration of nitrate-nitrogen in the summer (Jul-Sep) and the volume of water flowing out of the reservoir, 1996-2012. The volume of the reservoir is approximately 2000 AF.
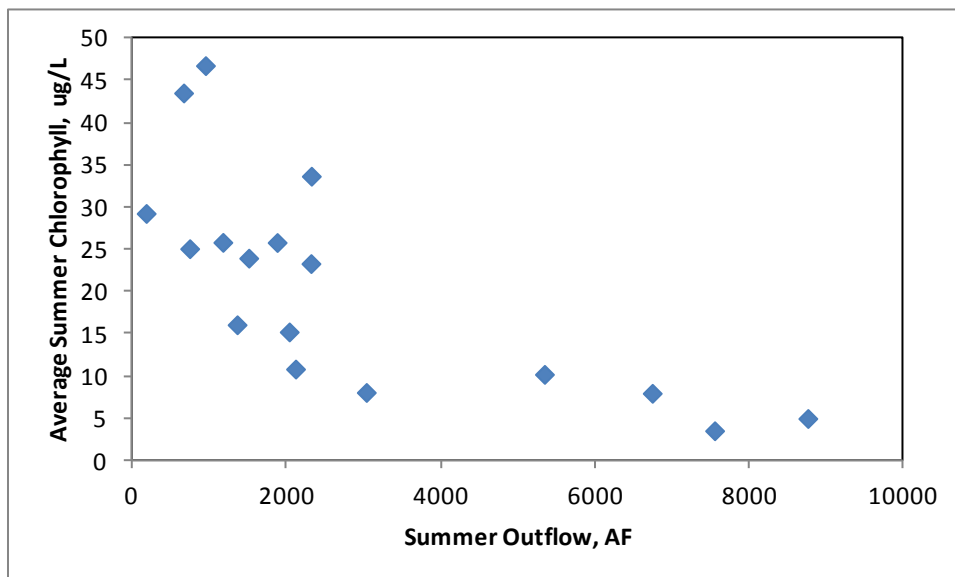

Figure 17. Relationship between the average concentration of chlorophyll in the summer (Jul-Sep) and the volume of water flowing out of the reservoir, 1996-2012. The volume of the reservoir is approximately 2000 AF.

Two approaches can be taken to put the role of recycling in perspective. The first is to determine the contribution of recycling under critical conditions, and the second is to make seasonal contrasts to separate the role of flow from the control of concentrations.

It is clear from the foregoing graphs that the highest phosphorus and chlorophyll concentrations occur in summers with the lowest flows, which could be considered critical conditions. Carried to the logical conclusion, we would expect algal abundance to be highest

when there is no summer inflow, at which time all additional phosphorus would be provided by recycling. In other words, phosphorus concentrations in the reservoir would show the greatest increase during the summer of those years with no additional inflow. Based on the recycling rates estimated previously, phosphorus concentrations could be expected to increase almost 70 ug/L from the beginning of July to the end of September. This outcome is consistent with observations for phosphorus concentrations in Bear Creek Reservoir (Figure 18) where all of the highest concentrations occur in the summer, concentrations tend to increase during the summer, and an increase of 70 ug/L is not rare.
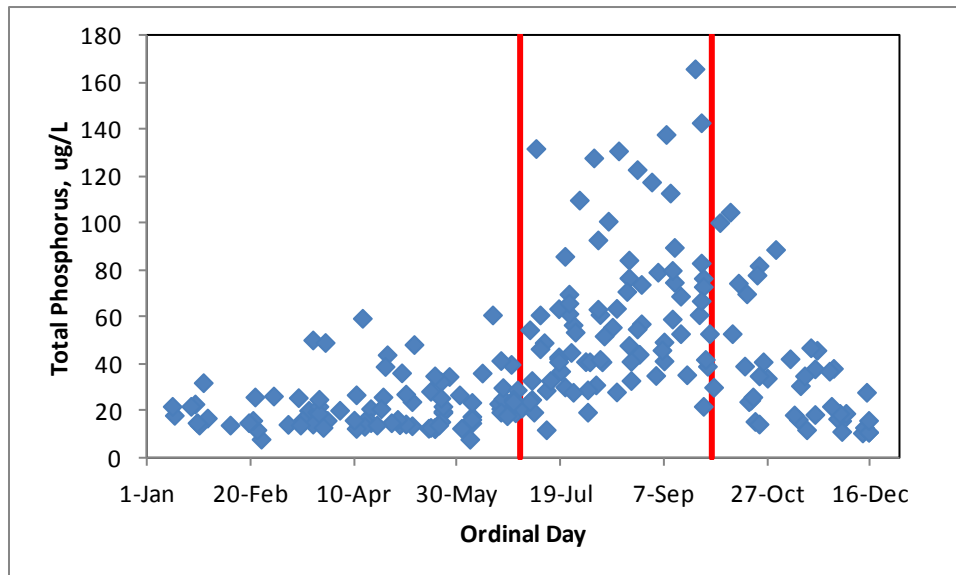

Figure 18. Total phosphorus concentrations in the top sample from Bear Creek Reservoir, 2000-2013. Samples from all years are plotted against ordinal day to highlight seasonal patterns. The two vertical bars mark the boundaries of summer – July through September – as defined in regulation.

We can bolster the conclusion regarding the role of recycling by comparing winter and summer concentrations of phosphorus in the tributaries. In order to account for potential flow effects, the data are plotted on a load duration curve (Figure 19). It is apparent that winter and summer loads are essentially the same over a wide range of flow conditions. The only difference appears to be that the lowest flows, which tend to have slightly higher concentrations, are more common in summer than in winter. Nevertheless, it is clear that whatever small differences there might be between summer and winter phosphorus levels, they are not enough to account for the summertime rise in phosphorus concentrations observed in the lake.
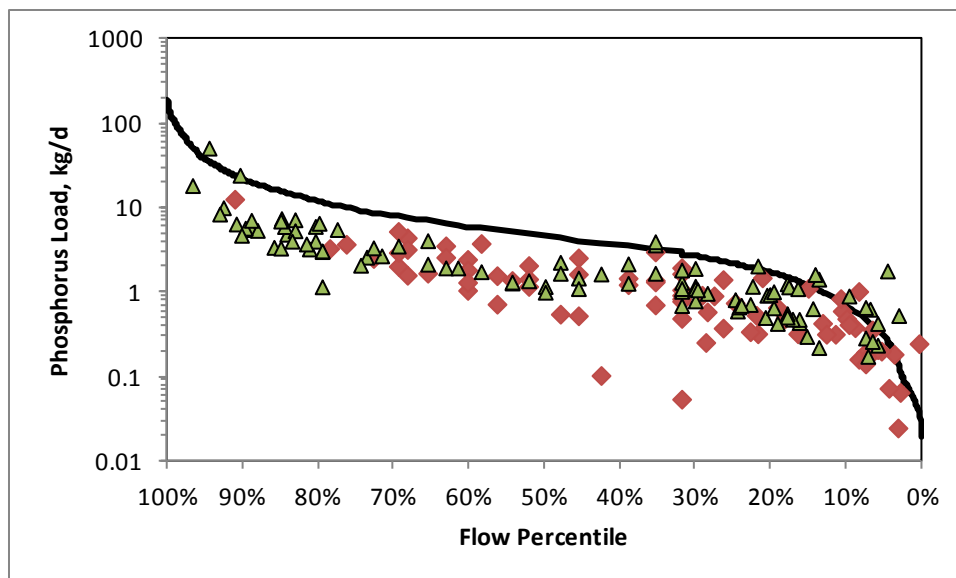
Figure 19. Bear Creek load duration curve (solid line) and seasonal values for observed loads (points) for 1996-2013. Summer values (Jul-Sep) are indicated with triangles (green) and winter (Nov-Mar) with diamonds (red). Points above the line indicate days on which the observed concentration exceeded the interim numeric value of 110 ug/L.

Conclusions about Phosphorus Sources

The conclusions drawn about the importance of phosphorus recycling have clear implications for the path forward. The first is that manipulation of external sources will have little or no effect on prospects for attaining the standard because external load plays little or no role under critical conditions. The second implication, which follows directly from the first, is that prospects for eliminating recycling will determine what additional steps, if any, will be needed for attaining the standard. Not until the recycling issue has been settled will we have a clear sense of what might be required.