Bear Creek Reservoir Load Translator

Phosphorus originating from various external sources comprises the “load” delivered to the reservoir. Load is usually assessed on an annual time step when it is used to predict concentrations in the reservoir. The quantitative linkage between external load and in-lake concentration has been called the “load translator” in previous discussions. The modeling concepts behind the load translator are well-developed, having been articulated more than 40 years ago. Of course, practical application of the concepts may present challenges for prediction of phosphorus concentration in any particular lake.

Mass balance models are typically used as load translators. Widely used models include one developed by Vollenweider (1975) and another developed by Dillon and Rigler (1974)(Equations 1 and 2). These models predict the concentration of phosphorus in the lake as a function of the phosphorus load delivered from the watershed, the hydrologic characteristics of the reservoir, and the amount of phosphorus retained in the reservoir.

$$TP = L / \left[\bar{z}(\sigma + \rho)\right]$$

Equation 1. Vollenweider equation where TP is in-lake total phosphorus (µg/L), L is annual phosphorus load per unit area (mg/m^2/y), z is mean depth (m), σ is the phosphorus sedimentation rate (y^{-1}), and ρ is the hydraulic flushing rate (y^{-1}).

$$TP = L(1 - R) / \bar{z}\rho$$

Equation 2. Dillon-Rigler equation where TP is in-lake total phosphorus (µg/L), L is annual phosphorus load per unit area (mg/m^2/y), R is the phosphorus retention coefficient, z is mean depth (m), and ρ is the hydraulic flushing rate (y^{-1}).

The models assume that all phosphorus comes from sources external to the reservoir. Annual load sets an upper bound on the concentration expected in the reservoir. The in-lake concentration is usually less that the input concentration because significant amounts of the external phosphorus load are deposited and retained in lake sediments. Each model incorporates a term that discounts the load in order to account for retention.

All components of each model, except phosphorus retention, are measured, making it possible to solve for retention in any year. However, a model can only be applied to future load scenarios if phosphorus retention can be estimated independently. The set of retention values derived from the historical record can be tested with various predictors. Hydrologic variables have been used to explain variation among lakes, but it is not a foregone conclusion that they will be suitable for explaining variation among years for a single lake. In the absence of a predictor, an average of the observed values may be the best estimate of retention.

The net amount of phosphorus retained is the difference between load and export. The external load component, which has already been presented in a previous document, is summarized in Table 1. Export is simply the amount of phosphorus that leaves the reservoir via the outflow. The basis for calculating export is explained below.

Year	Load, lbs/y	Export, lbs/y	Outflow, AF/y	Net Retention, lbs/y (% of load)
1991	18886	11060	31474	7826 (41.4)
1992	16181	7525	23466	8656 (53.5)
1993	11421	4961	16179	6460 (56.6)
1994	8690	2818	15759	5873 (67.6)
1995	10493	7709	74106	2784 (26.5)
1996	3215	995	27550	2219 (69.0)
1997	6439	3474	48198	2965 (46.0)
1998	10530	5840	76225	4689 (44.5)
1999	6510	4384	60002	2126 (32.7)
2000	1342	823	12778	519 (38.7)
2001	1749	1587	17008	162 (9.3)
2002	483	227	3199	256 (53.0)
2003	2273	3346	23141	-1072 (---)
2004	2802	1374	28526	1428 (51.0)
2005	3431	2820	34796	611 (17.8)
2006	1092	525	8793	567 (51.9)
2007				

Table 1. Phosphorus load and export estimates for Bear Creek Reservoir, 1991-2006. Net retention is calculated as the difference between load and export; it is also expressed as a percent of the load.

The amount of phosphorus leaving the reservoir is estimated from the outflow volume, which is measured daily, and the measured concentration, which is measured only on sampling dates. As was the case with estimating phosphorus loads, concentrations must be assigned to each day of the year. The basis for assigning concentrations to the outflow is different than the probabilistic approach applied to the inflows for reasons related to sources of variability. The “noisy” relationship between flow and concentration for the external loads is not expected for the export. Phosphorus concentrations in the outflow should be relatively stable over time, because the water is withdrawn from a large and relatively well-mixed volume of lake water. The large volume of the reservoir acts as a buffer against the kind of short-term variability that may affect concentrations in streams. In other words, concentration should be independent of outflow volume. Consequently, the best estimate of concentration to apply to the outflow is the “typical” concentration of the water that is being released.

The concentration of the phosphorus in the surface sample from the lake is used to represent the export concentration. Selection of the surface sample is consistent with the assumption of the mass-balance models that outflow concentration matches surface concentration in the lake. On a few dates, chiefly in the winter when ice conditions were unsafe, the outflow concentration is used in place of the lake surface sample.

It is clear from a time series (Figure 1) that temporal trends exist for outflow concentrations; a similar pattern was observed for the inflow concentrations. Distributions of phosphorus concentrations from each year help focus attention on key features in the data, and they demonstrate clearly the extent to which concentrations were reduced during the early 1990s (Figure 2). Variability appeared to increase from 2000-2003 for reasons that are not clear, although the increase might be related to operation or performance of aeration equipment. The data show a strong seasonal pattern in which concentrations are elevated progressively and substantially from May through September (Figure 3), suggesting a measurable role for internal loading.

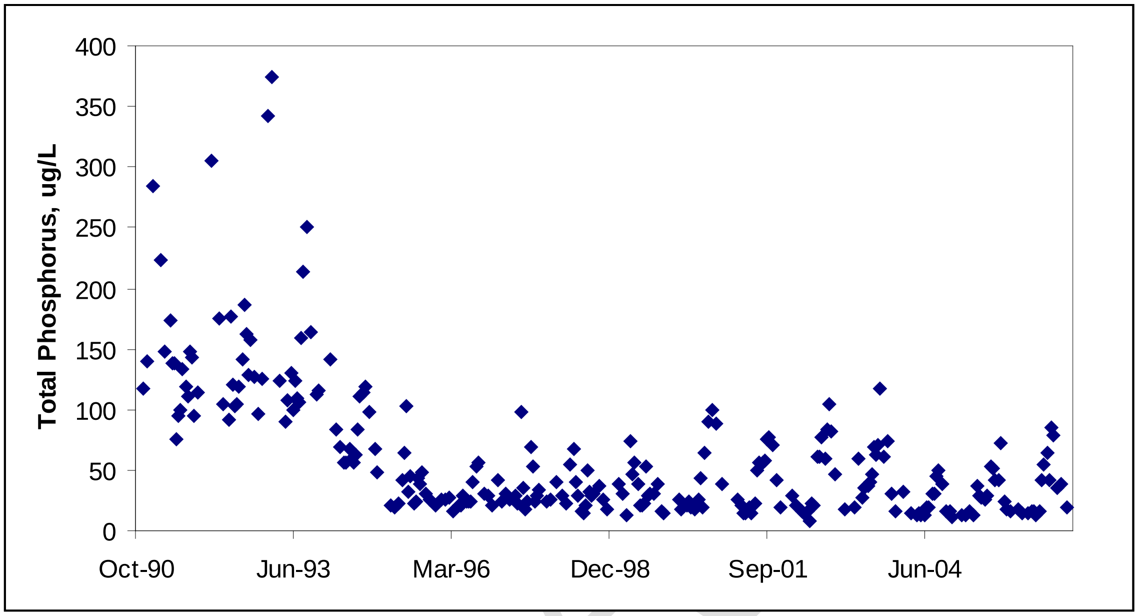

Figure 1. Total phosphorus concentrations in the surface water of Bear Creek Reservoir. On a few dates, chiefly in the winter months when ice conditions were unsafe, the outflow concentration was used.

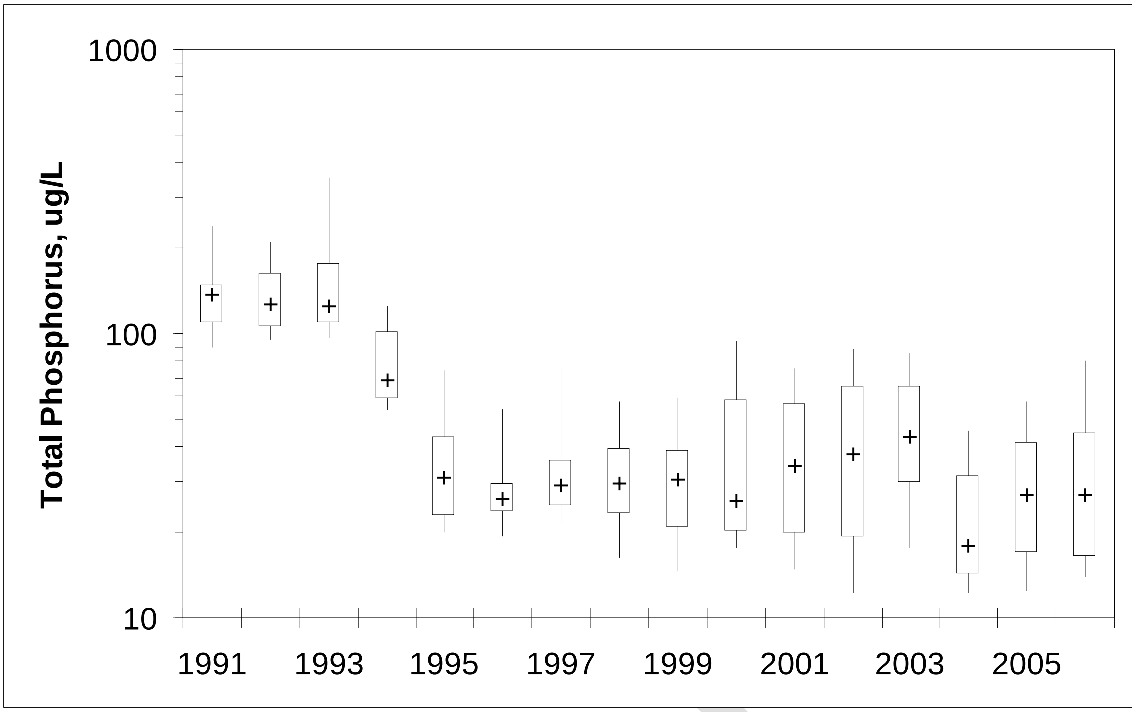

Figure 2. Annual distributions of phosphorus concentrations (log scale) measured in the Bear Creek outflow, as represented by box-and-whisker plots. The central 50% of measurements is enclosed by the box and the tips of the "whiskers" show the 5th and 95th percentiles. The annual median is shown as a symbol inside each box.

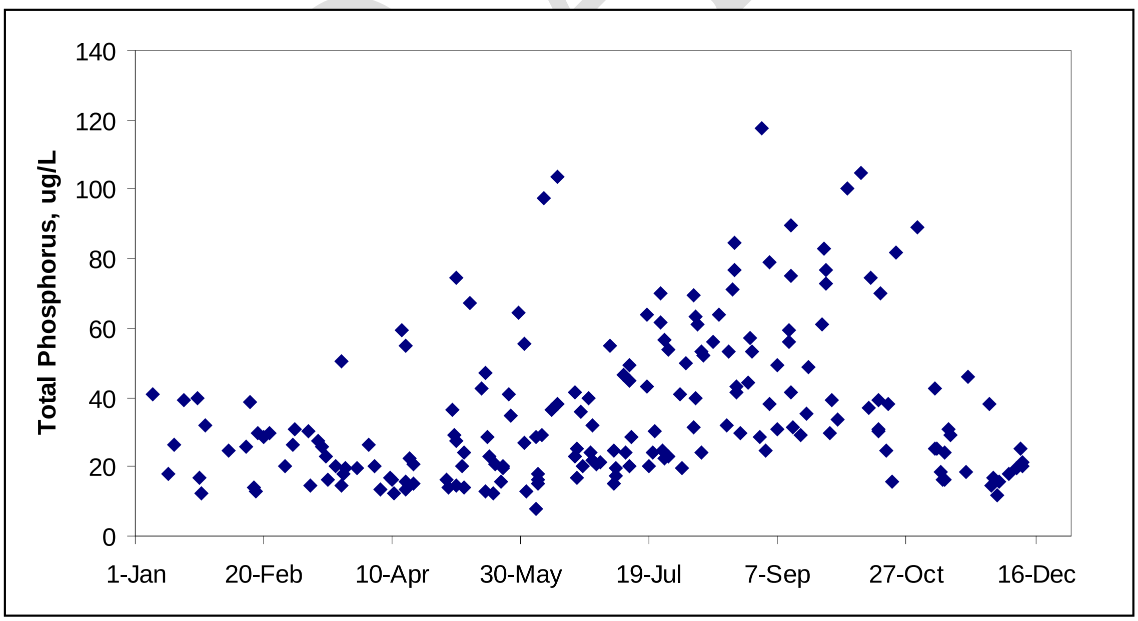

Figure 3. Seasonal pattern of phosphorus concentrations in the surface water of Bear Creek Reservoir, 1995-2006. Earlier years were omitted because the higher concentrations would have obscured the seasonal pattern.

Aggregation is applied to samples taken within seasons each year (Table 2). Stratification season medians were determined for each year in the period of record.

Differences among years may be relatively large. The same strategy is applied to the other months, even though it crosses the calendar year boundary. The median concentration is shown with the final year of each non-stratification season (e.g., Oct 1998 through Mar 1999 is shown with the 1999 data).

Year	Outflow, AF/y	Winter Phosphorus, mg/L	Stratification Phosphorus, mg/L	Input Phosphorus, mg/L
1991	31474	0.181	0.136	0.218
1992	23466	0.144	0.125	0.250
1993	16179	0.127	0.123	0.254
1994	15759	0.115	0.067	0.199
1995	74106	0.049	0.042	0.052
1996	27550	0.026	0.024	0.042
1997	48198	0.030	0.029	0.049
1998	76225	0.027	0.031	0.051
1999	60002	0.030	0.030	0.040
2000	12778	0.018	0.024	0.038
2001	17008	0.064	0.036	0.037
2002	3199	0.029	0.023	0.052
2003	23141	0.046	0.060	0.035
2004	28526	0.031	0.020	0.036
2005	34796	0.014	0.036	0.036
2006	8793	0.017	0.041	0.044
2007		0.039		

Table 2. Seasonal median phosphorus concentration in Bear Creek Reservoir. The stratification season extends from April through September and the winter season extends from October through March. Annual average (flow-weighted) concentrations are shown for perspective.

The frequency with which outflow concentrations exceed the input concentrations is an important clue that Bear Creek Reservoir experiences significant internal loading of phosphorus. In the early years of sampling, prior to operation of aerators, a role for internal loading was obvious because hypolimnetic concentrations were clearly elevated. Aerators were first installed in 1993 to address problems with dissolved oxygen, but also with the hope of curtailing internal load. Different technologies and operating strategies have been employed over time (Table 3), but it is now apparent that internal load has not been eliminated. The contribution of internal load to the phosphorus budget of the reservoir is probably significant, making its estimation necessary.

Year	Aerator Technology
1993	Three towers installed
1998	North and South towers failing
1999	Installed six barrel-type bottom aerators
2000	Still operating Middle tower
2001	Still operating Middle tower
2002	Installed eleven pan diffusers

Year	Aerator Technology
2004	Compressors operated on timers

Table 3. Timeline for installation and operation of aerators in Bear Creek Reservoir.

Estimating Internal Release of Phosphorus

It is common in productive lakes for phosphorus to be released from the sediments during the summer months. Although internal release is often associated with loss of oxygen in the hypolimnion, it has been recognized for some time that oxygen depletion is more of a correlate than a requirement. There are many shallow, productive lakes (like Cherry Creek Reservoir) that do not stratify persistently, but which show significant release of phosphorus from the sediments. The indirect evidence for internal release in Bear Creek Reservoir is similarly strong.

Quantifying internal release is difficult because direct measurements have not been made (and are unlikely in the future because the technical challenges are substantial). The internal load must be estimated indirectly, and accuracy depends on the soundness of assumptions made to facilitate the calculations. Assumptions are related mainly to the persistence of internal load over time and the retention of phosphorus that originates within the lake rather than from the watershed.

Internal load consists of phosphorus released from lake sediments under the proper physical and chemical conditions. In general, sediments must be relatively rich in organic material, and redox conditions must be such that phosphorus mobilized within the substrate can diffuse into the overlying water. What this usually means is that release is most likely from a relatively small portion of the lake bottom, the area of which is likely to remain roughly the same from year to year. The rate of release is sensitive to temperature, meaning that the duration of release is likely to be similar from year to year. Therefore, the first assumption for Bear Creek Reservoir is that the rate of internal release is likely to be of similar from year to year.

Phosphorus generated by internal release should enter the water column exclusively in the dissolved form, in sharp contrast to the external load for which a large component may be in the particulate fraction. Although the internal load may originate as dissolved phosphorus, it quickly becomes part of biomass in the lake, at which point it is subject to settling. This raises an accounting question related to the rate of release vs. the net effect on concentrations in the lake. Should the internal load be discounted with a phosphorus retention coefficient in the same manner applied to external load in mass balance equations? Rather than investing effort in trying to resolve this conundrum, it is sufficient to measure the net internal release and assume that the gross internal load is of no practical interest.

From a mass balance perspective, internal load adds phosphorus to the lake in a manner that is recorded in the export, but is not part of the measured (external) load. By diminishing the difference between export and external load, internal load makes it *appear* that the retention coefficient is smaller than is really the case. This happens because the normal mass-balance equations use a net retention coefficient, which is blind to the source (internal vs. external), but is scaled to the external load. Disentangling the retention coefficient from the internal load is most tractable in years when the external load is very small (e.g., 2002). When external load is negligible, internal load should be evident in the summer months.

The net effect of internal load can be determined by tracking changes in the phosphorus content of the reservoir between adjacent sampling dates. The phosphorus content is calculated on each sampling date using the concentrations recorded in the three grab samples (top, middle, and bottom of the water column) with assumptions about the volume of water represented by each of the samples. If the volume is partitioned into three strata of equal thickness, they represent 56%, 33%, and 11% of the volume respectively. The three values of concentration are assigned to these three strata and a volume-weighted concentration is calculated on each sampling date. Any change in phosphorus content between two adjacent dates can be explained on the basis of measured external load and export, plus any contribution from internal load.

The ideal scenario for observing the effect of internal loading would be a year in which there was minimal inflow; the drought of 2002 provides that scenario (Figure 4). The volume-weighted phosphorus concentration in the reservoir, which was about 20 ug/L early in the spring, began to rise steadily beginning in early June and reached a maximum of 106 ug/L in early October. The rate of increase was about 0.6 ug/L/d. It is not clear why concentrations declined after early October, although is may be related to operation of aerators, which were turned off just before the peak concentration was observed.

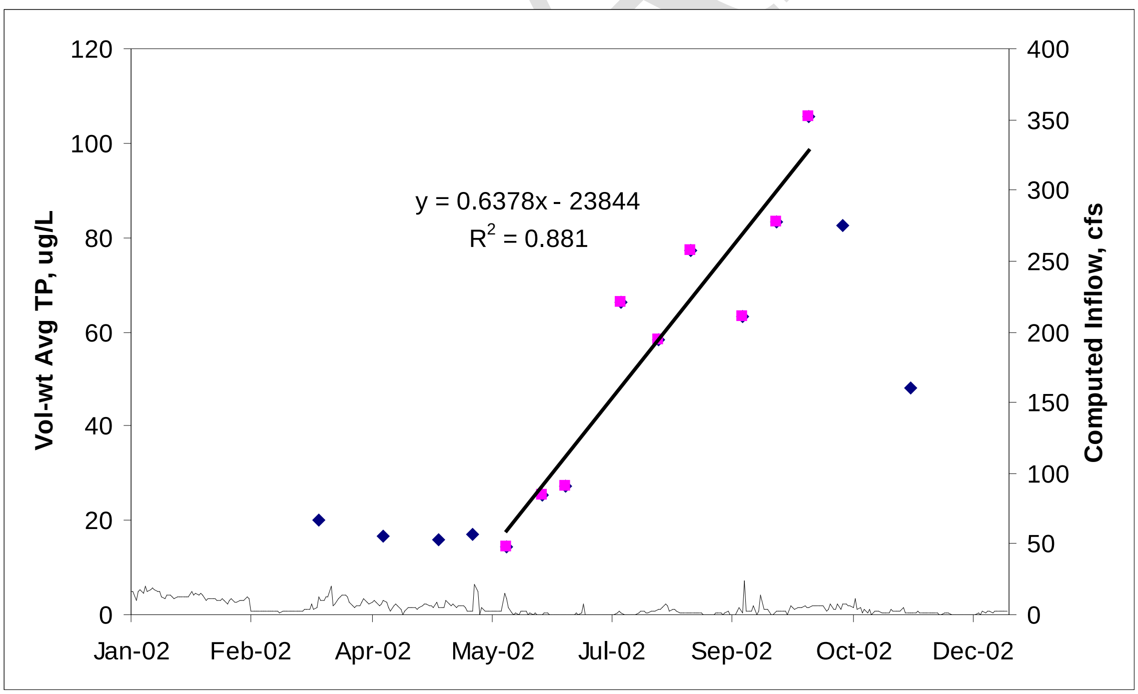

Figure 4. Whole-lake average phosphorus concentration on each sampling date in the drought year of 2002. Increasing concentrations from May through September reflect mainly the influence of internal loading. Computed inflow to the reservoir (solid line at the bottom of the graph) is very small; the right axis is scaled to be comparable to typical years.

If the pattern observed in 2002 represents the typical timing of internal release, it can serve as a guide for analyzing release rates in other years. Internal release depends on biological processes that are relatively sensitive to temperature. Consequently, temperature can be used as an approximate guide to the window of time in which release can be expected. In Bear Creek Reservoir, temperatures near the bottom are at or above 15^{o}C for the time period over which the release rate was assessed in Figure 4.

Assuming that temperature on the bottom is important for stimulating internal release, attention should be restricted to those years in which aerators de-stratified the reservoir providing more uniform temperatures and warming the bottom layer earlier in the year. In general, bottom temperatures exceeded 15^{o}C for a period of only one or two months in the years prior to 1999. After installation of the barrel aerators, in July 1999, bottom temperatures exceeded 15^{o}C for 3 to 4 months in each year. The years 2000-2006 are the focus for estimating internal load because the operating regime for the aerators was relatively consistent. Within that period of seven years, the release rate is generally highest when the annual inflow volume is smallest. Given that no adjustment has been made for phosphorus added to or released from the lake, this is expected. One anomaly in the pattern is 2006, which has a low inflow volume but a relatively poor relationship between gain in phosphorus content and time. The relationship for 2006 is improved dramatically if the last sampling date in September is excluded. Exclusion is justified because the large compressors were turned off earlier in the season than had been typical. While it is not entirely clear how aeration affects phosphorus concentrations, it is clear that in late fall, when aerators usually are off, phosphorus concentrations decline rather sharply.

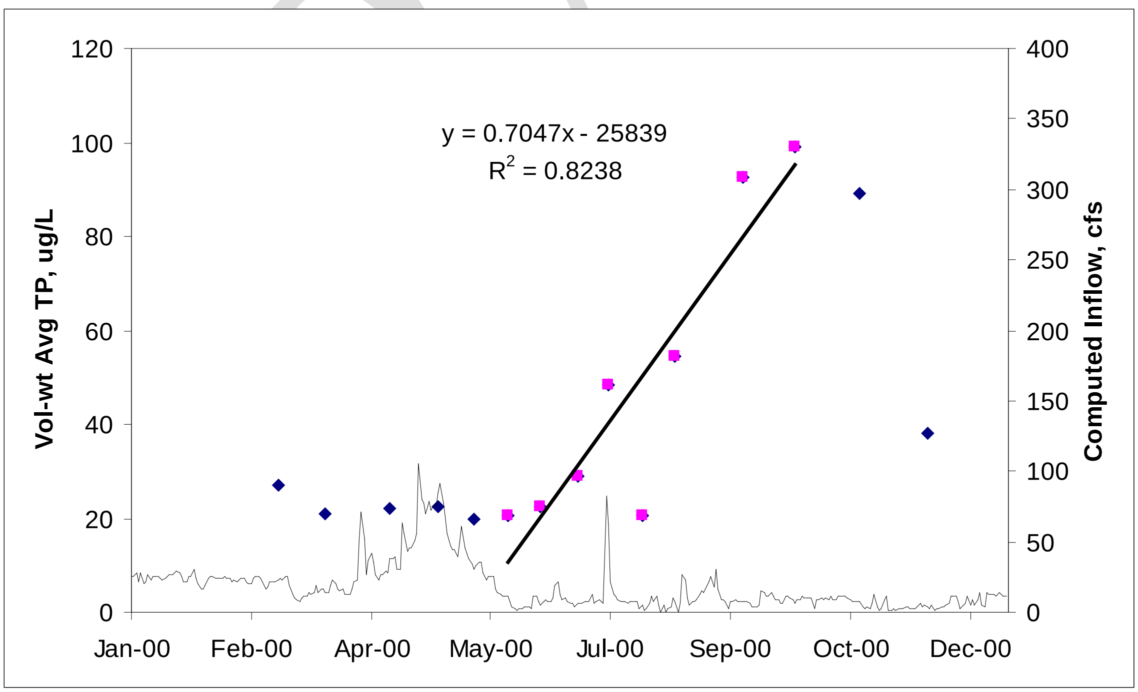

Figure 5. Whole-lake average phosphorus concentrations in 2000. The rate of change in concentration from May through September reflects mainly the influence of internal loading. Computed inflow (thin solid line) is shown on the right axis.

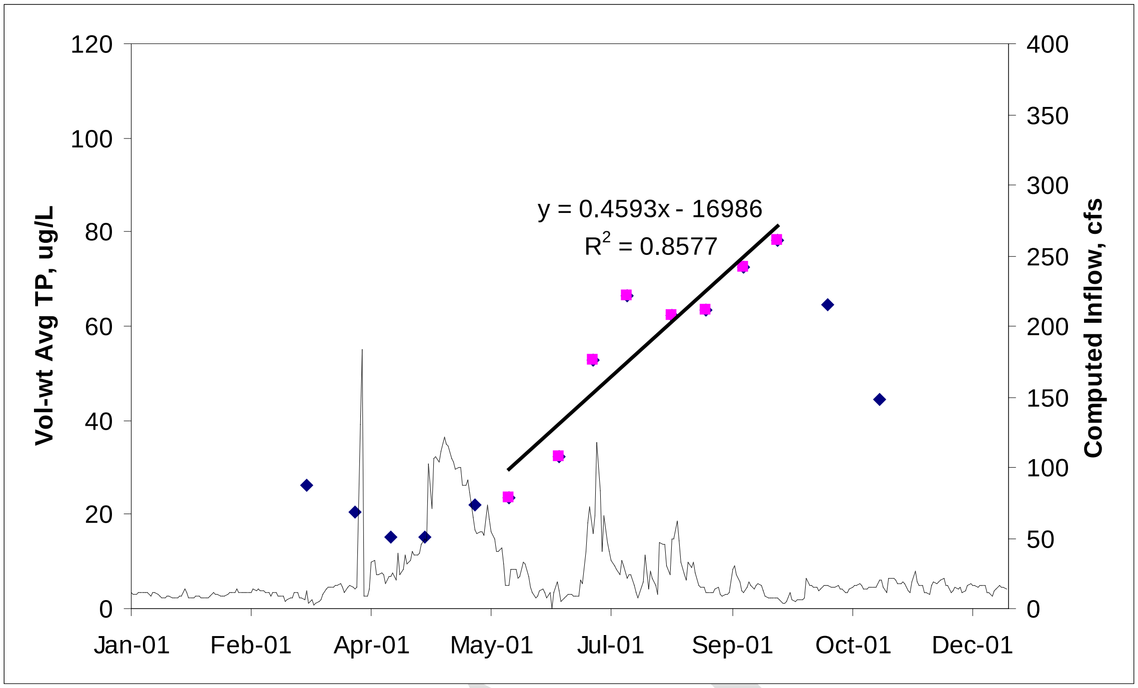

Figure 6. Whole-lake average phosphorus concentrations in 2001. The rate of change in concentration from May through September reflects mainly the influence of internal loading. Computed inflow (thin solid line) is shown on the right axis.

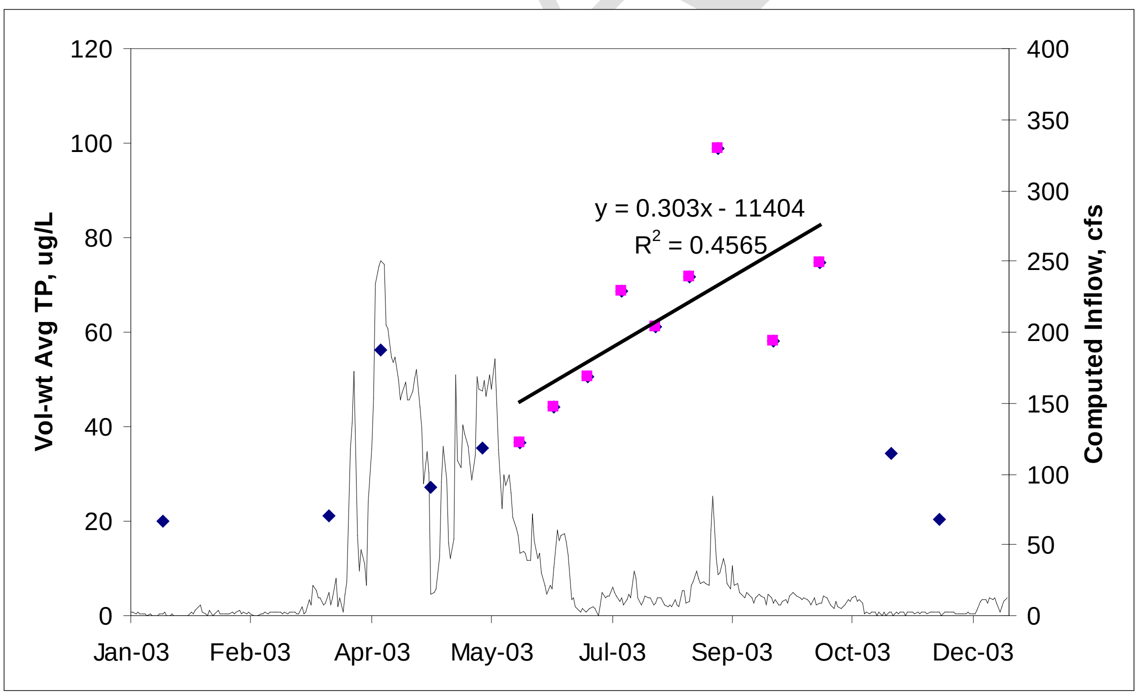

Figure 7. Whole-lake average phosphorus concentrations in 2003. The rate of change in concentration from May through September reflects mainly the influence of internal loading. Computed inflow (thin solid line) is shown on the right axis.

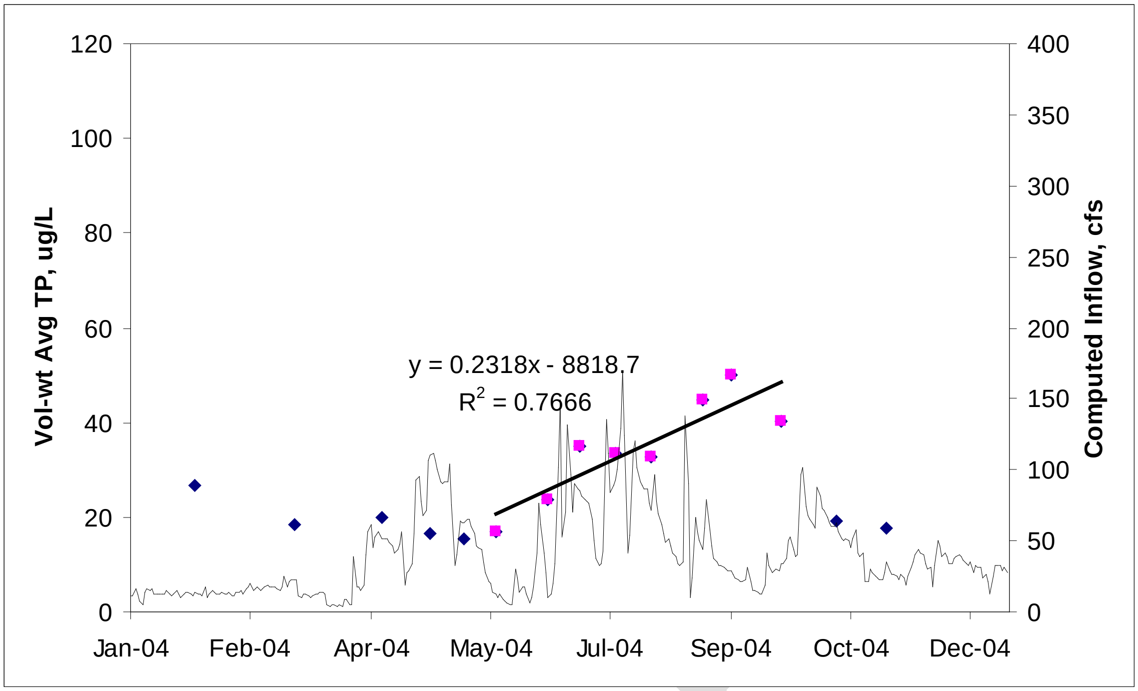

Figure 8. Whole-lake average phosphorus concentrations in 2004. The rate of change in concentration from May through September reflects mainly the influence of internal loading. Computed inflow (thin solid line) is shown on the right axis.

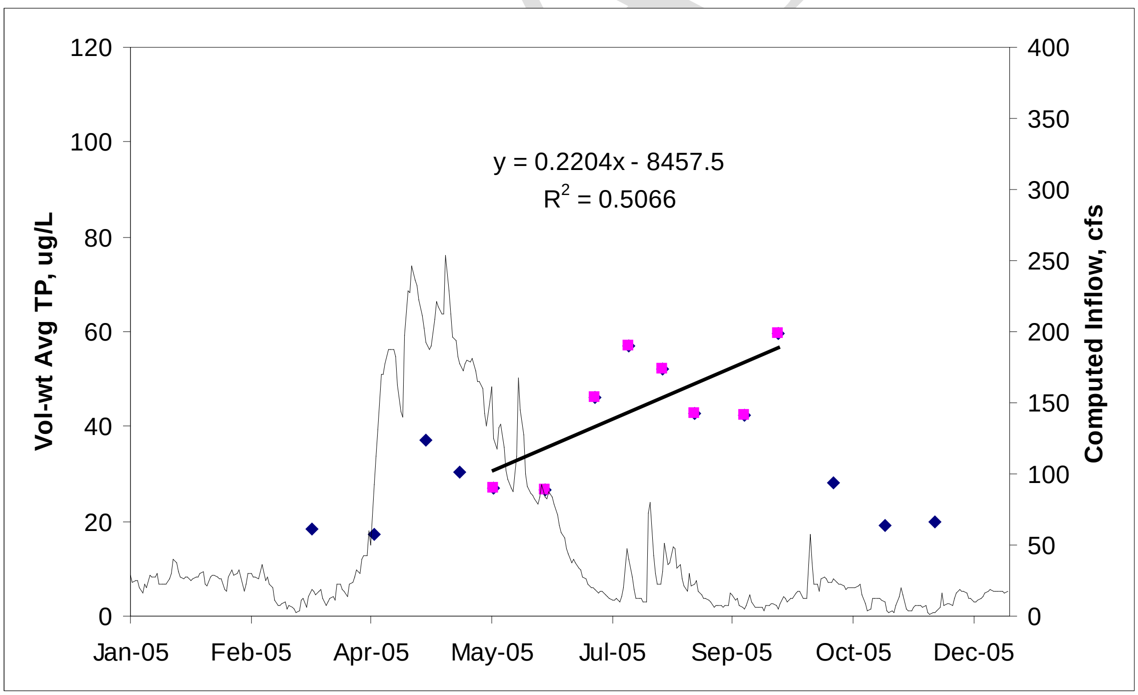

Figure 9. Whole-lake average phosphorus concentrations in 2005. The rate of change in concentration from May through September reflects mainly the influence of internal loading. Computed inflow (thin solid line) is shown on the right axis.

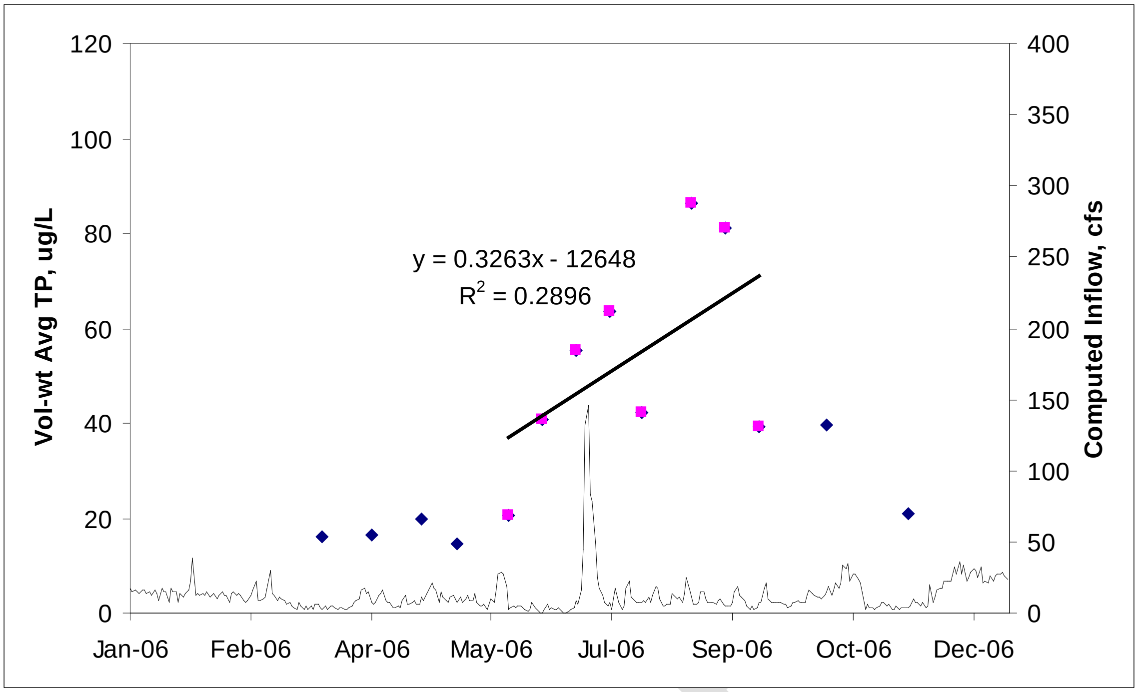

Figure 10. Whole-lake average phosphorus concentrations in 2006. The rate of change in concentration from May through September reflects mainly the influence of internal loading. Computed inflow (thin solid line) is shown on the right axis.

Year	Computed Inflow, AF/y	Slope, ug/L/d	R^2
2000	13101	0.705	0.824
2001	17353	0.459	0.858
2002	3437	0.638	0.881
2003	23693	0.370	0.465
2004	28891	0.232	0.767
2005	35147	0.220	0.507
2006	9128	0.627	0.762

Table 4. Rates of increase in phosphorus content (slope) in recent years when aerator operation was relatively consistent (see text). Slopes are calculated for sampling dates from the beginning of June through early October. The interval for 2006 was shortened slightly for reasons explained in the text. In general, slopes are higher and more variance is explained when inflows are low.

Based on the years with low inflows (2000-2002, 2006), the upper end for the rate of increase in phosphorus content is between 0.6 and 0.7 ug/L/d. Assuming a volume of 1900 AF and release over a period of about 130 days, internal contributes about 430 lbs of phosphorus per year. The internal load is probably constant from year to year, although its effect on in-lake concentrations may be obscured during years of high inflow volume.

Phosphorus Retention

The mass-balance models shown at the beginning of this document take slightly different approaches to the retention of phosphorus, and each is worth examining briefly. The

Vollenweider model assumes that retention is a proportion of phosphorus content in the lake, whereas the Dillon-Rigler model assumes that retention is a proportion of load (see Prairie 1989). Empirical relationships have been developed to predict retention for each model, and these are useful for exploring the relative merits of the two models. Some caution is advisable in viewing the results because the relationships were developed for explaining variation among lakes rather than year-to-year variation within a lake.

The sedimentation rate, σ, in the Vollenweider model can be estimated from an empirical relationship (Equation 3) developed by Canfield and Bachmann (1981). Predictions from the empirical relationship are compared with observed values from the period of study (Figure 11). There is little to suggest that the predictive relationship will be helpful in developing a load translator for Bear Creek Reservoir.

$$\sigma = 0.114 * (L / \bar{z})^{0.589}$$

Equation 3. Canfield-Bachmann equation for predicting the phosphorus sedimentation rate, σ, in artificial lakes as a function of external phosphorus load (L, mg/m^2/y) and mean depth (z, m).

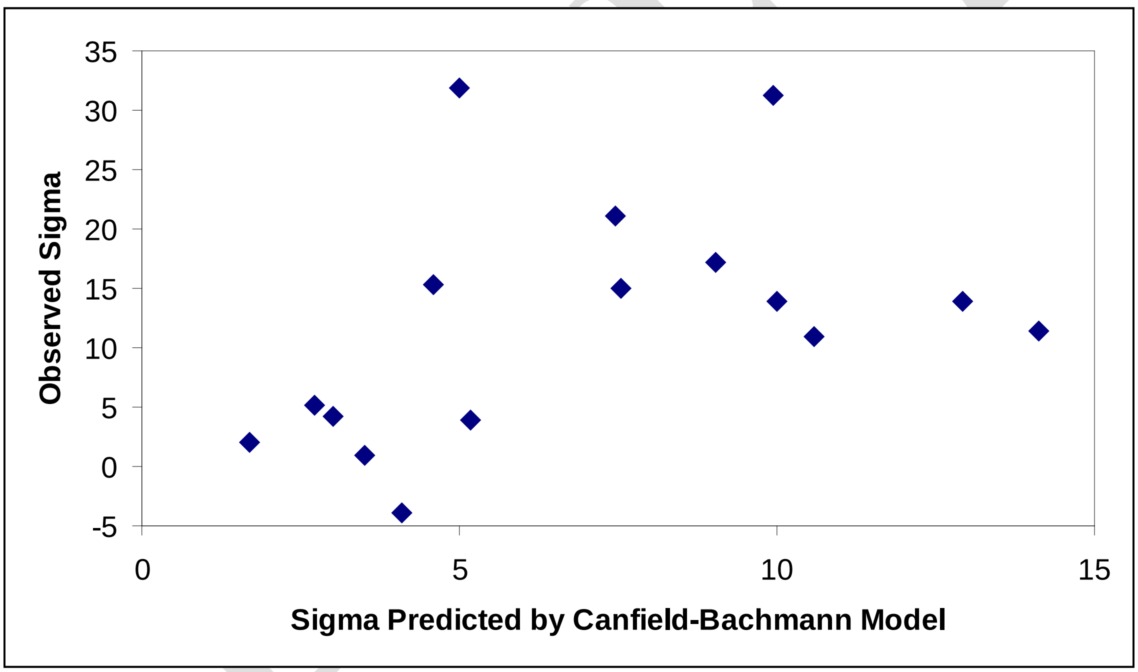

Figure 11. Observed vs. predicted values for the phosphorus sedimentation coefficient in the Vollenweider model.

The retention coefficient in the Dillon-Rigler model can be estimated from the OECD relationship (Equation 4), as developed for reservoirs (OECD 1982). Predicted values of the phosphorus retention coefficient are compared to the observed net retention values (Figure 12). Again, the performance of the predictive relationship is relatively poor.

$$R = \frac{1}{1 + \frac{1}{2\sqrt{\tau}}}$$

Equation 4. Phosphorus retention coefficient, R, as a function of hydraulic residence time, τ.

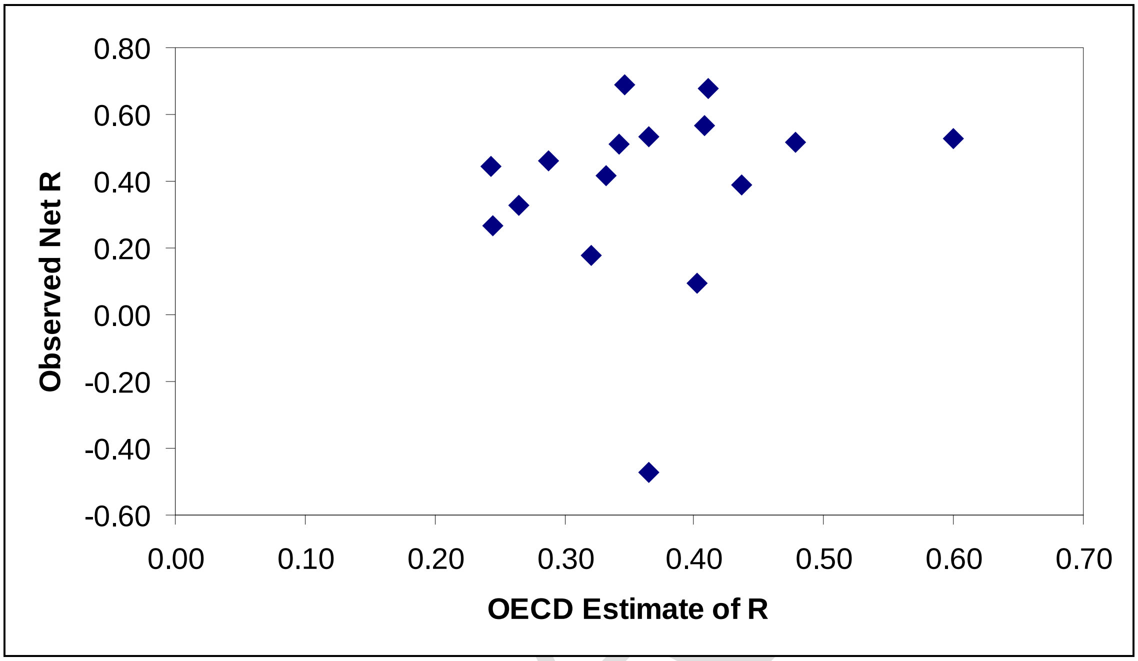

Figure 12. Observed vs. predicted values for phosphorus retention in the Dillon-Rigler model.

That neither predictive relationship offers a suitable basis for independent estimation of phosphorus retention is not particularly surprising. Those relationships were developed to explain variation among lakes, and they do not seem to perform very well when applied to the task of explaining variation among years for one lake. Similarly unsatisfying results have been obtained for other Colorado reservoirs. It would be a mistake, however, to conclude that there is no pathway to developing a load translator for Bear Creek Reservoir.

When the observed variation cannot be explained by the likely parameters, it is preferable to use an approach that defines central tendency for the observed values of retention. In this case, where internal load is strongly suspected, linear regression can be applied to explain variation in export as a function of external load. The slope of the relationship is the complement of the net retention coefficient as it is defined in the Dillon-Rigler model.

A comparison of export and load can be used to estimate the *net* retention coefficient (Figure 13). The data suggest that export represents about 64% of load, meaning that 36% of the load is retained in the reservoir. Some problems are apparent in the figure – there is one year when the export exceeds the load and two years when the export is about equal to the load. These are clues that internal load is potentially important (assuming that reservoir volume remains relatively constant, which it does). With the estimate of internal load now available, the internal load can be added to the external load and the figure re-plotted (Figure 14). The slope is changed very little by this exercise (retention is about 35%), and the data from 2003 continue to show that export exceeds load, albeit not by much.

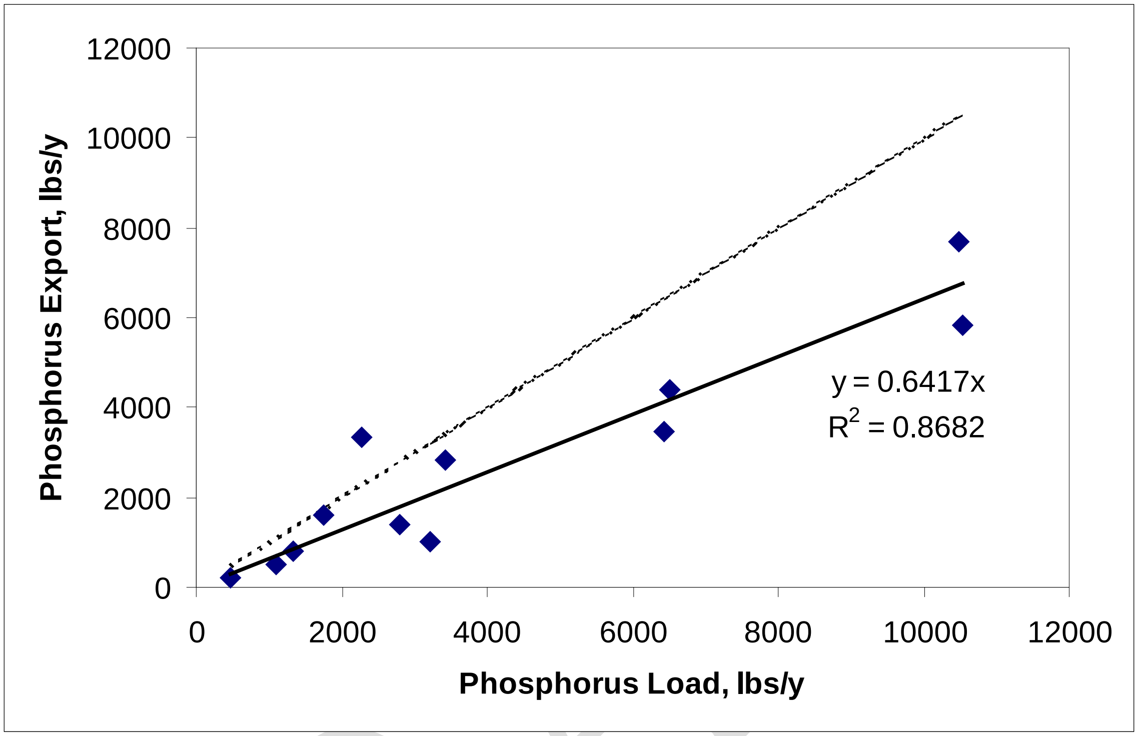

Figure 13. Phosphorus export as a function of external load in Bear Creek Reservoir, 1995-2006. The dashed line defines export equal to load; points above the line represent years in which export exceeds load. The solid line is the best fit for the observed values. The intercept has been set to zero.

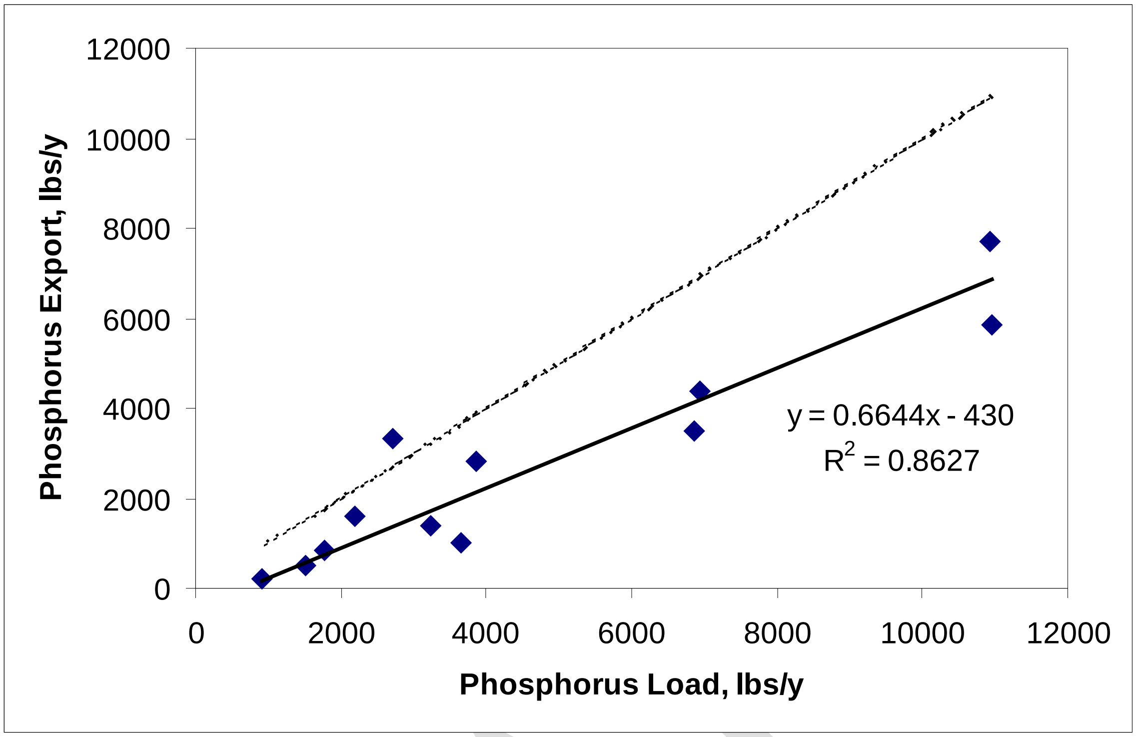

Figure 14. Phosphorus export as a function of external load in Bear Creek Reservoir, 1995-2006. The dashed line defines export equal to load; points above the line represent years in which export exceeds load. The solid line is the best fit for the observed values. The intercept has been set to equal to the estimate of net internal load (see text).

Developing a Load Translator

Specifying phosphorus retention as a fraction of load is consistent with use of the Dillon-Rigler model cited above. In fact, as long as reservoir volume remains relatively constant, the equation predicts in-lake concentration as a fraction of input concentration (in-lake equals input times one minus retention). Thus, if there were no internal load, the phosphorus concentration in Bear Creek Reservoir should be about 64% of the input concentration. However, internal load appears to be persistent in Bear Creek Reservoir, and it is a significant portion of total load in years with relatively low inflows. Even after including internal load, there remain some practical difficulties associated with implementing a load translator.

The mass-balance model predicts a volume-weighted annual average phosphorus concentration, but the goal for regulatory purposes is the phosphorus concentration of the mixed layer during the summer (Jul-Sep). In Bear Creek Reservoir, where the water mass typically is turned over 13 times per year (1987-2007), unless the input concentration does not vary over time, a question arises about the connection between the annual average concentration and the concentration during the summer months when attainment must be examined. The seasonal nature of internal loading also has bearing on this question. The effect of internal load on algal growth is likely to be very restricted in time. When lake phosphorus content was examined earlier, it was clear that, under the right conditions, internal load could boost the average concentration to 80-100 ug/L by the end of the summer from a starting point of about 20 ug/L in the spring.

The short residence time and importance of internal loading in Bear Creek Reservoir influence development of the load translator in a manner best described in narrative form. There is no apparent linkage between input volume and concentration, making it possible to use the typical flow-weighted annual average of phosphorus input, which is 41 ug/L (1995-2006). The input concentration has been adjusted to the outflow volume to be consistent with the mass-balance model approach (i.e., accounts for the loss of volume to evaporation). If 34% of the external load is retained, the expected concentration in the reservoir would be about 27 ug/L, which is at the low end of what has been observed in the mixed layer during the summer months (Jul-Sep). Internal load can be expected to augment the mixed layer concentration during the summer, but the effect is more pronounced in low flow years (Figure 13). Based on the trajectory of phosphorus concentrations recorded in 2002, the median summer concentration should be about 60 ug/L, which is close to the top end for observed summer medians.

The load translator proposed for Bear Creek Reservoir has two components, one that sets a baseline concentration determined by external load and another that augments the in-lake concentration based on internal load. The internal load component exerts maximum effect during low flow years. Some portion of the external load may be controllable, although estimating the amount is beyond the scope of the technical review. Nevertheless, it is clear that substantial reductions already were achieved in the early 1990s. The extent to which internal load can be controlled is not known; aeration does not eliminate internal load. Curtailing external load often has a delayed effect on internal load, but such an effect is usually observed within a decade. Clearly, the relative importance of internal load has implications for water quality expectations.

Citations

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