Summary of Activities To Comply with Phased TMAL Requirements

Prepared for the

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ABBREVIATIONS

AWT	Advanced Wastewater Treatment
ASCE	American Society of Civil Engineers
BAT	Best Available Technology
BMP	Best Management Practice
CDPS	Colorado Discharge Permit System
DRCOG	Denver Regional Council of Governments
EDB	Extended detention basin
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
ISDS	Individual Sewage Disposal System
µg/L	Micrograms per liter
mgd	Million gallons per day
mg/L	Milligrams per liter
MW	Monitoring Well
NPDES	National Pollutant Discharge Elimination System
NURP	Nationwide Urban Runoff Program
PRF	Pollutant Reduction Facility
PWSD	Parker Water and Sanitation District
TMAL	Total Maximum Annual Load
UDFCD	Urban Drainage & Flood Control District
USACE	United States Army Corps of Engineers

WQCC	Water Quality Control Commission
WQCV	Water quality capture volume
WWTP	Wastewater treatment plant

EXECUTIVE SUMMARY

This report summarizes the activities performed by the Cherry Creek Basin Water Quality Authority (Authority) to meet the chlorophyll *a* standard in Regulation No. 38[1] and the phased total maximum annual load (TMAL) requirements for phosphorus identified in Control Regulation No. 72[2] for the Cherry Creek Reservoir. These activities include thirteen (13) investigations called special studies identified at Section 72.3(4), one special study not identified in Regulation No. 72, and development of the Watershed and Reservoir Models. The results and conclusions from these activities, in conjunction with evaluation of different future scenarios using the new Watershed and Reservoir Models, were then used to provide the technical basis for revising the Reservoir chlorophyll *a* standard in Regulation No. 38 and revising various aspects of Control Regulation No. 72, including the phosphorus goal approach.

Special Studies and Investigations

The special studies and continuation of the Authority's monitoring program have provided data that has been instrumental in preparation of the Reservoir and Watershed Models. This information has been used to:

- Develop an appropriate and achievable Reservoir standard for chlorophyll *a* and Reservoir goal for phosphorus that is consistent with the data and supportive of the Reservoir's currently identified beneficial uses.

- Identify potential impacts from future watershed changes and to quantify water quality benefits of watershed controls. Modeling of future watershed scenarios, including continued growth, implementation of best management practices (BMP), retrofit of existing detention ponds, and completion of Rueter-Hess Reservoir, demonstrate that the watershed controls will be protective of the Reservoir's water quality.

Reservoir Model Redevelopment

An additional seven years of Reservoir data collected since the 2000 model version provided a 15-year data set (1992 to 2006)[3] by which to evaluate the chlorophyll *a* response to several variables, including in-lake phosphorus and nitrogen, and external phosphorus loads and concentrations, and to develop a more reliable Reservoir Model to predict chlorophyll *a* concentrations. Significant conclusions from the Reservoir Model analysis were:

> *In general, nitrogen limitation only occurs in freshwater systems when algae are saturated with phosphorus. By reducing P below the saturation level, it again becomes the limiting nutrient and algae biomass declines. P reduction is usually easier to accomplish than N reduction, because cyanobacteria can incorporate atmospheric nitrogen gas (N_2).* ***Therefore, phosphorus controls are still appropriate, so that it remains or again becomes the limiting nutrient****."*(emphasis added) (Freshwater Research, September 24, 2008, p.20).

[1] CDPHE, WQCC March 1, 2008. *Cherry Creek Reservoir Control Regulation, 5-CCR 1002-38*
[2] CDPHE, WQCC December 30, 2004. *Cherry Creek Reservoir Control Regulation, 5-CCR 1002-72*
[3] While data is available for 2007 and partial data for 2008, the work on the Reservoir Model was started in late 2006 and prior to 2007 data becoming available in time to incorporate the information.

> "*It is evident that the current TMAL based on loads will not achieve that goal [15-µg/L chlorophyll a standard].* ***It is proposed here that instead, a methodology that considers average inflow total phosphorus concentration as control variable be used***"- (emphasis added). (Freshwater Research, September 24, 2008, p3).

After consideration of additional factors, such as limnology based standards, eco-region principals, experience in other studies, and other influences, the recommended Reservoir standard is:

1. Correct the chlorophyll *a* standard by changing it from 15-µg/L as seasonal mean for the upper 3 meters from July through September for nine out of ten-years to 25-µg/L for eight out of ten-years, which is supported by 16-years of water quality data and both the Watershed and Reservoir Models.[4]

2. Change phosphorus control strategy from total inflow *load* (*i.e.*: 14, 270 pounds per year) to a *flow-weighted phosphorus concentration*[5] of 0.20-mg/L, which is supported by analysis of the data and the models.

Watershed Model Redevelopment

The Authority redeveloped the Watershed Model to predict total phosphorus loads from the Watershed to the Reservoir. The purpose of the model is to predict long-term changes in phosphorus loads, concentrations, and watershed yield volumes resulting from changes in the watershed land uses, pollutant management strategies and wastewater plant operations. The model accounts for the interaction of the stream and alluvium, which have different runoff volumes and transport velocities resulting in significantly different annual flows and loads into the Reservoir. In addition, surface flows contain both particulate and dissolved phosphorus, whereas alluvial flows are primarily dissolved forms of phosphorus. Therefore, it was determined that the Watershed Model should separate and track surface flows and alluvial flows, as well as dissolved and particulate phosphorus forms, requiring a more sophisticated model than proposed in 2000.

Phosphorus load is calculated and routed in two different forms. Dissolved phosphorus is that portion of the load that is assumed to travel at the same velocity as the surface and alluvial flow, *i.e.*: it is treated as a conservative ion. Particulate phosphorus is that portion of the load that is only present in surface flow and is assumed to settle or filter out when runoff infiltrates from the surface to the alluvium. Particulate phosphorus can also be mobilized during higher stream flow events that erode or scour the channel bed or banks, picking up particulate phosphorus attached to eroded material.

[4] The new standard would be measured seasonally (July through September) in the upper 3 meters.
[5] Flow-weighted phosphorus concentration means the total external phosphorus load, including precipitation, groundwater, stream flow, and un-gaged runoff, divided by total inflow volume. As used in this report, the term "external phosphorus load" means the total external load.

The redeveloped Watershed Model was created by an experienced team in the fields of hydrology, hydraulics, groundwater flow, and computer modeling over a three (3) year period.[6] After calibrating the model by comparing output for an eight (8)-year simulation period to measured data, and checking the model output for reasonableness by peer review, the model was used to project impacts of future watershed changes including development and new stormwater controls on phosphorus loads and concentrations, and runoff volumes. Key findings of the Watershed Model analysis included:

1. Implementation of post-construction BMP and completion of Rueter-Hess Reservoir could reduce median inflow concentration and phosphorus loads into the Reservoir when compared to existing conditions (Scenario B, Table 7), even with a 250% population growth in the watershed. Therefore, the Watershed Model demonstrated that the proposed Reservoir chlorophyll *a* standard of 25-µg/L could be met eight (8) out of ten (10) years and that currently identified beneficial uses of the Reservoir would continue to be protected, even with continued growth in the watershed.

2. Substantial reduction of external phosphorus loads are expected to occur with completion of Rueter-Hess Reservoir and implementation of minimum standard BMPs[7] for future development, but will *not* result in a similar reduction in phosphorus concentrations in the Reservoir inflow. This outcome is documented in the results of Scenario A and B found in Table 7 of this report and supports the proposed shift from a load-based watershed management strategy for phosphorus to a concentration-based strategy. However, modeling of BMPs for future development along with Rueter-Hess Reservoir demonstrated that the proposed Reservoir chlorophyll *a* standard of 25-µg/L could be met eight (8) out of ten (10) years.

3. Implementation of enhanced BMPs could further reduce external phosphorus concentrations to the Reservoir, providing an even greater benefit to Reservoir water quality. Enhanced BMPs consist of additional treatment of storm water beyond extended detention basins (EDB), such as filtering or infiltration. The cost of enhanced BMP (present worth of $131,000,000) was found to be from 4% to 9% of the capitalized value of the Reservoir, which is estimated to be from $1.4 to $3.3 billion. *See* Report Appendix. The cost of enhanced BMPs would be borne by new development and represents an increase in the current costs for BMPs.

4. Retrofitting existing detention basins could further reduce external phosphorus concentrations, providing even greater benefit to Reservoir water quality. Existing detention basins are BMPs that were constructed prior to the 2001 effective date of

[6] The following individuals participated from time to time in the development of the Model scope and review of the model algorithms and results: Dave Akers, Joni Nuttle, Dick Parachini, Jim Saunders, and Dan Beley, Division; Michelle Wind and Mark Richards, Brown and Caldwell; Rick Goncalves, RG Engineers; George Weaver and Mark Westberg, City of Greenwood Village; Kevin Wegener, City of Aurora; Max Grimes, Regulatory Management, Inc.; Steve Canton, GEI; Brian Rask, Halepaska and Associates; Jim Wulliman, Muller Engineering Company; Julie Vlier, Tetra Tech; Bruce Lytle, Lytle Water Solutions, Bob McGregor, AMEC; Larry Mugler, DRCOG; John Doerfer, UDFCD; Lanae Raymond, Arapahoe County; Ronda Sanquist, Jackson Kelly.
[7] The current minimum standard post construction BMP is the extended detention basin, which includes water quality capture volume.

Control Regulation 72. The retrofit would consist of supplemental filtration or other treatment of discharges from existing detention basins. The cost of retrofitting existing detention basins (present worth of $55,000,000) was found to be from 2% to 4% of the capitalized value of the Reservoir, which is estimated to be from $1.4 to $3.3 billion. *See* Report Appendix. The Authority could retrofit existing detention basins but will need to consider its right to access such detention basins.

5. Increasing the point source discharge limitation from 0.05- to 0.10-mg/L increased the median phosphorus loads from 9,098-pounds to 9,145-pounds (1%) when compared to the future watershed represented by Scenario B. which includes the completion of Rueter-Hess Reservoir and future development with BMPs. Increasing the point source discharge limit to 0.10-mg/L has minimal impact on phosphorus loads and concentrations entering the Reservoir, since both loads and concentrations increases are less than 1%.

Proposed Watershed Control Strategy (Control Regulation 72).

As a result of proposing a revised chlorophyll *a* 25-µg/L standard of for Regulation No. 38, further modifications to Control Regulation No. 72 are necessary. Proposed modifications to Control Regulation No. 72 relative to nonpoint source and regulated-stormwater watershed controls:

1. Converting from a phosphorus mass-based TMAL to a concentration-based control strategy,

2. Suspending the trade program found in Regulation No. 72 that allowed WWTPs to use BMPs to develop phosphorus credits, and

3. Improving flexibility and clarifying BMP requirements for new development and redevelopment projects in the watershed, while continuing with aggressive watershed controls.

The proposed modifications to Control Regulation No. 72 are not expected to change the following programs or requirements:

1. Monitoring and reporting requirements will stay the same, except that flow-weighted phosphorus concentration will be reported as mg/L instead of pounds per acre-foot.

2. Permittees will continue to implement BMPs, at the same or better level of protection for construction and post-construction for new development and redevelopment.

3. Implementation of Pollutant Reduction Facilities (PRF) to reduce phosphorus through planning, design, construction, maintenance and monitoring, except that effectiveness will be "measured" using discharge concentration instead of phosphorus mass immobilization. Since phosphorus concentration reduction benefits from future PRFs were *not* included in the Watershed Model, construction of future PRFs provides greater

confidence that the proposed flow-weighted phosphorus concentration goal of 0.20-mg/L can be met.

4. Education program implementation by the Authority.

5. Effluent limitation for point source discharges from wastewater treatment plants (WWTP) will remain at 0.05-mg/L.

1. INTRODUCTION

This report summarizes the activities performed by the Authority to meet the chlorophyll *a* standard in Regulation No. 38[1] and the phased TMAL requirements for phosphorus identified in Control Regulation No. 72[2] for the Reservoir. These activities include thirteen (13) investigations called special studies identified at Section 72.3(4), one (1) special study not identified in Regulation No. 72 and redevelopment of the Watershed and Reservoir Models. The results and conclusions from these activities, in conjunction with evaluation of different future scenarios using the redeveloped Watershed and Reservoir Models, were then used to provide the technical basis for revising the Reservoir chlorophyll *a* standard in Regulation No. 38 and revising various aspects of Control Regulation No. 72 including the phosphorus goal approach.

Special studies or other activities included[8]:

1. Construction of nonpoint source control projects;
2. Reservoir nutrient enrichment;
3. Development of event mean concentration for stormwater flows;
4. Quantification of soil and ground water background phosphorus levels;
5. Identification of industrial process wastewater sources and associated phosphorus loading;
6. Evaluation of phosphorus removal effectiveness of nonpoint source control structures;
7. Monitoring of shallow alluvial ground water loading in tributaries;
8. Quantification of individual sewage disposal system phosphorus loading;
9. Implementation of lower phosphorus effluent limits in permitted discharges;
10. Characterization of watershed hydrology to establish reference condition for evaluation of phosphorus loading;
11. Depth profiling of nutrient content for ground water;
12. Revised calculations of background sources, industrial process wastewater sources, and individual sewage disposal systems sources of phosphorus contributions; and
13. Revision to the chlorophyll *a* standard in Regulation No. 38 and the phosphorus goal in Regulation 72 for the triennial review[9].

In addition to the thirteen (13) special studies and other activities identified above, the Colorado Department of Public Health and Environment Water Quality Control Division (Division) and the Authority jointly funded another investigation not specifically identified in Regulation No. 72, which quantified ground water flow and phosphorus loads into the Reservoir. The groundwater inflow study also provided new basis for calculating a water budget so that inflows matched the United States Army Corps of Engineers (USACE) computed inflows, which required re-calculation of historic loads to the Reservoir. Recalculation of the flows and loads

[8] 5-CCR 1002-72.3(4).
[9] The current Regulation No. 72 contemplated only a change in the total maximum annual load, instead of both the Reservoir chlorophyll a standard and phosphorus goal proposed herein.

provided greater confidence in the Reservoir data to evaluate the chlorophyll *a* and phosphorus relationship.

In addition to the above activities and special studies, the Authority redeveloped the Watershed Total Phosphorus Model (Watershed Model) over a three year period with the capability of predicting long-term trends in water yield (*i.e.*: runoff volume) and phosphorus loads to the Reservoir as the result of changes in land use, watershed management strategies, and WWTP operations in the watershed. The principle model output is an eight-year annual summary of total phosphorus load and concentrations, and watershed yield volumes entering the Reservoir that includes direct precipitation, all stream flows, ungaged flows, and alluvial inflows.

The Authority used the Watershed Model to evaluate future development and watershed control scenarios to determine their effects on total external phosphorus discharged to the Reservoir. The Authority also redeveloped the Reservoir Model to incorporate seven (7) additional years of data from 1992 through 2006, re-evaluate correlations between chlorophyll *a* and nutrients, and provide a scientific basis for recommending an ambient chlorophyll *a* standard for Regulation No. 38.

Summaries, findings, and results of these activities and modeling efforts are presented in this report.

2. SPECIAL STUDIES

2.1 Construction of Non-point source control projects

The Authority has constructed wholly or in part, nine PRFs since 1990, of which eight are located within Cherry Creek State Park. These PRFs include stream stabilization, wetlands and wetland basins, EDBs, and shoreline stabilization measures. Most of these PRFs are monitored for changes in phosphorus loads and concentrations into the Reservoir and, therefore, provide supporting data to estimate benefits of watershed control measures discussed in Section 3, Watershed Model.

In 2008, the Authority began operation of a Reservoir destratification system that uses aeration to mix water and minimize the temperature stratification that can occur during hot dry summer months. The nutrient enrichment investigation (see Section 2.2) determined that during periods when the Reservoir was not being naturally mixed by wind activity algal growth activity was at its highest. Whereas this Reservoir mixing system is not for the purpose of controlling non-point source pollutants and, therefore water quality, it may provide water quality benefits to the Reservoir that were not accounted for in the annual data used to assess the Reservoir and develop the new chlorophyll *a* standard. Additional monitoring of the Reservoir mixing system has been implemented and the effects on water quality will be included in the Authority's next Annual Report to the Water Quality Control Commission (Commission).[10]

[10] It may require more than three years of Reservoir monitoring data to assess water quality benefits associated with the destratification system.

Construction of non-point source control projects has been a long-term activity of the Authority and the Authority recommends a continuation of this program.

2.2 Reservoir Nutrient Enrichment

Nutrient limitation of suspended algae (phytoplankton) in the Reservoir was studied in 2003[11]. The study involved collection of data on temperature and oxygen, nutrient concentrations, algal biomass (measured as chlorophyll *a*), and abundances of individual species of algae. Data was collected eight (8) times during the 2003 growing season from May through October, once per month for May, June, July, and October, and twice per month for August and September. The study also measured primary production (growth) of phytoplankton. In addition, nutrient enrichment experiments were performed on samples taken from the Reservoir on each of the sampling dates.

One conclusion of the study was related to stratification of the Reservoir[12].

> *Vertical profiles of temperature and oxygen showed that the lake stratifies only briefly during the growing season. Although phytoplankton within the top meter of the water column grow rapidly for brief intervals (e.g., two hours), algae that are moving freely with the lake water probably experience light deprivation during periods of deep mixing because growth is possible only within the top 1 to 2 m of the water column.*

This conclusion, along with recommendations of the author, was instrumental in the implementation of the Reservoir destratification (*i.e.*, mixing) system in 2007. The mixing system uses compressed air introduced at the bottom of the Reservoir to create a vertical circulation pattern that mixes the water in the deepest areas of the Reservoir. The primary objective of the mixing is to force algae, particularly bluegreen algae (cyanobacteria), to be light-limited through regular, vertical circulation, therefore, suppressing their growth.

The Reservoir destratification system, in conjunction with watershed controls, is a component of the Authority's strategy that work together to protect the water quality of the Reservoir.

The Reservoir nutrient enrichment special study is complete but the evaluation of the Reservoir destratification system is expected to continue for 2- to 3- more years.

2.3 Development of Event Mean Concentrations

Phosphorus loads to the Reservoir are estimated using the phosphorus concentration measured in the discharge from various land uses during a storm event. These event mean concentrations (EMC) data, which are used in the Authority's Watershed Model, were determined from data collected within the Denver Metropolitan area, but outside of Cherry Creek basin, except for one

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[11] Lewis, William M; Saunders, James F; and. McCutchan, James H; January 22, 2004. Studies of Phytoplankton Response to Nutrient Enrichment in Cherry Creek Reservoir, Colorado.

[12] Another Lewis et. al. study conclusion was that the Reservoir was nitrogen limited during 2003, which is reviewed in Section 5.6 of this report.

location at Shop Creek. In 2001, the Division opined[13] that the Authority's Watershed Model should be based on more representative data collected within the Cherry Creek basin.

The Authority conducted research into the development, interpretation, and use of EMC data for phosphorus load calculations. The results of this investigation were submitted to the Division in a report[14] that presented the technical basis for using regional data for EMCs collected by the Urban Drainage and Flood Control District (UDFCD) for four land uses: residential, commercial, industrial, and undeveloped land.

The Division commented on the Authority's investigation[15] accepting the recommendation for EMCs from residential, commercial, and industrial, but not for undeveloped land uses. The acceptance was conditioned on the Authority including additional Nationwide Urban Runoff Program (NURP) data for Colorado Springs in the data set and calculating EMC values based on the mean of all events for a particular land use category. These calculations were performed by the Division[16] who suggested the Authority use these data in the Watershed Model, which were subsequently applied (see Section 3, Watershed Model).

The Division's recommendation for undeveloped land uses was to perform additional EMC monitoring within Cherry Creek basin. The Authority believes that the background phosphorus special study and the calibrated Watershed Model demonstrate the appropriateness of the background EMC used in the model and that no further investigation into the EMC for undeveloped land is necessary at this time.

2.4 Quantification of background phosphorus

The Authority had prepared a special study[17] to evaluate groundwater and surface water phosphorus concentrations in the upper reaches of Cherry Creek in compliance with Section 72.3(4). Phosphorus species determined for the surface water included total phosphorus, total dissolved phosphorus and soluble reactive phosphorus (ortho-phosphate). Conclusions of the study included:

(1) The ground water system may not be continuous from the background location to Castlewood Canyon as the alluvium is discontinuous in this reach.

(2) The chloride concentration in the ground water at the background location appears to have been affected by anthropomorphic activities or localized geochemical conditions.

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[13] Lewis, William M. Jr. April 9, 2001. *Rationale, Scope of Work, and Priority for Special Studies as Part of a Phased TMAL Process for Cherry Creek Reservoir.*
[14] CCBWQA August 24, 2005. *Recommendations to Address the Event Mean Concentration Special Study Requirement in Control Regulation 72.*
[15] Division October 7, 2005. *August 24, 2005 Letter with Recommendations to Address Event Mean Concentration Special Study Requirements in Control Regulation No. 72.*
[16] Saunders, James F, July 11, 2005. *Phosphorus Fractionation in EMCs for the Cherry Creek Watershed Model*
[17] Halepaska and Associates, June 6, 2007. *West Cherry Creek Background Phosphorus Report.*

(3) Concentrations of sulfate, ammonia, nitrate, total dissolved phosphate, and soluble reactive phosphate are all lower in ground water at the background location compared to the downstream locations.

(4) Surface water concentrations were found to be above those measured downstream for orthophosphate and dissolved phosphorus during the spring season and for total phosphates in both the spring and fall seasons. This indicates that the relatively undeveloped upper reaches of the Cherry Creek Basin are a contributor to phosphorus concentrations in the basin.

The Authority and Division concluded[18] that the extensive data the Authority collected at Castlewood Canyon was representative of background conditions. The Authority reviewed aerial photographs of the upper basin to identify impervious areas for West Cherry Creek, which is the area with the greatest amount of urbanization in the watershed above Castlewood Canyon. The analysis[19] suggested that the upper watershed imperviousness averages about 6% which is consistent with industry standard impervious values for undeveloped land[20]. Therefore, the phosphorus from the upper basin identified in the above background study is likely from natural phosphorus in the soils.

The Authority and Division also concluded[18] that more extensive analyses of the Castlewood Canyon data was warranted to determine background loads and concentrations, which is presented below.

The Authority and the Division worked together to evaluate the results of the background special study to identify background loads from the basin into Cherry Creek Reservoir. The Division's approach[18] used a statistical analysis of the data that resulted in background total phosphorus load estimate of 5,248-pounds for a median flow year of 10,800-acre feet, which is equivalent to a concentration of 0.18-mg/L.

The Authority used its Watershed Model assuming no development in the watershed, point discharges, BMPs, or well-withdrawals to simulate a 48-year period. This Watershed Model run resulted in a mean annual, total phosphorus load of 4,960 pounds and mean annual runoff volume of 9,139-acre feet, which is equivalent to a concentration of 0.20-mg/L. Because the two independent analyses result in similar values, the background phosphorus load to Cherry Creek is considered to be the average of the two approaches, or 5,100 pounds during a mean flow year of 10,000-acre feet, which is equivalent to a concentration of 0.19-mg/L.

The Authority also investigated the phosphorus content in watershed soils in 1999[21]. Forty-four (44) soil samples, which were composites of three (3) to four (4) grab samples at each site, were obtained from four (4) major soils types: Bresser; Fondis; Stapleton; and Renohill. The average orthophosphate concentration for each soil type was 1.5-mg/kg of soil with very little variation in orthophosphate concentration among the soil types. The Halepaska investigation noted that

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[18] Saunders, James F October 16, 2007. *Cherry Creek Background Phosphorus.*
[19] William P. Ruzzo, PE, LLC December 23, 2008. *Impervious areas in the Cherry Creek watershed upstream of Castlewood Canyon.*
[20] Urban Drainage & Flood Control District 2008. *Urban Storm Drainage Criteria Manual.*
[21] J.C. Halepaska, December 9, 1999. *Cherry Creek Basin Soil Analysis Results*

"*…the orthophosphate concentrations from these unsaturated samples are generally less than one (1) percent of the total phosphorus concentrations observed in the quarterly sediment sampling of saturated soils in Cherry Creek channel over the past five years (300 to 1,500 mg/kg). This indicates that very little of the phosphorus stored in the stream sediments is soluble.*"

The background phosphorus special study is complete.

2.5 Industrial process wastewater sources

The Authority's watershed consultant researched the Division discharge records for industrial dischargers in Cherry Creek basin and only found information on two discharges[22]. DirecTV in Douglas County is permitted for septic system design discharge of 0.00045-mgd with a total phosphorus loading of six pounds per year. In 2008, Acme brick, dba Denver Brick Co. applied for a total phosphorus allocation of 0.21-pounds per year. No other industrial discharged have been identified in the Cherry Creek Basin. Because these discharges are insignificant in magnitude, less than tem pounds per year, they were not included in the Watershed Model.

Because these discharges are insignificant in magnitude (*i.e.*: less than 7-pounds), they were not included in the Watershed Model. The industrial process wastewater sources special study is complete.

2.6 Phosphorus removal effectiveness of nonpoint source control structures.

The Authority and the Division's Colorado Discharge Permit System (CDPS) Permit Section for the Phase II NPDES stormwater discharge permit program currently require local land use agencies in the Cherry Creek Basin to implement construction and post construction BMPs. The purpose of these BMPs is to immobilize phosphorus and other pollutants and prevent them from entering the Reservoir. However, it was not known if the reduction in phosphorus loads by the BMP is valid, due to the potential phosphorus flow out of these facilities related to seepage to the ground water.

The Authority prepared a scope of work, with approval from the Division, and retained a consultant to conduct Special Study No. 2[23]. This study was designed to evaluate if there are significant phosphorus losses out of the BMPs into the underlying ground water that are then reaching Cherry Creek Reservoir. Three BMP sites in the Cottonwood Creek basin were instrumented and monitored for 12-months mostly during 2007 for incoming and outgoing surface water and ground water phosphorus concentrations in the relatively shallow alluvium.

The conclusion of the study was that the:

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[22] Brown and Caldwell July 2004. Industrial Wastewater Treatment Spreadsheet.

[23] Lytle Water Solutions, Inc. March 2008. *Special Study No. 2 Final Report: Phosphorus Removal Effectiveness of PRFS*

"*…upgradient and downgradient phosphorus loading in the alluvial ground water indicates that there are no significant losses from these PRFs to the underlying ground water.*[24]".

Therefore, the data collected by the Authority as well as other local and national data used to predict the long term phosphorus immobilization of detention type BMPs can be used with confidence in the Watershed Model to predict future trends.

The phosphorus removal effectiveness of nonpoint source control structures special study is complete.

2.7 Shallow alluvial groundwater loading in tributaries.

In 2001, the Division noted[25] that alluvial transport of phosphorus was a significant component of the total phosphorus budget for the Reservoir. The Division also expressed concern about the potential effects of wastewater disposal and land use on the phosphorus content of alluvial waters, particularly tributary alluviums, which resulted in identification of this special study.

The Authority has not conducted an investigation of shallow alluvial groundwater loadings from Cherry Creek tributaries since 2001 that specifically meets this special study requirement. However, in 1998, the Authority had conducted a special study of potential individual sewage disposal systems (ISDS) concentrations in the Baldwin and Sulphur Gulch tributaries to Cherry Creek[26]. The results of the earlier 1998 study are presented here, along with previous analysis and testimony regarding the impacts of ISDS on phosphorus loads to the Reservoir in Section 2.8, Quantification of ISDS phosphorus loading. The earlier 1998 study results are presented as the technical basis to identify tributary, shallow-alluvial groundwater phosphorus loading, in light of Reservoir data that shows a correlation between flow-weighted phosphorus concentrations and Reservoir chlorophyll *a* concentrations.

The total dissolved phosphorous in alluvial groundwater for Bayou Gulch near the confluence with Cherry Creek at monitoring well BG-4 had a median value of 0.15-mg/L in the 1998 study. Monitoring equipment for Sulphur Gulch was damaged and no meaningful results were available. The 1998 study noted that:

> *When the total dissolved phosphorus concentration data at BG-4 (the most downgradient station on Bayou Gulch) are compared to the Cherry Creek main stem stations, it appears that there is virtually no input from Bayou Gulch to increasing phosphorus concentrations. To illustrate, well MW-1, which is located on the main stem of Cherry Creek down gradient of Bayou Gulch, has an average total dissolved phosphorus concentration of 0.19-mg/L during the study period…*

[24] The total annual load reduction for all three sites attributed to inflow into the groundwater is 2.3-pounds, compared to the 16-year median annual total load into the Reservoir of 8,270-pounds.
[25] Lewis, William M. Jr. April 9, 2001. *Rationale, Scope of Work, and Priority for Special Studies as Part of a Phased TMAL Process for Cherry Creek Reservoir.*
[26] John C. Halepaska Associates October 1998. *Evaluation of Water Quality Impacts from Leach Fields in Upper Cherry Creek Basin.*

The 1998 ISDS study showed that median groundwater phosphorus concentration in Bayou Gulch (*i.e.*: 0.15-mg/L), which has a number of ISDSs in the watershed, entering the Cherry Creek alluvium, was less than Cherry Creek alluvial aquifer concentrations of 0.19-mg/L at the nearest down gradient monitoring well. In addition, the cumulative groundwater concentrations entering the Reservoir have been relatively consistent, as illustrated by the phosphorus concentrations at MW-9 which are consistently between 0.16- and 0.21-mg/L.

Testimony provided in the September 2000 hearing[27] related to the 1998 ISDS study states:

> *"…None of the data from the study indicated a potential source load from ISDSs that would necessitate changes to the allocation in the Cherry Creek TMDL[28]. Nevertheless, the monitoring wells were observing net phosphorus concentrations after significant movement away from the ISDS through porous media. Therefore, while we do not believe that ISDSs currently pose a significant phosphorus load issue in the Upper Cherry Creek Basin, we would recommend that ISDS continue to be located at points removed from alluvial aquifer systems so that there is time for phosphorus attenuation by movement through colluvial soils and biological uptake by phreatophytes."*

Therefore, the Authority believes that additional groundwater studies for tributary alluvium phosphorus contributions are not warranted. However, relative to potential ISDS impacts on phosphorus from tributaries, the Authority supported 2004 changes in Regulation No. 72 that prohibits ISDS construction in designated 100-year floodplains, which are believed to reasonably represent an alluvial boundary.

2.8 Quantification of ISDS phosphorus loading

The discussion in Section 2.7 regarding alluvial groundwater loading in tributaries also applies to the quantification of ISDS phosphorus loading described in this section. A separate analysis was conducted using the results of the 1998 ISDS study and other available data in an attempt to further quantify phosphorus loading from ISDS.

An Authority watershed consultant[29] evaluated the available data on ISDSs within the Cherry Creek basin and provided an estimate of the nutrient loading from ISDSs into the Cherry Creek alluvium. The findings and conclusions of this investigation are as follows:

> *Based on this evaluation, the total estimated ISDS phosphorus loading to the Cherry Creek alluvium could range from 1,900 to 6,200 lbs/yr of total phosphorus. However, only a fraction of this load reaches the Reservoir. Water quality monitoring data, collected from 1992 to 2006, for alluvial flows and nutrient concentrations show annual alluvial phosphorus loading to the Reservoir of approximately 1,000 lbs/yr. The contribution of nutrient loading from ISDS to the 1,000 lbs/yr. to the Reservoir is uncertain, as other sources of nutrient to the alluvium are included in this loading estimate.*

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[27] Cherry Creek Basin Water Quality Authority 2000. *Prehearing Statement of the Cherry Creek Basin Water Quality Authority, Testimony of Bruce A. Lytle P.E.*
[28] Since Cherry Creek Reservoir is a standing water body, total maximum annual load (TMDL) is now applied to streams and total maximum annual load (TMAL) is applied to standing water bodies.
[29] Brown and Caldwell October 24, 2007. *Estimate of Nutrient Loading from Septic Systems in Cherry Creek Basin.*

The wide range in potential phosphorus loads from ISDS is believed to be due, in part, to the change in soluble concentration as ISDS flows moves from the source through colluvial soil during which time phosphorus is assimilated by the soil and phraetophytes. The closer to the ISDS the concentration is measured, the higher the value and, therefore, the load estimate.

Whereas the contribution of ISDSs toward the phosphorus loading into the Reservoir is uncertain, the Authority recognizes ISDSs as a type of non-point source pollution that should be minimized where possible. To that extent, the Authority supported a change in Regulation No. 72 in 2004 to prohibit construction of new ISDSs within the 100 year flood plain of Cherry Creek and its tributaries. A study of ISDSs showed that seepage from ISDSs within the flood plain/alluvial zone was not attenuated and readily reached Cherry Creek alluvium. However, the monitoring of Bayou Gulch for impacts from ISDS that were not located in alluvial soils (see Section 2.7) did not identify significant impacts from ISDS on the Cherry Creek alluvium.

If the ISDS load estimate is within the range of 1900- to 6200-pounds/year as suggested by the ISDS load analysis, ISDS loads are sufficiently large to have a potential impact on Reservoir water quality. Therefore, if the Commission does not support changing from a load-based to a concentration based TMAL, the Authority recommends additional investigations be conducted to further the understanding of how phosphorus loads from ISDSs can be reduced as the flow moves through colluvial soils and additional measures, such as connection to a WWTP, to minimize the contribution of ISDSs towards phosphorus loads into the Reservoir.

If the Commission does change to a concentration based TMAL, then previous investigations (see Section 2.7) provide data to support that ISDS are not a significant source of phosphorus concentrations and no further investigations are required at this time.

2.9 Implementation of lower phosphorus effluent limits

In 2001, the Division recommended[30] an investigation be prepared to identify practical phosphorus removal limits for different technologies, incremental costs for changes in technology and other measures that reduce phosphorus effluent limits from municipal WWTPs.

Since 2004 and in compliance with Regulation No.72, all point source discharges have permitted discharge limits of 0.05-mg/L of total phosphorus that account for 522 of the 2124-pound allocation of phosphorus in 2007[31]. This level of treatment is achieved by adding chemicals, mostly sulfate compounds, to precipitate dissolved phosphorus, which have increased sulfate concentrations in Cherry Creek. This treatment has the unintended consequence of possible impairment of water quality of Cherry Creek[32].

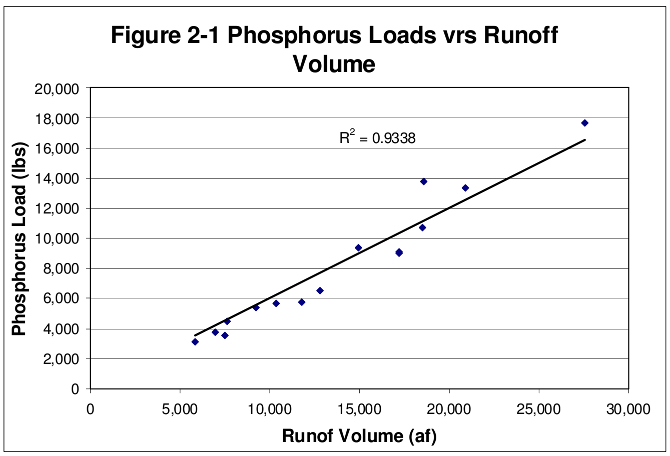
[30] Lewis, William M. Jr. April 9, 2001. *Rationale, Scope of Work, and Priority for Special Studies as Part of a Phased TMAL Process for Cherry Creek Reservoir.*
[31] CCBWQA March 2008. *2007 Annual Report*.
[32] Certain point source discharges commissioned a white paper to present information relevant to establishing a practical phosphorus removal limit in light of the associated costs and potential unintended consequences of maintaining the effluent phosphorus limit of 0.5 mg/L. *See* Lytle Water Solutions October 2008. *Technical Basis for Point Discharge Concentration Change to 0.10 Milligrams per Liter.*

The Authority believes that further investigation into lower phosphorus effluent limits for WWTPs is not warranted at this time.

2.10 Characterization of watershed hydrology

In 2001, the Division recommended[13] that a hydrologic reference condition should be established for evaluation of phosphorus loads to the Reservoir.

A comparison of total flow-weighted phosphorus loads and runoff volume to the Reservoir shows that there is a reasonable correlation between the two, such that a TMAL could be reasonably referenced to hydrology (see Figure 2-1 below). For instance, the median annual 15-year (1992 through 2006) inflow to the Reservoir is 12,800-acre feet, which could be used as the reference runoff volume for a specific TMAL. If the runoff volume were less, the TMAL would be adjusted downward and vice-versa, based on concentration.



Also, as part of the Authority's additional data collection and the Watershed Modeling effort, the annual flow into the Reservoir is now determined with greater reliability. During 2005, the Authority and the Division further jointly funded an investigation which quantified the groundwater flows and loads into the Reservoir with greater precision. This investigation also leads to recalculation of flows and loads into Cherry Creek, which are described further in Section 2.14 of this report.

However, due to the change in the watershed control strategy from phosphorus loads to concentration (see Section 5 and 6 below), the indexing of phosphorus loads to hydrology is no longer necessary. Therefore, if the Commission agrees with a concentration based approach to Regulation No. 72, the characterization of watershed hydrology special study is complete, otherwise this item requires that phosphorus loads be indexed to hydrology.

2.11 Depth profiling of nutrient content for groundwater

In 2001, the Division[13] believed that the Authority's alluvial wells "…*draw selectively from deep points in the alluvium*…and recommended a special study to identify the "…*chemical profile for phosphorus in the alluvium*…and "…*to better improve estimates of alluvial loading and to find out whether human presence has induced the development of a chemical profile in the alluvium*..."

To address these questions, the Authority prepared a scope of work, with approval from the Division, and retained a consultant to conduct Special Study No. 1[33]. Four new test wells were installed at the location of four existing monitoring sites (MW2, MW4, MW5, and MW9), which are located between Lake View Road in Cherry Creek State Park to upstream of the Pinery Water and Sanitation District WWTP. Water samples were obtained and analyzed for ten (10) constituents, including total phosphorus, soluble reactive phosphorus, and nitrate-nitrogen.

Findings of the investigation include:

(1) Subsurface geologic conditions vary between the test sites; however, the sediments are predominantly sand and gravel. There was evidence of stratification (layering) in each of the test holes formed by intermittent layers of silt and clay. Layers of silt and clay do not appear to be laterally continuous.

(2) There is a great deal of vertical and spatial variability in aquifer hydraulic conductivities in the water-bearing sediments.

(3) Concentrations of total phosphorus, soluble reactive phosphorus, and nitrate vary both vertically at individual depth profile test sites and between sites. The variations do not appear to be systematic. In some cases, the highest concentrations occur in the deepest parts of the aquifer, while at others, the highest concentrations occur at shallower depths. However, the highest concentrations generally occur in the deeper half of the aquifer.

(4) Phosphorus loading at the Reservoir is reasonably well represented by the composite monitoring well sampling. One-time depth profile sampling indicates that the results of weighted sampling and composite sampling differed by 7 percent.

The Division reviewed this special study[33] and noted that "*…the study reaches the very significant conclusion that loadings based on integrated alluvial chemistry differ little from those benefiting from the higher resolution provided by the new study…*"

Therefore, Special Study No. 1 confirms the Authority's historic practice of using composite monitoring well sampling as being representative of the alluvial phosphorus concentration for calculating alluvial loads to the Reservoir. The depth profiling of nutrient content for groundwater special study is complete and no further investigations are recommended at this time.

2.12 Revised calculations of phosphorus sources

The Authority will be requesting a modification of the control strategy for Regulation No. 72 that changes the phosphorus control approach from mass to concentration. Therefore, if the Commission agrees with a concentration based approach to Regulation No. 72, the revised calculations of phosphorus sources is no longer necessary, otherwise the Authority will revise the

[33] Lytle Water Solutions, LLC. August 2006. *Depth Profile Study of Phosphorus Concentrations in the Cherry Creek Alluvium Aquifer's.*

calculations of phosphorus from industrial process wastewater and individual sewage disposal system.

2.13 Revision of control regulation TMAL.

This summary report is provided as supporting documentation for the proposed changes to Regulation No. 72 which has a scheduled Water Quality Control Commission (WQCC) hearing date of March 2009. However, even if the Commission agrees with a concentration based approach to Regulation No. 72, a numeric value for the TMAL will be required, as suggested by the 2007 EPA guidance document for the preparation of TMDLs.

The proposed concentration based TMAL would be 0.20-mg/L, or 50th percentile, which would provide a 0.05-mg/L margin of safety. The flow-weighted phosphorus concentration TMAL would be determined by dividing the total external loads by the total inflow volume, including stream, groundwater, precipitation and un-gaged flow. Additional information is provided in the Authority's proposed language revisions for Regulations No. 38 and 72 and the basis and purpose for both regulations.

2.14 Quantification of Groundwater inflow to Cherry Creek Reservoir.

In 2004, the Authority and the Division jointly funded an investigation[34] to determine the amount of groundwater and phosphorus that enter the Reservoir. The executive summary of the report is presented in part below.

> *Direct measurements showed that seepage occurs primarily in shallow water between Cherry Creek and Cottonwood Creek over an area of approximately .036 km 2 (90 acres) as shown by use of seepage meters and piezometers. A zone of very intensive seepage occupies approximately 5700 m^2 (1.5 acres) within this seepage zone. In addition, seepage occurs in the wetland just above the lake shore where Cherry Creek and Cottonwood Creek enter the Reservoir. Seepage in this area, which totals about 1.1 km^2 (275 acres), was assumed to be the same as the mean for all measured rates within the submerged seepage zone at the lake edge.*
>
> *Total seepage, as estimated by these methods, was 2235 acre-feet per year. A separate estimate obtained through the application of mass-balance principles based on the differences in chemical composition of alluvial ground water and tributary runoff was 2255 acre-feet per year. Both of the estimates in these studies confirm a water-budget analysis based on USACE and Cherry Creek Basin Water Quality Authority data indicating that seepage is about 2200 acre-feet per year (about 20% of tributary flow). The study also shows that no significant amounts of flow leave the lake by seepage.*

The estimated seepage load of phosphorus to the Reservoir was reported to be 1,170-pounds per year. One of the significant outcomes from the groundwater inflow special investigation was the partitioning of total flows and the recalculation[35] phosphorus loads that are presented in the Authority's annual monitoring report. A summary of this effort is presented below.

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[34] Lewis, William M; Saunders, James F; and. McCutchan, James H; March 2005. *Estimation of Groundwater Flow into Cherry Creek Reservoir and its Relationship to the Phosphorus Budget of the Reservoir.*
[35] GEI Consultants, Inc. May 4, 2007. *Recalculation of Historical Loads 1992 to 2006*

The recalculation of external total phosphorus loads resulted in negligible changes to most annual estimates when compared to the historical loads.. The most noteworthy differences in the external loads occurred for 1995 and 2000 … Over the long-term period, the recalculation process resulted in an overall 3 percent reduction in the total external loads entering the Reservoir.

Similarly, the export recalculation (USACE outflow) resulted in negligible changes when compared to the historical export loads, except for 1999, which decreased by 2,891 …Similarly, the recalculation process resulted in an overall 4 percent reduction in the export loads leaving the Reservoir.

The recalculation process had the greatest affect on the net external loads for specific year ... but over the long-term period the total reduction in net external loads was only 2 percent.

The groundwater inflow investigation and recalculation efforts provided better understanding of the phosphorus loads and flows into the Reservoir, as well as improved confidence levels in the data and analysis that support the proposed changes to Regulation No. 72. This special study is complete.

3. WATERSHED PHOSPHORUS MODEL

3.1 Introduction

A redeveloped Watershed Model was necessary, in part, because of the difficulties in representing the interaction of the stream and alluvium, which have different volumes and transport velocities resulting in significantly different annual flows and loads into the Reservoir. Surface flows can travel a mile in about an hour, whereas alluvial flows can take 3- to 5-years to travel a mile. Alluvial flows were calculated to be 2,235-acre-feet per year (see Section 2.14), whereas surface flows have varied from as little as 2,500-acre feet to almost 24,000-acre-feet per year (see Table 9). In addition, surface flows contain both particulate and dissolved phosphorus, whereas alluvial flows are primarily dissolved forms of phosphorus. Therefore, it was determined that the Watershed Model should separate and track surface flows and alluvial flows, as well as dissolved and particulate phosphorus forms, requiring a more sophisticated model than proposed in 2000.

From mid-2006 through August of 2008, the Authority redeveloped the Watershed Model to calculate total phosphorus loads and water yield from the watershed into the Reservoir. The Watershed Model was the results of a collaborative effort[6] between several Authority consultants and the Division, who reviewed and commented throughout the process. The Division expressed support for the model in a memorandum on July 2, 2007[36].

The scientific basis and the results of the calibration efforts are described in detail in the model documentation[37], which compares the model predictions for an eight-year period to the

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[36] WQCD July 2, 2007. *Water Quality modeling in Support of the Cherry Creek Reservoir Control Regulation.*
[37] Brown and Caldwell December 22, 2008. *Cherry Creek Basin Watershed Phosphorus Model Documentation*.

monitoring results presented in the Authority's annual monitoring report[38] to the Commission (see section 3.4, this report). This model is referred to as the calibration model, from which future scenarios were then added to determine impacts from changes in watershed management approaches. The Watershed Model results – annual runoff volume, phosphorus loads and concentrations - for each scenario were then provided to Freshwater Research who used the Watershed Model results with the Reservoir Model to help predict potential chlorophyll *a* water quality benefits. A summary of the calibration model approach and findings are presented below in Section 3.2.

Following the calibration model discussion, the model results are presented for scenarios that were analyzed to determine the impact of future growth in the watershed and different management alternatives to reduce phosphorus discharged to Cherry Creek Reservoir. The scenarios were developed to show incremental changes in runoff volumes and phosphorus loads associated with a new Reservoir (*i.e.*: Rueter-Hess), enhanced watershed controls for future development, retrofit of existing BMPs for existing development, and changing discharge limits for WWTP. Enhanced watershed controls represent a more stringent regulatory approach which focuses on improving performance of standard, post-construction BMPs for future development. The retrofit of existing detention ponds represents an increased effort on the part of the Authority to construct watershed controls that improve Reservoir water quality for storm runoff from areas of existing development. Changing discharge limit to 0.1-mg/L provided insight into the sensitivity of changing regulatory limits on WWTP, relative to long-term phosphorus loads and concentrations.

One objective of the scenarios was to determine if the current chlorophyll *a* standard could be met in the future, based on maximum phosphorus loads and concentrations predicted by the Reservoir Model (see Section 5 below). Once it became apparent that the current phosphorus TMAL could not be met, scenario development focused on meeting the required phosphorus concentration and load limits to achieve the proposed Reservoir chlorophyll *a* standard.

The scenarios were evaluated in the following Watershed Model simulations, which are discussed in further detail in the report sections below:

a Scenario A analyzes future growth with current regulations, without including Rueter-Hess Reservoir. This model scenario reflects increases in development and WWTP discharge loads, as well as implementation of minimum construction and post-construction BMP requirements for future development. The scenario evaluates changes to flows and loads that could occur under current regulatory standards, but without Rueter-Hess Reservoir, when compared to the calibration model, which represents existing conditions. Results and comparisons for Scenario A are shown in Table 2.

b Scenario B analyzes future growth with current regulations, and with Rueter-Hess Reservoir. This model scenario investigates the changes in flows, loads and concentrations that would occur after Rueter-Hess Reservoir is completed and operational. In the context of the Watershed Model, Rueter-Hess being operational

[38] GEI Consultants, April 2008. *Cherry Creek Reservoir 2007 Annual Aquatic Biological Nutrient Monitoring Study and Cottonwood Creek Phosphorus Reduction Facilities Monitoring.*

means the ability to divert surface runoff and groundwater well diversions into the Reservoir for storage. The scenario provides insight into the benefits of what could be referred to as a large watershed BMP or PRF, which is Rueter-Hess Reservoir. This model scenario is also referred to as the baseline condition, since construction of Rueter-Hess Reservoir is underway and expected to be completed by 2011. Since Scenario B represents the likely future watershed condition, all subsequent scenarios are then compared to Scenario B. Results and comparisons for Scenario B are shown in Table 3.

c Scenario C analyzes future growth with Rueter-Hess Reservoir and Tier 1[39] Alternatives. This model scenario investigates the impact of enhanced watershed BMPs for future development that *increases* minimum BMP requirements (*i.e.*: more than just extended detention basins, EDB) to BMPs that further reduce discharge concentrations of phosphorus to values lower than expected for a standard EDB. This model provides insight into the benefits of enhancing minimum BMP requirements for significant new development and redevelopment. Thus Scenario C represents more aggressive watershed controls for regulated stormwater from future development and redevelopment. Results and comparisons for Scenario C are shown in Table 4.

d Scenario D analyzes future growth with Rueter-Hess and Tier 2[40] Alternatives. This model scenario investigates the impact of retrofitting existing detention ponds with additional treatment to further reduce discharge concentrations of phosphorus. Retrofit of detention ponds constructed prior to the 2001 was recognized by Control Regulation No. 72[41] as an appropriate watershed management strategy. Thus, Scenario D would represent future Authority constructed projects, PRF, that addresses primarily nonpoint source stormwater, although regulated stormwater is often contained in the inflow to a PRF. Results and comparisons for Scenario D are shown in Table 5.

e Scenario E analyzes an increase in allowable WWTP discharge concentrations. This model scenario investigated potential impacts associated with an increase in WWTP phosphorus discharge concentration from 0.05- to 0.10-mg/L. Results and comparisons for Scenario E are shown in Table 6.

For Scenarios C and D, which evaluate enhanced or retrofit BMPs respectively, the costs of enhanced or retrofit BMPs are also discussed. The cost analysis includes planning, design, capital, maintenance, and administrative costs for the improvements. To compare one-time costs (*i.e.*: capital) and regular costs (*i.e.* operations and maintenance), costs were converted to present worth based on 7% interest rate for a return period of 35-years, which were used in testimony for the 2000 standards hearings. This interest rate and return period were considered representative of finance costs and project life spans at that time and have been used by the Authority since the 2000 standards hearing to evaluate projects in a consistent manner.

[39] The Tier 1 designation is for the purpose of categorizing watershed improvement alternatives and in this case refers to improvements associated with new and redevelopment projects.
[40] The Tier 2 designation refers to improvements associated with retrofitting existing development.
[41] 72.5.3(e)(2)

It is important to note that Scenarios B through E represent long-term conditions in the watershed that includes ultimate development projections that do not have a specific time line, such as the year 2030 or 2050. In addition, the projected change in phosphorus loads for each scenario may not be achievable due to uncontrollable circumstances such as climate changes and changes in Reservoir management or physical characteristics by the USACE.

3.2 Calibration Model Summary

The Watershed Model calculates both water yield (acre-feet) and phosphorus load (total and dissolved, in pounds) during the eight year simulation period. When multiple eight year periods are connected, the results from the last of the eight years become the initial values for the next eight year period, which was then repeated six times. This approach allowed a simulation period of 48-years to be evaluated. The longer simulation period was found to be important since alluvial flows and loads from Castlewood Canyon can take over fifty years to travel to the Reservoir. The longer simulation period also provided greater understanding of the fate and transport of phosphorus as it travels through the watershed, since there are significant timing differences between surface and groundwater flow conditions before reaching the Reservoir. Additional discussion of the longer simulation period can be found in the Watershed Model documentation[37].

Runoff volume and phosphorus load are generated during precipitation runoff events and routed from the watershed sub-basins to the tributaries, which connect to Cherry Creek mainstem, and then flow downstream to the Reservoir. For the tributaries and mainstem, both surface water and alluvial flow conditions are calculated and routed through the system to account for travel time differences between surface and groundwater flow and changes in phosphorus concentrations due to sedimentation and remobilization processes. The model does not, however, attempt to account for adsorption, desorption, biological assimilation or the geochemical changes in phosphorus that can occur throughout the system.

Phosphorus load is calculated and routed in two different forms. Dissolved phosphorus is that portion of the load that is assumed to travel at the same velocity as the surface and alluvial flow, *i.e.*: it is a conservative ion. Particulate phosphorus is that portion of the load that is only present in surface flow and is assumed to settle or filter out when runoff infiltrates from the surface to the alluvium. Particulate phosphorus can also be mobilized during higher stream flow events that erode or scour the channel bed or banks, picking up particulate phosphorus attached to eroded material.

The Model is precipitation driven in that phosphorus loads are generated from the sub-basin runoff in the watershed by a rainfall event based on phosphorus event mean concentrations (EMC) for different land uses. Source of the land use information for the watershed is provided in the Watershed Model documentation. These phosphorus EMCs and the ability of BMPs to immobilize phosphorus are also based on long-term trends.

In the following report Sections 3.3 through 3.7, six tables are provided presenting the results of each model run when compared to the Calibration Model - or actual data, as is the case for the Calibration Model. Therefore, the comparison shows the changes from existing conditions each scenario would have if the scenario were implemented. The tables present the computed values for flows, phosphorus loads and concentrations for the specific model scenario and the Calibration Model. Also shown in the table are the median values for the eight year simulation period from 1995 through 2002 as well as the percent difference between the model run and condition to which the model run is compared.

3.3 Calibration Model Findings

Significant findings of the calibration Watershed Model include:

1. The Watershed Model is a base flow model and not a storm event model, where base flow is defined as runoff from lesser intense precipitation events or snow melt. The distinction between base flow and storm event is the assumption that any rainfall amount greater than 1-inch per hour, which has an approximate recurrence interval of two years, is a storm event. For storm events, the runoff and phosphorus algorithms are less precise at the higher rainfall intensities, although adjustments are made in the model to account for higher rainfall intensities. Comparison of modeled and monitored flow data confirms the reasonableness of the model algorithms for water yield.
2. Although the model evaluates dissolved and particulate phosphorus, the model is a reasonable predictor for total phosphorus only. The model does not attempt to evaluate adsorption, desorption, biological assimilation or geochemical effects on the many forms of phosphorus, which could alter the partitioning of total phosphorus as it moves through the watershed.
3. The model reasonably predicts monthly and seasonal peaks and valleys in watershed yield and phosphorus loads demonstrating sensitivity to fate and transport algorithms. The model also predicts long-term trends in water yield and phosphorus loads. This ability to predict both short and long term trends suggests that there are little or no major biases in the algorithms. However, the model is primarily used to predict long-term annual *changes* in phosphorus loads to the Reservoir, rather than actual flows and loads.
4. Calibration of the model using a substantial amount of runoff and water quality data demonstrates the reasonableness of the model algorithms and general approach. The model, however, is best used to predict *changes* in total phosphorus discharged to the Reservoir from watershed changes (such as development density and type, WWTP discharges, BMPs, and channel stabilization measures). Therefore, the summary tables provided below for the five (5) scenarios also present a percent difference from the calibration model, median flows and loads for the 48-year simulation period. Actual phosphorus loads and concentrations are best determined from monitored data.

3.4 Calibration Model Results

Table 1 compares results from the calibration model to the monitored data included in the Authority's annual monitoring report. The median predicted inflow volume is 8% greater, the median load is 31% greater, and the median concentration is 16% greater than monitored data. The greater difference in load prediction is a basis for concluding that the model is best used to predict *changes* in flows and loads, rather than actual values. Therefore, all subsequent discussions of various scenarios include a comparison to the calibration model, representing existing conditions. In addition, all the results are presented for the 48-year simulation discussed above.

3.5 Scenario A - Future Growth with Current Regulations, without Rueter-Hess Reservoir

Table 2 compares results from the calibration model to Scenario A, which includes the following assumptions:

a Rueter-Hess Reservoir is not operational. In this condition, the model options for surface diversions from Cherry Creek and supplemental well diversions from Cherry Creek alluvium are turned off.

b An increase in sub-basin imperviousness and, therefore, the resulting runoff volume, based on future land use projections. Phosphorus EMCs are not changed from the baseline condition as they are dependent only on general land use categories for residential, commercial, industrial and undeveloped land uses.

c Current minimum requirements for post construction BMPs for all new development. (*i.e.*: EDB with a total phosphorus discharge concentration of 0.24-mg/L, that is equally partitioned between particulate and dissolved phosphorus). The baseline model was modified to add EDB nodes to the outlet of 122-sub-basins before they discharge to a tributary as a reasonable approximation of all future, post-construction BMPs.

d Future WWTP volume and phosphorus load discharge increases, historic well pumping, and additional water from undefined sources.

Table 2 - Comparison of Calibration Model to Scenario A (Future Condtions without Rueter-Hess)

Year	Calibration Model Results			Future Conditions w/o Rueter Hess		
	Inflow (af)	Total Load (lbs)	Concent. (mg/l)	Inflow (af)	Total Load (lbs)	Concent. (mg/l)
1995	15,251	10,675	0.26	27,562	15,554	0.21
1996	6,258	4,269	0.25	14,697	8,271	0.21
1997	12,231	8,280	0.25	24,028	13,536	0.21
1998	17,727	11,586	0.24	29,892	16,395	0.20
1999	20,649	13,511	0.24	31,685	17,255	0.20
2000	16,979	10,251	0.22	24,346	12,645	0.19
2001	16,115	9,146	0.21	22,511	11,169	0.18
2002	9,166	5,686	0.23	16,624	8,593	0.19
Median	**15,683**	**9,699**	**0.24**	**24,187**	**13,090**	**0.20**
% Difference				**54%**	**35%**	**-16%**

Rueter-Hess Reservoir was modeled based on information provided by the PWSD, which is graphically illustrated in a PWSD document[42] and includes the following system components in the Watershed Model:

a In priority surface diversions from Cherry Creek pumped into Rueter-Hess Reservoir.

b Well pumping of historic consumptive use water from Cherry Creek alluvium into Rueter-Hess Reservoir.

c Return of non-reusable WWTP discharges to Cherry Creek.

Except for seepage through the Rueter-Hess embankment, all releases from the Reservoir are treated at the water treatment plant then discharged into the potable water system of PWSD and eventually discharged to Cherry Creek by the WWTP and recaptured and reused. Therefore, phosphorus from the surface diversion and alluvial wells is mostly retained in the Reservoir or is discharged at a lower concentration at the WWTP.

Evaluation of the existing watershed development patterns showed that there were 122-sub-basins out of 320-sub-basins where future growth will increase imperviousness by 10% or more. For these 122-subbasins, a model "node" was added to represent a future, post-construction BMP. The BMP algorithm simulates the EDBs which intercepts runoff from a sub-basin prior to the flow and load entering a tributary or the main stem. EDBs were selected because they are the minimum BMP constructed in the watershed based on the Authority's current requirements and Regulation No. 72. When runoff passes through a BMP, either the standard or enhanced EDB, there is no reduction in flow or the timing of the flow but discharge concentrations are reduced to a predetermined value, defined below.

Based on review of the American Society of Civil Engineers (ASCE) BMP database for EDBs, the median total phosphorus concentration of 0.24-mg/L was used as the discharge concentration lower limit from a BMP, equally partitioned between dissolved and particulate phosphorus. Therefore, if the particulate or dissolved concentration of incoming phosphorus fraction is higher than 0.12-mg/L, the concentration and therefore load is reduced. If the incoming particulate or dissolved concentration is already at or below 0.12-mg/L, then the EDB has no impact and the discharge concentration does not change.

The Authority data collected for Shop Creek and Cottonwood Creek show that concentrations from wetland type BMPs can reduce total phosphorus to levels in the range of 0.10- to 0.20-mg/L. The higher discharge concentration of 0.24-mg/L was considered appropriate for EDBs, since EDBs typically do not include significant wetlands. Also, EDBs for many developments have tributary watersheds that include directly connected impervious areas that result in higher concentrations of phosphorus in storm runoff than is the case for Shop Creek and portions of the Cottonwood Creek tributary watersheds.

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[42] Parker Water and Sanitation District April 12, 2007. *RHR and Cherry Creek Water Balances*

The evaluation of EDBs for future development assumes that the EDB will not measurably reduce runoff volume. Whereas some BMP data bases suggest a “loss in volume” for EDBs, the assumption here of no loss in volume is considered conservative, since higher volumes would produce greater phosphorus loads. The evaluation also assumed that the EDBs will not significantly affect the timing of the flow. Considering that the Watershed Model includes a simulation period of 48-years, the change in flow timing of a few hours through an EDB is not likely to have measurable impact on the results.

Evaluation of Phosphorus Loads and Runoff Volumes.

In Table 2, the median predicted inflow volume *increases* over the calibration model by 54% and the median load *increases* by 35%, due to additional surface runoff and phosphorus loads from future growth and increased wastewater flows and loads. However, the median predicted concentration *decreases* by 16%.

Table 2 shows that the median phosphorus concentration for Scenario A (*i.e.*: 0.20-mg/L) is less than the median concentration for the calibration model (*i.e.*: 0.24-mg/L) by 16%. This reduction in concentration is believed related to surface discharges from post construction EDBs, which infiltrate into the alluvium at the lower discharge concentration for dissolved phosphorus (*i.e.*: 50% of 0.24-mg/L equals 0.12-mg/L), thereby reducing the median concentrations. The boundary condition for the Watershed Model is the data at Castlewood Canyon, which is comprised almost entirely of surface flow with a total phosphorus concentration that ranges from 0.18- to 0.22-mg/L. Therefore, discharges from the enhanced and retrofit BMPs have the effect of diluting phosphorus concentrations in the alluvium, although it takes a long time to see these results.

As noted in the discussion of the Reservoir Model (Section 5.2 below), the median annual phosphorus load for Scenario A (Table 2, 13,090-pounds) exceeds the maximum annual load of 3,150-pounds required to meet the current in-lake chlorophyll *a* standard.

3.6 Scenario B - Future Growth with Current Regulations, with Rueter-Hess Reservoir

Table 3 compares results from the calibration model to Scenario B, which includes future development, but with Rueter-Hess Reservoir. Scenario B (also called the baseline model) includes the following assumptions:

a Rueter-Hess Reservoir is operational.

b An increase in sub-basin imperviousness and, therefore, the resulting runoff volume, based on future land use projections. Phosphorus EMCs are not changed from the baseline condition.

c Future WWTP volume and phosphorus load discharge increases (adjusted for the diversion of an equivalent WWTP volume from PWSD to Rueter-Hess Reservoir), historic well pumping, and additional water from undefined sources.

d In priority, native Cherry Creek water is diverted at the Rueter-Hess diversion structure, used in the water distribution system, and ultimately released through the WWTP back to Cherry Creek after initial use.

e Current minimum requirements for post construction BMPs for all new development (*i.e.*: EDB with a total phosphorus discharge concentration of 0.24-mg/L equally portioned between particulate and dissolved phosphorus). The baseline model was modified to include EDB nodes to the outlet of 122-sub-basins before they discharge to a tributary that are then routed to the main stem of Cherry Creek and to the Reservoir.

Evaluation of Phosphorus Loads and Runoff Volumes.

Table 3 shows that the median predicted inflow volume *increases* over the calibration model by 7%, compared to the 54% increase in runoff volume without Rueter-Hess Reservoir (Scenario A). Whereas the increase in volume can be attributed to additional surface runoff volume and increased wastewater flows from future growth, the increase (7%) is less than the increase (56%) without Rueter-Hess Reservoir. However, the median load *decreases* by 6%, and the median predicted concentration *decreases* by 17% with Rueter-Hess Reservoir.

Comparing Scenario A (Table 2) and B (Table 3) shows that Rueter-Hess Reservoir will *reduce* mean annual phosphorus loads by 3,992-pounds but the median phosphorus concentration does not change. This demonstrates that controlling phosphorus loads alone may not reduce phosphorus concentrations into the Reservoir.

As noted in the discussion of the Reservoir Model (Section 5.2 below), the median annual phosphorus load for Scenario B (Table 3, 9,098-pounds) exceeds the maximum annual load of 3,150-pounds required to meet the current in-lake chlorophyll *a* standard.

Table 3 - Comparison of Calibration Model to Scenario B (Baseline Model - Future Conditions with Rueter-Hess Reservoir)

Year	Calibration Model Results			Future Conditions w/Rueter Hess		
	Inflow (af)	Total Load (lbs)	Concent. (mg/l)	Inflow (af)	Total Load (lbs)	Concent. (mg/l)
1995	15,251	10,675	0.26	18,963	10,958	0.21
1996	6,258	4,269	0.25	8,784	5,050	0.21
1997	12,231	8,280	0.25	16,739	9,318	0.21
1998	17,727	11,586	0.24	22,479	12,136	0.20
1999	20,649	13,511	0.24	22,256	12,011	0.20
2000	16,979	10,251	0.22	16,825	8,878	0.19
2001	16,115	9,146	0.21	15,965	7,935	0.18
2002	9,166	5,686	0.23	11,619	6,155	0.20
Median	**15,683**	**9,699**	**0.24**	**16,782**	**9,098**	**0.20**
% Difference				**7%**	**-6%**	**-17%**

3.7 Scenario C - Future Growth with Rueter-Hess Reservoir and Tier One Alternatives.

The Watershed Model was also used to evaluate if additional watershed management strategies could sufficiently reduce phosphorus loads to meet the current standard of 15-µg/L chlorophyll *a*, nine out of ten years and at a reasonable cost. Scenario C Watershed Model was developed that included the following conditions:

a Rueter-Hess Reservoir is operational.

b Includes an increase in sub-basin imperviousness and, therefore, the runoff volume, based on future land use projections. Phosphorus EMCs are not changed from the baseline condition.

c Future WWTP volume and phosphorus load discharge increases (adjusted for the diversion of an equivalent WWTP volume from PWSD to Rueter-Hess Reservoir), historic well pumping, and additional water from undefined sources.

d In priority, native Cherry Creek water is diverted at the Rueter-Hess diversion structure, used in the water distribution system, and ultimately released through the WWTP back to Cherry Creek after initial use.

e Enhanced requirements for post construction BMPs for all new development were modeled based on achieving further reductions in phosphorus discharge concentration from BMPs for the 122-sub-basins described above. It was estimated that a total of 307 enhanced BMP would be constructed, based on an average development size of 100-acres with 45% imperviousness, which were simulated using the 122-EDB nodes added to the calibration model.

An evaluation of an EPA report for BMP performance[43], as well as review of the Authority's monitoring data for Shop Creek and Cottonwood\Peoria detention ponds[44], suggest that retention ponds, wetlands, filtration and infiltration type BMPs have median discharge concentrations for phosphorus that are lower than for extended detention basins, which is the current minimum requirement for significant new development. The mean, total-phosphorus discharge concentrations for enhanced BMPs range from 0.10- to 0.20-mg/L in the EPA report. For Shop Creek and Cottonwood Creek, the discharge concentrations for base flow are often less than 0.10-mg/L and typically below 0.20-mg/L for storm flows. The storm flow data for Cottonwood Peoria pond was evaluated (2004 to 2007) and the median, total-phosphorus concentration discharged from the pond was 0.19-mg/L.

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[43] EPA September 2002. *Consideration in the Design of Best Management Practices (BMP) to Improve Water Quality.*
[44] GEI Consultants, April 2008. *Cherry Creek Reservoir 2007 Annual Aquatic Biological Nutrient Monitoring Study and Cottonwood Creek Phosphorus Reduction Facilities Monitoring.*

When determining the appropriate discharge concentration to be used for enhanced BMPs, the principle of irreducible discharge concentrations was considered. Some studies[45] have shown the discharge from a BMP cannot be expected to be lower than background levels, based on current technology. Mean discharge values for wet and extended detention basins[45] suggest a lower limit for total phosphorus of 0.22-mg/L and for wetlands, a value of 0.19-mg/L. Others[46] however, believe that "*it is possible to get concentrations as low as desired, but in most cases achieving extremely low effluent concentrations may not be practical (i.e., would require treatment trains that may not be practical in urban areas that require treatments with small footprints or exotic methods)"*. Also considered was the lack of regular, long term maintenance to preserve a high level of performance would likely reduce long term performance for enhanced BMP all which go to reducing expectations for these BMP, resulting in higher discharge concentrations.

For the purpose of evaluating the benefits of enhanced BMPs for new development, it was assumed that the total phosphorus discharge concentration would be similar to the higher estimate of background concentrations (*i.e.*:0.20-mg/L), which is partitioned 40% dissolved (*i.e.*: 0.08-mg/L) and 60% (*i.e.*: 0.12-mg/L) particulate phosphorus, based on data from Cottonwood Creek Peoria Pond. It is noted that the dissolved fraction discharged from the enhanced BMP, 0.08-mg/L, is less than background levels discussed in Section 2.4, Quantification of Background Phosphorus, which is comprised mostly of dissolved phosphorus in the alluvium. If this discharge concentration from an enhanced BMP is achievable, as suggested by monitoring data, it could result in reduction in phosphorus concentrations to the Reservoir.

Evaluation of Phosphorus Loads and Runoff Volumes.

Presented in Table 4 is a comparison of the results between the Scenario B Baseline Model, which includes future development with Rueter-Hess Reservoir, and Scenario C described above, which includes the Baseline Model plus Tier 1 BMP alternatives. Table 4 shows that the median predicted inflow volume does not change since Tier 1 BMP enhancements were assumed to not change runoff volume. However, the total load *decreases* by 7% and the concentration *decreases* by 7%. This comparison suggests that if BMP performance can be improved, further reductions in phosphorus loads and concentrations may result. BMP performance improvements can be achieved either by requiring BMPs that are more advanced than EDBs, such as wetlands, sand filters, or infiltration, or by improving EDB performance through design modifications.

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[45] Center for Watershed Protection ----. *Irreducible Pollutant Concentrations Discharged from Stormwater Practices.* Article #65 Watershed Protection Techniques.
[46] US EPA September 2004. *Stormwater Best Management Practices Guide Volume 1 General Considerations.* EPA 600/R 04/121, Appendix e.

Table 4 - Comparison of Scenario B (Baseline Model - Future Conditions with Rueter Hess) to Scenario C (Baseline Model with Tier 1 BMP Alternatives)

Year	Baseline Model Results			Baseline Model Results Plus Tier 1		
	Inflow (af)	Total Load (lbs)	Concent. (mg/l)	Inflow (af)	Total Load (lbs)	Concent. (mg/l)
1995	18,963	10,958	0.21	18,963	10,194	0.20
1996	8,784	5,050	0.21	8,784	4,696	0.20
1997	16,739	9,318	0.21	16,739	8,657	0.19
1998	22,479	12,136	0.20	22,479	11,280	0.19
1999	22,256	12,011	0.20	22,256	11,158	0.19
2000	16,825	8,878	0.19	16,825	8,313	0.18
2001	15,965	7,935	0.18	15,965	7,443	0.17
2002	11,619	6,155	0.20	11,619	5,723	0.18
Median	**16,782**	**9,098**	**0.20**	**16,782**	**8,485**	**0.19**
% Difference				**0%**	**-7%**	**-7%**

Table 4 also suggests that over an extended period (*i.e.*: 48-years), some surface discharge from BMP is infiltrated into the alluvium at the lower discharge concentration for dissolved phosphorus (*i.e.*: 40% of 0.20-mg/L equals 0.08-mg/L, see discussion above). The boundary condition for the Watershed Model is the data at Castlewood Canyon, which is comprised almost entirely of surface flow with a total phosphorus concentration that ranges from 0.18- to 0.22-mg/L. Therefore, discharges from the enhanced BMP infiltrate into the alluvium at a lower concentration than at Castlewood Canyon and have the effect of diluting phosphorus concentrations in the alluvium, although it takes a long time to see these results.

As noted in the discussion of the Reservoir Model (Section 5.2 below), the median annual phosphorus load for Scenario C (Table 4, 8,485-pounds) exceeds the maximum annual load of 3,150-pounds required to meet the current in-lake chlorophyll *a* standard.

Estimated Costs

Since EDBs are currently the minimum post-construction BMP standard for significant new development, the *incremental* cost to implement enhanced BMPs was estimated (see Sheet 1 Appendix). The cost analysis for enhanced BMPs was based on simplified algorithms that equate BMP costs to some constant multiplied by the water quality capture volume (WQCV) or BMP surface area, which is then raised to some power. The analysis also evaluated the increase in operations and maintenance costs associated with more sophisticated BMPs. The *incremental* costs to implement enhanced BMPs for significant new development were estimated to be $131,000,000, which is present worth at 7% and 35-years. *See* Report Appendix.

Comparison of Costs to Economic Benefits

Evaluation of Scenario C costs and benefits requires comparison to Scenario B. Scenario B is the likely future condition where no additional watershed controls are implemented beyond that which are required under the current Regulation No. 72. By implementing Scenario C, there is a potential for an additional reduction in phosphorus concentration of 6% (*i.e.*: Table 7, 23% -

17%). The additional costs for BMPs ($131,000,000, Appendix Sheet 1) would be initially borne by development and likely be passed onto the consumers in terms of residential and commercial property prices. DRCOG's[47] population estimate for 2005 in Cherry Creek watershed was 152,800, which is projected to increase to 341,000 by 2030, an increase in of 223%. Unpublished 2008 population projections for 2035 are 383,600, an increase of 250%. Assuming these costs were borne by residential properties and assuming 2.8-persons per household, the growth in the watershed would add over 82,400 households and Tier 1 enhanced BMPs (Scenario C) would increase the cost of each home by approximately $1,600. *See* Report Appendix.

A cursory investigation into the likely order of magnitude for the total value of Cherry Creek State Park was conducted in 2000[48]. When compared to the recreational and regional economic impact of the Park, which was valued between $1.4-billion and $3.3-billion, Tier 1 improvements (Scenario C) would range from 4- to 9-% of the capitalized value of Cherry Creek State Park. *See* Report Appendix.

3.8 Scenario D - Future Growth with Rueter-Hess Reservoir and Tier 2 Alternatives.

The Watershed Model was also used to evaluate if other watershed management strategies could sufficiently reduce phosphorus loads to meet the current standard of 15-µg/L chlorophyll *a*, nine out of ten years and at a reasonable cost. Scenario D Watershed Model was developed to address detention ponds that were constructed prior to Phase II NPDES stormwater requirements, particularly in the lower watershed. Scenario D included the following conditions:

a Rueter-Hess Reservoir is operational.

b An increase in sub-basin imperviousness and, therefore, the resulting runoff volume, based on future land use projections. EDBs for future development are modeled separately, as described in Scenario A discussion, and do not include BMP enhancements described in Scenario C.

c Future WWTP volume and phosphorus load discharge increases (adjusted for the diversion of an equivalent WWTP volume from PWSD to Rueter-Hess Reservoir), historic well pumping, and additional water from undefined sources.

d In priority, native Cherry Creek water is diverted at the Rueter-Hess diversion structure, used in the water distribution system, and ultimately released through the WWTP back to Cherry Creek after initial use.

e Tier 2 - Retrofit of existing detention ponds that were constructed prior to 2001 which do not meet minimum EDB requirements.

[47] DRCOG April 27, 2007. *Metro Vision 2020 Clean Water Plan Appendix 6 Cherry Creek Reservoir Watershed.*
[48] Stratus Consulting, August 2, 2000. *Preliminary Evaluation of Recreation Value Provided by Cherry Creek State Park.*

Evaluation of sub-basins in the lower watershed showed that there were 104-sub-basins where significant development has already occurred. These 104 sub-basins, which do not include the 122-sub-basins in Tier 1 alternatives, were considered to be candidates for retrofit of existing detention ponds that likely do not meet EDB requirements, since development in the lower watershed predated 2001 when the EDB standard was established.

For the purpose of evaluating the benefits of retrofitting existing BMPs, it was assumed that the total phosphorus discharge concentration could be reduced to 0.24-mg/L, the same as estimated for future development EDBs. The discharge concentration was partitioned 50% dissolved and 50% particulate phosphorus. The technical bases for these values are described under Scenario B above.

Evaluation of Phosphorus Loads and Runoff Volumes.

Presented in Table 5 is a comparison of the results between Scenario B Baseline Model, which includes future development with Rueter-Hess Reservoir and Scenario D described above, which includes the Baseline Model plus Tier 2 BMP alternatives only. Table 5 shows that the median predicted inflow volume for Scenario D does not change since Tier 2 detention pond improvements were assumed to not change runoff volume. However, the total load *decreases* by 10% and the concentration *decreases* by 11%. This comparison suggests that if the performance of existing detention ponds can be improved, further reductions in phosphorus loads and concentrations may result. Detention pond performance improvements can be achieved either by retrofitting them to include wetlands or sand filters, or by proprietary filtration devices.

Table 5 - Comparison of Scenario B (Baseline Model - Future Conditions with Rueter Hess) to Scenario D (Baseline Model with Tier 2 BMP Alternatives)

Year	Baseline Model Results			Baseline Model Plus Tier 2		
	Inflow (af)	Total Load (lbs)	Concent. (mg/l)	Inflow (af)	Total Load (lbs)	Concent. (mg/l)
1995	18,963	10,958	0.21	18,962	9,862	0.19
1996	8,784	5,050	0.21	8,784	4,592	0.19
1997	16,739	9,318	0.21	16,739	8,350	0.18
1998	22,479	12,136	0.20	22,478	10,851	0.18
1999	22,256	12,011	0.20	22,256	10,747	0.18
2000	16,825	8,878	0.19	16,825	8,026	0.18
2001	15,965	7,935	0.18	15,965	7,218	0.17
2002	11,619	6,155	0.20	11,619	5,555	0.18
Median	**16,782**	**9,098**	**0.20**	**16,782**	**8,188**	**0.18**
% Difference				**0%**	**-10%**	**-11%**

Table 5 suggests that over an extended period (*i.e.*: 48-years), some surface discharge from BMP is infiltrated into the alluvium at the lower discharge concentration for dissolved phosphorus (*i.e.*: 50% of 0.24-mg/L equals 0.12-mg/L). The initial condition for the Watershed Model is the data at Castlewood Canyon, which is comprised almost entirely of surface flow with a total phosphorus concentration that ranges from 0.18- to 0.22-mg/L. Therefore, discharges from the enhanced or retrofit BMPs, which infiltrate into the alluvium at a lower concentration than at

Castlewood Canyon, may have the effect of diluting phosphorus concentrations in the alluvium, although it takes a long time to see these results.

Comparing Tables 4 and 5 also suggests that retrofitting existing BMPs not only reduces loads and concentrations by an additional 3% and 4%, but that retrofitting detention ponds is also more *cost effective* than constructing enhanced BMP primarily in the upper watershed, as seen by the discussion of costs presented below.

As noted in the discussion of the Reservoir Model (Section 5.2 below), the median annual phosphorus load for Scenario D (Table 5, 8,188-pounds) exceeds the maximum annual load of 3,150-pounds required to meet the in-lake chlorophyll *a* standard.

Estimated Costs

Cost estimates for retrofitting existing detention ponds (Sheet 2, Appendix) included the cost of a preliminary investigation to determine technical feasibility of retrofitting the ponds, followed by conceptual and final design of actual improvements. Construction, operation and maintenance costs were then added to the investigation and design costs. Since the cost of the original detention pond was not included, the costs for Scenario D are incremental to the original detention costs.

It was assumed that the most feasible approach would be to add a proprietary BMP, typically constructed underground, to minimize land disturbance and right of way or easement requirements associated with wetlands, sand filtration, or other similar BMPs that require more surface area. Also considered were legal costs associated with obtaining easement and related liability for long term maintenance of the improvements once completed. Whereas proprietary BMPs might keep construction costs lower, operations and maintenance cost were assumed to be higher than for EDBs or similar BMPs.

Costs to retrofit existing detention basins for areas that were mostly developed prior to 2001 was estimated to be $55,000,000, which is present worth at 7% and 35-years. *See* Report Appendix. Implementation of Tier Two alternatives (*i.e.*: retrofit of existing detention ponds) provides better phosphorus load and concentration reduction than for Tier One alternatives (*i.e.*: enhanced BMP for future development). Also, the cost of Tier Two alternatives is about 42% of the cost of Tier One alternatives.

Comparison of Costs to Economic Benefits

Evaluation of Scenario D costs and benefits requires comparison to Scenario B. Scenario B is the likely future condition where no additional watershed controls are implemented beyond that which are required under the current Regulation No. 72. The costs to retrofit existing detention basins (Scenario D, Tier 2 improvements) would be borne by the Authority through current taxes and fees and may not require additional funds from the general public. By implementing Scenario D, there is a potential for an additional reduction in phosphorus concentration of 9% (*i.e.*: Table 7, 26% - 17%), which is 50% better than projected for Scenario C with Tier 1 improvements.

A cursory investigation into the likely order of magnitude for the total value of Cherry Creek State Park was conducted in 2000[48]. When compared to the recreational and regional economic impact of the Park, which was valued between $1.4-billion and $3.3-billion, Tier 2 improvements (Scenario D) would range from 2- to 4-% of the capitalized value of Cherry Creek State Park, which is less than for Scenario C. *See* Report Appendix

3.9 Scenario E – Analysis of an Increase in WWTP Discharge Concentrations.

The Watershed Model was also used to evaluate the potential impacts from allowing WWTP to increase phosphorus discharge concentrations from 0.05- to 0.10-mg/L on the external loads and concentrations at Cherry Creek Reservoir. To model this scenario, the following assumptions were made.

a Rueter-Hess Reservoir is operational.

b An increase in sub-basin imperviousness and, therefore, the resulting runoff volume, based on future land use projections. Phosphorus EMCs are not changed from the baseline condition.

c Future WWTP volume and phosphorus load discharge increases (adjusted for the diversion of an equivalent WWTP volume from PWSD to Rueter-Hess Reservoir), historic well pumping, and additional water from undefined sources.

d In priority, native Cherry Creek water is diverted at the Rueter-Hess diversion structure, used in the water distribution system, and ultimately released through the WWTP back to Cherry Creek after initial use.

e The discharge concentration from all WWTPs was increased to 0.10–mg/L.

Evaluation of Phosphorus Loads.

Presented in Table 6 is a comparison of the results between the Baseline Model Scenario B and Scenario E described above, which includes the Baseline Model but with an increase in WWTP discharge to 0.10-mg/L.

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Table 6 - Comparison of Scenario B (Baseline Model - Future Conditions with Rueter Hess) to Scenario E (Baseline Model w/WWTP Discharge at 0.1-mg/l)

Year	Baseline Model Results			Baseline w/WWTP Disch at 0.1-mg/l		
	Inflow (af)	Total Load (lbs)	Concent. (mg/l)	Inflow (af)	Total Load (lbs)	Concent. (mg/l)
1995	18,963	10,958	0.21	18,962	11,007	0.21
1996	8,784	5,050	0.21	8,784	5,078	0.21
1997	16,739	9,318	0.21	16,739	9,367	0.21
1998	22,479	12,136	0.20	22,478	12,213	0.20
1999	22,256	12,011	0.20	22,256	12,080	0.20
2000	16,825	8,878	0.19	16,825	8,923	0.20
2001	15,965	7,935	0.18	15,965	7,975	0.18
2002	11,619	6,155	0.20	11,619	6,191	0.20
Median	**16,782**	**9,098**	**0.20**	**16,782**	**9,145**	**0.20**
% Difference				**0%**	**1%**	**1%**

Table 6 shows that the median predicted inflow volume for Scenario D does not change, since the only difference between the models in an increase in WWTP discharge concentrations. However, the median load increases by 1% (47-pounds) and the median concentration also increases by 1%, but the increase is in the third decimal. When compared to the Baseline Model, allowing the WWTP to discharge at 0.10-mg/L has minimal impact on phosphorus loads and concentrations entering the Reservoir, since both phosphorus load and concentration increases are less than 1%.

3.10 Summary of the Watershed Model Scenarios.

As noted in the discussion of the calibration model summary (Section 3.2), the Watershed Model is best used to predict long-term *changes* in phosphorus loads or concentrations for reasons discussed in the section. Therefore percent changes for each scenario were compared to the Calibration Model and are summarized below in Table 7. Comparison to the calibration model represents the changes expected when compared to historic conditions represented by the data collected from 1995 through 2002.

Table 7 - Summary of the Changes in Volume, Phosphorus Load and Concentration for each Scenario Compared to Calibration Model

Model Scenario	Report Table	Description	Comparison to Calibration model		
			% Change		
			Volume	P Loads	P Conc.
A	2	Future Conditions w/o Rueter Hess	56%	35%	-16%
B	3	Future Conditions with Rueter Hess (Baseline Model)	8%	-6%	-17%
C	4	Future Conditions, Rueter Hess and Tier 1 BMP Alternatives	8%	-13%	-23%
D	5	Future Conditions, Rueter Hess and Tier 2 BMP Alternatives	8%	-16%	-26%
E	6	Future Conditions, Rueter Hess and 0.1-mg/l WWTP Discharge	8%	-3%	-15%

Conclusions from inspection of Table 7 include:

1. Implementation of the current BMP requirements for future growth (*i.e.*: EDB) along with completion of Rueter-Hess Reservoir can reduce phosphorus concentrations from historic conditions by 17%, and phosphorus loads are reduced by 6% (Scenario B), even though population growth in the watershed is projected to increase by 250% by 2035.

2. Increasing WWTP discharge limit to 0.10-mg/L can still *reduce* phosphorus concentrations from historic conditions by 15% and phosphorus loads by 3% (Scenario E), suggesting minimal impacts from allowing a higher discharge limit.

3. Implementation of Tier 2 BMPs (*i.e.*: retrofit of existing detention ponds) can reduce phosphorus concentrations from historic conditions by 26% and phosphorus loads by 16%. Tier 2 BMPs provide greater benefit than Tier 1 BMPs and is less than half the projected costs for implementation, although the projected cost of $55,000,000 would require 50-years or more to implement with the Authority's current budget. *See* Report Appendix.

Table 7 was developed by making comparisons of each scenario to the Calibration Model and presenting the results as percent changes in values. To calculate actual values for volume, loads, and concentrations, the percent changes in these values from Table 7 were then applied to median values for volume, load, and concentration from Table 1 for the monitored data for the same eight-year period of record from 1995 through 2002 to develop Table 8 below.

Table 8 - Predicted Median Volume, Phosphorus Load and Concentration for Scenarios based on Monitored Data from 1995 to 2002.

Model Scenario	Report Table	Description	Predicted Values		
			Volume (af)	P Loads (lbs)	P-Conc (mg/l)
A	2	Future Conditions w/o Rueter Hess	22600	10000	0.17
B	3	Future Conditions with Rueter Hess (Baseline Model)	15700	7000	0.17
C	4	Future Conditions, Rueter Hess and Tier 1 BMP Alternatives	15700	6500	0.16
D	5	Future Conditions, Rueter Hess and Tier 2 BMP Alternatives	15700	6300	0.15
E	6	Future Conditions, Rueter Hess and 0.1-mg/l WWTP Discharge	15700	7200	0.18

Note: Volumes and loads are rounded to the nearest 100's.

Conclusions from inspection of Table 8 include:

1. The Watershed Model suggests that phosphorus concentrations for all scenarios can be reduced, possibly even below background levels, but phosphorus loads will still be above 6,300-pounds.

2. Both Tier 1 (Scenario C) and Tier 2 (Scenario D), which implement enhanced BMPs and retrofit of existing detention ponds, are predicted to have the greatest water quality benefit in terms of reduction in phosphorus concentrations.

4. HISTORIC RESERVOIR CONDITIONS

4.1 Reservoir Total Phosphorus

Routine monitoring data collected since 1992 indicates a general increasing pattern in July to September mean total phosphorus concentrations (Figure 4-1). During the period of record (1992-2006) considered for the development of the Reservoir Model, the July to September mean total phosphorus concentration ranged from 48 to 116 µg/L. This maximum value has even been superseded during the past two years (2007 & 2008) when seasonal mean total phosphorus concentrations reached 118 µg/L. These are the highest observed values since monitoring began in 1987 and are considerably greater than the median value of 75 µg/L (mean = 79 µg/L) observed during the period of record considered for the Reservoir Model (1992 to 2006). During this period, seasonal mean concentrations have always exceeded the total phosphorus goal of 40 µg/L.

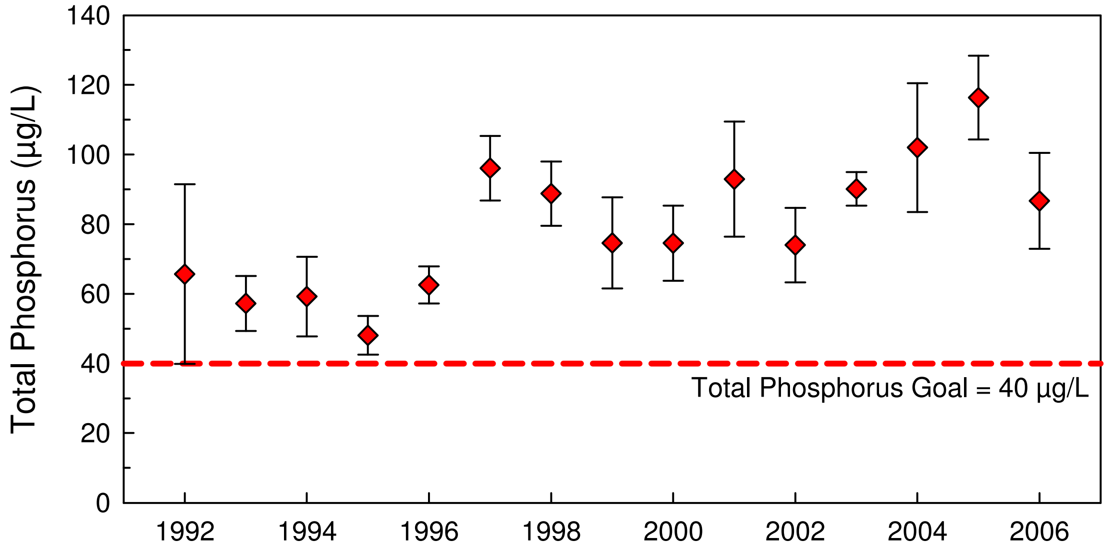

Figure 4-1: Seasonal mean (July to September) total phosphorus concentrations (µg/L) measured in Cherry Creek Reservoir, 1992 to 2006. Error bars represent a 95% confidence interval for each mean.

4.2 Reservoir Chlorophyll *a*

The seasonal mean chlorophyll *a* concentration has met the current standard of 15 µg/L only two times during the fifteen year period of record (Figure 4-2). Since 1992, there is no statistically significant upward or downward trend in the seasonal mean chlorophyll *a* concentration. However, since 1999, there has been a steady decline in the seasonal mean chlorophyll *a*, with the Reservoir meeting the standard in 2006. Despite the high seasonal total phosphorus concentrations in the Reservoir during recent years, chlorophyll *a* concentrations remain some of the lowest values observed (~ 15 µg/L) during the period of record. The cause of the recent downward trend is unknown but may be part of a long-term cyclic pattern.

Seasonal mean chlorophyll *a* concentrations have ranged from 14.7 to 28.9 µg/L, and when evaluated on a percentile basis to determine a level that is consistent with a compliance rate of eight (8) in ten (10) years, the resulting value is 25.8 µg/L. This suggests that 80 percent of the time (12 out of 15 years), the seasonal mean value was less than 25.8 µg/L and that 90 percent of the time, the seasonal mean value was less than 26.3 µg/L.

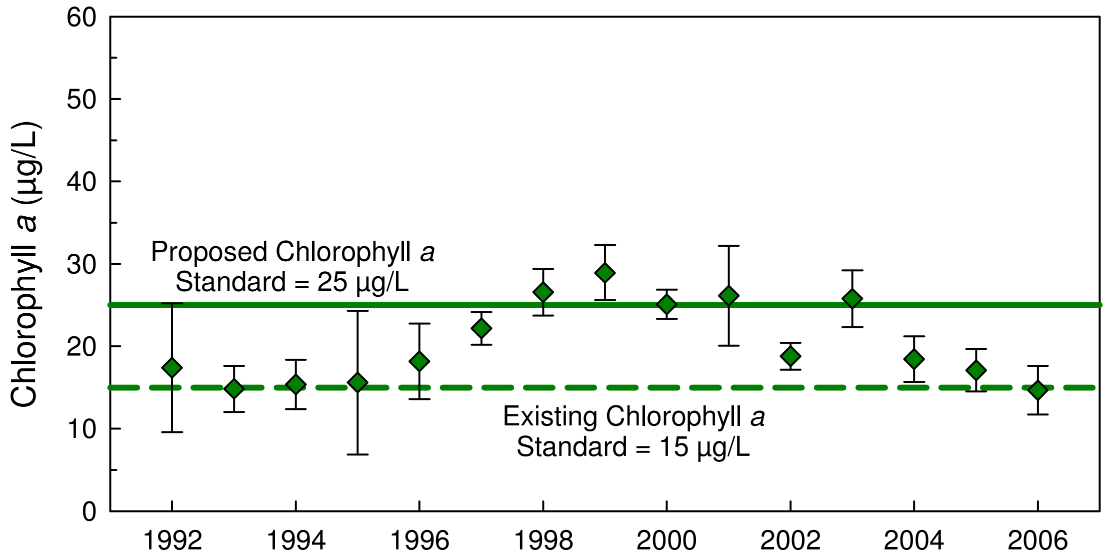

Figure 4-2: Seasonal mean (July to September) chlorophyll *a* concentrations measured in Cherry Creek Reservoir, 1992 to 2006. Error bars represent 95% confidence interval around each mean. The proposed chlorophyll *a* standard is shown for reference.

4.3 Flow-weighted Total Phosphorus Inflows to the Reservoir

The annual flow-weighted total phosphorus concentration is calculated as the annual external total phosphorus load divided by the USACE annual inflow to the Reservoir. This calculation takes into account all sources of inflow such as measured base/storm stream flows from monitoring sites on tributaries, direct precipitation, ungaged inflows from the near watershed, and alluvial contributions along with their associated loads.

This annual value can be further partitioned to highlight the monthly dynamics inherent in the annual calculation, given the current load calculation process. This allows one to evaluate the characteristics of the monthly flow-weighted total phosphorus concentrations with respect to the annual calculation (Figure 4-3). The box and whisker plots represent inter-quartile of the 12 monthly flow-weighted total phosphorus concentrations (*i.e.*, 25 to 75 percentiles) with the median value (horizontal line), while the whiskers represent the 5th and 95th percentile values within each year. The closed circles denote the annual flow-weighted total phosphorus concentration which highlights the magnitude of storm flow contributions in the Cherry Creek basin. Notably, since 2001 there has been a shift in the monthly flow-weighted total phosphorus concentrations to values consistently less than concentrations observed prior to 2001, and even less than the long-term mean value of 209 µg/L (0.209 mg/L). This observation lends further support to a concentration-based TMAL approach, and indicates a relatively stable period with respect to flow-weighted total phosphorus concentrations.

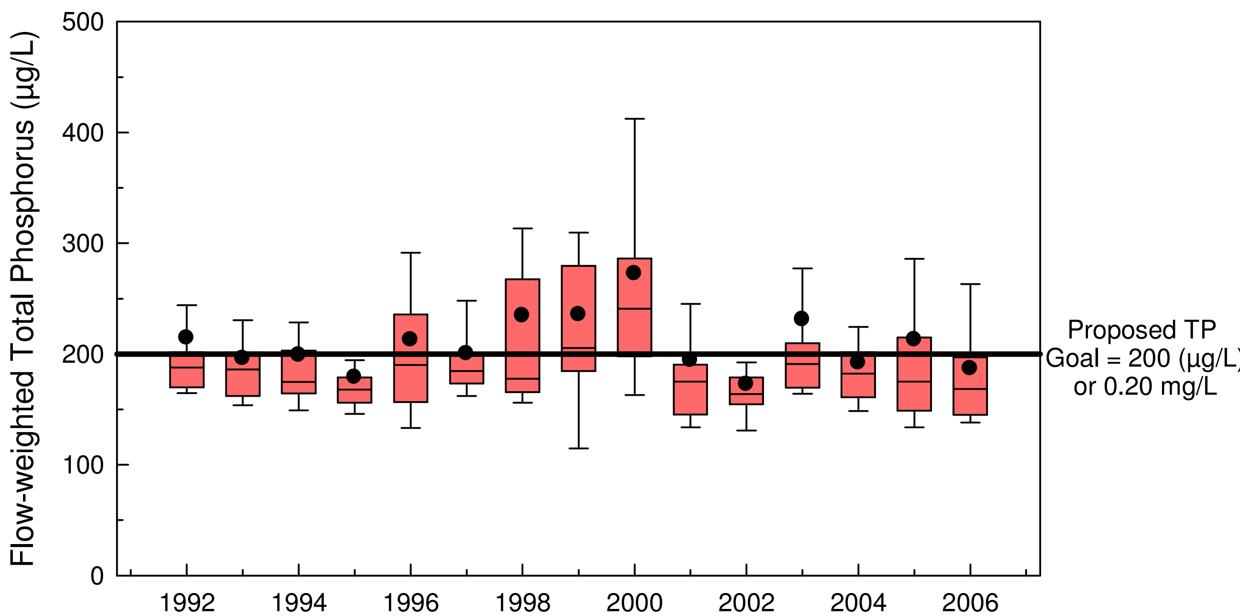

Figure 4-3: Box and whisker plots of the 12 monthly flow-weighted total phosphorus concentrations used to derive the annual flow-weighted total phosphorus concentration (median value is the horizontal line within box). The closed circles denote the annual flow-weighted total phosphorus concentration for respective year. The long-term mean value of annual flow-weighted total phosphorus concentrations is provided for reference.

5. RESERVOIR PHOSPHORUS MODEL

5.1 Summary

In 2006, the Authority retained Freshwater Research to redevelop the Authority's Reservoir Model, which was originally prepared in 2000 by Freshwater Research[49]. The primary purpose of this effort was to include the additional seven years of data (*i.e.*: 2000 through 2006)[3] and to identify the TMAL required to meet the current chlorophyll *a* standard of 15-µg/L nine out of ten years.

Several challenges had to be overcome: (1) the apparent lack of a significant correlation between Reservoir total phosphorus and chlorophyll *a* especially in recent years, (2) the difficulty in the identification of sediment derived P or internal loading, as is common in relatively shallow, mixed lakes and Reservoirs, and (3) the prediction of sedimentation or gross retention of P, which is related to point (2).

These challenges were addressed (1) by using a slightly changed chlorophyll *a*-total phosphorus regression equation based on the previous TMAL (2000), (2) by quantifying internal load with three partially independent approaches, and (3) by applying a retention model specifically developed for shallow lakes by the Organization of Economic Cooperation and Development.

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[49] Freshwater Research 2000a. *Cherry Creek Reservoir Dynamic Model,* and Freshwater Research 2000b. *Modeling future scenarios for Cherry Creek Reservoir.*

Compliance levels and 15-year averages and medians of the target variable chlorophyll *a* were determined with two basically different approaches: the traditional total phosphorus mass balance model where chlorophyll *a* is predicted from the total phosphorus-chlorophyll *a* regression and regression models that are based on direct correlations of chlorophyll *a* with the variables to be managed.

In general, the Reservoir Model application in the Reservoir TMAL-Control Regulation framework followed four steps.

1. A mass balance model for total phosphorus (TP) was developed for fifteen (15) individual year intervals with all available measured data (1992-2006) and specific constants were calibrated. In this approach chlorophyll *a* was predicted from a total phosphorus-chlorophyll *a* regression

2. In an alternate approach, regression models were developed based on direct correlations of chlorophyll *a* with the variables to be managed.

3. Compliance levels and 15-year averages and medians of the target variable chlorophyll *a* were determined with both approaches. In particular, a regression model where chlorophyll *a* is a function of annual average volume-weighted inflow (Tp_{in}) was used for various scenarios that can serve to set the TMAL.

4. Alternative standards for Cherry Creek were explored with three different approaches, including limnology, the eco-region principle and experience from other studies related to water quality standards. Further, the importance of the time frame for compliance and realistic attainability were explored.

5.2 Modeling Results

The results of the Reservoir Model also provide numerical values for external total phosphorus load, and the flow-weighted concentration required to meet the current standard that provided a basis for evaluating the various Watershed Model scenarios presented in Section 3 of this report. The regression

a Predicts a chlorophyll [a] concentration of 15 µg/L with an external load of 3,150-lbs/year

b Predicts a chlorophyll *a* concentration of 15-µg/L with an inflow concentration average of 167 µg/L

The report[50] included two significant conclusions:

a "*In general, nitrogen limitation only occurs in freshwater systems when algae are saturated with phosphorus. By reducing P below the saturation level, it again becomes the limiting nutrient and algae biomass declines. P reduction is usually easier to*

[50] Freshwater Research September 24, 2008. *Cherry Creek Reservoir Model and Proposed Chlorophyll Standard.*

accomplish than N reduction, because cyanobacteria can incorporate atmospheric nitrogen gas (N_2). ***Therefore, phosphorus controls are still appropriate, so that it remains or again becomes the limiting nutrient***[51]*.*"(emphasis added).

b "*It is evident that the current TMAL based on loads will not achieve that goal [15-µg/L chlorophyll a standard].* ***It is proposed here that instead, a methodology that considers average inflow TP concentration as control variable be used***[52]". (emphasis added).

The Reservoir Model was then used to recommend what the ambient chlorophyll *a* standard should be, consistent with the fifteen (15) years of data and scientific judgment. The attainment criteria of eight out of ten years for compliance were used to evaluate the future scenarios. This compliance schedule is similar to that proposed by the Division for the statewide nutrient criteria.

5.3 Evaluation of Future Watershed Scenarios

To evaluate future watershed scenarios, the Authority provided Watershed Model data in Tables 2 through 6[53] to Freshwater Research and requested that they provide the chlorophyll *a* that would result from implementation of each scenario for the compliance schedule of eight out of ten years. The long-term changes in the scenarios predict increased flow, increased, similar or decreased TP load, but consistently decreased average inflow phosphorus concentration TP_{in}. Table 7-9 from the Freshwater Research report is reproduced below to show how the chlorophyll *a* standard changes with the different scenarios.

[51] Ibid, page 20.
[52] Ibid, page 3.
[53] Note that the version of Table 6 provided to Freshwater Research for analysis understated the increase in phosphorus loads resulting from the change in WWTP discharge to 0.10-mg/L. Table 6 as shown was provided to GEI who utilized Freshwater Research equation to calculate the resulting chlorophyll a for Scenario E presented in Table 7-9. The same conclusions were drawn by GEI as by Freshwater Research, regarding increasing WWTP discharges to 0.10-mg/L, as presented in this report. In addition, variations in the Watershed Model results for phosphorus loads up to 3% have been found to have minimal affects on the results presented in Table 7-9 and also result in the same conclusions presented herein.

Table 7-9. Average chlorophyll concentrations and their frequency of being below the chlorophyll thresholds of 15.5 and 18.5 µg/L for scenarios predicted by the Brown & Caldwell watershed model ("of current" means *of current long-term average*)

Based on the chlorophyll regression with TP_{in}					Threshold*
Scenarios	TP_{in} in % of current	Chlorophyll average (µg/L)	Frequency <15.5	Frequency <18.5	Chlorophyll 80% Frequency (µg/L)
A Without Rueter Hess Reservoir	84%	16.1	53%	80%	18.5
B With Rueter Hess Reservoir, "Baseline Model"	85%	16.2	53%	80%	18.5
C Baseline Model (B) with Tier 1 - BMP Alternatives	79%	14.8	73%	93%	17.0
D Baseline Model (B) with Tier 2 - BMP Alternatives	76%	14.2	73%	93%	16.3
E Baseline Model (B) with WWTP Discharge of 0.1 mg/l	85%	16.3	53%	80%	18.5

Based on the chlorophyll regression with TP load					Threshold*
Scenarios	TP load in % of current	Chlorophyll average (µg/L)	Frequency <15.5	Frequency <18.5	Chlorophyll 80% Frequency (µg/L)
A Without Rueter Hess Reservoir	146%	22.7	0%	20%	27.5
B With Rueter Hess Reservoir, "Baseline Model"	101%	20.1	7%	47%	24.4
C Baseline Model (B) with Tier 1 - BMP Alternatives	94%	19.6	13%	47%	23.8
D Baseline Model (B) with Tier 2 - BMP Alternatives	91%	19.4	20%	47%	23.6
E Baseline Model (B) with WWTP Discharge of 0.1 mg/l	102%	20.1	7%	47%	24.5

* Threshold is the upper chlorophyll concentration at which the 80% frequency 12 out of 15 years is attained.

Conclusions of the Reservoir Model evaluation of Scenarios A through E are:

a *Because TP_{in} is 15-24 % smaller in all future scenarios A to E, chlorophyll a compliance is predicted to improve based on the TP_{in} –chlorophyll a regression. However, future external loads are variable depending on the scenarios and hence compliance is not always improved according to the TP load–chlorophyll a regression.*

b *In summary, there is no difference between the scenarios with (B) and without the Rueter-Hess Reservoir (A) and chlorophyll a can be expected to be below 15.5 µg/L about 53% of the time using the TP_{in} –chlorophyll a regression. Furthermore, there is no difference between scenario B and Scenario E that increases the WWTP discharge to 0.1 mg/L using either the TP_{in} –chlorophyll a or the TP load–chlorophyll a regression*

5.4 Alternative Standards Evaluation

The alternative standards evaluation for chlorophyll *a* resulted in the following findings and recommendations[54]:

[54] Freshwater Research September 24, 2008. *Cherry Creek Reservoir Model and Proposed Chlorophyll Standards.* P67

- *a* *If the conditions of the current algal blooms are deemed acceptable to the stake holders and public in general, the standard should be set to coincide with the observed 80% frequency at 26 µg/L….*

- *b* *In comparison to chlorophyll a targets in similar water bodies in other States, a 25 µg/L target seems feasible for Cherry Creek Reservoir.*

- *c* *Limnological deliberations based on the observation from other systems that nuisance bluegreen blooms increase at chlorophyll a concentration above 30 µg/L and Secchi transparency determine that a lower threshold of 21 – 22 µg/L would warrant acceptable water quality, even for contact sports, most of the time.*

- *d* *…the Jul-Sep chlorophyll a average should decrease in the future after a lag-time for equilibration under Scenarios A-E to 18.5 µg/L.*

5.5 Chlorophyll *a* and Phosphorus Relationship

The relationship between algal biomass (chlorophyll *a*) and phosphorus has been one of the most studied paradigms in limnology, with regression models based on data from multiple lakes and Reservoirs often revealing a significant correlation between algal biomass and phosphorus. However, when seasonal (Jul-Sep) mean data from 1992 to 2006 is evaluated for the Reservoir using a similar approach, there is no statistically significant correlation between chlorophyll *a* and phosphorus. This is due in large part to the extreme variability observed between years and the switching of the algal community from a community limited by phosphorus to one limited by nitrogen, or even co-limitation, as summer progresses.

In 2003, the nutrient enrichment study (Section 2.3) revealed that algal community became limited by nitrogen – not constantly, but as the summer progressed. However, the relationship between seasonal mean chlorophyll *a* and total nitrogen is also not statistically significant in Cherry Creek for the period of record. Despite the lack of statistically significant relationships between chlorophyll *a* and nutrients (total phosphorus and total nitrogen), excess phosphorus should be managed with the intent to reduce concentrations such that phosphorus consistently limits the growth of algae on a seasonal basis.

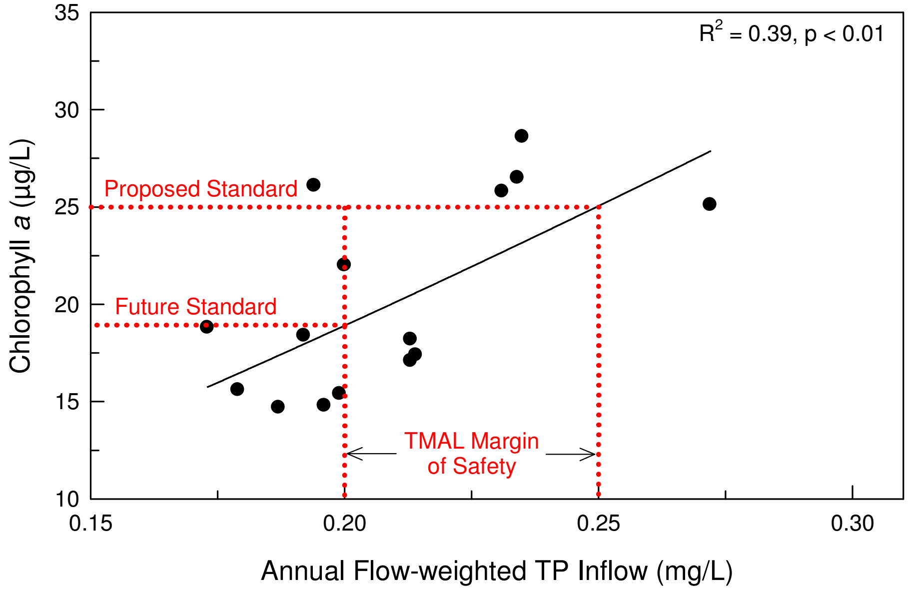
As the Reservoir mass balance model progressed, it became clear to Dr. Nurnberg that the variability in annual load (6-fold) and export (7-fold), combined with the uncertainty associated with linking external/internal phosphorus load to in-lake phosphorus concentration and then to chlorophyll *a*, meant that a load-based TMAL was not a reliable approach for the Reservoir. Therefore, Dr. Nurnberg explored other empirical relationships between chlorophyll *a* and watershed variables and found that seasonal mean chlorophyll *a* was significantly correlated to the log transformed annual flow-weighted total phosphorus concentration of the inflow. This relationship is more meaningful from a management perspective, because BMPs have proven to be effective in reducing phosphorus concentrations in storm flows. Furthermore, when compared to the baseline conditions, the Watershed Model Scenario C and D indicate reduced flow-weighted total phosphorus concentrations when using Tier 1 or Tier 2 BMPs (Section 3.7 and 3.8). This empirical relationship has provided the basis of linking the concentration-based TMAL to in-lake chlorophyll *a* concentrations.

Given the link between chlorophyll *a* and the flow-weighted phosphorus concentration[5], the next step was to identify a chlorophyll *a* standard that was consistent with historical conditions of the Reservoir, yet would serve as a threshold indicator of nuisance algal blooms, and preserve the beneficial uses of the Reservoir. Dr. Nurnberg's approach for establishing an appropriate chlorophyll *a* standard relied upon information derived from limnological conditions during the period of record for the Reservoir, from an eco-regional approach used by the US EPA for lakes and Reservoirs in Ecoregion IV, SubRegion 26, and from experience in other Reservoirs with existing chlorophyll *a* standards.

Reservoir conditions during the period of record (1992-2006) indicate that average chlorophyll *a* concentrations during July to September period was less than 26-µg/L for 80% of the time. Other limnological conditions, such as the chlorophyll *a* maximum associated with nuisance cyanobacteria and Secchi depth, indicated a lower threshold value of 21 to 22-µg/L. Existing chlorophyll *a* standards for water bodies in other states that include shallow Reservoirs similar to Cherry Creek, ranged from 20 to 40-µg/L, depending upon site-specific conditions and the targeted seasonal period. Based on this information and the consideration of the uncertainty associated with the autocorrelation of chlorophyll *a* from one year to the next, climate change, Watershed Model output, and the effectiveness of the destratification system, a chlorophyll *a* standard of 25 µg/L is achievable 8 out of 10 years.

Based on the proposed chlorophyll *a* standard of 25-µg/L, the corresponding average annual flow-weighted total phosphorus concentration would be approximately 0.250-mg/L (Figure 5-1). However, when the uncertainty of the regression relationship is placed in the context of conditions observed from 1992 to 2006, the Authority believes it is more appropriate to establish a flow-weighted total phosphorus goal of 0.20 mg/L – which provides a 0.05-mg/L margin of safety. The proposed annual flow-weighted total phosphorus goal more closely aligns with the observed average or median annual flow-weighted total phosphorus concentration of 0.209-mg/L and 0.200-mg/L, respectively. Since 2001, annual flow-weighted total phosphorus concentrations have been consistently less than the observed average and median values for the period of record, while July to September chlorophyll *a* concentrations have exhibited a decreasing trend. Furthermore, the observed flow-weighted total phosphorus concentrations and proposed flow-weighted total phosphorus goal are consistent with natural background total phosphorus conditions in surface water near Castlewood Canyon (0.19 mg/L), indicating that management strategies have proven to be beneficial despite the expansive population growth in the basin. In the future, depending upon the effectiveness of the destratification system along with the operation of Rueter-Hess Reservoir and the implementation of more aggressive watershed controls, the chlorophyll *a* standard may need to be reassessed in the future.

Figure 5-1. Relationship between chlorophyll *a* and annual flow-weighted TP.



5.6 Chlorophyll *a* Correlation with Phosphorus and Nitrogen

Cyanobacteria (cyanobacteria, or bluegreen algae, (bluegreens)) affect water quality. Bluegreens not only create unsightly conditions, especially scum leading to low water transparency, but can be toxic to mammals and humans[50].

The primary reason to establish a chlorophyll *a* standard or goal is to control the overabundance of algae and especially of cyanobacteria (or bluegreen algae), as they are more prevalent at higher chlorophyll *a* concentrations. When bluegreen abundance is compared with nutrient concentration it appears that total phosphorus – not total nitrogen - is the driving nutrient in the Reservoir. In particular, the log-log regression with total phosphorus is significant when the influential outlier of 2002 is removed (n=15, R^2=0.20, p=0.09; w/o outlier 2002, when bluegreen biomass was less than 2% of the long-term average, n=14, R^2= 0.34, p<0.05) and is also significant with external total phosphorus load (n=15, R^2=0.34, p=0.05; w/o outlier 1999: n=14, R^2= 0.57, p<0.01). Conversely total nitrogen is not correlated in any way (R^2=0.00).

Further, the log-log regression of Secchi transparency, another indicator of algae biomass, on total phosphorus is highly significant (n=15, R^2= 0.48, p<0.01). Again, there is no pattern detectable with total nitrogen (R^2= 0.005).

In summary, although there is no significant direct correlation between chlorophyll *a* and total phosphorus, there are many correlations that indicate the importance of total phosphorus in controlling water quality related to algae biomass in the Reservoir. In comparison, total nitrogen is not correlated in any relationships. The result that total phosphorus is the important variable that controls algae rejects any hypotheses that nitrogen is more important in the Reservoir, despite evidence of occasional Nitrogen-limitation in the Reservoir, e.g., nutrient enrichment experiments by Lewis et al[11] in summer 2003.

In general, nitrogen limitation only occurs in freshwater systems when algae are saturated with phosphorus. By reducing phosphorus below the saturation level, it again becomes the limiting nutrient and algae biomass declines. Phosphorus reduction is usually easier to accomplish than nitrogen reduction, because cyanobacteria can incorporate atmospheric nitrogen gas. Therefore, phosphorus controls are still appropriate, so that it remains or again becomes the limiting nutrient.

6. SUMMARY MODEL RESULTS AND CONCLUSIONS

Presented below are summary results and conclusions from the Watershed and Reservoir Model analyses divided into sections. The first section discusses the total external phosphorus loads and flow-weighted concentrations required to meet the current standard of 15-µg/L chlorophyll *a* nine (9) out of ten (10) years. This section also identifies whether phosphorus loads and concentrations can be reduced in the future by proposed improvements described by Watershed Model scenarios A through E to meet the current chlorophyll *a* standard.

The second section discusses a new approach for the chlorophyll *a* standard based on inflow phosphorus concentration instead of inflow phosphorus mass. The third section discusses the phosphorus load and concentration reduction benefits resulting from continued implementation of the current regulatory requirements as well as implementation of additional watershed control measures.

6.1 Current Reservoir Standard.

1. The Reservoir Model regression analysis shows that in order to meet the chlorophyll *a* standard of 15-µg/L nine (9) out of ten (10)years, requires:

   a An external load of no greater than 3,150-pounds per year

   b An inflow concentration no greater than 0.17-mg/L

2. Even with implementation of lower discharge limits on WWTPs (*i.e.*; 0.05-mg/L), and aggressive construction and post-construction BMPs since 2001 shows that the existing chlorophyll *a* standard of 15-µg/L nine (9) out of ten (10) years *cannot* be achieved. This conclusion is based on scientific analyses using the redeveloped Watershed and Reservoir Models, and additional data collected by the Authority from 2000 through 2006.

   a The phosphorus loads to the Reservoir exceed the 3,150-pound annual load required to meet the chlorophyll *a* 15-µg/L standard nine (9) out of ten (10) years. The lowest recorded external load from 1992 through 2006 was 3,114-pounds which occurred in 1993 and the median annual load from 1992 through 2006 was 6,492-pounds (see Table 9).

   b The inflow phosphorus flow-weighted concentration to the Reservoir required to meet the current standard has only been met twice in fifteen (15) years. The median concentration from 1992 through 2006 was 0.20-mg/L.

c Background phosphorus loads from the Cherry Creek basin were estimated to be 5,200-pounds, based on a median inflow of 10,000-acre feet, which is equivalent to an inflow concentration of 0.19-mg/L. Therefore, background loads are higher than maximum required to meet the current standard.

In summary, the data show that external phosphorus loads and concentrations to the Reservoir have exceeded the 3,150-pounds and 0.17-mg/L for the fifteen (15) years of analysis. The Watershed Model shows that the load and concentration necessary to meet current standards exceeds background projections, which are 5,000-pounds and 0.19-mg/L. Therefore, the current standard cannot be practically achieved, which is supported by both the Watershed and Reservoir Model analyses.

6.2 Chlorophyll *a* and Phosphorus Correlation

The Reservoir Model demonstrates that there is no significant direct correlation of chlorophyll *a* with total phosphorus in the Reservoir. The Reservoir Model, however, showed that there are correlations that indicate the importance of phosphorus in controlling water quality related algal biomass in the Reservoir. In comparison, total nitrogen in the Reservoir is not correlated with Reservoir chlorophyll *a and other algal biomass indicators*. The Reservoir Model also showed significant correlation between average annual inflow phosphorus concentrations and Reservoir chlorophyll *a* concentrations.

The significant correlation between flow-weighted phosphorus concentration and chlorophyll *a* concentration supports the regulatory change from a mass-based TMAL to a concentration based TMAL.

6.3 Analysis Of Future Scenarios.

The Watershed and Reservoir Models were used to evaluate the benefits of the five different scenarios, A through E. The Watershed Model predicted the inflow phosphorus loads and concentrations for each scenario; however, as noted above, the Watershed Model is best used to predict *changes* in phosphorus loads and concentrations, not actual values. Therefore, Table 7 was prepared to present loads and flows as a percent difference between each watershed management scenario and the calibration model representing existing conditions. In addition, Table 8 presents the predicted medians for volume, loads and concentrations based on the percent reductions in Table 7 and the medians for monitored data (Table 1) for the same period of record (1995 to 2002) used to calibrate the Watershed Model. Tables 7 and 8 are used to summarize the results of each Scenario below.

The Reservoir Model then used these percent differences to determine if each scenario would meet the current standard and what chlorophyll *a* standard could be achieved eight (8) out of ten (10) years, based both on phosphorus inflow concentration and loads. The results of these comparisons are presented below.

Also presented below for Scenarios C, D and E are the *additional* changes in loads and concentrations when compared to Scenario B, the likely future condition. This comparison provides insight into additional benefits resulting from each Scenario and requires presenting *differences* in percentage changes stated in Table 7.

The proposed chlorophyll *a* standard of 25-µg/L eight (8) out of ten (10) years and the flow-weighted phosphorus concentration goal of 0.20-mg/L are based on ambient Reservoir conditions as described in Section 5.5, Chlorophyll *a* and phosphorus Relationship. However, the Scenarios represent potential future improvements in water quality through the implementation of additional watershed controls -- even with a significant increase in new development -- and demonstrate that the proposed additional watershed controls may provide further water quality benefits. Therefore, the additional watershed controls represented by the Scenarios provide additional level of confidence that the chlorophyll *a* standard and phosphorus goal can be achieved.

1. The Watershed Model analysis of Scenario A and B shows that significant reduction of external phosphorus loads will not necessarily result in a similar reduction in phosphorus concentrations. This conclusion can be seen by inspecting Table 7 and comparing Scenarios A and B. The comparison shows that phosphorus loads are reduced significantly by constructing Rueter-Hess Reservoir when compared to historic long-term conditions, changing from an increase of 35% to a decrease of 6%. However, there is very little difference in phosphorus concentration with or without Rueter-Hess Reservoir, changing from a decrease of 16% to a decrease of 17%.

2. Potential benefits from maintaining current regulatory requirements (*i.e.*: standard BMP implementation for future development and WWTP discharge at 0.05-mg/L) along with the completion of Rueter-Hess Reservoir was investigated (Scenario B).

   a The Watershed Model showed Scenario B could reduce median inflow concentration by 17% and the phosphorus loads by 6% (Scenario B, Table 7). Based on these relative differences, the Watershed Model predicts that a median inflow phosphorus concentration of 0.17-mg/L and a phosphorus load of 7,000-pounds (see Table 8) may result. Whereas Scenario B median inflow concentration may be reduced to 0.17-mg/L, the inflow phosphorus loads still exceed the 3,150-pounds required to meet current standards and, therefore would not meet the current chlorophyll *a* standard.

   b The Reservoir Model showed that maintaining current regulatory requirements (Scenario B, Freshwater Research Table 7-9) may result in a chlorophyll *a* concentration of 19-µg/L with attainment criteria of eight (8) out of ten (10) years, based on inflow phosphorus concentration. Therefore, Scenario B results provide an additional level of confidence that the proposed chlorophyll *a* standard and phosphorus goal can be achieved.

3. Potential benefits from enhanced BMP implementation for future development (*i.e.*: BMPs which promote filtration and infiltration) was investigated. This is Scenario C, which includes the baseline Scenario, B plus Tier 1 improvements.

a Scenario C could reduce the median inflow concentration by as much as 23% and the total loads by 13% (Scenario C, Table 7), when compared to existing conditions (*i.e.*: Calibration model). Based on these relative differences, the Watershed Model predicts that a median inflow phosphorus concentration of 0.16-mg/L and a phosphorus load of 6,500-pounds may result. Whereas Scenario C median inflow concentration may be reduced to 0.15-mg/L, the inflow phosphorus loads still exceed the 3,150-pounds required to meet current standards, and therefore would not meet the current chlorophyll *a* standard.

b Scenario C could reduce the median inflow concentration an *additional* 6% and the total loads by 7% (Scenario C, Table 7), when compared to Scenario B, baseline future conditions. This comparison shows that requiring enhanced BMP could provide greater water quality benefits to the Reservoir than current regulatory requirements.

c The Reservoir Model shows that Scenario C with Tier 1 improvements (Scenario C, Freshwater Research Table 7-9), which included enhanced BMPs for future development, may result in a chlorophyll *a* concentration of 17-µg/L with attainment criteria of eight out of ten years, based on inflow phosphorus concentrations. Therefore, Scenario C results provide an additional level of confidence that the proposed chlorophyll *a* standard and phosphorus goal can be achieved.

d The projected present worth costs to implement Tier 1 improvements, approximated by modeling 122 developments averaging 100-acres in size, is $131,000,000, which includes enhanced BMP capable of limiting phosphorus discharges to no greater than 0.20-mg/L on a long term average. *See* Report Appendix. This cost is an incremental cost above and beyond the costs to implement the standard BMPs for future development, which is the EDB.

4. Potential benefits from retrofitting existing detention ponds to meet EDB-type levels of performance or better was investigated. Scenario D includes the baseline scenario plus Tier 2 BMP improvements.

a Scenario D could reduce the median inflow concentration by as much as 26% and the total loads by 16% (Scenario D, Table 7). Based on these relative differences, the Watershed Model predicts that a median inflow phosphorus concentration of 0.15-mg/L and a phosphorus load of 6,300-pounds may result. While Scenario D median inflow concentration may be reduced to 0.15-mg/L, the inflow phosphorus loads still exceed 3,150-pounds required to meet current standard, and therefore would not meet the current chlorophyll *a* standard.

b Scenario D could reduce the median inflow concentration an *additional* 9% and the total loads by 10% (Scenario D, Table 7), when compared to Scenario B, baseline future conditions. This comparison shows that retrofitting existing detention basins could provide greater water quality benefits to the Reservoir than current regulatory requirements, even more so than enhanced BMPs (Scenario C).

c The Reservoir Model (Scenario D, Freshwater Research Table 7-9) shows that Scenario D with Tier 2 BMP alternatives, which retrofit existing detention ponds to meet current EDB performance levels, may result in a chlorophyll *a* concentration of 16-µg/L with attainment criteria of eight (8) out of ten (10) years, based on inflow phosphorus concentrations. Therefore, Scenario D results provide an additional level of confidence that the proposed chlorophyll *a* standard and phosphorus goal can be achieved.

d The projected present worth costs to implement Tier 2 improvements is $55,000,000, which includes investigations, access easement and agreements, construction, and operations and maintenance to retrofit 104-existing detention basins to meet phosphorus discharge concentrations of 0.24-mg/L or less on a long term average basis. *See* Report Appendix. Since the Authority's current annual budget limitation for construction is from $800,000 to $900,000, implementation of Tier 2 improvements would exceed a 50-year time frame. *See* Report Appendix.

5. Potential impacts from allowing WWTP to increase the phosphorus discharge limit from 0.05- to 0.10-mg/L (Scenario E) were investigated.

a Scenario E could reduce the median inflow concentration by as much as 15% and the total loads by 3% (Scenario E, Table 7). Based on these relative differences from historic or existing conditions, the Watershed Model results predict a median inflow phosphorus concentration of 0.18-mg/L and a phosphorus load of 7,200-pounds. However, Scenario E median inflow concentration still exceeds 0.17-mg/L and the inflow phosphorus loads still exceed the 3,150-pounds necessary to meet current chlorophyll *a* standard.

b Scenario E could *increase* the median inflow concentration by 2% and the total loads by 3% (Scenario E, Table 7), when compared to Scenario B, baseline future conditions. This comparison shows that allowing an increase in point source discharges could reduce water quality benefits associated with current regulatory requirements as represented by Scenario B.

c The Reservoir Model shows that Scenario E, which increases point source discharges to 0.10-mg/L, would require the chlorophyll *a* standard to be no less than 19-µg/L with attainment criteria of eight out of ten years (Scenario E, Freshwater Research table 7-9[55]), based on inflow phosphorus concentrations, which is essentially the same as for Baseline Scenario B.

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[55] GEI evaluation of Freshwater Research results required modification to Table 7-9 to account for higher phosphorus loads from the Watershed Model Scenario E. The GEI analysis resulted in the following values. TPin (% of current) = 86%, Chlorophyll average = 16.6, Frequency <15.5 = 40% and <18.5 = 73%. The 80th percentile value is 18.9, so the Threshold Chlorophyll Frequency would be 19.

6.4 Recommended Reservoir Chlorophyll *a* Standard

Relative to a proposed chlorophyll *a* standard, the Freshwater Research report states:

a *… considering the uncertainties based on time lags, model predictions, climate change and aeration*[56] *treatment , we propose a standard of 25 µg/L to be reached 8/10 years (at an 80% level) for the near future*[57].

b *Limnological deliberations based on the observation from other systems that nuisance bluegreen blooms increase at chlorophyll a concentration above 30 µg/L and Secchi* [58]*transparency determine that a lower threshold of 21 – 22 µg/L would warrant acceptable water quality, even for contact sport, most of the time*[59].

6.5 Recommended Watershed Management Activities

When compared to the capitalized value of the Reservoir, the cost of Tier 1 improvements (*i.e.*: enhanced BMP) or Tier 2 improvements (*i.e.*: retrofit of existing detention basins) are not excessive, ranging from as little as 2% to a high of 9%. In addition, either Tier 1 or Tier 2 can provide significant reduction in phosphorus concentrations, ranging from 6% to 9% below what are expected in the future with Scenario B. The primary difference between the Tier 1 and Tier 2 alternatives is the cost and who pays the costs. Tier 1 costs are projected to be $131,000,000, which would be passed on to new development in the future growth area, where Tier 2 costs are projected to be $55,000,000, which could be borne by the Authority as part of its capital improvement program. *See* Report Appendix.

The basis for the Authority recommendation to begin with the implementation of Tier 2 improvements are:

1. Even without the Tier 1 or Tier 2 improvements, implementation of the current regulatory program (*i.e.* Scenario B) is projected to reduce phosphorus concentrations over existing conditions by 17% (Table 7), which will likely further improve Reservoir water quality. This means that drastic measures are not required in order to continue to see improvements in Reservoir water quality and Tier 2 improvements can be undertaken in a more deliberate manner to achieve the greatest benefits at the least cost.

2. Tier 2 improvements would be implemented by the Authority using its current funding capacity over the next 50-years or more, instead of adding more costs (around $1,600 per home) to the future home buyer by implementing Tier 1 improvements.

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[56] Whereas "aeration treatment" here means "destratification system", aeration sometime implies adding oxygen to the water. The Authority's destratification system's objective is to mix the Reservoir using an aeration-type system to minimize temperature differences between the surface and the bottom of the Reservoir.

[57] Freshwater Research September 24, 2008. *Cherry Creek Reservoir Model and Proposed Chlorophyll Standards.* p5.

[58] Many states have been using Secchi disk transparency as a water quality indicator in combination with or in addition to total phosphorus and chlorophyll. See. Freshwater Research December 2008. *Supplementary material about the chlorophyll standard and relationships with Secchi transparency.*

[59] Ibid, p67.

3. The Authority's Reservoir destratification project was briefly described in Section 2 of this report. Although one year of monitoring data suggests that the Reservoir destratification project may be showing some positive benefits, it will likely require two (2) to three (3) years of monitoring data before any benefits can be determined and quantified with any confidence. The water quality benefits of the destratification project should be better understood before requiring more aggressive BMPs for future growth, but investigation into retrofitting existing detention ponds (Tier 2, Scenario D) can begin immediately.

4. If over the next five (5) years water quality doesn't continue to improve, it would not be too late to require enhanced BMPs that the core of Tier 2 improvements at the next Rule-Making Hearing, given that the 250% growth projections are through the year 2035.

7. PROPOSED CHOROPHYLL *A* STANDARD AND PHOSPHORUS GOAL

After consideration of additional factors, such as limnology based standards, eco-region principals, experience in other studies, and other influences, the Authority recommends the Reservoir standard for chlorophyll *a* be changed to 25 µg/L as a seasonal mean for the upper 3 meter layer during the months of July, August, and September, with a compliance period of for eight (8) out of ten (10) years. This standard is supported by fifteen (15) years of water quality data and the Watershed and Reservoir Models.

In addition, the Authority is recommending that the phosphorus control strategy change from mass-based total phosphorus TMAL to a *concentration-based* TMAL with a goal of 0.20 mg/L as a flow-weighted value in the inflow to the Reservoir. This goal is supported by fifteen (15) years of water quality data and the Watershed and Reservoir Models.

Table 9 - Reservoir Water Quality Data

Year	Cholorophyll a	Secchi Depth	Total Phosphorus	Total Nitrogen	Normalized Phosphorus Loads	Annual Precipitation	Annual Inflow	Flow Weighted Concenration	
	(ug/l)	(m)	(ug/l)	(ug/l)	(lbs)	(inches)	(ac/ft)	(lbs/ac-ft)	mg/l
1992	17.4	0.95	66	970	5,364	18.5	9,210	0.58	0.21
1993	14.4	1.20	62	826	3,114	15.6	5,851	0.53	0.20
1994	15.4	1.10	59	1,144	3,785	10.2	6,998	0.54	0.20
1995	15.6	1.62	48	913	5,736	25.3	11,788	0.49	0.18
1996	20.5	1.60	62	944	4,425	15.5	7,654	0.58	0.21
1997	22.3	1.00	96	1,120	5,659	21.8	10,391	0.54	0.20
1998	26.5	1.09	89	880	13,322	20.0	20,902	0.64	0.23
1999	28.9	1.03	81	753	17,672	21.5	27,604	0.64	0.24
2000	25.2	0.96	81	802	13,788	17.8	18,611	0.74	0.27
2001	26.1	0.75	87	741	9,099	16.0	17,246	0.53	0.19
2002	18.8	0.91	74	858	3,525	12.9	7,511	0.47	0.17
2003	25.8	0.86	90	1,121	9,390	18.8	14,953	0.63	0.23
2004	18.4	0.85	102	977	8,974	20.3	17,203	0.52	0.19
2005	17.1	0.97	116	990	10,725	15.5	18,534	0.58	0.21
2006	14.7	1.05	87	914	6,492	16.7	12,799	0.51	0.19
Mean	20.5	1.06	80	930	8071	17.8	13817	0.57	0.21
Median	18.8	1.00	81	914	6492	17.8	12799	0.54	0.20
Minimum	14.4	0.75	48	741	3114	10.2	5851	0.47	0.17
Maximum	28.9	1.62	116	1144	17672	25.3	27604	0.74	0.27

Note: This table contains data provided in the Authority's annual nutrient monitoring report for 2007.[60]

[60] GEI Consultants, April 2008. *Cherry Creek Reservoir 2007 Annual Aquatic Biological Nutrient Monitoring Study and Cottonwood Creek Phosphorus Reduction Facilities Monitoring.*

APPENDIX

Cherry Creek Basin Water Quality Authority
COST ESTIMATE FOR TIER 1 - POST CONSTRUCTION BMP ALTERNATIVE

ISSUE This spreadsheet addresses Tier 1 incremental cost

REFERENCES

1 Brown, W., and T. Schueler. 1997. *The Economoics of Stormwater BMPs in the Mid-Atlantic Region.*
2 California Stormwater Quality Association. 2003. *Stormwater Best Management Practices Handbook*
3 EPA, NPDES website: http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm

ASSUMPTIONS

1 Sand filter basins (SFB) were used to estimate cost, but other BMPs can be used to achieve discharge conc.
2 The larger the BMP design tributary area, the lower the cost per impervious acre
Therefore, use "typical" development size of 100 acres with 45% imperviousnes as an average size
resulting in 45 impervious acres per site
3 The WQCV requirement, based on 40-hr drain time = 0.21 inches/impervious acre
4 Annual O&M costs at 2% of capital costs
5 Interest @ 7% Period = 35 yrs PWF = 12.95
6 Administration and contigency = 35% Engineering listed separately

DEVELOPMENT DATA

Number of sub-basins in model used to calculate impacts = 122
Total Area of sub-basins = 43376 acres
Sub-basin existing conditions imperviousness = 25.1%
Sub-basin future conditions imperviousness = 56.9%
Total increase in impervious area = 13794 acres
Then at 45% imperviousness, the total area of new development = 30652 acres
Then at 100 acres per site, the number of new detention sites = 307 sites

EDB COST ESTIMATE Cost, C = $12.4\ V^{0.76}$ (Ref 1)
V = Stormwater Volume, cf

Volume per site = 74869 cubic feet
Base Cost per EDB = $ 62,790
This cost per site is believed understated by a factor of 5- to 10-times, which is supported by Ref 2, EDB Fact Sheet
Adjustment Factor = 7.5
Adjusted cost per EDB = $ 471,000

SFB COST ESTIMATE Cost, C = K * A Ref (1)
K = cost per impervious acre
A = Area, acres
K = $ 18,000 Ref 3 average of reported values ranging from $3k to $50,
Base Cost per SFB = $ 810,000

INCREASE IN O&M COSTS

EDB O&M Cost = $ 9,420 per site
SFB O&M Cost = $ 16,200 per site
Incremental O&M Cost = $ 6,780 per site
Present worth of incremental O&M costs = $ 88,000 per site
Present worth of incremental O&M costs = $ 27,000,000 All new sites

ESTIMATE INCREMENTAL COST TO USE SFB INSTEAD OF EDB AS MINIMUM BMP REQUIREMENT

Capital cost increase = ***$ 339,000*** per site
Present worth of O&M cost increase = ***$ 88,000*** per site
Total Cost increase = ***$ 131,000,000*** All new sites

REASONABLENESS CHECK

Number of units per acres, avg = 3 Use low number for conservatism
Total number of new units = ***900***
Incremental cost per unit = ***$ 145,600*** Not unreasonable cost per unit increase

January 4, 2009.

Cherry Creek Basin Water Quality Authority
COST ESTIMATE FOR TIER 2 - TO RETROFIT EXISTING EDB TO IMPROVE PERFORMANCE

ISSUE This speadsheet addresses Tier 2 by using a proprietary BMP as a basis for estimating costs.

REFERENCES

1 EPA New England Center for Environmental Industry and Technology (CEIT). *Innovative Technology Inventory (ITI), Stormwater Managent, Inc. StormFilter.*

2 EPA New England Center for Environmental Industry and Technology (CEIT). *Storm Water Virtual Trade Show Stormwater management StormFilter.*

3 *NRDC Stormwater Strategies Community Responses to Runoff Pollution, Chapter 10 Strategies in the Pacific Northwest. Environmental Development at the Oregon Museum of Science and Industry.*

4 *USDOT, FHWA. Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring.*

APPROACH

To achieve an effluent conc of 0.24 mg/l TP requires the modified detention pond to be equal or better than an EDB
For estimating purposes, installing a proprietary BMP downstream of the detention pond was used since retroffing
with an underground structure is believed more probable than trying to create a wet pond with wetlands.

COST BASIS

Reference 1: 6 x 12 StormFilter unit costs $15,500 to treat 0.30 cfs plus $650 annual maintenance
Reference 2: End of pipe systems range from $10,000 to $60,000 for treatment rates up to 1.2-cfs.
Reference 3: 6 x 12 StormFilter unit costs $10,000 to $25,000 with larger CIP installations costing $100,000
Reference 4: 0.16-cfs costs $10,000 and 0.78-cfs systems cost $25,000 per manufacturer.

LAND USE DATA

Number of sub-basins in model used to calculate impacts =	104	
Total Area of sub-basins =	42196	acres
Sub-basin existing conditions imperviousness =	24.8%	

ASSUMPTIONS

1 Design basis is 0.3 cfs for the "standard" unit that cost $ 20,000
2 Assume units will be installed at the downstream end of an EDB based on 40 hr drain time
Assume average flow rate from EDB is 0.3 cfs, then WQCV = 43200 cubic feet
3 Assuming 24.8% imperviousness, then WQCV = 0.13 inches per acre or 487 cf/ac
Then for a WQCV = 43200 cf each unit would treat a total watershed area of 89 acres
4 Then for cost estimation, the number of retrofit facilities = 480
5 Interest @ = 7% Period = 35 yrs PWF = 12.95
6 Administration and contigency = 35%

COST ESTIMATE

A **Preliminary Siting Investigations** - Research possible existing EDBs for feasibility of retrofit.
Estimated engineering costs = $ 75,000

B **Conceptual Design** - Prepare preliminary design information for 6-sites for demonstration purposes.
Estimated engineering costs = $ 100,000

C **Evaluate Legal Access -** Legal and administrative costs to determine feasibility of obtaining legal access
Administrative costs = $ 50,000

C **Final Design/Construction** - Engineering Services.
Estimated engineering costs = $ 50,000

SUB-TOTAL INVESTIGATION COSTS ***$ 275,000***

D **Estimated Cost for Construction**

Unit cost, F&I =	$ 20,000
Site preparation =	$ 10,000
Storm sewer system =	$ 10,000
Easement/access =	$ 20,000
Monitoring equipment =	$ 3,000
Individual site engineering =	$ 2,000
Total Construction cost per unit =	***$ 65,000***
Contingency =	***$ 22,750***
Total Cost per unit =	***$ 87,750***
Total number of units =	***480***
Total Construction cost =	***$ 42,120,000***

E **Maintenance Costs**

Routine inspection per unit =	$ 480	2-hrs * $60/hr *4-times/yr
Scheduled clean out per unit =	$ 750	
Monitoring =	$ 750	
Annual O&M cost per unit =	***$ 1,980***	
Total annual O&M cost =	***$ 950,400***	
Present Worth =	***$ 12,305,500***	

F **Total Present Worth** ***$ 55,000,000***

January 4, 2009.