Development of a Site-Specific Nitrogen Standard for Chatfield Reservoir

Prepared for:

Chatfield Watershed Authority

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Introduction

Construction of Chatfield Reservoir was completed in 1975, a decade after flooding that caused 24 deaths statewide and more than $5 billion (2023 dollars) in damages across the Denver area. Although flood control was one of the primary reasons for construction of Chatfield Reservoir, the reservoir is also an important water supply for Denver, and Chatfield State Park is a popular destination for recreation in the Denver metro area.

Shortly after Chatfield Reservoir was filled, concerns were raised about the effects of nutrients on water quality in the reservoir and the potential for future degradation of water quality. Due to those concerns and the high value of the reservoir as a water supply and for recreation, Chatfield Reservoir was selected for a grant through the Clean Lakes Program of the US Environmental Protection Agency (EPA). The Clean Lakes Program was established in 1972 to provide financial and technical support for restoration and management of publicly owned lakes, and the program provided about $145 million in grants between 1976 and 1994. Grants through the Clean Lakes Program helped fund a series of Clean Lakes Studies, including the Chatfield Reservoir study that began in 1981.

Results of the Chatfield Reservoir Clean Lakes Study supported development of a proposal for a site-specific phosphorus (P) standard, and in 1984, the Water Quality Control Commission (WQCC) adopted a site-specific phosphorus standard of 27 µg/L. The standard for total P was intended to be consistent with a chlorophyll *a* target of 17 µg/L. After new information became available, the WQCC adopted a revised total-P standard (30 µg/L; 35 µg/L assessment threshold) and a chlorophyll *a* standard (10 µg/L; 11.2 µg/L assessment threshold) for Chatfield Reservoir in 2009. These standards apply to the mixed layer of the reservoir and have allowable exceedance frequencies of one in five years.

In support of the site-specific phosphorus standard adopted in 1984, the WQCC adopted the Chatfield Reservoir Control Regulation (Regulation No. 73) in 1989. The control regulation specified phosphorus-load allocations that were intended to be consistent with the site-specific phosphorus standard, and the load allocations were revised to reflect updated modeling projections and the 2009 revision of the numeric standards.

Following the March 2012 Rulemaking Hearing, the WQCC adopted interim numeric standards for chlorophyll *a*, total P, and total nitrogen (N), for Colorado lakes larger than 25 acres. The EPA approved the interim values for lakes but raised concerns about whether those values would be protective of classified uses in lakes with high yield of chlorophyll *a* per unit of total P or total N. The EPA recommended that Colorado "evaluate options for developing more protective alternative values or site-specific standards that can be applied to individual segments." The WQCC reconsidered the nutrient standards for lakes in the April 2023 Rulemaking Hearing and adopted revised table values for total P and total N (Table 1).

Table 1. Current table-value standards for chlorophyll *a*, total P, and total N. The standards for protection of aquatic life also apply to lakes with recreation (E, U, P) use. In addition to the chlorophyll standards for protection of aquatic-life and recreation uses, the chlorophyll standard for direct-use water supplies (DUWS) was adopted as a table value.

	Table-value standard, µg/L		
Constituent	Cold-water biota*	Warm-water biota*	DUWS**
Chlorophyll a	8	20	5
Total phosphorus	21	47	---
Total nitrogen	380	670	---

* Jul 1 – Sep 30 seasonal average for the mixed layer; 1-in-5 year exceedance frequency
** Mar 1 – Nov 30 seasonal average for the mixed layer; 1-in-5 year exceedance frequency

Prior to 2027, the WQCC will consider adoption of the new table-value standards (total P, total N) for a select group of Colorado lakes. After 2027, the WQCC will consider statewide adoption of the table values in the basin regulations. Presumably, the table values would be adopted after 2027 for all lakes larger than 25 acres, except where other site-specific standards already have been adopted. Chatfield Reservoir is designated as reviewable and has the following classifications: Agriculture, Aquatic Life Cold 1, Recreation E, and Water Supply. Temperature standards for cold, large lakes (CLL) apply to Chatfield Reservoir, and site-specific standards have been adopted for chlorophyll *a* and total P, but not for total N. Therefore, it is expected that the WQCC would adopt the total-N standard of 380 µg/L for Chatfield Reservoir unless an alternative, site-specific standard for total N were adopted.

In addition to the table-value P and N standards (Table 1) that can be adopted in the basin regulations, Section 31.17 of *The Basic Standards and Methodologies for Surface Water* (*Regulation No. 31, 5 CCR 1002-31*) offers three options for alternatives to the table values: 1) the WQCC may consider modification of the use classifications for lakes where the table values are infeasible, 2) under certain circumstances, the WQCC may consider temporary modifications of the numeric values, or 3) the WQCC may consider site-specific standards where it can be demonstrated that alternative numeric values would be more appropriate than the table values.

One approach for development of site-specific standards for total P and total N is described in Section 31.17 of *Regulation 31*. This approach utilizes information about chlorophyll *a* and Secchi transparency for the development of site-specific standards. An equation developed by Carlson (1977) for an unspecified set of lakes, presumably in

Minnesota, is used to predict Secchi transparency from measurements of chlorophyll *a*, and site-specific standards for total P and total N are calculated as functions of the ratio of observed to expected Secchi transparency. These equations were developed from the same statewide dataset that was available for development of the table-value standards listed in Table 1.

The Secchi-based approach described in *Regulation 31* will be a valuable tool for development of site-specific standards for some lakes. However, factors other than nutrients and light attenuation can affect the growth of suspended algae (phytoplankton) in lakes, and implicit assumptions with the Secchi-based approach may not be valid for all lakes. For example, chlorophyll *a* can be very low in some lakes where the ratio of observed to expected Secchi transparency is high and the yield of chlorophyll *a* per unit of total P or total N also is high; in such cases, setting nutrient standards according to the Secchi-based approach (i.e., numeric values less than the table values) could have no beneficial effect regarding protection of classified uses. Because the roles of different factors controlling phytoplankton growth in Chatfield Reservoir have not been quantified, the Secchi-based approach may not be appropriate, and alternative approaches for development of site-specific standards should be considered.

The purpose of this proposal is 1) to summarize important information relevant to site-specific nutrient standards and 2) to make recommendations for development of site-specific nutrient standards for Chatfield Reservoir. Because site-specific standards for chlorophyll *a* and total P already have been adopted for Chatfield Reservoir, the primary focus here is the development of a site-specific value for total N. However, the relationship between nitrogen and phytoplankton biomass (as chlorophyll *a*) in any given lake depends partly on the availability of phosphorus. Therefore, it is appropriate in this context to simultaneously consider the existing site-specific phosphorus standard for Chatfield Reservoir. Ultimately, the objective of the work proposed here is a proposal that could be submitted for consideration by the WQCC prior to the 2027 Rulemaking Hearing.

Background information

Nutrient-chlorophyll relationships for individual lakes are highly variable because several factors other than nutrients affect the growth of suspended algae in lakes. Thus, development of site-specific standards for phosphorus or nitrogen, by its very nature, requires consideration of the various factors that can control phytoplankton growth. Also, because the linkages between nutrients and phytoplankton growth are complex, strategies for development of nutrient criteria are fundamentally different from strategies for development of criteria for acutely toxic substances.

Growth of phytoplankton – Phytoplankton are an important source of nutrition for higher trophic levels, and Aquatic Life and Recreation uses for lakes are intimately tied to phytoplankton growth. However, high biomass of phytoplankton can cause various water-quality problems that interfere with Aquatic Life, Recreation, and Water Supply uses. High rates of photosynthesis raise the pH in lakes, and high pH is directly harmful to aquatic life. High pH can also indirectly harm aquatic life because pH affects ammonia toxicity. Some groups of phytoplankton produce harmful toxins, and toxin-producing species often dominate phytoplankton communities in highly productive lakes. Although photosynthesis produces oxygen, respiration of organic matter produced by phytoplankton consumes oxygen. Therefore, oxygen depletion is common in the deep water of many productive lakes. In addition to the effects of oxygen loss on fish and other forms of aquatic life, loss of oxygen can cause release of toxic metals from lake sediments. Loss of oxygen can also cause release (internal loading) of nutrients from lake sediments, and internal loading can further stimulate the growth of phytoplankton. Additionally, high biomass of algae can cause problems with taste and odor in municipal water supplies and can contribute to the formation of harmful disinfection byproducts.

Growth of phytoplankton requires carbon, nitrogen, phosphorus, and other elements that are the building blocks for algal cells. Availability of dissolved inorganic carbon rarely limits photosynthetic rates for phytoplankton, and some phytoplankton taxa can utilize dissolved organic carbon for growth. However, the availability of phosphorus or nitrogen can, and often does, limit the growth of phytoplankton in lakes. The ratio of carbon to nitrogen to phosphorus (C: N:P ratio) is relatively constant for phytoplankton cells. The nominal (Redfield) C: N:P ratio for algal biomass is 106:16:1 (molar ratio; 41:7.2:1 as a mass ratio), although the ratio varies somewhat across phytoplankton taxa and according to growth conditions. Thus, where the ratio of total nitrogen to total phosphorus (TN:TP ratio) is well above the Redfield ratio (e.g., molar TN:TP = 30:1 or 50:1), availability of phosphorus usually limits growth when phytoplankton biomass is high. Where the TN:TP ratio is well below the Redfield ratio, availability of nitrogen usually limits growth of phytoplankton when biomass is high. However, some groups of cyanobacteria obtain supplementary nitrogen for growth through biological N fixation, and limitation of phytoplankton growth cannot always be predicted from TN:TP ratios.

Although TN:TP ratios provide useful information about the potential for nutrient limitation, other information is required to demonstrate that either phosphorus or nitrogen limits phytoplankton growth at any given time. One way to test for nutrient limitation is by nutrient-addition assays, in which samples of lake water are incubated with and without added nutrients (e.g., +P, +N, +P and + N, control). After incubation of a set of samples that includes samples with and without added nutrients, increased growth of algae relative to the control (i.e., relative to samples without added nutrients) provides empirical evidence of nutrient limitation. Thus, results of nutrient-addition assays can indicate the following conditions: nutrients are not limiting (growth for control similar to growth for samples with added nutrients), phosphorus is limiting (increased growth for samples with added P than for samples without added P), nitrogen is limiting (increased growth for samples with added N than for samples without added N), or nitrogen and phosphorus are co-limiting (increased growth for samples with added P and N but not for controls or samples with added P or N).

In addition to phosphorus and nitrogen, many other factors can limit the growth of phytoplankton in lakes. Other elements, including silica and iron, sometimes limit phytoplankton growth. Light can limit algal photosynthesis, and the upper bounds for algal biomass in nutrient-rich lakes are related to light availability. For example, self-shading by algal cells, non-algal particulates, and dissolved humic substances (colored organic matter derived primarily from the decomposition of plants) reduce the light available to support phytoplankton growth. Temperature controls rates of biological processes, and growth rates of algae are suppressed at low temperatures (e.g., during winter, year-round in high-elevation lakes in Colorado). Also, water temperature affects vertical mixing in lakes, and mixing affects the light environment of phytoplankton cells, nutrient availability, and seasonal shifts in the composition of phytoplankton communities. Furthermore, algal growth can be suppressed in lakes with short water-residence time, and depth and other morphometric features of lakes can indirectly affect the growth of phytoplankton and phytoplankton biomass.

Because availability of P or N often limits the growth of phytoplankton and because some other factors that affect phytoplankton growth are difficult to control, nutrient control has been the primary means to control algal biomass in lakes. Control of phosphorus has been particularly effective in controlling algal growth in lakes. However, phytoplankton growth in coastal-marine systems can be limited by nitrogen, and the N:P ratio tends to be lower in nutrient-rich (eutrophic) lakes than in nutrient-poor (oligotrophic) lakes. Thus, dual control of nutrients (i.e., control of both P and N) has been used increasingly in algal-control strategies.

Development of numeric standards for nutrients – Neither phosphorus nor nitrogen is directly toxic to aquatic life, but nutrient pollution can alter ecosystems in ways that are harmful to aquatic life and adversely affect classified uses. Because some of the effects of nutrients on aquatic life and ecosystems are indirect and are modulated by various site-specific factors, development of numeric standards for nutrients is fundamentally different from development of standards for many acutely toxic pollutants (EPA 2010). Furthermore, because the effects of nutrients on ecosystems are so strongly dependent on site-specific factors, development of a single set of nutrient criteria for all lakes in the United States would be infeasible (EPA 2000). Instead of a single set of nationwide criteria, the EPA has supported the development of different sets of numeric standards that are applicable to states, regions, and individual lakes.

The EPA describes three types of approaches for development of nutrient criteria (EPA 2000, EPA 2010). The first is based on characterization of reference conditions for a state or a region. The second type of approach uses mechanistic modeling to define numeric standards, and the third is based on stressor-response relationships. The reference-condition approach is not well suited to Colorado lakes because nearly all pristine lakes in Colorado are small, natural lakes at high elevation and have little in common with Chatfield Reservoir or other relatively large lakes at low elevations. Mechanistic modeling is not ideally suited for development of nutrient standards in Colorado either because development of mechanistic models is costly even for individual lakes and few lakes have been studied well enough to support parameterization of such models. The stressor-response approach, which relies on empirical relationships between concentrations of nutrients and one or more factors linked to classified uses (e.g., chlorophyll *a*), has been used for development of statewide nutrient standards in Colorado and could be used for development of site-specific standards.

Generally, table-value nutrient standards, such as those adopted for Colorado lakes, are intended to protect classified uses across large groups of lakes. However, because many factors other than nutrients affect phytoplankton growth, nutrient-chlorophyll relationships for large groups of lakes can be poor. Therefore, table-value standards such as those adopted for Colorado tend to overprotective of uses for some lakes and underprotective of uses for other lakes. Standards for Colorado lakes were developed with a quantile-regression approach such that table values for P and N are consistent with nutrient-chlorophyll relationships for lakes with moderately high yield of chlorophyll *a* per unit of total P or total N. The underlying intent with this approach is to protect classified uses for lakes with all but the highest yields of chlorophyll *a* per unit of total P or total N, such that the table-value standards rarely would be underprotective. Conversely, the existing table values are overprotective of uses for lakes with low yield of chlorophyll *a* per unit of total P or total N.

In the absence of site-specific information that would support development of alternative values, implementation of generally overprotective table-value standards helps ensure protection of classified uses for most lakes. However, for lakes where table values would be overprotective, implementation of those standards can be costly and may provide no additional benefit regarding protection of classified uses. Therefore, for some lakes in Colorado, development of site-specific standards will play a critical role in finding the proper balance between protection of classified uses and the cost of standards implementation.

Monitoring data for Chatfield Reservoir show that, for most years, biomass of phytoplankton (as chlorophyll *a*) is well below the values that would be expected, based on the numerical relationships reflected in the table-value standards for nutrients in Colorado lakes (i.e., yield of chlorophyll *a* per unit of total N is particularly low for Chatfield Reservoir). Chatfield Reservoir is near the lower elevational boundary for Aquatic Life Cold lakes in Colorado, and monitoring data do not suggest limitation of phytoplankton growth by abnormally low water temperatures. Some possible explanations for the low yield of chlorophyll *a* per unit of total N include light attenuation by non-algal particles, high TN:TP ratios, and short water-residence time. However, the specific cause of low yield of chlorophyll *a* per unit of total N has not been determined.

Nutrients, chlorophyll *a*, and other relevant variables have been monitored in Chatfield Reservoir since concerns were first raised about the effects of nutrients on water quality in the reservoir. Consequently, the long-term record of water-quality monitoring makes it possible to evaluate the site-specific response of chlorophyll *a* to concentrations of nitrogen in Chatfield Reservoir.

Recommendations for development of a site-specific nitrogen standard

The EPA has recommended three types of approaches (reference conditions, mechanistic modeling, stressor response) for development of nutrient criteria for aquatic systems. Nearly all pristine lakes in Colorado are small lakes at high elevation, and reference conditions for such lakes are not applicable to Chatfield Reservoir or other similar lakes. Theoretically, a mechanistic model could be used to predict chlorophyll concentrations in Chatfield Reservoir over a range of concentrations of total N. However, lakes are complex systems, and development, calibration, and validation of a mechanistic model suitable for determination of site-specific standards would be challenging and costly. The third (stressor-response) approach described by EPA relies on empirical relationships between nutrients and one or more response variables, either for a set of lakes or for an individual lake. This type of approach can be used where available data support analyses of relationships between nutrient concentrations and a response variable that is linked, either directly or indirectly, to classified uses (EPA 2010). Thus, data requirements for the stressor-response approach are modest in comparison with the data requirements for most mechanistic models. The stressor-response approach was used for development of statewide standards for phosphorus and nitrogen and is recommended here as a basis for development of a site-specific nitrogen standard for Chatfield Reservoir.

The proposed approach for development of a site-specific nitrogen standard for Chatfield Reservoir follows the EPA (2010) recommendations and is analogous to the approach that the Water Quality Control Division (WQCD) used for development of the statewide table values for lakes. Other supplementary analyses also are described here and could be considered in the future to provide further support for any numeric value that would be put forward for consideration by the WQCC.

Assembly of the data set – Sources of data for development of a site-specific nitrogen standard include water-quality data collected by the Chatfield Watershed Authority and its partners, as well as hydrologic data for Chatfield Reservoir, its tributaries, and the South Platte River downstream of the reservoir.

Water-quality data (2012 – 2022 or 2023) provided by the Chatfield Watershed Authority will be the primary source of information for development of nutrient-chlorophyll relationships that will serve as the basis for a site-specific nitrogen standard. Water-quality data from other sources (e.g., USGS) also may be assembled and combined with data provided by the Chatfield Watershed Authority. Because water-quality data for Chatfield Reservoir have been collected by various groups and different analytical methods have been used over the past decade, the data set will be screened carefully for completeness and to identify statistical outliers that may be erroneous. Any results that are excluded from analyses will be documented, as will decisions about handling of values below method-detection limits and minimum reporting limits.

Water-residence time affects the growth of phytoplankton in lakes, and short residence time often is associated with low yield of chlorophyll *a* per unit of total P and total N. Therefore, relevant hydrologic data will be assembled for Chatfield Reservoir and flowing waters upstream and downstream of the reservoir. These data include gage records (US Geological Survey, Colorado Division of Water Resources) and other hydrologic data collected by Denver Water.

In addition to data for Chatfield Reservoir and the South Platte River watershed, water-quality data will be assembled for a set of Colorado lakes to support analyses of statewide nutrient-chlorophyll relationships. Prior to the April 2023 Rulemaking Hearing of the WQCC, the WQCD assembled water-quality data for about 180 Colorado lakes. However, many lakes included in the WQCD data set were sampled only once or twice during the July – September growing season, and the data set contained many erroneous values. Therefore, a new data set for Colorado lakes will be assembled using a subset of data from the WQCD data set, in combination with water-quality data for other Colorado lakes. Like the data set for Chatfield Reservoir, decisions about exclusion of statistical outliers, decisions about minimum sample size, and other decisions related to screening of the data set will be documented.

Data processing and analyses – Chlorophyll *a* standard have been adopted for Colorado lakes to protect specific classified uses. The table-value standards for chlorophyll *a* (i.e., 8 µg/L for Aquatic Life Cold lakes, 20 µg/L for Aquatic Life Warm lakes) target specific trophic states and are intended protect Aquatic Life and Recreation uses. These values strike a balance between avoidance of water-quality problems (e.g., high pH, oxygen depletion) that are common at higher trophic states and protection of recreational fisheries that depend on the growth of algae. Preservation of the historical trophic state of the reservoir also was considered in setting the site-specific chlorophyll values for Chatfield Reservoir (initially as a goal of 17 µg/L; subsequently adopted as a numeric standard of 10 µg/L in 2009). Similarly, the main objective in developing a site-specific nitrogen standard for Chatfield Reservoir would be to determine the range of concentrations of total N that are consistent with the 10 µg/L chlorophyll *a* target, which was adopted to protect Aquatic Life and Recreation uses and to preserve the historical trophic state of the reservoir.

The initial steps in the methods proposed here include descriptive (statistical) analyses of the monitoring data for Chatfield Reservoir. Relevant data include measurements of phosphorus and nitrogen fractions, chlorophyll *a*, Secchi transparency, temperature, and other water-quality variables that could affect chlorophyll yield. Analyses would be limited to approximately the last ten years of the monitoring record. Although comprehensive monitoring of water quality for Chatfield Reservoir began in 1981 with the Clean Lakes Study, records older than about ten years may not be relevant to current conditions. *Regulation 38* specifies that measurements for assessment of the 10 µg/L standard for chlorophyll *a* should be representative of the mixed layer of the reservoir during July – September. Therefore, mixed depths will be determined from profiles of temperature, and daily and seasonal (July – September) means will be calculated for total P, total N, chlorophyll *a*, Secchi transparency, and other relevant variables. In addition to these water-quality variables, residence time will be calculated for each day of the record, to support analyses of the effect of residence time on chlorophyll yield.

The central goal with the analyses proposed here is to quantify the response of chlorophyll *a* to total N (i.e., the response to the stressor) in Chatfield Reservoir. The same four-step approach that was used for development of statewide table values for total P and total N will be applied to monitoring data specific to Chatfield Reservoir. The site-specific chlorophyll *a* standard (i.e., 10 µg/L) has an allowable exceedance frequency of one in five years and will be adjusted from the 80th percentile to a median value, using a relationship for monitoring results for Chatfield Reservoir and other, similar reservoirs with adequate monitoring data. Quantile regression then will be used to derive the target for the seasonal-mean value of total N. The 0.75 quantile was chosen by the WQCD to represent relationships between nutrients and chlorophyll *a* for development of statewide values, although other quantiles could be considered for Chatfield Reservoir. The resulting seasonal-mean concentration of total N then will be converted to an 80th percentile value.

Preliminary analyses indicate that yield of chlorophyll *a* per unit of total N is lower for Chatfield Reservoir than for many other Colorado lakes, but it will be important to understand the factors other than nutrients that limit algal growth in Chatfield Reservoir. Secchi transparency, water temperature, and residence time are some of the variables that can affect the yield of chlorophyll *a* per unit of total N. Stepwise multiple regression will be used to identify covariates that could improve the precision for predictions of chlorophyll *a* from total nitrogen alone. As with the site-specific approach described in *Regulation 31*, the ratio of observed to expected Secchi transparency will be considered here, but other variables also will be considered as potential covariates.

Optional supplementary analyses – The approach described here for development of a site-specific nitrogen standard is based on the stressor-response approach recommended by EPA. Depending on results of analyses proposed here, supplementary analyses in the second half of 2024 or 2025 could provide additional support for a proposed site-specific standard. For example, nutrient-addition assays could help demonstrate that concentrations equal to or greater than a proposed numeric value for nitrogen would not stimulate growth of algae in Chatfield Reservoir or in the South Platte River downstream of the reservoir. Also, if available monitoring data would support such analyses, loss-rates for total N could be quantified for the South Platte River downstream of Chatfield Reservoir (e.g., through mass-balance modeling). Collectively, these supplementary analyses could help to demonstrate that any proposed site-specific nitrogen standard for Chatfield Reservoir would be protective of classified uses, both for the reservoir and for downstream waters.

Deliverables

Deliverables for the proposed work will include historical monitoring data in spreadsheet form, a report that describes the approach for development of the proposed numeric value, and presentations at meetings. Ultimately, the report would serve as written testimony in support of a proposal for consideration by the WQCC, prior to the 2027 Rulemaking Hearing. Before submission of a proposal to the WQCC, results presented in the written report would be presented in a meeting with the Chatfield Watershed Authority. Results would also be presented in a separate meeting with representatives of the WQCD, to provide an opportunity for questions and comments prior to submission of the final proposal.

References

Carlson, R. E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22: 361 – 369.

US Environmental Protection Agency. 2000. Nutrient Criteria Technical Guidance Manual – Lakes and Reservoirs, First Edition. EPA-822-Boo-001.

US Environmental Protection Agency. 2010. Using Stressor-response Relationships to derive Numeric Nutrient Criteria. EPA-820-S-10-001.

Estimated budget

Task 1. Assembly and review of monitoring data	
1.1 Monitoring data for Chatfield Reservoir	$3400
1.2 Monitoring data for other Colorado lakes	$6800
Task 2. Data analyses (development of proposed nitrogen standard)	$20600
Task 3. Preparation of a written report	$16800
Task 4. Presentations at meetings	$5700
Total cost, not expected to exceed	**$53300**