Technical Comparison of Watershed Protection Control Regulations

Colorado has watershed protection control regulations that are intended to counter the threat of eutrophication to reservoirs. Eutrophication refers to enrichment of the nutrient supply, chiefly through human actions, and the resulting, undesirable increase in the abundance of algae in the reservoir. The strategy behind control regulations is to curtail algal growth by controlling the supply of nutrients to the reservoir. Each of the four reservoir control regulations grew out of a Clean Lakes study performed during the 1980s. The Clean Lakes Program supported efforts by states to restore publicly-owned lakes. These reservoirs were perceived to be at risk of eutrophication due to impending development and population growth.

Each Clean Lakes study characterized water quality conditions and investigated the response of the reservoir to observed nutrient loads. Development of quantitative relationships between observed load and response enabled the prediction of response under future load scenarios. Once water quality goals were defined, it became possible to determine the nutrient load consistent with those goals.

Water quality goals were expressed in terms of chlorophyll and phosphorus concentrations. It was assumed that chlorophyll, which measures algal abundance, is the basis for protection of uses even though it is not, by itself, toxic. Existing control regulations are built on the assumption that phosphorus is the limiting nutrient or, if it is not always the limiting nutrient, it is the single most important nutrient when it comes to control of algal biomass. Accordingly, phosphorus became the standard on which the control regulations are based.

The function of the control regulation is to guide implementation of controls necessary to ensure attainment of the standard. The quantitative relationships (translators) describing response as a function of load are used in reverse to calculate the load consistent with attainment of the adopted standard. The allowable load is adjusted some to account for the range of hydrologic conditions that might occur in the future and to incorporate a margin of safety. The implementation component of the strategy, which will not be considered in this document, involves the partitioning of sources, allocation of allowable load, and identification of control measures.

In preparation for a formal review of the primary technical components of the Chatfield and Bear Creek control regulations, it is helpful to start with a brief comparison of the four existing reservoir control regulations. The comparison considers purpose and origin, as well as the technical core, which includes the underlying standard, the translator linking chlorophyll and phosphorus concentrations, and the translator linking phosphorus concentration to phosphorus load. It is the first in a series of evaluations in which the individual technical facets will be reviewed in considerable detail.

Clean Lakes Studies

To understand the origin of the control regulations, it is helpful to re-visit the original reports from the Clean Lakes studies. In each case, there was relatively little historical information on which to base a characterization of water quality conditions, and certainly not enough to document trends. Two of the reservoirs were relatively new at the time of the Clean Lakes studies. The studies were of brief duration, consisting of only a year or two of data collection, making conclusions inherently tentative.

The reports suggest that it was difficult to settle on water quality goals. There was some ambivalence about whether the goal should be to maintain or to improve water quality. In addition, user perception studies conducted at Chatfield and Cherry Creek reservoirs did not yield precise thresholds (Aukerman 1982).

For three of the reservoirs, maintenance of water quality was specified as the general goal for water quality (Table 1), although there was some hedging even on this goal. Flexibility was retained by wording that can be paraphrased as follows 'maintain chlorophyll as close as possible to present concentrations.' Only for Bear Creek Reservoir was there an explicit expression of interest in improving conditions. The goal for Lake Dillon – to maintain 1982 conditions – was not articulated in the Clean Lakes study, but did appear in the control regulation. Some goals have been modified in the years since they were first stated.

Initially, the control regulations were based on a numeric standard for total phosphorus concentration, except for the Bear Creek control regulation which is based on a narrative standard. Basing a control regulation on a phosphorus standard was practical insofar as implementation was based on phosphorus control. At the same time, however, phosphorus does not affect uses directly. In that regard, adoption of a chlorophyll standard could be justified. Chlorophyll has been adopted in place of phosphorus as the standard for Cherry Creek Reservoir, and has been discussed as a standard for Dillon and Chatfield. Phosphorus and chlorophyll standards are not mutually exclusive; they also could be applied in tandem or in a tiered scheme.

Data from the Clean Lakes studies provided a useful starting point for the technical components of the control regulations, but there were clearly opportunities for, and expectations of, improvement. The opportunities for improvement of control regulations occur regularly through the triennial review process. Each control regulation has benefited from continued study, and it is worth mentioning the technical refinements based on new data. Because changes to standards or translators have the potential to cause considerable anxiety among stakeholders, it is important to show that changes are well-justified.

Item	Dillon	Cherry Creek	Chatfield	Bear Creek
Reservoir completed	1963	1950	1975	1982
Goal derived from Clean Lakes study	Maintain 1982 trophic status	Maintain chl = 10.7 ug/L	Maintain chl = 14.6 ug/L	Shift to mesotrophic-eutrophic boundary
Clean Lakes chlorophyll, ug/L	1981: 6.7 1982: 7.3	10.7	14.6[3]	19
Clean Lakes phosphorus, ug/L	1981: 7.0 1982: 7.4	32	23.7[3]	111
Total phosphorus standard or goal, ug/L	7.4[1]	40[2]	27[1]	
Chlorophyll standard or goal, ug/L		15[1]	17[2]	
Averaging period	Jul-Oct	Jul-Sep	Jul-Sep	Mid Jun-Sep[4]
Frequency		9 of 10 yrs		
Concentration translator	Modified Dillon-Rigler	Modified Jones-Bachman	Modified Jones-Bachman	Prairie et al. (1989)
Load translator	Vollenweider	Vollenweider	Vollenweider	
Phosphorus retention estimator	Empirical, after Prairie (1989)	Modified Canfield-Bachmann	Modified Canfield-Bachmann	
TMAL, lbs/y	10,162	14,270	59,000	65,000[4]
TMAL hydrology, AF/y (year)	212,000 (1982)	10,977 (2000)	261,000 (Q10)	
[1] – adopted standard				
2 – implied by translator				
3 – Jul-Sep average				
4 – not in the control regulation				

Table 1. Comparison of general features of reservoirs subject to control regulations. See text for explanation of details.

Concentration translator

For a control regulation, the measure of success is attainment of the underlying numeric standard, which initially was phosphorus. As mentioned previously, the connection between phosphorus and chlorophyll is central to each control regulation because it links use protection (chlorophyll) to the presumed causal agent (phosphorus). The linkage between chlorophyll and phosphorus is based on a concentration translator, which is a regression line in each of the original Clean Lakes studies. These lines were not developed exclusively with Clean Lakes data due to the brevity of the studies and the scarcity of historical information. Instead, an equation was selected from the literature to characterize the linkage between chlorophyll and phosphorus concentrations, and it was adapted to match existing data, usually by adjusting the intercept. While this approach was expedient and necessary at the time, it does mean that there is room for improvement as more data become available.

In the Lake Dillon study, for example, a published equation (Dillon and Rigler 1974) was modified by adjusting the intercept until the line passed through the two points derived from the study (Figure 1). Modification of an existing equation was a logical approach to creation of a site-specific regulation. As more data accumulated through the monitoring efforts that followed adoption of the control regulation, it became evident that the translator could be improved. The concentration translator for Lake Dillon has been revised twice since the control regulation was adopted; the present version includes a term incorporating water load as an additional predictor variable.

For Cherry Creek Reservoir, the equation of Jones and Bachmann (1976) was used without adjustment because it predicted 1982 concentrations well. As monitoring data accumulated, it became apparent that there were shortcomings in the original model selection. The basis for linking chlorophyll and phosphorus has been changed since the control regulation was first adopted. In addition, the standard is now set in terms of chlorophyll and the goal is defined for phosphorus.

The concentration translator developed for Chatfield Reservoir was simply the Jones-Bachmann equation with the intercept adjusted such that the line passed through the 1982 data. A revision to the relationship was proposed in a 1992 review by Woodward-Clyde, but it was not used to propose regulatory changes.

A more complicated relationship, involving both nitrogen and phosphorus as predictors of chlorophyll, was proposed for Bear Creek, but it has not been applied in a regulatory context. Because Bear Creek Reservoir has a narrative standard that describes the water quality goals in terms of trophic status, there has not been a need to specify a formal linkage between chlorophyll and phosphorus.

The concentration translators developed as part of the Clean Lakes studies assumed implicitly that there was a direct correspondence between chlorophyll and phosphorus; for example, evaluation of the Lake Dillon equation at 5 ug/L total phosphorus predicts 4 ug/L of chlorophyll. As data sets have grown for the four reservoirs, it has become increasingly clear that natural variation is large and that the approach to the concentration translator is in need of review. A plot of seasonal average chlorophyll against seasonal average phosphorus for any of these reservoirs shows considerable variation that is not explained by the simple regression lines selected as translators during the Clean Lakes studies (Figure 2).

As an alternative to existing regression lines, the Division is proposing a simple response ratio (chlorophyll concentration divided by phosphorus concentration) as the basis for describing how much chlorophyll to expect in a lake that has a known amount of phosphorus. There is nothing novel in the approach, which was used by EPA in analyses of National Eutrophication Survey data more than 30 years ago (Hern et al. 1981). Much more will be said about this topic in a subsequent meeting.

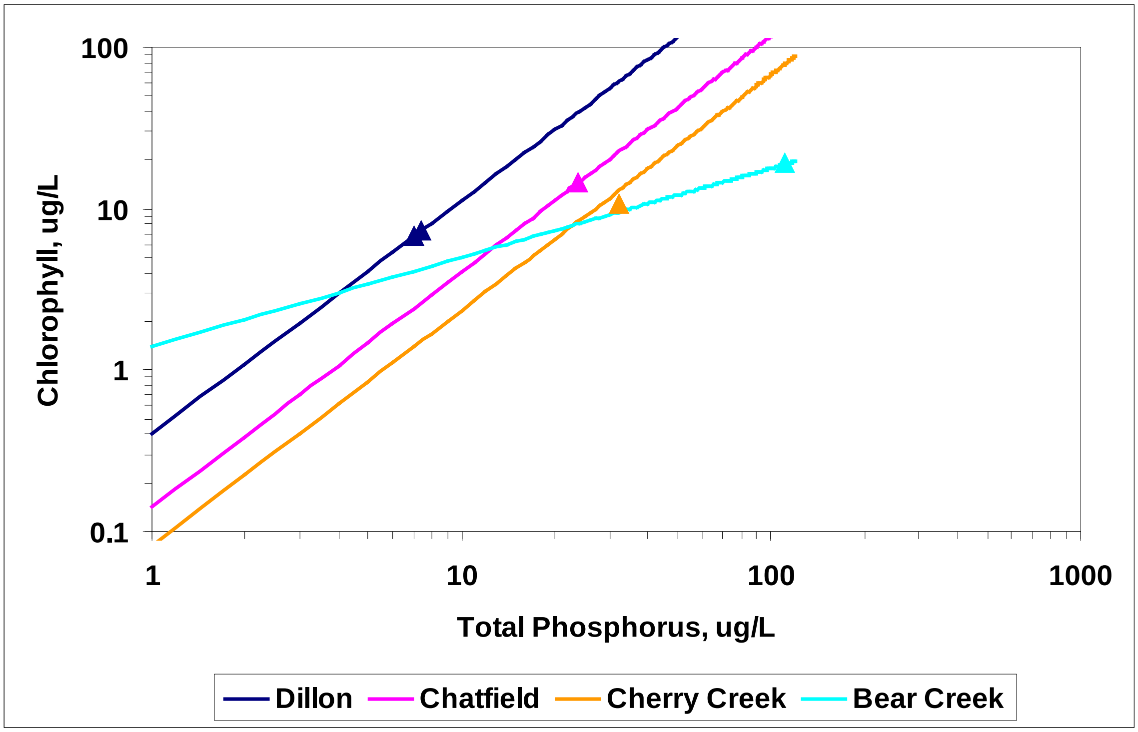

Figure 1. Concentration translators developed for each reservoir using data from Clean Lakes studies. Each line (log-log relationship) is based on a published equation or modification thereof. Each point represents conditions observed during the Clean Lakes studies.

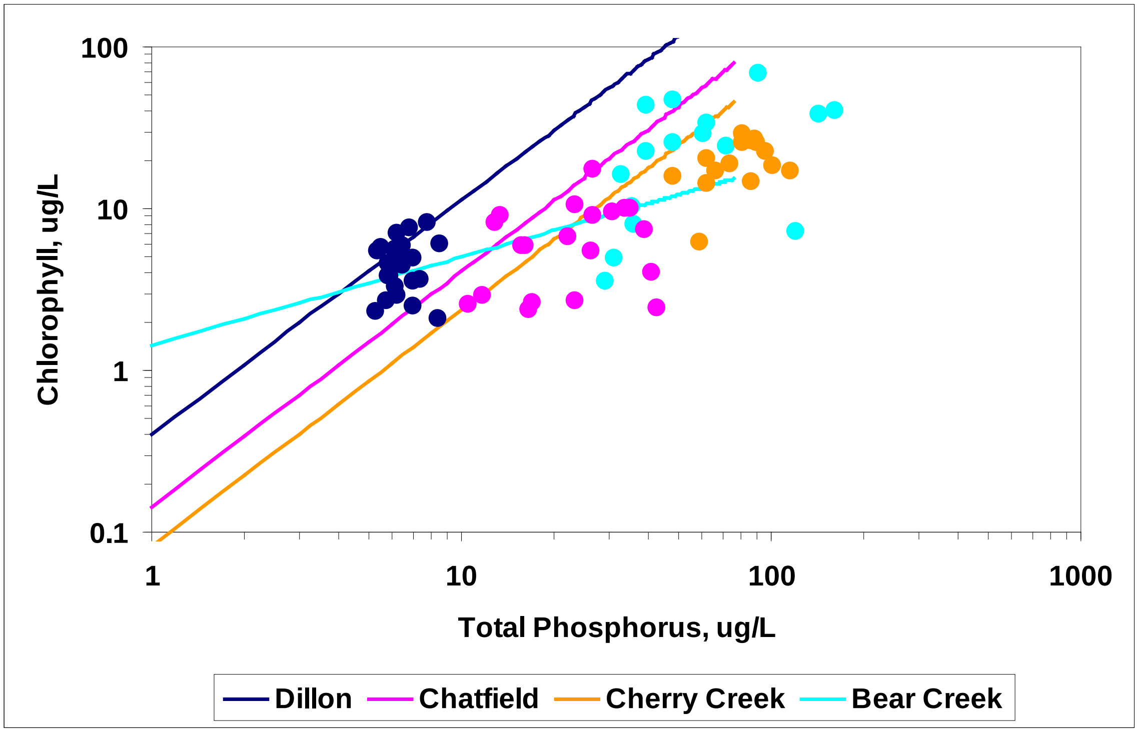

Figure 2. Concentration translators from the Clean Lakes studies (as shown in Figure 1) with observed values from many years of monitoring.

Load translator
The concentration of phosphorus in the lake is a function of the phosphorus load delivered from the watershed, the hydrologic characteristics of the reservoir, and the amount of phosphorus retained by the reservoir. Although the linkage is non-linear and contains several parameters, it is typically handled with a single equation, which is the load translator. It is fundamentally a mass-balance calculation in which phosphorus retention may be estimated independently.

Three of the control regulations used the well-known Vollenweider (1975) equation to calculate phosphorus concentration. The sedimentation coefficient has been estimated by different approaches. For Lake Dillon, the sedimentation coefficients were back-calculated from the Vollenweider equation using values measured from each of the years in the study. It was assumed further that the difference between years in the coefficient could be explained by a linear dependence on runoff. The approach taken for Chatfield and Cherry Creek reservoirs was to apply an existing equation (Canfield-Bachmann 1981; equation for artificial lakes), with an adjustment to match the one year of data.

$TP = L/\left[\bar{z}(\sigma + p)\right]$, **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 retention coefficient (y^{-1}), and p is the hydraulic flushing rate (y^{-1}).

$\sigma = 0.114\left(L/\bar{z}\right)^{0.589}$, **Canfield-Bachmann equation** for artificial lakes with terms defined as above for the Vollenweider equation.

The load translator is even less likely to have been reviewed recently than the concentration translator. Part of the problem is that protocols for the estimation of phosphorus load and phosphorus export are not well developed for all of the control regulation lakes. This hinders efforts to estimate directly the retention of phosphorus. Over the years, a considerable amount of information has been acquired for each lake, making it possible to validate (or modify) the load translators.

For Lake Dillon, the empirical approach developed to estimate phosphorus retention in the Clean Lakes study was replaced later with an empirical equation from Prairie (1989). For Cherry Creek Reservoir, the modification of the Canfield-Bachmann equation developed in the Clean Lakes study is being replaced with an equation developed by Nurnberg (1984). The original equation for Chatfield, also a modified version of Canfield-Bachmann, was reviewed in a study by Woodward-Clyde (1992), but does not appear to have been changed. It is not clear if a predictive equation has been developed for application to Bear Creek Reservoir, although the Clean Lakes study describes predicting in-lake TP with the Dillon-Rigler model, which contains a term for retention.

It seems likely that a key issue with the load translator will involve the basis for predicting the retention value. This is another topic to be addressed in a future session.

Summary

The purpose of this document is to compare the four control regulations chiefly on the technical basis for linking water quality goals with nutrient loads. In addition to a simple summary of concentrations and translators, this is an opportunity to recount the history of technical reviews and to characterize the transparency of the technical basis for allowable loads in each reservoir. The technical underpinnings of the control regulations have not remained static over time. Changes have been made as new information became available. The simple premise of the Division's review process is that these regulations should be dynamic by reflecting scientific advances based on new data, but that there should also be consistency in terms of process.

Citations

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