Bear Creek Reservoir Technical Review Part 1: Background

Bear Creek Reservoir was constructed as a flood-control reservoir for protecting the Denver area.[1] It is located within a park operated by the City of Lakewood and is a heavily used recreational amenity. There are two primary tributaries – Bear Creek and Turkey Creek – that make up most of the watershed. The Bear Creek watershed, which comprises about 75% of the drainage area, begins in the Mount Evans Wilderness Area (Figure 1). The reservoir itself is relatively small – 110 surface acres and 2000 acre-feet (AF) of storage at multi-purpose pool elevation.

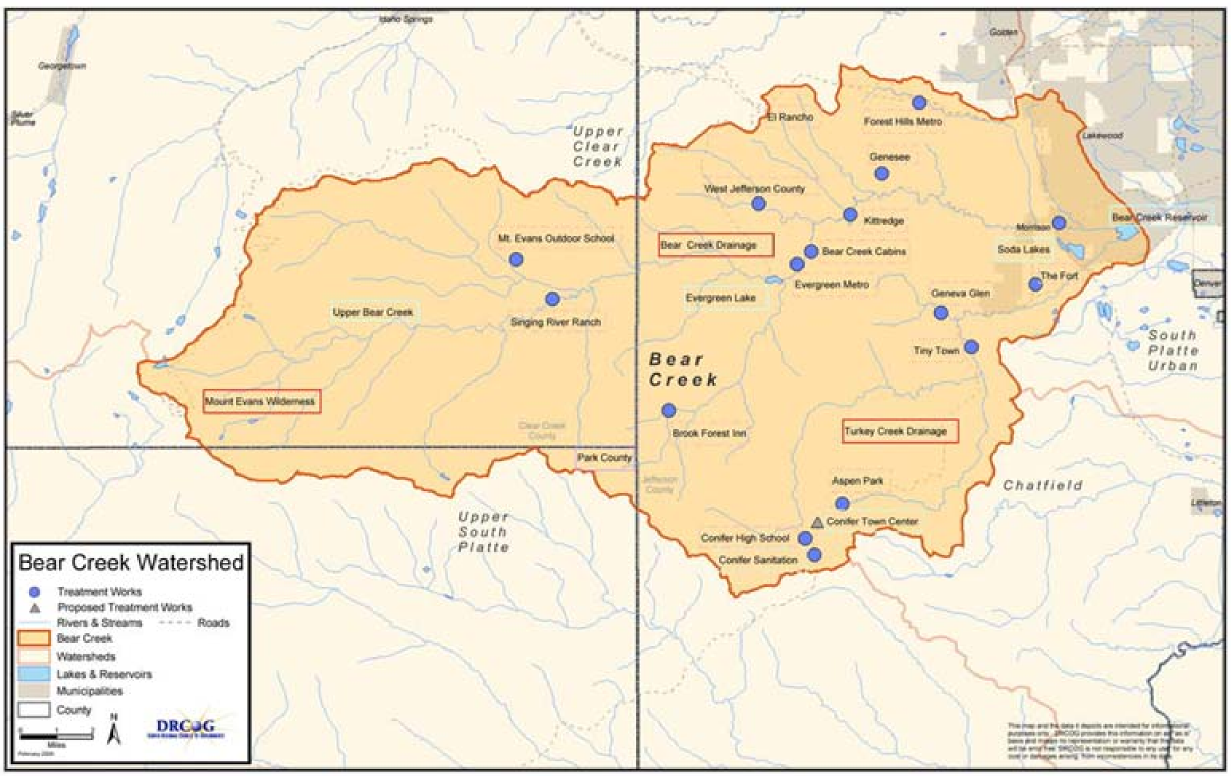

Figure 1. Location map of the Bear Creek Reservoir Watershed as defined for Control Regulation No. 74.

The first concerted effort to evaluate water quality in Bear Creek Reservoir began with the Clean Lakes Study[2], which was carried out in 1988 and 1989 (DRCOG 1992). The study concluded that the reservoir was enriched with nutrients, causing algal abundance to be higher than desirable. The study recommended that limits be placed on phosphorus loads in order to reduce algal abundance.

[1] Bear Creek Reservoir is one of three reservoirs comprising the Tri-Lakes Project constructed by the US Army Corps of Engineers. The other two reservoirs are Chatfield and Cherry Creek.
[2] The Clean Lakes program, which was established in 1972, provided technical assistance to States for the purpose of restoring water quality in publicly-owned lakes. No funds have been appropriated since 1994.

The findings and recommendations of the Clean Lakes study led to adoption of site-specific nutrient standards and a control regulation. Adoption of site-specific nutrient criteria placed Bear Creek – along with Dillon, Cherry Creek, and Chatfield reservoirs – in the forefront of efforts to prevent eutrophication in Colorado, and decades ahead of statewide adoption of nutrient criteria. The criteria adopted for Bear Creek Reservoir took the form of a narrative standard, in contrast to the numeric standards adopted for the other lakes covered by control regulations. Furthermore, the narrative recognized explicitly that the reservoir was too productive and that the trophic state needed to be changed. The control regulation, which implements the phosphorus source controls that are intended to ensure attainment of the standard, differs from those developed for the other three reservoirs in that phosphorus allocations were defined only for point sources. The Commission's actions to maintain water quality were timely, and the limits imposed on point source dischargers had a dramatic effect on phosphorus loads as will be shown later.

Water Quality Monitoring

The Bear Creek Watershed Association[3] has maintained an active water quality monitoring program since late 1990, shortly after completion of the Clean Lakes study. Water quality has been monitored in the reservoir and at many sites in the watershed. Four of those sites – reservoir index site, Bear Creek inflow, Turkey Creek inflow, and Bear Creek outflow – are included in the present technical review. Data from other monitoring sites will be useful later when developing allocations[4] within the basin.

The long record of monitoring data makes it possible to evaluate trends over time in nutrient sources to the reservoir. Annual box-and-whisker plots[5] are particularly useful for this task because they convey information about variability within each year, in addition to the mean or median. Constructing box-and-whisker plots for each year in the period of record provides a convenient basis for assessing trends in variability as well as central tendency. The Association's monitoring program provides analyses of various nutrient fractions for phosphorus (soluble reactive, total dissolved, and particulate) and nitrogen (dissolved ammonia and nitrate). For the most part, however, this review is limited to total phosphorus.

Total phosphorus concentrations in Bear Creek (Figure 2) and Turkey Creek (Figure 3) show clearly the benefit of reducing wastewater effluent concentrations. Significant reductions in effluent concentrations were reflected in concentrations measured in both tributaries after 1994. A similar graph was prepared for total phosphorus (Figure 4) in the reservoir outflow, and the temporal trends match those of the tributaries.

[3] A description of the association and its activities can be found at: http://www.bearcreekwatershed.org/
[4] The task of developing allocations within the basin is beyond the scope of the present technical review.
[5] A box-and-whisker plot is defined by five characteristics of the values measured in a given year. Those characteristics include the 25th, 50th (median), and 75th percentiles of the data, as well as two more extreme measures such as the max and min, or the 95th and 5th percentiles (as shown in the figures presented here).

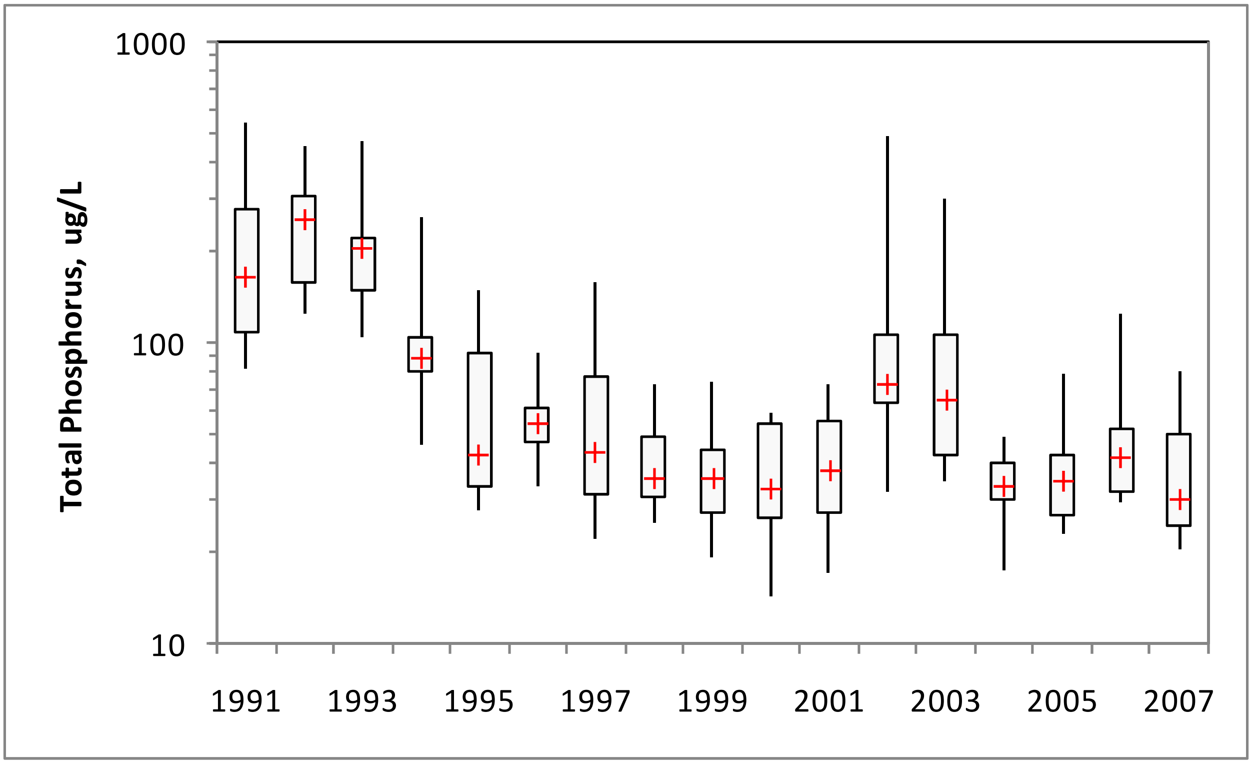

Figure 2. Annual distributions of total phosphorus concentrations in Bear Creek. Each annual box-and-whisker plot shows the central 50% of the concentrations (the "box") measured during the year, and the tips of the "whiskers" indicate the 5th and 95th percentile concentrations. The annual median concentration is indicated with a "+" symbol within each box.

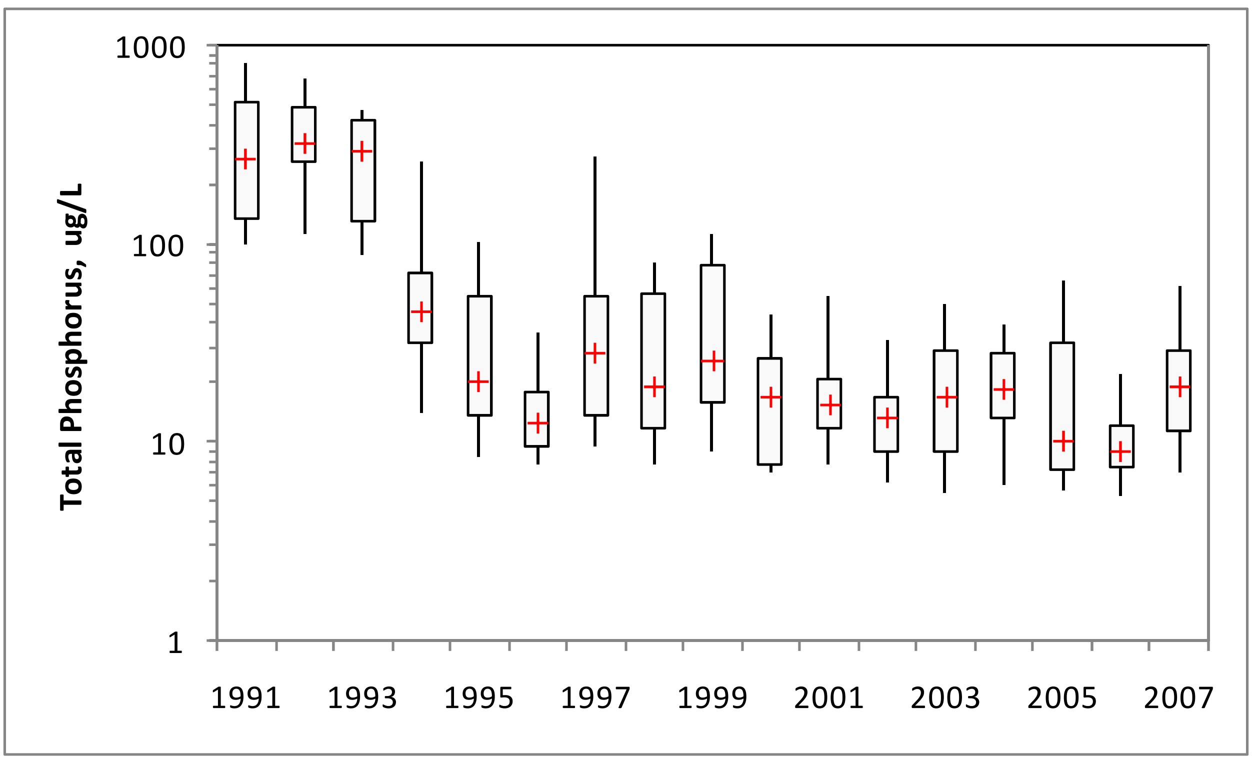

Figure 3. Annual distributions of total phosphorus concentrations in Turkey Creek. See Figure 2 for features of the graph.

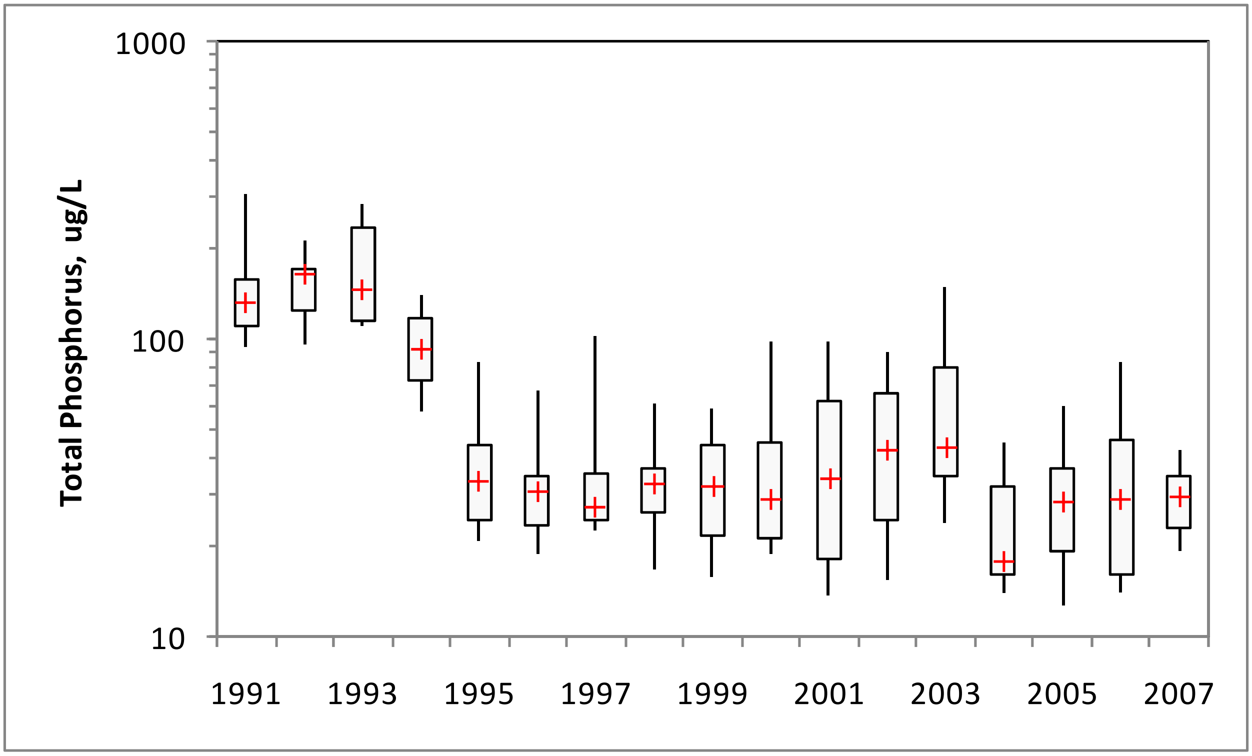

Figure 4. Annual distributions of total phosphorus concentrations in reservoir outflow. See Figure 2 for features of the graph.

In the reservoir, phosphorus concentrations also have been measured at three depths (top, middle, and bottom). Box-and-whisker plots are used to characterize summer conditions (July-September) in the mixed layer during each year. The near surface sample (called the “Top” sample in most reports) is assumed to be representative of the mixed layer. In practice, thermal stratification often is not evident because aerators have been used to prevent stratification throughout the summer months in most years since 1993.

Total phosphorus concentrations in the mixed layer decreased sharply after 1994, consistent with the pattern observed for the tributaries (Figure 5). In addition, phosphorus concentrations tend to be higher during low-flow years (e.g., 2002) than high-flow years (e.g., 1998) for reasons to be examined later. Chlorophyll concentrations also show an effect of hydrology whereby algal abundance tends to be higher in low-flow years (Figure 6).

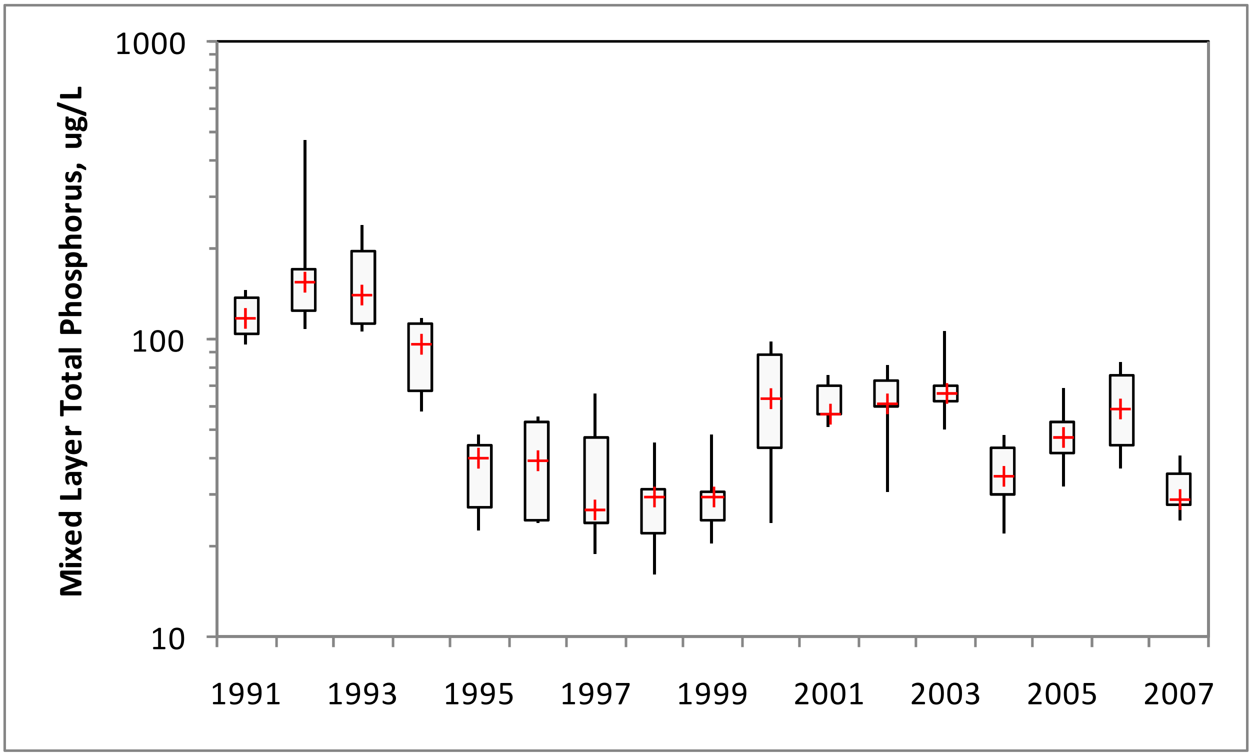

Figure 5. Distributions of total phosphorus concentrations in the mixed layer of the reservoir during the summer months. See Figure 2 for features of the graph.

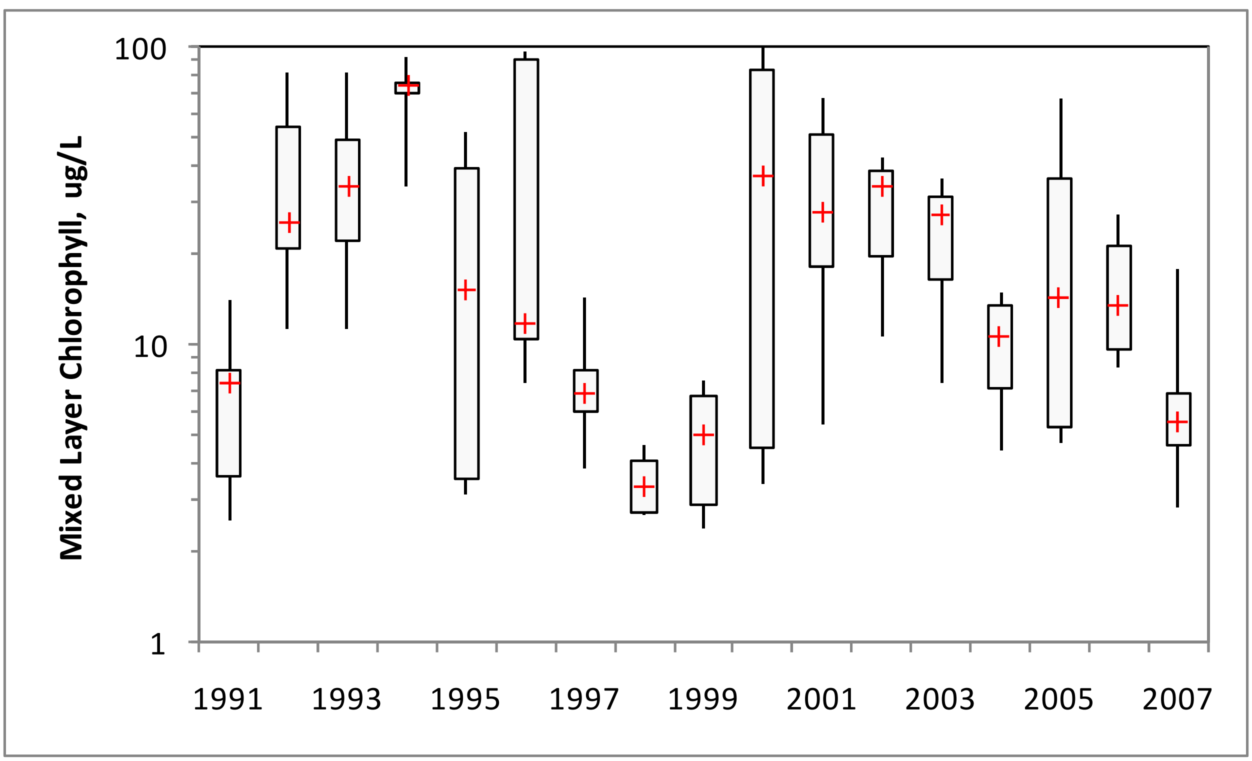

Figure 6. Distributions of chlorophyll concentrations in the mixed layer of the reservoir during the summer months. See Figure 2 for features of the graph.

Another water quality constituent of considerable concern for Bear Creek Reservoir is the concentration of dissolved oxygen.[6] When the reservoir experienced thermal stratification during the summer, oxygen concentrations would decrease rapidly in the lower layer, the hypolimnion.[7] During the Clean Lakes study, anoxic conditions occurred in the hypolimnion during the summer as a result of the high levels of algal abundance. Concern about dissolved oxygen concentrations prompted a decision to install aerators in 1993 (Table 1). At first, aeration was supposed to add oxygen to the hypolimnion without disrupting thermal stratification. That technology performed relatively poorly, and concerns about dissolved oxygen remained sufficiently strong to warrant placing the reservoir on the 303(d) list in 1996. After bottom aerators were installed in 1999, stratification was disrupted and aeration became more effective (Figure 7).

Year	Aerator Technology
1993	Three towers installed
1998	North and South towers failing
1999	Installed 6 barrel-type bottom aerators
2000	Still operating Middle tower
2001	Still operating Middle tower
2002	Installed 11 pan diffusers
2004	Compressors operated on timers

Table 1. Chronology of aerator technology and operation in Bear Creek Reservoir.

[6] The narrative standard contains a specific provision regarding dissolved oxygen concentration. (See Exhibit 4)
[7] When thermal stratification occurs in a lake, it establishes two distinct layers (*epilimnion* and *hypolimnion*) separated by a boundary layer (*metalimnion*). The upper layer, or epilimnion, is mixed by the wind and subject to gas exchange with the atmosphere. It is a relatively homogeneous environment in terms of physical and chemical conditions. Most algal growth occurs within the epilimnion. The lower layer, or hypolimnion, is physically isolated from any exchange with the atmosphere; decomposition in this layer consumes oxygen without replenishment. The boundary layer is a region of steep physical and chemical gradients that restricts contact between the upper and lower layers.

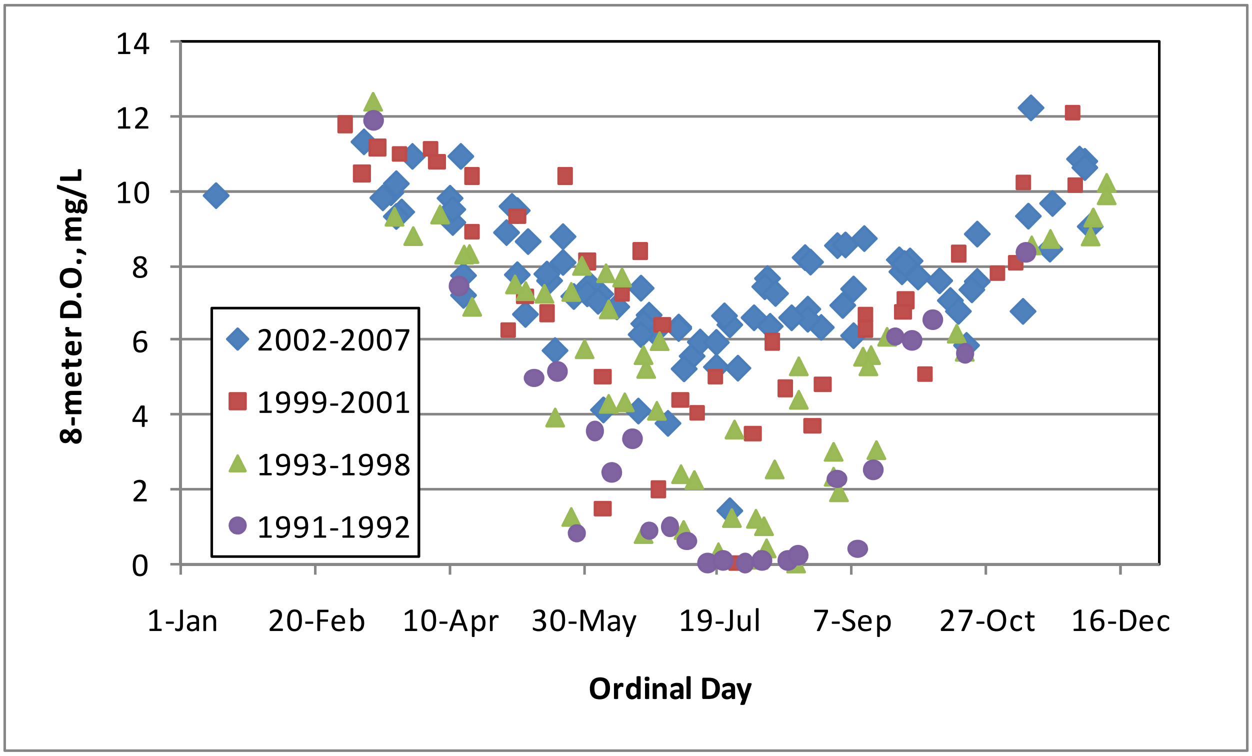

Figure 7. Deep water (8 meters below surface) dissolved oxygen concentrations in Bear Creek Reservoir, 1991-2007. The data are aggregated across years by plotting against ordinal day. Years are segregated according to aerator technology (see Table 1): 1991-1992 – no aeration; 1993-1998 – hypolimnetic aeration without disrupting stratification; 1999-2001 – full water column aeration with barrel aerators; 2002-2007 – full water column aeration with pan diffusers.

It is apparent that aeration has become progressively more effective in dealing with oxygen depletion as better technologies have been employed and operation strategies have been honed through experience. Nevertheless, even in recent years, there have been times when dissolved oxygen concentrations in deep water have fallen below what would be expected in a well-mixed system. Persistent concerns about dissolved oxygen concentrations have kept Bear Creek Reservoir on the Monitoring & Evaluation list. Moreover, there is a broader concern about what is being accomplished with aeration because even a completely effective aeration system is only treating the symptoms of excessive algal abundance.

Context for Evaluating Water Quality

Water quality in Bear Creek Reservoir has improved significantly since the Clean Lakes study was undertaken 20 years ago. Reductions in phosphorus loads have reduced phosphorus concentrations in the reservoir, and algal abundance is lower. Aeration has improved dissolved oxygen conditions, although the accompanying de-stratification makes it difficult to determine how the hypolimnetic oxygen compares with what is required. In a comparative sense, water quality is better, but the more important context for evaluating water quality is by reference to the existing narrative standard.

A site-specific, narrative standard was adopted for Bear Creek Reservoir in 1992. The narrative standard is based on trophic state,[8] with specific mention of phosphorus and dissolved oxygen. However, the wording of the narrative (see below) makes it difficult to determine attainment.

> *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.*

Numeric criteria are not specified in the narrative, but two numeric targets can be inferred; these targets will help determine the adequacy of present water quality. Trophic state, for example, can be defined on the basis of chlorophyll concentrations. One widely used classification scheme (OECD 1982) places the eutrophic-mesotrophic boundary at a chlorophyll concentration of 8 ug/L. Other schemes may define the boundary with a different chlorophyll concentration, but it should be clear from Figure 6 that summer concentrations in Bear Creek Reservoir are usually well above the desired trophic state. By implication, if algal abundance is too high, nutrients (e.g., phosphorus) are too high as well.

The narrative also defines expectations for dissolved oxygen concentrations in the hypolimnion ("…provide for the survival and growth of cold water aquatic life species."). In effect, existing dissolved oxygen criteria for protection of cold water aquatic life (6 mg/L; 7 mg/L for spawning) would be applied to the upper half of the hypolimnion. Thus, the site-specific narrative is very strict for dissolved oxygen, and there is some question about how to apply it to a reservoir subject to de-stratification. Nevertheless, it would be hard to claim that dissolved oxygen concentrations are routinely in attainment of the narrative.

The Division concludes that although water quality has improved since the time of the Clean Lakes study, the reservoir is not in attainment of the narrative standard. Consequently, it is time to review expectations and to consider recasting standards in numeric form. Several steps are necessary for completing the technical review and creating the basis for new site-specific nutrient criteria.

The first step involves estimation of phosphorus loads to the reservoir as the basis for predicting summer phosphorus concentrations (Exhibit 3). Estimation of phosphorus loads depends on a thorough understanding of flow sources and the factors influencing phosphorus concentrations in each of those sources. Prediction of phosphorus concentrations requires knowledge of phosphorus sedimentation rates and the potential for internal loading.[9]

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[8] Trophic state characterizes the level of algal productivity in a lake. Broad categories classify lakes with low (oligotrophic), moderate (mesotrophic), or high (eutrophic) levels of productivity. The concentration ranges for chlorophyll and nutrients associated with each category are taken from the OECD classification scheme.

[9] The phosphorus delivered to the reservoir by surface or ground water sources constitutes the *external load* in the sense that it is new to the reservoir. It is common for a large portion of the external load to be retained in the lake sediments. Often, the retained phosphorus is "buried" and unavailable to algae. However, under certain environmental conditions, the retained phosphorus can be released back into the lake. This is called *internal load*, and it can augment external load for many years even after external load is reduced.

The second step in the analysis is the development of site-specific nutrient criteria (Exhibit 4). The Division regards this step as an opportunity to translate the existing narrative standard into numeric values for one or more constituents, with the intent of preserving the water quality goals set forth previously by the Commission. Where numeric standards can be justified, they facilitate assessment by avoiding the subjectivity inherent in a narrative standard.

Finally, the allowable phosphorus load is developed to link the proposed water quality standards to the control regulation. The existing control regulation contains allocations for POTWs, but does not define the total load consistent with attainment of the narrative standard. This is a serious shortcoming that should be remedied. In addition, it is necessary to describe the steps to be taken in the future to complete the partitioning of the allowable phosphorus load and to revise, if necessary, the allocations.