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Energy Water Information Government

Integrated Evaluation of Boulder Reservoir Water Treatment Facility Source Water Protection and Treatment Improvements Study

Prepared for:
City of Boulder Utilities Division
1739 Broadway Street
Boulder, Colorado 80306

Prepared By:
Black & Veatch Corporation
6300 South Syracuse Way
Suite 300
Centennial, Colorado 80111

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Executive Summary

The Integrated Evaluation of Boulder Reservoir Water Treatment Facility Source Water Protection and Treatment Study (Integrated Study) was performed within the context of an ongoing effort by the City of Boulder (City) to establish definitive drinking water quality and quantity goals as a framework for planning and implementing future improvements throughout the City's drinking water system. One central strategy for achieving the City's water quality goals is to implement a multi-barrier approach to protecting the City's drinking water supply from both biological and chemical contaminants. Barriers may include source water protection measures that either reduce or prevent introduction of contaminants, or minimize their passage throughout the drinking water system through treatment. A multi-barrier strategy to control drinking water contaminants provides superior public health protection. *The purpose of the Integrated Study is to evaluate source water protection alternatives and treatment alternatives from previous work conducted for the City and develop a long-term plan for meeting regulatory and City water quality goals at the Boulder Reservoir Water Treatment Facility (BRWTF).*

A. Overview

In 2003, the Source Water Quality Protection Study (Phase 1 Study) was completed by Black & Veatch to identify and evaluate alternative approaches to improve and protect source water quality for the BRWTF, based on forecasted regulatory requirements as well as internal City-established goals. *This study recommended that raw water be conveyed by gravity flow from Carter Lake to BRWTF in a dedicated pipeline year-round*. Concurrently, the Predesign Report for Near-Term Improvements for the Boulder Reservoir Water Treatment Plant (Predesign Report) was completed by MWH, which presented near-term, mid-term and long-term recommendations for improvements at BRWTF. Near-term improvements were completed in 2005 and included the installation of dissolved air flotation (DAF) pre-treatment facilities, baffling the clearwell, and providing on-site residuals lagoons. The City has begun the budget planning process for the addition of mid-term improvements at BRWTF, which include chlorine dioxide

pre-oxidation, pre-sedimentation, filter backwash water treatment, and pH adjustment. *The Pre-design Report also recommended evaluation of ultraviolet (UV) disinfection, membrane technologies, ozone oxidation, and granular activated carbon (GAC) adsorption as potential treatment processes as part of a long-term multi-barrier water delivery strategy for BRWTF.* For the purposes of this assessment mid-term improvements are assumed to be included in the BRWTF treatment process train, and addition of long-term improvements was evaluated based on this updated baseline treatment capability.

B. Background

Raw water is conveyed to BRWTF from Carter Lake through a 21-mile long, open, earthen canal, referred to as the Boulder Feeder Canal (BFC), which ultimately discharges into Boulder Reservoir (Figure 1-1). Between April and October, the City diverts raw water from BFC just upstream of Boulder Reservoir and delivers it through a pipeline directly to BRWTF. During the remaining months, when BFC is not in operation, raw water is pumped from Boulder Reservoir to BRWTF for treatment. Both BFC and Boulder Reservoir have several features that make them vulnerable to source water quality degradation, as listed in Table 1-1 and shown on Figures 1-2 and 1-3.

C. Source Water Quality Evaluation

Review and extensive analysis of existing historical biological, physical, and chemical water quality data for potential raw water sources for BRWTF, including Carter Lake, BFC, and Boulder Reservoir, was performed. Based on this evaluation, B&V *believes that Carter Lake has superior overall water quality as a raw water source for BRWTF compared with BFC and Boulder Reservoir.* Although Carter Lake is ultimately the source of all raw water for BRWTF, conveyance through BFC and storage in Boulder Reservoir lead to substantial degradation in a number of water quality parameters. Of particular concern are the introduction of chemical contaminants and pathogenic microorganisms during raw water conveyance through BFC and storage in Boulder Reservoir, as well as increased salt content due to dissolution of naturally occurring minerals in Boulder Reservoir sediments. Also of concern are objectionable tastes and odors that result from seasonal algal blooms and increased manganese levels

due to oxygen depletion in Boulder Reservoir. Carter Lake is much less susceptible to these types of water quality degradation because of its surrounding topography and the protected status of the Colorado-Big Thompson Project lakes, reservoirs, and tunnels that supply its water. Analysis of 35 years of historical data for Carter Lake do not indicate any long-term degradation in the overall water quality, and *B&V believes that the water quality of Carter Lake will continue to be suitable as a water source for BRWTF for decades to come.*

D. Contaminant Barrier Requirements

The BRWTF currently meets or exceeds all National Primary and Secondary drinking water regulations during routine operation, and based on source water quality data reviewed, will likely continue to do so for the foreseeable future. However, finished water quality in areas served by BRWTF is vulnerable to short-term degradation due to seasonal variation in Boulder Reservoir water quality and acute contamination episodes in either BFC or Boulder Reservoir. Of particular concern are microbial contamination in BFC or Boulder Reservoir, disinfection byproduct formation during treatment and distribution, contamination by organic micro-pollutants in BFC and Boulder Reservoir, seasonal manganese uptake, taste or odor episodes in Boulder Reservoir, and non-uniform total dissolved solids (TDS) and sulfate concentration across the distribution system when BRWTF uses Boulder Reservoir as its source.

The City has established a set of drinking water quality goals and operational treatment practices in order to ensure public health, minimize distribution system deterioration, and provide uniformly high quality water to all its customers. Several of the City's drinking water quality goals are more stringent than standards required by state and federal drinking water regulations (Appendix 1), in some instances based on prudent concerns related to public health and in others to enhance the palatability and uniformity of finished drinking water. Specific City drinking water goals that exceed mandated regulatory standards include turbidity (health), microbial pathogens (health), disinfection byproducts (health), taste and odor (aesthetic), sodium (uniformity), sulfate (uniformity), total dissolved solids (uniformity), fluoride (health), manganese (aesthetic), and pH (deterioration). Because the City relies on two separate

facilities supplied with source waters of seasonally differing water quality, there are inherent operational challenges and potential cost implications associated with meeting its drinking water quality goals, as discussed throughout this report.

For the purposes of this study, the minimum contaminant barrier requirements were those specified by enforceable USEPA and CDPHE Primary Drinking Water Standards. Contaminant barriers associated with Secondary Drinking Water Standards and City drinking water quality goals were also evaluated in this report. However, the contaminant barriers considered were not required to completely satisfy these non-enforceable secondary standards in all cases, largely for compelling economic reasons. The barrier requirements for BRWTF, based on current state and federal regulatory requirements and City water quality goals, were identified through review of source water quality data for Carter Lake and BFC, and operational data from BRWTF. Barriers for microbial pathogens, disinfection byproducts (DBPs), organic micro-pollutants, manganese, taste and odor, and inorganic contaminant control were evaluated.

E. Multi-Barrier Alternatives Performance Evaluation

The relative performance of multi-barrier water delivery alternatives developed in this study was evaluated using the Kepner-Tregoe® (K-T®) decision analysis procedure. K-T® Decision Analysis is a systematic procedure that encompasses the fundamental thought pattern people use to make choices. Performance criteria in K-T® decision analysis are classified either as MUST criteria that each candidate problem solution must absolutely satisfy in order to be included in the decision process, or WANT criteria that are desirable but not mandatory for each candidate problem solution to satisfy. Two MUST decision criteria were considered including Regulatory Compliance and Water Rights Portfolio Yield. Twenty-eight WANT criteria in five categories including Finished Water Quality, Source Water, Treatment Operations, Risk, and Environmental and Public Acceptance were evaluated in the decision process. An ad hoc City staff committee representing drinking water quality, water resources, operations, and senior management functions assigned weights to the set of WANT criteria to establish the relative importance of each in ranking BRWTF water delivery alternatives based on the collective expertise and experience of the committee members.

F. Multi-Barrier Water Delivery Alternatives

Conceptual improvements that could be included in a multi-barrier water delivery alternative at BRWTF were screened for applicability based on several factors including integration with the existing treatment process train, probable performance, and economic considerations. Potential conceptual improvements were evaluated based on their ability to address one or more of the contaminant barriers identified including microbial pathogens, DBPs, organic micropollutants, manganese, taste and odor, and TDS and sulfate. The general strategy of the screening process was to give greater consideration to conceptual alternatives that where possible addressed more than one contaminant barrier, thereby minimizing the number of conceptual improvements and complexity of proposed multi-barrier water deliver alternatives.

Candidate multi-barrier approaches were developed for BRWTF by combining conceptual improvements that address identified drinking water quality vulnerabilities in source water conveyance to and treatment at BRWTF. Only those conveyance and treatment barriers that were selected in the screening process previously described were included in BRWTF multi-barrier alternatives. The combination of conceptual improvements selected for each delivery alternative was based on providing process redundancy and operational continuity at BRWTF.

Not all possible combinations of screened barriers were included in alternative evaluations, but each screened barrier was incorporated in at least one water delivery alternative. The multi-barrier delivery alternatives developed for this study would produce finished water that meets all current state and federal drinking water standards; however, it is important to note that not all of these alternatives continuously meet the City's drinking water goals.

- Alternative 1: This water delivery alternative incorporates preoxidation with chlorine dioxide followed by full conventional treatment and free chlorine disinfection. A centralized contact basin for preoxidation contact time is included to allow use of both BFC and Boulder Reservoir raw water sources. Presedimentation for turbidity and suspended solids control would also be provided by the preoxidation contact basin, but because no coagulant would

be added prior to basin contact no credit towards *Cryptosporidium* treatment would be provided. Residual chlorine dioxide and chlorite would be quenched by ferrous sulfate addition prior to coagulation.

This barrier combination serves as the baseline BRWTF multi-barrier water delivery alternative. *This baseline alternative would not meet the City's water quality goals with respect to pathogen control, nor would it meet finished water TDS and sulfate goals when raw water is provided from Boulder Reservoir. No effective barrier for organic micropollutant control is provided by this alternative.*

- Alternative 2: This alternative incorporates UV disinfection with the barriers provided by Alternative 1. *This alternative would not meet the City's TDS and sulfate water quality goals when Boulder Reservoir was online, nor would it provide an effective barrier for organic micropollutant control.*

- Alternative 3: This alternative adds both GAC adsorption and UV disinfection to the contaminant barriers provided by baseline Alternative 1. *This alternative would not meet the City's TDS and sulfate water quality goals when raw water was supplied from Boulder Reservoir.*

- Alternative 4: This alternative utilizes the contaminant barriers in baseline Alternative 1 with granular media filtration replaced by submerged low-pressure membrane filtration retrofitted into the existing filter boxes. *This alternative would not meet the City's TDS and sulfate water quality goals, nor would it provide an effective barrier for organic micropollutant control.*

- Alternative 5: This alternative adds ozone oxidation to the contaminant barriers provided by baseline Alternative 1. *This alternative would not meet the City's water quality goals with respect to pathogen control during cold weather operation at BRWTF, nor would it meet finished water TDS and sulfate goals.*

- Alternative 6: Carter Lake pipeline for turbidity, suspended solids, manganese, taste and odor, organics, DBP, and inorganics control followed by chlorine dioxide preoxidation for additional pathogen, taste and odor, organics, and DBP control. *This alternative meets*

all the City's water quality goals, and provides at least one barrier for each contaminant category evaluated.

G. Non-Economic Performance of Water Delivery Alternatives

The relative performance of multi-barrier water delivery alternatives was evaluated using the K-T® decision analysis procedure. Each water delivery alternative was ranked by its ability to satisfy the non-economic performance criteria relative to all other alternatives. The general approach taken in ranking BRWTF water delivery alternatives against each criterion was that wherever possible prevention of contamination during raw water delivery to BRWTF is a superior strategy to subsequent treatment at BRWTF. *This approach is consistent with the century old paradigm for drinking water treatment, which is based on treating the highest quality source water available with the simplest and most robust treatment process train.*

As shown in Table ES-1, non-economic performance scores for the BRWTF alternatives evaluated in this study were clustered between 0.5 and 0.6 for all but Alternative 6, which had a performance score of 0.942.

Table ES-1

Non-Economic Performance Scores[(1)]

Alternative	1	2	3	4	5	6
Performance Score	0.512	0.573	0.606	0.554	0.603	0.942

[(1)]Performance scores are expressed on a 0 to 1 scale, with a higher value indicating better performance.

The non-economic analysis performed here indicates that Alternative 6 is the highest ranked BRWTF multi-barrier water delivery alternative, followed by Alternatives 1 through 5 with non-economic performance scores that were grouped in a substantially lower range. The sensitivity of this alternative ranking to the criteria weights assigned was evaluated using the sensitivity analysis

feature of the Criterium DecisionPlus® software package used to perform decision analysis calculations. The ranking of BRWTF multi-barrier water delivery alternatives was not sensitive to the weight assigned to any criterion.

H. Cost Opinions

The relative economic merit of multi-barrier water delivery alternatives was evaluated based on a life-cycle cost present value analysis that included capital, operation and maintenance (O&M), and project financing costs. A common set of unit process and O&M costs to each BRWTF multi-barrier water delivery alternative. The Class 4 planning level cost opinions, typically accurate to within +50 percent to −30 percent, presented here reflect use of standard engineering practices and were prepared without the benefit of detailed engineering designs.

Table ES-2

Cost Opinions in Millions of Dollars

Alternative	**1**	**2**	**3**	**4**	**5**	**6**
Capital[(1)]	0.0	2.4	21.9	13.2	13.6	21.1
Annual O&M[(2)]	0.17	0.21	0.86	0.42	0.32	0.19
Net Present Value[(3)]	5.2	9.3	53.4	29.2	26.7	17.1[(3)]

[(1)]Capital cost opinions include material and construction estimates for process equipment and basins, any additional structures needed to house process equipment, electrical service, instrumentation and control, site work, yard piping, and general contracting. Engineering, legal, and administrative expenses were estimated to be 20 percent of the material and construction cost subtotal. A contingency factor of 25 percent was applied to the material and construction subtotal.

[(2)]O&M included treatment chemical, other consumables such as UV lamp and ballast replacement, GAC replacement, pumping and other energy costs, and scheduled equipment maintenance. An average daily flow rate of 5 mgd was used to calculate variable consumable and energy O&M costs.

[(3)]A 30-year life-cycle was assumed. Because the expected useful life of large diameter subterranean transmission mains is considerably longer than 30 years, the residual value of the Carter Lake Pipeline beyond this time was credited to the net present value cost opinion for Alternative 6. Other common economic analysis parameters used include a 2007 baseline, an O&M inflation rate of 4 percent, a loan interest rate of 6 percent, and a present worth factor of 4 percent.

I. Preferred Water Delivery Alternative

Both performance and cost varies widely among the six BRWTF water delivery alternatives evaluated. *Considering source water quality information, relative risk of source water contamination, regulatory requirements, City drinking water quality goals, and operational flexibility B&V believes that Alternative 6, complete source water containment from Carter Lake to BRWTF with chlorine dioxide preoxidation, is the most desirable and preferred alternative*. Although Alternative 6 does not have the lowest net present value among those evaluated, it has a number of compelling benefits that are not provided by the other alternatives including:

- Of the BRWTF multi-barrier water delivery alternatives evaluated here, Alternative 6 alone follows the century old paradigm of drinking water treatment in that it treats the best available water source with the simplest and most robust combination of processes.

- Alternative 6 has the best non-economic performance by a wide margin. This alternative satisfied 22 of 28 criteria evaluated as well or better than the other alternatives.

- Alternative 6 is unique among those evaluated in that it alone addresses the near and long term potential for continued degradation of water quality in existing BRWTF sources due to continued residential development, extensive agricultural land use, and increasing recreational use. Although notable advances in treatment technology have been made in recent years, contaminant removal during drinking water treatment is still an imperfect science. Thus, as has traditionally been the case, preventing source water contamination provides a more robust barrier than subsequent treatment as the first line of defense in protecting public health.

- Other regional drinking water providers also desire to use a dedicated pipeline from Carter Lake for raw water delivery to their facilities. Combining raw water conveyance to BRWTF with that of other providers allows more efficient use of scarce regional water resources.

- Full containment of raw water conveyance from Carter Lake to BRWTF would provide additional flexibility in managing the City's water resources portfolio. Other water delivery alternatives require seasonal storage of raw water in Boulder Reservoir for use when BFC in not in service. Year-round storage in Carter Lake would remove the need to project annual seasonal storage required in Boulder reservoir, and thus avoid the undesirable consequences that result if seasonal Boulder Reservoir storage is substantially overestimated.

- Conveyance of raw water through a Carter Lake pipeline would be consistent with the City's historical policy of protecting source water quality by providing full containment from its other water sources.

- Full containment from Carter Lake to BRWTF would provide a much more uniform raw water quality, substantially simplifying treatment optimization and increasing treatment process reliability.

- Alternative 6 is the only BRWTF water delivery approach that provides at least one robust barrier for each contaminant category considered in this study.

Chapter 1

Introduction

This chapter describes the purpose, background, and approach of the Integrated Evaluation of Boulder Reservoir Water Treatment Facility Source Water Protection and Treatment Improvements study (Integrated Study). In addition, this chapter briefly describes recent regulatory changes that may affect drinking water treatment at the Boulder Reservoir Water Treatment Facility.

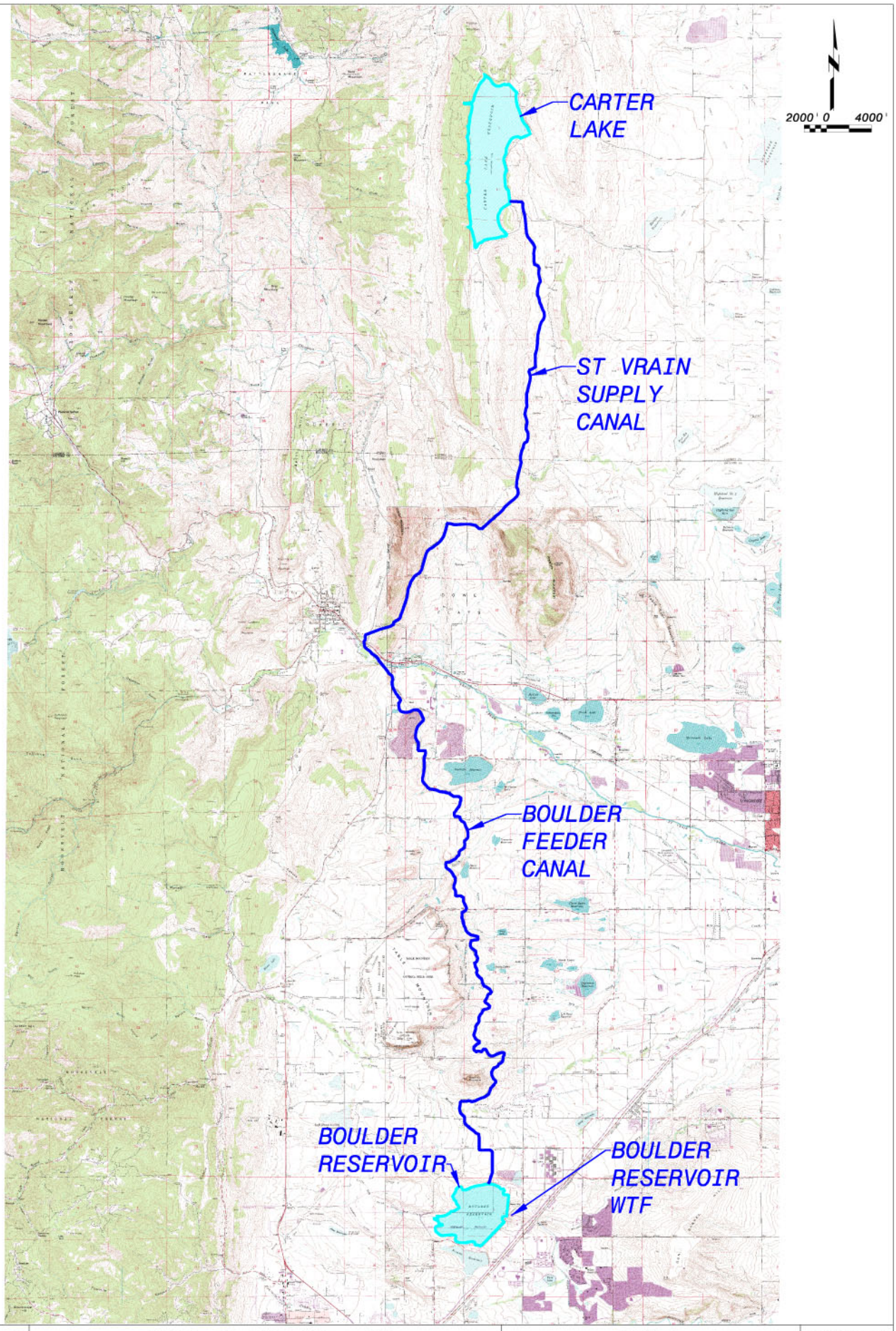
A. Purpose

The purpose of the Integrated Study is to evaluate source water protection alternatives from the Source Water Quality Planning Study (Phase I Study) and treatment alternatives from the Predesign Report for Near-Term Improvements (Predesign Report) and develop a long-term plan for meeting regulatory and City of Boulder (City) water quality goals at the Boulder Reservoir Water Treatment Facility (BRWTF). Multi-barrier alternatives have been evaluated based on a set of performance criteria developed by City staff, and consideration of life cycle costs associated with each alternative.

The Integrated Study was performed within the context of an ongoing effort by the City to establish definitive drinking water quality and quantity goals as a framework for planning and implementing future improvements throughout the City's drinking water system. One central strategy for achieving the City's water quality goals is to implement a multi-barrier approach to protecting the City's drinking water supply from both biological and chemical contaminants. Barriers may include source water protection activities that either reduce or prevent introduction of contaminants, or minimize their passage throughout the drinking water system through treatment. A multi-barrier strategy to control drinking water contaminants affords superior public health protection.

B. Project Background

Raw water is conveyed to BRWTF from Carter Lake through a 21-mile long, open, earthen canal, referred to as the Boulder Feeder Canal (BFC), which



	CITY OF BOULDER, CO BRWTF MULTI-BARRIER APPROACH STUDY	BRWTF RAW WATER SUPPLY ROUTE	FIGURE 1-1

ultimately discharges into Boulder Reservoir (Figure 1-1). Between April and October, the City diverts raw water from BFC just upstream of Boulder Reservoir and delivers it through a pipeline directly to BRWTF. During the remaining months, when BFC is not in operation, raw water is pumped from Boulder Reservoir to BRWTF for treatment. Both BFC and Boulder Reservoir have several features that make them vulnerable to source water quality degradation, as listed in Table 1-1 and shown in Figures 1-2 and 1-3.

Table 1-1

Boulder Feeder Canal and Boulder Reservoir Vulnerabilities to Water Quality Degradation

BFC	Boulder Reservoir
• Open channel • 51 outfalls discharge into BFC • 11 street crossings • Uncontrolled access • Neighboring land uses • Herbicides routinely applied • Bank scouring during storm events	• Open to recreational uses including swimming and motorized boating • Overland flow drainage • Naturally occurring manganese • Algal blooms leading to T&O episodes • Higher TDS due to mineral dissolution • High turbidity from wind action and BFC flows • Reduced treatability due to higher temperature

In 2003, the Source Water Quality Protection Study (Phase 1 Study) was completed by Black & Veatch (B&V) to identify and evaluate alternative approaches to improve and protect source water quality for the BRWTF, based on forecasted regulatory requirements as well as internal City-established goals. It was recommended that the following alternatives be carried forward for further investigation:

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City of Boulder, Colorado – Multi-Barrier Approach Study

Outfalls, Erosion, and Road Crossings on Boulder Feeder Canal

Figure 1-2

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City of Boulder, Colorado – Multi-Barrier Approach Study

Outfalls and Stormwater Diversions to Boulder Feeder Canal

Figure 1-3

Near-Term – Boulder Reservoir Management – Utilize Boulder Reservoir as a year-round terminal reservoir rather than divert raw water directly from the BFC. Raw water will then be pumped from Boulder Reservoir to the BRWTF.

Long-Term – Pipeline from Carter Lake to the BRWTF – Construct a 21-mile raw water pipeline from Carter Lake that would deliver water year-round to the BRWTF by gravity flow.

Since that time, the City has modified the intake structure at the Boulder Reservoir to reduce the manganese load to the BRWTF. In addition, the City recently participated with other drinking water providers in a study to further explore the feasibility of a pipeline from Carter Lake to the BRWTF. The study evaluated potential pipeline alignments and refined capital cost opinions for each of the participants. However, some of the entities included in the study may not participate in the pipeline, which would potentially increase the City's share of the cost.

At the same time the Phase 1 Study was being developed, the Predesign Report for Near-Term Improvements for the Boulder Reservoir Water Treatment Plant (Predesign Report) was completed by MWH. This plan presented near-term, mid-term and long-term recommendations for improvements at the BRWTF. Near-term improvements were completed in 2005 and included the installation of dissolved air flotation (DAF) facilities, baffling the clearwell, and providing on-site residuals lagoons. Recommended mid-term and long-term improvements included:

Mid-Term – Chlorine dioxide
Pre-sedimentation
Filter backwash water treatment
pH adjustment

Long-Term – Ultraviolet (UV) disinfection
Membranes
Ozone
Granular activated carbon (GAC) caps on existing filters

The mid-term treatment process improvements listed above have not yet been implemented, but the City has begun the budget planning process for their addition at BRWTF. For the purposes of this assessment mid-term improvements are assumed to be included in the BRWTF treatment process train, and addition of long-term improvements was evaluated based on this updated baseline treatment capability.

The City has requested that B&V utilize the findings of the two previous reports referenced above to develop a multiple-barrier approach that combines the most cost effective means of meeting the City's water quality and quantity goals. This study is especially timely in light of the City Council's recent endorsement of the development of an 11-mile recreational trail along the BFC from U.S. 36, southeast of Lyons, to the Boulder Reservoir. A city and county staff team assessed the potential impacts of the trail and identified mitigation measures through a community and environmental assessment process (CEAP). The primary issue identified in the CEAP was the potential impacts of the proposed trail on the City's drinking water supply for the BRWTF.

C. Regulatory Environment and City Water Quality Goals

The recently promulgated Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) and City drinking water quality goals will influence the development and evaluation of multi-barrier drinking water delivery alternatives at BRWTF.

1. Regulatory Environment

The regulatory environment surrounding drinking water quality has continuously evolved over the past 30 years, and will likely continue to do so in the future. The most recent regulations that impact surface water treatment are the Stage 2 Disinfectants and Disinfection Byproducts Rule (Stage 2 DBPR) and Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR), promulgated on January 4, 2006 and January 5, 2006, respectively. Collectively, these regulations balance the risk-risk tradeoff between health concerns related to exposure to pathogenic microorganisms, particularly *Cryptosporidium*, and disinfection byproducts formed in chlorinated drinking water. These regulations will be progressively implemented over the next 5 to 7 years. Based on the

regulatory effort required to assess public risk, toxicity or infectivity, and avoidance or treatment costs associated with emerging drinking water contaminants, B&V believes that significant additional drinking water standards related to pathogens, particulates, and disinfection byproducts are unlikely to be promulgated until after implementation and initial compliance with the Stage 2 DBPR and LT2ESWTR are complete.

B&V believes that the most likely area in which new drinking water standards could be promulgated during the next 10 years will be organic micropollutants. Over the past 5 years there has been growing recognition and concern regarding the health effects of endocrine disrupting compounds (EDCs), pharmaceutically active compounds (PhACs), and personal care products (PCPs) that enter drinking water supplies through municipal wastewater discharges and non-point sources. Research into the occurrence, fate, and health effects of a wide range of potential EDCs, PhACs, and PCPs is ongoing. The United States Environmental Protection Agency (USEPA) has promulgated an unregulated contaminant monitoring rule (UCMR) to evaluate the occurrence of organic micropollutants in drinking water supplies. In addition, USEPA has developed a repeating 5-year process to evaluate the need to regulate specific micropollutants identified in Candidate Contaminant Lists (CCLs). Of 60 contaminants (50 chemicals and 10 microbes) identified in CCL1 (March 1998), 20 were classified as priorities for regulatory determination; however, 12 of these were found to have insufficient information to support a regulatory determination. None of the remaining 8 contaminants were recommended for regulation in the final determinations announced in March 2003. CCL2, promulgated in February 2005, identifies 9 microbes and 42 chemicals that are scheduled for regulatory determination in 2010. Although USEPA has the authority to promulgate new drinking water standards at any time, B&V believes it is unlikely that additional regulations will be promulgated for any of these contaminants before the regulatory determinations of CCL2 are finalized.

2. City Drinking Water Quality Goals

The City has established a set of drinking water quality goals and operational treatment practices in order to ensure public health, minimize distribution system deterioration, and provide uniformly high quality water to all its

customers. Several of the City's drinking water quality goals are more stringent than standards required by state and federal drinking water regulations (Appendix 1), in some instances based on prudent concerns related to public health and in others to enhance the palatability and uniformity of finished drinking water. Specific City drinking water goals that exceed mandated regulatory standards include turbidity (health), microbial pathogens (health), disinfection byproducts (health), taste and odor (aesthetic), sodium (uniformity), sulfate (uniformity), total dissolved solids (uniformity), fluoride (health), manganese (aesthetic), and pH (deterioration). Because the City relies on two separate facilities supplied with source waters of seasonally differing water quality, there are inherent operational challenges and potential cost implications associated with meeting its drinking water quality goals, as discussed throughout this report.

D. Contaminant Barrier Requirements

The barrier requirements for BRWTF, based on current state and federal regulatory requirements and City water quality goals, were identified through review of source water quality data for Carter Lake, BFC, and operational data from BRWTF. Barriers for microbial pathogens, disinfection byproducts (DBPs), organic micro-pollutants, manganese, taste and odor, and inorganic contaminant control were evaluated. The potential impacts of both long-term average water quality and short-term acute contamination episodes were considered.

E. Multi-Barrier Alternatives Performance Evaluation

The relative performance of multi-barrier water delivery alternatives developed in this study was evaluated using the Kepner-Tregoe® (K-T®) decision analysis procedure. K-T® Decision Analysis is a systematic procedure that encompasses the fundamental thought pattern people use to make choices. The specific techniques that define the systematic procedure used in K-T® Decision Analysis expand and refine the elements of this thought pattern:

- We appreciate that there is a choice to be made.
- We consider the specific factors that should be satisfied for the choice to succeed.

- We decide what course of action best satisfies these factors.
- We consider the risks associated with the chosen course of action that could jeopardize its success.

The following sections describe the nine steps that constitute the K-T® Decision Analysis process

1. State the Decision

The decision statement describes the "choice dilemma" that is to be resolved in a decision-making process, indicates an intended result, and sets limits on the choice being made. A decision statement is a short and concise description of the choice to be made that includes a choice word (select, choose, pick, etc.), an intended result, and one or two key modifiers that broaden or narrow the range of the choice. The decision statement also specifies the *level* at which the current choice is to be made based on *implied prior decisions*. The decision statement for this project is:

"Select a multi-barrier water delivery approach for the BRWTF."

2. Develop the Objectives

The second step in K-T® Decision Analysis is to develop decision objectives, which consists of the set of criteria that will influence the decision. This set of decision criteria forms a basis to help evaluate BRWTF water delivery alternatives fairly. City staff developed criteria in five categories including finished water quality, source water, treatment operations, risk, and environmental and public acceptance, as outlined in Chapter 4.

3. Classify the Objectives into MUSTs and WANTs

Each of the criteria that form the set of decision objectives is classified based on its role in the decision: those criteria that are mandatory for any acceptable decision alternative are classified MUSTs, whereas those criteria that are desirable for any acceptable decision alternative are classified as WANTs. The set of decision criteria developed in Chapter 4 are also classified in that chapter.

4. Weigh the WANTs

The relative importance of WANT criteria in the decision at hand is established by assigning numerical weights between 1 and 10 to each. City staff assigned relative weights to the WANT decision criteria as described in Chapter 6.

5. Generate Alternatives

Candidate solutions to the problem defined in the decision statement, termed alternatives, are developed based on review of the decision criteria set, regulatory requirements, industry standards, and decision group experience and judgment. Conceptual improvements previously identified in the Phase 1 Study and Pre-design Report, as well as those in the LT2ESWTR Microbial Toolbox (Table 3-4), were reviewed for applicability to either source water conveyance to or treatment at BRWTF. Conceptual improvements that were determined to be potentially feasible were grouped into candidate water delivery alternatives based on meeting the barrier requirements identified in Chapter 3.

6. Screen the Alternatives through the MUSTs

Each alternative developed in step 5 is screen against the minimum set of requirements defined by mandatory MUST criteria. Only those alternatives that completely satisfy all MUST criteria are considered further in the decision process. The BRWTF multi-barrier water delivery alternatives developed in Chapter 5 satisfy the MUST criteria as classified in Chapter 4.

7. Compare the Alternatives Against the Wants

The performance of each decision alternative against the set of WANT criteria is evaluated in comparison to all other alternatives to establish a relative ranking of alternatives. The relative performance ranking of BRWTF water delivery alternatives is described in Chapter 6.

8. Consider the Adverse Consequences

Adverse consequences associated with selection of each alternative are identified and reviewed to understand the risks associated with each.

9. Make the Best Balanced Decision

A balanced decision regarding the most appropriate alternative solution to the decision statement requires collective consideration of relative alternative ranking and potential adverse consequences of each alternative. For this study, an economic evaluation of capital and operation and maintenance (O&M) costs was also conducted, as described in Chapter 7. Both non-economic performance and economic life-cycle value of BRWTF water delivery alternatives were considered in selection of a recommended BRWTF water delivery alternative, as described in Chapter 8.

Chapter 2

Source Water Quality

This chapter provides a brief overview of the existing BRWTF source water system and its historical operation. An evaluation of water quality for the potential sources that could be used to supply BRWTF, including Carter Lake, BFC, and Boulder Reservoir, is also provided. The quality of raw water delivered to BRWTF by the BFC and Boulder Reservoir systems was evaluated for their current configurations with no additional source water protection features added, and with full containment from Carter Lake to BRWTF as recommended in the Phase I Source Water Protection Study.

A. Existing BRWTF Source Water System

Historically, operation of BRWTF has ultimately relied on delivering raw water through BFC, either directly to BRWTF or to Boulder Reservoir for subsequent use. During canal operation, raw water is typically diverted from BFC at a location upstream of Boulder Reservoir and delivered through a pipeline to BRWTF for treatment and distribution. Any remaining flow continues in BFC for a short distance and discharges to Boulder Reservoir where it is stored for water exchanges, downstream irrigation or as a reserve raw water supply for treatment at BRWTF. When the canal is not in operation, raw water is pumped from Boulder Reservoir to BRWTF.

1. Boulder Feeder Canal

The open channel BFC generally follows a north to south route traversing the lower slopes of the foothills. As such, it tends to capture a significant amount of surface runoff that originates uphill and to the west. Although a riparian habitat along the canal could, to some extent, naturally attenuate contamination, the channel bottom and banks are regularly maintained by Northern Colorado Water Conservancy District (NCWCD) to prevent growth of vegetation. Therefore, although the raw water at its source in Carter Lake is of a very high quality, significant degradation generally occurs as the water travels the length of the BFC.

The resulting variable water quality delivered to BRWTF and/or Boulder Reservoir can pose significant treatment challenges to the City. The BRWTF staff must frequently adjust treatment operations in response to raw water quality changes due to weather and human or animal activities. Unfortunately, existing BRWTF monitoring and treatment technologies have not always provided the ability to respond quickly enough to rapid water quality changes and there have been occasions when the facility has been taken off-line to avoid the possibility of violating treated water quality standards. Operational changes in treatment are also required each time the raw water supply is switched between BFC and Boulder Reservoir.

2. Boulder Reservoir

Boulder Reservoir is a low volume, shallow, Class 1 warm water fishery owned by the City of Boulder and operated by NCWCD. The reservoir has a surface area of approximately 700 acres and a capacity of about 13,270 acre-feet (ac-ft). Historically, BRWTF has primarily used the Boulder Reservoir supply only during the winter months when BFC is not in service. Water from Boulder Reservoir must be delivered by pumping from RWTF Raw Water Pumping Station.

Boulder Reservoir is a multipurpose reservoir that is used year round for a variety of recreational activities including special events that bring in large numbers of people for short durations. As a result, the reservoir is subject to water quality degradation resulting from both body contact recreation and non-body recreational activities such as fishing and boating. These activities contribute to general water quality degradation and an increase in BRWTF raw water supply contaminant load.

Flows from BFC have in the past been as high as 2.5 times the reservoir volume. These flows are significant in that high flows tend to improve water quality by keeping the reservoir water mixed and fresh, which helps reduce stratification that occurs in the summer. However, the City has no control over these flows, which can vary significantly from year-to-year. In addition, the reservoir provides a degree of dilution, settling, and natural processes to break down contaminants before raw water reaches BRWTF.

During the late summer, natural temperature stratification occurs in the reservoir and a hypolimnetic layer low in dissolved oxygen forms in the deeper regions of the reservoir. This condition results in the release of soluble manganese from reservoir sediment into the water column and causes taste and odor treatment concerns at BRWTF.

The water in the reservoir has higher total dissolved solids (TDS) including sodium, sulfate, and hardness compared with water entering from BFC. Turbidity in the reservoir is typically less than 10 nephelometric turbidity units (NTU), but wind action and high canal flows can increase turbidity to as high as 150 NTU. Additional water quality concerns include objectionable tastes and odors, which may be a byproduct of hypolimnetic anoxia.

B. Water Quality Data Sources

Source water quality data for Carter Lake, BFC, and Boulder Reservoir were reviewed. Water quality data were collected from previous reports prepared for the City as well as supplemental data supplied by the City. Data obtained from USEPA and United States Geologic Survey (USGS) online databases were also reviewed. Table 2-1 lists source water data reviewed for this study. Not all analyses cover the entire sampling period or all three source waters.

C. Source Water Quality Data Summary

Water quality data reviewed for this study were evaluated for both spatial and temporal coverage of the associated source waters. Table 2-2 lists the average water quality data for each raw water source and the following sections provide a summary of the data evaluation by source water.

1. Carter Lake

Carter Lake is a relatively deep (140 feet) upland reservoir. Upland reservoirs receive imported water by utilizing hydraulic structures and typically very small runoff areas. Carter Lake is surrounded by Bureau of Land Management lands and has no natural tributaries. The lake is open to motorized boating, but has historically had excellent water quality with only slight seasonal variations.

Table 2-1

Water Quality Data Sources

Parameter	Data Source	Time Period
Microbiological		
Giardia, *Crypto*, FC	Phase I Study[1]	Pre 2004
Giardia, *Crypto*	Predesign Report[2]	1992-2000
Giardia, *Crypto,* TC, FC, HPC	Water Treatment Evaluation Study[3]	Pre 1999
Giardia, *Crypto*, FC	Boulder Reservoir WTP Assessment[4]	1994-2000
Giardia, *Crypto,* TC, FC, EC	City of Boulder[5]	1995-2005
Giardia, *Crypto*	BFC Proposed Trail Study[6]	1997-2000
TC, FC, EC, FS	USGS National Water Information System[7]	1970-2004
Physical Parameters		
pH, turbidity, temperature, DO, SC	Phase I Study	Pre 2004
pH, turbidity, temperature, DO, SC	Predesign Report	1992-2000
pH, turbidity, color, odor	Water Treatment Evaluation Study	Pre 1999
pH, turbidity, temperature, DO, SC	Boulder Reservoir WTP Assessment	1994-2000
pH, temperature, DO, SC	USGS Water-Resources Report 99-4091[8]	1997-1998
pH, turbidity, temperature, DO, SC, true color, ORP, flow	City of Boulder	1995-2005
pH, transparency, temperature, DO, SC	USGS National Water Information System	1970-2004
Chemical Parameters		
Cations, anions, alkalinity, Fe, Mn	Phase I Study	Pre 2004
Cations, anions, alkalinity, Fe, Mn	Predesign Report	1992-2000
Cations, anions, alkalinity, metals	Water Treatment Evaluation Study	Pre 1999
Cations, anions, alkalinity, Fe, Mn	Boulder Reservoir WTP Assessment	1994-2000
Fe, Mn, Se, U, N, P, trace metals	USGS Water-Resources Report 99-4091	1997-1998
Cations, anions, alkalinity, Fe, Mn, P, NO_3^-, NO_2^-	City of Boulder	1995-2005
Cations, anions, alkalinity, metals	USGS National Water Information System	1970-2004

Table 2-1

Water Quality Data Sources (continued)

Parameter	Data Source	Time Period
Organic Parameters		
Chlorophyll a, TOC, UVA_{254}	Phase I Study	Pre 2004
Chlorophyll a, TOC, SUVA	Predesign Report	1992-2000
TOC, DBPs	Water Treatment Evaluation Study	Pre 1999
Chlorophyll a, TOC, UVA_{254}	Boulder Reservoir WTP Assessment	1994-2000
Chlorophyll a, TOC, UVA_{254}	City of Boulder	1995-2005
Chlorophyll a/b, TOC	USGS National Water Information System	1970-2004
TOC	Bureau of Reclamation[9]	2005

Abbreviations:
DBPs – disinfection byproducts, DO – dissolved oxygen, EC – *Escherichia coli*, FC – fecal coliforms, FS – fecal streptococci, HPC – heterotrophic plate count, ORP – oxidation-reduction potential, SC – specific conductance, SUVA – specific ultraviolet absorbance (UVA_{254}/TOC), TC – total coliforms, TOC – total organic carbon, UVA_{254} – ultraviolet absorbance at 254 nm.

[1]Source Water Quality Planning Study, Black & Veatch, April 2003.
[2]Predesign Report for Near-Term Improvements for the Boulder Reservoir Water Treatment Plant, MWH, June 20, 2003.
[3]Water Treatment Plant Evaluation Study (WTPS – Erie, CO), HDR Engineering Inc., February 2006.
[4]Assessment of the Boulder Reservoir Water Treatment Plant, McGuire Environmental Consultants Inc., May 2001.
[5]City of Boulder Drinking Water Program, various data provided by the City of Boulder
[6]Assessment of Pathogen Risk of a Proposed Trail on the Boulder Feeder Canal (BFC), Boulder County Colorado, CH Diagnostic & Consulting Service, Inc., October 10, 2000.
[7]United States Geological Survey, National Water Information System: USGS 06742500 Carter Lake near Berthoud, CO, http://nwis.waterdata.usgs.gov/usa/, accessed June 09, 2006.
[8]Water-Quality Conditions, Hydrologic Budget, and Sources and Fate of Selected Trace Elements and Nutrients in Boulder Reservoir, Boulder, Colorado, 1997-98. USGS Water-Resources Investigations Report 99-4091.
[9]Northern Colorado Water Conservancy Database, Bureau of Reclamation – Carter Lake Station CL-DAM1, 2005.

Table 2-2

Average Water Quality Data for Carter Lake, Boulder Feeder Canal, and Boulder Reservoir

Water Quality Parameter	Carter Lake[1]	Boulder Feeder Canal[2]	Boulder Reservoir[3]
Monitoring Period	1970−2005	1997−2005	1997−2005
Temperature (°C)	10.2	11.5	14.2/16.8
pH (s.u.)	7.6	8.2	7.6/8.2
DO (mg/L)	7.9	10.1	4.9/8.2
Turbidity (NTU)	N/A	5.4	25/9
Specific conductance (µmho/cm)	71	109	284/295
Total dissolved solids (mg/L)[4]	43	66	172/180
Total suspended solids (mg/L)	N/A	7	18/6
Secchi depth (m)	2.6	N/A	1.3
Hardness (mg/L as $CaCO_3$)	40	48	120/122
Alkalinity (mg/L as $CaCO_3$)	31	39	66/66
Sodium (mg/L)	2.2	3.4	10.3/9.6
Sulfate (mg/L)	3	14	77/78
Iron, dissolved (µg/L)	9	10	4/3
Manganese, dissolved (µg/L)	3	< 10	88/8
Phosphorous, dissolved (µg/L)	12	15	22/14
Nitrate + nitrite (mg/L)	0.07	0.03	0.02/0.01
Total organic carbon (mg/L)	3.6	3.5	3.5/3.6
Chlorophyll *a* (µg/L)	1.4	N/A	3.9
E. coli (CFU/100 mL)	1	66	58/8
Fecal coliform (CFU/100 mL)	< 1	38	20/7
Giardia (cysts/L)	ND[3]	0.32 to 0.49	< 0.001
Cryptosporidium (oocysts/L)	ND	0.02 to 0.16	0.01

[1]Samples collected from Carter Lake when ice cover was not present.
[2]Samples collected during periods of canal operation only, typically April through October.
[3]Samples collected 0.5 m above the bottom/composite epilimnion samples.
[4]TDS = 0.61×Specific conductance
N/A – Not available.
ND – Not detected.

a. Microbial Characteristics

The microbial quality of Carter Lake has historically been excellent, due in large part to its location, small runoff area, and limited human impact. Sample data for total coliforms, fecal coliforms, *E. coli*, and fecal streptococci are consistent with surface water that is minimally impacted by human and animal wastes. The following summarizes the historic microbial quality of Carter Lake.

- Fecal coliform measurements collected between 1970 and 2001 averaged less than 1 colony forming unit per 100 milliliters (CFU/100 mL), with a maximum concentration of 17 CFU/100 mL. Only three percent of the samples reviewed had concentrations greater than 1 CFU/mL.

- All *E. coli* monitoring results reviewed between 2001 and 2004 were less than or equal to 1 CFU/100 mL.

- No data on protozoan levels in Carter Lake was reviewed; however, between 1998 and 2003, neither *Giardia* nor *Cryptosporidium* was detected in raw water conveyed through a pipeline from Carter Lake to the City of Erie, Colorado.

b. Physical Characteristics

Physical water quality parameters in Carter Lake are typical of relatively deep lakes with small catchments, as summarized below.

- Raw water pH is neutral to slightly alkaline.

- Turbidity and specific conductance are low.

- The average temperature of water in Carter Lake between 1970 and 2004 was 10.2 degrees Celsius (°C), with maximum and minimum recorded values of 24°C and 0.5°C, respectively. Temperature stratification with depth was observed in summer months, with seasonal overturn events in the spring and fall.

- Dissolved oxygen in the hypolimnion is below saturation during summer months; however, generally remains above 3 milligrams per liter (mg/L).

c. Chemical Characteristics

The following provides a summary of the chemical characteristics of Carter Lake.

- Carter Lake displays chemical characteristics consistent with highly pristine mountain waters derived primarily from snowmelt including low alkalinity, hardness, and TDS. Figure 2-1 shows TDS and sulfate concentrations for the period 1970 to 2004.

- Because Carter Lake is situated in an area with low mineral content soils, there is little opportunity for metals uptake into the water column.

- Both iron and manganese concentrations have been continuously below EPA's Secondary Maximum Contaminant Levels (SMCLs) of 0.3 mg/L and 0.05 mg/L, respectively for data reviewed between 1973 and 2004.

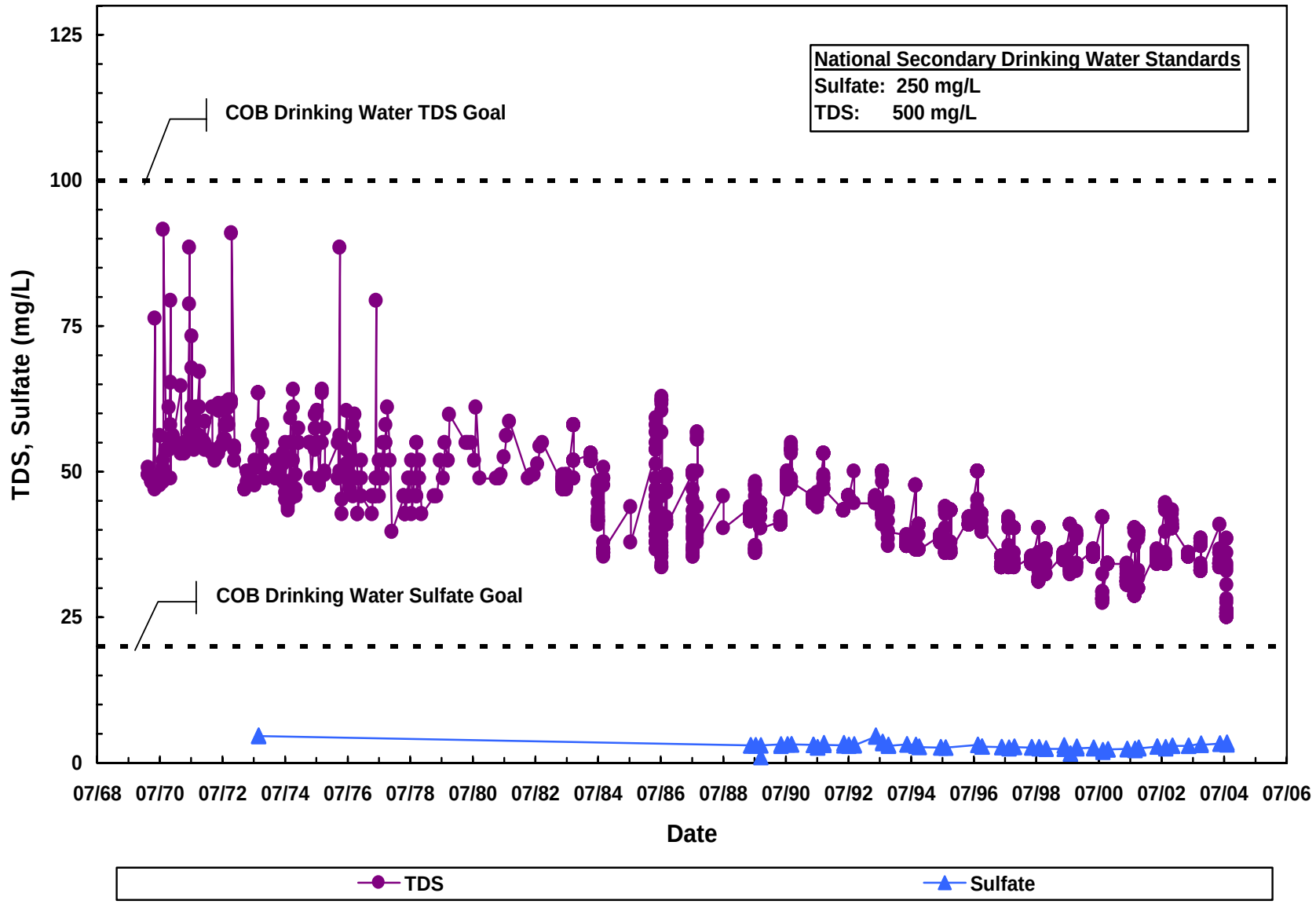
- The productivity of Carter Lake is classified as oligotrophic based on Secchi depth, chlorophyll *a*, and total phosphorous concentrations. TOC concentrations average 3.5 mg/L and vary little with season. Based on these considerations the potential for serious taste and odor problems related to algal blooms in Carter Lake is low.

2. Boulder Feeder Canal

The BFC is bordered by a variety of public and private lands that have agricultural, industrial, residential, and recreational usages. Because of its open construction, BFC experiences surface runoff and has 51 outfalls and 11 street crossings along its length. Therefore, although water quality in Carter Lake has historically been excellent, significant degradation typically occurs as water flows through BFC.

a. Microbial Characteristics

The City of Boulder Drinking Water Program has conducted extensive reconnaissance of water quality in the BFC in recent years, particularly related to microbial degradation. Data collected between 1995 and 2005 were reviewed



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Total Dissolved Solids and Sulfate in Carter Lake

Figure 2-1

and yearly baseline fecal coliform contamination values were calculated after excluding anomalously high values associated with acute contamination events. Fecal contamination in BFC appears to be increasing with time, as shown graphically on Figure 2-2. Both average monthly (June through October) and maximum monthly fecal coliform concentrations increased over the time period examined. Because the trends represented by these data do not include acute contamination events, they represent a conservative estimate of fecal contamination in BFC.

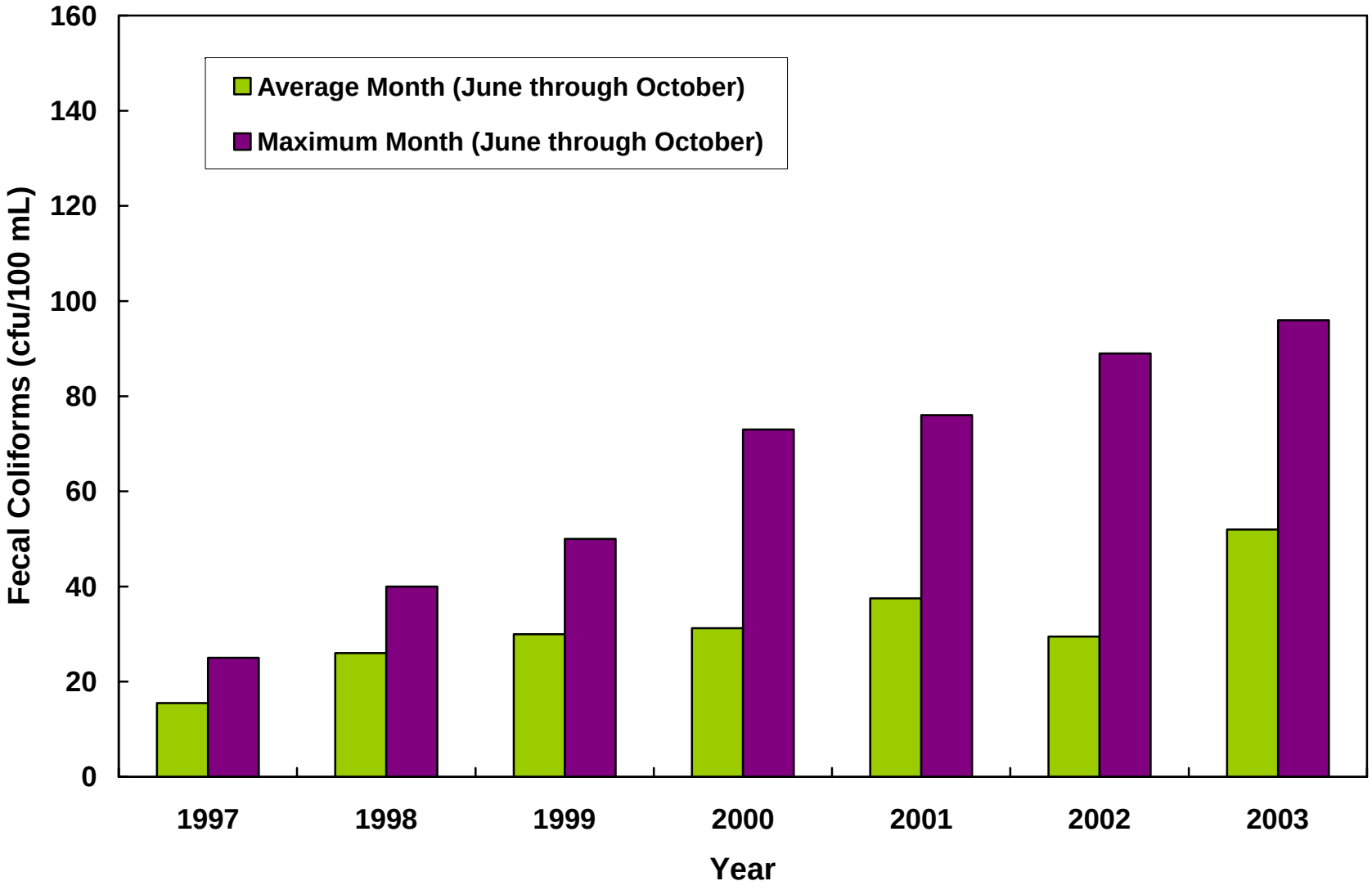
Review of extensive bacteriological reconnaissance monitoring data collected during the 1995 through 2005 BFC operating seasons reveal the following:

- *E. coli* and fecal coliform levels were measured at multiple locations along BFC, with a total of 307 *E. coli* measurements collected on 78 days during the 2002 through 2005 canal operating seasons and a total of 328 fecal coliform measurements collected on 89 days during the 1995 through 2003 canal operating seasons, respectively. Samples were not collected at all locations on every sample date. The cumulative frequencies of bacterial contamination in BFC based on this data are given in Figure 2-3.

- Bacterial water quality varies spatially along the length of BFC, with higher levels of degradation frequently occurring downstream, as shown in Figure 2-4.

- Bacterial water quality varies temporally in BFC, with positive correlation between canal flow and rainfall and contamination. Figure 2-5 illustrates the magnitude of an elevated *E. coli* contamination episode in BFC captured in July 2005.

- The bacterial quality of water delivered by BFC to BRWTF is significantly degraded compared with that of the original Carter Lake source water. *E. coli* and fecal coliforms are typically present in BFC water at the BRWTF intake in concentrations of tens to thousands of CFU/100mL and tens to hundreds of CFU/100 mL, respectively, compared to concentrations typically less than 1 CFU/100 mL in Carter Lake.



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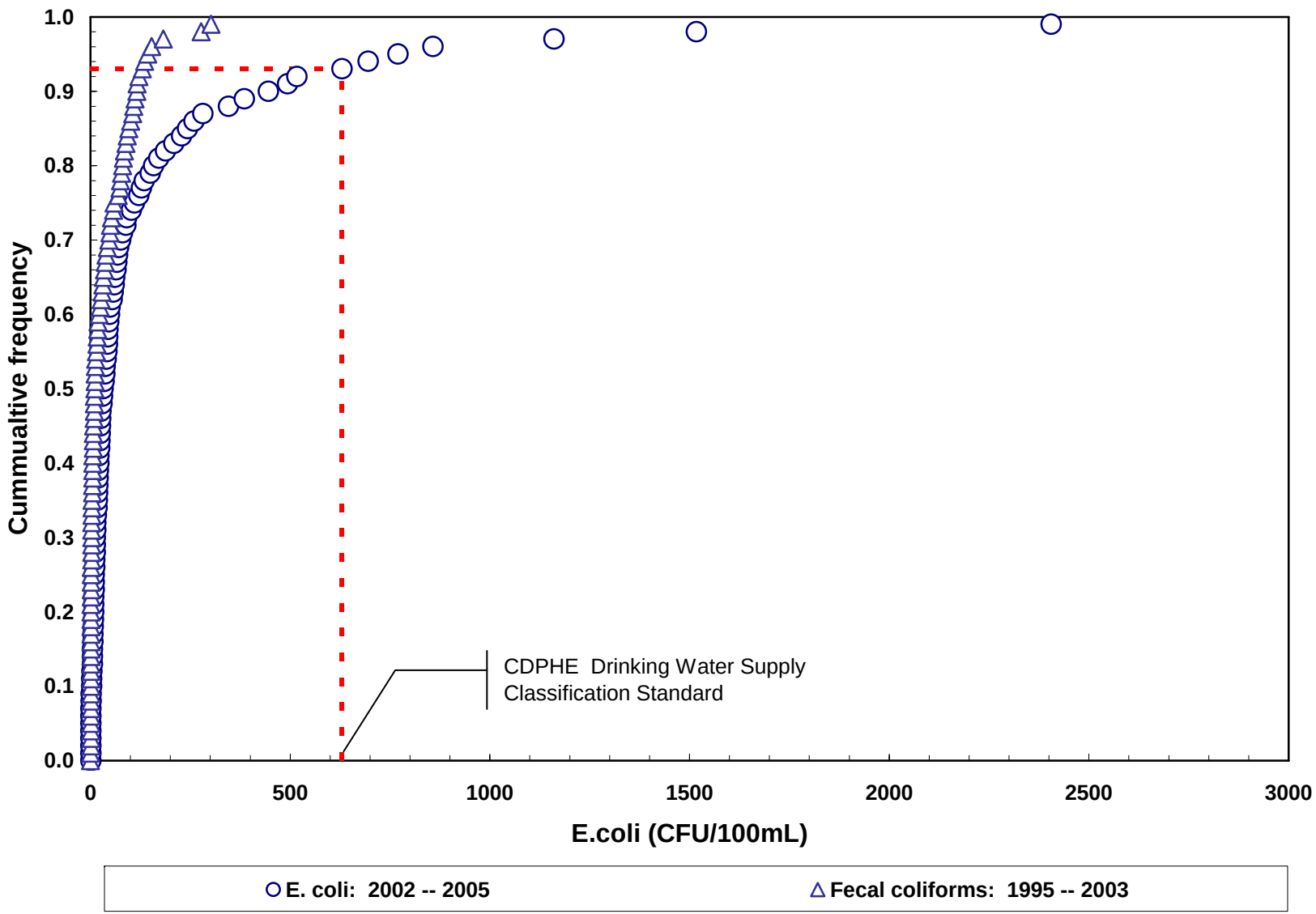
Historical Fecal Coliform Concentrations in BFC

Figure 2-2



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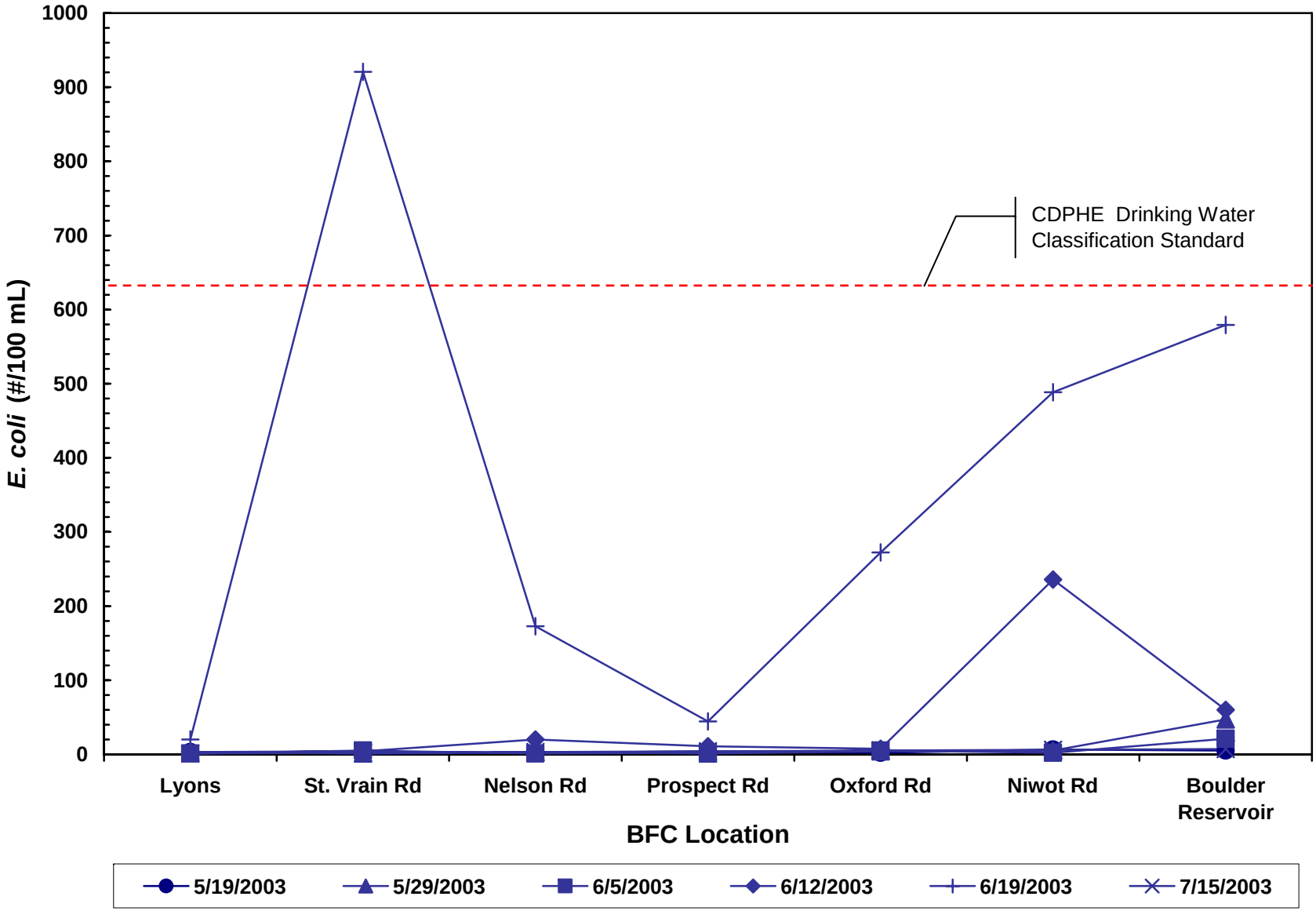
Cumulative Frequency of Bacterial Contamination in BFC

Figure 2-3



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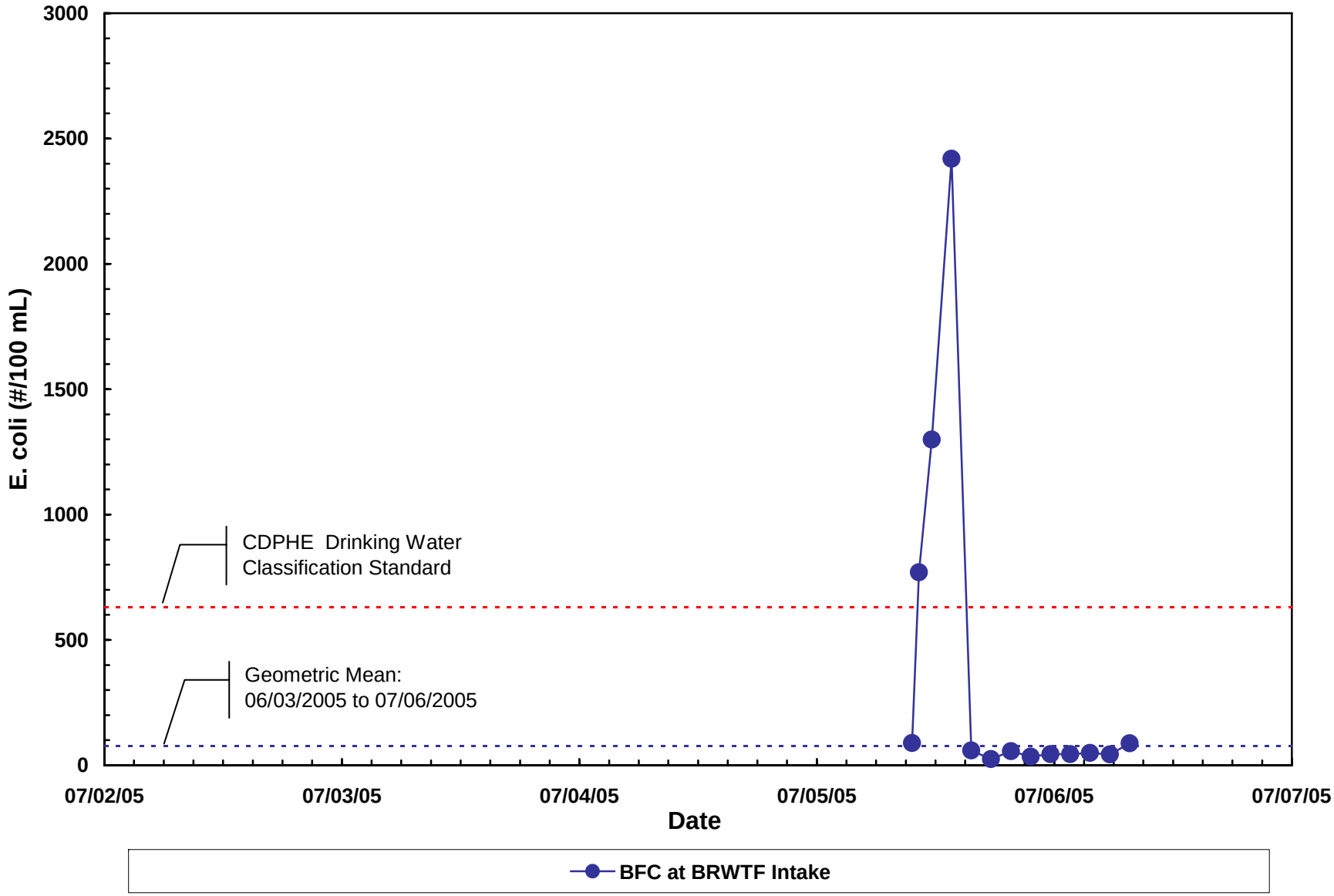
Elevated *E. coli* Contamination Episodes in BFC – Spatial Variation

Figure 2-4



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Elevated *E. coli* Contamination Episodes in BFC – Temporal Variation

Figure 2-5

These data highlight the potential for microbial contamination of BFC water through surface runoff, outfalls, and scouring of the canal banks.

Extensive reconnaissance for protozoan contamination in BFC has also been conducted over the past decade. The following summarizes these findings.

- *Giardia* has been regularly detected in BFC samples at an average concentration between 0.32 and 0.49 cysts per liter (cysts/L), with positive occurrence in 68 percent of samples. The maximum *Giardia* concentration detected between 1994 and 2004 was 2.00 cysts/L.

- *Cryptosporidium* has frequently been detected in BFC samples at an average concentration between 0.02 oocysts per liter (oocysts/L) and 0.16 oocysts/L, with a maximum reported concentration of 3.04 oocysts/L.

- The frequency of *Cryptosporidium* detection was lower than that of *Giardia*, with positive occurrence in between 11 and 23 percent of BFC samples.

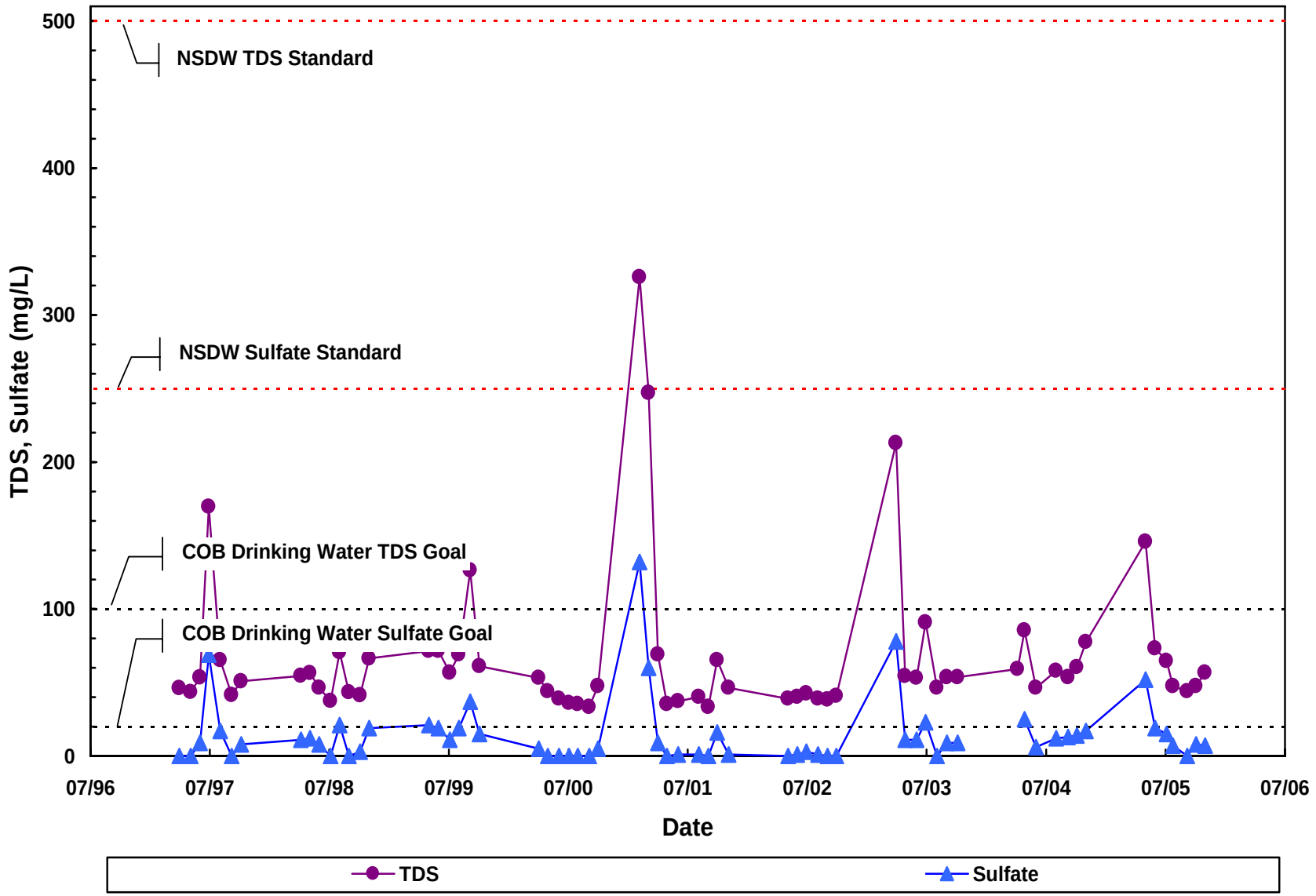
- Monte Carlo simulation was used to predict probable *Cryptosporidium* concentrations in BFC resulting from various levels of recreational trail usage along BFC as a function of canal flowrate. Results from these simulations indicated potential for significant degradation in BFC water quality due to *Cryptosporidium* contamination from adjacent recreational use.

b. Physical Characteristics

Physical water quality parameters in BFC are similar to those of Carter Lake, with slight increases in temperature, pH, and dissolved oxygen.

c. Chemical Characteristics

Chemical water quality of BFC was also similar to that of Carter Lake, with only marginally higher average mineral content, although short-term seasonal increases in TDS and sulfate do occur, as shown in Figure 2-6. TOC at the BRWTF intake on BFC is similar to that in Carter Lake.



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Total Dissolved Solids and Sulfate in BFC

Figure 2-6

3. Boulder Reservoir

Boulder Reservoir is located atop mineralized soils that have relatively high native sulfate and manganese. There are two natural tributaries and several ditches that drain into Boulder Reservoir, increasing the nutrient loading and potentially introducing contaminants. Boulder Reservoir is also used year-round for a variety of recreational purposes including fishing, boating, and swimming, which can also contribute to pathogen and contaminant loading.

a. Microbial Characteristics

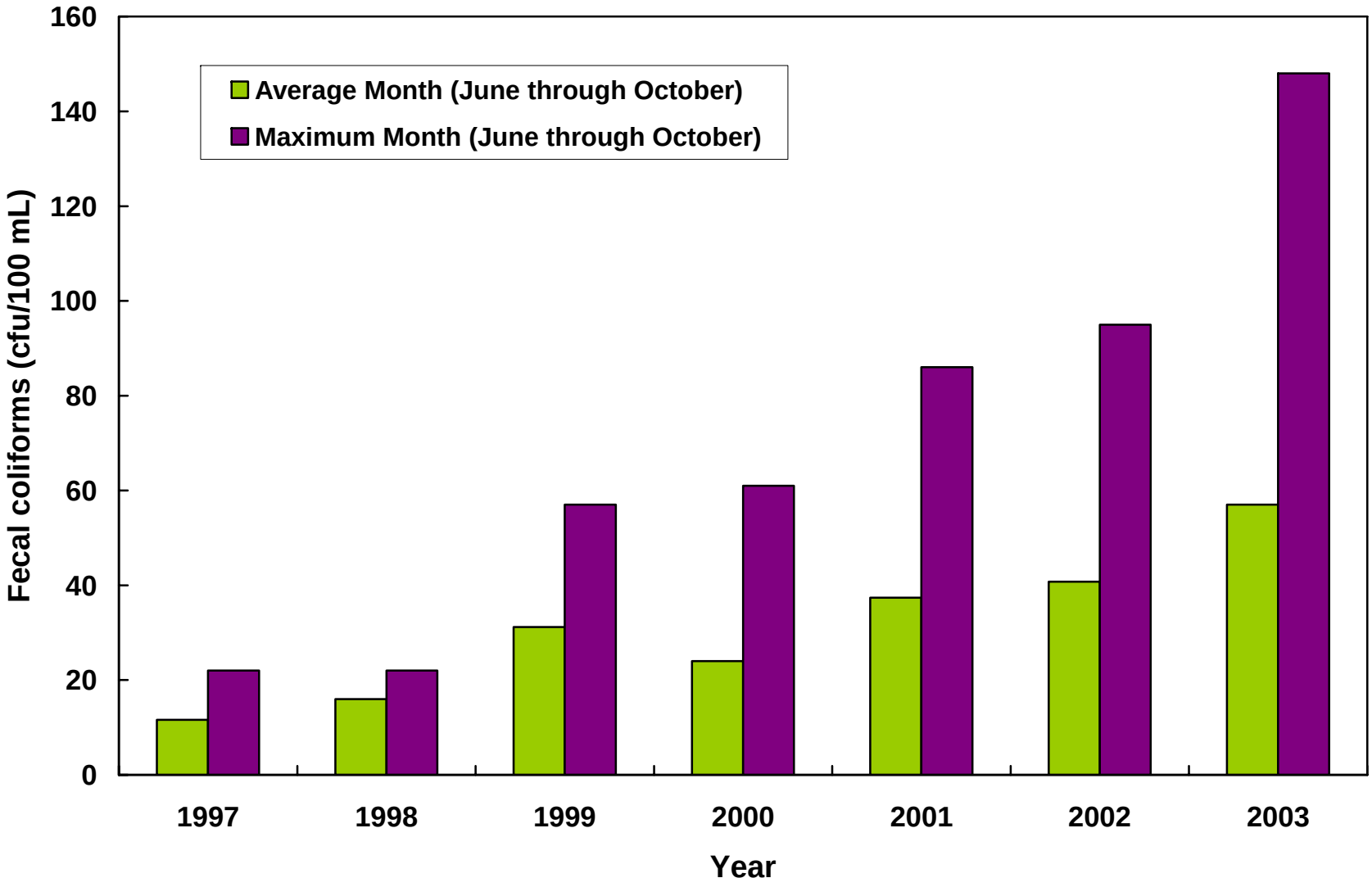
The microbial water quality of Boulder Reservoir is vulnerable to pathogen contamination due to operation of Boulder Feeder Canal. The following summarizes the bacterial characteristics of Boulder Reservoir.

- Sampling of Boulder Reservoir by City staff demonstrates a causal link between fecal contamination in the reservoir and operation of BFC. Fecal coliforms are present at or below the detection limit during the months when BFC is not in operation. However, during the months that BFC is in operation fecal coliforms are typically present at measurable concentrations.

- Both *E. coli* and fecal coliform concentrations in the hypolimnion (0.5 meters above the bottom of the reservoir) are slightly less than their respective average concentrations in BFC.

- Fecal contamination in Boulder Reservoir appears to be increasing with time, as shown graphically on Figure 2-7, based on both seasonal and maximum monthly average fecal coliform data. Samples collected from the hypolimnion between 1997 and 2003 show similar increasing trends as previously described for BFC over the same time period.

- Although fecal contamination of Boulder Reservoir through surface tributaries and recreational use have been documented, the relatively low tributary flows (roughly eight percent of BFC flow) and vertical stratification during warm weather months of BFC operation make it unlikely that these contaminant sources account for elevated fecal coliform levels in the reservoir hypolimnion.



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Historical Fecal Coliform Concentrations in Boulder Reservoir Hypolimnion

Figure 2-7

Protozoan contamination has been detected less frequently and at lower concentrations than in BFC. The following summarizes the protozoan characteristics of Boulder Reservoir.

- *Giardia* was detected in 8 percent of samples collected from Boulder Reservoir between 1997 and 2004, with a maximum concentration of 0.3 cysts/L. *Cryptosporidium* was not detected in these samples. However, *Cryptosporidium* was reported at an 8 percent incidence rate in earlier sampling with a maximum concentration of 0.2 oocysts/L.

- Dilution and natural attenuation processes that occur in the reservoir likely contribute to the lower protozoan detection rate compared with BFC.

b. Physical Characteristics

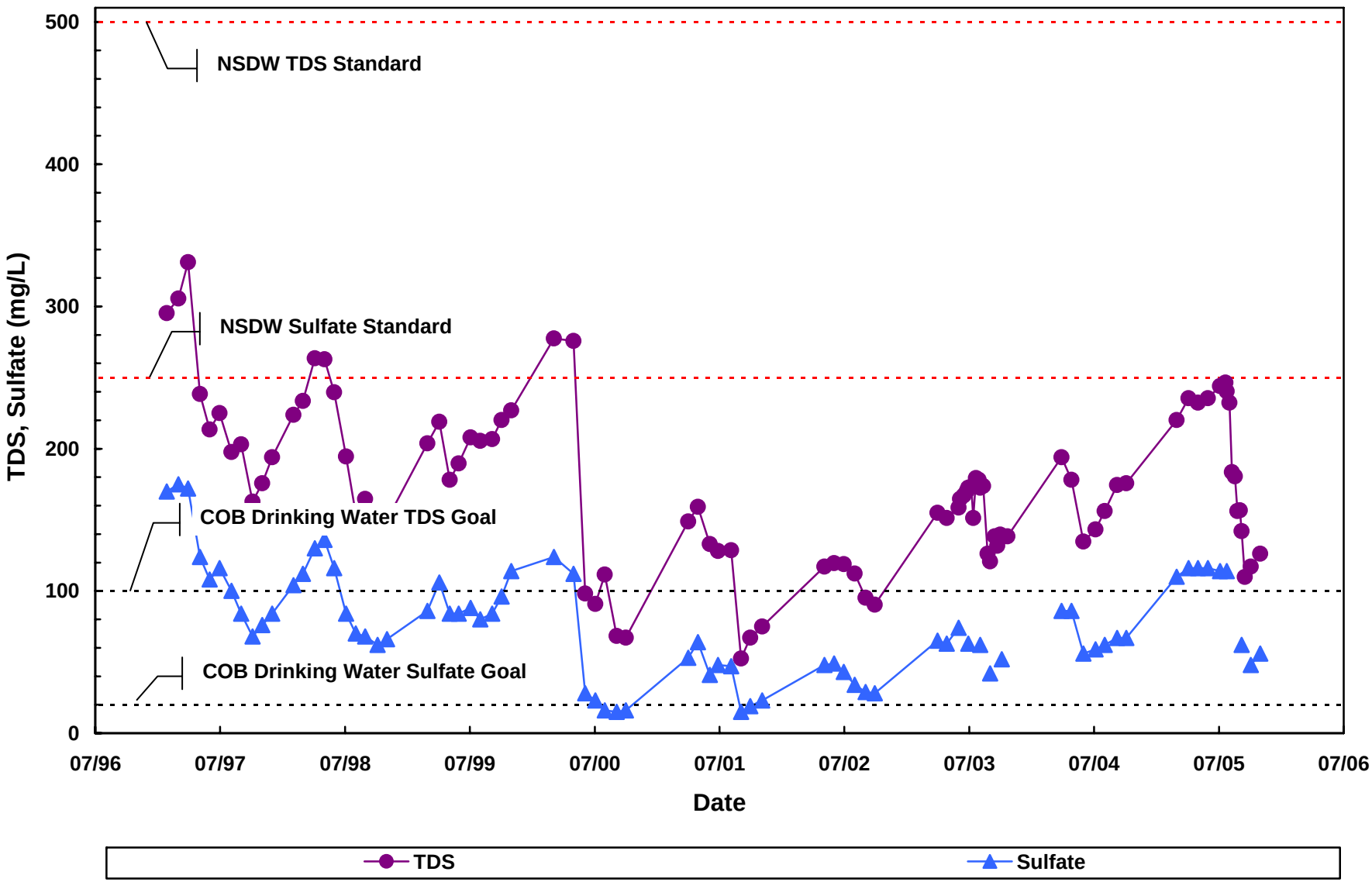
Physical water quality parameters in Boulder Reservoir are moderately different than those of Carter Lake and BFC; with similar pH, lower dissolved oxygen, and higher temperature, turbidity, total dissolved solids, and specific conductance (Table 2-2). Secchi depth is lower than in Carter Lake indicating reduced water clarity. Seasonal variation in physical water quality is observed as discussed below.

c. Chemical Characteristics

Chemical water quality in Boulder Reservoir is degraded compared to Carter Lake and BFC. The following summarizes chemical water quality in Boulder Reservoir.

- Dissolution of naturally occurring mineral deposits in Boulder Reservoir sediments leads to dramatically increased TDS, hardness, alkalinity, sodium, sulfate, and manganese (Table 2-2).

- TDS and sulfate concentrations in Boulder Reservoir vary with season, generally decreasing when BFC is in service and increasing when BFC is not in service, as shown on Figure 2-8.



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Total Dissolved Solids and Sulfate in Boulder Reservoir

Figure 2-8

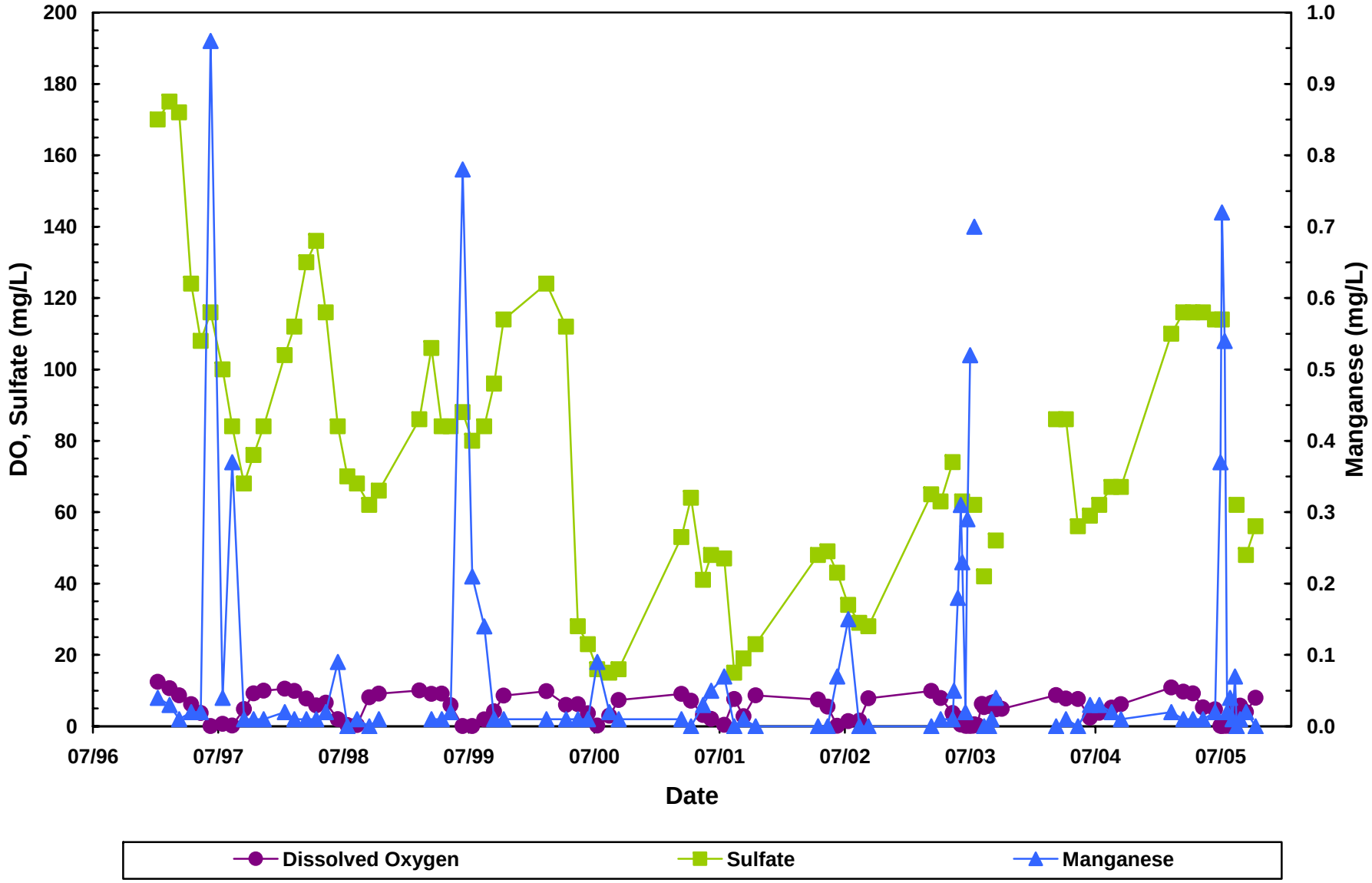
- The productivity of Boulder Reservoir is classified as mesotrophic, based on the lower Secchi depth, higher chlorophyll *a*, and higher total phosphorous concentrations compared to Carter Lake. Based on these considerations the potential for serious taste and odor problems related to algal blooms in Boulder Reservoir is moderate. TOC in Boulder Reservoir is similar to that in BFC and Carter Lake.

d. Seasonal Water Quality Variation

Physical and chemical water quality in Boulder Reservoir follows a repeating seasonal pattern that results in vertical stratification in the water column, impacting treatability at BRWTF when operation is from the reservoir intake. Vertical stratification in Boulder Reservoir is reinforced by inflow from BFC that is lower in temperature than either the epilimnion or hypolimnion year-round. During the summer months when reservoir water temperature increases, the hypolimnion becomes anaerobic, and manganese is mobilized from native sediments. Manganese mobilization is generally followed by a dramatic decrease in sulfate concentration throughout the summer and fall, as illustrated on Figure 2-9. Sulfate concentration is re-established throughout the water column in the winter when biological activity is reduced.

Comparison of the water temperatures in BFC at BRWTF and the epilimnion (surface layer) of Boulder Reservoir indicate that water entering the reservoir from BFC is consistently cooler than the surrounding reservoir, as shown on Figure 2-10. The higher bacterial contaminant concentrations in the hypolimnion of Boulder Reservoir may be attributed to the settling of the cooler, and thus denser, BFC water into the hypolimnion. This can cause short-circuiting of much of the reservoir volume, resulting in a reduced mixing and dilution volume. Because the reservoir intake for BRWTF is located in the hypolimnion, short-circuiting of potentially pathogen loaded BFC water is particularly undesirable. Further studies are necessary to quantify the extent of short-circuiting.

The seasonal variation in hypolimnion water quality is characteristic of microbially mediated activity. Heterotrophic bacteria couple the oxidation of organic matter with the reduction of inorganic terminal electron acceptors to gain energy for metabolism. Bacteria preferentially exploit electron acceptors in order of greatest energy generation, resulting in a temporal sequence of utilization



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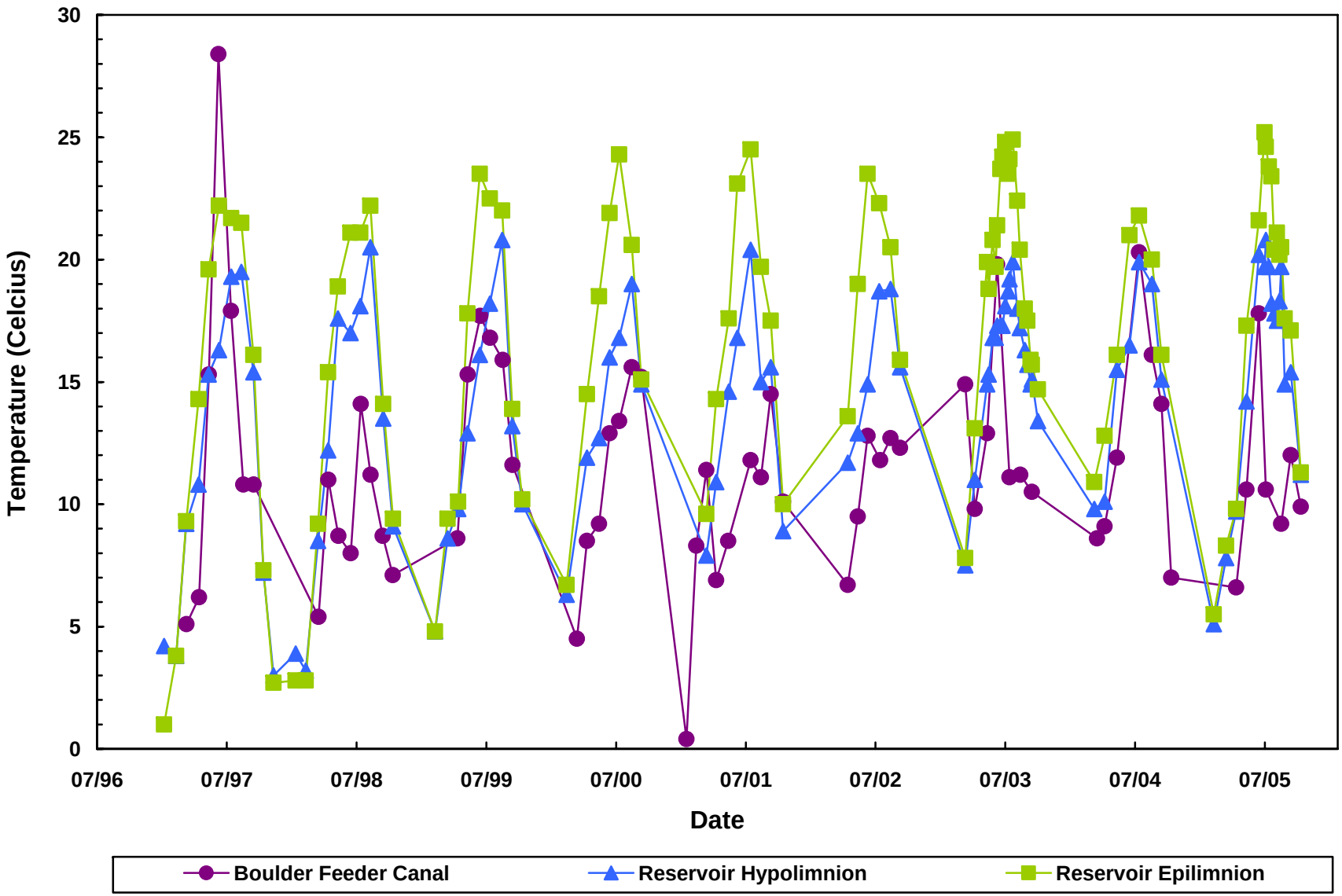
Effect of Thermal Stratification on Dissolved Oxygen, Manganese, and Sulfate Concentrations in Boulder Reservoir Hypolimnion

Figure 2-9



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Water Temperatures in BFC and Boulder Reservoir

Figure 2-10

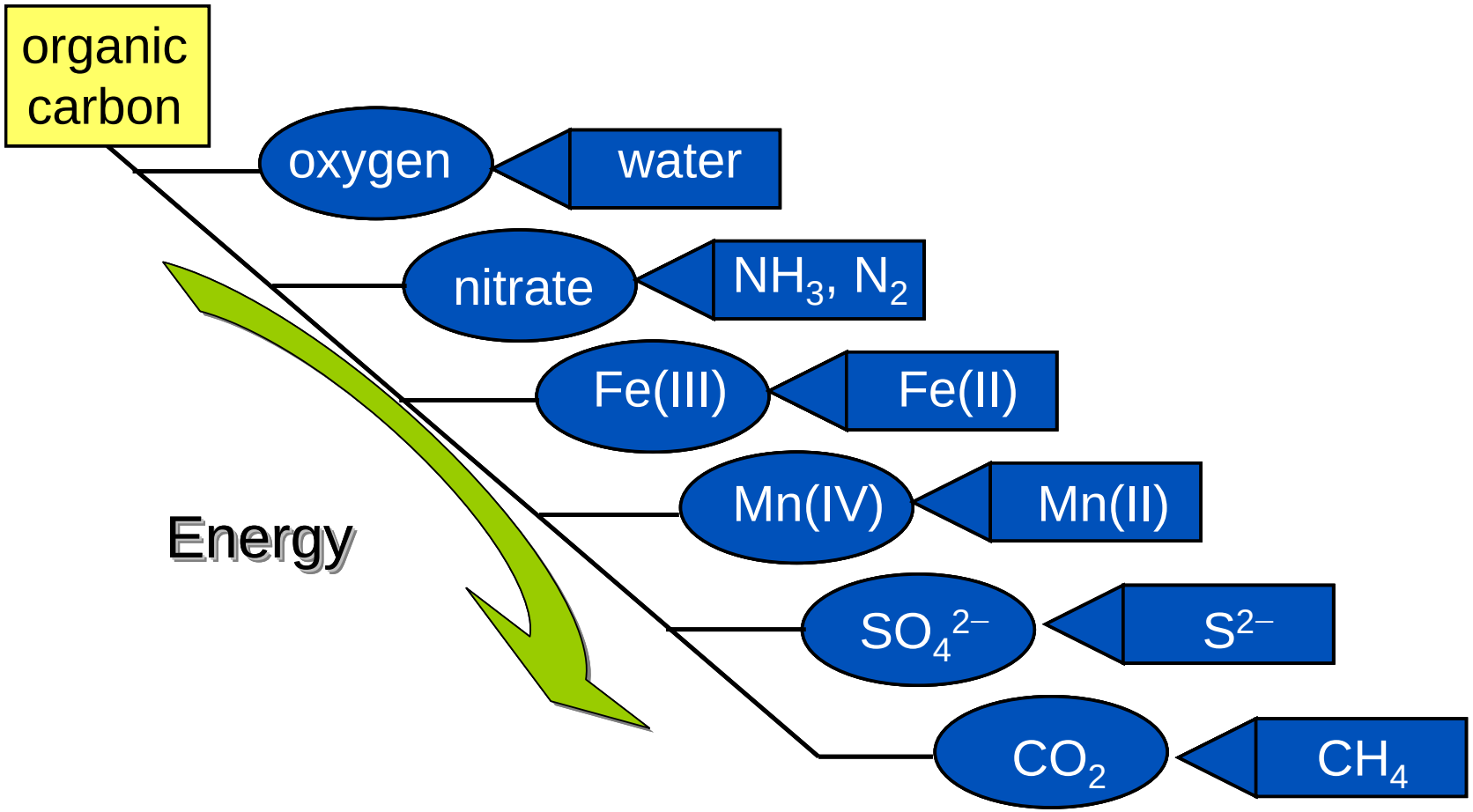
(Figure 2-11). The sequence of oxygen depletion followed by Mn(II) production and ultimately sulfate reduction observed in the hypolimnion of Boulder Reservoir is consistent with microbial activity based on low iron and nitrate concentrations.

Variation in physical water quality parameters also supports seasonal stratification in Boulder Reservoir. Lower temperature, pH, and dissolved oxygen, as well as higher turbidity and suspended solids, are all indicative of stratification. However, several key chemical constituents including hardness, alkalinity, total dissolved solids, total organic carbon, and sulfate remain relatively constant with reservoir depth. A scenario that mechanistically explains this apparent inconsistency may be related to a thermally generated density gradient as BFC water flows into Boulder Reservoir, as illustrated on Figure 2-12.

In this scenario, BFC water entering Boulder Reservoir sinks to the bottom due to its lower temperature and higher density, where dissolved oxygen is depleted by microbial respiration. As anaerobic water flows away from the BFC inlet in the hypolimnion, manganese dioxide (MnO_2) in bottom sediment is first microbially reduced releasing soluble manganese (Mn^{2+}), followed by sulfate reduction. Dissolution of other soluble minerals in bottom sediment also occurs, increasing TDS. Inflow of water to the hypolimnion from BFC is balance by withdrawal for BRWTF treatment and upwelling to the epilimnion. At the interface between the hypolimnion and epilimnion soluble Mn^{2+} is oxidized by molecular oxygen, re-precipitating particulate MnO_2 that settles back into the hypolimnion. Thus, mixing from below maintains anaerobic conditions in the hypolimnion, while promoting otherwise somewhat similar chemical water quality throughout the water column.

D. BRWTF Operational Data

Operational water quality data for BRWTF provided by the City was reviewed with respect to the treatment barriers currently in place for microbial, disinfection byproduct, organic contaminant, manganese, taste and odor, and inorganic contaminant control. Data for the years 1997 through 2005 indicate that finished water from BRWTF generally meets all current Primary and Secondary National Drinking Water Standards. However, several aspects of finished water quality that may impact the decision on whether or not to



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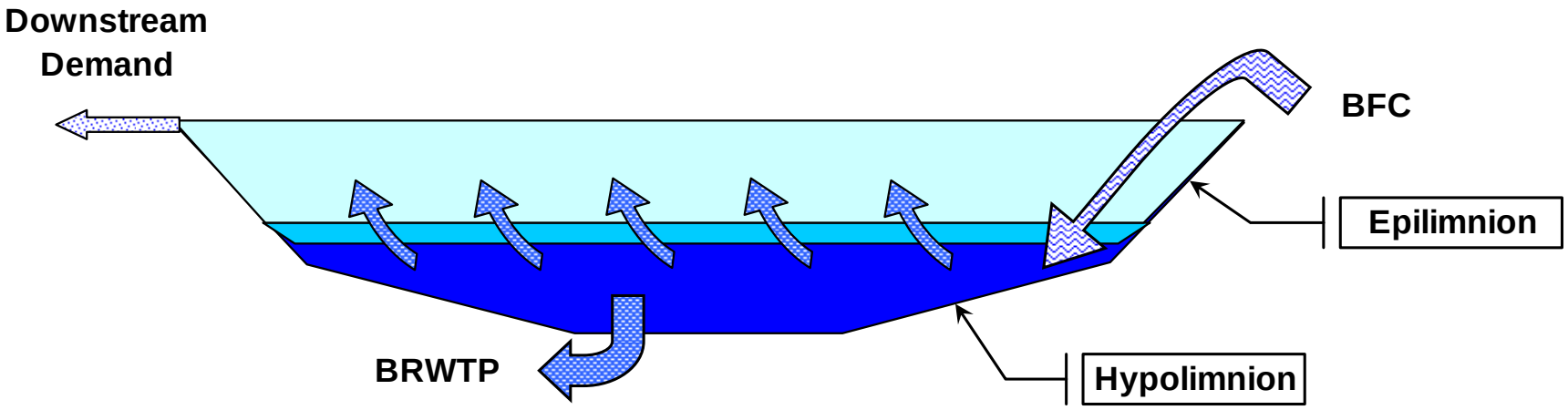
Microbial Energy Generation through Preferential Respiration with Inorganic Terminal Electron Acceptors

Figure 2-11



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Hydraulics of Thermally Generated Vertical Stratification in Boulder Reservoir

Figure 2-12

implement mid-term and long-term improvements to BRWTF identified in previous studies were noted, as described in the following sections.

1. pH

BRWTF finished water pH varied between 7.15 and 8.78 s.u. during the period of data reviewed, as shown on Figure 2-13.

2. TOC Removal

Historical TOC removal at BRWTF was reviewed as summarized in the following.

- BRWTF has consistently met the TOC removal mandated by the Stage 1 Disinfectants and Disinfection Byproducts Rule based on the running annual average (RAA) of quarterly values, as illustrated on Figure 2-14.

- Since mid 2002 the RAA TOC removal at BRWTF has declined. Several individual monthly values were below the required RAA.

3. Disinfection Byproduct Formation

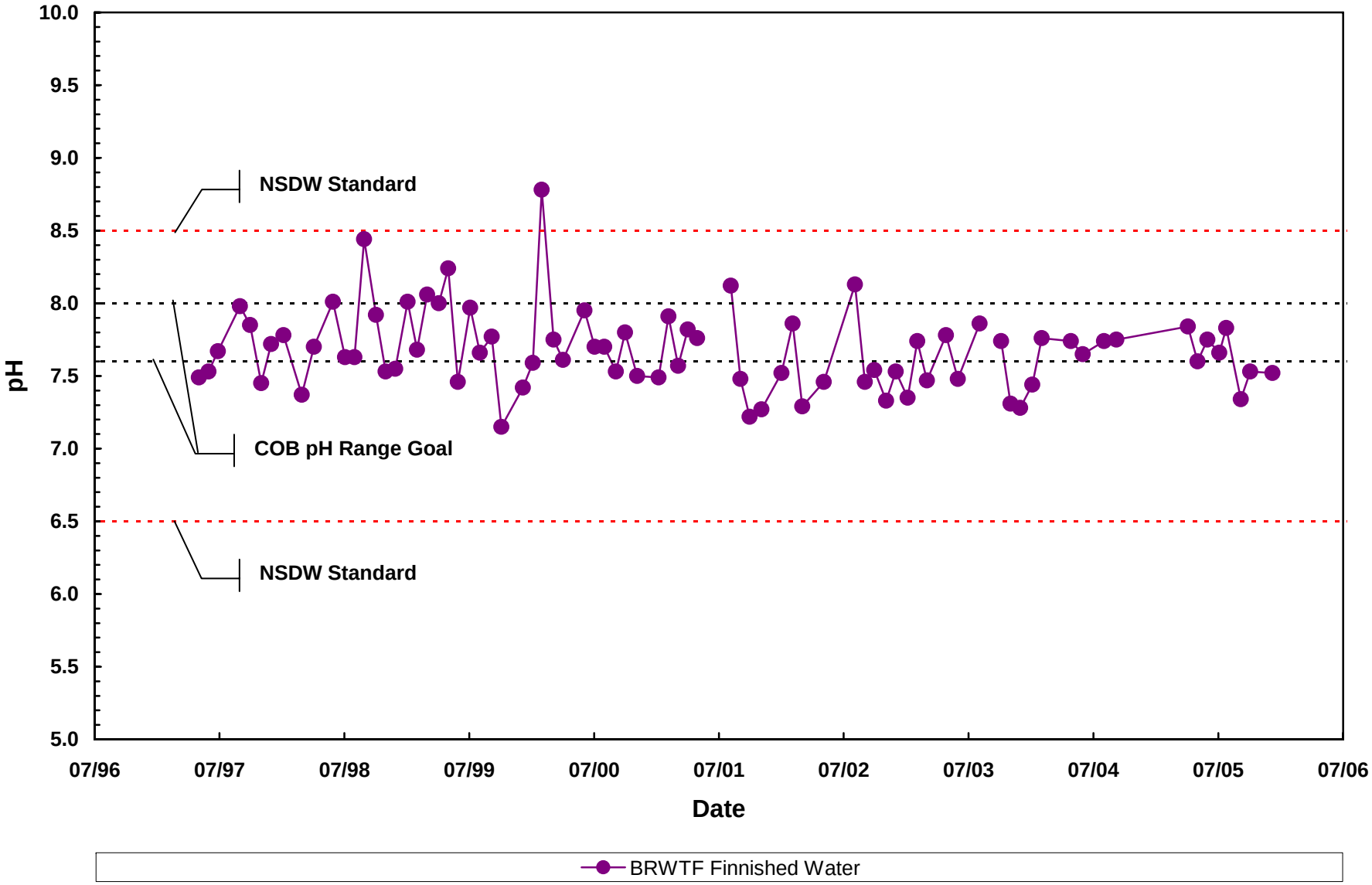
Formation of currently regulated disinfection byproducts that result from chlorination of drinking water was reviewed, as summarized below.

- Trihalomethane and haloacetic acid formation in areas served by BRWTF followed a seasonally recurring pattern with highest concentrations occurring in mid to late summer, as shown in Figure 2-15 and 2-16, respectively.

- Both trihalomethane and haloacetic acid formation show increasing trends in peak concentration since mid-2002, which correlates with the trend of decreasing TOC removal previously noted.

4. Total Dissolved Solids and Sulfate

Review of total dissolved solids and sulfate data for BRWTF finished water reveal the following:



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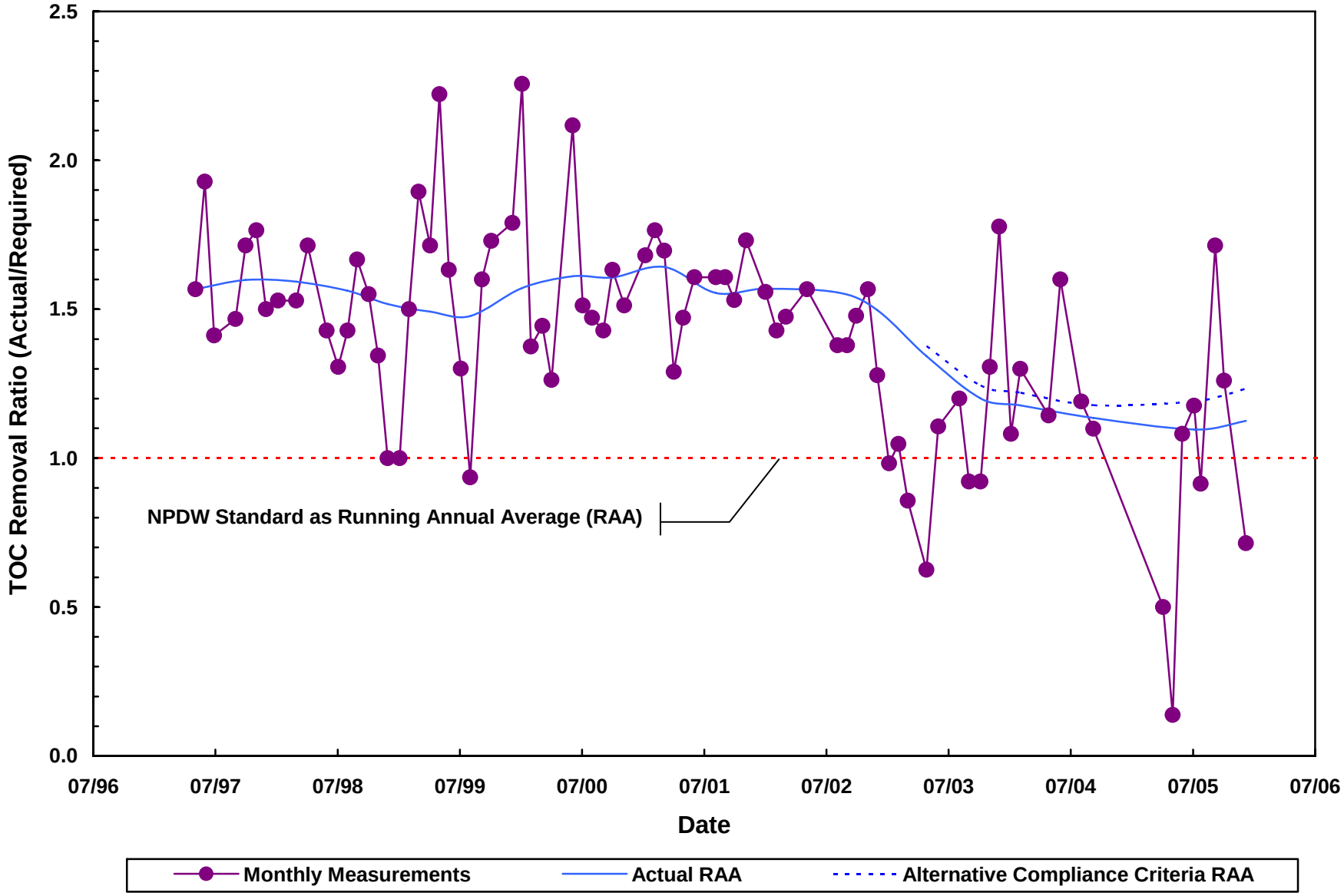
Boulder Reservoir Water Treatment Facility Finished Water pH

Figure 2-13



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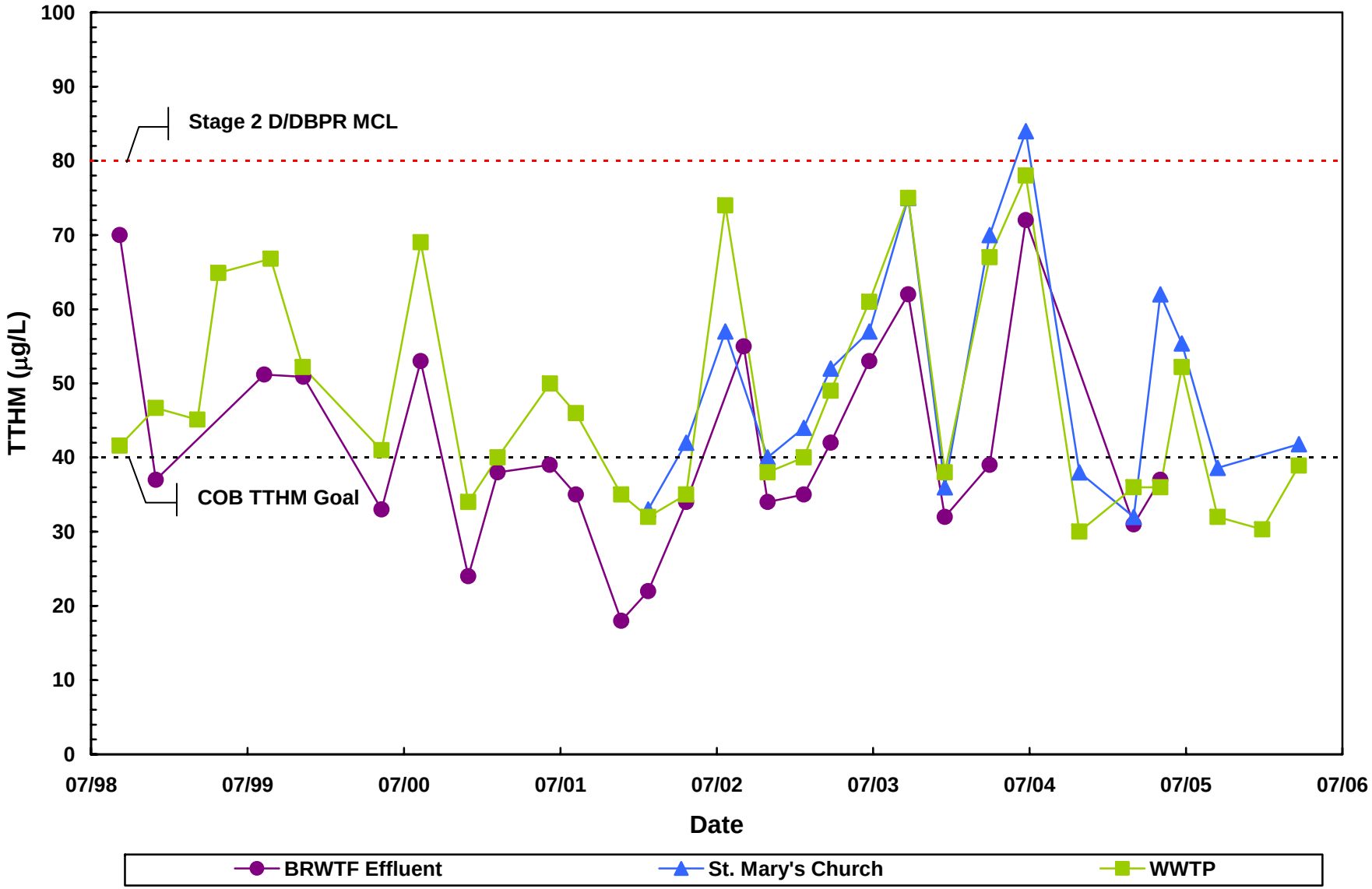
Boulder Reservoir Water Treatment Facility TOC Removal

Figure 2-14



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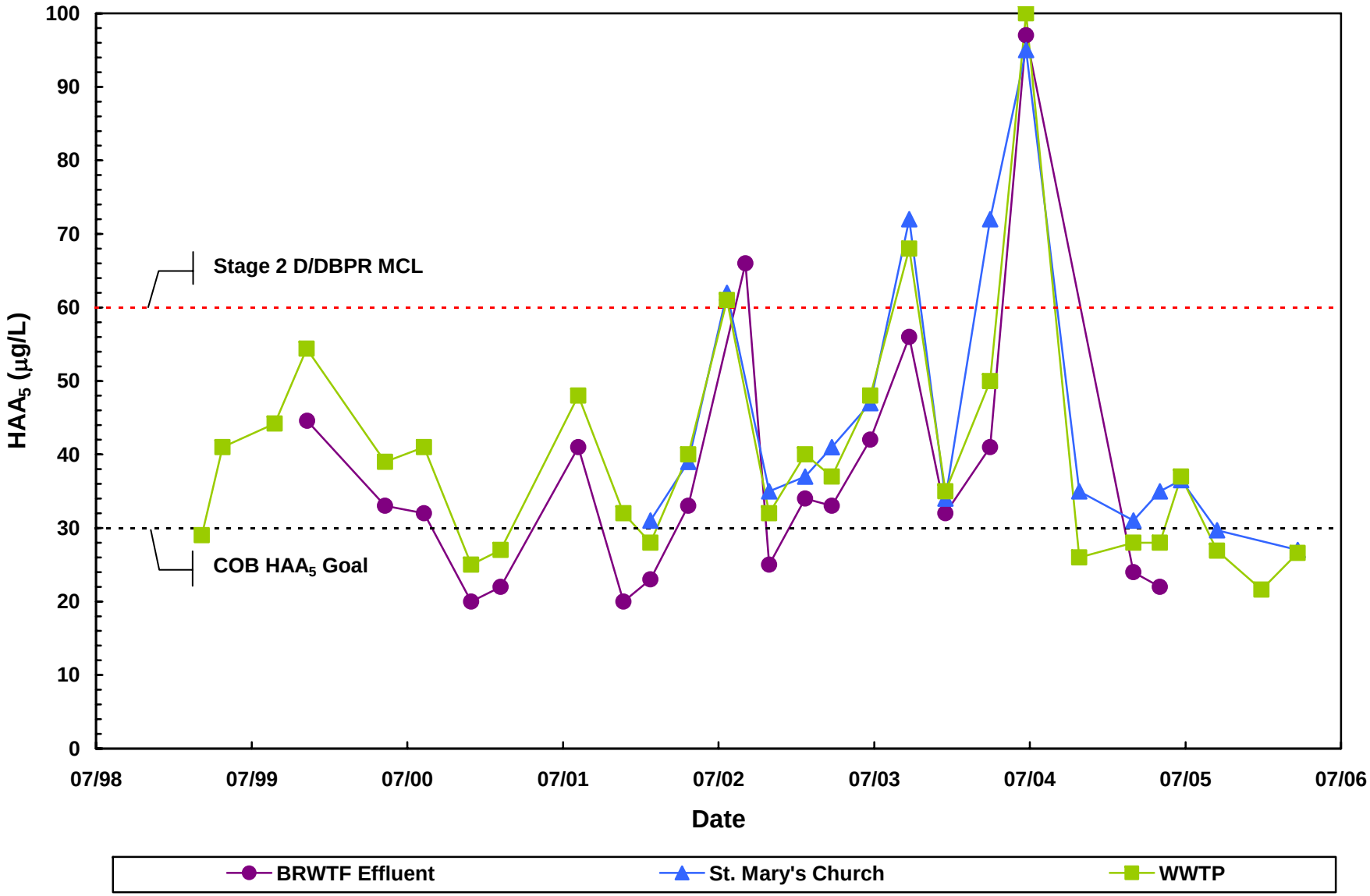
Boulder Reservoir Water Treatment Facility Finished Water TTHM

Figure 2-15



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Boulder Reservoir Water Treatment Facility Finished Water HAA5

Figure 2-16

- TDS and sulfate levels in BRWTF finished water vary throughout the year, with peak concentrations in late winter to early spring, as shown on Figure 2-17.

- Because there are no treatment processes for inorganic ion removal currently installed at BRWTF, TDS and sulfate concentrations in finished drinking water essentially mirror those of BFC and Boulder Reservoir source waters.

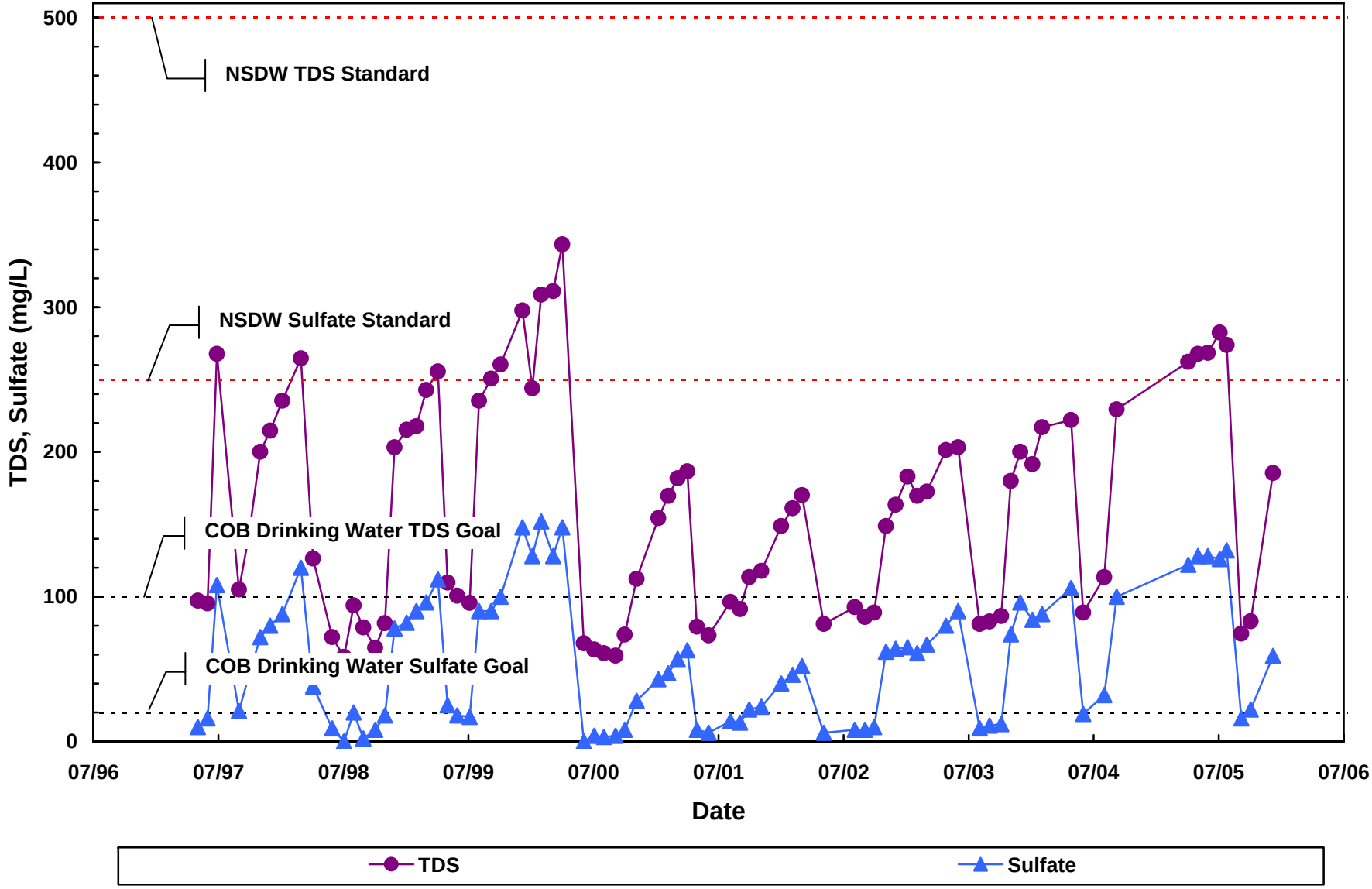
E. Summary of BRWTF Source Water Quality

Based on review and extensive analysis of existing biological, physical, and chemical water quality data, *B&V believes that Carter Lake has superior overall water quality as a raw water source for BRWTF compared with BFC and Boulder Reservoir.*

1. Microbial Source Water Quality Data

The microbial quality of water conveyed directly to the BRWTF through the BFC is at risk, with potential for high levels of fecal matter as a result of acute contamination episodes. Routine water quality monitoring of BFC has demonstrated an increasing trend in fecal coliform contamination between 1997 and 2003. *Giardia* has routinely been detected in BFC water, and *Cryptosporidium* has been detected occasionally. Protozoan contamination in Boulder Reservoir has been detected at much lower concentrations compared to BFC. Based on samples collected from BFC and Boulder Reservoir between 1997 and 2004, the BRWTF would fall into bin 1 under the LT2ESWTR, requiring no additional treatment for *Cyptosporidium.* Coliform bacteria and protozoan pathogen levels in Carter Lake have routinely been at or below their respective method detection limits.

Caution should always be exercised when interpreting protozoan monitoring results, particularly in untreated surface waters, where turbidity and suspended solids may interfere with (oo)cyst recovery. Effective detection of protozoa in natural waters requires separation from aggregated colloids and particles as well as other particles of similar size. The filtration technique used in



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Boulder Reservoir Water Treatment Facility Finished Water TDS and Sulfate

Figure 2-17

early Information Collection Rule monitoring was notoriously unreliable for protozoan recovery and results based on this method are highly suspect. The immunomagnetic separation technique used in EPA Method 1623 is somewhat more reliable, but protozoan recovery from spiked natural water samples using this technique is still routinely less than 50 percent. Finally, routine monitoring samples only a very small fraction of 1 percent of total flow through BFC and Boulder Reservoir, making the probability of capturing transient protozoan contamination events unlikely.

2. Physical and Chemical Source Water Quality Data

Analysis of biological, physical, and chemical source water quality data collected in Boulder Reservoir between 1997 and 2004 indicates mesotrophy, (moderate nutrient levels) consistent with increased probability of algal blooms and seasonal development of anoxic conditions at depth in the reservoir. Anoxia in the reservoir hypolimnion can be correlated with microbially mediated release of soluble manganese from bed sediment, which could in turn be entrained in water supplied to the BRWTF through a submerged intake structure. In contrast, Carter Lake is classified as oligotrophic (low nutrient levels) consistent with low potential for algal blooms. Anoxic conditions in the hypolimnion of Carter Lake have not been observed.

3. BRWTF Operational Water Quality Data

Review of operational data from BRWTF demonstrates trends of decreasing TOC removal and increasing disinfection byproduct formation since mid-2002. Because of the forthcoming shift from system-wide running annual average to locational running annual average calculation of disinfection byproduct concentrations for compliance purposes, the potential impacts of mid-term and long-term improvements on TOC removal and DBP formation should be carefully considered.

F. Sustainability of Carter Lake as a BRWTF Source

There will undoubtedly be seasonal and annual changes in Carter Lake water quality in response to climactic conditions. However, 35 years of historical data for Carter Lake do not indicate any long-term degradation in the overall

water quality from this source. *B&V believes that the water quality of Carter Lake will continue to be suitable as a water source for BRWTF for decades to come.* The following sections discuss our views on the future water quality of Carter Lake.

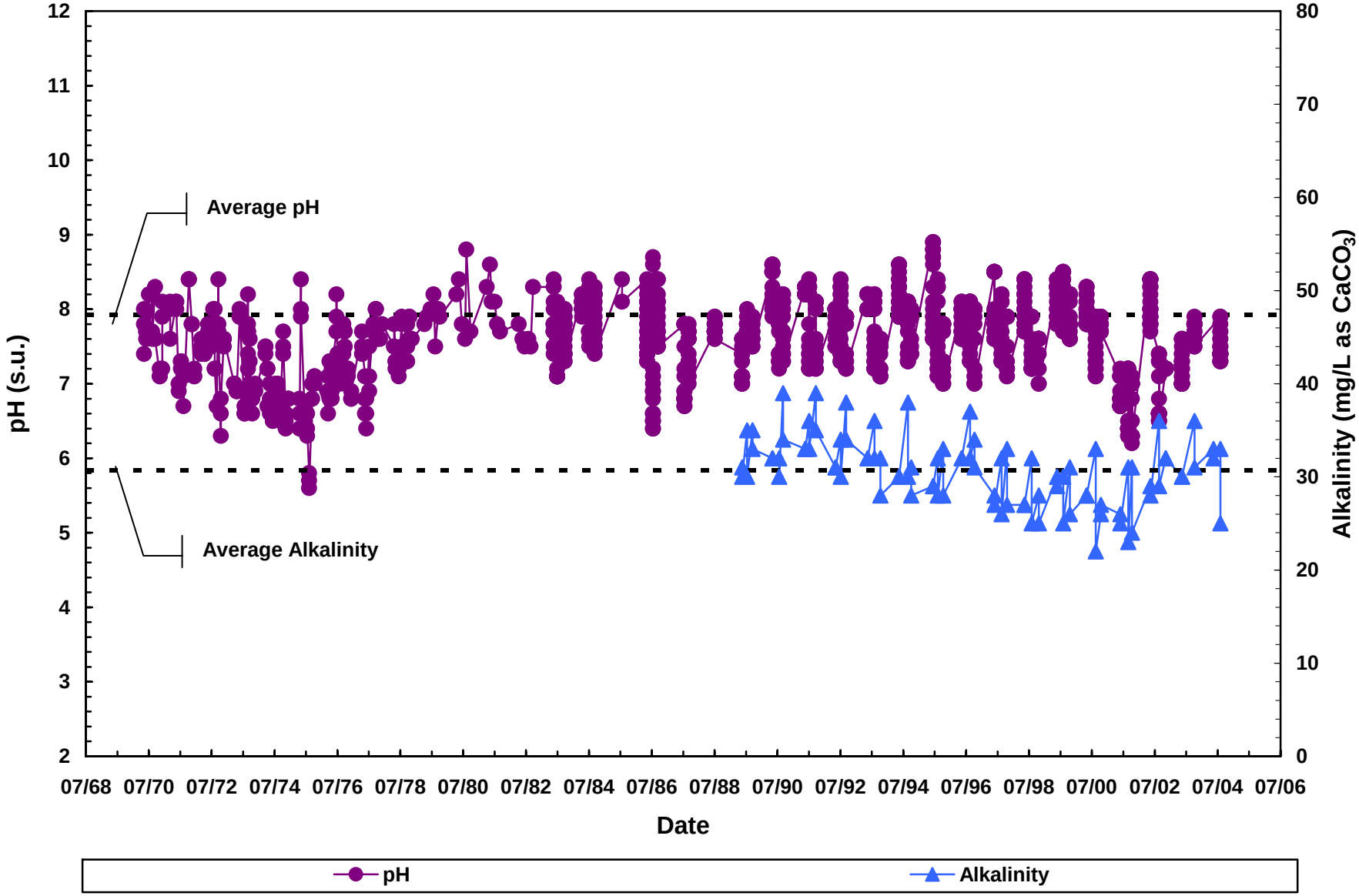
1. Physical and Chemical Water Quality Trends

Important water quality parameters including pH, alkalinity, and hypolimnetic oxygen concentration have not shown any deteriorating trends with time, as shown in Figures 2-18 and 2-19. The minimum recorded hypolimnion oxygen concentration in Carter Lake is approximately 3 mg/L, indicating that fully anoxic conditions associated with taste and odor and soluble iron or manganese issues do not occur in Carter Lake. Total dissolved solids (TDS) and dissolved sulfate have shown a slight decreasing trend based on historical data (Figure 2-1), indicating improving water quality.

2. Trophic Status

Perhaps the best indicator of the overall water quality of a lake is its trophic status, which reflects the biological productivity in the water body. Biological productivity in a water body is frequently classified based on potential for algal growth, which if excessive may lead to rapid seasonal changes in water quality. Lakes and reservoirs are classified as oligotrophic, mesotrophic, eutrophic, or hypereutrophic based increasing potential for excessive algal growth or seasonal algal “blooms”. A number of trophic status indices (TSI) have been proposed based on a single or multiple water quality parameters as measures of algal biomass, including Secchi depth (water clarity), total phosphorus level, and chlorophyll *a*.

Historical trends for Secchi depth, total phosphorus, and chlorophyll *a* in Carter Lake have not shown any tendency toward lower water quality, as shown in Figures 2-20 through 2-22. Of these parameters, chlorophyll *a* is the most direct indication of algal biomass. Carter Lake would be classified as oligotrophic based on chlorophyll *a* content, with a low potential for water quality degradation due to algal blooms (Figure 2-22).



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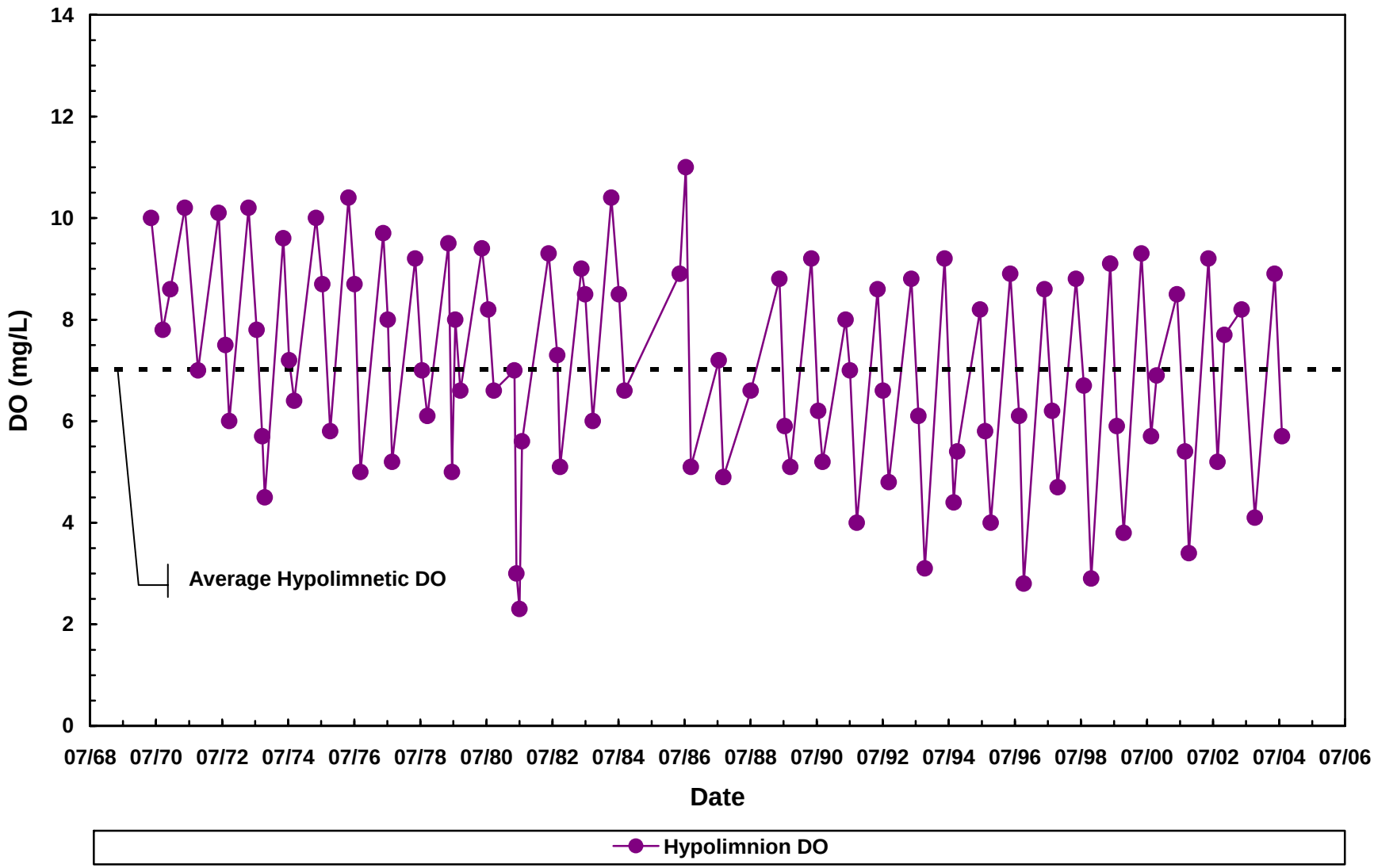
pH and Alkalinity in Carter Lake

Figure 2-18



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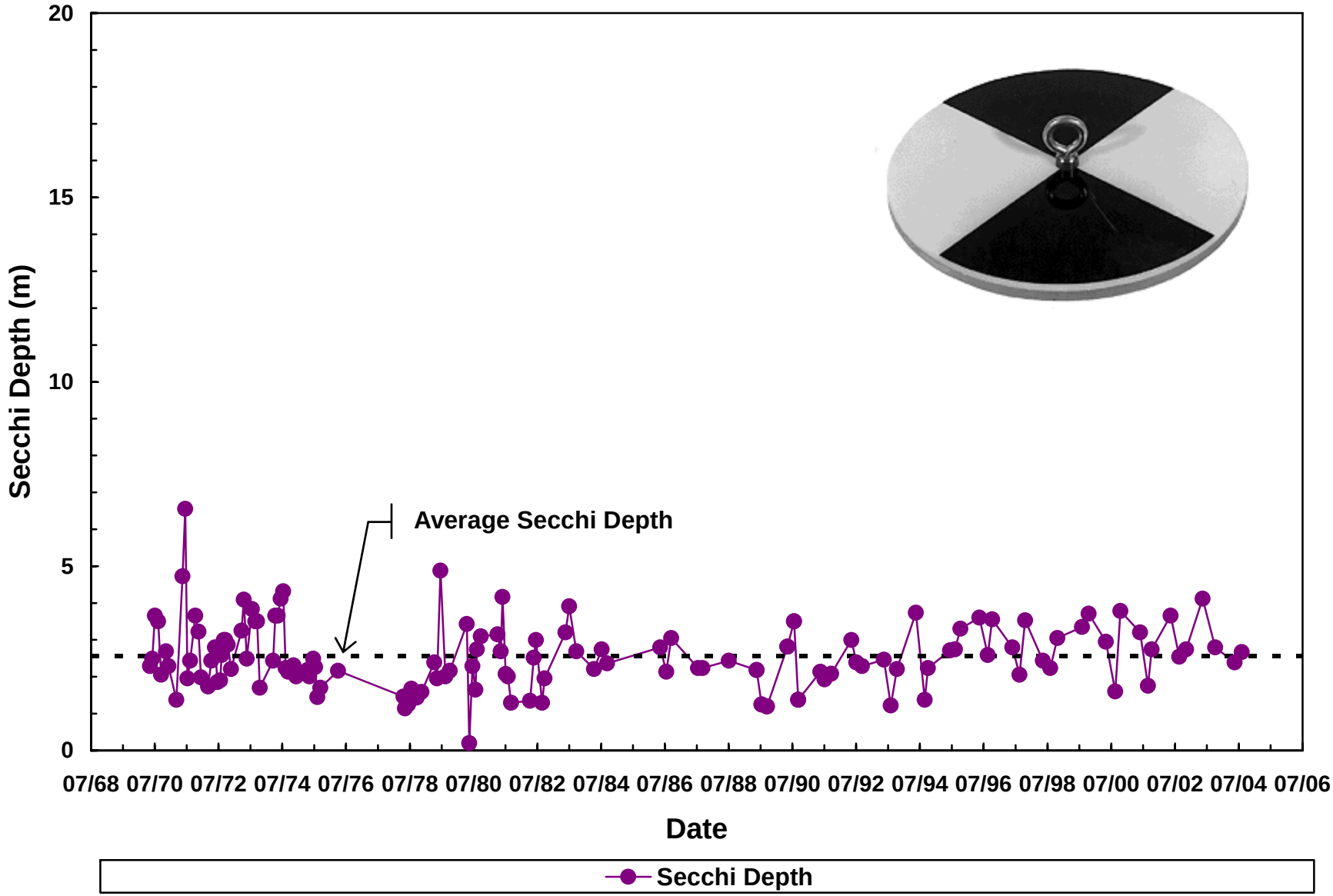
Hypolimnetic Dissolved Oxygen in Carter Lake

Figure 2-19



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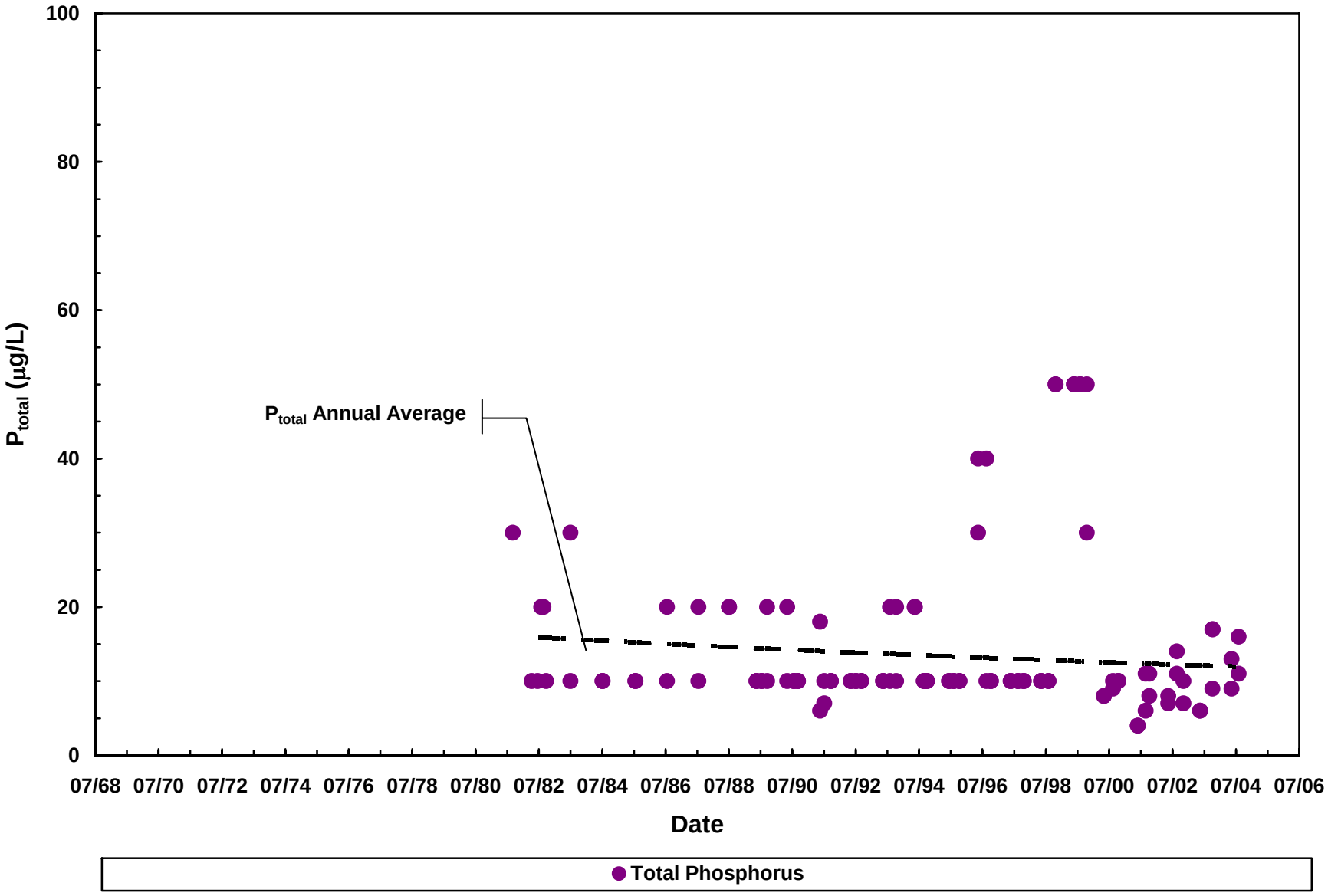
Secchi Depth in Carter Lake

Figure 2-20



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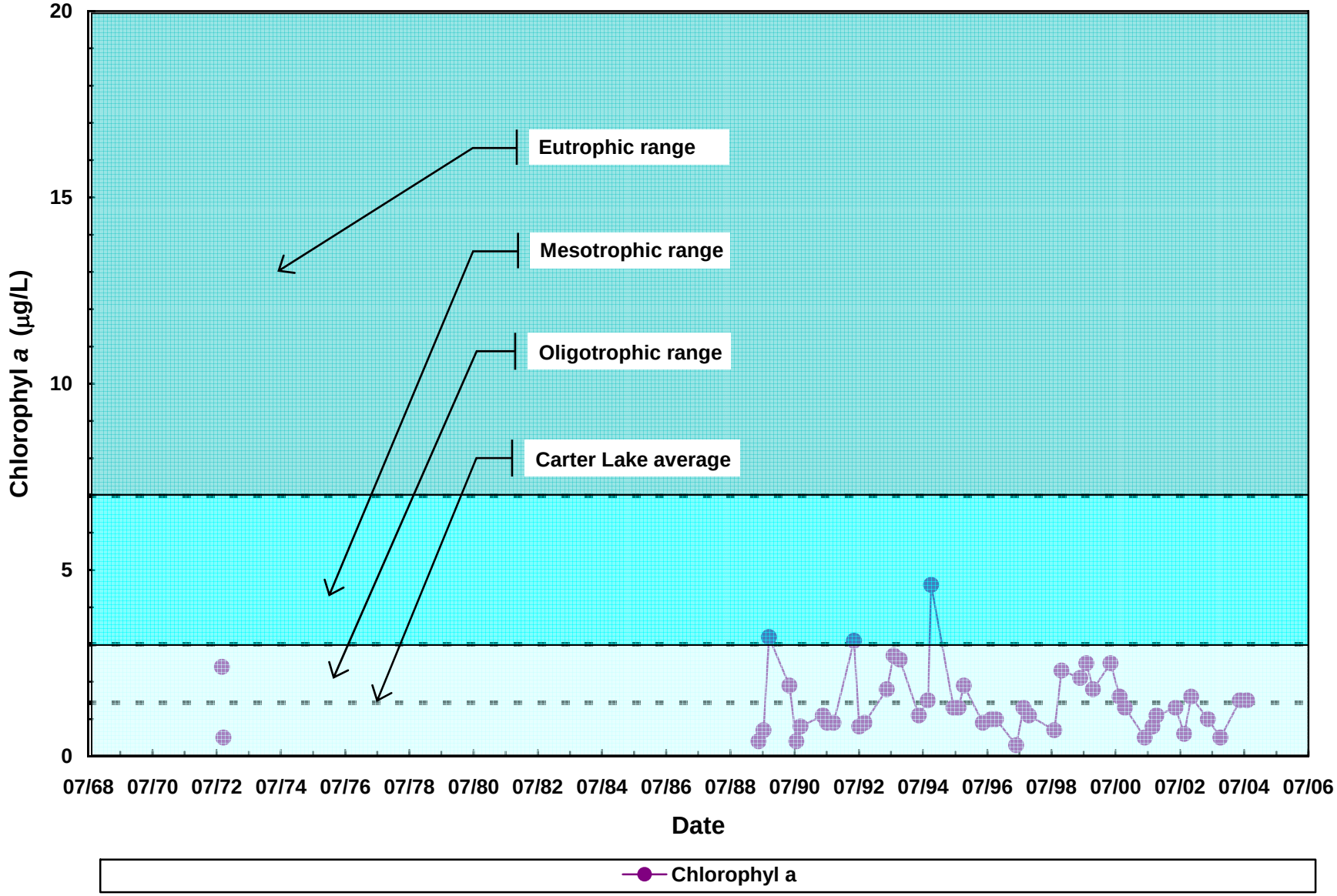
Total Phosphorus in Carter Lake

Figure 2-21



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Chlorophyll *a* in Carter Lake

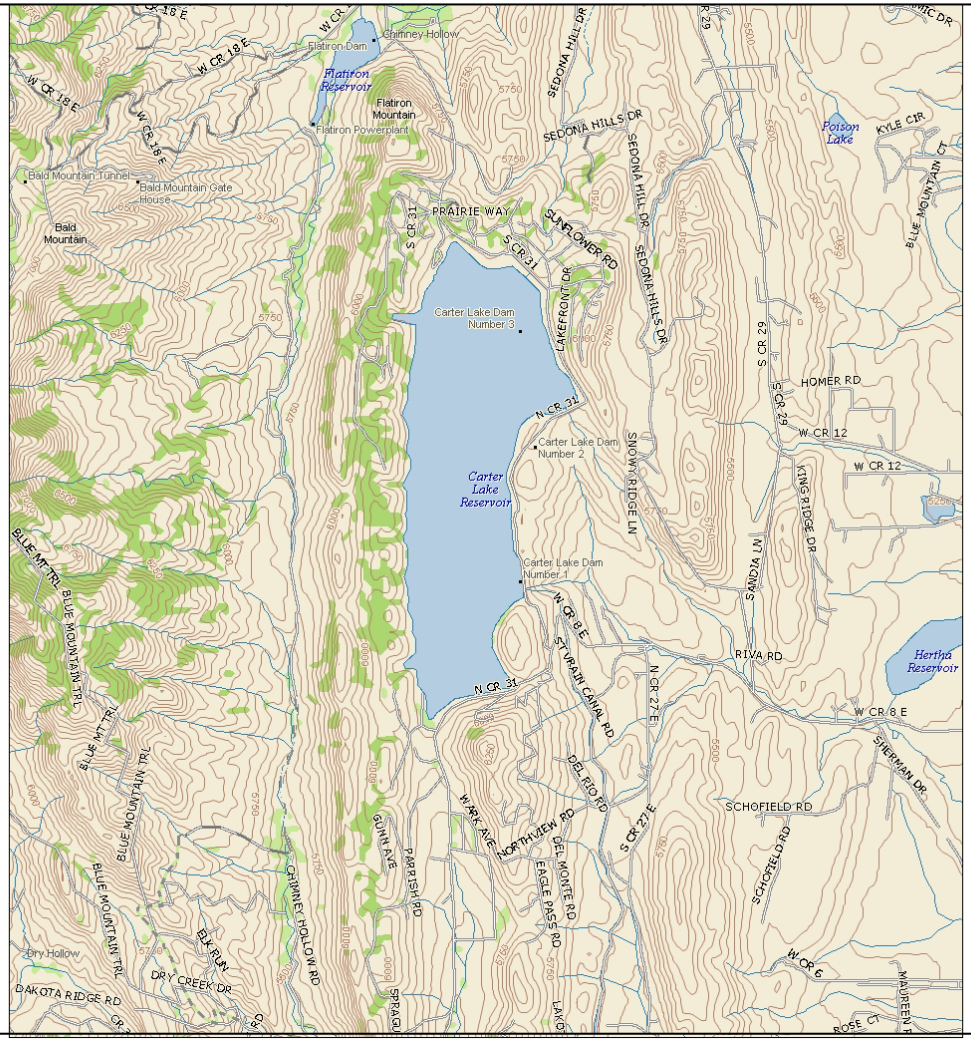
Figure 2-22

3. Watershed Protection

Carter Lake has a well protected watershed with minimal potential for future water quality degradation due to point or non-point contaminant sources. Two dams form Carter Lake in a natural depression in topography, resulting in a very small watershed, as shown in Figure 2-23. The lake is surrounded by steep forested terrain and has no natural tributaries. Much of the surrounding land resides in protected forests, parks, and recreational areas. Lands bordering Carter Lake are also not suitable for large scale agricultural concerns, and natural topography is not amenable to large scale industrial operations. Carter Lake has a capacity of 112,230 ac-ft providing a large dilution volume for any contaminant introduced directly or from surface runoff. Long-term water quality degradation due to concentration of point or non-point contaminant inputs is mitigated by seasonal water use, with greater than 50 percent annual turnover in the lake being typical.

The Colorado-Big Thompson (CBT) Project supplies water to Carter Lake through a series of reservoirs, lakes, tunnels, and conduits. As such, the water quality in Carter Lake is to a large extent dependent on water quality in upstream waterbodies including Flatiron Reservoir (760 ac-ft), Pinewood Reservoir (2,181 ac-ft), Lake Estes (3,068 ac-ft), Mary's Lake (927 ac-ft), Grand Lake/Shadow Mountain Reservoir (17,354 ac-ft), and ultimately Lake Granby (539,800 ac-ft), as shown on Figure 2-24. Flatiron and Pinewood Reservoirs have similar topographic features as Carter Lake and are located in undeveloped areas. Lake Estes has natural inflow from the Big Thompson River water shed in Rocky Mountain National Park and CBT flow from Mary's Lake. Mary's Lake has no measurable natural inflow and receives CBT water from Grand Lake via the Alva B. Adams Tunnel. Grand Lake is surrounded by Rocky Mountain National Park on three sides and Shadow Mountain Reservoir on the fourth. CBT water collected on the West Slope is pumped to Grand Lake through Shadow Mountain Reservoir.

Because of the native topography and protected status of much of the land surrounding the CBT Lakes and Reservoirs that ultimately supply Carter Lake, B&V believes that municipal, agricultural, or industrial development on the scale necessary to substantially degrade water quality in the CBT watershed is not likely during the 30-year planning horizon of our study. Although



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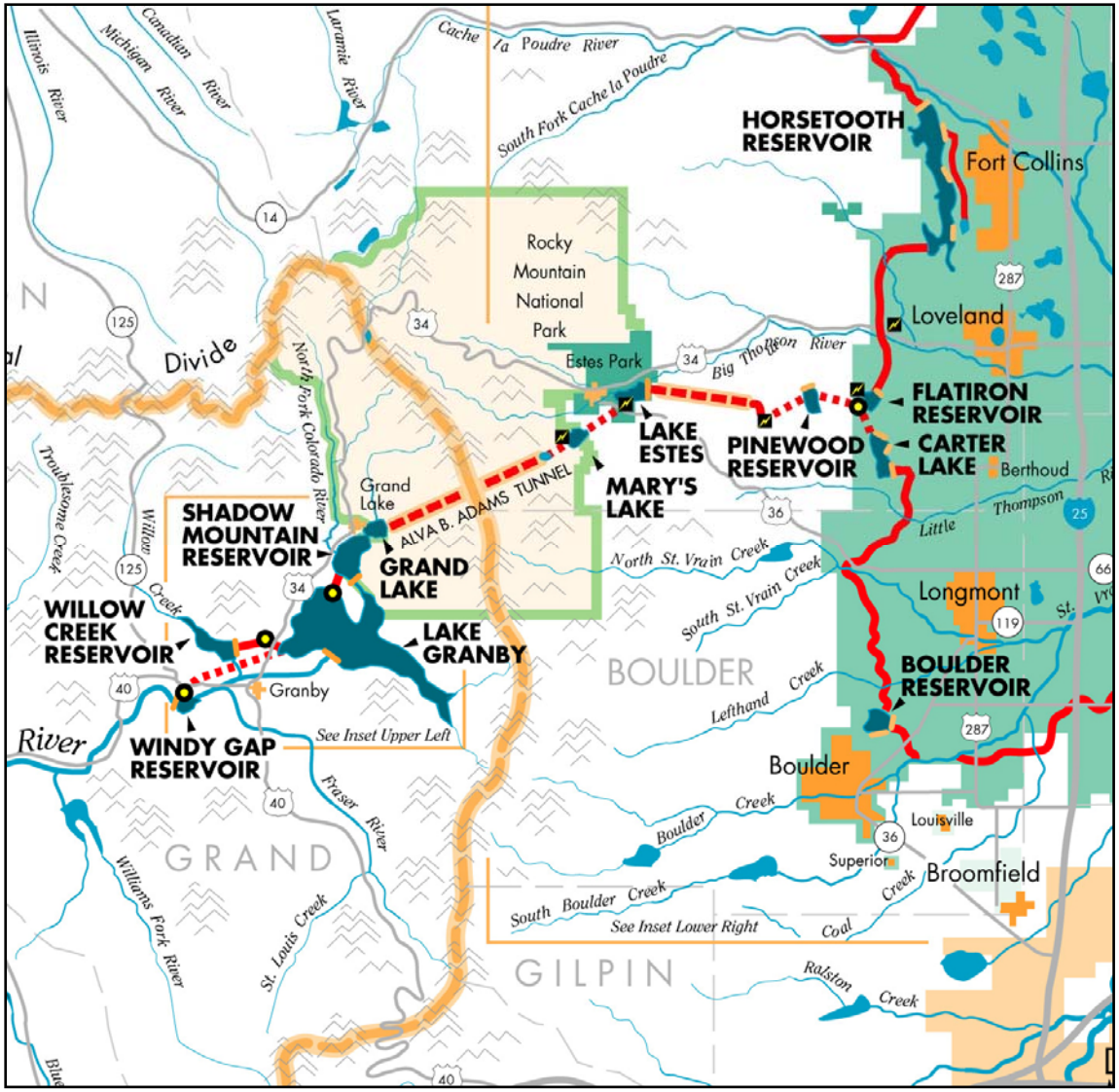
Carter Lake Watershed Topography

Figure 2-23



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Colorado-Big Thompson Project Supply to Carter Lake

Figure 2-24

development will undoubtedly continue in selected locations adjacent to CBT facilities, most notably Estes Park and Grand Lake, natural topography will tend to limit this growth and any potential adverse impact it might have on CBT water quality.

4. CBT System Operation

The operational practices used by The Northern Colorado Water Conservancy District to manage the water supply in the CBT system also tend to mitigate any impacts of seasonal water quality fluctuations in upstream reservoirs and Lakes on water quality degradation in Carter Lake. The vast majority of CBT water transferred to Carter Lake in any water year occurs during the winter and early spring, when water quality is not affected by temperature stratification, algal blooms, or hypolimnetic oxygen depletion in the upstream lakes and reservoirs. Furthermore, the large storage volumes and detention times of the CBT supply system to Carter Lake provide the opportunity for substantial natural attenuation of micropollutants that could potentially enter from intentional or unintentional sources.

5. Potential for Contamination by Pathogens

The potential for future contamination of CBT water by pathogenic protozoa such as *Giardia* and *Cryptosporidium* is an important consideration regarding the need for additional treatment at BRWTF. B&V believes that there is a low probability that pathogenic protozoa concentrations in CBT water delivered to Carter Lake will increase substantially during the 30-year planning horizon of our study. Protozoa such as *Giardia* and *Cryptosporidium* do not reproduce outside of an animal host, and therefore do not independently multiply in natural waters. Contamination of natural waters by *Giardia* and *Cryptosporidium* occurs through input of human fecal matter in inadequately treated municipal and domestic wastewater, or animal fecal matter from wildlife or domestic livestock. There are currently four municipal wastewater treatment facilities permitted by USEPA located in the CBT watershed area, which serve a combined population of approximately 20,000 people. B&V is unaware of any water quality monitoring data that would suggest that these facilities are currently releasing discharges to the CBT system that result in *Cryptosporidium*

concentrations above natural background levels (LT2ESWTR bin 1). Based on topography and protected surrounding land uses B&V believes that it is unlikely that a concentrated animal feeding operation of sufficient magnitude to negatively impact CBT water quality will be located in the CBT watershed. Based on the size of the CBT system we also believe that there is a negligible possibility of substantial and widespread *Cryptosporidium* contamination of CBT water from wildlife fecal matter.

Chapter 3

Delivery Alternative Contaminant Barriers

This chapter describes the different categories of contaminant barriers, defined by regulatory requirements and City finished water quality goals, for drinking water produced at BRWTF with each of the source waters considered in this study. The two water sources for BRWTF considered here were (1) seasonal use of the BFC and Boulder Reservoir and (2) direct conveyance to BRWTF through a dedicated pipeline. These two sources provide distinctly different raw water quality to BRWTF as discussed in Chapter 2, which impacts the combination of drinking water treatment processes that best addresses contaminant barriers in a cost-effective multi-barrier water delivery approach.

The BRWTF currently meets or exceeds all National Primary and Secondary drinking water regulations during routine operation, and based on source water quality data reviewed in Chapter 2, will likely continue to do so for the foreseeable future. However, finished water quality in areas served by BRWTF is vulnerable to short-term degradation due to seasonal variation in Boulder Reservoir water quality and acute contamination episodes in either BFC or Boulder Reservoir. Of particular concern are microbial contamination in BFC or Boulder Reservoir, DBP formation during treatment and distribution, contamination by organic micro-pollutants in BFC and Boulder Reservoir, seasonal manganese uptake, taste or odor episodes in Boulder Reservoir, and non-uniform total dissolved solids (TDS) and sulfate concentration across the distribution system when BRWTF uses Boulder Reservoir as its source.

Because these factors pose a potential threat to drinking water quality, the City has established drinking water quality goals that are in some instances more stringent than state or federal regulatory requirements to ensure public health. Appendix 1 lists the City's water quality goals. For the purposes of this study, the minimum contaminant barrier requirements were those specified by enforceable USEPA and CDPHE Primary Drinking Water Standards. Contaminant barriers associated with Secondary Drinking Water Standards and City drinking water quality goals were also evaluated in this report. However, the contaminant

barriers considered were not required to completely satisfy these non-enforceable secondary standards in all cases, largely for compelling economic reasons.

A. Barriers for Microbial Pathogen Control

Over the past two decades the Environmental Protection Agency (EPA) has issued a series of increasingly stringent Drinking Water Regulations designed to protect the public from microbial pathogens such as viruses, *Giardia*, and *Cryptosporidium* that may be present in surface water supplies. Because turbidity is often used as an indicator of microbial water quality, it is also regulated in drinking water produced from surface water sources. Relevant regulations include the Surface Water Treatment Rule (SWTR), Interim Enhanced Surface Water Treatment Rule (IESWTR), LT1ESWTR, and most recently the Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR). Each rule specifies treatment techniques required to achieve specified levels of physical removal or inactivation of specific microbial pathogens in drinking water.

1. Overview

Turbidity in water is caused by suspended particles that scatter or absorb incident light, thereby reducing the water's clarity. Soil and mineral weathering products and microorganisms including bacteria, algae, and protozoa are the principal sources of turbidity in natural waters, either occurring naturally or as the result of agricultural, municipal or industrial activity. The IESWTR established a combined filter effluent (CFE) limit for turbidity of less than or equal to 0.3 nephelometric turbidity units (NTU) in at least 95 percent of monthly samples and a limit of 1 NTU for all samples, with additional limits on individual filter effluent (IFE) turbidity. The City has set internal water quality goals for turbidity of less than or equal to 0.1 NTU in at least 95 percent of all IFE samples and less than 0.15 NTU for all CFE samples.

Turbidity removal is perhaps the oldest form of drinking water treatment, traditionally relying on clarification and granular media filtration. Standard practice now includes chemical pre-treatment that modifies particle surface chemistry to improve removal. Enhanced clarification processes such as

ballasted flocculation and dissolved air flotation (DAF), as well as membrane filtration are also now being used to for turbidity removal.

Based on an improved understanding of *Cryptosporidium* occurrence in surface waters and treatment process limitations, LT2ESWTR has established risk-targeted log-removal/inactivation levels for *Cryptosporidium* in addition to those specified in earlier rules. The primary purposes of this rule are to protect public health from illness due to *Cryptosporidium* and other microbial pathogens in drinking water and to address risk-risk trade-offs with the control of disinfection byproducts. Because this regulation links the required level of drinking water treatment with source water quality, a careful evaluation of source water protection and treatment options is required to ensure public health protection and regulatory compliance.

LT2ESWTR classifies source water quality into four bins based on average *Cryptosporidium* concentration and treatment type, and specifies associated levels of additional treatment required. Table 3-1 lists the required levels of additional treatment for WTPs that utilize conventional treatment consisting of chemical coagulation, flocculation, clarification, and granular media filtration.

Table 3-1

LT2ESWTR Cryptosporidium Treatment Requirements for Conventional WTPs

Bin Designation	Cryptosporidium Concentration (oocysts/L)	Additional Removal/Inactivation Treatment Required
1	Less than 0.075	None
2	0.075 or higher, but less than 1.0	1-log
3	1.0 or higher, but less than 3.0	2-log
4	3.0 or higher	2.5-log

As a public water system serving a population greater than 100,000, the City is required to conduct 24 months of initial source water monitoring beginning in October 2006, or submit grandfathered existing monitoring data to establish average *Cryptosporidium* concentrations for LT2ESWTR bin determination at BRWTF. Historical *Cryptosporidium* monitoring data for Carter Lake, BFC, and Boulder Reservoir collected between 1997 and 2006 indicate that these source waters would be classified in Bin 1 with respect to LT2ESWTR compliance, requiring no additional treatment for *Cryptosporidium*. However, if grandfathered existing data were not accepted by the regulatory primacy agency, then LT2ESWTR bin classification would be based on the results of additional source water monitoring. If these additional monitoring data were to indicate substantially higher *Cryptosporidium* levels in either BFC or Boulder Reservoir than historical levels, additional *Cryptosporidium* treatment requirements at BRWTF could be triggered.

As part of its water quality goal setting process, the City has determined that a minimum of one additional log-removal/inactivation of microbial pathogens above regulatory requirements is prudent to protect public health. Table 3-2 lists the required and target log-removal/inactivation for regulated microbial pathogens based on meeting federal regulations and City water quality goals.

Table 3-2

Required and Target Log-Removal/Inactivation for Regulated Microbial Pathogens

Regulation/Goal	Pathogen		
	Viruses	***Giardia***	***Cryptosporidium***
Regulatory Requirement	4	3	3[(1)]
City Goal	5	4	5[(2)]

[(1)]Assumes LT2ESWTR Bin 1 classification.
[(2)]Provides for potential BFC and Boulder Reservoir LT2ESWTR bin 2 classification.

2. Existing Barriers for Microbial Pathogen Control

BRWTF utilizes chemical pre-treatment, DAF, and granular media filtration for turbidity control. Historical operating data indicates turbidity in finished water from BRWTF has exceeded the City's goal 0.1 NTU 14 percent of the time. Existing barriers for microbial pathogen control in place at BRWTF include conventional treatment (coagulation, flocculation, dissolved air floatation, and filtration) and chemical disinfection with free-chlorine. The presumptive log-removal/inactivation of viruses, *Giardia*, and *Cryptosporidium* credited to conventional treatment under the SWTR and IESWTR are listed in Table 3-3. The balance of virus and *Giardia* treatment required under the SWTR is currently provided by chemical disinfection with free-chlorine.

Table 3-3

Regulatory Requirements and Additional Pathogen Removal/Inactivation to Meet City Goals at BRWTF

Pathogen	Conventional Treatment	Disinfection	Regulatory Requirement	Additional Needed to Meet City Goal
Viruses	2	2	4	1
Giardia	2.5	0.5	3	1
Cryptosporidium	3	--	3*	2*

* Assumes LT2ESWTR Bin 1 classification.

3. Potential Additional Barriers for Microbial Pathogen Control

The LT2ESWTR Microbial Toolbox is a list of potential treatment options for additional *Cryptosporidium* removal/inactivation, as given in Table 3-4. Table 3-4 also gives a preliminary evaluation of the potential applicability of these techniques at BRWTF. Because of the pristine microbial quality of Carter Lake is low (Chapter 2, Section C.1.a), full containment of source water in a dedicated pipeline to BRWTF would also provide an additional barrier.

Table 3-4

LT2ESWTR Microbial Toolbox

Treatment Technique	Removal/ Inactivation Credit	Applicability	Comments
Source Water Protection and Management			
Watershed Control Program	0.5	Likely	Treatment cost avoidance and direct credit
Prefiltration			
Presedimentation and Coagulation	0.5	Possible	Reduces acute loading to BRWTF
Two-Stage Lime Softening	0.5	Unlikely	Not required by source water hardness
Bank Filtration	0.5 – 1.0	Possible	Boulder Reservoir delivery alternative
Treatment Performance			
Combined Filter Performance	0.5	Likely	Presumptive operational credit
Individual Filter Performance	0.5	Likely	Presumptive operational credit
Demonstration of Performance	Variable	Unlikely	Requires state approved protocol
Additional Filtration			
Bag and Cartridge Filters	2.0 singly, 2.5 in series	Possible	Additional pumping, small footprint
Membrane Filtration	Demonstrated removal efficiency	Possible	Retrofit in existing filter boxes
Second Stage Filtration	0.5	Unlikely	Additional pumping likely
Slow Sand Filtration	2.5 – 3.0	Unlikely	Additional pumping likely
Inactivation			
Chlorine Dioxide	Based on measured CT	Likely	Manganese and taste & odor control
Ozone	Based on measured CT	Likely	Manganese and taste & odor control
UV	Based on validated UV dose	Likely	Advanced oxidation of EDCs with H_2O_2

B. Barriers for Disinfection Byproduct Control

DBPs are compounds formed during drinking water treatment through reaction of chemical disinfectants with either organic or inorganic constituents present in the source water.

1. Overview

The most widespread and well documented class of DBPs is halogenated organic compounds formed by reaction of free-chlorine and natural organic matter. Typically, only 30 to 60 percent of halogenated organic DBPs are chemically identifiable, with trihalomethanes (THMs) and haloacetic acids (HAAs) occurring in the highest concentrations. The Stage 2 Disinfectants and Disinfection Byproduct Rule (Stage 2 DBPR) standards for total THMs and five HAAs (HAA_5) are 80 and 60 micrograms per liter (μg/L), respectively, measured as locational running annual averages (LRAAs) at each monitoring site. The City has set internal water quality goals of 40 μg/L and 30 μg/L for THMs and HAAs as LRAAs, respectively.

Disinfection of drinking water with ozone leads to formation of low-molecular weight organic byproducts through oxidation of NOM, and bromate (BrO_3^-) by oxidation of bromide (Br^-). The organic by-products are primarily aldehydes, ketoacids, and carboxylic acids that are not currently believed to pose a health hazard and are therefore not regulated in drinking water. Bromate is believed to be a human carcinogen and is currently regulated by the Stage 1 Disinfectants and Disinfection Byproduct Rule (Stage 1 DBPR) at 10 μg/L, with a future maximum contaminant level (MCL) of 5 μg/L under consideration. The City currently has no internal water quality goal for bromate.

Chlorine dioxide (ClO_2) is much less reactive with NOM compared with free-chlorine or ozone, and produces very few halogenated organic DBPs. However, the reduced inorganic byproducts chlorite (ClO_2^-) and chlorate (ClO_3^-) may be produced during onsite ClO_2 generation or by ClO_2 oxidation of NOM and reduced iron or manganese. Stage 1 DBPR set an MCL of 1 mg/L for chlorite. Chlorate is currently not regulated in drinking water due to a lack of conclusive evidence regarding adverse health effects. The City currently has no internal water quality goals for chlorite or chlorate.

Combined-chlorine (NH_2Cl – monochloramine) is also much less reactive with NOM than free-chlorine, producing on average less than 20 and 50 percent of the THM and HAA concentrations, respectively, at comparable disinfectant concentrations. Reaction between combined-chlorine and certain cationic resins and polymers has recently been implicated in the formation of nitrosodimethylamine (NDMA), which is classified as a probable human carcinogen by USEPA. NDMA is not currently regulated in drinking water, but has an estimated 10^{-6} cancer risk at 0.7 nanograms per liter (ng/L), which is below the level often measured in chloraminated drinking water. The City currently has no internal water quality goal for NDMA.

2. Existing Barriers for DBP Control

DBP precursor removal at BRWTF relies solely on TOC removal by enhanced coagulation; alternative oxidants are not currently used, nor is activated carbon adsorption applied. Although BRWTF has consistently met the treatment technique requirement for TOC removal (Figure 2-14), the City's THM and HAA water quality goals have not been met consistently (Figures 2-15 and 2-16). Between 1998 and 2006, the City's goals have been exceeded in 56 to 70 percent of THM samples, and 65 to 90 percent of HAA samples, collected from locations served exclusively by the BRWTF.

3. Potential Additional Barriers for DBP Control

Treatment technologies that seek to minimize DBP formation follow one of three strategies related to the reactions between chemical disinfectants and organic or inorganic source water constituents: (1) remove the undesirable byproduct once formed, (2) alter the reaction conditions so as to reduce byproduct formation, or (3) reduce or remove one of the byproduct precursors. Because DBPs are generally non-volatile, solid phase adsorption processes have long been viewed as candidates for DBP removal from finished drinking water. Granular activated carbon (GAC) adsorption and ion exchange (IX) have been extensively explored as treatment techniques for organic and inorganic DBP removal, respectively. However, these processes have not been widely deployed for DBP removal from finished drinking water because of limitations

including insufficient adsorption capacity, lack of specificity for targeted DBPs, undesirable interactions with residual disinfectants, and operational and economic considerations.

Controlling DBP formation by altering reaction conditions such as temperature or contact time is of only limited value or practicality. Utilities have very little if any control over source and finished water temperatures, and lowering water temperature during treatment is economically unviable. Although the point(s) of disinfectant application may sometimes be moved further downstream in the treatment process train, disinfection contact time requirements and distribution system residence time limit the extent to which contact time can be reduced. For these reasons, minimizing DBP formation during drinking water treatment has largely focused on reducing or removing DBP precursors, and has governed development of the interrelated set of microbial and DBP regulations over the past decade.

Strategies for DBP precursor removal include use of alternative disinfectants, precipitative NOM removal by enhanced coagulation, and NOM adsorption on activated carbon. Ozone, chlorine dioxide, chloramines and UV light have been used to either partially or completely replace free-chlorine, thereby lowering THM and HAA formation. However, alternative chemical disinfectants do produce other DBPs as previously discussed. Stage 1 DBPR mandates a treatment technique for NOM removal in facilities that utilize conventional treatment of surface water based on source water total organic carbon (TOC) and alkalinity concentrations, as indicated in Table 3-5.

Table 3-5

Percent TOC Removal Required by Enhanced Coagulation for Surface Water Systems Utilizing Conventional Treatment

Source Water TOC (mg/L)	Source Water Alkalinity (mg/L as $CaCO_3$)		
	0–60	**>60 – 120**	**> 120**
> 2.0 to 4.0	35.0	25.0	15.0
> 4.0 to 8.0	45.0	35.0	25.0
> 8.0	50.0	40.0	30.0

Alternative Compliance Criteria:

(1) Source water TOC < 2.0 mg/L
(2) Finished water TOC < 2.0 mg/L
(3) Source water TOC < 4.0 mg/L, alkalinity > 60 mg/L as $CaCO_3$, TTHM < 40 μg/L, and HAA < 30μg/L
(4) TTHM < 40 μg/L and HAA < 30μg/L, and only chlorine used for disinfection and residual maintenance
(5) Source water SUVA prior to any treatment ≤ 2.0 L/mg·m
(6) Treated water SUVA ≤ 2.0 L/mg·m

C. Barriers for Organic Micro-Pollutant Control

Organic micro-pollutants enter source waters from industrial and municipal effluents, agricultural runoff, and unregulated waste discharge.

1. Overview

Organic micro-pollutants encompass a wide range of chemical compounds with diverse physical and chemical properties. Historically important classes of synthetic organic compounds (SOCs) include solvents, plasticizers, propellants, petroleum additives, chemical intermediates, herbicides, and pesticides. Emerging SOC classes of concern that are not currently regulated include endocrinologically active compounds (EDCs), pharmaceutically active compounds (PhACs), and personal care products (PCPs). Although SOCs typically occur at low concentrations in source waters, and at trace levels in drinking water supplies, many of these compounds are highly toxic or carcinogenic and therefore pose a health risk if present in drinking water. There

are currently national primary drinking water standards for 62 SOCs and pending standards for another 38 listed in the Contaminant Candidate List 2. The City currently has no internal water quality goal for specific organic micro-pollutants.

2. Existing Barriers for Organic Micropollutant Control

There are currently no known industrial or municipal effluent discharges to Carter Lake, BFC, or Boulder Reservoir; although, all three water sources for BRWTF are potentially subject to organic micro-pollutant contamination to varying degrees through surface runoff and unregulated waste releases. Carter Lake is the least susceptible of BRWTF sources because of its remote location, small catchment area and lack of natural tributaries, and restricted adjacent land usage. Boulder Reservoir is somewhat more vulnerable to organic micro-pollutant contamination due to natural tributaries and ditches that flow in and extensive recreational use. BFC is highly vulnerable to organic micro-pollutant contamination because of its extended length with virtually uncontrolled access, numerous outfalls and street crossings, and adjacent residential, commercial, agricultural, and recreational land uses. There are no dedicated SOC treatment processes at BRWTF, and only very limited organic pollutant removal is provided by DAF and co-precipitation during natural organic matter (NOM) coagulation.

3. Potential Additional Barriers for Organic Micropollutant Control

Organic micro-pollutant control in drinking water supplies utilizes watershed management to limit effluent discharges, as well as treatment processes including air stripping, chemical oxidation, coagulation, activated carbon adsorption, reverse osmosis, and advanced oxidation for removal during treatment. Chemical characteristics such as volatility, polarity, charge, molecular weight, and solubility, determine which processes are appropriate for SOC removal during drinking water treatment. Because the potential for introduction of organic micropollutants into Carter Lake is low (Chapter 2, Section C.1), full containment of source water in a dedicated pipeline to BRWTF would also provide an additional barrier.

D. Barriers for Manganese Control

Manganese may be present in ground and surface waters that are in contact with manganese containing minerals, occurring as either soluble Mn^{2+} (reduced form) or precipitated MnO_2 (oxidized form), depending on pH and oxygen concentration.

1. Overview

Aesthetic issues associated with manganese in drinking water include staining of laundry and fixtures and unpleasant taste. Manganese concentrations of less than 0.5 milligrams per liter (mg/L) may promote bacterial growth in reservoirs and drinking water distribution systems. Consumer complaints regarding aesthetic issues associated with manganese in drinking water have been documented at concentrations as low as 0.02 mg/L. There are presently no known adverse health effects of manganese in drinking water, but the USEPA has set a secondary maximum contaminant level (SMCL) for manganese at 0.05 mg/L based on aesthetic concerns. The City has set an internal goal of 0.03 mg/L for manganese in finished drinking water.

2. Existing Barriers for Manganese Control

Manganese concentrations in Carter Lake have historically been very low year-round. Manganese concentrations increase only slightly as a result of conveying water to BRWTF through BFC. However, seasonal manganese mobilization is routinely observed in Boulder Reservoir during late summer and early fall due to hypolimnetic anoxia produced by thermal stratification. Although the manganese concentration in the hypolimnion of Boulder Reservoir exceeds the City's goal in 33 percent of samples, with levels of 0.5 mg/L to 1.0 mg/L not uncommon, manganese loading in BRWTF influent has historically been minimized by using the low manganese BFC source almost exclusively during periods when stratification results in mobilization. Because oxidation of Mn^{2+} with oxygen and free-chlorine is relatively slow at pH less than 9.5, the efficiency of manganese removal for the conventional treatment process configuration currently in place at BRWTF may not be sufficient if Boulder Reservoir was used as the water source year-round.

3. Potential Additional Barriers for Manganese Control

Manganese control during drinking water treatment most often involves oxidation of soluble Mn^{2+} to particulate MnO_2, with subsequent removal by clarification or filtration. Manganese removal through autocatalytic adsorption and oxidation on MnO_2 coated filter media surfaces is also practiced, and less frequently by ion exchange, nanofiltration/reverse osmosis or precipitative softening. Because the potential for soluble manganese release from bed sediments in Carter Lake is low (Chapter 2, Sections C.1.b and C.1.c), full containment of source water in a dedicated pipeline to BRWTF would also provide an additional barrier.

E. Barriers for Taste and Odor Control

Objectionable tastes and odors in drinking water may occur due to the presence of microbial metabolites and degradation products, anthropogenic volatile and synthetic organic compounds, and naturally occurring inorganic compounds.

1. Overview

Numerous microbial species belonging to cyanobacteria, green algae, diatom, and flagellate groups that may be present in surface waters produce odors variously described as sweet, grassy, musty, earthy, swampy, fishy, and septic. Geosmin and 2-methylisoborneol (MIB) are the most well known microbial odor-causing metabolites found in drinking water supplies, producing earthy and musty odors, respectively. Medicinal and phenolic off-tastes and odors are often associated with drinking water supplies developed from source waters that receive organic solvents, pesticides, and petroleum products from industrial effluent, agricultural runoff, and liquid waste disposal. Often, these chemicals produce tastes and odors that are not directly attributable to a parent organic compound, but rather to chlorinated disinfection byproducts that occur in discharged waste effluents or finished drinking water. Thermal stratification in lakes and reservoirs often leads to anaerobic conditions at depth, releasing inorganic taste and odor compounds through mobilization of soluble iron and manganese (Fe^{2+} and Mn^{2+}) from insoluble oxide minerals in bottom sediments, as well as sulfide production. There are currently no national drinking water

regulations for taste; however, USEPA has set a SMCL for odor at a threshold odor number of three. The City has set an internal water quality goal of no detectable tastes or odors in finished drinking water.

2. Existing Barriers for Taste and Odor Control

BRWTF currently depends largely on source water control strategies for taste and odor control, as chemical oxidation with free-chlorine is only marginally effective at controlling algal metabolites and oxidizing soluble manganese. Algicides are periodically applied in BFC, but not to Carter Lake or Boulder Reservoir. There is no aeration for volatile organic removal or activated carbon or ion exchange processes for soluble contaminant removal, nor is there is a routine monitoring program for seasonal formation of algal taste and odor compounds in Carter Lake, BFC, or Boulder Reservoir.

3. Potential Additional Barriers for Taste and Odor Control

Taste and odor control in drinking water supplies may rely on source water management or removal during treatment, or frequently a combination of both strategies. Source water management strategies include lake and reservoir aeration, chemical inhibition of algal growth, watershed management to limit nutrient input, and effluent discharge restrictions. Chemical characteristics of taste and odor compounds such as volatility, polarity, charge, molecular weight, and solubility, determine which processes are appropriate for their removal during drinking water treatment. Treatment processes commonly used for taste and odor control include aeration, chemical oxidation, activated carbon adsorption, ion exchange, and precipitation. Because the potential for objectionable taste or odor episodes in Carter Lake is low (Chapter 2, Section C.1.c), full containment of source water in a dedicated pipeline to BRWTF would also provide an additional barrier.

F. Barriers for Inorganic Contaminant Control

Natural waters contain a variety of inorganic constituents that occur primarily as the result of mineral weathering and leaching reactions in soil, sediment, and rock formations; although, industrial, municipal, agricultural, and surface runoff effluents may in some instances contribute inorganic constituents.

1. Overview

Inorganic constituents typically occur in ionic form in aqueous solution, and may be present as suspended and colloidal solids or dissolved species. Major cations (positively charged) in natural waters include sodium, potassium, calcium, magnesium, iron, and manganese; whereas, major anions (negatively charged) include bicarbonate, chloride, sulfate, sulfide, nitrate, nitrite, fluoride, and silicate. Other trace inorganic constituents that may be present in source waters are alkali and alkaline metals, other metallic elements, and nonmetals. There are currently National Primary Drinking Water Standards for 16 inorganic elements and compounds, and National Secondary Drinking Water Standards for 10 inorganics. There is also a National Secondary Drinking Water Standard for pH of 6.5 to 8.5 standard units (s.u.), as an indicator of finished water quality and corrosivity. The City has set internal water quality goals for sodium (5 to 20 mg/L), sulfate (less than 20 mg/L), TDS (less than 100 mg/L), fluoride (0.9 $\pm$ 0.1 mg/L), and pH (7.8 $\pm$ 0.2 s.u.) that are more restrictive than required by state and federal regulations.

2. Existing Barriers for Inorganic Contaminant Control

BRWTF utilizes conventional treatment for suspended and colloidal inorganic contaminant removal. No dedicated processes for dissolved inorganic contaminant removal are currently in place at BRWTF. The City's water quality goals for sulfate and TDS have historically been routinely exceeded (Figure 2-17). In addition, finished water pH at the BRWTF has routinely been outside the City's desired range, exceeding the upper limit and falling below the lower limit 10 percent and 42 percent of the time, respectively.

3. Potential Additional Barriers for Inorganic Contaminant Control

Suspended and colloidal inorganic constituents may be effectively removed from source waters by standard treatment methods including coagulation, clarification, and filtration. However, with the exception of several regulated metals, dissolved inorganic constituents are typically only poorly removed by these methods, if at all. The concentrations of multivalent ions may be reduced by precipitative softening or ion exchange, but reverse osmosis is the only practical treatment method to lower TDS or remove monovalent ions.

Because the potential for naturally-occurring or human-induced inorganic contamination in Carter Lake is very low (Chapter 2, Section C.1.c), full containment of source water in a dedicated pipeline to BRWTF would also provide an additional barrier.

Chapter 4

Multi-Barrier Approach Decision Criteria

This chapter describes the criteria developed as part of a structured K-T® decision analysis model used to rank BRWTF multi-barrier water delivery alternatives. This set of decision criteria forms the basis of a fair and balanced evaluation of BRWTF multi-barrier water delivery alternatives. City staff developed decision model criteria in 5 categories including finished water quality, source water, treatment operations, risk, and environmental and public acceptance.

A set of preliminary decision model performance criteria was presented to City staff by B&V in a workshop held on August 16, 2006. Over the next several months, an ad hoc City staff committee (BRWTF Multi-Barrier Project Working Group) representing drinking water quality, water resources, operations, and senior management functions refined the preliminary decision model performance criteria through a series of scheduled meetings and informal communications. Based on the collective expertise and experience of the Project Working Group members, the set of decision model performance criteria ultimately chosen was reviewed and finalized in a workshop held on December 14, 2006.

A. Mandatory MUST Criteria

As described in Chapter 1, performance criteria in K-T® decision analysis are classified either as MUST criteria that each candidate problem solution must absolutely satisfy in order to be included in the decision process, or WANT criteria that are desirable but not mandatory for each candidate problem solution to satisfy. Two MUST decision criteria were developed by the Project Working Group.

1. Regulatory Compliance

For a candidate decision model alternative to be considered as an acceptable BRWTF multi-barrier water delivery approach it must be capable of continuously meeting all enforceable USEPA and CDPHE drinking water

regulations and standards. This MUST criterion assumes that BRWTF will be adequately maintained and operated in accordance with its design specifications. Furthermore, this MUST criterion assumes that only raw water delivered through BFC, pumped from Boulder Reservoir, or conveyed directly from Carter Lake through a dedicated pipeline will be utilized at BRWTF.

2. Water Rights Portfolio Yield

Each candidate BRWTF multi-barrier water delivery alternative must be capable of maintaining the current expected yield of the City's water rights portfolio and must not reduce the current level of flexibility in selecting drinking water sources from its water rights portfolio.

B. Desirable WANT Criteria

The Project Working Group developed 28 decision model performance criteria in five categories including finished water quality, source water, treatment operations, risk, and environmental and public acceptance, as listed in the following sections. These criteria are satisfied by the BRWTF multi-barrier water delivery alternatives outlined in Chapter 5 to varying degrees.

1. Finished Water Quality Criteria

Finished water quality WANT criteria related to each of the contaminant barrier categories detailed in Chapter 3 were incorporated including pathogens, disinfection by-products, organic micropollutants, manganese, taste and odor, and inorganic contaminants, as listed in Table 4-1.

Table 4-1

Finished Water Quality Criteria for BRWTF Multi-Barrier Water Delivery Alternatives

Criteria	Comments
Pathogens	What are the recent trends in microbial water quality in BFC, Boulder Reservoir, and Carter Lake? How likely are acute pathogenic contamination events in these raw water sources? Are barriers sufficient to prevent pathogens from passing through BRWTF at levels that could jeopardize public health?
Disinfection Byproducts	Which DBPs will be formed and at what levels? Can source water as well as treatment controls be used to minimize DBP formation?
Organic Micro-Pollutants	How significant is the potential risk of organic chemical contamination during source water conveyance or storage? To what extent can treatment processes mitigate acute or chronic organic chemical contamination?
Manganese	What is the extent and duration of seasonal manganese mobilization? Can source water as well as treatment controls be used to limit manganese concentrations?
Taste and Odor	What is the extent and duration of seasonal taste and odor episodes associated with algal blooms or manganese mobilization? Can source water as well as treatment controls be used to minimize objectionable tastes and odors?
Inorganic Contaminants	What is the potential for inorganic contamination during source water conveyance or storage? Can source water as well as treatment controls be used to mitigate inorganic contamination?

2. Source Water Portfolio Criteria

Decision model performance criteria related to management of the City's source water portfolio were identified, as listed in Table 4-2.

Table 4-2

Source Water Portfolio Criteria for BRWTF Water Delivery Alternatives

Criteria	Comments
Source Water Quality Consistency	What is the extent of seasonal and short-term source water quality fluctuation to BRWTF? Do these fluctuations impact treatment at BRWTF and for how long?
Water Rights Yield	What is the availability of raw water for direct use? Is the ability to manage stored reservoir water throughout the year and during droughts maximized? Can water rights yield be increased through enhanced water management or capacity of facilities?
Portfolio Flexibility	How many options are available for delivering raw water to BRWTF? How difficult is it to switch water sources in response to changing conditions? Are there seasonal limitations on use of raw water sources?
Availability of Raw Water Delivery Facilities	What is the expected reliability of infrastructure for raw water delivery to BRWTF? What are the capacity limitations of these delivery methods? Are their restrictions on the use of water delivery infrastructure due to external factors that affect operations or water quality?

3. Water Treatment and Operations Criteria

Decision model performance criteria related to water treatment and BRWTF operations were identified, as listed in Table 4-3.

Table 4-3

Water Treatment and Operations Criteria for BRWTF Water Delivery Alternatives

Criteria	Comments
Worker Safety	What types and amounts of treatment or cleaning chemicals that staff will be exposed to? What are the durations of these exposures? Will staff be exposed to high voltage electrical shock hazards? Are physically intensive maintenance procedures such as cleaning intake grates required?
Process Flexibility	What is the maturity and robustness of treatment technologies? Is the number of treatment process technologies required to provide required contaminant barriers minimized?
Process Reliability	Is raw water delivered with consistent quality and flow? Can consistent year-round treatment be provided with minimal process failure?
Process Redundancy	Are multiple barriers provided for contaminant categories of concern? Is back-up capability provided for critical treatment operations?
Maintenance	Can all maintenance be performed by City staff or will an outside contractor be required? Will routine replacement of consumable items such as lamps or membranes be required?
Staffing	What are the levels of staffing and supervision required? What levels of expertise and certification are required?
Residuals Processing	What are the quantities and characteristics of residuals produced by new treatment processes? Will residuals disposal require special environmental permitting?

4. Risk Criteria

Decision model performance criteria associated with risk of source water contamination, adverse impact of additional regulatory requirements on BRWTF operations, infrastructure vulnerability, and chemical usage and delivery were identified, as listed in Table 4-4.

Table 4-4

Risk Criteria for BRWTF Water Delivery Alternatives

Criteria	Comments
Acute Contamination	What is the potential for acute or "slug-loading" of contaminants that could disrupt or disable water delivery from BRWTF either temporarily or long term? Is there potential for undetected breakthrough of these contaminants?
Chronic Contamination	What is the risk associated with non-point contaminant sources in BRWTF raw water supplies that could pose a threat to public health? Are these contaminants difficult to remove or inactivate through treatment?
Adaptability to Change	What is the risk to public health associated with potential near- and long-term source water quality degradation? What is the potential for future regulatory non-compliance?
Infrastructure Vulnerability	What is the likelihood that damage to infrastructure could impede purveyance or treatment of the potable water supply?
Consumable Delivery/Usage	Are there consumables such as process specific chemicals, membranes, or lamps that would impede treatment or public health protection if delivery was interrupted? To what extent are alternate sources of these critical treatment consumables available?

5. Environmental and Public Acceptance Criteria

Decision model performance criteria associated with environmental and public acceptance issues specific to BRWTF were identified, as listed in Table 4-5.

Table 4-5

Environmental and Public Acceptance Criteria for BRWTF Water Delivery Alternatives

Criteria	Comments
Adjacent Land Use Compatibility	Are there critical wildlife habitats, archeologically sensitive, or historically significant lands adjacent to conveyance structures? What impact might adjacent agricultural, industrial, commercial, recreational, and residential tracts have on conveyance?
Finished Water Uniformity	How uniform is finished water quality across the distribution system? Does finished water from BRWTF meet City water quality goals?
Construction	What are the land area footprint and associated restoration requirements? Will extensive underground excavation and associated materials handling be required?
Consumer Confidence	What is the level of consumer confidence with finished water delivered from BRWTF?
Permitting	Are there sensitive environmental or public acceptance issues that would make required permitting difficult? What measures are available to mitigate these concerns?
Energy Requirements	What are the operational energy requirements and what are their secondary environmental effects? Is there potential for renewable energy generation?

Chapter 5

Multi-Barrier Approach Alternatives

The integration of source water protection and treatment technologies into multi-barrier water delivery approaches for BRWTF is detailed in this chapter. Additional conceptual improvements recommended in the Phase I Source Water Protection Study and Predesign Report including full containment from Carter Lake to BRWTF, UV light disinfection, membrane filtration, ozone, and GAC were considered here. Barriers for microbial pathogen control listed in the LT2ESWTR Microbial Toolbox (Table 3-4) were also considered in this study. *However, not all of the City's drinking water quality goals were fully satisfied by all multi-barrier water delivery alternatives evaluated, primarily due to compelling economic considerations.*

A. Conceptual Improvement Screening

Conceptual improvements that could be included in a multi-barrier water delivery alternative at BRWTF were screened for applicability based on several factors including integration with the existing treatment process train, probable performance, and economic considerations. Potential conceptual improvements were evaluated based on their ability to address one or more of the contaminant barriers identified in Chapter 3 including microbial pathogens, DBPs, organic micropollutants, manganese, taste and odor, and TDS and sulfate. The general strategy of the screening process was to give greater consideration to conceptual alternatives that where possible addressed more than one contaminant barrier, thereby minimizing the number of conceptual improvements and complexity of proposed multi-barrier water deliver alternatives.

1. Source Water Protection

Full containment from Carter Lake to BRWTF was the only source water protection improvement considered in this study. Other strategies such as large scale improvements to stormwater diversion along BFC or around Boulder

Reservoir, BFC road crossings, and hydraulic structures were not recommended in the Phase I source water protection study, and were beyond the scope of this study.

2. Prefiltration

Prefiltration options in the LT2ESWTR Microbial Toolbox, including pre-sedimentation, two-stage lime softening, and bank filtration, receive low inactivation/removal credit were not selected for inclusion in multi-barrier alternatives. These treatment processes could provide an additional minimal barrier for pathogens, but would not generally provide substantial additional barriers for other contaminant categories. Because of the mineralized soils that contribute to manganese and TDS increases while raw water is held in Boulder Reservoir, bank filtration could even lead to raw water quality degradation.

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3. Treatment Performance

Combined filter effluent and individual filter effluent performance credit was considered an effective component of any multi-barrier treatment alternative. These options assign additional *Cryptosporidium* log-inactivation/removal credit based on maintaining filter turbidity levels below target values, thus require no additional treatment processes. BRWTF has a treatment process optimization program in place, so additional contaminant barrier credit based on demonstration of further enhanced performance is likely, and was considered in this study.

4. Additional Filtration

Additional filtration technologies including bag or cartridge filters, second stage granular media filtration, and slow sand filtration were not included in multi-barrier water delivery alternatives evaluated in this study. As with the prefiltration options previously discussed, these additional filtration options would provide only marginally increased log-inactivation/removal credit for *Cryptosporidium*, and provide little in the way of additional barriers for other contaminant categories. The hydraulic profile of the existing BRWTF would also not accommodate additional filtration without substantial supplemental pumping, increasing O&M costs. The limited benefit of these additional filtration to finished

water quality of the well designed and operated full-conventional treatment provided by the existing BRWTF were not viewed as sufficient to justify the associated large capital cost, increased O&M costs, and additional filter backwash/cleaning requirements. However, due to the relatively high log-removal credit possible with low-pressure membrane filtration, it was included as a treatment process option in the BRWTF multi-barrier water delivery alternatives evaluated.

5. Oxidation/Inactivation

Chemical oxidation can potentially provide additional barriers for microbial pathogens, DBPs, organic micropollutants, manganese, and objectionable tastes and odors, depending on the oxidant used and its point of application. Addition of chlorine dioxide for DBP, manganese, and taste and odor control is included in the City's mid-term improvements plan, and is therefore assumed as part of the baseline treatment for the long-term improvements evaluated here. Ozone was also evaluated in this study because of its superior performance for taste and odor control, ability to oxidize many organic micropollutants, and additional pathogen inactivation. UV disinfection was also evaluated due to its superior disinfection performance for bacteria, viruses, and protozoan pathogens. These treatment processes result in relatively low headloss, simplifying their integration with the existing hydraulic profile at BRWTF.

6. GAC Adsorption

Granular activated carbon was evaluated in this study based on additional barriers for DBPs, organic micropollutants, and objectionable tastes and odors that it may provide. Although GAC adsorption has headloss restrictions similar to the filtration technologies previously considered, the multiple potential finished water quality benefits that it may provide were viewed as sufficient to warrant the added complexity and cost of integrating this process into the existing BRTWF hydraulic profile.

B. Grouping Conceptual Improvements into Alternatives

Candidate multi-barrier approaches were developed for BRWTF by combining conceptual improvements that address identified drinking water quality

vulnerabilities in source water conveyance to and treatment at BRWTF. Only those conveyance and treatment barriers that were selected in the screening process previously described were included in BRWTF multi-barrier alternatives. The combination of conceptual improvements selected for each delivery alternative was based on providing process redundancy and operational continuity at BRWTF.

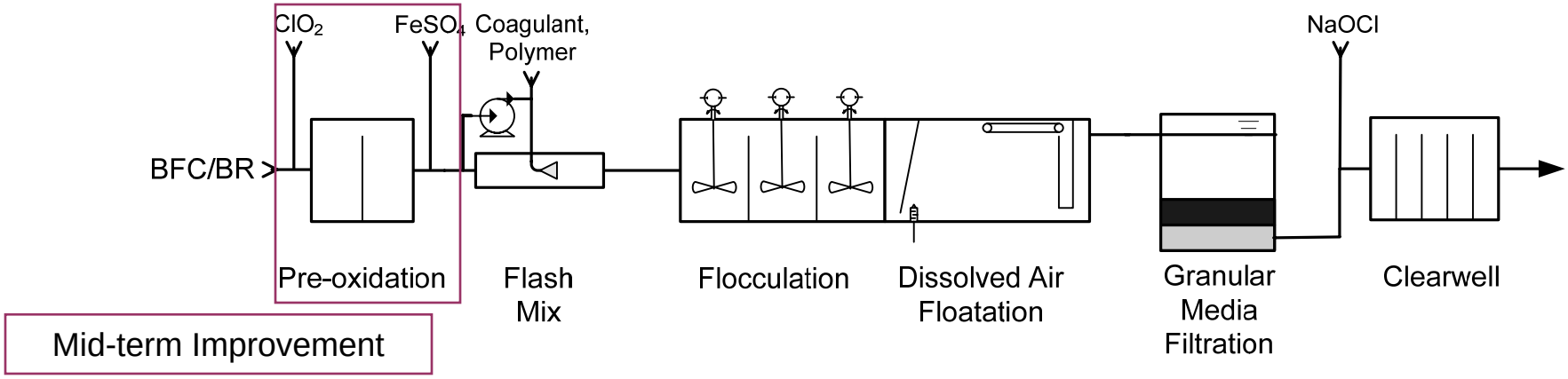
Not all possible combinations of screened barriers were included in alternative evaluations, but each screened barrier was incorporated in at least one water delivery alternative. The multi-barrier delivery alternatives developed for this study would produce finished water that meets all current state and federal drinking water standards; however, it is important to note that not all of these alternatives continuously meet the City's drinking water goals as discussed below.

1. BFC and Boulder Reservoir Seasonal Delivery Alternatives

Five water delivery alternatives that provide seasonal raw water delivery to BRWTF through BFC or by pumping from Boulder Reservoir were developed, as shown schematically on Figures 5-1 through 5-5. Each of these delivery alternatives is based on the existing conventional treatment at BRWTF and residual disinfection with free chlorine. In addition, chlorine dioxide preoxidation added as part of the ongoing mid-term improvements program was also assumed.

- Alternative 1: This water delivery alternative incorporates preoxidation with chlorine dioxide followed by full conventional treatment and free chlorine disinfection. A centralized contact basin for preoxidation contact time is included to allow use of both BFC and Boulder reservoir raw water sources. Presedimentation for turbidity and suspended solids control would also be provided by the preoxidation contact basin, but because no coagulant would be added prior to basin contact no credit towards *Cryptosporidium* treatment would be provided. Residual chlorine dioxide and chlorite would be quenched by ferrous sulfate addition prior to coagulation.

  This barrier combination serves as the baseline BRWTF multi-barrier water delivery alternative. *This baseline alternative would not meet the City's water quality goals with respect to*



Primary MCL	Microbial Pathogens	✓	✓	✓	✓
Primary MCL	Disinfection Byproducts	✓	✓	✓	
Primary MCL	Micro-Pollutants				
Secondary MCL	Manganese	✓		✓	
Secondary MCL	Taste and Odor	✓			
Secondary MCL	TDS and Sulfate				

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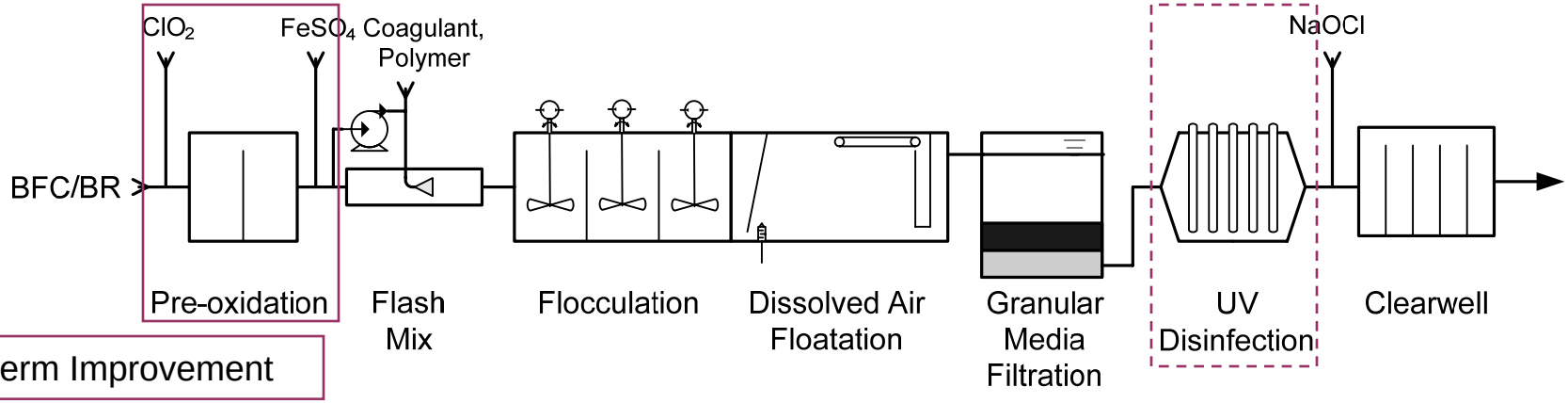
Alternative 1: Boulder Feeder Canal/Boulder Reservoir Seasonal Delivery with ClO_2 Pre-oxidation

Figure 5-1



Mid-term Improvement

Long-term Improvement

		Pre-oxidation	Flash Mix	Flocculation	Dissolved Air Floatation	Granular Media Filtration	UV Disinfection	Clearwell
Primary MCL	Microbial Pathogens	✓		✓	✓	✓	✓	✓
Primary MCL	Disinfection Byproducts	✓		✓	✓	✓		
Primary MCL	Micro-Pollutants							
Secondary MCL	Manganese	✓			✓			
Secondary MCL	Taste and Odor	✓						
Secondary MCL	TDS and Sulfate							

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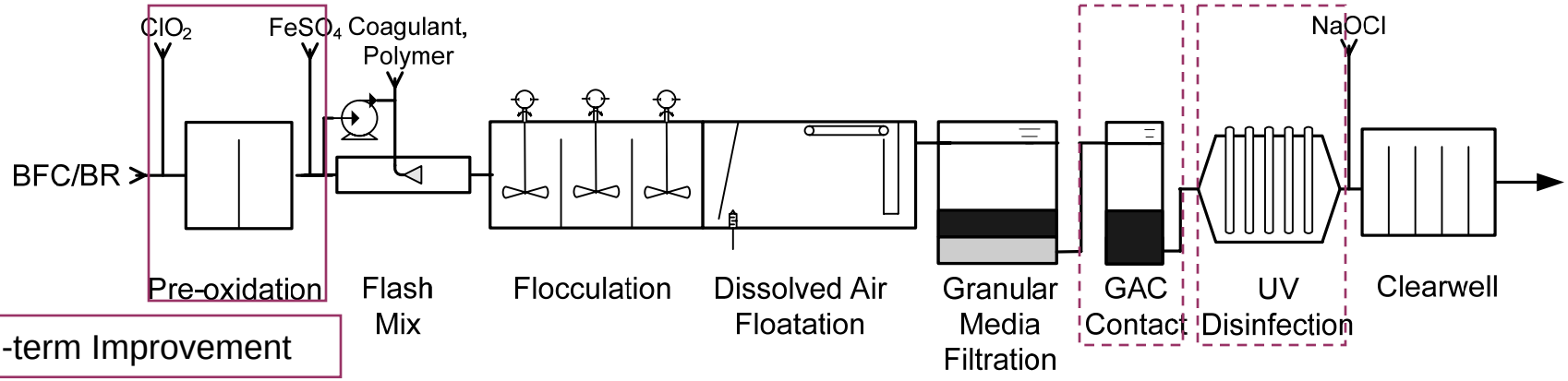
Alternative 2: Boulder Feeder Canal/Boulder Reservoir Seasonal Delivery with ClO_2 Pre-oxidation and UV Disinfection

Figure 5-2



Mid-term Improvement

Long-term Improvement

		Pre-oxidation	Flash Mix	Flocculation	Dissolved Air Floatation	Granular Media Filtration	GAC Contact	UV Disinfection	Clearwell
Primary MCL	Microbial Pathogens	✓	✓	✓		✓		✓	✓
Primary MCL	Disinfection Byproducts	✓	✓	✓		✓	✓		
Primary MCL	Micro-Pollutants						✓		
Secondary MCL	Manganese	✓				✓			
Secondary MCL	Taste and Odor	✓					✓		
Secondary MCL	TDS and Sulfate								

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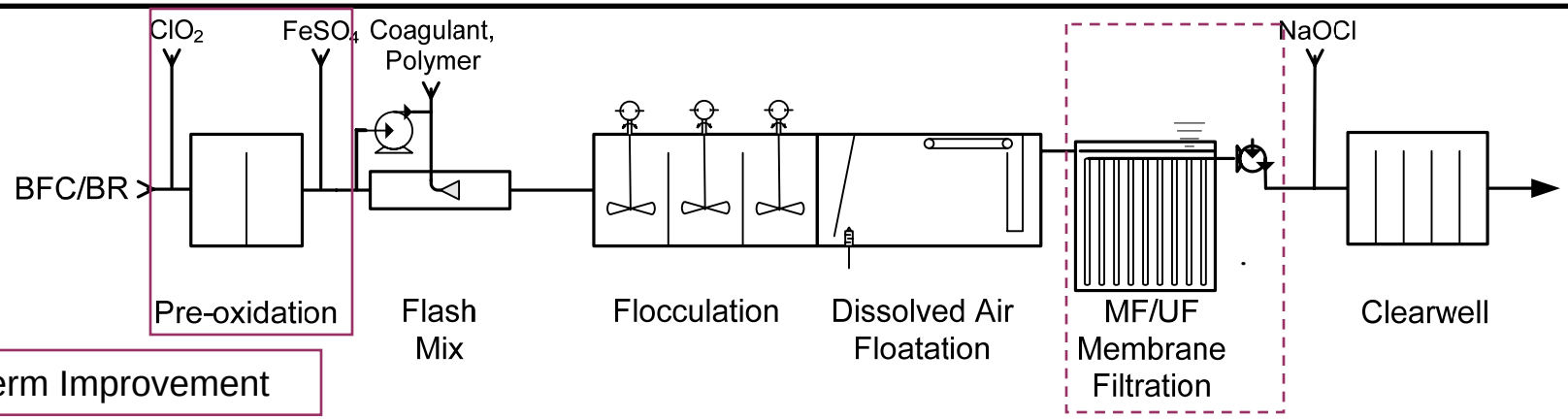
Alternative 3: Boulder Feeder Canal/Boulder Reservoir Seasonal Delivery with ClO_2 Pre-oxidation, GAC Adsorption and UV Disinfection

Figure 5-3



Mid-term Improvement

Long-term Improvement

Primary MCL	Microbial Pathogens	✓	✓	✓	✓
Primary MCL	Disinfection Byproducts	✓	✓	✓	
Primary MCL	Micro-Pollutants				
Secondary MCL	Manganese	✓		✓	
Secondary MCL	Taste and Odor	✓			
Secondary MCL	TDS and Sulfate				

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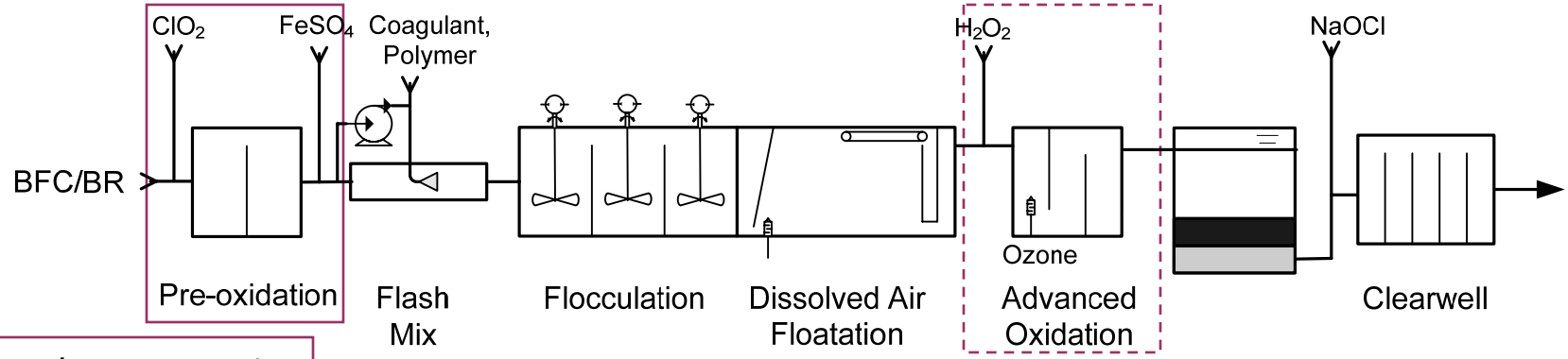
Alternative 4: Boulder Feeder Canal/Boulder Reservoir Seasonal Delivery with ClO_2 Pre-oxidation and Submerged MF/UF

Figure 5-4



Mid-term Improvement

Long-term Improvement

Primary MCL	Microbial Pathogens	✓	✓	✓	✓	✓
Primary MCL	Disinfection Byproducts	✓	✓	✓	✓	
Primary MCL	Micro-Pollutants			✓		
Secondary MCL	Manganese	✓		✓	✓	
Secondary MCL	Taste and Odor	✓		✓		
Secondary MCL	TDS and Sulfate					

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Alternative 5: Boulder Feeder Canal/Boulder Reservoir Seasonal Delivery with ClO_2 Pre-oxidation and Advanced Oxidation

Figure 5-5

pathogen control, nor would it meet finished water TDS and sulfate goals when raw water is provided from Boulder Reservoir. No effective barrier for organic micropollutant control is provided by this alternative.

- Alternative 2: This alternative incorporates UV disinfection with the barriers provided by Alternative 1. *This delivery alternative would not meet the City's TDS and sulfate water quality goals when Boulder Reservoir was online, nor would it provide an effective barrier for organic micropollutant control.*

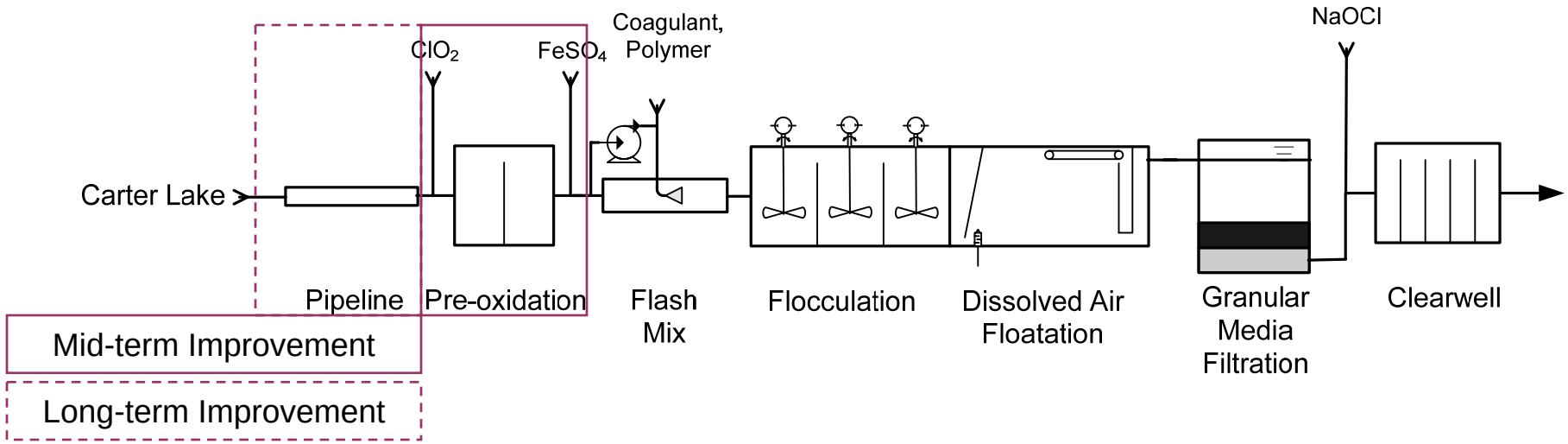
- Alternative 3: This alternative adds both GAC adsorption and UV disinfection to the contaminant barriers provided by baseline Alternative 1. *This delivery alternative would not meet the City's TDS and sulfate water quality goals when raw water was supplied from Boulder Reservoir.*

- Alternative 4: This alternative utilizes the contaminant barriers in baseline Alternative 1 with granular media filtration replaced by submerged low-pressure membrane filtration retrofitted into the existing filter boxes. *This delivery alternative would not meet the City's TDS and sulfate water quality goals, nor would it provide an effective barrier for organic micropollutant control.*

- Alternative 5: This alternative adds ozone oxidation to the contaminant barriers provided by baseline Alternative 1. *This water delivery alternative would not meet the City's water quality goals with respect to pathogen control during cold weather operation at BRWTF, nor would it meet finished water TDS and sulfate goals.*

2. Carter Lake Pipeline Delivery Alternative

Because a dedicated pipeline from Carter Lake for raw water delivery to BRWTF provides barriers for each contaminant category except DBP control, only one water alternative using this delivery method was developed, as shown schematically on Figure 5-6. This alternative utilizes the existing conventional treatment at BRWTF and residual disinfection with free chlorine. In addition, chlorine dioxide preoxidation added as part of the ongoing mid-term improvements program was also assumed.



Primary MCL	Microbial Pathogens	✓	✓	✓	✓	✓
Primary MCL	Disinfection Byproducts		✓	✓	✓	
Primary MCL	Micro-Pollutants	✓				
Secondary MCL	Manganese	✓	✓		✓	
Secondary MCL	Taste and Odor	✓	✓			
Secondary MCL	TDS and Sulfate	✓				

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Alternative 6: Carter Lake Pipeline Delivery with ClO_2 Pre-oxidation

Figure 5-6

- Alternative 6: Carter Lake pipeline for turbidity, suspended solids, manganese, taste and odor, organics, DBP, and inorganics control followed by chlorine dioxide pre-oxidation for additional pathogen, taste and odor, organics, and DBP control. *This water delivery alternative meets all the City's water quality goals, and provides at least one barrier for each contaminant category evaluated.*

3. Water Delivery Alternatives Summary

The candidate water delivery alternatives outlined here integrate a range of conceptual improvements with existing treatment processes to provide multi-barrier approaches for drinking water treatment at BRWTF. Table 5-1 summarizes the barriers provided in each alternative for identified water quality vulnerabilities.

As indicated in Table 5-1 BRWTF candidate water delivery Alternatives 1, 2, and 4 do not provide effective barriers for organic micropollutants and, and the degree of organic micropollutant control provided by Alternative 3 varies with GAC age. Only Alternative 3 provides TDS and sulfate in finished water that is consistent with City drinking water goals. Alternatives 1, 2, and 5 also do not satisfy the City's finished water quality goals for *Cryptosporidium* control, as shown in Table 5-2.

Table 5-1

Barriers for Water Quality Vulnerabilities at BRWTF

Alternative	Pathogens	DBPs	Organic Micro-pollutants	Mn	Taste & Odor	TDS/ Sulfate
1	ClO_2[2] Conv. treat. NaOCl	ClO_2[2] Conv. treat.	NB	ClO_2[2] Conv. treat.	ClO_2[2]	NB
2	ClO_2[2] Conv. treat. UV NaOCl	ClO_2[2] Conv. treat.	NB	ClO_2[2] Conv. treat.	ClO_2[2]	NB
3	ClO_2[2] Conv. treat. NaOCl	ClO_2[2] Conv. treat. GAC[3]	GAC[3]	ClO_2[2] Conv. treat.	ClO_2[2] GAC[3]	NB
4[1]	ClO_2[2] Conv. treat. NaOCl	ClO_2[2] Conv. treat.	NB	ClO_2[2] Conv. treat.	ClO_2[2]	NB
5	ClO_2[2] Conv. treat. AOP NaOCl	ClO_2[2] Conv. treat. AOP	AOP	ClO_2[2] Conv. treat. AOP	ClO_2[2] AOP	NB
6	Pipeline ClO_2[2] Conv. treat. NaOCl	ClO_2[2] Conv. treat.	Pipeline	Pipeline ClO_2[2]	Pipeline ClO_2[2]	Pipeline

Abbreviations:
ClO_2 – chlorine dioxide, Conv. treat. – conventional treatment (coagulation, flocculation, plate assisted sedimentation, filtration), NaOCl – free chlorine, NB – no barrier, UV – ultraviolet light disinfection, GAC – granular activated carbon adsorption, AOP – advanced oxidation process (ozone/H_2O_2).

[1]Low pressure membrane filtration (MF/UF) instead of granular media filtration.
[2]Partial barriers for pathogen and taste and odor control and robust barriers for DBP and manganese control.
[3]Partial barriers for organic micropollutants and taste and odor and robust barrier for DBP control.

Table 5-2

Microbial Pathogen Barriers for BRWTF Delivery Alternatives

Barrier	*Cryptosporidium*	*Giardia*	Viruses
Conventional Treatment	3.0	2.5	2.0
Combined Filter Performance	0.5	0.5[1]	–
Individual Filter Performance	0.5	0.5[1]	–
Chlorine Dioxide[2]	0.02/0.06	0.67/1.58	0.96/2.39
Ozone[3]	0.52/1.60	12.49/31.55	26.64/66.60
Free Chlorine[4]	–	0.54/1.21	12.33/30.15
UV Disinfection[5]	4.0	4.0	0.5
Pipeline[6]	1.5	1.5	–
Alternative	***Cryptosporidium***	***Giardia***	**Viruses**
1	*4.02/4.06*	4.71/6.29	15.29/34.54
2	8.02/8.06	8.71/10.29	15.79/35.04
3	8.02/8.06	8.71/10.29	15.79/35.04
4	5.52/5.56	6.71/8.29	15.29/34.54
5	*4.54*/5.66	17.20/37.84	41.93/101.1
6	5.52/5.56	6.21/7.79	16.79/36.04
City Goal	5.0	4.0	5.0

[1]Assumes same log-removal as for *Cryptosporidium* because *Giardia* is substantially larger.

[2]LT2ESWTR log-inactivation credit: 1 mg/L chlorine dioxide residual, 10 min. contact.3°C and 15°C.

[3]LT2ESWTR log-inactivation credit: 1 mg/L ozone residual, 10 min. contact, 3°C and 15°C.

[4]LT2ESWTR log-inactivation credit: 1 mg/L free chlorine residual, 10 min. contact, 3°C and 15°C.

[5]LT2ESWTR log-inactivation credit, UV dose 40 mJ/cm^2, no temperature dependence.

[6]*Cryptosporidium* and *Giardia* log-removal set equal to equivalent log-removal based on ratio of historical bacterial concentrations in BFC and Carter Lake.

Chapter 6

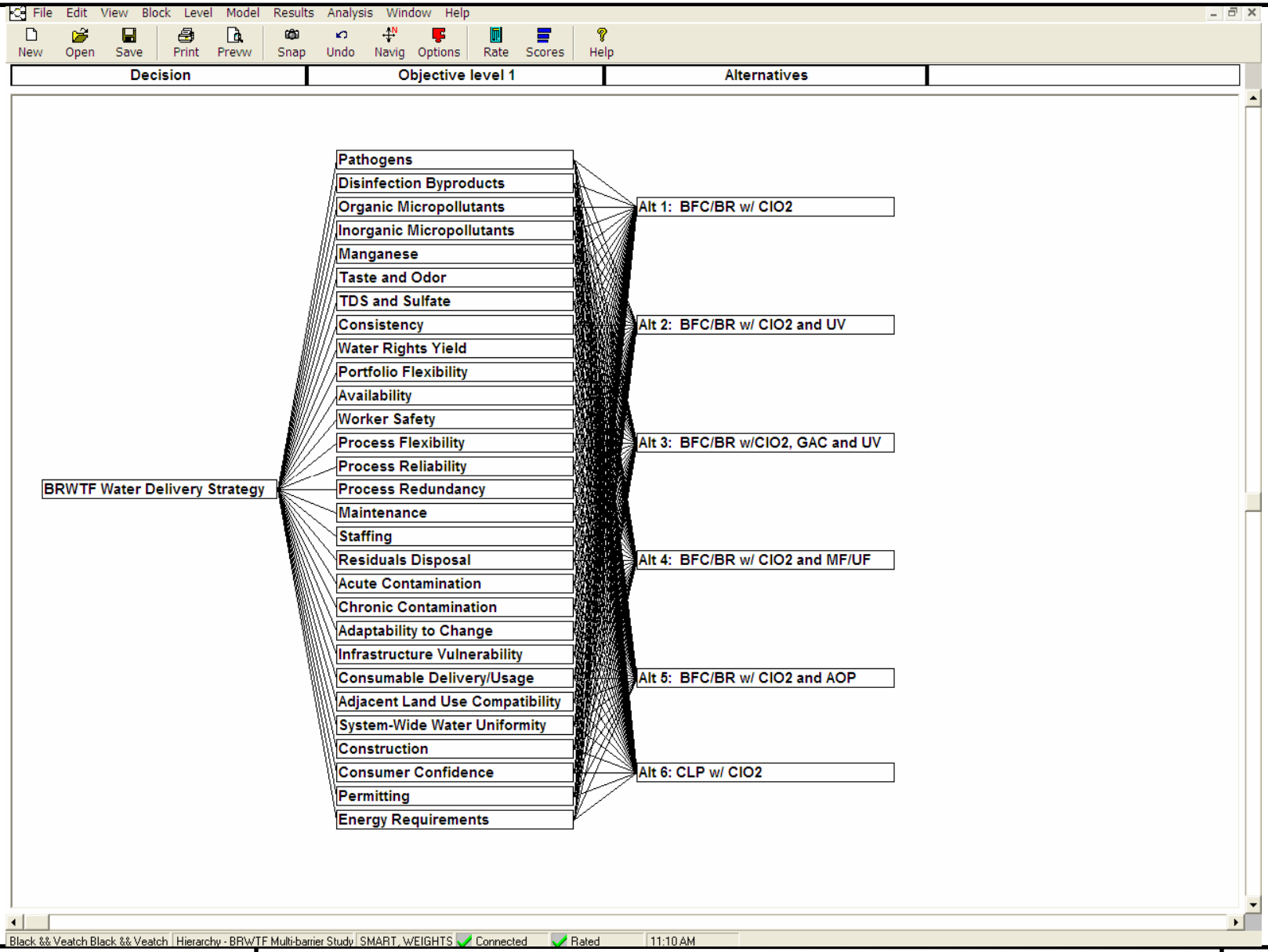
Non-Economic Performance Evaluation

The relative performance of multi-barrier water delivery alternatives developed in Chapter 5 was evaluated using the K-T® decision analysis procedure outlined in Chapter 1. The complete non-economic performance decision model including decision statement, criteria developed in Chapter 4, and multi-barrier water delivery alternatives developed in Chapter 5 is shown on Figure 6-1. Each water delivery alternative was ranked by its ability to satisfy the non-economic performance criteria relative to all other alternatives.

A. Non-Economic Performance Criteria Weighting

The set of non-economic performance criteria developed in Chapter 4 were evaluated for their relative importance in selecting a multi-barrier water delivery alternative for BRWTF. City staff assigned each performance criteria a weight between 1 and 10, with the highest value for the most important criteria. An ad hoc City staff committee (BRWTF Multi-Barrier Project Working Group) representing drinking water quality, water resources, operations, and senior management functions held a series of informal meetings and communications to develop a preliminary set of performance criteria weights based on the collective expertise and experience of the committee members. These preliminary criteria weights were formalized based on the dialog of a workshop held on December 14, 2006 between working group members and B&V. Table 6-1 lists the relative weights assigned to each decision criteria.

As part of the K-T® decision analysis process, the weight assigned to each criterion was normalized such that the sum of normalized criteria weights is equal to 1.0. Normalized criteria weights are termed priorities, as shown in Table 6-1. It should be noted that this normalization process does not change the relative importance of each criterion weight in determining water delivery alternative scores.



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K-T® Decision Analysis Model for BRWTF Multi-Barrier Approach Water Delivery Alternative Selection

Figure 6-1

Table 6-1

BRWTF Performance Criteria Weights and Water Delivery Alternative Scores

		Model Weights		Alternative Ranking Against Criteria						
Decision Statement	**Criteria**	**Weights**	**Priorities**	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**	**Alt 5**	**Alt 6**	**Alternatives:**
Select a Multi-Barrier Water Delivery Approach for BRWTF	Pathogens	10	0.056	2	10	10	10	3	6	Alt 1: BFC/BR w/ ClO2
	Disinfection Byproducts	7	0.039	9	9	9	9	10	9	Alt 2: BFC/BR w/ ClO2 and UV
	Organic Micropollutants	6	0.033	2	3	7	2	10	8	Alt 3: BFC/BR w/ ClO2, GAC and UV
	Inorganic Micropollutants	4	0.022	6	6	6	6	8	10	Alt 4: BFC/BR w/ ClO2 and MF/UF
	Manganese	6	0.033	8	8	8	8	8	10	Alt 5: BFC/BR w/ ClO2 and AOP
	Taste and Odor	6	0.033	5	5	7	5	10	8	Alt 6: CLP w/ ClO2
	TDS and Sulfate	6	0.033	3	3	3	3	3	10	
	Consistency	6	0.033	2	2	2	2	2	10	
	Water Rights Yield	10	0.056	5	5	5	5	5	10	
	Portfolio Flexibility	8	0.044	5	5	5	5	5	10	
	Availability	9	0.050	5	5	5	5	5	10	
	Worker Safety	10	0.056	10	7	6	6	6	10	
	Process Flexibility	6	0.033	6	8	8	8	10	6	
	Process Reliability	9	0.050	7	6	5	6	6	10	
	Process Redundancy	9	0.050	6	8	9	6	10	10	
	Maintenance	3	0.017	10	7	4	8	6	10	
	Staffing	3	0.017	8	7	7	9	5	10	
	Residuals Disposal	5	0.028	7	7	5	5	5	10	
	Acute Contamination	10	0.056	3	3	3	3	3	10	
	Chronic Contamination	10	0.056	2	5	7	5	8	10	
	Adaptability to Change	8	0.044	2	5	7	5	8	10	
	Infrastructure Vulnerability	2	0.011	4	4	4	4	4	10	
	Consumable Delivery/Usage	1	0.006	10	8	5	4	4	10	
	Adjacent Land Use Compatibility	8	0.044	4	4	4	4	3	10	
	System-Wide Water Uniformity	3	0.017	3	3	3	3	3	10	
	Construction	1	0.006	10	7	4	7	6	4	
	Consumer Confidence	8	0.044	6	7	10	7	7	10	
	Permitting	1	0.006	10	8	6	8	8	6	
	Energy Requirements	5	0.028	5	3	3	4	2	10	
				0.512	**0.573**	**0.606**	**0.554**	**0.603**	**0.942**	**Alternative Performance Scores**

B. BRWTF Multi-Barrier Alternative Performance Scores

The multi-barrier alternatives developed in Chapter 5 were ranked against the weighted decision criteria listed in Table 6-1. B&V established the relative performance of each water delivery alternative against each decision criterion in turn by assigning scores between 1 and 10, with the highest value for the alternative(s) that best satisfied the intent of the criterion. It is important to note that assigning a score of 10 to an alternative for any given criterion does not imply that the alternative satisfies the criterion perfectly, but rather that it most closely satisfies the intent of the criterion. Remaining alternatives were assigned lower scores based on their ability to satisfy the given criterion relative to the alternative that best satisfies that criterion.

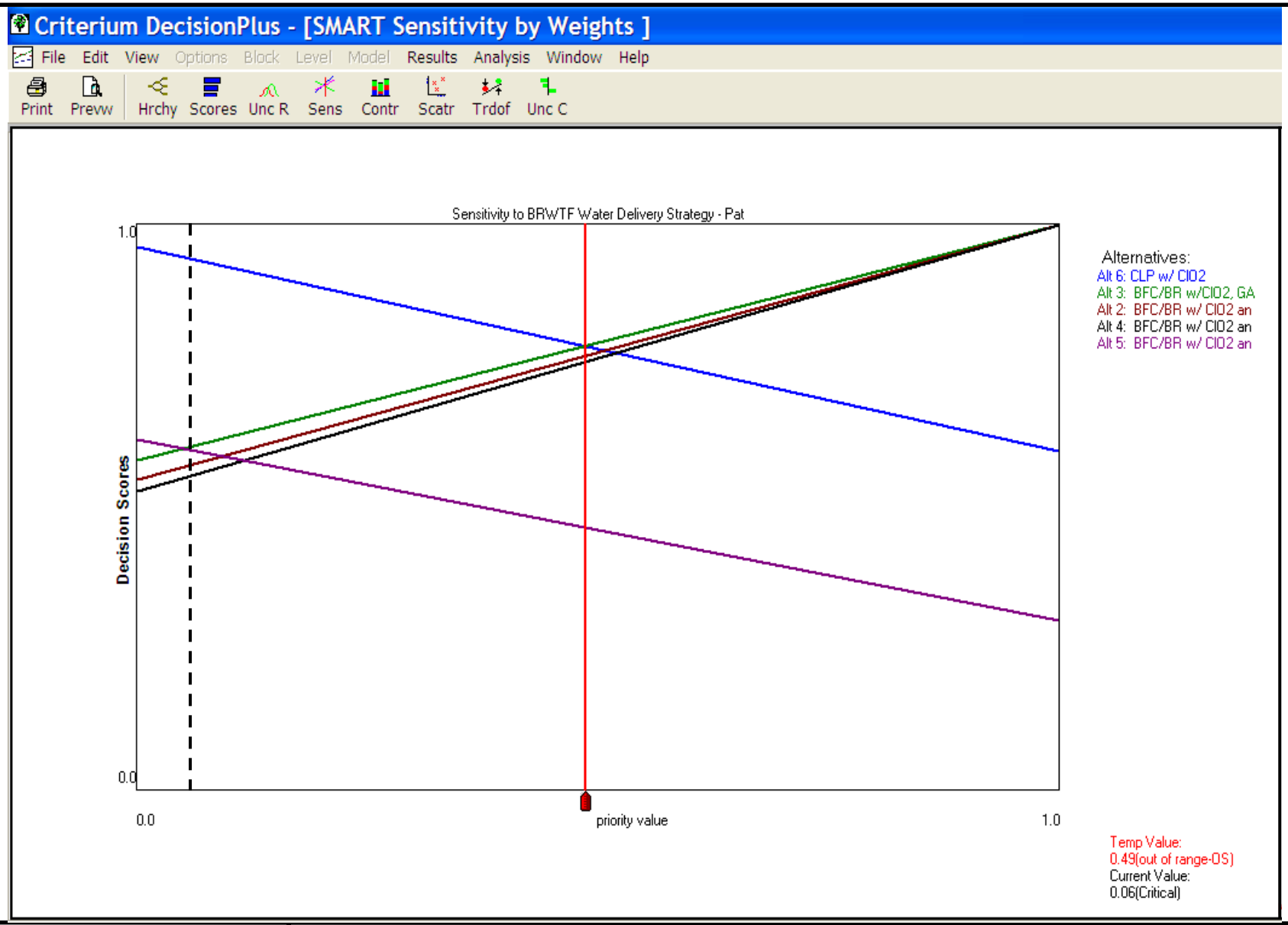
The general approach taken in ranking BRWTF water delivery alternatives against each criterion was that wherever possible prevention of contamination during raw water delivery to BRWTF is a superior strategy to subsequent treatment at BRWTF. The working group developed a preliminary set of guidelines for scoring alternatives against each criterion, as listed in Appendix 2. Minor changes discussed in a workshop held January 18, 2007 with the project Working Group and B&V were incorporated with the preliminary guidelines to formalize the multi-barrier water delivery scoring process. Worksheets used during BRWTF multi-barrier water delivery alternative scoring are given in Appendix 2.

In the K-T® decision analysis process performance scores for each alternative are calculated as the sum of the products of decision model criteria priorities and each set of respective alternative scores. These performance scores are expressed on a scale of 0 to 1, with higher values indicating better alternative performance. As shown in Table 6-1, non-economic performance scores for the BRWTF water delivery alternatives evaluated in this study were clustered between 0.5 and 0.6 for all but Alternative 6, which had a performance score of 0.942.

C. Alternative Performance Sensitivity Analysis

The non-economic analysis performed here indicates that Alternative 6 is the highest ranked BRWTF multi-barrier water delivery alternative, followed by Alternatives 1 through 5 with non-economic performance scores that were

grouped in a substantially lower range. The sensitivity of this alternative ranking to the criteria weights assigned was evaluated using the sensitivity analysis feature of the Criterium DecisionPlus® software package used to perform decision analysis calculations. The change in each decision model criteria weight required to alter the ranking of alternatives was determined, as illustrated graphically in Figure 6-2 for the Pathogens criterion. In this figure, the dashed vertical line shows the criterion weight assigned by the Project Working Group, and the vertical solid red line indicates the *critical priority value* (critical normalized weight) required to alter the BRWTF water delivery alternative ranking. Thus, if the Pathogens criterion assigned priority value of 0.056 were increased to 0.49 or greater then Alternative 3 would be the highest ranked alternative. However, the Pathogens criterion was assigned the maximum weight of 10, so a critical priority value of 0.49 would correspond to a criterion weight substantially greater than 10 (161 in this case). Because adjusting any assigned criterion weight to a value outside the 0 to 10 range used in the decision analysis procedure would be meaningless, the ranking of BRWTF multi-barrier water delivery alternatives was not sensitive to the weight assigned to the Pathogens criterion. Similar analysis of all other decision model criteria indicates that the ranking of alternatives was not sensitive to the weight assigned to any criterion.



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BRWTF Multi-Barrier Water Delivery Alternative Ranking Sensitivity: Pathogens Criterion

Figure 6-2

Chapter 7

Multi-Barrier Approach Economic Evaluation

The relative economic merit of multi-barrier water delivery alternatives developed in Chapter 5 was evaluated based on a life-cycle cost present value analysis that included capital, O&M, and project financing costs.

A. Economic Evaluation Principles and Parameters

The economic analysis performed in this study was based on applying a common set of unit process and O&M costs to each BRWTF multi-barrier water delivery alternative. The Class 4 planning level cost opinions presented here reflect use of standard engineering practices and were prepared without the benefit of detailed engineering designs. As defined by The Association for the Advancement of Cost Engineering, Class 4 cost opinions of this type are generally considered to have an accuracy range of plus 50 to minus 30 percent. Any actual project cost would depend on current labor and material costs, competitive market conditions, final project scope, bid date, and other variable factors. These cost opinions are perhaps best used to compare relative multi-barrier water delivery alternative costs, rather than actual project costs.

A 30-year life-cycle was assumed for each water delivery alternative evaluated consistent with industry standard expected service lives for major drinking water treatment equipment. Because the expected useful life of large diameter subterranean transmission mains is considerably longer than 30 years, the residual value of the Carter Lake Pipeline beyond this time was credited to the net present value cost opinion for Alternative 6. Useful life for large diameter welded steel pipe of the type proposed for the Carter Lake Pipeline was conservatively estimated using representative survival functions to be 70 years (Quantifying Future Rehabilitation and Replacement Needs of Water Mains, AWWARF, 1998). Other common economic analysis parameters used include a 2007 baseline, an O&M inflation rate of 4 percent, a loan interest rate of 6 percent, and a present worth factor of 4 percent.

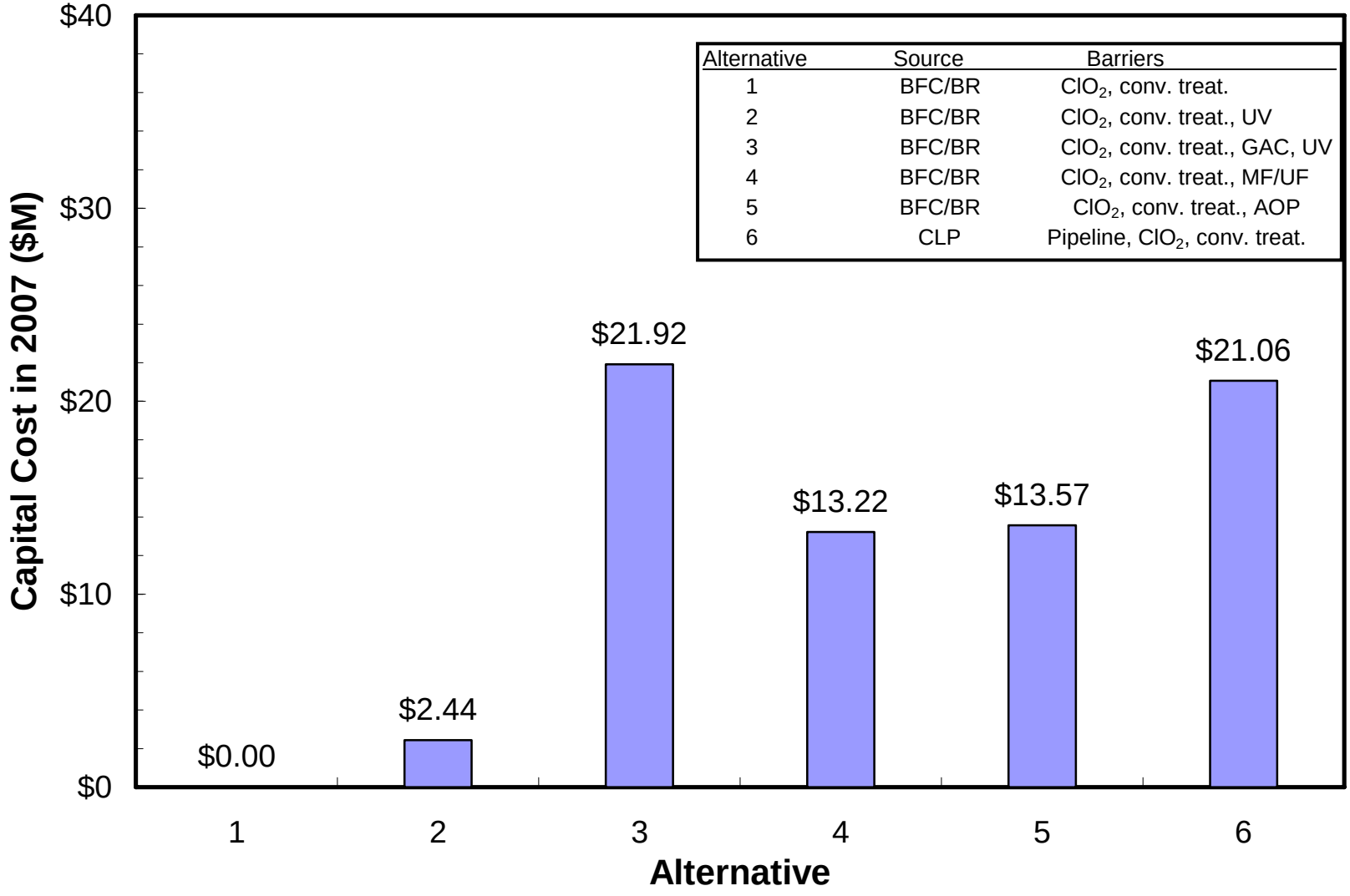
B. Capital Cost Opinions

Capital cost opinions include material and construction estimates for process equipment and basins, any additional structures needed to house process equipment, electrical service, instrumentation and control, site work, yard piping, and general contracting. Engineering, legal, and administrative expenses were estimated to be 20 percent of the material and construction cost subtotal. Similarly, a contingency factor of 25 percent was applied to the material and construction subtotal. Present value life-cycle capital cost opinions were generated using the economic parameters given above for a firm capacity of 16 mgd at BRWTF.

The capital cost opinions for BRWTF multi-barrier water delivery alternatives evaluated as part of this study are given in 2007 dollars as shown in Figure 7-1, and the associated life-cycle present value of these capital costs are given in Figure 7-2. As shown in Figure 7-1, the capital costs varied widely between no additional capital expenditure for Alternative 1 and $22M for Alternative 3. The present value of these capital costs are slightly higher due to project financing at 6 percent interest over the 30-year project life-cycle. The present value of Alternative 6 is substantially less than its estimated cost in 2007 dollars because the residual value of the pipeline beyond 30 years was credited to this alternative. It should be noted that these capital costs estimates are in addition to any capital costs related to planned mid-term improvements including chlorine dioxide pre-oxidation and finished water pH adjustment.

C. O&M Cost Opinions

O&M costs were determined for the 30-year life-cycle used for economic evaluation purposes. These O&M estimates included treatment chemical, other consumables such as UV lamp and ballast replacement, GAC replacement, pumping and other energy costs, and scheduled equipment maintenance. An average daily flow rate of 5 mgd was used to calculate variable consumable and energy O&M costs. This production rate was slightly higher than the 4.55 mgd average daily flow in 2006 to account for future growth in the BRWTF service area.



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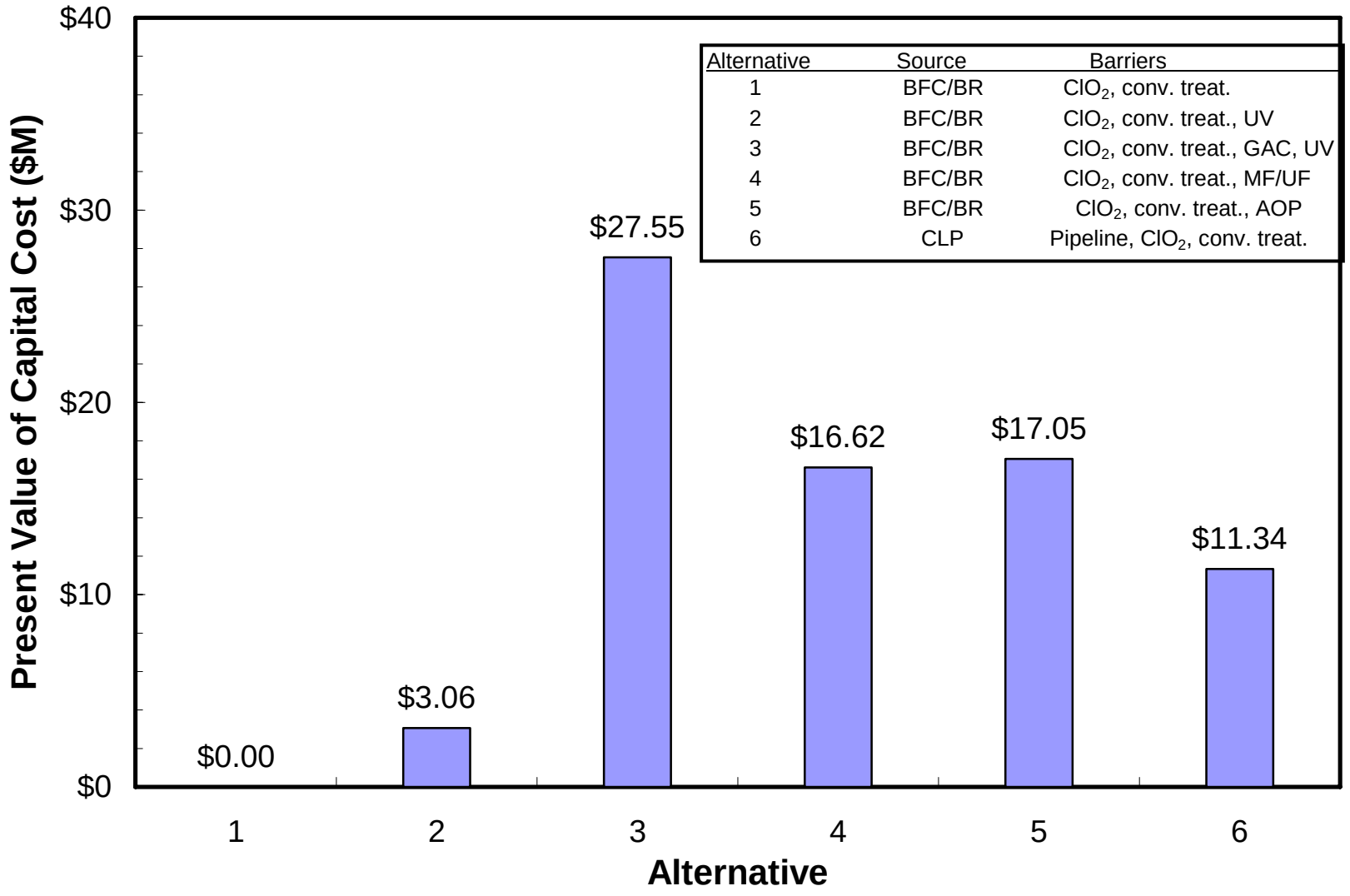
Capital Costs for BRWTF Multi-Barrier Approach
Water Delivery Alternatives in 2007 Dollars

Figure 7-1



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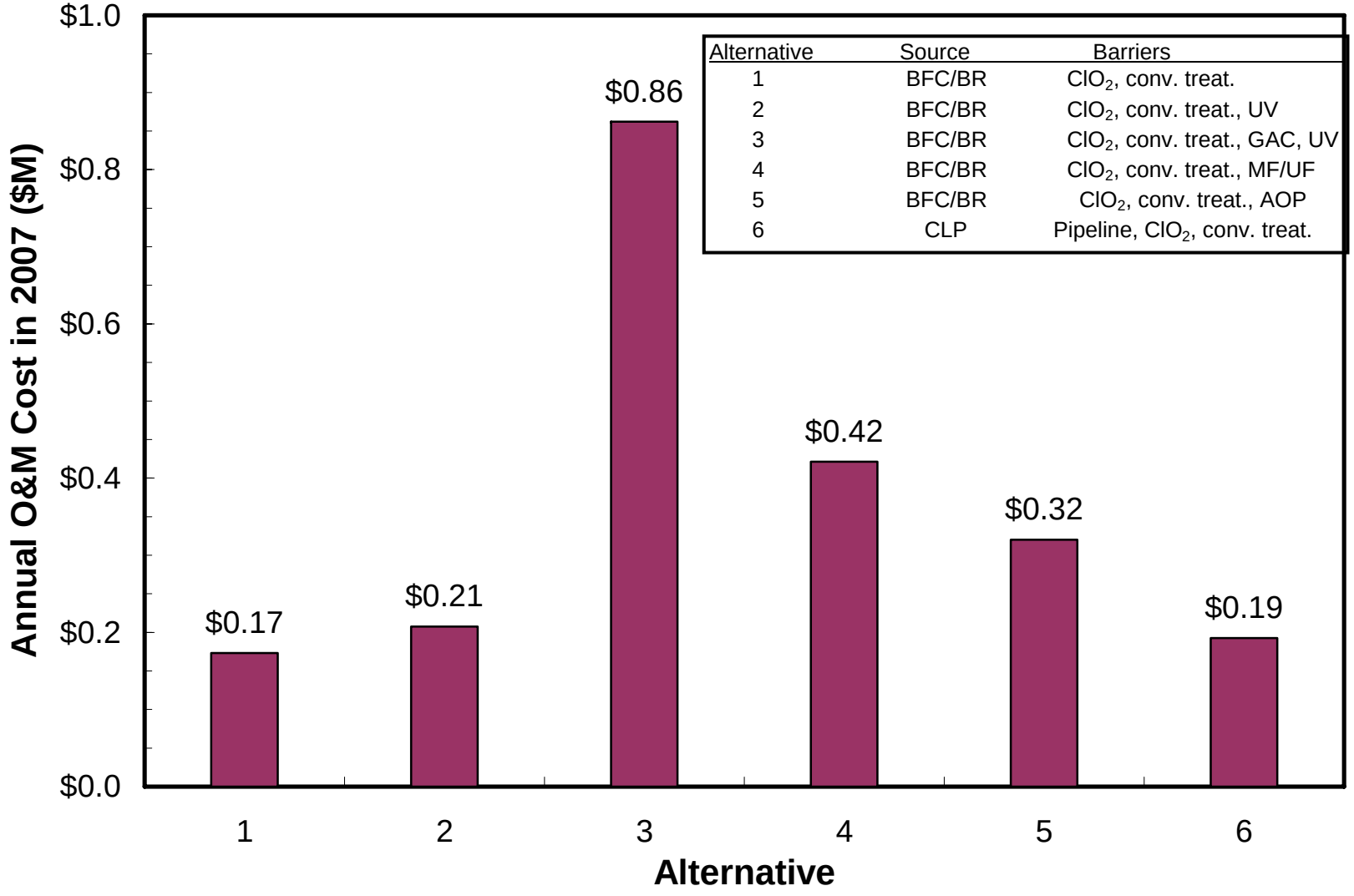
Present Value of Capital Costs for BRWTF Multi-Barrier Approach Water Delivery Alternatives

Figure 7-2

Annual O&M cost opinions for BRWTF multi-barrier water delivery alternatives evaluated as part of this study are given in 2007 dollars as shown on Figure 7-3, and the associated life-cycle present value of these O&M costs are given in Figure 7-4. Annual O&M costs for Alternatives 1, 2, and 6 were clustered between $170k and $210k, with considerably higher values of $860k, $420k, and $330k for Alternatives 3, 4, and 5. The higher annual O&M estimates for Alternatives 3, 4, and 5 reflect costs associated with semi-annual GAC replacement, membrane replacement and cleaning chemicals, and precursor chemicals for advanced oxidation, respectively. The present value of these O&M costs reflects an annual inflation rate of 4 percent, applied each year throughout the project life-cycle. The additional O&M costs for chlorine dioxide preoxidation and pH adjustment planned as mid-term improvements were include for all water delivery alternatives.

D. Net Present Value Opinions

The total net present value cost opinions for BRWTF multi-barrier water delivery alternatives were calculated as the sum of net present capital and O&M costs, as shown on Figure 7-5. Water delivery alternative net present value estimates varied widely between $5.2M and $53.4M, based largely on the number and type of additional contaminant barriers. The comparatively lower net present values for Alternatives 1 and 2 reflect the lack of an effective barrier for organic micropollutants, and a less robust set of barriers for taste and odor control. The comparatively higher net present values for Alternatives 3 and 5 reflect a premium required when organic micropollutant and taste and odor control are provided by treatment rather than source water protection, whereas Alternative 4 has a higher net present value due primarily to membrane replacement costs.



Alternative	Source	Barriers
1	BFC/BR	ClO_2, conv. treat.
2	BFC/BR	ClO_2, conv. treat., UV
3	BFC/BR	ClO_2, conv. treat., GAC, UV
4	BFC/BR	ClO_2, conv. treat., MF/UF
5	BFC/BR	ClO_2, conv. treat., AOP
6	CLP	Pipeline, ClO_2, conv. treat.

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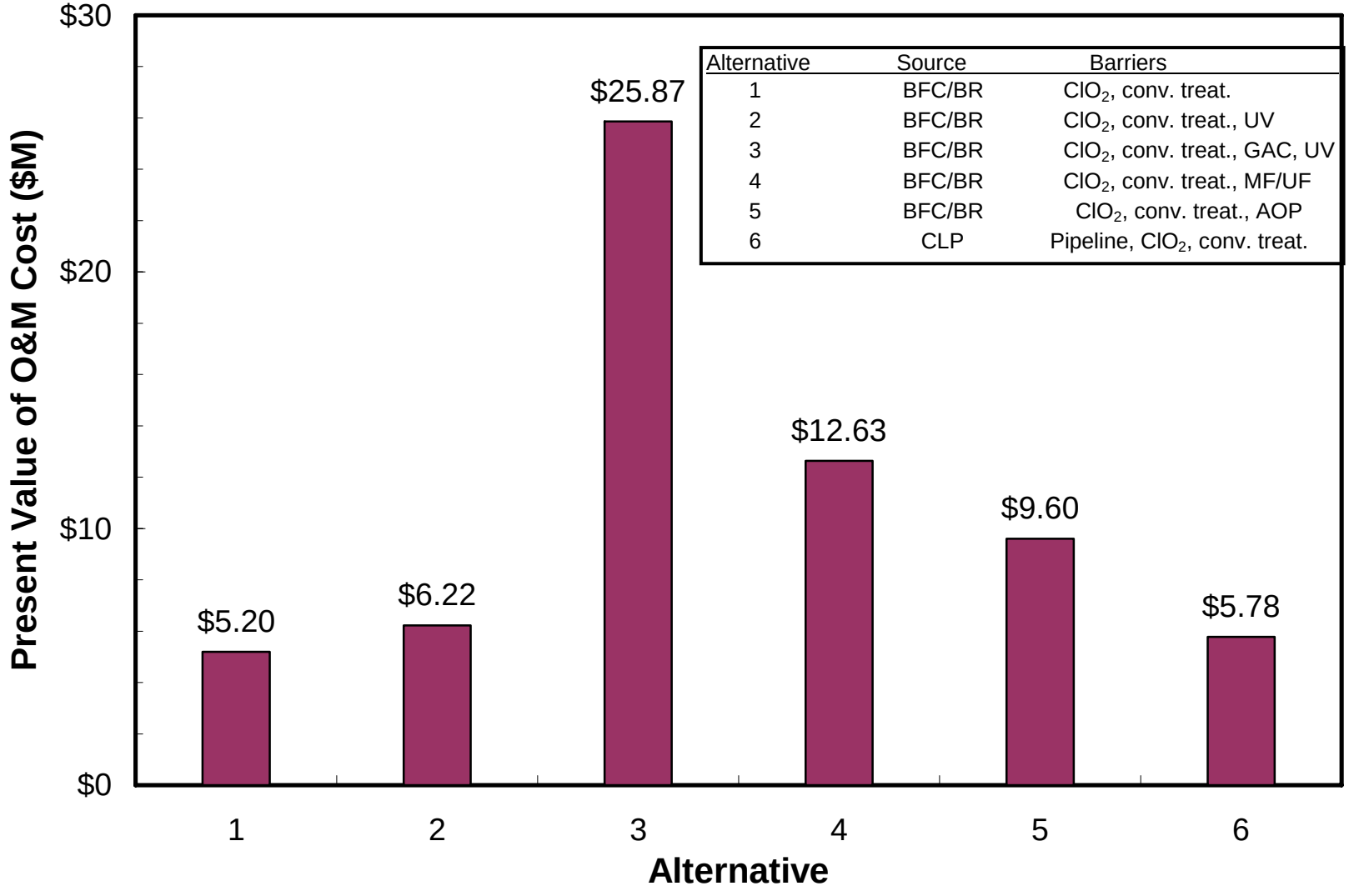
Annual O&M Costs for BRWTF Multi-Barrier Approach
Water Delivery Alternatives in 2007 Dollars

Figure 7-3



Alternative	Source	Barriers
1	BFC/BR	ClO_2, conv. treat.
2	BFC/BR	ClO_2, conv. treat., UV
3	BFC/BR	ClO_2, conv. treat., GAC, UV
4	BFC/BR	ClO_2, conv. treat., MF/UF
5	BFC/BR	ClO_2, conv. treat., AOP
6	CLP	Pipeline, ClO_2, conv. treat.

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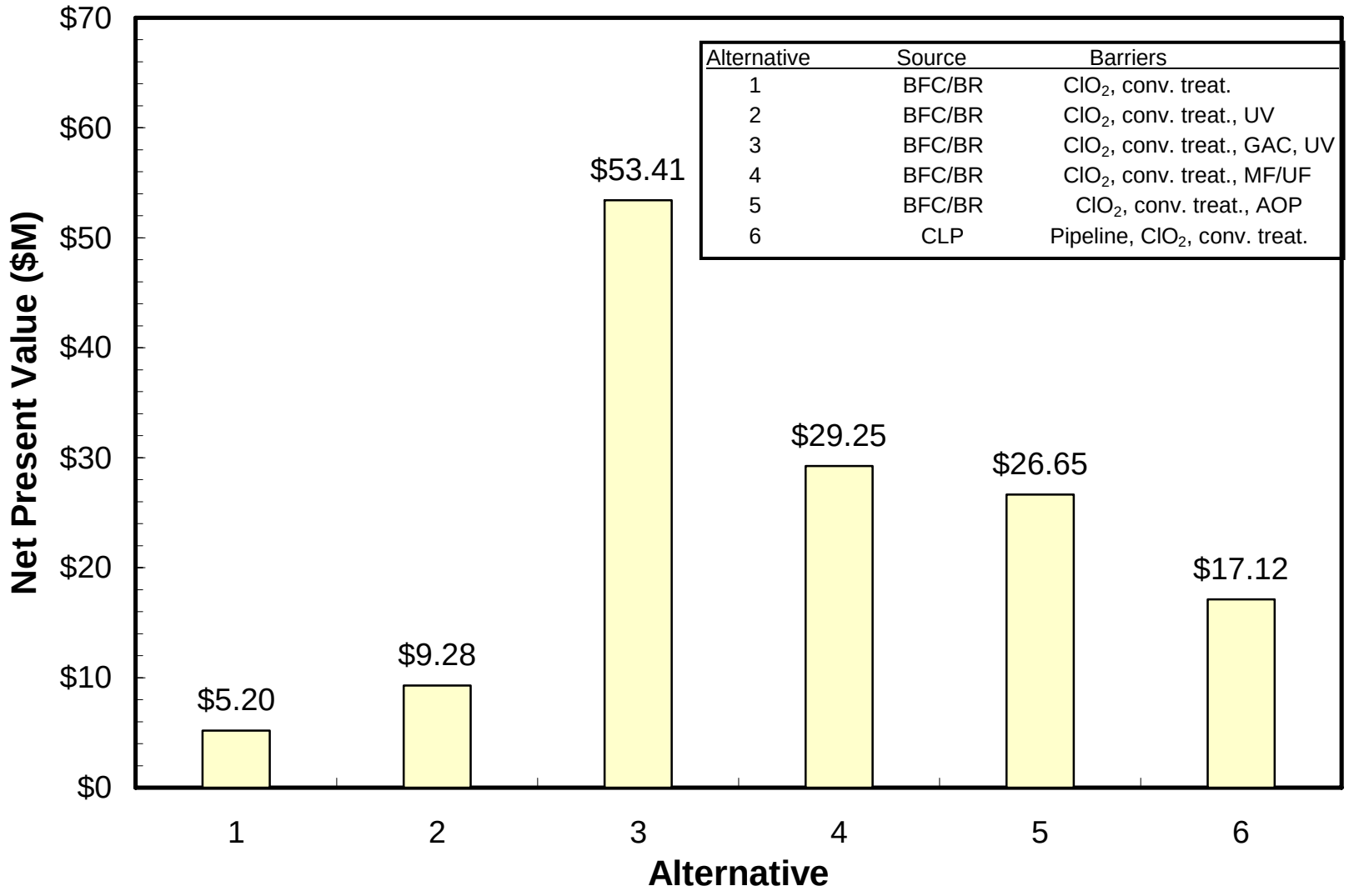
Present Value of O&M Costs for BRWTF Multi-Barrier Approach
Water Delivery Alternatives

Figure 7-4



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Net Present Value of BRWTF Multi-Barrier Approach
Water Delivery Alternative Selection

Figure 7-5

Chapter 8

Preferred BRWTF Multi-Barrier Alternative

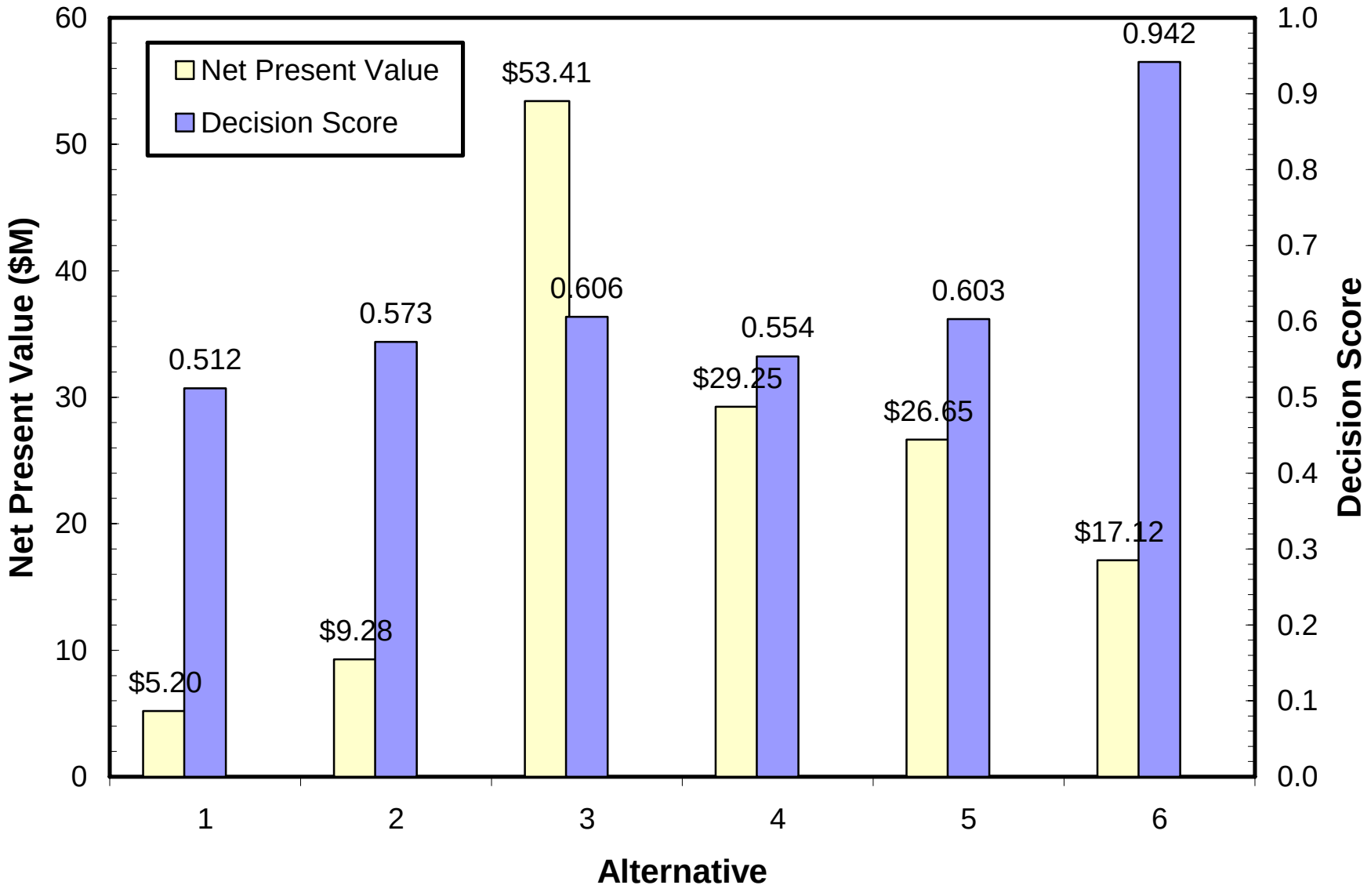
The non-economic performance score of each BRWTF multi-barrier water delivery alternative was determined using the Kepner-Tregoe® decision analysis procedure. Economic evaluation of each water delivery alternative was also performed, based on the net present value of each alternative, which includes capital costs, operation and maintenance costs, and project financing. This chapter presents these non-economic performance and economic evaluations together to provide a cost-performance comparison of BRWTF multi-barrier water delivery alternatives. Based on a balanced assessment of source water quality information, regulatory requirements, City drinking water quality goals, non-economic performance scoring, and net present cost economic evaluations a preferred BRWTF multi-barrier water delivery alternative is identified.

A. Cost-Performance Comparison

Non-economic performance scoring and economic evaluations of candidate multi-barrier BRWTF alternatives were described in Chapters 6 and 7, respectively. Because of the large variations in alternative performances and net present values, these values are shown side-by-side to help assess the relative benefits for each water delivery alternative, as shown in Figure 8-1.

B. Preferred BRWTF Water Delivery Alternative

Both performance and cost varies widely among the six BRWTF water delivery alternatives evaluated. *Considering source water quality information, relative risk of source water contamination, regulatory requirements, City drinking water quality goals, and operational flexibility B&V believes that Alternative 6, complete source water containment from Carter Lake to BRWTF with chlorine dioxide preoxidation, is the most desirable and preferred alternative*. Although Alternative 6 does not have the lowest net present value among those evaluated, it has a number of compelling benefits that are not provided by the other alternatives including:



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Cost-Performance Comparison for BRWTF Water Delivery Alternatives

Figure 8-1

- Of the BRWTF multi-barrier water delivery alternatives evaluated here, Alternative 6 alone follows the century old paradigm of drinking water treatment in that it treats the best available water source with the simplest and most robust combination of processes.

- Alternative 6 has the best non-economic performance by a wide margin. This alternative satisfied 22 of 28 criteria evaluated as well or better than the other alternatives.

- Alternative 6 is unique among those evaluated in that it alone addresses the near and long term potential for continued degradation of water quality in existing BRWTF sources due to continued residential development, extensive agricultural land use, and increasing recreational use. Although notable advances in treatment technology have been made in recent years, contaminant removal during drinking water treatment is still an imperfect science. Thus, as has traditionally been the case, preventing source water contamination provides a more robust barrier than subsequent treatment as the first line of defense in protecting public health.

- Other regional drinking water providers also desire to use a dedicated pipeline from Carter Lake for raw water delivery to their facilities. Combining raw water conveyance to BRWTF with that of other providers allows more efficient use of scarce regional water resources.

- Full containment of raw water conveyance from Carter Lake to BRWTF would provide additional flexibility in managing the City's water resources portfolio. Other water delivery alternatives require seasonal storage of raw water in Boulder Reservoir for use when BFC in not in service. Year-round storage in Carter Lake would remove the need to project annual seasonal storage required in Boulder reservoir, and thus avoid the undesirable consequences that result if seasonal Boulder Reservoir storage is substantially overestimated.

- Conveyance of raw water through a Carter Lake pipeline would be consistent with the City's historical policy of protecting source water quality by providing full containment from its other water sources.

- Full containment from Carter Lake to BRWTF would provide a much more uniform raw water quality, substantially simplifying treatment optimization and increasing treatment process reliability.

- Alternative 6 is the only BRWTF water delivery approach that provides at least one robust barrier for each contaminant category considered in this study.

Goal: Provide Safe and Reliable Potable Water			
Strategy	**Action**	**Measurable Criteria**	
Comply with all drinking water regulations.	• Continue high quality treatment • Evaluate DBP compliance forecast and establish DBP reduction plan, if needed. • Perform LT2 monitoring, establish treatment bin, and install treatment as required.	Achieve 100% compliance for all standards	
Use best practices to maintain high quality treated water.	• Jar test regularly • Evaluate filter media on a regular basis • Investigate problem filters when they become apparent	BRWTP: • SCD: 0± 0.5 • Zeta Potential: 0 – -5 • Settled Turbidity: < 1 NTU 90% of time sampling every 15 minutes • Settled Turbidity: < 2 NTU at all times • Start-up Filter Turb: ≤ 0.3 NTU at end of 30 minutes • Filter Turb: ≤ 0.1 NTU in 95% of IFE 15 minutes samples; • Filter Turb: ≤ 0.15 NTU at all times • Filter Particle Count: <25/mL for particles > 2 μm in 95% of • Filter Loading Rate: ≤ 5 gpm/sqft • Filter Run Time: > 60 hours • Filter Rest Before Start-up: ≥ 3 hours • Inactivation: > 95% of	Betasso WTP: • SCD: 0 • Zeta Potential: -3 • Zeta Alkalinity: ≥ 9.0 mg/L • Settled Turbidity: < 3.0 NTU • Settled pH: 6.4 – 6.8 • Settled Cl2: 0.5 mg/L • Filter Run time: ≤ 40 hours • Filtration Rate: 5 gpm/sf or 5 mgd max • Hydraulic change/filter: < 1.0 mgd • Filter Rest Time: 3 hours • Start-up Filter Turb: < 1 NTU w/in 15 min of startup • Filter turbidity: < 0.15 NTU

		minimum performance measure • Cl_2 Dose: < 2.0 mg/L • Combined filter effluent Cl_2: 0.4 mg/L	• Filter particle count: < 25 total counts • Combined filter turbidity: < 0.1 NTU • Combined filter particle counts: < 25 total counts • Combined filter Cl_2: 0.1 mg/L
Seek alternative methods to increase delivered water quality.	• Implement necessary upgrades to the BRWTF to ensure a multi-barrier system. • Improve clarification treatment. • Partnership for Safe Water – Phase III • Implement the AWWA Standard for Water Treatment Plant Operations and Management (G200-05) • Join AwwaRF (American Water Works Association Research Foundation)	BRWTF finished water: • pH: 7.8 ± 0.2 • Alkalinity: 40 to 50 mg/L $CaCO_3$ • Hardness: <60 ppm • Turbidity: < 0.1 NTU • Sulfate: < 20 ppm • Sodium: 5-20ppm • TDS: < 100 ppm • Conductivity: < 200 μmhos/cm • Temperature: < 20 ^{o}C • Fluoride: 0.9 ± 0.1 mg/L • Cl_2: 1.1+ 0.1 mg/L Manganese: < 0.03 mg/L	Betasso finished water: • pH: 7.8+ 0.2 • Alkalinity: 45 + 3 mg/L $CaCO_3$ • • Turbidity: < 0.1 NTU • • • • • • • Fluoride: 0.9 + 0.1 mg/L • Cl_2: 1.2 + 0.1 mg/L
	• Improve disinfection	Meet minimum daily control levels: • 99.99% removal of *Giardia* • 99.999% removal of *Cryptosporidium* • 99.999% removal of enteric viruses	

Deliver similar and consistent finished water quality from both plants.	• Set uniform levels for water quality parameters. • Develop program to bring water from both plants into consistent range for measured parameters. • Control pH and/or ORP of finished water.	Maintain finished water: • Hardness < 60 mg/L • Alkalinity 40 to 50 mg/L • pH: 7.8 ± 0.2 • Turbidity < 0.1 NTU • Sulfate < 20 mg/L • Sodium: 5-20 mg/L • TDS < 100 mg/L • Specific Conductance < 200 umhos/cm • Temperature < 20 oC • No detectable taste and odor • Manganese < 0.03 mg/L • Fluoride: 0.9 ± 0.1 mg/L
Maintain consistent water quality throughout the distribution system.	• Minimize effect of mixing regions by implementing consistent multiple-plant finished water quality program • Implement the AWWA Standard for Distribution System Operations and Maintenance (G200-04)	
	• Develop a monitoring program for the distribution system and a plan for adjusting water quality where necessary.	pH: 7.8 ± 0.3 at 95% of locations sampled monthly for total coliforms Free Cl2: 0.5 ± 0.1 mg/L at 95% of locations samples monthly
	• Investigate Pb/Cu corrosion behavior and status.	No Lead and Copper Rule violations
	• Develop a bacterial regrowth action plan.	Maintain heterotrophic plate count bacteria levels < 100 counts/mL in 95% of monthly distribution system samples
	• Develop a plan to meet DBP criteria for reduced monitoring under Stage 1 DBPR and Stage 2 DBPR.	Maintain locational running annual average TTHM and HAA5 levels less than 40 ug/L and 30 ug/L, respectively.
	• Develop a plan to maintain water quality in distribution system reservoirs	

Reinforce distribution system integrity	Implement and maintain effective backflow prevention program. • Require mandatory installations for all new construction • Create a retrofit program for existing connections • Require and perform an annual check of all BFPs • Require mandatory installation of BFPs for temporary connections during construction • Perform routine inspection of construction sites to assure compliance • Require mandatory BFPs for source water hydrants • Assess staffing needs for implementation	
	• Ensure integrity of all distribution system storage tanks.	Pass weekly inspection of all tanks to assure integrity.
Meet all customer demands during normal operations and critical demands during emergencies or droughts.	• Acquire adequate water rights	Maintain • > 20 years: No interruption of outdoor use • > 100 years: No interruption of outdoor use with major loss • 1,000 years: No interruption of indoor essential use
	Deliver sufficient raw water to treatment plants	• Minimum storage: 3-5 MG • Minimum source delivery to WTPs: o Betasso – greater of 5 MGD or Zone 3 indoor use o Boulder Reservoir – 5 MGD
Ensure daily reliable plant operations at design flows	Implement plant maintenance management program	• Minimum production: o Betasso – greater of 5 MGD or Zone 3 indoor use o Boulder Reservoir – 5 MGD • Maximum production: o Betasso - entire system demand:

		internal use demand plus a margin of safety (16 MGD) o Minimize unscheduled shutdowns of BRWTP
Meet daily demand fluctuations and maintain minimum fire flow protection levels	• Provide sufficient storage • Operate to meet demands and to optimize water quality in the distribution system.	Maintain total storage: • Winter Daily: > 18 MG • Summer Daily: > 28 MG • Absolute Minimum: 5 MG • Maintain zone-specific storage: • Daily: > • Absolute Minimum: • Firm Yield Capacity Requirements by Zone:
Improve source water quality protection	• Develop a source water protection rules • Implement source water reservoir management plans • Continue source water monitoring program to track water quality conditions temporally and spatially • Implementation of a mid-level intake at Boulder Reservoir (completed 2005) • Implementation of a manganese control strategy using source management techniques (e.g., in situ aeration) • Improve communication and coordination for source water selection • Develop and communicate a Risk Index • Coordinate with NCWCD to maximize flow through Boulder Reservoir • Determine best source based on treatability and quality • Coordinate with County Planning to ensure watershed protection in planning process	• Hold routine weekly meetings of appropriate staff to make source water selection decisions
Integrate public health risk factors into source water and treatment management decisions.	• Develop a Public Health Protection Index (PHPI) or Risk Index	

	• Establish Stakeholder group to assist in PHPI process • Establish consensus of internal and external decision-makers on the PHPI applications.	
Improve knowledge of emerging contaminant occurrence	• Perform the monitoring program included in the Unregulated Contaminant Monitoring Regulation. • Continue to track unregulated contaminants to determine risk and evaluate monitoring need.	• Volunteer for AwwaRF participation in research projects of interest
Goal: Provide Responsive Customer Service		
Strategy	**Action**	**Measurable Criteria**
Deliver aesthetically pleasing and safe water	• Evaluate causes of past customer complaints • Develop program for system flushing • Implement program for customer response to complaints	Continuous decrease in water quality customer complaint calls
Disseminate water quality and utility information to the public	• Update web site with: o Summarized customer survey results o Water quality "frequently asked questions" o Water quality data • Distribute annual CCR	
Identify areas of improvement for customer service and utility management	• Participate in Qual Serve (AWWA)	
Develop public education programs	• Source water quality • Source water protection	
Goal: Operate Cost Effectively		
Strategy	**Action**	**Measurable Criteria**
Establish utility rates that reflect water services delivered to customers, including 1. Quality 2. Volume 3. Education 4. Source management and protection 5. Demand management	• Complete economic analysis of rates • Establish new water rates as appropriate	

6. Treatment 7. Distribution		
Goal: Promote Environmental Stewardship of our Natural Resources		
Strategy	**Action**	**Measurable Criteria**
Reduce total system demands	• Implement and support the Board-approved water conservation program "Comprehensive Conservation Program"	Reduce total system demands as follows: • Single Family: 6.22 MGD • Multiple Family: 4.94 MGD • Commercial/Industrial: 6.16 MGD • Municipal: 0.76 MGD • Unaccounted-for-water: 1.28 MDG • Total Demand: 19.4 MGD
Definitions: Goal = End toward which effort is directed Strategy = Blueprint, design, game plan, project, scheme Action = Something done or effected Criteria = Measurable standard on which a judgment or decision may be based.		

APPENDIX 2

DECISION MODEL CRITERIA AND ALTERNATIVE SCORING

Changes adopted pursuant to project Working Group workshop held January 18, 2007
[1]Finished Water Quality -- Corrosion removed -- no significant difference among alternatives -- Organic micropollutants and emerging contaminants combined -- Mn, T&O, and TDS/SO_4^{2-} added -- significant difference among alternatives [2]Source Water -- No changes to Boulder staff draft criteria of 01/03/07 [3]Water Treatment/Ops -- Monitoring/remote sensing removed -- 0 weight assigned -- Reliability/redundancy split into 2 criteria [4]Risk -- Power interruption removed -- no significant difference among alternatives [5]Environ./Public Accept -- No changes to Boulder staff draft criteria of 01/03/07

Objectives and Criteria for a Multi-Barrier Approach to Treated Water – Fall 2006

I. Musts for ALL Alternatives:

A. Meet Regulations

B. No loss of water yield

1. The City has a water rights portfolio and raw water system facilities that are used to provide sufficient raw water to meet the City's needs in accordance with adopted reliability criteria. The reliability criteria have been used to define the level of water use restrictions that might be needed for droughts with specified recurrence intervals to avoid lowering of reservoirs below safe levels to the point that delivery of water for essential health and safety needs is jeopardized. Any alternative for raw water delivery needs to be capable of maintaining the current expected level of yield of the City's water rights and must not reduce the current level of flexibility in selecting water sources.

II. Finished Water Quality Criteria

A. Pathogens - Health issue. *Disease causing organisms*.

1. A higher ranking will be given to those alternatives that best address limiting the potential for public health impacts from pathogens. Alternatives will be ranked by:
   a. Source water vulnerability
      1) Pathogen indicator counts
      2) Potential for pathogen introduction
   b. Treatment
      1) Log removal and tool box – use regulatory limits
      2) Potential for pathogens to pass through treatment process
2. Factors to consider
   a. The intent of this criterion is to address pathogen risk by selecting the best source water quality and/or treatment techniques
   b. See attached source water quality table

B. Disinfection By-Products (DBPs) - Health issue. *Formed when disinfectant (i.e. chlorine) combines with naturally occurring and/or other compounds in the water or from the disinfectant itself.*

1. A higher ranking will be given to those alternatives that minimize DBP formation and/or reduce DBP's. Alternatives will be ranked by

a. Source water
   1) Precursors (TOC)
   2) Chlorine dosage
b. Treatment
   1) Removal
   2) Oxidation and/or absorption of precursors

2. Factors to consider
   a. The intent of this criterion is to address the potential for DBP formation
   b. Similar average TOC values (3.5 mg/L) are present in Boulder Reservoir, BFC and Carter Lake
   c. See attached source water quality table

C. Micro-organic Compounds - Health issue. *Man made carbon compounds.*

1. A higher ranking will be given to those alternatives that provide the best protection against the introduction and/or removal of organic compounds (ie. pesticides, hydrocarbons) and limits the risk of organic compounds passing on to the consumer in the finished water. Alternatives will be ranked by:
   1) Source water vulnerability to organic compounds
   b. Treatment
      1) Contaminants passing through treatment
      2) Absorb organic compounds
2. Factors to consider
   a. The intent of this criterion is to evaluate the potential for man made organic compounds to enter the source water and possibly be passed on to consumers
   b. Potential for organic compounds to enter the source water – intentional, accidental or due to recreation activities
   c. Standard maintenance activities that can introduce organic compounds
   d. Potential for non-point source contributions due to precipitation events and agricultural return inflows
   e. Available source water dilution

D. Inorganic Compounds - Health issue. *Non-natural toxic chemicals such as arsenic and cyanide.*

1. A higher ranking will be given to those alternatives that provide the best protection against the introduction and/or removal of toxic inorganic compounds. The alternatives will be ranked by:
   a. Source water vulnerability to inorganic toxic compounds and chemicals
   b. Treatment

2. Factors to consider
   a. The intent of this criterion is to evaluate the potential for non-natural and natural toxic inorganic compounds to enter the source water and possibly be passed on to consumers in the finished water.

E. Emerging Contaminants - Health issue. *Unregulated contaminants that pose a health risk. Examples are gasoline additives, microbes smaller than Cryptosporidium that are resistant to chlorine, pharmaceutical drugs, new disinfection-by-products and new pesticides.*

1. A higher ranking will be given to those alternatives that provide the best protection against the introduction and/or removal of emerging contaminants to the source water and being passed on to consumers in the finished water. The alternatives will be ranked by:
   a. Source water vulnerability
      1) Gasoline additives
      2) Microbes smaller than Cryptosporidium that are resistant to chlorine
      3) Pharmaceutical drugs
      4) New pesticides
      5) New disinfection-by-products
   b. Treatment-removal and absorption capability for all categories of emerging contaminants
2. Factors to consider
   a. The intent of this criterion is to address the potential for future regulated constituents and plan ahead in a cost effective and proactive manner
   b. Animal activity
   c. Non-point sources
   d. Wastewater discharges

F. Corrosion- Health and consumer confidence issue. *Aggressive water that will leach harmful metals from pipes into the water (lead and copper).*

1. A higher ranking will be given to those alternatives that create the lowest potential for aggressive water. The alternatives will be ranked by:
   a. Source water
      1) Alkalinity
      2) pH
      3) Sulfate
   b. Treatment
      1) Corrosion control
      2) Match Betasso treated water
2. Factors to consider

a. The intent of this criterion is to provide finished water that is not considered aggressive
b. A pH below 7.8 is more corrosive
c. Alkalinity around 48 mg/L is less corrosive
d. High alkalinity above 100 mg/L increases copper corrosion potential
e. Low alkalinity increases both lead and copper corrosion potential
f. See attached source water quality table

III. Source Water

A. Water Rights Yield

1. Yield of the City's water rights portfolio is maximized over time by fully using direct flow water when available and strategic use of available reservoir storage water. Evaluation of alternatives should consider:
   a. Ability to manage stored reservoir water throughout the year
   b. Ability to manage stored reservoir water during droughts
   c. Access to raw water sources available for direct use
   d. Potential for increasing water rights yield through enhanced water management or capacity of facilities

B. Consistency of quality and quantity 24/7

1. A higher ranking will be given to those alternatives that provide the best potential for consistent finished water quality. The alternatives will be ranked by:
2. Source water
   a. Operational ease of delivering raw water at a consistent flowrate
   a. Operational ease of delivering raw water of a consistent quality
   b. Ability to blend raw water sources to improve quality
2. Treatment
   a. Reliability: Consistent treatment operation year-round with less process failure.
   b. Efficiency: Minimize chemical usage and operations staff efforts.
3. Facts to consider
   a. High quality treated water is more easily attained when raw water sources feeding the treatment plant are uniform in both quality characteristics and in flow rate of delivery. The intent of this criterion is to assess the impact on water treatment from inconsistent source water quality, including reliability and efficiency and the need for additional treatment process barriers.

C. Portfolio Flexibility (Flexibility in use of raw water supplies)

1. System reliability improves with flexibility in selection of raw water sources in response to changes in treated water demands or amount

of raw water available from a source. Evaluation of alternatives should consider:
a. Number of options available for means of delivering raw water
b. Ease of changing water sources in response to changing conditions
c. Seasonal limitations of use on raw water sources

D. Availability of Raw Water Delivery Facilities

1. Management of raw water sources is made more difficult by facilities that are unavailable for raw water delivery. Evaluation of alternatives should consider:
   a. Reliability of facilities
   b. Capacity limitations
   c. Restrictions on facilities use due to external factors affecting operations or water quality

IV. Water Treatment / Operations Criteria

A. Worker safety

1. Alternatives will be ranked highest based on least amount of staff interaction or exposure required. The alternatives will be ranked by:
   a. Chemicals
      1) Type (degree of hazard)
      2) Amount required
   b. Processes
      1) Type (complexity, hazard)
      2) Number (how many processes required)
   c. Infrastructure maintenance
      1) Cleaning grates/strainers at intakes
      2) High power
      3) Mechanical complexity
   d. Factors to consider
      1) The intent of this criterion is to evaluate the potential risk to staff based on type and amount of chemical required and type and number of processes required.

B. Process Flexibility

1. Alternatives will receive highest ranking based on the most flexibility in processes (number and type) required. The alternatives will be ranked by:
   a. Maximizing the maturity and robustness of the technology
   b. Maximizing the fabrication and engineering design of the various facilities, unit processes and components.
2. Factors to consider

a. The purpose of this criterion is to compare the need for treatment processes. The more robust and flexible a process is the broader the range of treatment concerns addressed will.
b. As source water variability and vulnerability increases the number and/or complexity of processes will increase.
c. Treatment – add table of data to support
   1) Oxidation – manganese, turbidity
   2) Caustic and/or acid - pH fluctuations
   3) Coagulant - turbidity fluctuations

C. Reliability/Redundancy

1. A higher ranking will be given to those alternatives that provide the best potential for consistent finished water quality. The alternatives will be ranked by:
   a. Source water
      1) Operational ease of delivering raw water at a consistent flow rate
      2) Operational ease of delivering raw water of a consistent quality
      3) Ability to blend raw water sources to improve quality
   b. Treatment
      1) Reliability: Consistent treatment operation year-round with less process failure.
      2) Efficiency: Minimize chemical usage and operations staff efforts.
      3) Minimize need to adjust treatment processes and/or chemical dosage on regular basis.
   c. Factors to consider
      1) High quality treated water is more easily attained when raw water sources feeding the treatment plant are uniform in both quality characteristics and in flow rate of delivery. The intent of this criterion is to assess the impact on water treatment from inconsistent source water quality, including reliability and efficiency and the need for additional treatment process barriers.

D. Maintenance

1. A higher ranking will be given to alternatives that:
   a. Minimize the complexity of facilities, unit processes and components
   b. Maximize the expected life of facilities, unit processes and components
   c. Maximize the maturity of the technology, fabrication and engineering design of the various facilities, unit processes and components

E. Monitoring/Remote Operation

1. A higher ranking will be given to those alternatives that exhibit lower complexity and higher reliability.
   a.
2. Facts to consider
   a. The intent of this criterion is to compare the complexity and reliability of the monitoring requirements of each alternative. It does not include the monetary cost of monitoring since this will be part of the monetary evaluation.

F. Staffing

1. A higher ranking will be given to those alternatives that minimize the requirements based on these parameters: include:
   a. Total number of staff
   b. Expertise of staff
   c. Supervision
2. Facts to consider
   a. The intent of this criterion is to compare the staffing requirements of each alternative. It does not include the monetary cost of staffing since this will be part of the monetary evaluation.

G. Residuals disposal

1. Alternatives will be ranked by least volume and best quality of residuals.
   a. Source water
   b. Treatment
2. Factors to consider
   a. Locations for residuals disposal are becoming increasingly difficult to find so it is important to minimize the production of residuals. (Recent analyses indicate current residuals may contain low levels of radioactivity making it even more difficult to dispose of.)

V. Risk

A. Unexpected Acute Contamination

1. A higher ranking will be assigned to those alternatives that best minimize potential public health impacts from such risk. The alternatives will be evaluated by
   a. Potential for slug-loading of a large amount of harmful contaminant(s) with potential for treatment breakthrough

   b. Potential for slug-loading of contaminant(s) with the capability for disabling or disrupting water service on a temporary or long-term basis
2. Facts to consider
   a. Initial specific risk/contaminant/treatability criteria and assessments for water supplies addressed in this study have been developed as a part of the 2003 Water Utility Vulnerability Study. Further development of detailed source/treatment risk assessment information for these supply/treatment system, as well as for the entire city of Boulder treatment/source portfolio, is currently being planned by the city's utility security work group(with the goal of incorporating the findings into this and other related long-term utility planning efforts).

B. Unexpected Chronic Contamination

1. A higher ranking will be assigned to those alternatives that best minimize potential public health impacts from such risk. Alternatives will be evaluated by
   a. Potential for contamination from bodily contact with the source (wild or domestic animal and/or human)
   b. Potential for contamination from other recreational activities adjacent to supply
   c. Potential for contamination from outfalls emptying into supplies
2. Facts to consider
   a. The intent of this criterion is to address day-to-day risks due to existing non-point-sources in water supplies. Focus is on contaminants that are difficult to remove or inactivate through treatment and on events that could cause a moderate to significant waterborne disease.
   b. Initial specific risk/contaminant/treatability criteria and assessments for water supplies addressed in this study have been developed as a part of the 2003 Water Utility Vulnerability Study. Further development of detailed source/treatment risk assessment information for these supply/treatment system, as well as for the entire city of Boulder treatment/source portfolio, is currently being planned by the city's utility security work group(with the goal of incorporating the findings into this and other related long-term utility planning efforts).

C. Adaptability to Unexpected Future Changes -

1. Future changes in source water quality. A higher ranking will be assigned to those alternatives that best minimize risk of public health impacts from potential future increases in source WQ risks.

   a. The intent of this criterion is to address the tendency toward increased risk over time from contaminant sources noted in (A.2.) as a function of:
      1) Local or regional policy(s) regarding activities allowed or encouraged in or near drinking water supplies.
2. Facts to consider
   a. Increased level of impacting activities over time in popular water supply corridors.
   b. Increased source contamination risks/loading will increase background public health risks as well as increase the likelihood of peaking events/ waterborne disease outbreak(s). Specific risk information to support this criterion to be developed in risk assessment efforts noted above.
3. Future changes in regulatory standards. A higher ranking will be assigned to those alternatives that best minimize risk of non-compliance with future drinking water standards.
4. Facts to consider
   a. The intent of this criterion is to address the risk of drinking water quality standards (especially those pertaining to source water risks) becoming significantly more stringent in the future.
   b. Potential inability for city to meet future standards to the extent that CIP and other planning does not anticipate regulatory dynamics/ upcoming challenges. (See discussion on significant limitations of current standards which contributes to likelihood of increased future stringency).

D. Infrastructure Vulnerability

1. A higher ranking will be assigned to those alternatives that best minimize risk of damage to infrastructure that would impede purveyance or treatment of the potable water supply. The alternatives will be evaluated by
   a. Potential for impacts from natural events (i.e. weather-related events)
   b. Potential for impacts from accidental or intentional events
2. Facts to consider
   a. The intent of this criterion is to address risks to facilities in sources and treatment which would impede delivery of drinking water to the city's distribution system.
   b. Why it is a problem: Interferes with reliable delivery of water for drinking and other potable uses and for fire protection.

E. Power interruptions

3. A higher ranking will be assigned to those alternatives that best minimize risk of power interruptions with potential to impede

purveyance or treatment of the potable water supply. The alternatives will be evaluated by

a. Potential for power interruptions affecting the treatment plant processes
b. Potential for power interruptions affecting the transmission of water to the distribution system

4. Facts to consider
   a. Power interruptions can result in serious consequences for both water supply and quality. To the extent that an interruption interferes with water treatment plant processes, tap water quality is at risk (including regulatory compliance capability). Water transmission may also be compromised by a power outage to the extent that pumping/ system telemetry are impacted.

F. Chemical Delivery/Usage

5. A higher ranking will be assigned to those alternatives that best minimize risk from potential chemical delivery interruptions which would impede treatment and public health protection capability. The alternatives will be evaluated by
   a. Potential for treatment chemical interruption (i.e. distance of source from plant, mode of transportation, frequency of deliver)
6. Facts to consider
   a. The intent of this criterion is to address risks to WQ/public health from interruption of availability/ delivery of chemicals required to treat water for potable use.
   b. Lack of such chemicals in sufficient quantity could preclude the city's ability to treat water to quality or quantity levels needed.

VI. Environmental and Public Acceptance

A. Adjacent land use Compatibility

1. Chemical hazards (us on neighbors)
2. Recreational use (neighbors on us
3. Development
4. Road crossings

B. System-Wide Water Uniformity

1. The desirability of providing equal water quality to all customers

   a. Quote from Ridge Dorsey re: Industry need to pretreat water "We could go through our list of permitted industries an give you a count from that select group, but that would not be representative of the entire city. Many industry types such metal plating, electronics

assembly, food/beverage manufacturing, pharmaceutical, R&D labs, even auto washing prefer to use de-ionized water, and sometimes ultra pure (reverse osmosis) water. Potable water for these commercial applications would likely need to be treated to specific industry standards in any location. I'm not aware of any industry that did not locate to Boulder due to water quality."

C. Construction Impacts

1. A higher ranking will be given to those alternatives that exhibit these characteristics:
   a. Minimizing the impacted land area and associated restoration requirements
   b. Minimizing underground excavation and associated materials handling
   c. Minimizing the number of subcontractors and suppliers
2. Facts to consider
   a. The intent of this criterion is to compare the construction impacts of each alternative. It does not include the monetary cost of construction since this will be part of the monetary evaluation.

D. Consumer Confidence

3. A higher ranking will be given to those alternatives that provide the highest consumer confidence.
   a. Source
      1) Finished water taste, odor, temperature and appearance.
      2) Manganese
      3) Hardness.
      4) Effects on local business
   b. Treatment
      1) match Betasso Treated water
   c. Facts to consider
      1) The intent of this criterion is to evaluate public perception and acceptance of treated water.

E. Permitting

F. Energy Requirements

3. The intent of this criterion is to compare the energy requirements and the secondary affects of these requirements. It does not include the monetary value of the energy requirements since this will be part of the monetary evaluation. The alternatives will be rated based on minimizing the quantity of the following:
   a. Capacity/load rating (MVA)

b. Net energy consumption (use minus production) (Mw-hr)
c. Equivalent amount of coal (tons)
d. Equivalent amount of SO2 (tons)
e. Equivalent amount of NOx (tons)
f. Equivalent amount of CO2 (tons)

VII. Other Criteria

A. Public Acceptance

The intent of this criterion is to compare the anticipated public acceptance of each alternative. It does not include the monetary cost of any project mitigation designed for public acceptance since this will be part of the monetary evaluation. A higher ranking will be given to those alternatives that exhibit these characteristics:

a. Minimizing the visual impacts of based on the need for above grade buildings and facilities
b. Minimizing acquisition of land, easements and right-of-way
c. Promoting economic sustainability within the city's service area

Alternative Scoring Worksheets

Water Quality: Pathogens

Alternative	Treatment Strategy	Score	Comments: Additional log removal		
			Crypto	Giardia	Viruses
1A	ClO_2	2	0.02	0.67	0.96
1B	ClO_2 + UV	10	4.02	4.67	1.46
1C	ClO_2 + GAC + UV	10	4.02	4.67	1.46
2A	ClO_2	2	0.02	0.67	0.96
2B	ClO_2 + UV	10	4.02	4.67	1.46
2C	ClO_2 + AOP	3	0.54	13.16	27.60
3	CLP + ClO_2	6	1.52*	2.17*	2.46*

*Based on 1.50 log reduction in E.coli by using CLP

Water Quality: DBPs

Alternative	Treatment Strategy	Score	Comments: ClO_2 > O_3, GAC varies, UV -- no effect
1A	ClO_2	9	
1B	ClO_2 + UV	9	
1C	ClO_2 + GAC + UV	9	TOC removal varies with GAC life-cycle
2A	ClO_2	9	
2B	ClO_2 + UV	9	
2C	ClO_2 + AOP	10	
3	CLP + ClO_2	9	Pipeline gives consistent water quality allowing treatment optimization

UV -- no contribution to DBP reduction
ClO_2 -- Effective oxidation of NOM
AOP -- Effective oxidation of NOM
GAC -- effective adsorption depending on GAC age

Water Quality: Organic Micropollutants

Alternative	Treatment Strategy	Score	Comments: AOP > GAC >> UV ≅ ClO_2
1A	ClO_2	2	Minimal oxidation
1B	ClO_2 + UV	3	Minimal oxidation and photolytic degradation
1C	ClO_2 + GAC + UV	7	Adsorption varies with contaminant and GAC age
2A	ClO_2	2	Minimal oxidation
2B	ClO_2 + UV	3	Minimal oxidation and photolytic degradation
2C	ClO_2 + AOP	10	Reservoir dilution + effective oxidation
3	CLP + ClO_2	8	Source water protection + minimal oxidation -- EDCs have very low concentratio

Water Quality: Inorganic Micropollutants

Alternative	Treatment Strategy	Score	Comments: Reduced As, U, Cr, Pb, Cd, Cu
1A	ClO_2	6	Oxidant + conventional treatment
1B	ClO_2 + UV	6	Oxidant + conventional treatment
1C	ClO_2 + GAC + UV	6	Oxidant + conventional treatment
2A	ClO_2	7	Oxidant + conventional treatment
2B	ClO_2 + UV	7	Oxidant + conventional treatment
2C	ClO_2 + AOP	8	Optimized oxidation + conventional treatment
3	CLP + ClO_2	10	Source water protection + reservoir dilution + oxidant +conventional treatment

Water Quality: Manganese

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	8	Source water avoidance + effective oxidant
1B	ClO_2 + UV	8	Source water avoidance + effective oxidant
1C	ClO_2 + GAC + UV	8	Source water avoidance + effective oxidant
2A	ClO_2	7	Variable Mn -- effective oxidation
2B	ClO_2 + UV	7	Variable Mn -- effective oxidation
2C	ClO_2 + AOP	8	Variable Mn + Two stage optimized oxidation
3	CLP + ClO_2	10	Source water protection + effective oxidation

Water Quality: Taste and Odor

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	5	Moderately effective oxidant
1B	ClO_2 + UV	5	Moderately effective oxidant
1C	ClO_2 + GAC + UV	7	Moderatelty effective oxidant, adsorption varies with contaminant and GAC age
2A	ClO_2	5	Moderately effective oxidant
2B	ClO_2 + UV	5	Moderately effective oxidant
2C	ClO_2 + AOP	10	Optimized oxidation
3	CLP + ClO_2	8	Source water protection + moderately effective oxidant

Water Quality: TDS and Sulfate

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	3	Seasonal reservoir usage + no treatment
1B	ClO_2 + UV	3	Seasonal reservoir usage + no treatment
1C	ClO_2 + GAC + UV	3	Seasonal reservoir usage + no treatment
2A	ClO_2	2	Year-round reservoir use + no treatment
2B	ClO_2 + UV	2	Year-round reservoir use + no treatment
2C	ClO_2 + AOP	2	Year-round reservoir use + no treatment
3	CLP + ClO_2	10	Source water protection

Source Water: Consistency

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	2	Seasonal canal usage with low TDS & sulfate
1B	ClO_2 + UV	2	Seasonal canal usage with low TDS & sulfate
1C	ClO_2 + GAC + UV	2	Seasonal canal usage with low TDS & sulfate
2A	ClO_2	5	Year-round reservoir use with higher TDS & sulfate, seasonal Mn occurance
2B	ClO_2 + UV	5	Year-round reservoir use with higher TDS & sulfate, seasonal Mn occurance
2C	ClO_2 + AOP	5	Year-round reservoir use with higher TDS & sulfate, seasonal Mn occurance
3	CLP + ClO_2	10	Year-round CLP with low TDS & sulfate

Source Water: Water Rights Yield

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	5	Seasonal reservoir usage
1B	ClO_2 + UV	5	Seasonal reservoir usage
1C	ClO_2 + GAC + UV	5	Seasonal reservoir usage
2A	ClO_2	2	Year-round reservoir usage
2B	ClO_2 + UV	2	Year-round reservoir usage
2C	ClO_2 + AOP	2	Year-round reservoir usage
3	CLP + ClO_2	10	Year-round CLP usage

Source Water: Portfolio Flexibility

Alternative	Treatment Strategy	Score	Comments: Time limit on reservoir storage (use it or lose it)
1A	ClO_2	5	Requires seasonal reservoir storage
1B	ClO_2 + UV	5	Requires seasonal reservoir storage
1C	ClO_2 + GAC + UV	5	Requires seasonal reservoir storage
2A	ClO_2	2	Requires year-round reservoir storage
2B	ClO_2 + UV	2	Requires year-round reservoir storage
2C	ClO_2 + AOP	2	Requires year-round reservoir storage
3	CLP + ClO_2	10	No reservoir storage required

Source Water: Availability

Alternative	Treatment Strategy	Score	Comments: Both BFC and BR ultimately require canal use
1A	ClO_2	5	Requires seasonal reservoir storage
1B	ClO_2 + UV	5	Requires seasonal reservoir storage
1C	ClO_2 + GAC + UV	5	Requires seasonal reservoir storage
2A	ClO_2	4	Requires year-round reservoir storage
2B	ClO_2 + UV	4	Requires year-round reservoir storage
2C	ClO_2 + AOP	4	Requires year-round reservoir storage
3	CLP + ClO_2	10	No limitation on availability

Water Treatment/Operations: Worker Safety

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	10	No additional energized equipment and maintenance
1B	ClO_2 + UV	7	Additional energized equipmentand maintenance
1C	ClO_2 + GAC + UV	6	Additional energized equipment, maintenance, and GAC replacement
2A	ClO_2	10	No additional energized equipment and maintenance
2B	ClO_2 + UV	7	Additional energized equipment and maintenance
2C	ClO_2 + AOP	6	Additional energized equipment, maintenance, and chemical handling
3	CLP + ClO_2	10	No additional energized equipment and maintenance

ClO_2	0
UV	-3
GAC	-1
AOP	-4
CLP	0

Water Treatment/Operations: Process Flexibility

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	6	Adjustable oxidation
1B	ClO_2 + UV	8	Adjustable oxidation and UV disinfection
1C	ClO_2 + GAC + UV	8	Adsorption varies with contaminant and GAC age, adjustable UV disinfection
2A	ClO_2	6	Adjustable oxidation
2B	ClO_2 + UV	8	Adjustable oxidation and UV disinfection
2C	ClO_2 + AOP	10	Greatest flexibility for TOC, DBPs, T&O, Mn
3	CLP + ClO_2	6	Adjustable oxidation

Water Treatment/Operations: Process Reliability

Alternative	Treatment Strategy	Score	Comments: Knowledge and operational control of process(es)
1A	ClO_2	7	ClO_2 mature (chlorite), source water variability
1B	ClO_2 + UV	6	ClO_2 mature (chlorite), UV adolescent, source water variability
1C	ClO_2 + GAC + UV	5	GAC adolescent, UV adolescent, source water variability
2A	ClO_2	8	ClO_2 mature (chlorite), source water variability
2B	ClO_2 + UV	7	ClO_2 mature (chlorite), UV adolescent, source water variability
2C	ClO_2 + AOP	7	ClO_2 mature (chlorite), AOP adolescent, source water variability
3	CLP + ClO_2	10	Pipeline mature, ClO_2 mature (chlorite)

Source water variability		Technology	
BFC	-3	Mature	0
BR	-2	Adloescent	-1
CLP	0	New	-2

Water Treatment/Operations: Process Redundancy

Alternative	Treatment Strategy	Score	Comments: Maximize barriers	Barriers
1A	ClO_2	6		8.0
1B	ClO_2 + UV	8		10.5
1C	ClO_2 + GAC + UV	9		11.5
2A	ClO_2	6		8.0
2B	ClO_2 + UV	8		10.5
2C	ClO_2 + AOP	10		13.0
3	CLP + ClO_2	10		13.0

$$\text{Score} = \frac{(n_{barrier} - 0)}{(N_{barrier} - 0)} \times 10$$

$n_{barrier}$= # barriers in alternative
$N_{barrier}$= max # barriers in alternatives

Water Treatment/Operations: Maintenance

Alternative	Treatment Strategy	Score	Comments: Deducts for each additional maintenance requirement
1A	ClO_2	10	No additional maintenance
1B	ClO_2 + UV	7	Additional maintenance for UV
1C	ClO_2 + GAC + UV	4	Additional maintenance for GAC (3) and UV
2A	ClO_2	10	No additional maintenance
2B	ClO_2 + UV	7	Additional maintenance and UV
2C	ClO_2 + AOP	6	Additional maintenance for AOP
3	CLP + ClO_2	10	No additional maintenance

ClO_2	0
UV	-3
GAC	-3
AOP	-4
CLP	0

Water Treatment/Operations: Staffing

Alternative	Treatment Strategy	Score	Comments:	Effort	Expertise	Supervision
1A	ClO_2	8		-1	0	-1
1B	ClO_2 + UV	7		-1	-1	-1
1C	ClO_2 + GAC + UV	7		-1	-1	-1
2A	ClO_2	8		-1	0	-1
2B	ClO_2 + UV	7		-1	-1	-1
2C	ClO_2 + AOP	5		-1	-2	-2
3	CLP + ClO_2	10		0	0	0

Base score = 10

Treatability

BFC	Worst	-1	0	-1
BR	Intermediat	-1	0	-1
CLP	Best	0	0	0

Water Treatment/Operations: Residuals Disposal

Alternative	Treatment Strategy	Score	Comments	Solids: Quantity	Quality	Chemicals
1A	ClO_2	7		-1	-2	0
1B	ClO_2 + UV	7		-1	-2	0
1C	ClO_2 + GAC + UV	5		-3	-2	0
2A	ClO_2	6		-1	-3	0
2B	ClO_2 + UV	6		-1	-3	0
2C	ClO_2 + AOP	5		-1	-3	-1
3	CLP + ClO_2	10		0	0	0

Base score = 10

Risk: Acute Contamination

Alternative	Treatment Strategy	Score	Comments: Source water protection only, no treatment
1A	ClO_2	3	Highly vulnerable, BFC
1B	ClO_2 + UV	3	Highly vulnerable, BFC
1C	ClO_2 + GAC + UV	3	Highly vulnerable, BFC
2A	ClO_2	5	Moderately vulnerable, reservoir dilution
2B	ClO_2 + UV	5	Moderately vulnerable, reservoir dilution
2C	ClO_2 + AOP	5	Moderately vulnerable, reservoir dilution
3	CLP + ClO_2	10	Minimally vulnerable

Risk: Chronic Contamination

Alternative	Treatment Strategy	Score	Comments: Micropollutants and emerging contaminants	Pathogens	Organics	Inorganics
1A	ClO_2	2		-3	-3	-2
1B	ClO_2 + UV	5		0	-3	-2
1C	ClO_2 + GAC + UV	7		0	-1	-2
2A	ClO_2	5		-2	-2	-1
2B	ClO_2 + UV	7		0	-2	-1
2C	ClO_2 + AOP	9		0	0	-1
3	CLP + ClO_2	10		0	0	0

Prevention takes precendence over treatment

Base score = 10

BFC	-3	-3	-3
BR	-2	-2	-2
CLP	-1	-1	-1

ClO_2	0	0	+1
UV	+3	0	0
GAC	0	+2	0
AOP	+2	+3	+1
CLP	+3	+2	+2

Risk: Adaptability to Future Regulatory Environment

Alternative	Treatment Strategy	Score	Comments	Pathogens	Organics	Inorganics
1A	ClO_2	2		0	0	+1
1B	ClO_2 + UV	5		+3	0	+1
1C	ClO_2 + GAC + UV	7		+3	+2	+1
2A	ClO_2	2		0	0	+1
2B	ClO_2 + UV	5		+3	0	+1
2C	ClO_2 + AOP	8		+2	+3	+2
3	CLP + ClO_2	10		+4	+2	+3

Base score = 1

ClO_2	0	0	+1
UV	+3	0	0
GAC	0	+2	0
AOP	+2	+3	+1
CLP	+3	+2	+2

Risk: Infrastructure Vulnerability

Alternative	Treatment Strategy	Score	Comments: Source water infrastructure contamination only
1A	ClO_2	4	Highly vulnerable
1B	ClO_2 + UV	4	Highly vulnerable
1C	ClO_2 + GAC + UV	4	Highly vulnerable
2A	ClO_2	5	Moderately vulnerable, reservoir difficult to decontaminate
2B	ClO_2 + UV	5	Moderately vulnerable, reservoir difficult to decontaminate
2C	ClO_2 + AOP	5	Moderately vulnerable, reservoir difficult to decontaminate
3	CLP + ClO_2	10	Minimally vulnerable

Both BFC and BR ultimately rely on canal to deliver water

Source	Risk Probability	Severity	Score
BFC	High	High	4
BR	Low	V. High	5
CLP	V. Low	V. Low	10

V. High	-4
High	-3
Mod	-2
Low	-1
V. Low	-0

Risk: Consumable Delivery/Usage

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	10	No Additional risk
1B	ClO_2 + UV	8	
1C	ClO_2 + GAC + UV	5	
2A	ClO_2	10	No Additional risk
2B	ClO_2 + UV	8	
2C	ClO_2 + AOP	4	
3	CLP + ClO_2	10	No Additional risk

Chemical	Risk
ClO_2	-2
UV	-2
GAC	-3
O_3	-3
H_2O_2	-3

Environmental and Public Acceptance: Adjacent Land Use Compatibility

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	4	Development, road crossings, recreation
1B	ClO_2 + UV	4	Development, road crossings, recreation
1C	ClO_2 + GAC + UV	4	Development, road crossings, recreation
2A	ClO_2	4	Development, road crossings, recreation
2B	ClO_2 + UV	4	Development, road crossings, recreation
2C	ClO_2 + AOP	3	Development, road crossings, recreation, LOX delivery
3	CLP + ClO_2	10	No incompatibilities

Base score = 1

LOX delivery	1
Development	2
Road crossings	2
Recreational use	2

Environmental and Public Acceptance: System Wide Finished Water Uniformity

Alternative	Treatment Strategy	Score	Comments: Primarily TDS and Sulfate
1A	ClO_2	3	Higher inorganic content during reservoir use
1B	ClO_2 + UV	3	Higher inorganic content during reservoir use
1C	ClO_2 + GAC + UV	3	Higher inorganic content during reservoir use
2A	ClO_2	2	Continuously higher inorganic content
2B	ClO_2 + UV	2	Continuously higher inorganic content
2C	ClO_2 + AOP	2	Continuously higher inorganic content
3	CLP + ClO_2	10	Source water most closely matches Betasso source

Environmental and Public Acceptance: Construction

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	10	ClO_2
1B	ClO_2 + UV	7	ClO_2 + UV
1C	ClO_2 + GAC + UV	4	GAC + UV
2A	ClO_2	10	ClO_2
2B	ClO_2 + UV	7	ClO_2 + UV
2C	ClO_2 + AOP	6	ClO_2 + AOP
3	CLP + ClO_2	4	CLP + ClO_2

ClO_2	0
UV	3
GAC	3
AOP	4
CLP	6

Environmental and Public Acceptance: Permitting/Regulatory Acceptance

Alternative	Treatment Strategy	Score	Comments
1A	ClO_2	10	ClO_2
1B	ClO_2 + UV	8	ClO_2 + UV
1C	ClO_2 + GAC + UV	6	GAC + UV
2A	ClO_2	10	ClO_2
2B	ClO_2 + UV	8	ClO_2 + UV
2C	ClO_2 + AOP	8	ClO_2 + AOP
3	CLP + ClO_2	6	CLP + ClO_2

ClO_2	0
UV	2
GAC	2
AOP	2
CLP	4

Environmental and Public Acceptance: Consumer confidence

Alternative	Treatment Strategy	Score	Pathogens	DBPs	Organics	Inorganics	Manganese	T&O	TDS/SO_4
			Comments: Avoidance takes precedence over treatment						
1A	ClO_2	6	0	+1	0	+1	+2	+2	0
1B	ClO_2 + UV	7	+1	+1	0	+1	+2	+2	0
1C	ClO_2 + GAC + UV	10	+2	+2	+1	+1	+2	+3	0
2A	ClO_2	7	+1	+1	+1	+2	+1	+1	0
2B	ClO_2 + UV	8	+2	+1	+1	+2	+1	+1	0
2C	ClO_2 + AOP	9	+1	+1	+2	+2	+1	+2	0
3	CLP + ClO_2	10	+1	+1	+1	+2	+2	+2	+1

Base score = 0

Avoidance							
BFC	0	0	0	0	+1	+1	0
BR	+1	0	+1	+1	0	0	0
CLP	+1	0	+1	+1	+1	+1	+1
Treatment							
ClO_2	0	+1	0	+1	+1	+1	0
UV	+1	0	0	0	0	0	0
GAC	0	+1	+1	0	0	+1	0
AOP	0	0	+1	0	0	+1	0
CLP	0	0	0	0	0	0	+1

Environmental and Public Acceptance: Energy Requirements

Alternative	Treatment Strategy	Score	Comments: Based on relative additional energy usage	
1A	ClO_2	5	$22,750	5
1B	ClO_2 + UV	3	$28,663	3
1C	ClO_2 + GAC + UV	3	$28,663	3
2A	ClO_2	2	$32,500	2
2B	ClO_2 + UV	1	$38,413	1
2C	ClO_2 + AOP	2	$32,500	2
3	CLP + ClO_2	10	$0	10