THESIS

EVALUATION OF DECENTRALIZED ALTERNATIVES FOR SEPARATE TREATMENT AND SUPPLY OF INDOOR WATER: FORT COLLINS CASE STUDY

Submitted by
Daniel Fourness
Department of Civil and Environmental Engineering

In partial fulfillment of the requirements
For the Degree of Master of Science
Colorado State University
Fort Collins, Colorado
Spring 2015

Master's Committee:

Advisor: Sybil Sharvelle

Neil Grigg
Scott Glick

Copyright by Daniel Fourness 2015

All Rights Reserved

ABSTRACT

EVALUATION OF DECENTRALIZED ALTERNATIVES FOR SEPARATE TREATMENT AND SUPPLY OF INDOOR WATER: FORT COLLINS CASE STUDY

The replacement of aging water infrastructure in the City of Fort Collins, CO provides an opportunity to evaluate the applicability of dual distribution and decentralized water treatment alternatives in comparison to the existing conventional system. The purpose of an alternative approach is to meet future water demands and quality standards which can be achieved by treating less water through the separation of supply for outdoor irrigation and fire flow from potable demand. Energy consumption required for the production of potable water and deteriorating water quality due to water age provide motivation for this evaluation. Few existing projects have demonstrated the applicability of dual water supply and decentralized treatment at a city-wide scale. This study explores these alternative approaches separating supply of water for indoor use and how decentralized water treatment may integrate into such an approach.

Four water treatment and distribution alternatives were considered in comparison to the existing system using a Multi-Criterion Decision Analysis (MCDA) tool with eleven performance metrics assessed from a triple bottom line of economic, social and environmental perspectives. Alternatives were defined as city-wide dual distribution, neighborhood-scale treatment with dual distribution, point-of-entry treatment, and separated irrigation. This study focused specifically on evaluation of dual water supply alternatives incorporating decentralized treatment which reduce additional distribution infrastructure and water age in comparison to centralized treatment.

A common selection process for both neighborhood-scale and point-of-entry treatment was used to recommend the most applicable systems for decentralized alternatives. An ultrafiltration package system with chlorine disinfection was recommended neighborhood-scale system due to compact design, low chemical requirements, consistent water quality and amenability to remote monitoring. Activated Carbon/Kinetic Fluxion Media filtration with ultraviolet disinfection was recommended for point-of-entry treatment system based on low capital costs, simplistic operation, low chemical requirements, and small system size.

Results of the evaluation illuminate key drivers which dictate the competitiveness of dual water supply with decentralized treatment alternatives with the existing centralized conventional model. The largest advantages are reduced chemical use, improved water age and quality, adaptability to new water management strategies and revenue opportunities from increased capacity at the existing treatment facility. Neighborhood-scale treatment and dual distribution incurs large capital costs while consuming substantially more energy due to pumping. Disruption associated with the installation of neighborhood-scale treatment facilities and dual distribution networks has a negative effect on society and intensifies environmental concerns for greenhouse gas emissions and stormwater pollution. Point-of-entry treatment increases the risk of rate changes related to drastically higher maintenance costs and personnel needs. Both alternatives are strongly affected by the lack of defined regulations for these approaches at a city-wide scale.

Overall, dual distribution and decentralized water treatment alternatives were not economically competitive with the existing system and offered negligible social advantages. Environmental benefits were realized for both alternatives which can be largely attributed to improved water quality due to shorter water age. Dual distribution with central treatment alternative results suggest that separating potable water from irrigation and fire flow is a practical solution that may

be competitive with conventional water production in a city-wide application. While dual water distribution for separate supply of indoor water may have some advantages over conventional systems, the decentralized alternatives do not appear to offer a competitive advantage compared to the existing conventional system.

ACKNOWLEDGEMENTS

I would first like to thank Dr. Sybil Sharvelle for her guidance and expertise throughout the *Fort Collins Utilities Dual Systems Study* project and its organization into this report. I am appreciative of the additional flexibility she provided while coordinating the start of a new professional position while completing this thesis and the advisement she provided while working towards my degree. I owe a deep debt of gratitude to Jeanne Cole for her leadership on the study and patience with the comprehensive analysis that we worked to provide. I would like to thank Dr. Neil Grigg and Dr. Larry Roesner for their efforts and contributions to the Dual Systems study. Additionally, I would like to thank Dr. Grigg and Dr. Scott Glick for their support and participation as committee members. I am also grateful to Jon Haukaas for his direction and constructive feedback as a representative of Fort Collins Utilities. Lastly, I would like to thank the City of Fort Collins for providing funding and support for the study which allowed me to pursue my degree.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

CDPHE	Colorado Department of Public Health & Environment
CIP	Cast Iron Pipe
GAC	Granular Activated Carbon
gpm	Gallons per minute
KDF	Kinetic Degradation Fluxion Media
MCDA	Multi-Criteria Decision Analysis
POE	Point-of-Entry
PVC	Polyvinyl Chloride
RO	Reverse Osmosis
RTS	Remote Telemetry Systems
SDWA	Safe Drinking Water Act
TBL	Triple Bottom Line
U.S. EPA	United States Environmental Protection Agency
UV	Ultraviolet Disinfection

1.0 INTRODUCTION AND OBJECTIVES

1.1 Background and Motivation

Several fundamentally interrelated issues have motivated the consideration of alternative approaches to conventional centralized water treatment and distribution including energy consumption, operating costs and deteriorating water quality. Dual distribution systems and decentralized water treatment are common strategies to combat these growing issues. This study define aspects of treatment system selection, distribution network design and criteria formation and analysis involved in the evaluation of decentralized treatment alternatives for the dual distribution of raw and potable water for the City of Fort Collins, CO.

Alternative approaches to the conventional water provision model must address both the treatment and delivery of water resources. Dual distribution systems are comprised of two parallel distribution networks which separate raw, reclaimed or lightly-treated water from the provision of potable quality supply for domestic demand (Okun, 1997). Decentralized drinking water treatment refers to the small-scale purification and local distribution of potable water (Peter-Varbanets et. al 2008).

Determining the feasibility of alternatives incorporating decentralized treatment into dual distribution systems requires the definition of a balanced evaluative process, considering both the most competitive alternatives while also meeting the constraints of economic, social and environmental limitations. The focus of this thesis is the evaluation of the applicability of these approaches to a new paradigm in water provision in which a smaller volume of potable quality water is delivered to the home for direct human consumption while separating the supply for other domestic uses such as outdoor irrigation and fire flow.

1.2 Research Objectives

Evaluation of decentralized treatment alternatives for the dual distribution of raw and potable water was comprised of four fundamental objectives:

- Evaluate most appropriate treatment technologies for integration into a municipal scale dual distribution system
- Assess the costs and benefits associated with installation of selected decentralized water treatment technologies for supply of indoor water in select case study neighborhoods in the City of Fort Collins where raw water would supply irrigation and fire demand
- Evaluate alternative approaches to existing water treatment and distribution in the City of Fort Collins, Colorado
- Examine regulatory considerations pertinent to the application of decentralized treatment and dual distribution systems

Chapter 2 provides a definition of the current motivations for a shift in approach to water treatment and delivery in the United States and a review of the state of knowledge on dual distribution systems and decentralized water supply. Formation of a decision making process for the selection of decentralized water treatment systems is discussed in Chapter 3. In Chapter 4, selected decentralized treatment systems are incorporated into alternative approaches and evaluated in comparison to existing water treatment and distribution in the City of Fort Collins. Chapter 5 outlines potential regulatory issues most pertinent to the application of decentralized treatment and dual distribution alternatives. Lastly, a summary of the key findings of the evaluation of alternative approaches to conventional water treatment and distribution are presented in Chapter 6.

2.0 LITERATURE REVIEW

2.1 Introduction

One of the most fundamental societal challenges throughout human history has been the provision of a safe water supply. Development of stable societies is dependent on the availability of fresh water and the ability to treat and distribute it to populations. In the United States, the current conventional approach for public water systems is to treat a raw water source at a central facility and distribute potable water to consumers through a single distribution system. Water is treated to an increasingly stringent potable standard in preparation for all domestic uses. Only 1% of potable water is used for direct human consumption including drinking and cooking (Cotruvo, 2002). Other varieties of human contact account for roughly 25% of total consumption leaving nearly 75% to activities such as toilet flushing, lawn irrigation, fire-fighting and exterior use. Differing water quality requirements for these uses suggests that not all domestic water consumption requires potable quality supply and opens the door for alternative approaches to water provision such as decentralized treatment and dual distribution.

2.2 Alternatives to Conventional Treatment and Distribution

There are many individual innovative treatment technologies which aim to make better use of water resources producing higher quality with less energy. However, the scope of this study necessitates the exploration of entirely alternative approaches. Two broad complementary strategies are dual distribution systems and decentralized water treatment. These approaches can be implemented together to direct the delivery of potable water for domestic consumption while meeting irrigation and fire flow demands with alternative supply.

2.2.1 Dual Distribution Systems

Dual distribution systems are comprised of two distribution networks separating potable from non-potable. Raw, reclaimed or lightly-treated water is delivered through a distribution system running parallel to a potable delivery system (Okun, 1997). Dual distribution networks are configured in order to separately deliver potable water indoors while providing access to non-potable water for outdoor use (Figure 2.1).

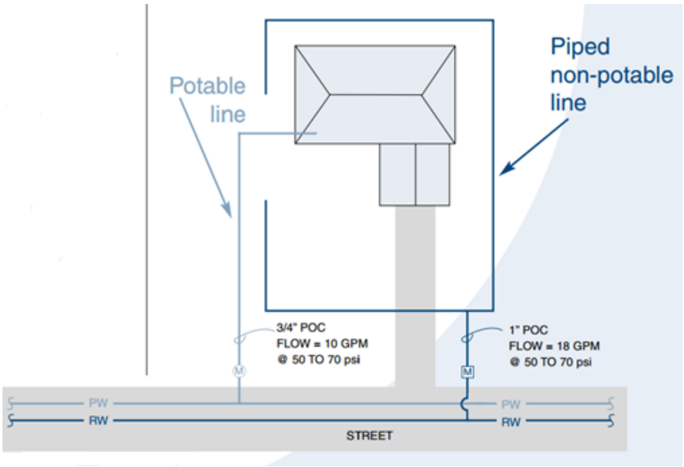


Figure 2.1 – Dual Distribution System Connection Configuration (Satterfield, 2009)

In the United States, the prevalence of dual distribution systems is increasing due to water scarcity and the need to address wastewater treatment issues (Grigg et al. 2013). An added advantage that is receiving growing attention is the flexibility of a dual distribution system to operate with alternative water sources such as raw, gray or reclaimed water (Satterfield, 2009). This flexibility is a key benefit in response to increasing source water scarcity due to population growth. The potential use of alternative water sources in dual distributions networks in exemplified in Figure 2.2 in comparison to existing conventional single distribution systems.

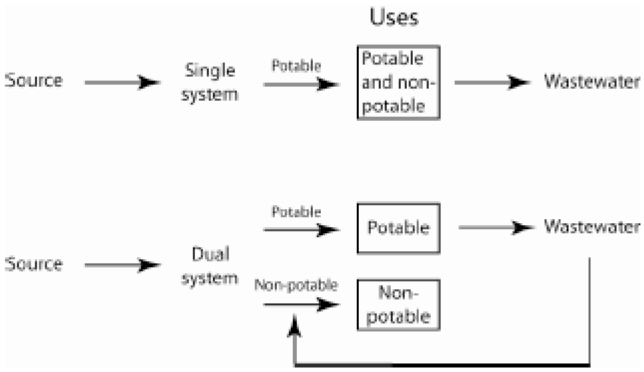


Figure 2.2 – Comparison of Single and Dual Distribution Systems (Grigg et al. 2013)

There are more than 330 dual distribution systems currently in place in the United States (Grigg et al. 2013). Dual distributions systems are commonly applied to independently distribute reclaimed water due to source water shortages instead of the separation of raw water for fire flow and irrigation demand. A large number of these systems are found in California (143) and Florida (77) as depicted in Figure 2.3.

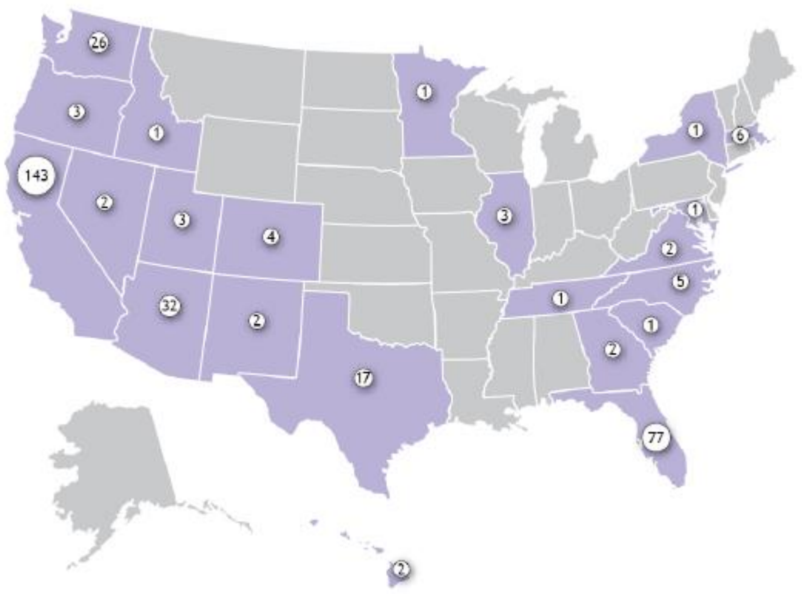


Figure 2.3 – Current Dual Distribution Systems in the United States (Grigg et al. 2013)

In areas throughout the arid west, the motivation for the installation of dual distribution systems is related to water scarcity and better allocation of water, energy and capital. Other areas of the country focus on agricultural demands or improvements in potable water quality distribution.

2.2.2 Decentralized Drinking Water Treatment

Decentralized drinking water treatment is defined as the small-scale purification and local distribution of potable water (Peter-Varbanets et. al 2008). Figure 2.4 depicts what a decentralized water treatment system may look like in comparison to conventional centralized treatment.

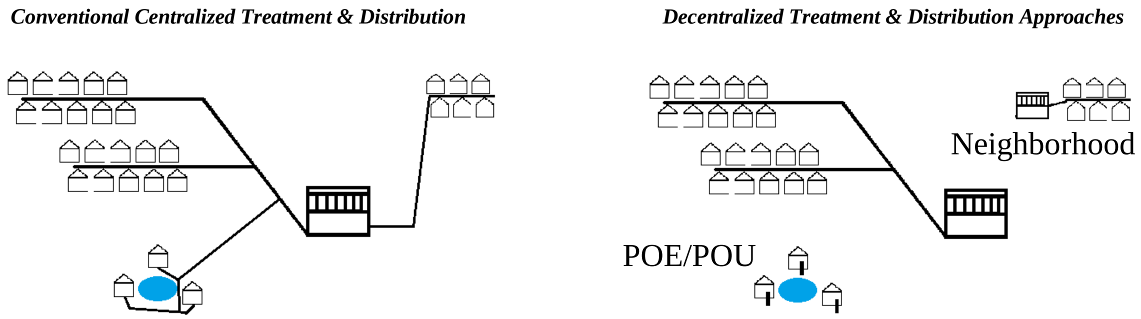


Figure 2.4 – Comparison of Conventional Centralized Water Treatment to Decentralized Approaches

There are many forms of decentralized water treatment. Neighborhood-scale treatment systems can produce water for small communities while water can also be treated at the connection or point-of-entry (POE) to the home or point-of-use (POU) inside the home (Figure 2.4). POU devices only treat water used for activities involving direct human consumption such as drinking or cooking at a tap while POE units treat all of the water entering a home, business or institution at the connection to the distribution system. Figure 2.5 demonstrates the differences between POU and POE treatment.

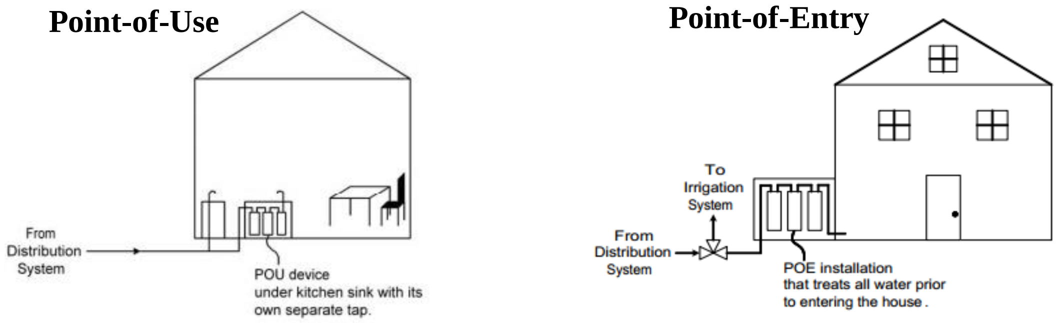


Figure 2.5 – Typical POU and POE Installation (U.S. EPA, 2006)

These strategies are particularly applicable for use in smaller remote or rural communities due to the barrier costs of constructing, upgrading or expanding a central treatment facility (U.S. EPA, 2002). However, the value of decentralized treatment may not be limited to just these applications. Municipal approaches to treat a small volume of potable quality water may include the use of neighborhood-scale treatment facilities, point-of-entry systems at connections or point-of-use units within the home. Cost and energy savings are potential realizations from a decrease in the amount of water treated while the delivery time from treatment to tap would be substantially reduced resulting in lower risks for disinfection byproduct formation and microbial contamination. The addition of decentralized treatment to a dual supply approach will limit the amount of necessary dual distribution infrastructure and further reduce water age in comparison to centralized treatment. Point-of-entry treatment allows for potable and raw water to be delivered to connections separately without the requirement of a dual distribution network.

Each implementation situation must be carefully assessed in terms of economic, social and environmental factors in order to determine if a decentralized treatment approach is truly feasible. Cost, size, and operational details will determine the limit at which these approaches are not advantageous to conventional centralized treatment and distribution. These concerns place critical emphasis on the selection of appropriate decentralized treatment methods (Hamouda et al. 2010) as discussed in detail in Chapters 3 and 4.

2.3 Drivers for Dual Water Supply and Decentralized Water Treatment

The motivation for the formation of alternative approaches to conventional water treatment and distribution is related to the costs of excess treatment for a large percentage of treated water and deteriorating water quality due to oversized distribution networks (Cotruvo, 2002). Treating the entire domestic demand to potable quality requires a substantial amount of energy and operating cost (Plappally et al. 2012). Single distribution networks must be sized for peak day water use in addition to fire demand, resulting in longer residence times which allow water quality to deteriorate during delivery and lower flows to deposit sediment (U.S. Fire Administration, 2008).

2.3.1 Energy Consumption for Excess Treatment

The production and delivery of potable drinking water is highly energy intensive. Energy consumption in the water sector is approximately 3-4% of national energy consumption in the United States and 30-40% of municipal energy use (Leiby et al. 2011). This equates to an estimated $4 billion in annual expenditures nationally. Table 2.1 shows the conventional drinking water treatment energy consumption ranges in several other developed countries in comparison to the United States.

Table 2.1 – Conventional water treatment energy consumption rates (Plappally et al. 2012)

Country	Energy consumption ranges (kW h/m^3)
Australia	0.01-0.2
Taiwan	0.15-0.25
USA	0.184-0.47
Canada	0.38-1.44
Spain	0.11-1.5
New Zealand	0.15-0.44

Separation of treatment for different domestic demands would result in tangible cost savings related to energy consumption. One study showed that a reduction of 10% in energy consumption in the water industry represents a savings of more than $400 million (Leiby et al. 2011). 33% of total energy use is directly proportional to the volume of water treated at the conventional surface water treatment facility in the City of Fort Collins (Figure 2.6).

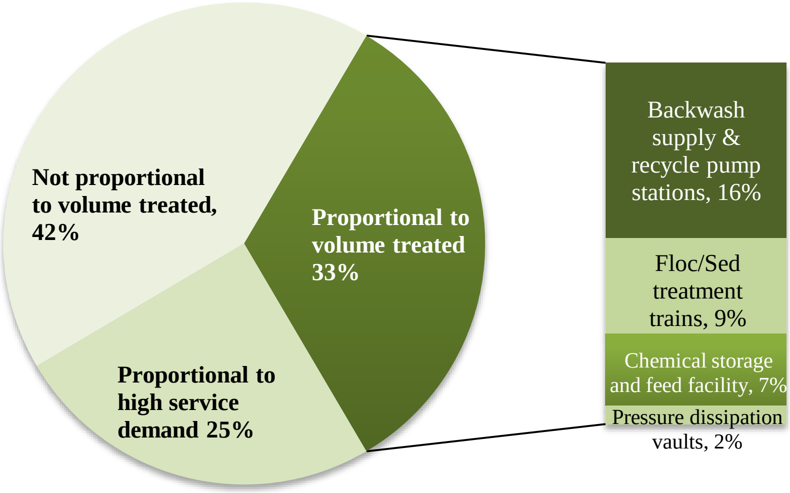


Figure 2.6 – City of Fort Collins Water Treatment Facility Energy Use Proportional to Treated Water Volume (Cole et al. 2015)

These values are based on treating all domestic demand to the highest water quality standards. Reducing the amount of volume of water treated is an effective way to decrease energy consumption. Eliminating the need to treat all water to potable quality through the use of decentralized treatment and dual distribution could have perceptible economic, social, and environmental benefits.

2.3.2 Oversizing of Distribution System Deteriorating Water Quality

Potable water distribution system design is driven by the need to provide fire flows and peak demands. It should be noted that there is no federal legal requirement in the United States that dictates that distribution systems must provide fire flows (U.S. Fire Administration, 2008). Instead, municipalities develop their own ordinances to define a flow rate and duration required to combat a major fire incident (Kirmeyer et al. 1999). In normal operating conditions this means that the system is oversized, increasing the residence time of the treated water in the system. As a result, residual disinfectant levels are depleted and the risk of formation of disinfection byproducts increases. Additionally, deteriorating water quality concerns associated with a declining disinfectant residual such as microbial growth and taste & odor issues are compounded by low velocities during normal conditions which allow sediment to deposit and accumulate (Kirmeyer et al. 2000). Maintaining necessary pressure on a larger system increases pumping costs and addressing elevated contamination issues results in higher O&M costs. Distributing a lower amount of treated water would allow the use of smaller piping within the system producing higher water quality throughout the delivery process and decreasing O&M costs.

2.4 Implementation of Dual Water Supply and Decentralized Treatment

This study aims to evaluate the integration of dual water supply and decentralized treatment approaches into an existing conventional city-wide system. The purpose of separating these two networks is to eliminate the need to meet fire flow demands with potable quality water, allowing the potable network to distribute water through a smaller system resulting in shorter residence times and higher water quality. Existing distribution infrastructure would transition to raw water transmission to the decentralized treatment facility or point-of-entry treatment unit. Installing a dual distribution system after decentralized treatment will shorten water age, improving water quality.

The implementation of decentralized treatment alternatives incorporating dual distribution for raw and potable water demands is an innovative approach. Few existing projects have attempted these strategies at a city-wide scale. The case studies provided reflect relatable applications of these technologies separately in order to demonstrate existing implementations and challenges of systems similar to those selected later in this report.

2.4.1 Dual Water Distribution Case Studies

Dual distribution systems provide the opportunity to deliver a variety of alternative water sources for different purposes not necessarily motivated by water shortages and irrigation needs. Separate distribution of raw water can provide fire flow and irrigation demands while reducing the overall volume of treated water for domestic uses. Additionally, smaller diameter potable networks reduce water age, improving water quality. The absence of case studies related to raw water distribution reflects that this is not currently a common practice, likely due to a lack of urgency to invest in new infrastructure. This study will focus on the separate distribution of raw water through dual supply opportunities to address energy and water quality considerations in Fort Collins, CO.

Irvine Ranch Water District Dual Distribution Case Study

The Irvine Ranch Water District (IRWD) in Irvine, CA delivers treated potable and reclaimed water separately to over 4,000 connections in Southern California through the use of a dual distribution system (Asano et al. 2009). Recycled water services in the district began in the

1960s for agriculture with the purpose of reducing potable water use for non-potable demands. In 1991, distribution expanded to commercial customers using reclaimed water produced by the Michelson Recycling Plant, accounting for approximately 25% of the total water demand (Grigg et al. 2013). In this way, the system has significantly extended an increasingly scarce water supply while meeting the demand needs of agriculture, industry and commercial pursuits in the region. Figure 2.7 shows part of the reclaimed non-potable network used to distribute water to meet agricultural demands.

Figure 2.7 – Non-potable Network in the Irvine Ranch Water District (IRWD, 2015)

Denver Water Dual Distribution

Denver Water in Denver, CO provides potable water to 1.3 million customers in the Denver metropolitan area (Denver Water, 2010). Source water is collected from three systems including the South Platte River, Western Slope and Moffat basin systems which are governed through prior appropriation with strict water rights. This complicates the implementation of water reuse in the dual distribution system introduced in 2004 delivering reclaimed water for landscape irrigation and industrial cooling through more than 50 miles of pipe (Denver Water, 2010). Installation of a dual distribution system is less expensive than the development of new and increasingly rare water sources (Grigg et al. 2013). This project is part of a growing precedent for the use of dual distribution systems for the separation of potable and non-potable water delivery in the State of Colorado.

Figure 2.8 – Purple Pipe used to distinguish the non-potable distribution system in Denver (McGraw Hill, 2012)

Additional Selected Dual Distribution Case Studies

A short summary of additional case studies demonstrate the nature of the current application of dual distribution systems in the United States (Table 2.2).

Table 2.2 – Selected Dual Distribution Case Studies

Location	Non-potable Water Source	Use	Source
Cary, NC	Reclaimed wastewater	Irrigation, Cooling towers	Town of Cary, 2013
East Bay Municipal Utility District, Oakland, CA	Reclaimed wastewater	Irrigation, Toilet flushing, Cooling towers	EBMUD, 2008
Cape Coral, FL	Reclaimed wastewater	Irrigation, Cooling towers, Fire fighting	Godman & Kuyk, 1997
Westminster, CO	Reclaimed wastewater	Landscape irrigation, Industrial use	DCWRA, 2012
St. Petersburg, FL	Reclaimed wastewater	Landscape irrigation (primarily lawn)	McKenzie, 2005

Dual distribution systems for reclaimed water have largely been employed as a response to dwindling source waters and focused on the delivery of reclaimed water for agricultural, commercial and industrial customers rather than the residential sector (Grigg et al. 2013).

Separate distribution of raw water does not achieve these savings. Provision of fire flows has potential but is limited by acceptance and reliability (Grigg et al. 2013).

2.4.2 Decentralized Treatment Case Studies

Decentralized water treatment is typically implemented in rural and remote small systems applications. Utilization of decentralized treatment for dual water supply at city-wide scale will reduce the volume of water treated and water age and improve water quality by shortening water age. The addition of decentralized treatment to dual supply approaches will limit the amount of necessary dual distribution infrastructure and further reduce water age in comparison to centralized treatment. Existing distribution infrastructure can serve as transmission for raw water to neighborhood-scale treatment facilities. Point-of-entry treatment does not require a dual distribution network while allowing for potable and raw water to be delivered to connections separately.

Point-of-Entry Case Studies (Activated Carbon and UV Disinfection)

In many cases, POE treatment systems are installed to treat a specific local contaminant that is of concern. In such cases, systems target a specific contaminant to meet the corresponding MCL. In other cases, POE units provide additional treatment for municipal potable water delivery. A summary of eight case studies provided in the U.S. EPA "Guidance for Implementing a Point-of-Use or Point-of-Entry Treatment Strategy for Compliance with the Safe Drinking Water Act" throughout the country utilizing later selected POE treatment strategies is provided (Table 2.3). Each selection demonstrates a different target contaminant or scope of application. Out of the 25 listed POE case studies, 14 chose granular activated carbon as a treatment technology and an additional four selected ultraviolet disinfection. Most studies reported satisfactory treatment performance for target contaminants.

Table 2.3 – Selected POE Case Studies (U.S. EPA, 2002)

Community	Year	Treatment Type	Contaminant	# of units	Performance
Honeywell Site, PA	1995	GAC	TCE	20	Units have reduced levels below detection since installation
Suffolk County, NY	1985	GAC	Aldicarb	>100	>93% of devices operated satisfactory. Premature breakthrough due to improper installation
Hudson, WI	2001	GAC	TCE, TC, PCE	350	Excellent performance, one confirmed incidence of breakthrough in 7 years
Lyman Run State Park, PA	2000	UV	Microbial	4	Operating for 15 years without incident
Florida	1987	GAC	EDB, Aldicarb, Hydrocarbons	842	Effective (detailed information not available)
Silverdale, PA	1985	GAC	TCE	49	Reduced TCE below target in 95% of samples
Grand Junction, CO	2000	UV	Microbial	20	Inconsistent results due to seasonal variability of raw water turbidity
Putnam County, NY	1987	GAC	TCE, TCA, PCE, Benzene, Toluene, Xylene, CCl_4	67	Satisfactory, contaminant level not found over 5 mg/L

Neighborhood-Scale Water Treatment Case Study

As part of a study by the EPA titled “Alternative Low Maintenance Technologies for Small Water Systems in Rural Communities” (1991) a package ultrafiltration membrane treatment plant was installed to investigate cost-effectiveness in the removal of microbial contaminants and the ability to automate operations to limit cost (U.S. EPA, 2003). The existing system treated water by slow sand filter and chlorine disinfection for a community of approximately 100 people. The cost of a conventional water treatment system was estimated by consultants to be $328,000, necessitating a cost-effective alternative. A variety of neighborhood-scale treatment technologies were considered before selecting a package 10,000 gallon per day ultrafiltration (UF) system comprised of three membrane cartridge elements, feed and recirculation pumps, bag pre-filter, and control panel. The total size of the system was 12’10”x7’x3’ and was installed in a cinder block enclosure set on a 12’x24’ concrete pad. Automation using a programmable logic controller focused on water quality instruments and sensors allowing it to be monitored remotely. Advantages of the package UF system were low engineering and installation costs, improved monitoring, decreased operations costs, and improved water quality and consistency.

Figure 2.9 – Packaged UF system and building in McDowell County, WV (U.S. EPA, 2003)

2.5 *Summary*

Consideration of alternative approaches to conventional centralized water treatment and distribution is motivated by several interrelated factors. A substantial amount of energy and operating cost is spent in the production of potable water. Peak demand and fire flow requirements dictate the sizing of distribution networks, resulting in deteriorating water quality due to longer transmittal time. Decentralized water treatment and dual distribution systems are two complementary alternative approaches to solving these issues which will be evaluated in comparison to a conventional approach in the City of Fort Collins, Colorado.

Dual distribution systems are comprised of two parallel distribution networks. One delivers raw, reclaimed or lightly-treated water while the other provides potable quality supply to meet specific domestic demands. Water scarcity, energy use and costs have encouraged installation of dual distribution systems throughout the United States. More than 330 dual distribution systems have been successfully installed in the United States. At this point, dual distribution systems have largely been employed as a response to dwindling source waters and focused on the delivery of reclaimed water for agricultural, commercial and industrial customers rather than the residential sector. Reliability and water quality are two factors that limit the acceptance of dual distribution networks to meet fire flow demands.

Decentralized drinking water treatment refers to the small-scale purification and local distribution of potable water. Neighborhood-scale systems, point-of-entry treatment and point-of-use units are all existing forms of decentralized treatment with successful implementation throughout the United States. Case studies in remote and unique situations such as rural communities, seasonal facilities, and small municipalities have demonstrated that these systems are capable of treating water to potable quality standards. Each implementation situation must be carefully assessed in terms of economic, social and environmental factors to determine if a decentralized treatment approach is truly feasible. The limit to the application of decentralized approach in comparison to a conventional centralized strategy depends on a balance of cost, size, conditions, operational details and other factors. Application of decentralized treatment for dual water supply at city-wide scale will reduce the volume of water treated and water age and improve water quality by shortening water age.

The implementation of decentralized treatment alternatives incorporating dual distribution for raw and potable water demands is an innovative approach. Few existing projects have attempted these strategies at a city-wide scale which limits the understanding of associated costs and benefits. The focus of this thesis is on the benefits of a new paradigm in water provision through these approaches in which a smaller volume of potable quality water is delivered to the home for direct human consumption while separating the supply for other domestic uses such as outdoor irrigation and fire flow. Design alternatives will be evaluated in feasibility comparison to a conventional system.

3.0 DECENTRALIZED TREATMENT SYSTEM SELECTION

3.1 Introduction

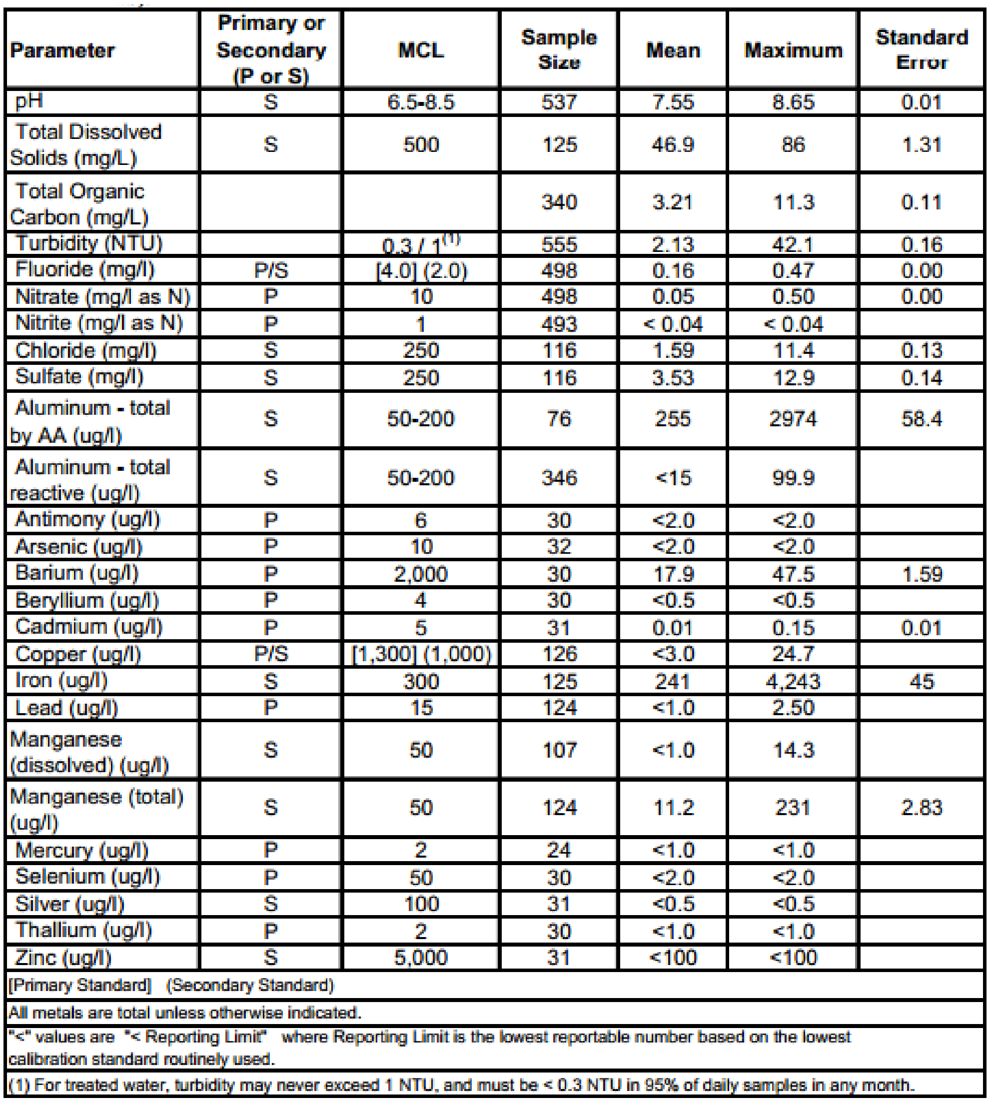
This chapter focuses on the selection of decentralized treatment systems for application in evaluation of alternative water treatment and distribution designs for the City of Fort Collins, Colorado. Many treatment technologies can be applied to decentralized systems and the most appropriate treatment process train needed to be identified for POE and neighborhood systems to estimate costs and benefits for these systems for dual water distribution in the City of Fort Collins. These results fed into a larger decision making framework applied to assess alternatives for dual water distribution for the City of Fort Collins Case Study (Cole et al. 2015). It was necessary to first define source water quality and demand conditions in the project area before forming a common selection process for both neighborhood-scale and point-of-entry (POE) systems. Descriptions of each approach are provided along with a detailed summary of the available technologies and specific criteria used to compare them. Lastly, recommendations are presented based on results of the selection process.

3.1.1 Source Water Quality

The Fort Collins Utilities Water District receives raw water from two sources: the Cache la Poudre River and Horsetooth Reservoir. The headwaters of the Cache la Poudre River begin on the eastern slope of Colorado while the Colorado-Big Thompson project supplies Horsetooth Reservoir with snowmelt and rainwater from the western slope (FC Gov, 2013). These sources are then combined as necessary at a flow blending facility located at the existing centralized water treatment facility.

The Cache la Poudre River is regarded as a high quality, pristine water source due to a lack of prior human impact before arriving at the water treatment facility. As a river in a mountain region, the source is subject to large fluctuations associated with snowmelt. This reduces parameters like alkalinity and hardness in the spring while increasing total organic carbon (TOC) and turbidity (Upper CLP, 2008). A comparison of raw Cache la Poudre source water parameter measurements to drinking water standards is shown in Table 3.1.

Table 3.1 Drinking Water Standards Compared to Mean and Max Values for Raw Poudre River water 1997-2007 (Fort Collins Water Quality Lab)



Parameter	Primary or Secondary (P or S)	MCL	Sample Size	Mean	Maximum	Standard Error
pH	S	6.5-8.5	537	7.55	8.65	0.01
Total Dissolved Solids (mg/L)	S	500	125	46.9	86	1.31
Total Organic Carbon (mg/L)			340	3.21	11.3	0.11
Turbidity (NTU)		0.3 / 1(1)	555	2.13	42.1	0.16
Fluoride (mg/l)	P/S	[4.0] (2.0)	498	0.16	0.47	0.00
Nitrate (mg/l as N)	P	10	498	0.05	0.50	0.00
Nitrite (mg/l as N)	P	1	493	< 0.04	< 0.04	
Chloride (mg/l)	S	250	116	1.59	11.4	0.13
Sulfate (mg/l)	S	250	116	3.53	12.9	0.14
Aluminum - total by AA (ug/l)	S	50-200	76	255	2974	58.4
Aluminum - total reactive (ug/l)	S	50-200	346	<15	99.9	
Antimony (ug/l)	P	6	30	<2.0	<2.0	
Arsenic (ug/l)	P	10	32	<2.0	<2.0	
Barium (ug/l)	P	2,000	30	17.9	47.5	1.59
Beryllium (ug/l)	P	4	30	<0.5	<0.5	
Cadmium (ug/l)	P	5	31	0.01	0.15	0.01
Copper (ug/l)	P/S	[1,300] (1,000)	126	<3.0	24.7	
Iron (ug/l)	S	300	125	241	4,243	45
Lead (ug/l)	P	15	124	<1.0	2.50	
Manganese (dissolved) (ug/l)	S	50	107	<1.0	14.3	
Manganese (total) (ug/l)	S	50	124	11.2	231	2.83
Mercury (ug/l)	P	2	24	<1.0	<1.0	
Selenium (ug/l)	P	50	30	<2.0	<2.0	
Silver (ug/l)	S	100	31	<0.5	<0.5	
Thallium (ug/l)	P	2	30	<1.0	<1.0	
Zinc (ug/l)	S	5,000	31	<100	<100	

[Primary Standard] (Secondary Standard)

All metals are total unless otherwise indicated.

"<" values are "< Reporting Limit" where Reporting Limit is the lowest reportable number based on the lowest calibration standard routinely used.

(1) For treated water, turbidity may never exceed 1 NTU, and must be < 0.3 NTU in 95% of daily samples in any month.

Areas of concern are the pathogens, TOC and geosmin (Upper CLP, 2008). Microbial pathogens such as *Giardia lamblia* and *Cryptosporidium* represent a health risk producing water borne illnesses if not treated. Elevated TOC levels effect the efficiency of coagulation and sedimentation during treatment and act as a substrate for the formation of DBPs. Geosmin is an organic compound released by the decomposition of cyanobacteria (blue-green algae) or filamentous bacteria which causes taste and odor issues even though it does not represent a human health risk. Overall, the Cache la Poudre River provides high quality source water in comparison to drinking water standards.

Water that fills Horsetooth Reservoir as a part of the Colorado-Big Thompson (CBT) Project is transported from the upper Colorado River to the Big Thompson watershed. As another comparatively pristine water source there are a few additional issues related to the storage of water in a 150,000 acre-ft capacity reservoir. Parameters of concern include TOC, geosmin, manganese related to low dissolved oxygen levels during turnover, and benzene, toluene, ehtylbenzene and xylene (BTEX) from the use of petroleum based fuels (Horsetooth WQMP, 2009). All of these issues must be carefully monitored and addressed during treatment.

3.1.2 Existing Water Treatment Facility and Distribution

The existing Fort Collins Water Treatment Facility (FCWTF) is an 87-MGD capacity conventional water treatment plant located at the north end of the City of Fort Collins against Horsetooth Reservoir. Originally built in 1967 as a peaking plant to aid the original Fort Collins Water Treatment Plant, the current facility now houses four separate process treatment trains as a result of multiple expansions including raw water conveyance, chemical feed systems, filtration, clearwell, storage reservoirs, backwash supply and solids handling (Master Plan, 2010). Today, all four treatment trains consist of coagulation, flocculation, clarification, mixed-media filtration and chlorine disinfection added at the clearwells.

Currently, the FCWTF produces average of roughly 25 MGD with a peak demand around 50 MGD. This value varies throughout the year due to irrigation demand as shown in Figure 3.1.

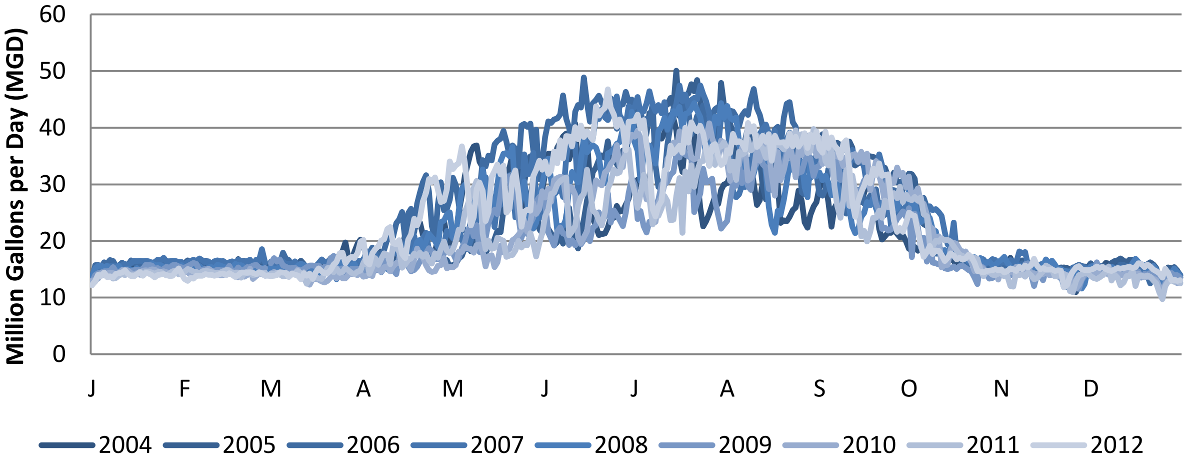


Figure 3.1 - Fort Collins Utilities Daily Demand (Data from City of Fort Collins 2004-2012)

A base demand of approximately 15 MGD can be determined from this figure meaning that 40-50% of the total treated demand at the FCWTF is consumed by landscape irrigation (Figure 3.1). Population projections show that in the next 20 years, the FCWTF will still have more than enough capacity to handle peak demands shown in Figure 3.2.

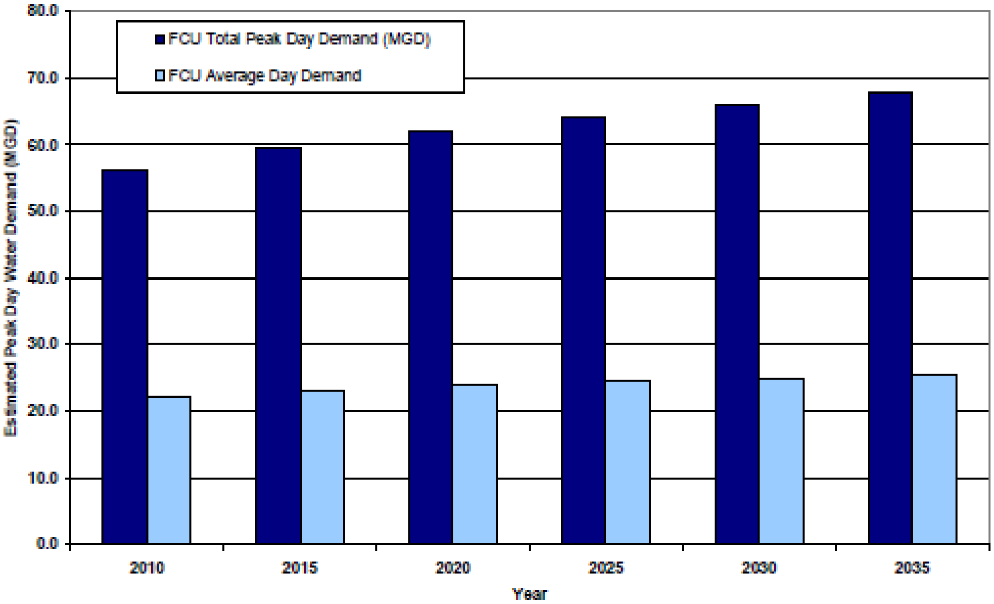


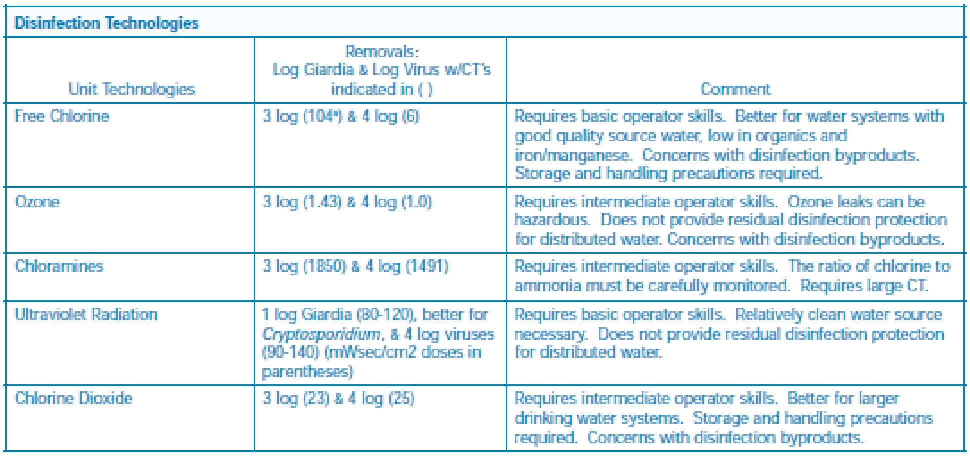
Figure 3.2 – Fort Collins Utilities Service Area Demand (Fort Collins Utilities, 2010)

Treated potable quality water is delivered through a single distribution system sized for peak and fire flow demand. Initially comprised of cast iron pipe (CIP) prior to 1976 the network is now additionally composed of ductile iron pipe (DIP) used through 2005 and more recently polyvinyl chloride (PVC).

3.1.3 Decentralized Treatment Compliance

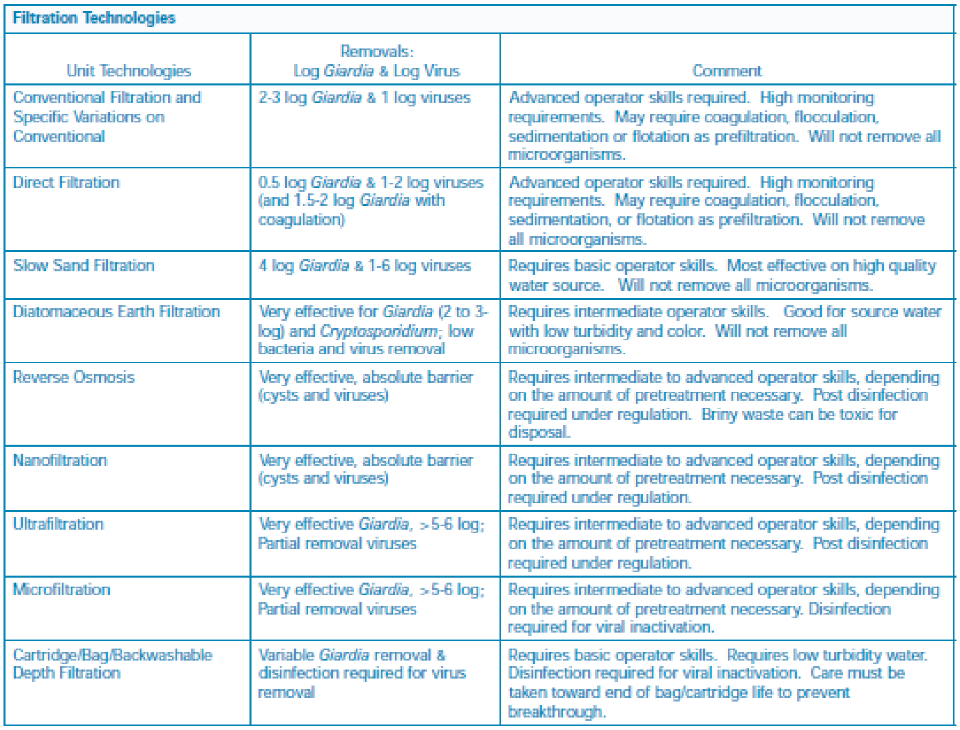
Decentralized systems employ many of the same treatment technologies implemented in centralized treatment facilities (U.S. EPA, 2002). Depending on the quality and origin of the water source, systems typically will be comprised pre-treatment, filtration and disinfection processes. Under the general requirements of Article 7 of the Colorado Primary Drinking Water Regulations (CPDWR), public water systems that are under the direct influence of a surface water source must employ filtration as a treatment technique (CDPHE, 2010). Additionally, these systems are required to provide disinfection treatment. Table 3.2 summarizes common treatment technologies applied in small system decentralized applications.

Table 3.2 – Surface Water Treatment Compliance Technology Table (U.S. EPA, 2003)



Disinfection Technologies

Unit Technologies	Removals: Log Giardia & Log Virus w/CT's indicated in ( )	Comment
Free Chlorine	3 log (104*) & 4 log (6)	Requires basic operator skills. Better for water systems with good quality source water, low in organics and iron/manganese. Concerns with disinfection byproducts. Storage and handling precautions required.
Ozone	3 log (1.43) & 4 log (1.0)	Requires intermediate operator skills. Ozone leaks can be hazardous. Does not provide residual disinfection protection for distributed water. Concerns with disinfection byproducts.
Chloramines	3 log (1850) & 4 log (1491)	Requires intermediate operator skills. The ratio of chlorine to ammonia must be carefully monitored. Requires large CT.
Ultraviolet Radiation	1 log Giardia (80-120), better for *Cryptosporidium*, & 4 log viruses (90-140) (mWsec/cm2 doses in parentheses)	Requires basic operator skills. Relatively clean water source necessary. Does not provide residual disinfection protection for distributed water.
Chlorine Dioxide	3 log (23) & 4 log (25)	Requires intermediate operator skills. Better for larger drinking water systems. Storage and handling precautions required. Concerns with disinfection byproducts.



Filtration Technologies

Unit Technologies	Removals: Log *Giardia* & Log Virus	Comment
Conventional Filtration and Specific Variations on Conventional	2-3 log *Giardia* & 1 log viruses	Advanced operator skills required. High monitoring requirements. May require coagulation, flocculation, sedimentation or flotation as prefiltration. Will not remove all microorganisms.
Direct Filtration	0.5 log *Giardia* & 1-2 log viruses (and 1.5-2 log *Giardia* with coagulation)	Advanced operator skills required. High monitoring requirements. May require coagulation, flocculation, sedimentation, or flotation as prefiltration. Will not remove all microorganisms.
Slow Sand Filtration	4 log *Giardia* & 1-6 log viruses	Requires basic operator skills. Most effective on high quality water source. Will not remove all microorganisms.
Diatomaceous Earth Filtration	Very effective for *Giardia* (2 to 3-log) and *Cryptosporidium*; low bacteria and virus removal	Requires intermediate operator skills. Good for source water with low turbidity and color. Will not remove all microorganisms.
Reverse Osmosis	Very effective, absolute barrier (cysts and viruses)	Requires intermediate to advanced operator skills, depending on the amount of pretreatment necessary. Post disinfection required under regulation. Briny waste can be toxic for disposal.
Nanofiltration	Very effective, absolute barrier (cysts and viruses)	Requires intermediate to advanced operator skills, depending on the amount of pretreatment necessary. Post disinfection required under regulation.
Ultrafiltration	Very effective *Giardia*, >5-6 log; Partial removal viruses	Requires intermediate to advanced operator skills, depending on the amount of pretreatment necessary. Post disinfection required under regulation.
Microfiltration	Very effective *Giardia*, >5-6 log; Partial removal viruses	Requires intermediate to advanced operator skills, depending on the amount of pretreatment necessary. Disinfection required for viral inactivation.
Cartridge/Bag/Backwashable Depth Filtration	Variable *Giardia* removal & disinfection required for virus removal	Requires basic operator skills. Requires low turbidity water. Disinfection required for viral inactivation. Care must be taken toward end of bag/cartridge life to prevent breakthrough.

One important distinction in the classification of decentralized treatment technologies is the difference between compliance and variance technologies as defined in the 1996 SDWA Amendments for small systems. A compliance technology refers to a technology that achieves compliance with a maximum contaminant level (MCL) and satisfies a treatment technique (TT) requirement whereas a variance technology is only specified for a size and source combination for which there is no compliance technology (U.S. EPA, 2003). Point-of-use units are not permitted by the U.S. EPA to achieve compliance with an MCL for microbial contaminants. Point-of-entry systems and satellite treatment facilities are classified as compliance technologies and therefore are more suitable candidates for a decentralized treatment strategy. Federal regulations address POE devices used for compliance but neglect the use of POU units. The focus of this thesis will be limited to compliance strategies for decentralized treatment including POE and neighborhood-scale system technologies.

3.2 Decision Making Approach

The assessment of decentralized treatment system options requires a decision making strategy. This evaluation began with basic research on available systems, including literature review, case studies and collection of manufacturer data. Initial comparisons were made for these available technologies based on common advantages and disadvantages as well as applicability to the source water quality. These comparisons led to the selection of five different treatment system options for each approach.

Using an Excel based multi-criterion decision analysis (MCDA) developed by Dr. Darrel Fontane and Dr. Sybil Sharvelle, five main criteria were chosen in order to assess differences between the options. Within these main criteria, sub-criteria were selected which could be evaluated either qualitatively or quantitatively. This process required further research of each system type relating to the listed sub-criteria. Once the data was gathered, it was entered into the MCDA tool which normalizes both qualitative and quantitative data so that it may be combined to form a total score for each system option.

Figure 3.3 is a graphic summary of the decision making strategy for selection of a neighborhood scale water treatment system.

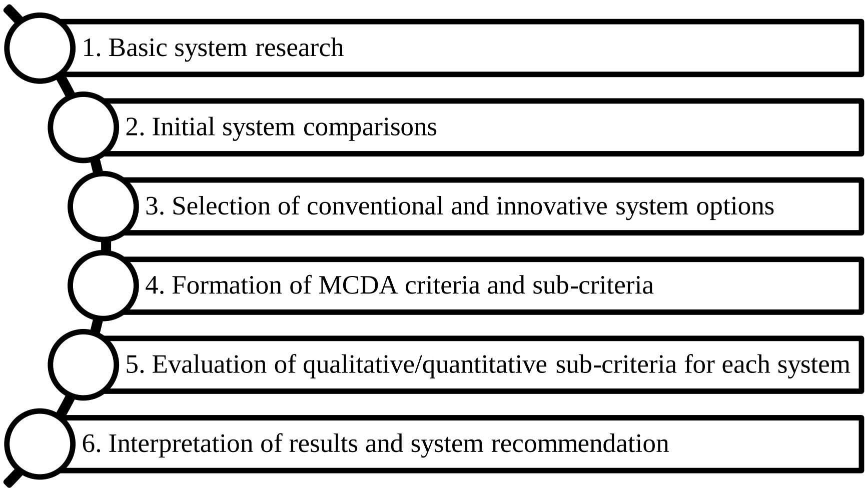


Figure 3.3 – Decision making strategy for selection of Neighborhood Scale Water Treatment System

3.3 Overview of Criteria Analysis

To analyze the treatment system options in a comprehensive and transparent manner, a Multi-Criterion Decision Analysis (MCDA) approach was designed to compare the most crucial criteria that would differentiate the selected configurations. Limiting the MCDA to five main criteria helped to make the process more manageable while focusing on the most important factors. The five main criteria used in the analysis were:

- Cost
- Energy Usage
- Maintenance Requirements
- Performance
- Implementation

Within each main criterion, specific sub-criteria were directly evaluated either quantitatively or qualitatively. The same main criteria were used for both neighborhood-scale and POE systems specifying applicable performance metrics for each type of system. These sub-criteria are listed for both POE and neighborhood-scale treatment and further defined later in the chapter (Table 3.2).

Table 3.2 – Definition of Main and Sub-Criteria for Decentralized Treatment System Selection

Main Criteria	Neighborhood-Scale Systems	Point-of-Entry
Cost	• Capital cost (2014 USD) • Operations cost (2014 USD)	• Capital cost (2014 USD) • Operations cost (2014 USD)
Energy Use	• Total energy use (kWh/year) • Percent recovery (%)	• Process energy use (kWh/year) • Minimum pressure requirement (psi)
Maintenance Requirements	• Employee time required (hours/week) • System lifetime (years) • Operational complexity (qualitative) • Chemical requirements (qualitative) • Sludge production (%)	• Operational complexity (qualitative) • Component replacement frequency • Waste produced (qualitative)
Performance	• Removal of *Giardia lamblia* (log removal) • Removal of *Cryptosporidium* (log removal) • Removal of viruses (log removal) • Influent turbidity limit (NTU)	• Virus removal (qualitative) • Influent turbidity limit (NTU) • Organic contaminant removal (qualitative) • Inorganic contaminant removal (qualitative) • Recovery efficiency (%)
Implementation	• System size (ft^2) • Opportunity for add-ons (qualitative) • Availability (qualitative) • Community Disturbance (qualitative)	• System size (ft^3) • Availability (qualitative)

Within the MCDA, each sub-criterion was given a qualitative or quantitative score. The tool normalizes these scores into a 1 to 5 scale with the best score receiving a 5, the worst score a 1 and linearly interpolating the values in between. In this way, each main criterion received a total score as the average of its sub-criteria scores. The total system score then is an average of the main criteria scores as part of the weighted average method (WAM). Additionally, the same criteria will be evaluated using the Promethee Method which is an outranking based method that compares each alternative to the others in terms of main criteria. A higher main criteria score translates to a value of 1 and the lesser scoring alternative receives a 0. This 1 or 0 value is then multiplied by a normalized weight dictated by importance factors.

3.4 Neighborhood-Scale System Selection

In a neighborhood-scale system approach, the existing water treatment plant would be bypassed allowing existing potable distribution lines to deliver raw or minimally pre-treated water throughout the city to neighborhood scale water treatment plants. From these neighborhood scale plants, a dual distribution system would be installed requiring the installation of a smaller diameter line to deliver potable water to the service connections at residences and businesses. The motivation for this evaluation is to determine which type of water treatment system would be most applicable for neighborhood scale use in the City of Fort Collins.

System sizing was based on three sample neighborhoods chosen in the City of Fort Collins. Each neighborhood represents different development periods and land use. While the makeup of each of these neighborhoods is intentionally different, water use remains relatively steady throughout. Using a peak factor of 2.5, the indoor water demand ranged from 0.85 MGD to 1.05 MGD. For the purposes of this evaluation, a design capacity of 1.0 MGD was used for selection of neighborhood-scale treatment systems.

3.4.1 Assumptions

In accordance with the *Colorado Primary Drinking Water Regulations*, filtration is required as a treatment technique for public water systems supplied by a surface water source. Each public water system providing filtration must also provide disinfection treatment sufficient to ensure 3-log inactivation of *Giardia lamblia* and 4-log inactivation/removal of viruses as well as a residual disinfectant entering the distribution systems that connect be less than 0.2 mg/L for over 4 hours (CDPHE, 2010). This disinfection process must be continuous and is required for all water supplies. For this reason, an assumption was made that all treatment system configurations must include chlorine disinfection in order to maintain a residual within the new potable distribution system. Additionally, the second assumption made is that all systems will need potable water clearwell storage on site and require the same building demands such as HVAC, lighting, and general maintenance.

Package water treatment plants are pre-manufactured treatment facilities used to treat water in small communities (U.S. EPA, 2000). At lower capacities package plant systems provide a strong list of advantages compared to standard plant designs. Installation of package plants significantly reduces capital costs through pre-engineering and pre-manufacturing the facilities. These plants compartmentalize processes, decreases total plant footprint and are easy to automate, reducing operator time. In addition, at the 1.0 MGD capacity, total production costs can be decreased up to 20% (Clark & Morand, 1981). For these reasons this evaluation incorporated the use of package plant treatment systems.

3.4.2 Available Neighborhood-Scale System Treatment Technologies

After an initial review of the most common types of neighborhood-scale systems, the number of potential treatment system options was limited to five. These systems were separated between conventional systems similar to the existing centralized water treatment facility in place and more innovative approaches. The systems evaluated were:

- Conventional Treatment
- Automated Conventional Treatment

- Ultrafiltration
- Direct Filtration
- Up-flow Adsorption-Clarification

The following system outlines detail information on the reason each system was selected for this application, general advantages and disadvantages and the suggested system configuration.

Conventional Treatment

Scaling down the conventional potable water treatment system from the centralized size to a neighborhood scale is the first option considered in order to produce a base line for other systems to be compared to. Conventional treatment consists of five main processes: coagulation, flocculation, clarification, filtration and disinfection. At the existing centralized treatment facility, flocculation and sedimentation (typically using plate or tube settlers) is followed by dual-media gravity filtration followed by chlorine disinfection providing a residual of 0.6 mg/L at the clearwell (FCU, 2010). Conventional treatment plants rely on charge neutralization and sweep flocculation in order to destabilize solid contaminants (U.S. EPA, 2013). Coupling this destabilization with filtration removal and disinfection provides the required inactivation/removal of contaminants, bacteria and viruses. The conventional treatment process is shown in Figure 3.4.

Advantages of conventional treatment are operator familiarity, proven success, and regulatory acceptance. However, conventional water treatment plants have larger footprints, use more chemicals and are less efficient than other technologies.

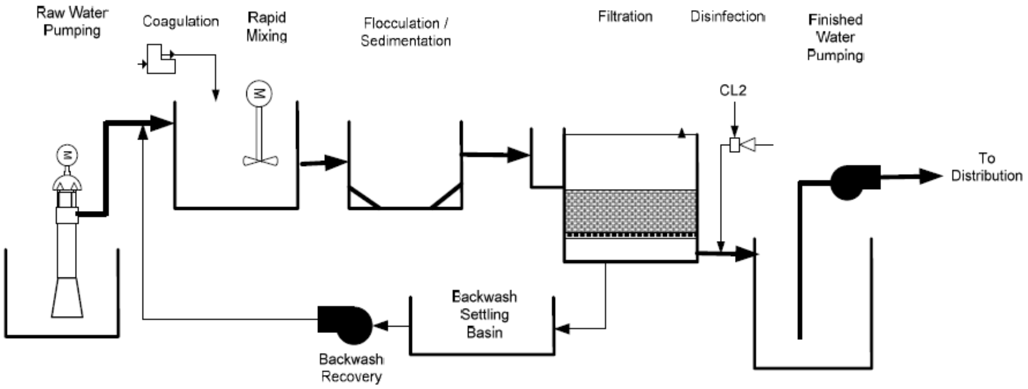
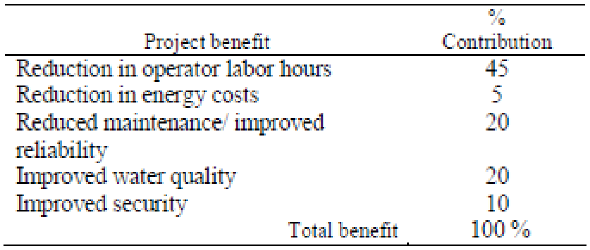


Figure 3.4 – Conventional treatment plant schematic (U.S. EPA, 2008)

Automated Conventional Treatment

Plant automation can be installed in order to make a conventional treatment plant more competitive with innovative technologies. Each system process in a conventional treatment is compatible with either manual or automatic control. Aspects that may be added to automate a conventional system include raw water flow controllers, influent quality sensors, streaming current detectors and pH controllers for coagulation, constant-rate filtration controller, backwash flow controllers, and residual chlorinator controllers. Each of these automation packages can result in the unattended automatic operation of a water treatment facility. Controllers require online monitoring inputs as well as software packages and hardware to run them. The Environmental Protection Agency (EPA) has produced a detailed report on the *Costs and Benefits of Complete Water Treatment Plant Automation* in which the operation and components of these automation packages are specified. Additionally, their research showed substantial benefits from the automation of these plants shown in Figure 3.5.



Project benefit	% Contribution
Reduction in operator labor hours	45
Reduction in energy costs	5
Reduced maintenance/ improved reliability	20
Improved water quality	20
Improved security	10
Total benefit	100 %

Figure 3.5 – Breakdown of benefits from conventional full-plant automation (U.S. EPA, 2008)

Using case studies and methods offered in *Costs and Benefits of Complete Water Treatment Plant Automation,* typical reductions were estimated for labor, energy and maintenance based on conventional water treatment system data presented in this chapter.

<u>Ultrafiltration</u>

Ultrafiltration is a form of membrane filtration which utilities a pressure gradient to separate high-molecular weight particulates and macromolecules to produce potable water. In the hierarchy of membrane filtration, ultrafiltration (UF) is more selective than microfiltration (MF) but less than nanofiltration (NF). Ultrafiltration is able to remove suspended solids, colloids, bacteria and viruses with a particle size of 0.005 to 0.1 microns.

General advantages of the ultrafiltration process are that no chemicals are required for treatment, the quality of effluent remains constant, compact plant sizes and the ability to meet regulatory standards for pathogen removal. Balancing these benefits are high costs, membrane fouling and pretreatment requirements. According to the *State of Colorado Design Criteria for Potable Water Systems 4.3.8*, ultrafiltration is an acceptable form of filtration (CDPHE, 2013).

There are four different types of ultrafiltration membrane geometry: tubular, hollow fiber, plate & frame and spiral wound. Each geometry has unique advantages and drawbacks which are summarized in Table 3.3. Spiral wound filters maximize surface area at the expense of cost and susceptibility to poor water quality. Plate & frame filters are typically used for poor water quality. Tubular membranes require less pre-treatment but consume more space and money (Lenntech, 2014). Performance metrics such as recovery rate, module size, maintenance and cost favor hollow fiber membranes which is the reason they were selected for this application.

Table 3.3 – Comparison between the different types of geometry – Ultrafiltration Membranes (Lenntech, 2014)

	Tubular	**Hollow Fiber**	**Plate & Frame**	**Spiral Wound**
Ultrafiltration	Yes	>95%	Yes	Yes
Cleaning Ease	+	+++	-	-
Pre-treatment	+++	+	-	+
Recovery Rate	+	+++	+	++
Module Size	-	++	+	++
Cost per m^2	-	+++	+	+++

In addition to membrane geometry, plant configuration plays a large role in performance. There are two options for ultrafiltration module configurations: pressurized or immersed. Pressurized systems are controlled by a feed pump which elevates the feed water pressure without increasing permeate pressure (Lenntech, 2014). The immersed ultrafiltration configuration suspends membranes in the feed water in an open basin shown in Figure 3.6. The pressure is provided by the water column on the influent side in addition to a suction pump on the permeate side to produce the total trans-membrane pressure. Immersed systems are configured with multiple basins with permeate pumps which allows the isolation of maintenance to a single train instead of the entire system.

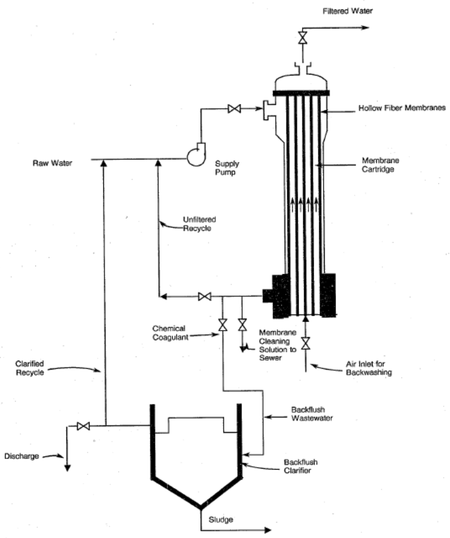


Figure 3.6 – Ultrafiltration membrane system process (U.S. EPA, 1991)

Ultrafiltration systems have a variety of unique advantages as a small-system solution. They can be installed as package plants with options for expansion using membranes coupled in trains to meet capacity needs. Ultrafiltration membranes are capable of robust treatment and modular design for flexibility in process and capacity. In addition, systems come prefabricated to minimize site work and installation costs in addition to utilizing the smallest footprint of any of the systems analyzed.

Direct Filtration

Another option for a small community neighborhood scale water treatment system is direct filtration. This system has been mirrored at the centralized scale which is why it may be considered at a neighborhood plant scale. While this may be applicable during most times of the year, periods of high runoff and high turbidity may limit the effectiveness of this system. The *State of Colorado Design Criteria for Potable Water Systems 4.3.5* lists direct filtration as an acceptable form of filtration for meeting potable water quality standards (CDPHE, 2010). In general, direct filtration uses coagulants and rapid mixing but omits the sedimentation step and instead removes suspended solids through filtration only. Foregoing the sedimentation step allows for a drastic reduction in system size. This process is most applicable to raw water with a consistent turbidity level of 10 NTU or less (USACE, 1999). Again, package plants are recommended for small surface water systems in order to decrease system complexity and installation and design costs. These direct filtration package plants also include automated chemical dosing which reacts to real-time information on raw and finished water quality. A typical plant will use mechanical or hydraulic flocculators and rapid sand gravity filtration (USACE, 1999). The filters are then backwashed in the same manner as a conventional plant. Solids produced are collected in sludge and need to be disposed of, potentially by recycling filter backwash water and holding it in a thickener before removal. A schematic of the direct filtration process is shown in Figure 3.7.

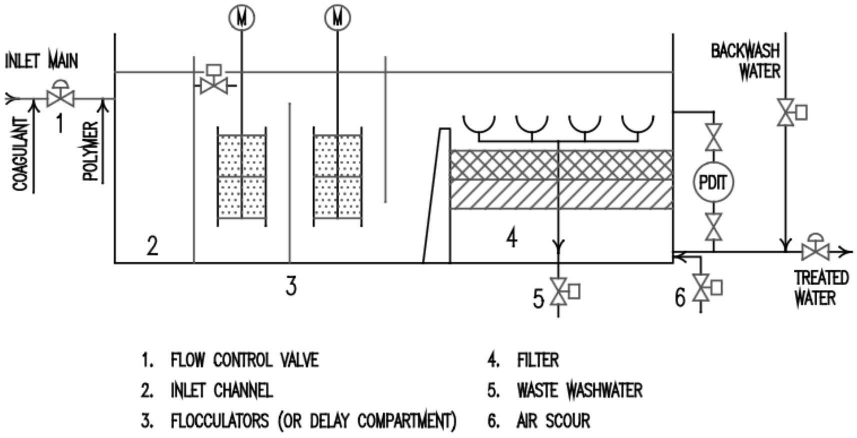


Figure 3.7 – Direct filtration system schematic (Aquatec-Maxon, 2013)

Advantages of the direct filtration system are lowered capital costs, reduced space requirements, decreased sludge quantities, and reduced coagulant doses (Burns et al, 1984). However, there are disadvantages in influent turbidity limits, shorter response time for operator adjustment, and less detention time for taste and odor issues (U.S. EPA, 2013).

Typical packaged DF systems do not require a clarifier which correlates to a small footprint. Filtration is handled by dual-media or multi-media filter bed options which are coupled with choice of chlorine, hypochlorite, ozone or UV disinfection systems. Filter backwash is automatic based on either a pre-determined headloss or total elapsed time first through air scouring followed by high-rate water backwashing. Some packaged systems may include options for mechanical or hydraulic flocculation (Corix, 2013). These systems provide 2-log inactivation for Giardia and must be coupled with a disinfection system to meet treatment and residual requirements.

Up-flow Adsorption-Clarification and Dual-Media Filtration

The up-flow adsorption-clarification (AC) water treatment process combines the processes of coagulation, flocculation and clarification into a single step as shown in Figure B.8. After flash mix addition of a chemical coagulant the water flows upwards through a clarifier, passing through a bed of buoyant adsorption media which removes flocs and reduces loading for a high-rate dual media filter in the second step (Corix, 2013). Air scouring is required for the adsorption media and is more frequent than filter backwashing due to the amount of solids removed in the adsorption-clarification process (NDWC, 1997). The flocculation process is enhanced by contact with retained solids (Jones et al, 2008). At the end of this process, a chlorine disinfection system would need to be installed for inactivation and residual requirements.

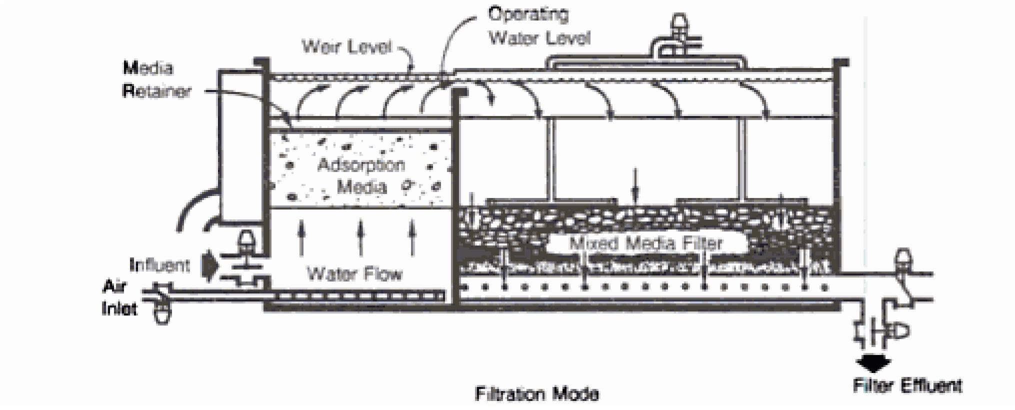


Figure 3.8 – Adsorption-clarification treatment process (U.S. EPA, 1991)

Advantages of the adsorption-clarification treatment systems are small footprints, low operational complexity, quiet operation, and longer system lifetimes. The disadvantages of these systems are high chemical and energy requirements.

Adsorption-clarification systems are designed for stable turbidity levels which rarely exceed 30 NTU. Using a tortuous path adsorption clarifier and rapid rate filtration, these systems achieve effluent turbidity of 0.1 NTU and provide 2.5-log inactivation of Giardia and Cryptosporidium. Chlorine disinfection would need to be coupled with this system in a clearwell as well as an area for waste solids treatment. Typical systems are capable of treating up to 1.5 MGD and can improve capacity with multiple trains (Corix, 2013)

3.4.3 Evaluation of Sub-Criteria for Neighborhood-Scale Systems

Within each of the five main criteria, sub-criteria are defined which can be evaluated qualitatively or quantitatively. A definition of each sub-criterion and an explanation of the way that the values were collected or calculated is provided.

Cost

Capital Cost –Total capital cost of the system including system cost and installation cost calculated quantitatively in dollars ($)

Operations Cost – Estimated typical annual operations cost for system operation, maintenance and repairs calculated quantitatively in annual dollars ($)

Energy Use

Total energy use – Annual energy input needed to operate the treatment facility evaluated in kWh/year

Energy efficiency – Quantitative value calculated as kWh/MG (kilowatt hours per million gallons treated)

Percent recovery – Measurement of the potable water produced over the amount of influent in terms of percentage

Maintenance Requirements

Employees time required – Number of total employee hours required per week

System lifetime – Rated quantitative value in years of total expected system lifetime before replacement

Operational complexity – Qualitative assessment of how complex the system is to operate, evaluated from very low to very high based on Table 3-4 in the report “Safe Water from Every Tap”

Sludge production – Relative assessment of total solids residual (sludge) production compared to conventional treatment (reported as a percent of total solids produced)

Chemical requirements – Qualitative assessment of the relative amount of chemicals required in each treatment process

Performance

Removal of *Giardia lamblia* - The State of Colorado requires 3-log removal of *Giardia lamblia*. Criterion measured in terms of log removal (ex. 99.9% removal = 3-log)

Removal of *Cryptosporidium* - The State of Colorado requires 4-log removal of *Cryptosporidium*. Criterion measured in terms of log removal (ex. 99.99% removal = 4-log)

Removal of viruses – The State of Colorado requires 4-log virus removal. Criterion measured in terms of log removal (ex. 99.99% removal = 4-log)

Influent turbidity limit – Measure of recommended influent turbidity limitation in NTU

Implementation

System size – Total system footprint measured in square feet not including the assumed chlorine disinfection system or waste solids treatment

Opportunity for expansion – A qualitative assessment of the ability of the system to expand in capacity rated from very low to very high based on system advantages

Availability – How common is each system evaluated qualitatively from very low to very high based on manufacturer data

Community disturbance – Qualitative assessment of the community disturbance associated with solids residual production and handling including trucking to landfills or other waste handling practices

3.4.4 Results and Recommendations for Neighborhood-Scale System Selection

Evaluating neighborhood scale water treatment system selection is a function of comparing different stakeholder weighting scenarios and ranking methods. A comprehensive analysis of the results was completed in order to recommend the most applicable system option. Input data was evaluated according to the value-based Weighted Average Method (WAM). Equal-weighting of main criteria was used for decision making in this project.

Table 3.4 provides the average main criteria scores for each neighborhood scale system alternative.

Table 3.4. Main criteria average scores (Maximum score of 5)

Main Criteria	Conventional	Automated Conventional	Ultrafiltration	Direct Filtration	Up-flow Adsorption-Clarification
Cost	1.29	1.82	1.30	3.62	3.09
Energy Use	3.90	5.00	1.00	4.74	2.85
Maintenance Requirements	2.00	2.68	3.84	3.72	3.80
Performance	2.65	2.98	4.22	1.00	1.44
Implementation	2.08	1.40	4.80	2.40	3.55

Up-flow Adsorption-Clarification and Direct Filtration systems have the lowest capital cost and received the highest scores despite a conservative estimates for operations and maintenance costs while Ultrafiltration received the lowest score. Direct Filtration requires the least amount of energy and highest percent recovery whereas Ultrafiltration again received the lowest score for large energy use and low recovery. The differences between these systems in terms of maintenance could have been exaggerated by the choice of sub-criteria. Employee time required and system lifetime were given the same weight as operational complexity, chemical requirements and sludge production. Employee time estimates were highly variable and may actually have as large of a discrepancy between system choices.

Performance sub-criteria favored Ultrafiltration which provides the highest level of treatment as a stand-alone option. However, each system is assumed to also include chlorine disinfection which would ensure that all water meets potable drinking standards. Lastly, implementation favors the innovative technologies such as Ultrafiltration and Up-flow Adsorption Clarification. These systems have a small footprint with many manufacturer options and opportunities for simple system capacity expansion.

Final results for both the Weighted Average Method and Promethee Method are displayed in Figures 3.9 and 3.10. System scores and input values are reported in Appendix A.

Overall weighted-average method (WAM) scores for the five alternative neighborhood-scale system treatment packages show Direct Filtration was the top choice (Figure 3.9). Ultrafiltration was next and Up-flow Adsorption Clarification completed the top three choices which are all classified as innovative technologies. Automating conventional treatment made the system more competitive with the innovative systems but maintained distinguishable distance in score.

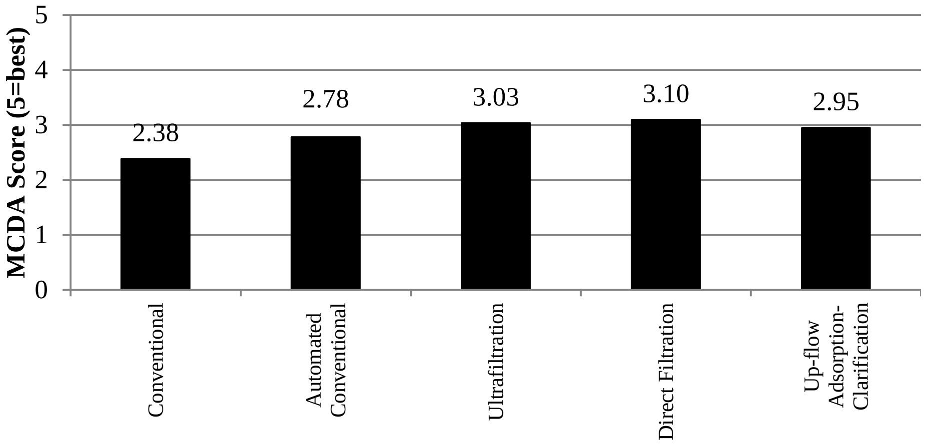


Figure 3.9 – Total score (WAM) for Neighborhood-Scale System Selection (Max Score = 5)

The treatment packages were also compared using the out-ranking Promethee Method in which alternatives are compared directly according to sub-criteria with the better option receiving a 1 and the lesser a 0. Results of this analysis are shown in Figure 3.10. A more positive score reflects a stronger treatment option in comparison to other alternatives.

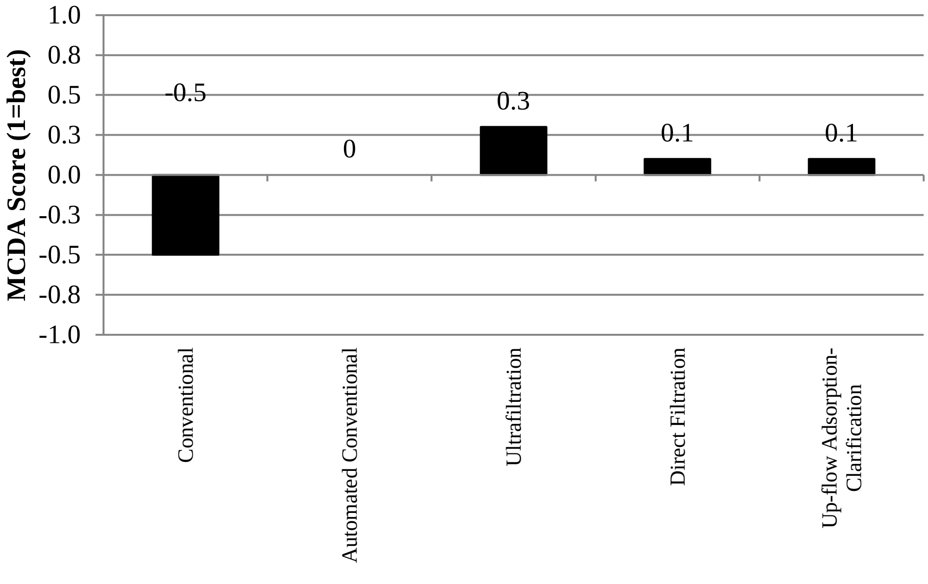


Figure 3.10 – Total score (PROMETHEE) for Neighborhood-Scale System Selection

As seen in Figure 3.12, the alternatives do not maintain their ranking order among the top three options. In this analysis, this shows that the magnitudes of particular advantages and disadvantages do affect the final results for system selection. This adds to the uncertainty of the indistinguishable WAM results. An outranking method does not incorporate the relative degree of each advantage or disadvantage. Ultrafiltration is revealed the strongest option, followed by Direct Filtration and Up-flow Adsorption-Clarification.

Considering the value of both methods, the recommended system for implementation in the neighborhood-scale treatment alternative will be Ultrafiltration based on the consistency of scores. Ultrafiltration scored high in three of five categories. Distinguishing characteristics were shown to be operations cost, energy use, chemical use, sludge production, system size, opportunity for expansion, and availability. Other factors that lacked enough precision or differentiation to distinguish between systems were capital costs, employee time required, system lifetime and removal performance. Proposals from WesTech for applicable Ultrafiltration and Adsorption-Clarification package plant systems are attached in Appendix A.

3.5 *Point-of-Entry Treatment System Selection*

Point-of-Entry (POE) treatment devices are designed to treat all water entering a home, business, school or facility for domestic potable use. Incoming distributed water may be directed to outdoor use while the indoor portion of the total flow is treated by a POE device installed prior to entry as shown in Figure 3.11.

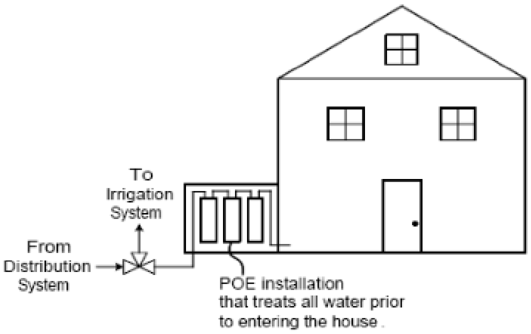


Figure 3.11 – Point-of-Entry schematic (U.S. EPA, 2003)

In a POE treatment approach, raw water would pass through the existing water treatment facility, leaving open the potential for centralized treatment and monitoring if necessary. Existing potable distribution lines would deliver raw or minimally pre-treated water to each home or business connection also referred to as the point-of-entry (POE) where small scale systems will treat water to a potable quality to be used in building.

For every connection a point-of-entry (POE) treatment system is required by EPA regulation and Colorado State Law (CDPHE). These systems must be capable of treating water to the same standards as centralized treatment regarding the Safe Drinking Water Act (SDWA) and CDPHE guidelines. According to the *Small Drinking Water Systems Handbook* (U.S. EPA, 2003) the public water system must maintain responsibility for operating and maintain all parts of the treatment system. This reference served as a guide for the implementation of POE systems and the city-scale in this study. The motivation for this evaluation is to determine which type of water treatment system would be most applicable for POE treatment in the City of Fort Collins.

3.5.1 Assumptions

Several assumptions were used in this analysis in order to eliminate information that would be common to all systems in Alternative #3 implementation or would not help distinguish one system from another. These assumptions included:

- Blended raw water from both sources (Colorado – Big Thompson and Cache la Poudre) delivered to POE connection through existing distribution system
- Centralized chemical addition for alkalinity, fluoridation and pH control in order to meet Lead & Copper Rule requirements and protect distribution system from corrosion
- POE treatment systems operate using distribution system pressure

- Reported treatment energy required for pumping and backwashing processes
- Performance metrics evaluated at single family connection level (10-15 gpm capacity)
- Installed outdoors, above ground in weather-proof enclosure
- Sediment pre-filters (particulate filters) necessary for all systems to limit influent turbidity
- UV disinfection implemented with all systems
- All systems equipped with a required mechanical warning/alarm
- Administrative and monitoring costs have been excluded from this study

Further details such as sizing for multi-family and commercial connections, location and protective enclosures, monitoring systems and other factors were considered in the final project MCDA using the selected POE treatment package.

3.5.2 Available POE Treatment Technologies

There are many types of POE treatment systems available on the market today. The fundamental setup requires a filtration unit and a disinfection unit (Cotruvo, 2002). The most common types of POE systems are listed below:

Filtration

Activated Carbon Filtration
Microfiltration/Ultrafiltration
Reverse Osmosis
Ion Exchange
Kinetic Degradation Fluxion Media
Distillation
Aeration
Modular Slow Sand Filtration
Activated Alumina

Disinfection

Ultraviolet Light
Ozone
Chlorine
Silver Impregnated Carbon

A study from the National Homeland Security Research Council and the U.S. EPA, *Investigation of POU/POE Treatment Devices as a Means of Security* (U.S. EPA, 2006) listed the most promising technologies for point-of-use (POU) and point-of-entry (POE) water treatment shown in Figure 3.12.

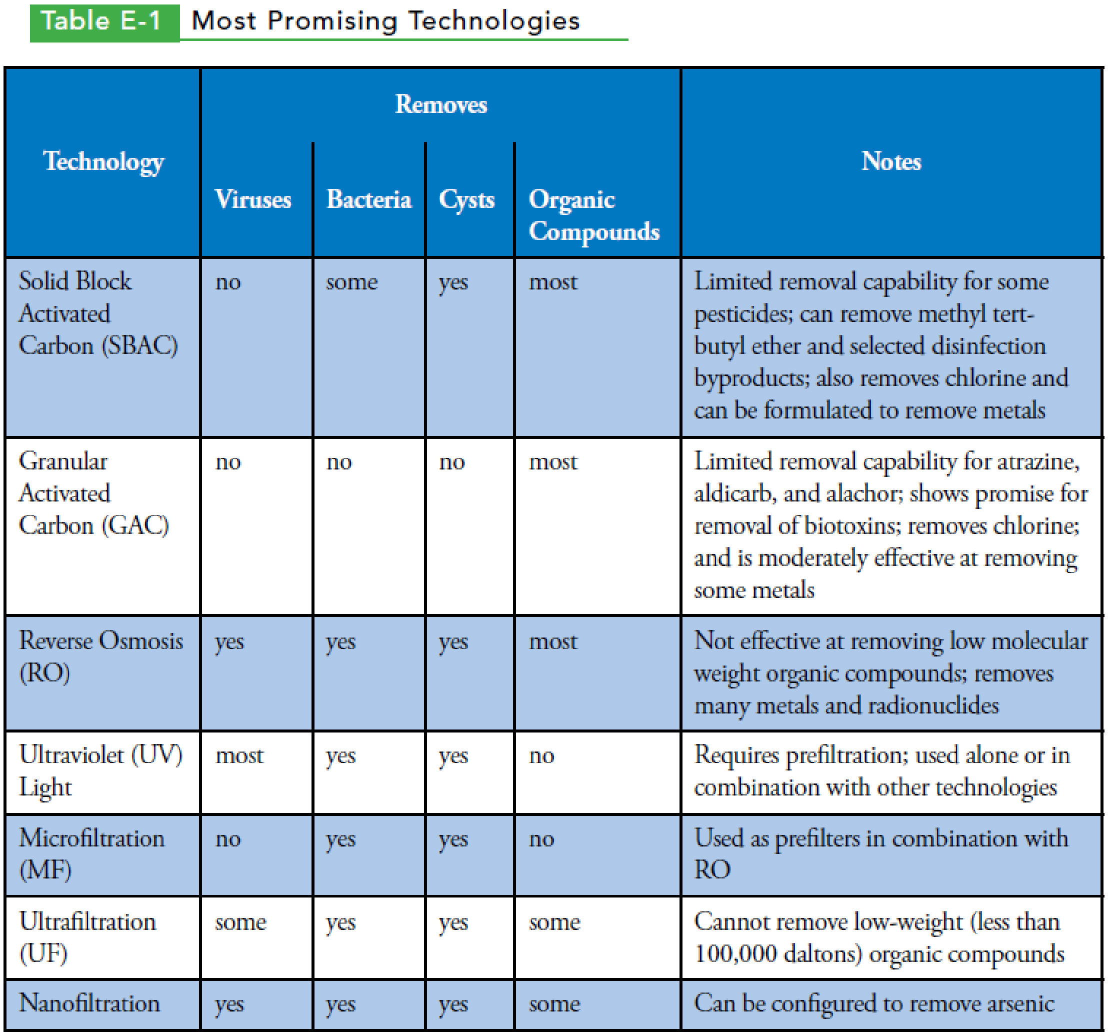


Table E-1 Most Promising Technologies

Technology	Removes				Notes
	Viruses	Bacteria	Cysts	Organic Compounds	
Solid Block Activated Carbon (SBAC)	no	some	yes	most	Limited removal capability for some pesticides; can remove methyl tert-butyl ether and selected disinfection byproducts; also removes chlorine and can be formulated to remove metals
Granular Activated Carbon (GAC)	no	no	no	most	Limited removal capability for atrazine, aldicarb, and alachor; shows promise for removal of biotoxins; removes chlorine; and is moderately effective at removing some metals
Reverse Osmosis (RO)	yes	yes	yes	most	Not effective at removing low molecular weight organic compounds; removes many metals and radionuclides
Ultraviolet (UV) Light	most	yes	yes	no	Requires prefiltration; used alone or in combination with other technologies
Microfiltration (MF)	no	yes	yes	no	Used as prefilters in combination with RO
Ultrafiltration (UF)	some	yes	yes	some	Cannot remove low-weight (less than 100,000 daltons) organic compounds
Nanofiltration	yes	yes	yes	some	Can be configured to remove arsenic

Figure 3.12 – Table E-1 Most Promising Technologies (National Homeland Security Research Center/EPA, 2006)

While UV was the only listed disinfection in the study, a brief analysis of the advantages and limitations of the most common disinfection options at the POE scale shown in Table 3.5 justified this result.

Table 3.5 – Point-of-Entry Disinfection System Comparison

Treatment System	Ultraviolet Radiation	Chlorine	Ozone
Advantages	-Most common POE disinfection unit -No addition of chemicals -No generation of DBPs -More effective against Crypto & Giardia than Chlorine -Not affected by ammonia or pH -Simplistic design	-Provides residual disinfectant -Reliable and effective against wide range of pathogens -Flexible dosing control	-More effective than chlorine for viruses/bacteria -No residuals -Generated onsite (safety) -No regrowth of microorganisms -Short contact time
Disadvantages	-No residual in piping (less of a concern in POE) -Sensitive to turbidity	-Taste and odor -Requires individual Cl dosing for each system -Chlorine storage -No nitrate removal -Increase in TDS	-More complex than UV or Cl, requires complicated equipment (efficient contact) -Reactive and corrosive -High cost of treatment

Ultraviolet light is the most common POE disinfection treatment option for a variety of reasons including effectiveness against *Cryptospordium* and *Giardia lamblia* without the addition of chemicals. Ozone includes safety and cost issues and chlorine faces a large feasibility issue when attempting to provide the correct dosage for over 30,000 systems citywide.

Research on the POE system market and treatment applicability reflected the filtration system options listed in the U.S. EPA study. A similar system comparison was performed for these filtration technologies in Table 3.6.

Table 3.6 – Point-of-Entry Filtration System Comparison

Treatment System	Reverse Osmosis	Activated Carbon/KDF	Micro/Ultra Filtration	Ion Exchange	Distillation
Advantages	-Removes inorganics -Small in size -Removes dissolved minerals & metals, microorganisms, colloids, dissolved inorganics -Removes dissolved minerals & metals, microorganisms,	-Removes organics -Long lifetime -Simple, economical maintenance -Does not require electricity (minus backwashing) -Coupled with KDF improves lifetime, prevents fouling and removes heavy metals	-Significantly lower rejection rate than RO -Highest quality water per unit energy -No chemical additives	-Reduces hardness -Selective exchange removes heavy metals -Removes dissolved inorganics -Salt-free conditioners do not require chemicals	-Removes broad range of contaminants effectively -Reusable

	colloids, dissolved inorganics				
Disadvantages	-Reject water volume and disposal -Different removal rates for turbidity and DOC -Low efficiency -Risk of bacterial contamination in membrane -Energy requirements	-Generates fines from carbon -Large effective pore size -Channeling (less filtration resistance) -Potential for fouling	-Larger pore size than RO, more dissolved particles (inorganics) pass -Allow dissolved salts and metals to pass	-Does not remove viruses or bacteria -Salt softeners require chemicals -Most systems require resin regeneration	-Some contaminants can be carried into the condensate -Careful maintenance required -Very high energy consumption -Large space requirements -Slow process – cannot produce enough water for indoor daily needs

After initial analysis, the following five treatment systems were selected for further evaluation:

1. Reverse Osmosis with UV
2. Activated Carbon/KDF with UV
3. Ultrafiltration with UV
4. Reverse Osmosis with Activated Carbon and UV
5. Activated Carbon/KDF and Ion Exchange with UV

These systems meet the requirement for filtration and disinfection and represent the most common POE configurations with varying levels of treatment robustness. Distillation was eliminated as a viable treatment option for this alternative due to high energy consumption and an inability to produce the quantities of potable water required for indoor use.

The following technology outlines detail information on the reason each system was selected for this application, general advantages and disadvantages and the suggested system configuration.

Reverse Osmosis – (RO) uses a semi-permeable membrane and applied pressure to overcome osmotic pressure to remove minerals, metals, colloids and dissolved inorganics. It is typically preceded by a particulate filter and may include an optional activated carbon filter for organics if necessary. RO is the most robust treatment option but requires high energy, achieves low recovery rates and costs more than other POE technologies (Rozelle et al, 1987).

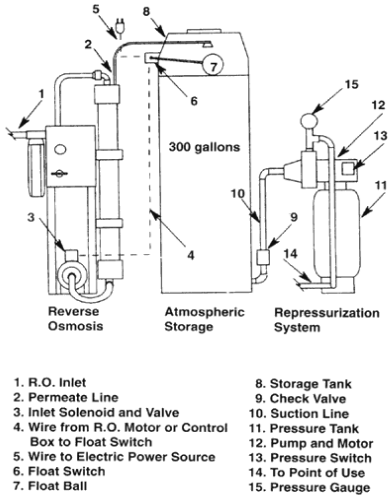


Figure 3.13 – Reverse osmosis POE system with storage (Pure Water Products, LLC)

Activated Carbon – (AC) eliminates taste and odor issues, turbidity and organic contaminants. Both granular activated carbon (GAC) and solid block activated carbon (SBAC) filters are small-system compliant. They are also typically preceded by particulate filters to reduce influent turbidity and require frequent maintenance including backwashing and filter media replacement (U.S. EPA, 2006).

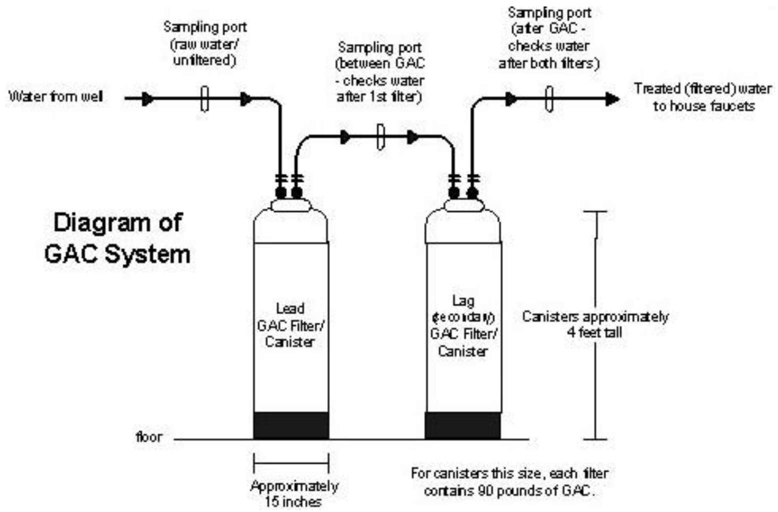


Figure 3.14 – Activated carbon POE system (Minnesota Department of Health, 2014)

Ultrafiltration – (UF) is a membrane process with pore size ranging from 0.01 to 0.04 μm for the removal of proteins, suspended solids, viruses, bacteria and cysts. Membranes can be cleansed and reused instead of disposed of like activated carbon media. A particulate filter is usually required for operation (U.S. EPA, 2006).

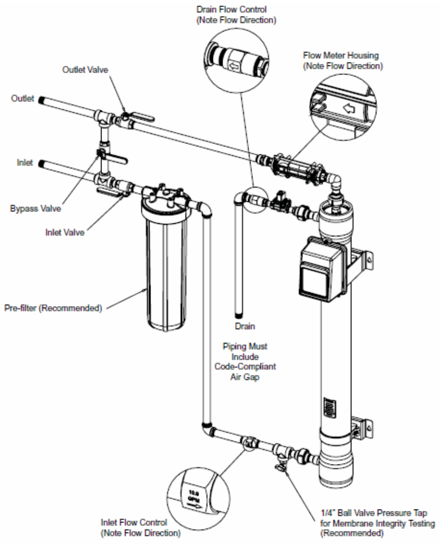


Figure 3.15 – Ultrafiltration POE system (Pentek FreshPoint, 2013)

Kinetic Degradation Fluxion Media – KDF media filtration is a process by which electro-chemical reactions produced by copper and zinc allow redox reactions to take place. Zinc forms the anode and copper acts as a cathode creating an electrolytic cell. In this way, charged contaminants are removed through the exchange of electrons, converting them into harmless components or by bonding to charged media surfaces (Home Plus Water, 2014). Generally used in conjunction with activated carbon, KDF is capable of removing chlorine, hydrogen sulfide, heavy metals, iron as well as reducing radon, sediment and VOC's (KDF Fluid Treatment Inc., 2014).

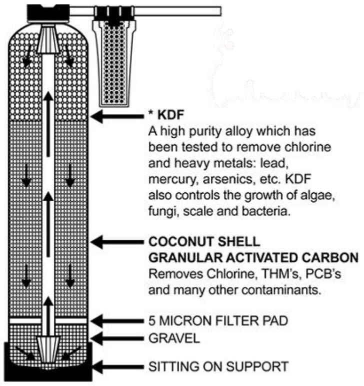


Figure 3.16 – Whole house KDF/Activated Carbon filter (WM Filter, 2014)

Ion Exchange – (IX) is a process in which ions in solution are exchanged for ions of the same charge in an engineered resin. In water treatment, this is commonly referred to as "water softening" involving the removal of hardness including calcium, magnesium, iron and manganese using sodium and potassium ion exchange. Selective ion exchange is one way to removal heavy metals such as lead, cadmium and zinc in addition to selenium (Lenntech, 2014). Salt-free water softeners use no additional electricity or chemicals and condition hardness using catalytic media so that it will not adhere to surfaces. Important for this application is IX capability to remove Selenium (NAMC, 2010) which is found in high levels in FCU surface water sources.

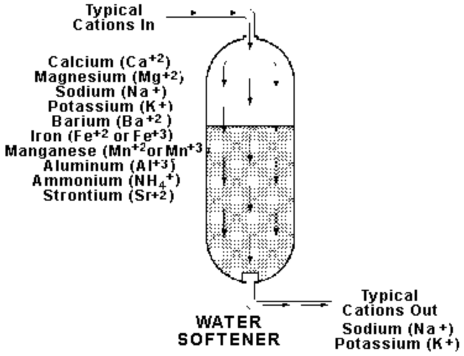
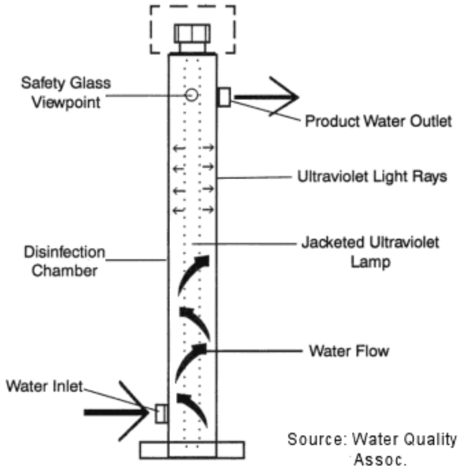


Figure 3.17 – Ion exchange vessel (Water Softener News, 2013)

<u>Ultraviolet Disinfection</u> – (UV) uses ultraviolet radiation which destroys bacteria and viruses while also breaking down some organic contaminants. UV has been approved for use in small water systems such as POU and POE. It is susceptible to high turbidity levels and does not provide a disinfection residual. However, it is the most common POE disinfection system due to effectiveness, low cost and operational simplicity (National Drinking Water Clearinghouse, 2000).



Source: Water Quality Assoc.

Figure 3.18 – UV POE disinfection system (Water Quality Association, 2009)

3.5.2 Definition of Criteria

Within each of the five main criteria, sub-criteria (or performance metrics) are defined which can be evaluated in a qualitative or quantitative way. Each sub-criterion needs a definition and an explanation of the way that the values were collected or calculated.

Cost

Capital Cost –Total capital cost of the system including system cost and installation cost calculated quantitatively in dollars (2014 USD)

Operations Cost – Estimated typical annual operations cost for system operation, maintenance and repairs calculated quantitatively in annual dollars (2014 USD)

Energy Use

Process energy use – Process energy input needed for operation such as pumping and backwashing in kWh/MG

Minimum pressure requirement – Pressure required for system to operate in pounds per square inch (PSI)

Recovery efficiency – Measurement of the potable water produced over the amount of influent in terms of percentage

Maintenance Requirements

Operational complexity – Qualitative assessment of how complex the system is to operate, evaluated from very low to very high

Component replacement frequency – Collective number of treatment system components needing yearly replacement (#/year)

Waste produced – Qualitative evaluation of the level of waste stream produced by the treatment process from very low to very high

Performance

Virus removal – The State of Colorado requires 4-log virus removal. Criterion measured in terms of log removal (ex. 99.99% removal = 4-log)

Influent turbidity limit – Measure of recommended influent turbidity limitation in NTU

Organic contaminant removal – Qualitative assessment of the level of organic contaminant removal

Inorganic contaminant removal – Qualitative assessment of the level of inorganic contaminant removal

Implementation

System size – Total system footprint measured in square feet not including the assumed chlorine disinfection system or waste solids treatment

Opportunity for expansion – A qualitative assessment of the ability of the system to expand in capacity rated from very low to very high based on system advantages

Availability – How common is each system evaluated qualitatively from very low to very high based on manufacturer data

Community disturbance – Qualitative assessment of the community disturbance associated with solids residual production and handling including trucking to landfills or other waste handling practices

3.5.3 Results and Recommendations for POE System Selection

Using an equal-weighted-criteria MCDA, data on performance metrics were collected for each system option. Input data can be found in the Appendix B. Results of the main criteria ratings are shown in Table 3.7.

Table 3.7. Main criteria average scores (Maximum score of 5)

Main Criteria	Reverse Osmosis	Activated Carbon/KDF	Ultrafiltration	Reverse Osmosis with Activated Carbon	Activated Carbon/KDF with Ion Exchange
Cost	2.15	5.00	2.99	1.00	4.19
Energy Use	1.24	5.00	3.34	1.68	3.80
Maintenance Requirements	1.98	4.33	3.56	1.00	3.77
Performance	3.33	4.00	3.65	4.30	4.00
Implementation	3.33	4.68	3.00	1.00	4.47

From this study, Activated Carbon/KDF filtration coupled with UV disinfection represents the highest scoring point-of-entry treatment option. The key drivers for this finding include the low capital cost of the equipment, simplistic operation, low energy requirements and smaller system size. KDF increases the both the effectiveness and lifetime of the activated carbon (Pure-Earth, 2014). The critical assumption is that all five system packages will be capable of treating raw influent water to a potable standard equivalent to the existing central treatment facility.

The addition of a salt-free ion exchange (“water conditioner”) component to the Activated Carbon/KDF system maintains the advantages of the simpler package while addressing the variable hardness seen throughout the current water sources (Colorado-Big Thompson and Cache la Poudre). However, the addition of ion exchange increases the size, cost and maintenance of the system.

Reverse Osmosis provides the most thorough treatment in this study but is severely limited by capital cost, energy use, operational complexity, low recovery rates and system size. Low scores in these performance sub-criteria suggest that another technology would be preferable if able to meet potable water quality standards.

Ultrafiltration presents a compromise between Reverse Osmosis and other filtration technologies. Treatment capacity is still very high and small system size and availability make these systems competitive in performance and implementation. However, capital cost and energy use reduce the overall score for membrane technologies.

Overall weighted-average method (WAM) scores for the five alternative point-of-entry treatment packages are displayed in Figure 3.19. From best to worst the package scores were Activated Carbon/KDF, Activated Carbon/KDF with Ion Exchange, Ultrafiltration, Reverse Osmosis, Reverse Osmosis with Activated Carbon.

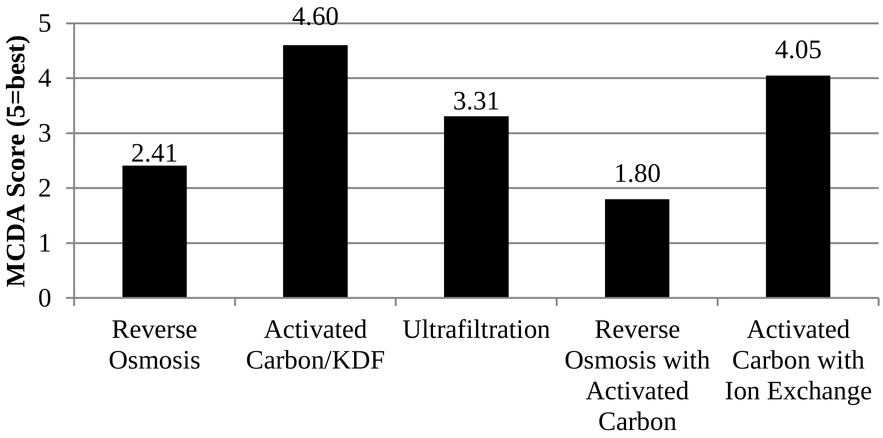


Figure 3.19 –Total score (WAM) for POE system selection (Max Score = 5)

The treatment packages were also compared using the out-ranking Promethee Method in which alternatives are compared directly according to sub-criteria with the better option receiving a 1 and the lesser a 0. Results of this analysis are shown in Figure 3.12. A more positive score reflects a stronger treatment option in comparison to other alternatives.

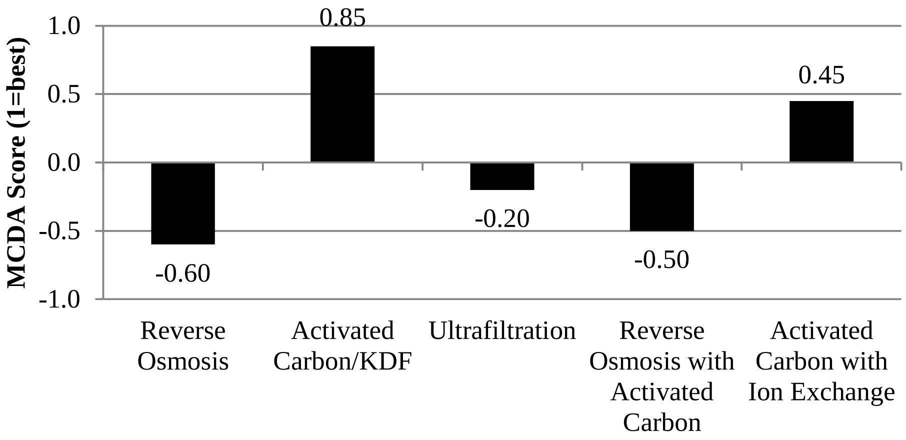


Figure 3.20 – Total score (PROMETHEE) for POE system selection

As seen in Figure 3.20, the alternatives maintain their ranking order. In this analysis, this shows that the magnitudes of particular advantages and disadvantages do not affect the final results for system selection. Activated Carbon/KDF packages remain the highest ranked alternatives with membrane filtration options behind. The only difference in the results of this method compared to WAM is that the addition of GAC to Reverse Osmosis scores better than a Reverse Osmosis-only package.

Because of the small amount of performance metrics, the applicability of this study for determination of a point-of-entry treatment system package for the project alternative may lack certain insights that a more thorough investigation would provide. Detailed information for these systems is not uniformly available. Some performance metrics are explicitly dependent on water quality, creating wide variability in estimates for sub-criteria such as energy use, recovery percentage and maintenance frequency. To better evaluate these systems pilot and field testing is highly recommended in order to verify unit efficacy, determine an appropriate maintenance schedule and identify operational issues (U.S. EPA, 2002). After completing a pilot test, adjustments can be made to the existing values in this study to determine which system package is most applicable.

For the purposes of selecting a treatment system POE approach using the existing distribution system in the City of Fort Collins, Activated Carbon/KDF filtration is the recommended treatment. Coupling this with sediment pre-filtration and ultraviolet disinfection completes a robust treatment capacity determined in this evaluation to be capable of meeting the same water quality standards as the existing centralized treatment facility. There are many additional options for combining treatment technologies in order to target specific contaminants. Water quality monitoring during pilot testing will determine if these packages will meet treatment standards or require additional technologies.

3.6 Summary

Decentralized treatment systems were selected for application in an evaluation of alternative water treatment and distribution designs for the City of Fort Collins, Colorado. Decisions for treatment applicability were made based on the raw water quality data from Fort Collins Utilities Water Quality Reports from both the Cache la Poudre River and Horsetooth Reservoir (C-BT) which outline a set of relatively pristine surface water sources, highlighting issues with Copper, Selenium, E. coli, Geosmin, and turbidity. A common selection process for both neighborhood-scale and point-of-entry systems was defined in order to determine the most applicable treatment solution in the project area. This framework consisted of basic system research, initial system comparisons, selection of alternatives, Multi-Criterion Decision Analysis based on common criteria, and interpretation of results to produce a system recommendation. Performance metrics were adjusted accordingly to evaluate main criteria for neighborhood-scale and point-of-entry systems.

Neighborhood-scale treatment systems were divided into conventional and innovative technologies. Design neighborhood demand determined a system capacity of 1.0 MGD which suggested the use of package treatment plants for their small footprint and low design and installation costs. Equally-weighted MCDA results using the WAM and Promethee methods showed that conventional water treatment scored lower than innovative technologies. Ultrafiltration was consistently the highest scoring treatment technology and the chosen recommendation due to small system size, low chemical requirements, consistent water quality and amenability to remote monitoring.

Five point-of-entry treatment packages were chosen for comparison using the MCDA. All systems were sized to handle single-family home capacity. Both weighted average method and Promethee method results showed that Activated Carbon/Kinetic Fluxion Media filtration coupled with ultraviolet disinfection was the highest scoring point-of-entry treatment system and recommended for implementation in an alternative design for the City of Fort Collins. Key drivers were low capital cost of the equipment, simplistic operation, low energy requirements and smaller system size.

The system selection process represents a basic approach for determining applicable technologies. Performance metric input can vary between manufacturers and final scores are based on only five main criteria. More specific information on costs and energy use should be updated if available due to the conservative estimates used for some treatment systems. Lastly, pilot testing is highly recommended before committing to a certain technology in order to assess the real-world performance with source water. The two system recommendations made in this analysis only reflect the non-prioritized comparison of current market systems. However, due to the comprehensive nature of the defined main criteria, the selection of the highest scoring system as compared to another closely ranked option will not dramatically affect the comparison of a total city-wide treatment and distribution design alternative.

4.0 COMPARISON OF WATER TREATMENT AND DISTRIBUTION ALTERNATIVES IN FORT COLLINS, CO

4.1 Introduction and Project Description

Implementation of alternative water treatment and distribution strategies is not necessarily limited to small remote systems. As aging water infrastructure in larger communities is replaced, there is an opportunity to evaluate new approaches to long-term goals such as meeting increased future water demands and quality standards while using sustainable replacement practices and limiting the impact on the community and environment. Members of the public water utility in the City of Fort Collins, Colorado approached our research group with an idea for a study on evaluating decentralized and dual distribution system alternatives with the purpose of separating irrigation and fire flow from potable demand for domestic indoor uses. Motivation for this idea was a response to aging water infrastructure, excess treatment energy and potable quality issues related to oversized distribution piping. The scope of this project involved the comparison of four alternative treatment and distribution configurations with the existing system for the city analyzed through a Multi-Criterion Decision Analysis (MCDA) based on performance metrics in the triple bottom lines of economic, social and environmental factors. The focus of this chapter is the use of neighborhood-scale and point-of-entry treatment systems in comparison to the existing conventional treatment and distribution systems in the City of Fort Collins.

4.2 Methodology

In order to mirror the qualitative triple bottom line decision making approach used by city employees, an MCDA was created incorporating eleven main criteria each evaluated from an economic, social and environmental standpoint using both qualitative and quantitative performance metrics. The result is a triple bottom line set of scores for each alternative in comparison to the existing system. Relative importance factors for each main criterion were assigned to give weight to stakeholder priorities based on input collected from nine different departments in the city government. MCDA triple bottom line scores using the Weighted Average Method (WAM) were reported based on both an equally weighted and stakeholder average relative importance profiles on a scale of one to five with five being the maximum achievable score.

4.2.1 Main Criteria and Performance Metrics

Eleven main criteria were selected after discussion with members of the utility and research group.

1. Impacts of new infrastructure
2. Energy use
3. Routine maintenance
4. Staffing
5. Consumer water quality
6. Use of city water corridors
7. Risk of limited supply
8. Risk of rate changes
9. Opportunity for new water management strategies
10. Revenue opportunities
11. Regulatory/Political risk

For each main criterion a set of one to three performance metrics were developed in order to evaluate the economic, social and environmental aspects of the alternatives. Both quantitative and qualitative performance metrics were assessed equally on a scale of one to five. Tables 4.1 through 4.3 list these performance metrics.

Table 4.1 - Economic Performance Metrics

Criteria	Economic Performance Metrics
1. Impact of new infrastructure	1.1 Capital costs for new distribution and water treatment infrastructure associated with the proposed alternatives 1.2 Replacement costs of existing and proposed alternative infrastructure
2. Energy use	2.1 Total energy use in water treatment and distribution 2.2 Return on renewable energy at water treatment facility 2.3 Revenue from selling carbon credits
3. Routine maintenance	3.1 Chemicals, media, filters, and repairs for water treatment 3.2 Distribution system operations and maintenance (flushing, surveying, and pipe repairs)
4. Staffing	4.1 Full time employee equivalent for water treatment and distribution system operations 4.2 Cost of workforce transitional training
5. Consumer water quality	5.1 Health care costs associated with exposure to disinfectant by-products 5.2 Costs associated with potential cross-connection failure 5.3 Costs associated with a source water contamination event
6. Use of city water corridors	6.1 Avoided transaction costs associated with converting water rights from irrigation to municipal
7. Risk of limited supply	7.1 Costs associated with alternative water supplies 7.2 Risk of obsolete infrastructure
8. Risk of rate changes	8.1 Confidence in operations & maintenance projections
9. Opportunity for new water management	9.1 Savings on later implementing an alternative water management strategy that could benefit from a dual distribution system
10. Revenue opportunities	10.1 Revenue generated from using extra capacity at water treatment facility to sell treated water wholesale to neighboring communities
11. Regulatory/Political risk	11.1 Costs associated with changing an alternative back to existing or to make changes needed to meet new regulations 11.2 The costs associated with increase in communication and managing public perception

Table 4.2 - Social Performance Metrics

Criteria	Social Performance Metrics
1. Impact of new infrastructure	1.1 Disruption to community – the inconvenience of construction to the community and disruption to local business 1.2 Increase in temporary employment
2. Energy use	2.1 Health impacts associated with air pollution
3. Routine maintenance	3.1 Disruption to community
4. Staffing	4.1 Employment and job security 4.2 Increased earning potential for a higher skilled workforce
5. Consumer water quality	5.1 Drinking water quality as a function of water age in distribution system 5.2 Potential health risks from a cross-connection failure 5.3 Potential health risks from a source water contamination event
6. Use of city water corridors	6.1 Enhancement of the City's water corridors 6.2 Benefits to local ditch companies
7. Risk of limited supply	7.1 Resiliency of infrastructure to changes in supply
8. Risk of rate changes	8.1 Affordability of monthly water bill for low or fixed income households
9. Opportunity for new water management strategies	9.1 Being an innovative community and potential to increase ISFs for recreational uses
10. Revenue opportunities	10.1 Improve water security in neighboring communities and increasing jobs in Fort Collins
11. Regulatory/Political risk	11.1 Public acceptance of the alternatives

Table 4.3 - Environmental Performance Metrics

Criteria	Environmental Performance Metrics
1. Impact of new infrastructure	1.1 GHG emissions 1.2 Temporary stormwater pollution
2. Energy use	2.1 GHG emissions in CO2e
3. Routine maintenance	3.1 GHG emissions in CO2e 3.2 Chemical consumables for water treatment
4. Staffing	4.1 Employee transport GHG emissions CO2e
5. Consumer water quality	5.1 Water quality of receiving water bodies
6. Use of city water corridors	6.1 Benefits to species and natural systems
7. Risk of limited supply	7.1 Effects variable supply could have on the City's water corridors
8. Risk of rate changes	8.1 Potential changes in irrigation water demand due to rate changes
9. Opportunity for new water management strategies	9.1 Increase in in-stream flows due to using alternative sources of water will result in benefits to species and natural systems
10. Revenue opportunities	10.1 Decreasing need for new water treatment facility construction in the regional community
11. Regulatory/Political risk	11.1 Loss of environmental benefits gained from the alternatives

4.2.2 Project Alternatives

Four different alternatives were considered in comparison to the existing system. Each design either treats water centrally or incorporates a decentralized treatment approach and may or may not require the installation of dual distribution system.

Central/Dual Alternative: Use of the existing central water treatment facility is maintained for treatment of indoor demand while a city-wide dual distribution system delivers raw and potable water separately. Raw water demand is distributed through the existing network in order to meet irrigation demand and fire flow requirements. A newly constructed potable distribution system will supply potable water for indoor use.

Neighborhood Alternative: Raw water for indoor demand is transmitted to new neighborhood water treatment facilities through the existing network and then distributed post-treatment through a new potable distribution system. Fire flow requirements and irrigation demand are met by distributing raw water via the existing distribution system in place in each neighborhood.

Point-of-Entry (POE) Alternative: The existing central treatment facility may be bypassed or used in a lesser capacity to lightly treat water for certain characteristics related to the transmission of raw water which will be distributed through the existing distribution system to the service connection. At this point raw water is diverted to the irrigation system and water for indoor use is treated to potable quality at a point-of-entry water treatment system.

Separated Irrigation Alternative: Use of the existing central water treatment facility will be maintained in order to meet water demand for fire flow requirements and indoor use. Raw water will be withdrawn directly from the City's network of irrigation ditches and canals and delivered through a new raw water irrigation distribution network.

4.3 City of Fort Collins Water Infrastructure and Supply

This study was commissioned by the Fort Collins Utilities (FCU) Water District which encompasses the majority of the city as one of six separate water districts that serve areas within city limits. The City of Fort Collins is located in northern Colorado along the front range of the Rocky Mountains in Larimer County bordering the State of Wyoming. The FCU Water District maintains access to high quality source water and currently utilizes a significantly oversized central treatment facility and single distribution network.

4.3.1 Neighborhood Selection

It was not feasible to produce design alternatives for the entire city due to the amount of information and time required. Instead, three sample neighborhoods were selected in order to represent the different periods of development in the city. The City of Fort Collins exemplifies three different phases of growth, based on land use, lot size, water demand and pipe material. Each chosen neighborhood was roughly one square mile in size. The three chosen neighborhoods became the Old Town district (prior to 1960s), low density residential (1960s-1990s) and mixed use (1990s to present). Due to the scope of the work related to data collection and distribution modeling, this thesis focuses on the Old Town District design neighborhood, shown in Figure 4.1. A more thorough analysis is provided in the March 2015 report *Fort Collins Utilities Dual Water Systems Study*. (Cole et al. 2015).

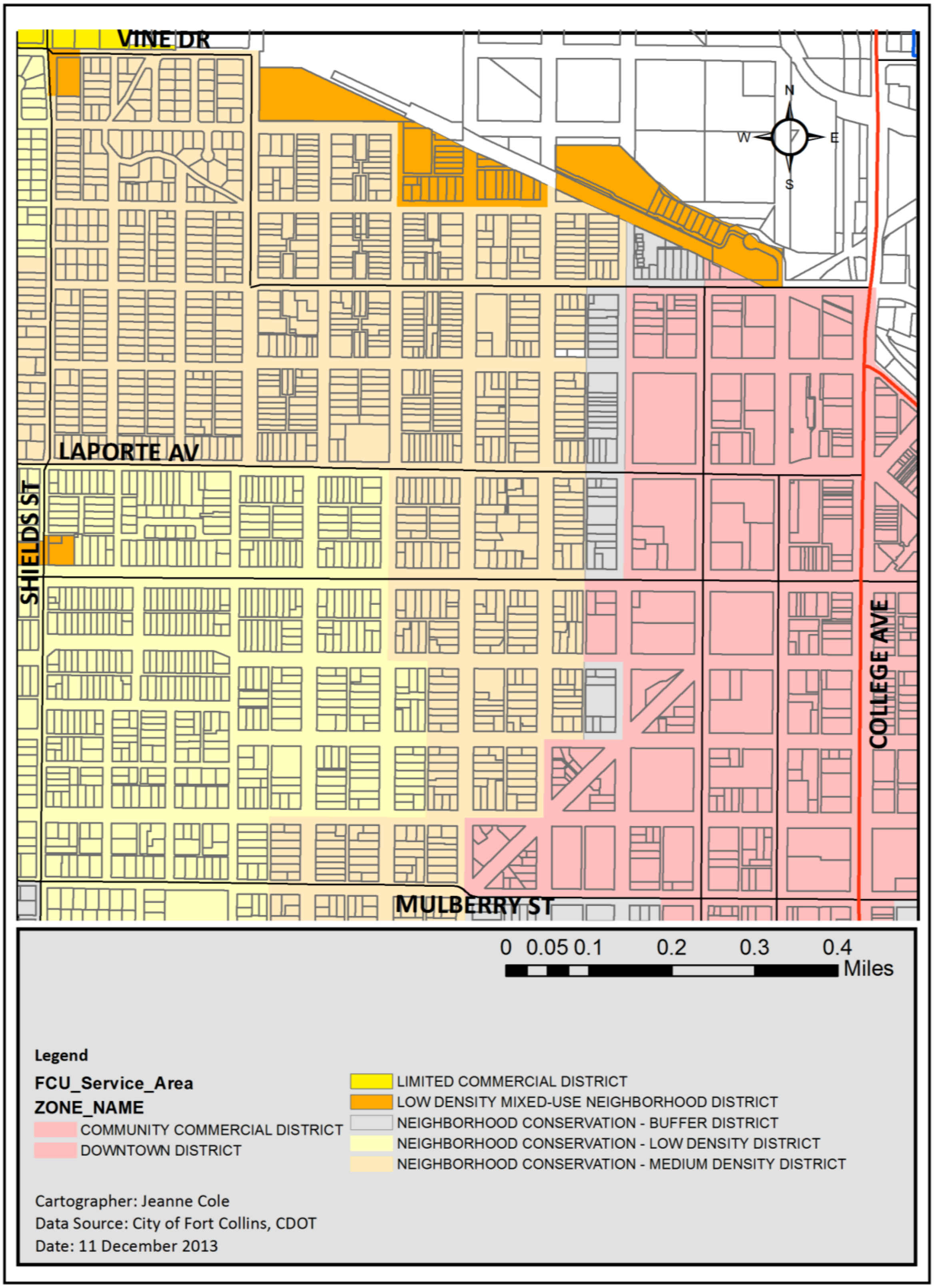


Figure 4.1 – Design Neighborhood #3: Old Town District (Cole et al. 2015)

Using the City of Fort Collins parcel shapefiles from the FCMaps application as well as service line data from UVIEW, the type and number of total connections was counted by hand and then multiplied by average base and irrigation demand for land use type to determine the total demand for the design neighborhood summarized in Table 4.4.

Table 4.4 – Design Neighborhood #3: Old Town District Water Demand (FCU, 2004-2012)

Land Use Type	Service Type	# Services	Average Monthly Base Water Demand (gal/service)	Average Monthly Irrigation Water Demand (gal/service) April to October	Annual Base Demand (gallons)	Annual Irrigation Demand (gallons)
Commercial	Commercial	179	22,223	10,332	47,734,815	12,946,605
	Comm. Sprinkler	16	3,514	204,538	674,624	22,908,251
Low Density Mixed Use	Commercial	4	15,445	28,658	741,376	802,410
	Multi-family	8	35,262	19,335	3,385,161	1,082,732
	Single	2	4,457	6,875	106,973	96,247
Conservation - Buffer	Commercial	13	16,418	14,390	2,561,265	1,309,481
	Single	85	4,493	3,831	4,582,397	2,279,162
Conservation - Low Density	Comm. Sprinkler	5	2,427	36,336	145,627	1,271,760
	Single	562	4,169	5,528	28,112,457	21,747,275
Conservation - Medium Density	Commercial	15	12,309	30,183	2,215,558	3,169,212
	Comm. Sprinkler	4	6,007	220,059	288,335	6,161,646
	Multi-family	1	21,431	8,451	257,177	59,158
	Duplex	12	6,429	3,305	925,777	277,625
	Single	706	4,058	4,042	34,382,339	19,976,857
Total Services		***1,612***	***Total Demand (gal/yr)***		***126,113,881***	***94,088,421***
Average Neighborhood Daily Demand (gpd)					***345,517***	***439,666***

4.4 Neighborhood Water Treatment and Dual Distribution System

This alternative allows raw or lightly treated water to be transmitted through the existing distribution system to neighborhood-scale treatment facilities. Irrigation water will bypass these facilities and a new potable distribution system will then deliver treated water. Figure 4.2 provides a general city-wide schematic for the alternative.

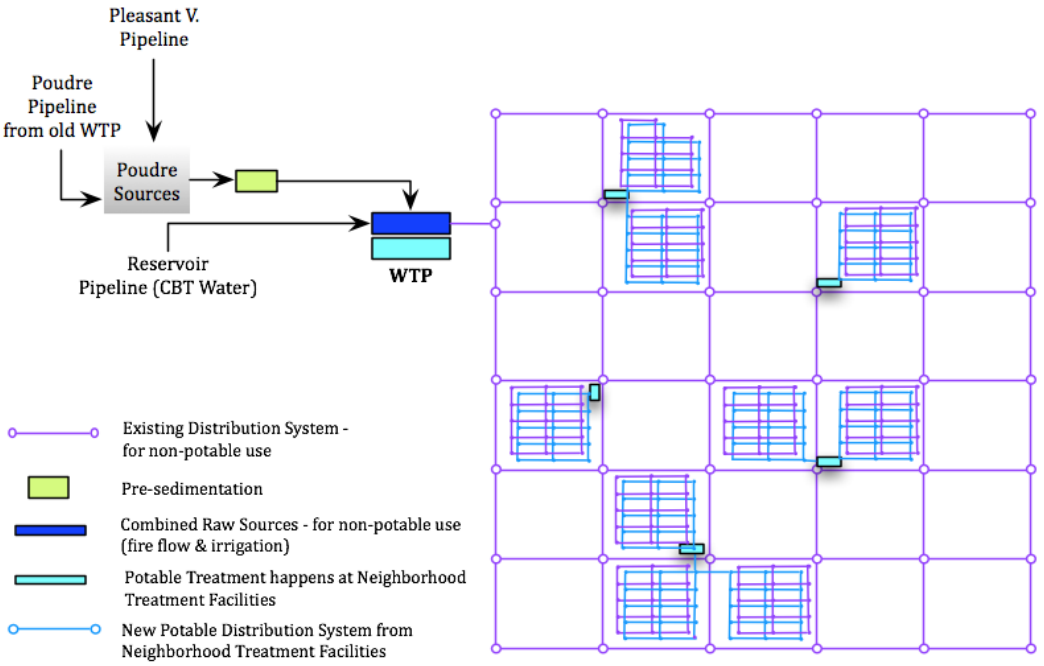


Figure 4.2 – Neighborhood-Scale Water Treatment with Dual Distribution (Cole et al. 2015)

4.4.1 Neighborhood-Scale Treatment System

Design neighborhoods from the City of Fort Collins were used to determine an average system capacity of 1.0 MGD with a peak factor of 2.5. Package plants were selected due to advantages at small capacity such as reduced design and installation costs, automated maintenance, and smaller system footprints (Clark & Morand, 1981). The treatment system selection process is outlined in Chapter 4 with the most applicable technology found to be an Ultrafiltration package plant. Major advantages of Ultrafiltration are small system footprint, consistent finished water quality, better removal of *Cryptosporidium* and *Giardia lamblia* than media filtration, amenability to remote monitoring, and no addition of coagulant (U.S. EPA, 2001).

Assumptions were made that all systems will include chlorine disinfection and clearwell storage and general buildings requirements and that such requirements would not vary substantially among alternatives. For this reason, these components were not included in the comparison of treatment technologies. Chlorination systems and clearwell storage are sized for the capacity of the treatment facility rather than the treatment technology.

The recommended Ultrafiltration Neighborhood-Scale Treatment Facility would require package plant modules with a total capacity of 1.0 MGD coupled with a 250,000 gal clearwell and chlorine injection for disinfection residual. Raw source water would be treated centrally for alkalinity, fluoridation and pH control. These systems require 1-2 operators and operations and monitoring can be optimized using centrally managed remote monitoring systems. At this capacity, each package plant would produce up to 20,000 gal/day of backwash waste volume, which would be discharged to the wastewater collection system (WesTech , 2014). A diagram of the system is shown in Figure 4.3. A proposal for this system is attached in Appendix A.

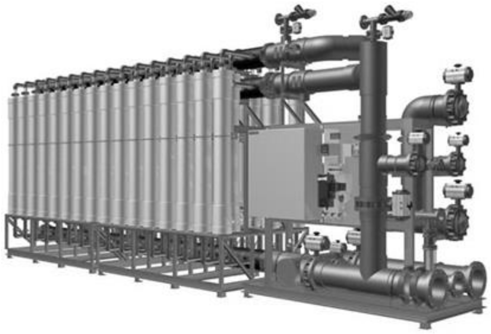


Figure 4.3 - WesTech AltaFilter Ultrafiltration Membrane System (WesTech Engineering Inc., 2014)

4.4.2 Neighborhood Dual Distribution System

Neighborhood-scale treatment systems receive lightly treated source water via the existing distribution system. Rough filtration, chemical stabilization for LCR requirements and fluoridation will all be maintained at the existing central treatment facility. Irrigation demand and fire flow will bypass the neighborhood treatment facilities and continue through the existing distribution lines while a new potable distribution system will deliver treated water from the neighborhood facility to the connections. This disruption in the distribution network will necessitate a pump in order to regulate flowrate and pressure requirements in the system.

The necessary distribution system networks were modeled using EPANET2 from the U.S. EPA. For the Old Town district design neighborhood, neighborhood-scale treatment systems with dual distribution required two network scenarios. A new potable distribution system and pump were optimized using the base demand for the neighborhood with a peak factor of 2.5. The existing distribution system was then designed to handle irrigation and fire flow demands. To maintain consistency, the network layout for the existing distribution system was used as a framework for the new potable distribution system.

4.5 Point-of-Entry Water Treatment

The POE alternative maintains use of the existing distribution system to deliver raw or lightly treated water to POE treatment units at each potable connection. POE treatment consists of a filtration unit and a disinfection unit used to treat all water entering the facility for potable use (Schowalter, 2006). Figure 4.4 provides a general city-wide schematic for the alternative.

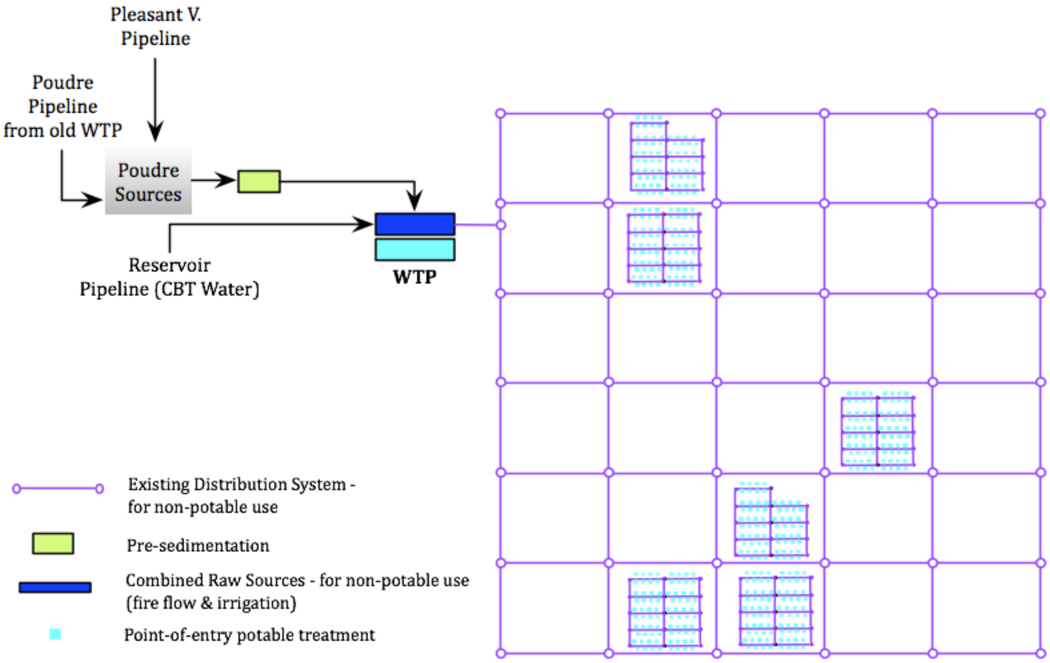


Figure 4.4 – Point-of-Entry Decentralized Water Treatment (Cole et al. 2015)

4.5.1 Point-of-Entry Treatment System

After an initial comparison process, five system packages were selected for investigation including Reverse Osmosis, Activated Carbon/Kinetic Degradation Fluxion Media, Ultrafiltration, Reverse Osmosis with Granular Activated Carbon, and Activated Carbon with Ion Exchange. A small-scale MCDA was used to evaluate these alternatives based on main criteria including cost, energy use, maintenance, performance and implementation using both the Weighted Average (WAM) and Promethee methods.

Overall the highest scoring treatment package was Activated Carbon/KDF media with a sediment pre-filter and UV disinfection. More detailed information on the treatment package selection process is provided in Chapter 3.

This treatment package is a four-step process (Figure 4.5). The process begins with mechanical sediment filtration to remove suspended particles at either the 1 or 5-micron level depending on water quality. The next step is electrochemical/oxidation-reduction with Kinetic Degradation Fluxion Media (KDF) for the removal of heavy metals and inorganics. Following KDF, granular activated carbon (GAC) filtration handles the removal of organic contaminants. Lastly, ultraviolet (UV) disinfection ensures that finished water meets requirements for microbial contaminants and virus removal (UV Max, 2014).

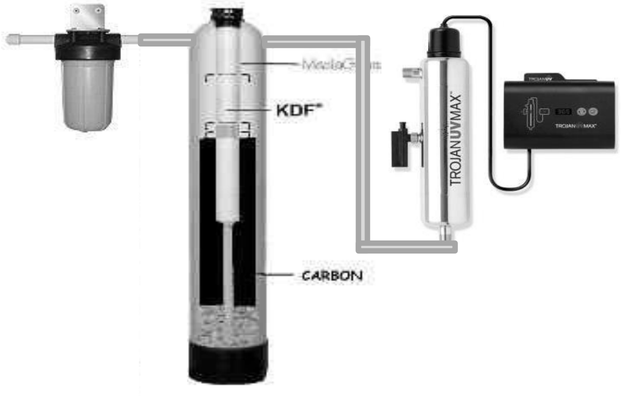


Figure 4.5 – Recommended POE treatment package (Pelican Water Systems, KDF Fluid Treatment, Trojan UV Max, 2014)

Raw source water is treated centrally for alkalinity, fluoridation and pH control is distributed to each potable connection. This system is capable of treating fines, organics, inorganics and microbial contaminants while maintaining low capital costs and energy use with a comparatively moderate level of maintenance and operation complexity. However, it is important to note that there are many additional options for combining treatment technologies in order to target specific contaminants. Water quality monitoring during pilot testing is critical in order to determine if this package will meet treatment standards (U.S. EPA, 2002).

In this analysis, assumptions were made based on current regulations. A further discussion of regulatory barriers and alternative management strategies can be found in Chapter 5. POE systems must be owned, controlled and maintained by the public water system (PWS) – Fort

Collins Utilities (U.S. EPA, 2002). Routine maintenance will include inspection of systems, replacement of sediment pre-filters, KDF and GAC media, and UV lamp and sleeves. All systems must have mechanical warnings or automatic shutoff devices to notify customers of operational problems (U.S. EPA, 2002). Most commonly this requires an electrical conductivity and total dissolved solids meter. Systems will be installed outdoors in weatherproof protective enclosures at each connection allowing easier access for Fort Collins Utilities. A detailed monitoring plan must be approved by the State of Colorado. All systems must undergo initial monitoring in the first year of operation followed by one third of all systems in each subsequent year (U.S. EPA, 2007). Water quality sampling will be based on current monitoring at the existing Central Water Treatment Facility.

4.5.2 Existing Distribution System

Several functions will be maintained at the existing water treatment facility including raw water filtration, chemical stabilization for LCR requirements, and fluoridation. The existing distribution network will be used to deliver this lightly treated water to the customers. At the connection, raw water for irrigation will be diverted and domestic demand will be treated to potable water standards at a POE treatment system.

4.6 Stakeholder Relative Importance

Input on relative importance of the eleven main criteria was collected from 17 representatives of city departments. Seven distinct stakeholder groups were formed from these responses by combining groups with similar relative importance profiles. These stakeholder groups are defined as Planning, Institute for the Built Environment, Economic Health/Urban Renewal, Communications & Public Involvement, Transportation Planning, Natural Areas, and

Engineering. Stakeholder group relative importance factors were calculated as the average of one to seven representative responses (Figures 4.6 through 4.12). The number of representatives (n) is reported for each group. Stakeholder groups with three or more representatives display a standard deviation to show the variation of the responses for each criterion among a group. Planning provided the most balanced ratings for all criteria from a triple bottom line standpoint (Figure 4.6). The highest ratings were given to the economic impacts of new infrastructure, energy use, and risk of rate changes and environmental revenue opportunities. The Institute for the Built Environment showed a wide range of ratings (Figure 4.7). The largest variability was in economic ratings. Environmental ratings were typically the highest followed by social. Economic Health/Urban Renewal gave emphasis to economic and social aspects of main criteria with the exception of consumer water quality and regulatory/political risk (Figure 4.8). Communications & Public Involvement displayed a wide variety of importance responses (Figure 4.9). Economic impacts of new infrastructure, energy and routine maintenance were highly rated as were social impacts of new infrastructure and regulatory/political risk and environmental use of city water corridors. Transportation Planning also exhibited balanced relative importance ratings with several economic and social outliers (Figure 4.10). Natural Areas grouped together respondents giving high environmental ratings to all criteria (Figure 4.11). Engineering demonstrated balanced importance ratings for the triple bottom line for each criterion with variability in the comparative rating between criteria (Figure 4.12).

From these profiles, it is evident that each stakeholder group provides a unique set of relative importance ratings from the triple bottom line perspective of the main criteria. Detailed stakeholder response information is provided in Appendix C.

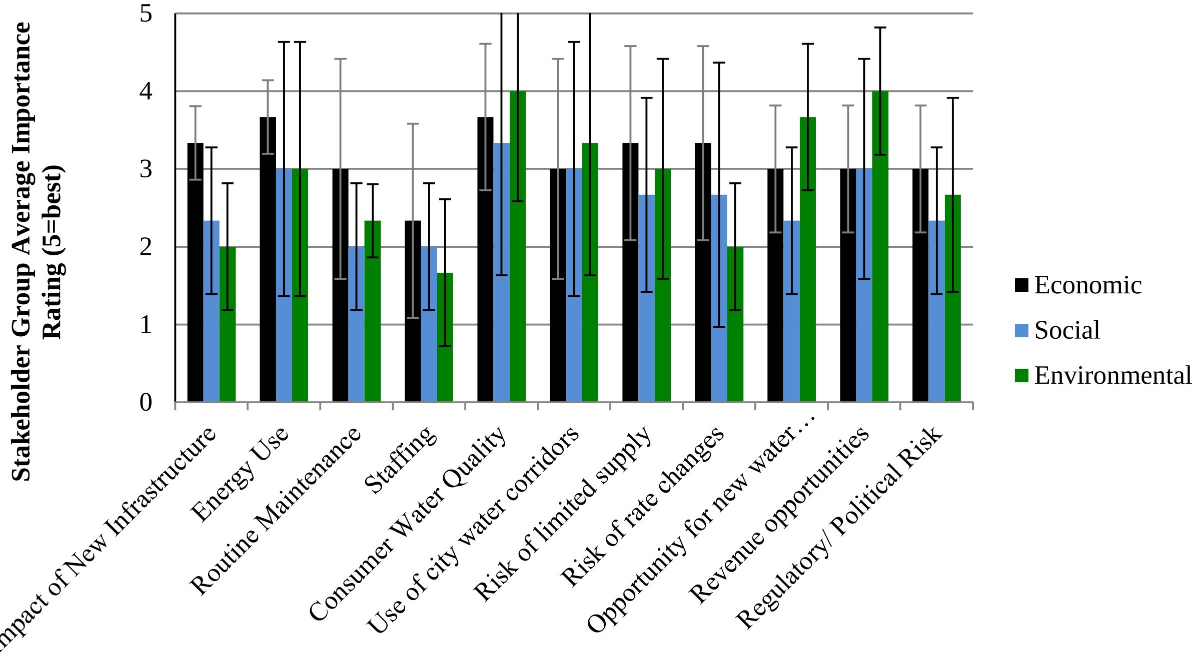


Figure 4.6 – Relative Importance Ratings for Planning +/- 1 Standard Deviation (n=3)

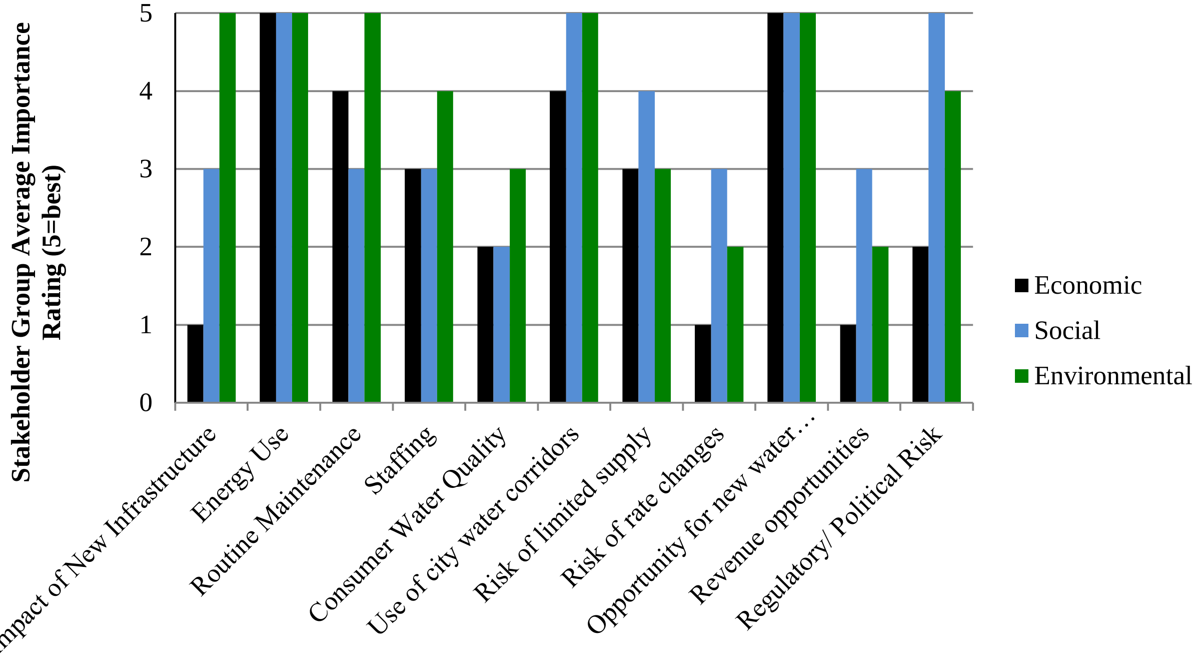


Figure 4.7 – Relative Importance Ratings for Institute for the Built Environment (n=1)

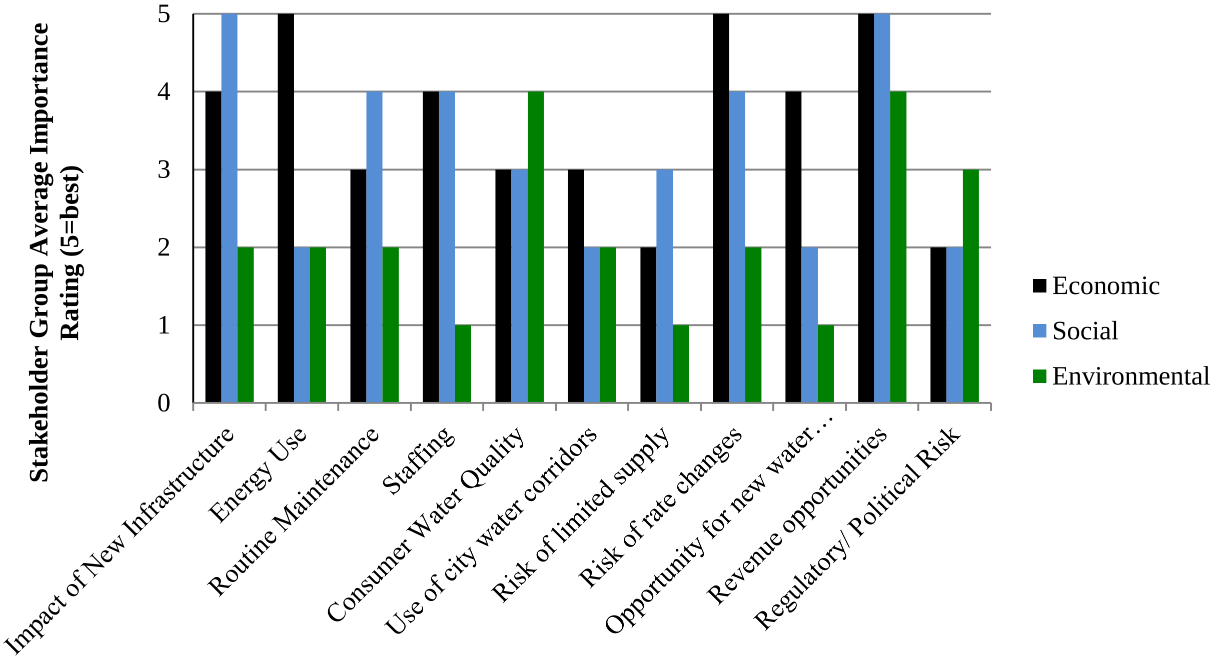


Figure 4.8 – Relative Importance Ratings for Economic Health/Urban Renewal Authority (n=1)

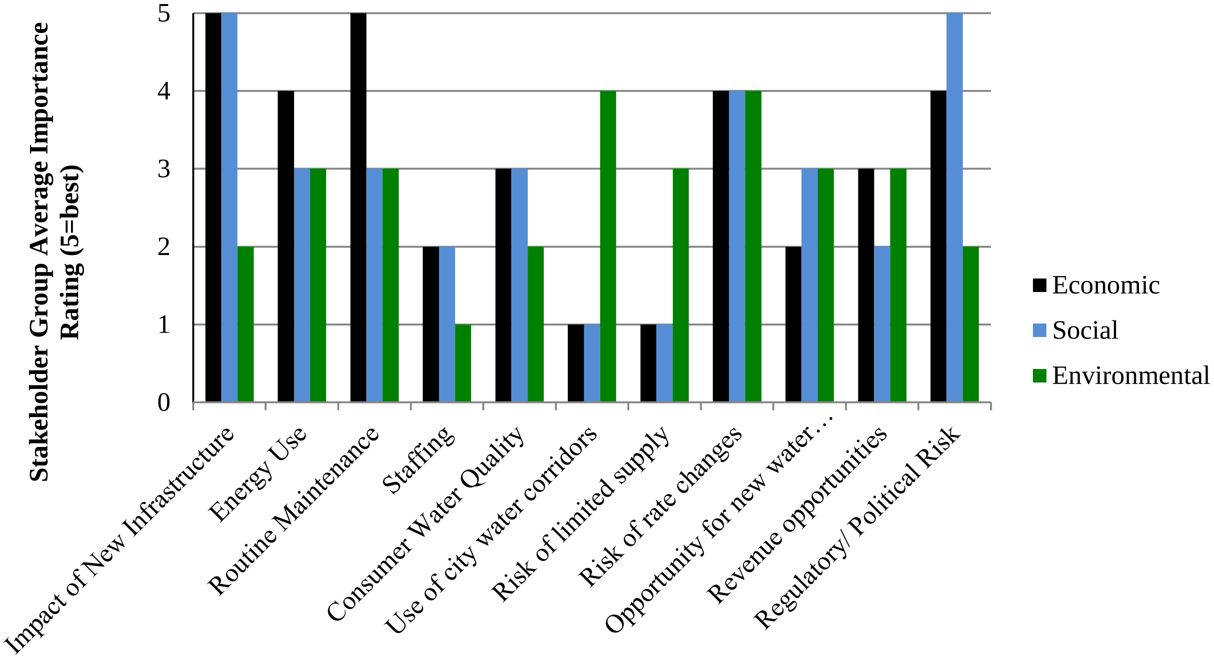


Figure 4.9 – Relative Importance Ratings for Communications & Public Involvement (n=1)

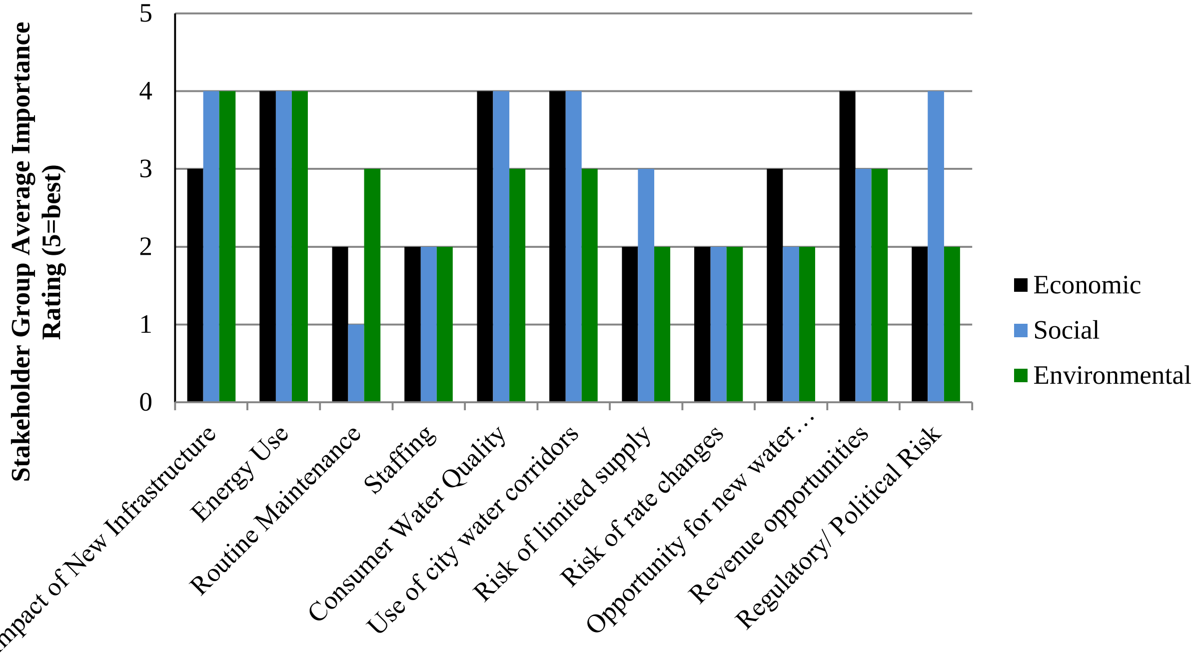


Figure 4.10 – Relative Importance Ratings for Transportation Planning (n=1)

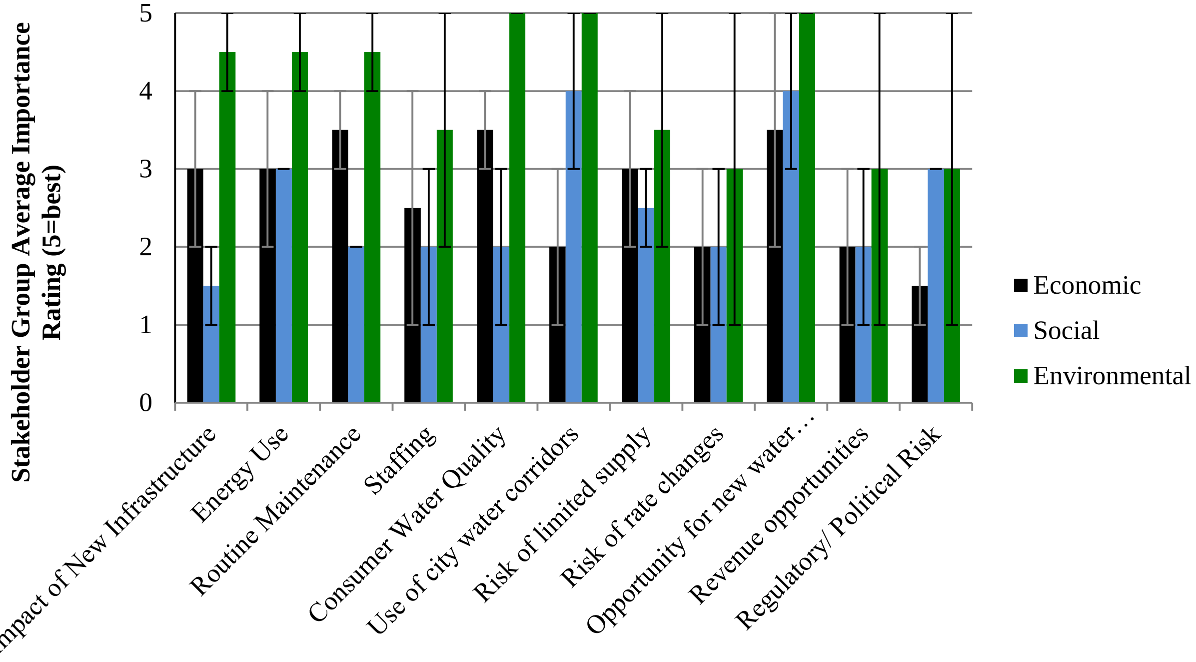


Figure 4.11 – Relative Importance Ratings for Natural Areas (n=3)

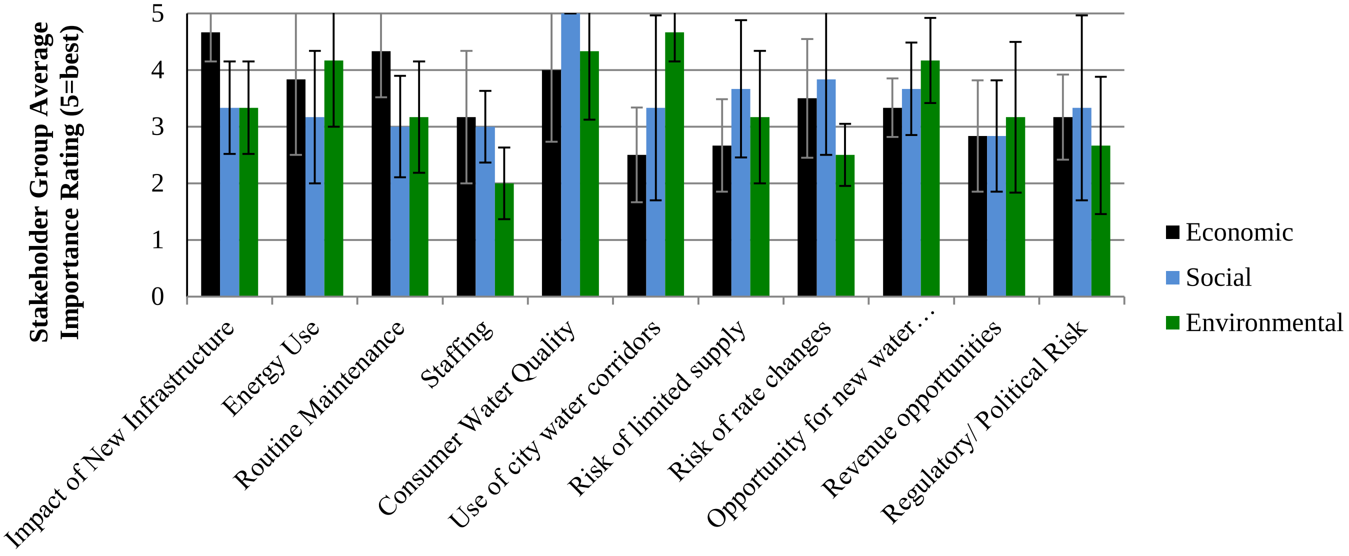


Figure 4.12 – Relative Importance Ratings for Engineering (n=7)

Results from averaging all stakeholder relative importance factors shows a balanced set of average ratings ranging from roughly 2.5 to 4 on a scale of 1 to 5 (Figure 4.13). The spread of responses is similar for all criteria. Four criteria received the highest ratings from an economic perspective, three from social, and four from environmental. All of these observations suggest a balanced profile created by a highly variable set of responses representing interests of departments in the City of Fort Collins.

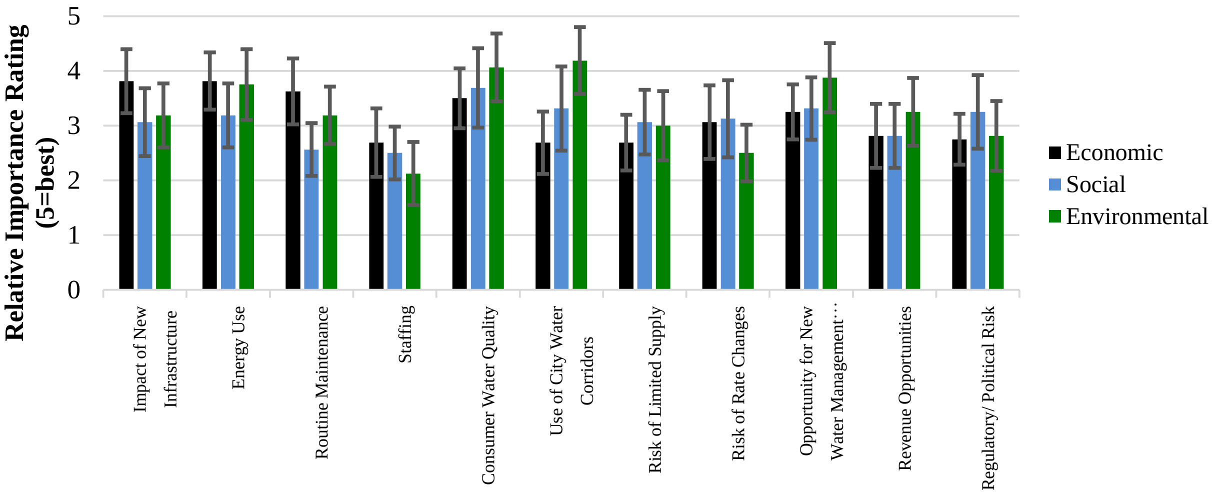


Figure 4.13 – Relative Importance Ratings for Main Criteria by Stakeholder Average +/- 1 Standard Deviation (5 = best)

Engineering/Utilities, Communications & Public Involvement and Transportation Planning each demonstrated balanced responses among the triple bottom line perspectives (Figure 4.14). Deviations from this pattern are exemplified by the low environmental importance rating from Economic Health/Urban Renewal Authority or the high environmental importance rating for Natural Areas. This average relative importance rating profile is used for the analysis of the MCDA for each design neighborhood.

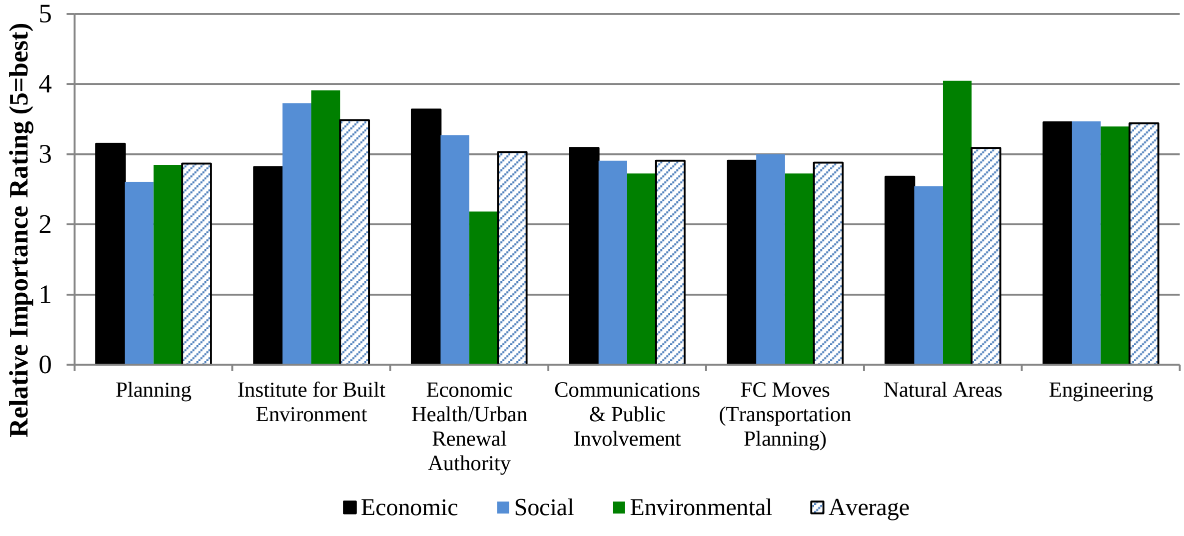


Figure 4.14 – Summary of Average Relative Importance Ratings by Stakeholder Group from a TBL Perspective +/- 1 Standard Deviation (5=best)

4.7 Results

The simplified results of this analysis focus on the performance of the Neighborhood and Point-of-Entry decentralized alternatives in comparison to the existing system in the Old Town District. Two different weighting scenarios were considered to provide a thorough examination of the effects of relative importance. Equal weights were applied to all criteria to compare the alternatives without assigned priority. This establishes a baseline to measure the effect of stakeholder priorities. To contrast equal weighting, the MCDA was also run using the average of all the stakeholder group priorities.

4.7.1 Equal Weighting Results

MCDA results are presented with equal weighting for all criteria (Figure 4.15). Evaluating the triple bottom line in the absence of stakeholder preference produces a baseline for the comparison of the impacts average stakeholder relative importance ratings. Decentralized water treatment alternatives including neighborhood and POE routinely score lower than centralized treatment alternatives with the exception of the environmental perspective. The largest disadvantages are economic while the social scores show a relative draw between the three alternatives. An inverse trend between economic cost and environmental benefit surfaces among the alternatives.

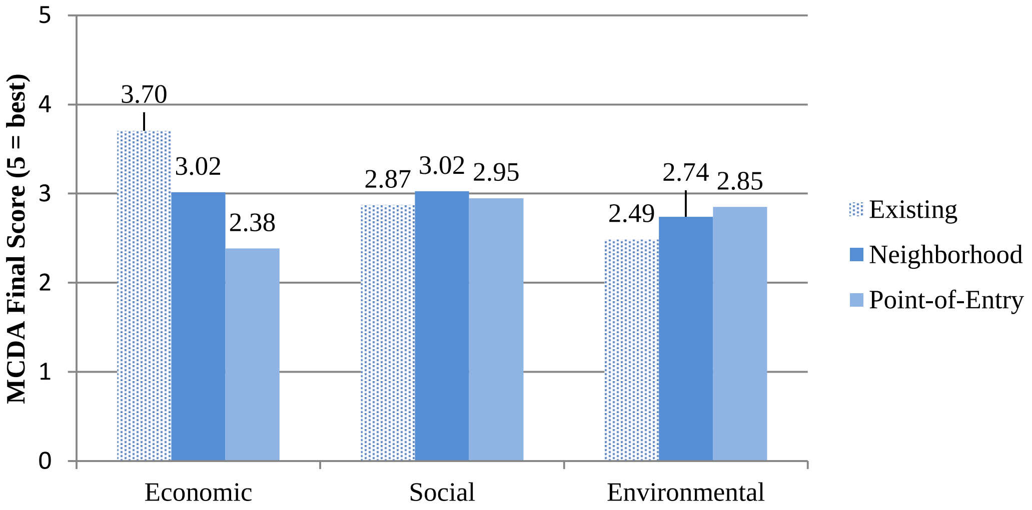


Figure 4.15 –MCDA Equal Weighting Results (5 = best)

4.7.2 Average Stakeholder Results

MCDA results are presented in box and whisker plots to display the average score for all stakeholder scenarios, one standard deviation in each direction and the minimum and maximum stakeholder scores (Figure 4.16).

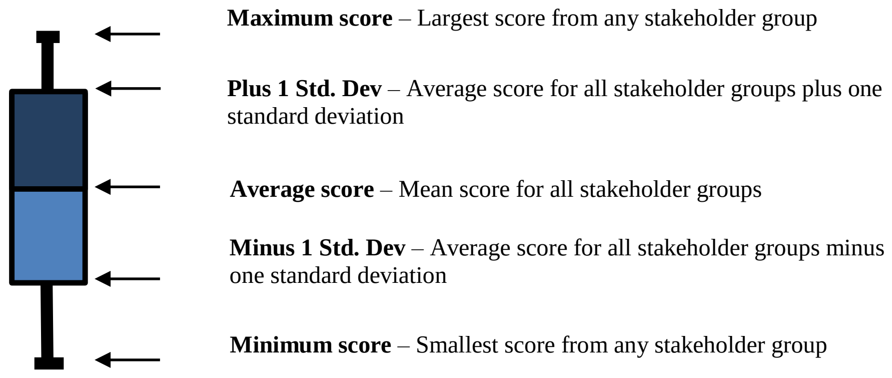


Figure 4.16 – Description of box and whisker MCDA results

A box and whisker plot is provided for MCDA results in the Old Town District comparing decentralized options to the existing system (Figure 4.17). The outcome is a comparison of the triple bottom line for each alternative with a visual display of the spread of the values.

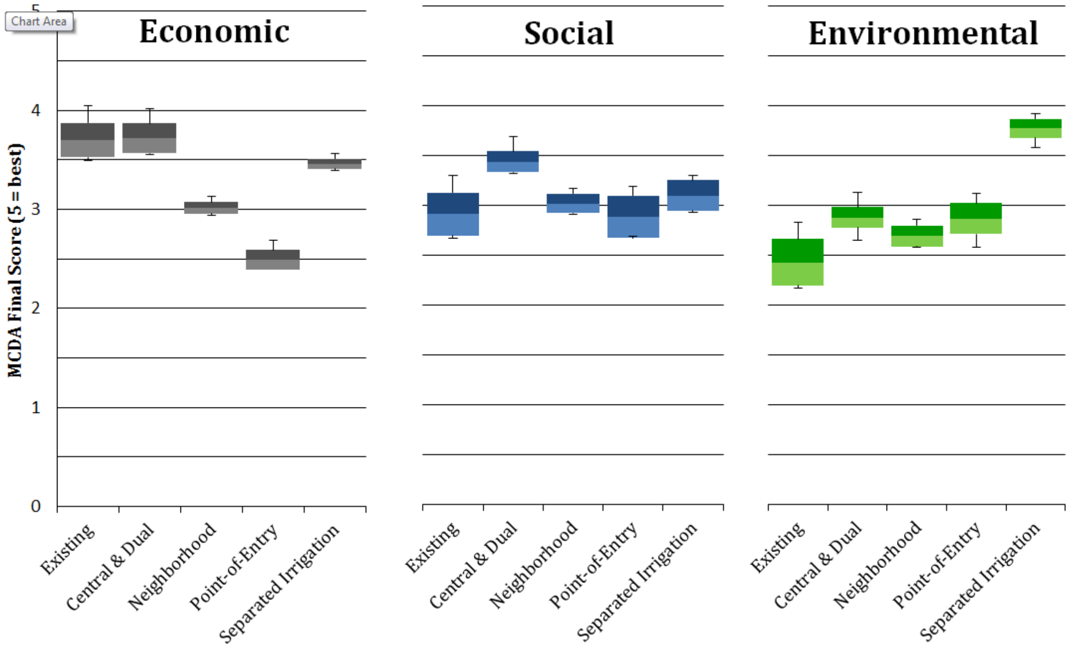


Figure 4.17 – MCDA Stakeholder Average Weighting Results

The equally weighted MCDA results are very similar to the results using the average of the stakeholder relative importance of the criteria which was expected when averaging results from a diverse group of stakeholders. Some alternatives show a larger spread in the stakeholder results than others, displayed predominantly by the existing system across each bottom line (Figure 4.17). The existing system continues to score best which can be attributed to the emphasis stakeholders placed on the impacts of new infrastructure, routine maintenance and regulatory and political risk which favors the existing system which does not require additional infrastructure, cost or risk. Both alternatives displayed a smaller variance in results as a general rule with the exception of the social bottom line for POE. Scores for decentralized water treatment show the same trends as the equally weighted scenario. The existing system has a noticeable advantage from the economic perspective while decentralized treatment displays a higher score from the environmental perspective, led by POE. Social scores again are relatively equal, though the existing system scores the best. The additional costs of POE systems make this alternative unattractive compared to central water treatment. The combination of the costs and additional energy required for the neighborhood water treatment pumping make this option more economically and environmentally expensive.

4.7.3 Individual Criteria Evaluation

A deeper analysis of the 11 main criteria provides insight into the composite bottom line scores. Explanations of MCDA ratings are provided for economic, social and environmental results for each main criterion (Figures 4.18 to 4.27).

Impacts of new infrastructure

Impacts of new infrastructure include both capital costs and replacement costs of infrastructure related to treatment and distribution (Figure 4.18). The existing system does not require additional capital costs for new infrastructure and assumes a 70-year lifetime for related replacement costs. Neighborhood-scale treatment with dual distribution requires the addition of both new treatment facilities and potable distribution networks, resulting in a large capital cost

($15,500,000) as compared to the installation of POE units at each connection ($10,300,000). Replacement frequency has a dramatic effect on the feasibility of POE units which have an assumed lifetime of 20 years compared to 50 for neighborhood-scale treatment systems. Social scores are balanced between short-term factors including the negative disruptions to the community related to new infrastructure installation for decentralized systems balanced by the benefit of related temporary employment. Installation of POE units is substantially less disruptive than new neighborhood-scale treatment systems and dual distribution networks. Environmental concerns are GHG emissions and stormwater pollution which are both largest for the most disruptive installation associated with neighborhood-scale treatment and dual distribution.

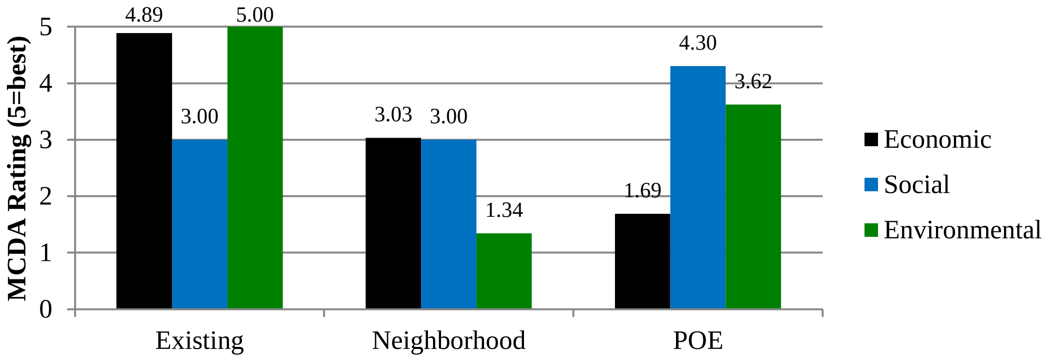


Figure 4.18 – MCDA Rating Comparison for Impacts of New Infrastructure

<u>Energy use</u>

Energy use is simply related to the energy consumed for treatment and distribution and the associated benefits and drawbacks concerning this value for each alternative. Both decentralized treatment alternatives consume a larger amount of energy annually than the existing system (70,685 kWh/year). Neighborhood-scale treatment and dual distribution has the highest energy consumption (121,412 kWh/year) due to pumping requirements. POE units are largely reliant on distribution system pressure to drive normal operation with the exceptions of backwashing and ultraviolet disinfection (78,504 kWh/year). Performance metrics under this criteria are all related to energy consumption which is reflected in consistent score values across the triple bottom line for each alternative (Figure 4.19).

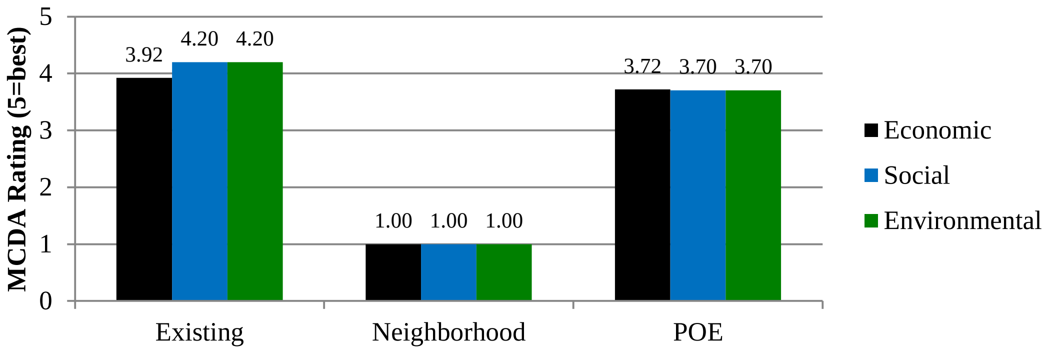


Figure 4.19 – MCDA Rating Comparison for Energy Use

Routine maintenance

Routine maintenance was split into treatment and distribution maintenance requirements. The addition of a dual network increases the required maintenance and creates potential for community disruption. Decentralized treatment maintenance requires travel and added time and cost for employees. Community disruption is greater for additional pipe maintenance than it is for small treatment component replacement which explains why POE scores well socially and neighborhood-scale treatment and dual distribution receives a much lower rating (Figure 4.20).

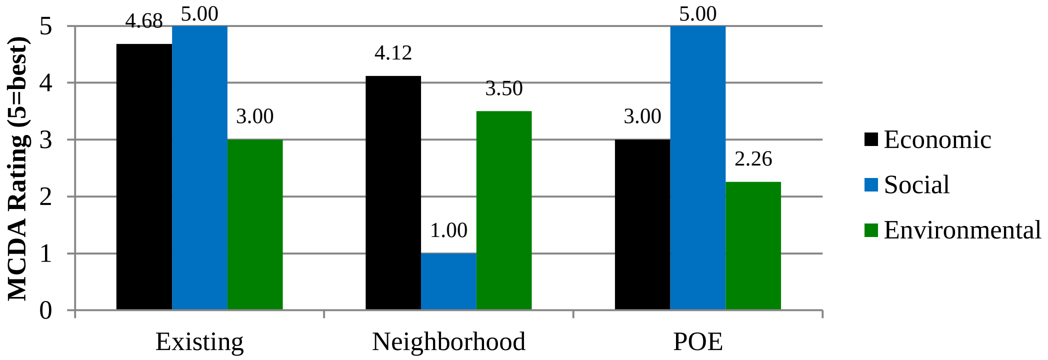


Figure 4.20 – MCDA Rating Comparison for Routine Maintenance

Staffing

Staffing takes into account the number of employees required for operation and maintenance of the proposed alternative systems. Decentralized treatment requires more employees than the existing system mainly due to maintenance requirements. Many treatment operations can be automated which places emphasis on maintenance. The advantage of centralized treatment is that maintenance takes place in a single location. Geographical spacing of treatment systems increases travel time and entails many more systems. Staffing becomes a reflection of the number of treatment systems. The main advantage is social related to employment opportunities for operations and maintenance personnel. These factors result in increasing social ratings for decentralized treatment and decreasing economic and environmental scores with additional systems (Figure 4.21).

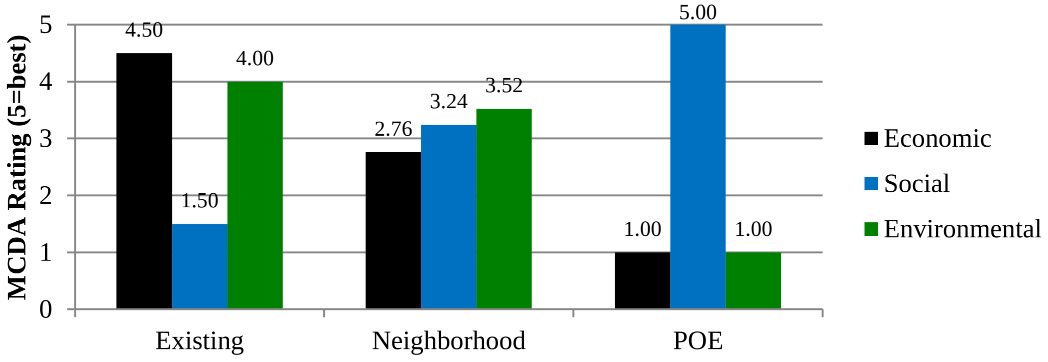


Figure 4.21 – MCDA Rating Comparison for Staffing

Consumer water quality

Main metrics of consumer water quality consider the production of disinfection by-products (DBPs), cross-connections and source water contamination. Dual distribution systems increase the likelihood of cross-connections while POE units improve the ability to respond to these failures by treating water directly at the connection. Smaller diameter potable distribution pipes reduce water age, as does decentralized treatment which improves the closer to the connection treatment occurs. POE units using ultraviolet disinfection do not utilize chlorine which may form DBPs. Using fewer chemicals improves the water quality of receiving water bodies. Overall, this results in higher environmental ratings for decentralized treatment and dual distribution alternatives with slightly diminished economic and social benefits in comparison to the existing system (Figure 4.22).

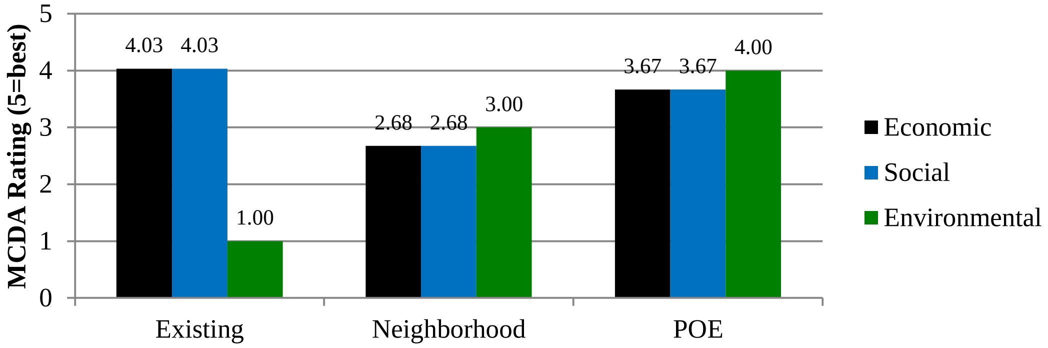


Figure 4.22 – MCDA Rating Comparison for Staffing

Use of city water corridors

Use of the city water corridors is benefit of the Separated Irrigation alternative only.

Risk of limited supply

The risk of limited supply considers the availability of an alternative to distribute alternative water supplies as a response to limited supplies. The driving economic concern is whether new infrastructure may become obsolete. Dual distribution systems become obsolete with conservation measures or reductions in irrigation and raw water usage (Figure 4.23).

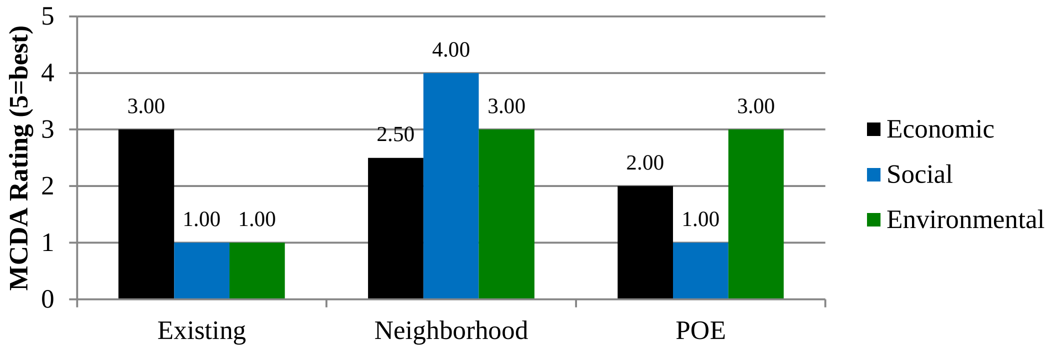


Figure 4.23 – MCDA Rating Comparison for Risk of Limited Supply

Risk of rate changes

Changes in O&M costs were assumed to be directly related to changes in utility rates. POE requires substantially higher O&M costs than the existing system while automated neighborhood-scale package treatment systems require less than existing (Figure 4.24). Economic ratings were based on the confidence in O&M cost projections for which decentralized treatment has not been previously well defined at the scale of this project. With increased rates, irrigators may be motivated to conserve water use which drives the large environmental advantage for POE treatment.

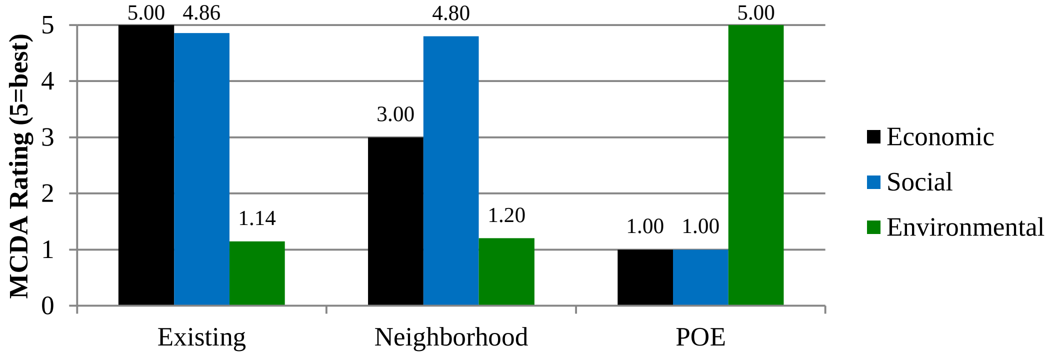


Figure 4.24 – MCDA Rating Comparison for Risk of Rate Changes

Opportunity for new water management strategies

Incorporating new sources of alternative water supplies is dependent on the length of dual distribution system implemented. Investment in systems capable of handling different water sources improves the ability of the system to respond to future water management strategies (Figure 4.25).

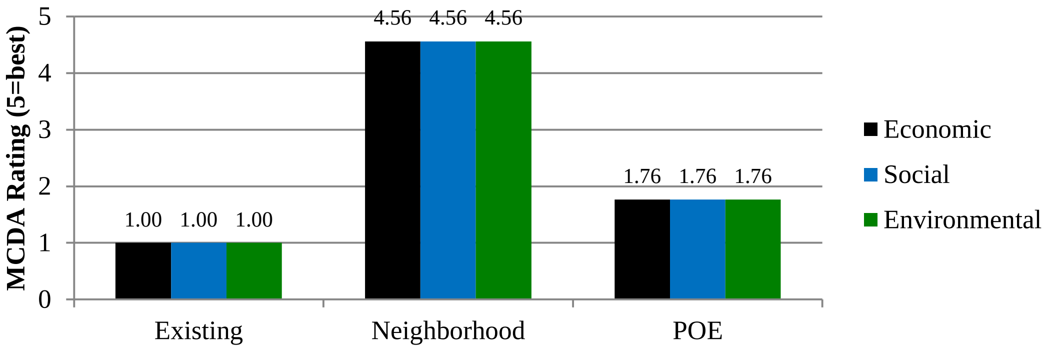


Figure 4.25 – MCDA Rating Comparison for Opportunity for New Water Management Strategies

Revenue opportunities

Decentralized treatment alternatives free up capacity at the existing central water treatment facility. This provides the utility an opportunity to generate revenue through the sale of additional treated water to neighboring communities (Figure 4.26). This metric is based on the additional capacity (907 MG/year) for neighborhood-scale and POE water treatment which produces large advantages across the triple bottom line.

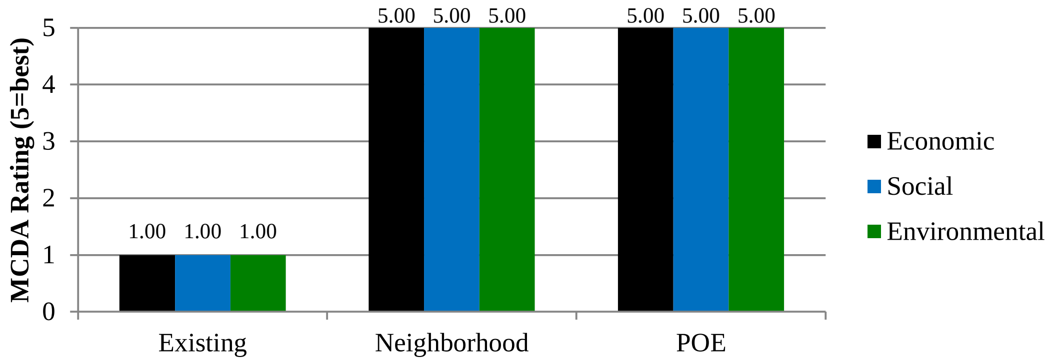


Figure 4.26 – MCDA Rating Comparison for Revenue Opportunities

<u>Regulatory/Political risk</u>

The applicability of dual water supply and decentralized treatment at a city-wide scale is largely unprecedented leaving concerns about the lack of a defined regulatory structure for these systems with is discussed in detail in Chapter 5. In contrast to alternative approaches, the existing system operates under a well-defined regulatory framework. Treatment and distribution regulations must be further defined for dual water supply and decentralized treatment in order to limit the regulatory and associated political risks of implementing these alternatives.

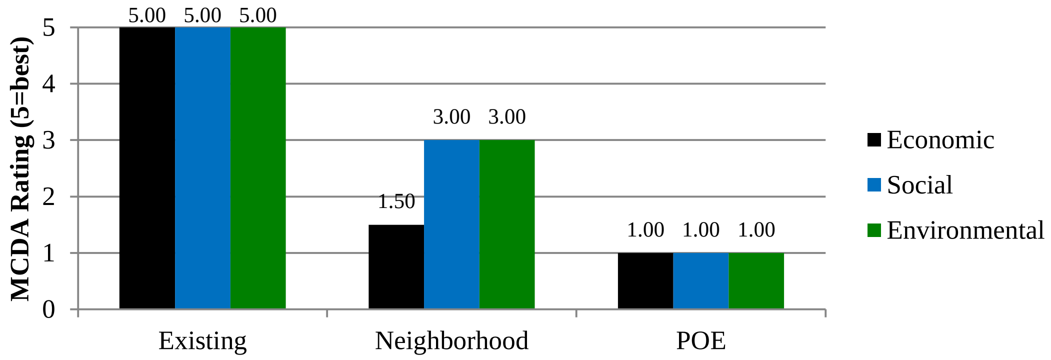
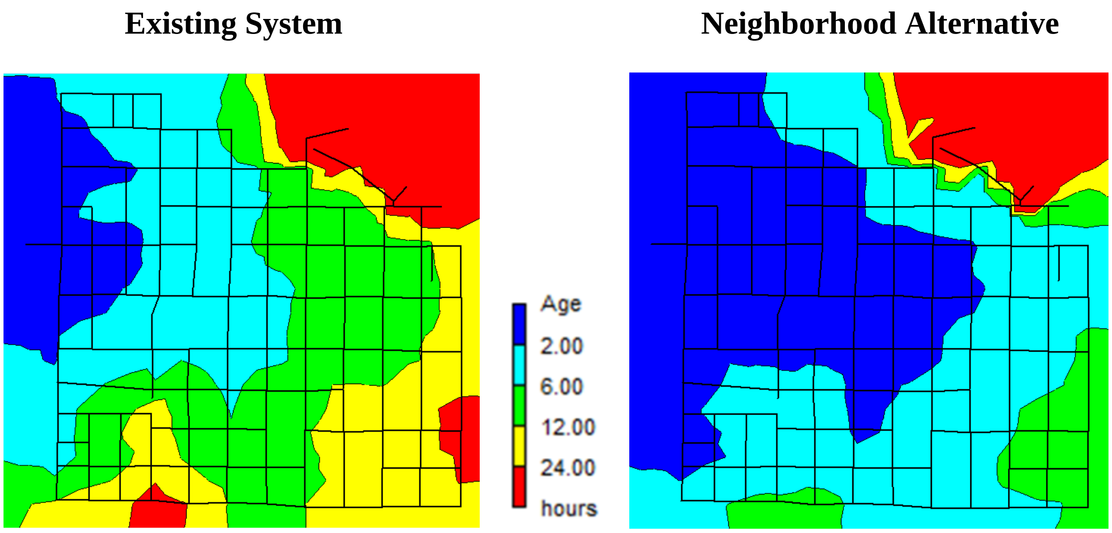


Figure 4.27 – MCDA Rating Comparison for Regulatory/Political Risk

Overall, the results of this analysis illuminate several key drivers which dictate the competitiveness of dual distribution and decentralized water treatment alternatives with the existing centralized conventional model. The largest advantages are a product of reduced chemical use, improved water age and quality, adaptability to new water management strategies and revenue opportunities from increased capacity at the existing treatment facility. This reduction in water age is due to smaller pipe sizing in the neighborhood-scale treatment and dual distribution and location of POE units (Figure 4.28).


Existing System

Neighborhood Alternative

Figure 4.28 – Comparison of Water Age Profile in the Old Town District

Key drivers which limit the applicability of dual water supply and decentralized treatment are more specific for each alternative. Neighborhood-scale treatment and dual distribution incurs large capital costs while requiring substantially more energy due to pumping. POE treatment greatly increases the risks of rate changes related to substantially higher O&M costs. Both alternatives are affected by the lack of defined regulations for these approaches at a city-wide scale.

POE systems require substantially more maintenance than any other alternative due to decentralization of treatment and the number of systems that must be maintained. Total O&M costs are driven by the outstanding cost for treatment system component replacement including sediment pre-filters, GAC/KDF media, and UV lamps and sleeves. Additionally, scheduling and travel related to these responsibilities make up a sizeable percentage of total requirements as shown (Table 4.5).

Table 4.5 – Maintenance Required Per Connection

Component	Freq (per year)	Duration (hr)	Hrs/Year	Cost/Year
Sediment Filter	1.6	0.25	0.40	$12.46
GAC/KDF	0.2	0.5	0.10	$3.12
UV	1.2	0.5	0.60	$18.70
Sampling	0.3	0.25	0.08	$2.60
Scheduling	0.3	0.5	0.17	$5.19
Travel	3.7	0.25	0.92	$28.56
Central Monitor	Incorporated into staffing estimate separately			
TOTAL			2.18	$70.63

In addition to O&M cost, staffing requirements are greatly increased in this alternative for the same reasons. These two drivers affect multiple performance metrics in economic, social and environmental considerations such as O&M cost, staffing requirements, employment and job security, affordability of rates (assumed to be related to O&M costs) and employee transport greenhouse gas emissions.

To evaluate the impact of the additional cost and staffing requirements associated with a citywide Point-of-entry alternative, a cost-sharing scenario with property owners was considered. For this analysis, several assumptions were used to frame a potential approach to make the alternative more competitive. These assumptions were defined as:

- Component replacement (sediment filter, GAC/KDF media, UV lamps and sleeves) would become the responsibility of the connection owner
- 25% of assumed original maintenance would be attributed to repairs and troubleshooting measures which would remain the responsibility of the utility
- Scheduling and travel would adjust according to the amount of utility replacement needed
- Sampling would remain the responsibility of the utility
- Regulations for POE system operation would be adjusted to allow this scenario

One important note is that currently, there are regulatory barriers to the delegation of operations and maintenance responsibilities to homeowners as outlined in §1412(b)(4)(E)(ii) of the Safe Drinking Water Act, which is discussed in further detail in Chapter 5. As stated in the assumptions, this analysis disregards potential regulatory barriers.

This shared O&M scenario was compared to the existing case used for analysis in this study (Figure 4.29).

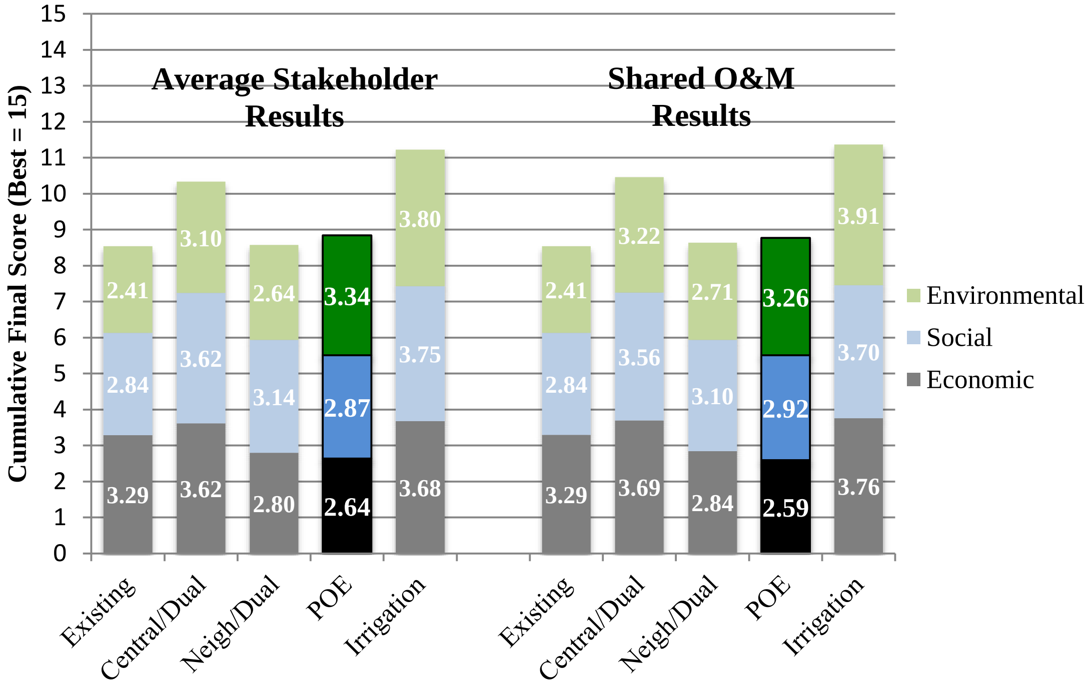


Figure 4.29 - Base scenario average stakeholder MCDA-TBL results comparison with shared O&M for POE scenario MCDA-TBL for Neighborhood #1 (Best = 15)

These results display a slight rise in environmental rating for the POE alternative mirrored by a small decline in the economic and social scores. Overall, sharing O&M responsibilities does not improve the ranking of the POE alternative or produce a substantial change in economic, social or environmental scores. This scenario demonstrates that competitiveness of point-of-entry treatment is limited by additional factors.

4.7.4 Centralized Treatment with Dual Distribution Alternatives

The overall study found that the Central/Dual and Separated Irrigation alternatives scored favorably in comparison to the decentralized treatment alternatives as well as the existing system. Economic and social results were close between the two and made it difficult to distinguish an advantage. However, Separated Irrigation produced a substantial advantage in the environmental bottom line. These results suggest that in a city-wide application, separating potable water from irrigation and fire flow is a practical solution that may be competitive with conventional water production. More detailed information can be found in the *Fort Collins Dual Water Systems Study* (Cole et al. 2015).

4.7.5 Limitations of the MCDA Approach

Analysis of these results is limited due to the adjusted MCDA approach that was used. The weighted average method introduces scaling issues as each performance metric is rated from one to five, distorting the advantages given between close results. The adjusted MCDA approach used to create a triple bottom line involved 20 economic, 16 social and 13 environmental performance metrics in order to evaluate 11 main criteria across the triple bottom line. With so many metrics, dilution of main project drivers could be a concern. In our analysis, more precise quantitative metrics are valued evenly with less precise qualitative assessments which limits the resolution to distinguish between alternatives. Additional analysis methods are recommended to assess the robustness of the results.

4.8 Summary

Replacement of aging water infrastructure in the City of Fort Collins motivated a study to evaluate new approaches to meet future water demands and quality standards in a sustainable way that limits the impact on the community and environment. These approaches included concepts of dual distribution and decentralized water treatment systems with the purpose of separating domestic potable use from irrigation and fire flow demand. Four alternatives were analyzed in comparison to the existing system using a Multi-Criterion Decision Analysis (MCDA) tool using eleven performance metrics evaluated from an economic, social and environmental perspective producing a triple bottom line.

Alternatives were defined as city-wide dual distribution, neighborhood-scale water treatment with dual distribution, point-of-entry treatment, and separated irrigation. In this chapter neighborhood-scale and point-of-entry decentralized treatment options were isolated against the existing system to provide perspective on the feasibility of decentralized treatment with and without dual distribution. Input was collected from stakeholders to produce relative importance factors, giving priority to certain criteria over others in the MCDA analysis. To contrast this, an equally weighted scenario was applied as well.

The results of this analysis illuminate several key drivers which dictate the competitiveness of dual distribution and decentralized water treatment alternatives with the existing centralized conventional model. The largest advantages are a product of reduced chemical use, improved water age and quality, adaptability to new water management strategies and revenue opportunities from increased capacity at the existing treatment facility. This reduction in water age is due to smaller pipe sizing in the neighborhood-scale treatment and dual distribution and location of POE units.

Key drivers which limit the applicability of dual water supply and decentralized treatment are more specific for each alternative. Neighborhood-scale treatment and dual distribution incurs large capital costs while requiring substantially more energy due to pumping. POE treatment greatly increases the risks of rate changes related to substantially higher O&M costs. Both alternatives are affected by the lack of defined regulations for these approaches at a city-wide scale.

Overall, dual distribution and decentralized water treatment alternatives were not economically competitive with the existing system and offered negligible social advantages. Environmental benefits were realized for both alternatives which can be largely attributed to improved water quality due to shorter water age. Centralized treatment with dual distribution alternative results suggest that separating potable water from irrigation and fire flow is a practical solution that may be competitive with conventional water production in a city-wide application.

5.0 REGULATORY CONSIDERATIONS FOR DECENTRALIZED TREATMENT AND DUAL DISTRIBUTION SYSTEMS

5.1 Introduction

Alternative approaches to centralized treatment and conventional distribution are subject to regulatory constraints that may affect the feasibility of implementation for certain applications. Decentralized treatment technologies are typically regulated for use in small systems or remote locations targeting specific contaminants or providing additional treatment for existing municipal potable sources. The aim of this chapter is to outline the most pertinent regulatory challenges for POE and small systems as well as those affecting the use of dual distribution.

5.2 Decentralized Treatment Regulations

Implementing a decentralized water treatment alternative requires an adjustment in water quality monitoring procedures and technology. Increasing the number of systems increases the number of monitoring locations. Neighborhood-scale treatment and point-of-entry treatment both operate under small public water system regulations (those serving fewer than 10,000 people) (U.S. EPA, 2003).

5.2.1 Small Systems Compliance

The federal government defines “small systems” as those which service fewer than 10,000 customers which is further distributed into the size categories in Table 2.2. In 1996, amendments to the SDWA stipulated that treatment performance and affordability be evaluated for small systems in the medium (3,301-10,000 customers), small (501-3,300 customers) and very small (25-500 customers) categories (U.S. EPA, 2003). With these evaluations came a regulatory movement to require small systems to meet the same criteria as larger systems. These regulations and their applicability are summarized in Table 5.1.

Table 5.1 – Small System Regulatory Summary (U.S. EPA, 2003)

Regulation	Summary	What Systems are Affected?
Microbiological (National Primary Drinking Water Regulations [NPDWR]	Coliform MCL	All types and sizes
Volatile Organic Chemicals [NPDWR]	MCLs	All community water systems (CWS) and non-transient (NTNCWS)
Radionuclides	MCLs	All types and sizes
Radon	MCLs	All types and sizes
Inorganic Chemicals [NPDWR]	MCLs	All CWS and NTNCWS
Total Coliform Rule	No more than 5% of samples positive for coliform (distribution system sampling)	All types and sizes
Surface Water Treatment Rule	3-log removal *Giardia*, 4-log virus inactivation, filtration treatment	All surface water and groundwater under influence from surface water
Lead and Copper Rule	Distribution system action levels	All CWS and NTNCWS
Arsenic	MCLs	All CWS and NTNCWS
Ground Water Rule	Appropriate use of disinfectants, multi-barrier approach	All systems using ground water as source
Long Term 1 Enhanced Surface Water	2-log removal *Cryptosporidium*, 0.3 NTU turbidity, TOC reductions for precursor removal	All surface water and groundwater under influence from surface water
Filter Backwash Rule	Recycling filter backwash with treatment	All conventional and direct filtration systems
Stage 1 Disinfectants/Disinfection By-Products Rule	Maximum residual disinfectant levels set	CWS and NTNCWS that use chemical disinfectant
Long Term 2 Enhanced Surface Water	Balance microbial and DBP formation	All types and sizes
Contaminant Candidate List	Potential new MCLs	All types and sizes

The U.S. EPA has approved the use of centrally managed point-of-entry treatment systems in order to achieve compliance for small public water systems with maximum contaminant levels (MCLs) specified in the SDWA (U.S. EPA, 2002). There are several key regulatory barriers related to the implementation of a point-of-entry treatment alternative at a citywide scale.

Point-of-entry compliance strategies are explicitly approved for small public water systems in SDWA PL 104-182, Sec. 105, §1412(b)(4)(E)(ii). The 1996 amendments to the SDWA define small systems as those servicing less than 10,000 people. Implementation of this alternative at a citywide scale would service more than 130,000 customers in the Fort Collins Utility District. The reason that large/very large system categories have been excluded from this amendment is likely related to the limits of cost and operational requirements that define the upper bound at which decentralized treatment is no longer cost effective compared to centralized treatment (Cortruvo, 2002). Point-of-entry treatment is typically applicable to small rural or remote communities (Hamouda, 2010), usually less than a hundred connections. To approve use of a point-of-entry strategy at the city-wide scale, the regulation would need to include large/very large service populations.

Point-of-entry treatment units are required to be owned, controlled and maintained by the public water system or by a hired contractor. The public water system must maintain oversight for all responsibilities including installation, maintenance and sampling (U.S. EPA, 2002). Additionally, delegation of any of these responsibilities to a connection owner is prohibited. This regulation limits the ability of a shared operations & maintenance scenario unless waived by appropriate governing bodies such as CDPHE and U.S. EPA.

Implementation of a point-of-entry treatment alternative will also require regular access to treatment units located on customer property in order to perform installation, maintenance and sampling duties (U.S. EPA, 2002). The local government may pass an ordinance allowing access to treatment units for service personnel as well as requiring customers to use point-of-entry units and grant authority to the public water service to disconnect a connection that has been tampered with (U.S. EPA, 2002). Outdoor installation is a less invasive option for maintenance and sampling while also increasing security from tampering or bypassing.

5.2.2 Monitoring Considerations

The Safe Drinking Water Act (SDWA) stipulates national general sample monitoring schedules for small systems. These regulations are based on the same acute and chronic target contaminants that large/very large systems are responsible for addressing. Table 5.2 summarizes the monitoring requirements for small systems. Monitoring frequency depends on the water source type and the size of the system.

Table 5.2 - General Sample Monitoring Schedule for Small Systems (U.S. EPA, 2003)

Contaminant	Minimum Monitoring Frequency
Acute contaminants – Immediate risk to human health	
Bacteria	Monthly or quarterly, depending on system size and type
Nitrate	Annually
Protozoa and viruses	Future requirements for Ground Water Rule may require monitoring and testing
Chronic Contaminants – Long-term health effects if consumed at certain levels for extended periods	
Volatile organics	Surface water systems – annually
Synthetic organics	Once every three years
Inorganics/metals	Surface water systems – annually
Lead and copper	Annually
Radionuclides	Once every four years

Due to the nature of these requirements, neighborhood-scale treatment and point-of-entry treatment will necessitate different approaches for monitoring strategies than the current centralized approach. One important assumption common to both alternatives is the maintenance of chemical addition at the central water treatment facility to maintain alkalinity levels, add fluoride and control pH. Raw surface water will be collected and blended at the existing facility. This will allow for continued raw source water quality monitoring at the central facility as well as the use of the existing water quality laboratory.

Neighborhood-Scale Treatment Monitoring

Neighborhood-scale package treatment plants may be equipped with sensor and operating devices that can be monitored remotely. Remote Telemetry Systems (RTS) allow operators to operate, monitor and control water treatment systems from a centralized location (U.S. EPA, 2003). This greatly reduces operations and maintenance costs and improves the level of monitoring control. Some systems are more amenable to RTS implementation and these were factored into the selection process for neighborhood-scale treatment. In particular, membrane filtration and disinfection are more amenable treatment technologies than conventional coagulation/filtration. Table 5.3 lists the amenability score for various technologies according to the U.S. EPA *Small Drinking Water Systems Handbook* (U.S. EPA, 2003).

Table 5.3 - Amenability of RTS to Treatment Technologies for Small Systems (5=most) (U.S. EPA, 2003)

Technology	Amenability for Automation/Remote Monitoring & Control
Oxidation/Filtration	1-2
Ion exchange	3-4
Activated alumina	1-2
Coagulation/Filtration	1-2
Dissolved air flotation	1-2
Diatomaceous earth filtration	3-4
Slow sand filtration	3-4
Disinfection	4-5
Membrane filtration systems	3-4
Reverse Osmosis	3-4
Adsorption	3-4

Connecting neighborhood-scale treatment facilities through RTS is an applicable solution to monitoring decentralized facilities. The existing water treatment facility already incorporates a SCADA system collecting one-minute and 15-minute continuous data for monitored parameters (City of Fort Collins, 2010). The additional costs to incorporate these decentralized facilities into the SCADA monitoring system may be estimated using the cost ranges in Table 5.4.

Table 5.4 - Cost Estimates for SCADA System Components (U.S. EPA, 2003)

SCADA System Component	Component Option	Range of Costs
Hardware	Main Computer	$1,000-3,500
	SCADA Unit	$500-30,000
Software	Operating System	$250-750
	Telemetry System	$500-30,000
	Data Collection & Loggers	$250-8,000
Communication Medium	Telephone	$75-125
	Cellular	$250-500
	Radio	$1,500-3,500
	Satellite	$20,000-75,000
Instrumentation	Valves	$25-1,500
	Switch	$25-300
	Sensor	$350-85,000

Point-of-Entry Treatment Monitoring

Point-of-entry treatment systems are required to meet maximum contaminant levels (MCLs) as dictated in the SDWA. With systems at every single potable connection in the city, continuous monitoring for every contaminant is impractical. Typical sampling programs specify target contaminants which are tested for according to a defined monitoring plan which must be approved by the state (U.S. EPA, 2002). Each system must monitor the water quality to demonstrate compliance with the SDWA. Once the system has met all contaminant goals, one third of all units must be sampled annually. Regulations are not clearly defined for a case in which the POE system receives raw or lightly treated surface water.

For the purposes of this analysis, target contaminants were identified according to current monitoring at the existing central water treatment facility as described in the 2010 Horsetooth Influent Water Quality Report, 2011 Cache la Poudre Influent Water Quality Report and 2010 City of Fort Collins Drinking Water Quality Policy Annual Report. These target contaminants include synthetic organic contaminants, volatile organic contaminants, barium, nitrate, selenium, and chloride. A cost for this sampling package was estimated using information from the CDPHE Laboratory Services Division – Water Testing and is summarized in Table 5.5.

Table 5.5 - Target Contaminant Sampling Costs - CDPHE Lab Services Water Testing (CDPHE, 2014)

Target Contaminant	Cost/Sample
Synthetic Organic Contaminants (SOCs)	$106.00
Volatile Organic Contaminants (VOCs)	$106.00
Barium	$20.50
Nitrate	$31.50
Selenium	$20.50
Chloride	$21.50

One third of all POE systems will undergo this suite of contaminant testing annually. Additional contaminant testing for SDWA compliance will remain a function of the central treatment facility. Remote monitoring for every system is severely limited by cost and space and would not be practical at the city-wide scale. SDWA regulations also require the use of mechanical warning devices to automatically notify customers of operational problems (U.S. EPA, 2003). These warning devices have been incorporated into the capital cost for the alternative.

5.3 Dual Distribution System Regulations

The purpose of this section is to discuss the regulatory considerations most relevant to the defined alternatives for the City of Fort Collins in relation to the current system. This is not a comprehensive analysis of the regulations related to the implementation of dual distribution systems.

5.3.1 Non-potable Distribution Regulations

There are currently no national regulations for the distribution of non-potable water. Several states have established their own regulations such as California and Florida. The AWWA Distribution and Plant Operations Division Committee on Dual Water Distribution Systems stated that more study is needed before national standards can be adopted.

5.3.2 Disinfection Residual Requirements

Residual disinfectant is required in drinking water distribution systems to provide a final barrier against contamination. The State of Colorado outlines these requirements in the Colorado Primary Drinking Water Regulations, Articles 7 and 13 (CDPHE, 2010). There are several important stipulations outlined in these articles including that:

- All public water distribution systems must use disinfection unless a waiver has been obtained from the Water Quality Control Division.
- All systems must maintain a detectable disinfectant residual in the distribution system.
- Surface water systems are required to maintain a 0.2 mg/L disinfectant residual at the entry point to the distribution system.

Chlorine disinfection is used in the existing water treatment and distribution system in the City of Fort Collins. Decentralized treatment alternatives produce a regulatory concern related to the definition of the entry point. According to the Colorado Department of Public Health and Environment (CDPHE), there is no regulatory difference in the definition of transmission lines and distribution lines (Ingels, 2014). A distribution line is a network that is linked to potable connections (CDPHE, 2009). The entry point is then more specifically defined as the point at which potable quality water enters a distribution system after treatment for delivery to potable connections (Ingels, 2014).

The following entry point scenarios are produced based on these regulatory interpretations:

- Neighborhood-scale treatment – The entry point is located post treatment facility at the entrance to the potable distribution system. A disinfectant residual is not required prior to the decentralized treatment facilities.
- Point-of-entry treatment – The entry point is located post treatment, which is after the connection. No disinfectant residual is required due to the absence of a distribution

system. As the regulation is written, a waiver must be obtained from CDPHE in order to forgo residual disinfection.

Point-of-entry treatment entry point and disinfection regulations must be further defined to determine whether a disinfectant residual is required. For the purposes of this analysis, it was assumed that in the absence of a distribution system with treatment at the connection, a waiver would be granted to forgo residual disinfection. This assumption provides the opportunity to use alternative technologies that do not produce a residual such as ultraviolet disinfection.

5.3.3 Reversion to Potable Distribution System

If an alternative does not meet compliance standards, there is a risk that the alternative system would need to be reverted to the existing system configuration. Raw water irrigation transmission lines would then need to meet potable distribution standards. This conversion back to potable distribution requires more than a chlorine flush to return the system to potable use. Flushing procedures may include drag cleaning, hydraulic-jet cleaning or electric scraper cleaning (AWWA, 2001). Sliplining and replacement measures are significantly more expensive but may be necessary in more extreme contaminant situations (Ingels, 2014).

5.4 Summary

Regulatory constraints may affect the feasibility of alternative approaches to conventional water treatment and distribution. A brief summary of the regulations related to the application of decentralized water treatment and dual distribution systems in Fort Collins, CO reveals several pertinent concerns.

Decentralized treatment technologies are regulated for use in small systems or remote locations targeting specific contaminants or providing additional treatment for existing municipal potable sources. Neighborhood-scale and POE systems fall under a treatment response for small systems, defined as those serving fewer than 10,000 customers, which could limit the validity of these approaches at a larger scale. POE systems are required to be owned, operated and maintained by a public water system and need regular access for installation, maintenance and monitoring. Monitoring is significantly more difficult in decentralized applications and guided by a provided schedule for the frequency of defined acute and chronic contaminants.

Dual distribution systems are subject to potentially relevant regulations as well. Disinfection residual is required for all public distribution systems unless a waiver is obtained from the appropriate governing body (CDPHE in Colorado). Potable distribution systems are defined by the location of the entry point at which potable water enters a distribution network after treatment. The delivery of raw or lightly treated water to a neighborhood treatment facility or POE unit would necessitate a clearer definition of this concept. Additionally, if the non-potable network needs to be reverted to potable quality distribution, additional flushing measures may produce cost barriers.

6.0 CONCLUSIONS

6.1 Alternative Water Treatment and Distribution

Conventional treatment and delivery of potable water in the United States is under pressure to adapt now more than ever. Production of potable water consumes a substantial amount of energy and cost. Sizing distribution networks to meet peak demand and fire flow requirements extends water age and delivery time producing deteriorating water quality concerns. Interrelated concerns such as these have motivated the consideration of alternative approaches such as decentralized water treatment and dual distribution.

An investigation into the competitiveness of decentralized water treatment within a municipal scale dual distribution system was formed based on the application of these approaches in Fort Collins, CO. This study was prompted by the potential benefits of a new paradigm in water provision through approaches in which a smaller volume of potable quality water is delivered to the home for direct human consumption while separating the supply for other domestic uses such as outdoor irrigation and fire flow.

6.2 Selection of Decentralized Treatment Systems

A common selection process for both neighborhood-scale and point-of-entry treatment was used to recommend the most applicable systems for decentralized alternatives. An ultrafiltration package system with chlorine disinfection was recommended neighborhood-scale system due to compact design, low chemical requirements, consistent water quality and amenability to remote monitoring. Activated Carbon/Kinetic Fluxion Media filtration coupled with ultraviolet disinfection was recommended for point-of-entry treatment system based on low capital costs, simplistic operation and system size.

6.3 Comparison of Treatment and Distribution Alternatives in Fort Collins, CO

Four alternatives were analyzed in comparison to the existing system using a Multi-Criterion Decision Analysis (MCDA) tool with eleven performance metrics evaluated from an economic, social and environmental perspective producing a triple bottom line. Alternatives were defined as city-wide dual distribution, neighborhood-scale water treatment with dual distribution, point-of-entry treatment, and separated irrigation.

Results of the evaluation illuminate key drivers which dictate the competitiveness of dual distribution and decentralized water treatment alternatives with the existing centralized conventional model. The largest advantages are a product of reduced chemical use, improved water age and quality, adaptability to new water management strategies and revenue opportunities from increased capacity at the existing treatment facility. Neighborhood-scale treatment and dual distribution incurs large capital costs while consuming substantially more energy due to pumping. . Environmental concerns are GHG emissions and stormwater pollution which are both largest for the most disruptive installation associated with neighborhood-scale treatment and dual distribution. Point-of-entry treatment increases the risk of rate changes related to drastically higher maintenance costs and personnel needs. Installation of POE units is substantially less disruptive than new neighborhood-scale treatment systems and dual distribution networks. Both alternatives are strongly affected by the lack of defined regulations for these approaches at a city-wide scale.

6.4 Regulatory Considerations

Decentralized treatment technologies are regulated for use in small systems or remote locations targeting specific contaminants or providing additional treatment for existing municipal potable sources. Neighborhood-scale and POE systems fall under a treatment response for small systems which could limit the validity of these approaches at a larger scale. POE systems are required to be owned, operated and maintained by a public water system and need regular access for installation, maintenance and monitoring. Monitoring is more difficult in decentralized applications and guided by a provided schedule for the frequency of defined acute and chronic contaminants.

Disinfection residual is required for all public distribution systems unless a waiver is obtained from the appropriate governing body (CDPHE in Colorado). Potable distribution systems are defined by the location of the entry point at which potable water enters a distribution network after treatment. The delivery of raw or lightly treated water to a neighborhood treatment facility or POE unit would necessitate a clearer definition of this concept. Additionally, if the non-potable network needs to be reverted to potable quality distribution, additional flushing measures may produce cost barriers.

6.5 Application of Alternative Approaches to Water Treatment and Distribution

Overall, dual distribution and decentralized water treatment alternatives are not economically competitive with the existing system and offered negligible social advantages. Environmental benefits were realized for both alternatives which can be largely attributed to improved water quality due to shorter water age. Of note is that alternatives which maintained centralized treatment for distribution of indoor water separate from raw water were found to have advantages in all three bottom lines when compared to the existing system. These results suggest that separating potable water from irrigation and fire flow is a practical solution that may be competitive with conventional water production in a city-wide application. However, decentralized systems may not offer substantial benefit when there is a desire to treat and supply indoor water separately from outdoor and fire water.

Conventional water treatment and distribution is currently undergoing a transition in which investigation of alternative approaches has been motivated by economic, societal and environmental factors. Dual treatment and supply of indoor water separate from outdoor/fire water including decentralized water treatment has been considered to address concerns with existing systems. The triple bottom line multi-criterion decision analysis evaluation of two alternative designs incorporating neighborhood scale small-system treatment with dual distribution networks and point-of-entry treatment using an existing distribution system demonstrated that these approaches are currently not competitive with the conventional approach employed by the City of Fort Collins. Regulations must be more explicitly defined for dual water supply and decentralized treatment systems in order to properly evaluate their feasibility at a city-wide scale. Future research efforts should be focused on the optimization of maintenance requirements and reduction of energy consumption for dual water supply and decentralized treatment alternatives. Neighborhood-scale and point-of-entry treatment remain best suited for small and remote system applications. Continued exploration of alternative potable water production approaches through comprehensive analyses such as those provided in this report is critical to the sustainable use of our increasingly limited water resources.

REFERENCES

Aquatec-Maxcon. (2013). “WATERPURE - DF Direct Filtration Water Treatment Plants.” *[Product Literature]*. Melbourne, Australia.

Briliam Engineering Services, LLC. (2011). “Feasibility Study for a Joint Water Treatment Plant.” Prepared for the La Plata Archuleta Water District and the Town of Bayfield, CO.

Burns, S., Adams, V., Maloney, S. (1984). "Direct Filtration Versus Conventional Water Treatment in the Intermountain Region." Paper 580.

City of Fort Collins. (2010). “City of Fort Collins Water Treatment Facilities Master Plan, Vol. 1.” Fort Collins, CO.

City of Fort Collins. (2011). “Plan Fort Collins - Plan Summary.” Fort Collins, CO.

City of Fort Collins. (2011-2014). “Demographic Information - Fort Collins Population Estimates 2011-2014.” <http://www.fcgov.com/planning/trends.php?key=advanceplanning/trends.php> (November 12, 2014)

Clark, R. and Morand., J. (1981). “Package Plants: A Cost Effective Solution to Small Water System Treatment Needs,” Journal of the American Water Works Association, Vol. 73, No. 1, pp 24-30.

Clarkson, C., Shrader, M. (1998). “Trident Water Treatment System.” Virginia Tech. (April 9, 2014).

Cole, J., Sharvelle, S., Grigg, N., Roesner, L. Fourness, D. (2015). “Fort Collins Utilities Dual Water Systems Study.” *Colorado State University*. Prepared for Fort Collins Utilities, Fort Collins, CO.

Colorado Department of Public Health and Environment, Water Quality Control Commission. (2013). “Regulation No. 31 – The Basic Standards and Methodologies for Surface Water Colorado.” Denver, CO.

Colorado Department of Public Health and Environment. (2010). “Colorado Primary Drinking Water Regulations.” Denver, CO.

Colorado Department of Public Health and Environment. (2013). “State of Colorado Design Criteria for Potable Water Systems.” Safe Drinking Water Program Implementation. Policy #5. Denver, CO.

Colorado Water Conservation Board. (2011). “Statewide Water Supply Initiative 2010.”

Corix. (2013). “Adsorption Clarification Water Treatment Plants.” [*Product Literature]*, http://www.cec-ltd.com/upload/CWS_BRO_CEC_AC_v2%20LoRes.pdf (April 8, 2014)

Corix. (2013). “Direct Filtration.” [*Product Literature]*, <http://www.corix.com/corix-companies/water-systems/water-treatment/technology/direct-filtration.aspx> (May 1, 2014)

Cortruvo, J. (2002). “Approaches for Providing Potable Water in Small Systems.” National Rural Water Association.

Douglas County Water Resource Authority (DCWRA). (2012). “Why Two is Better Than One: Enter the Dual Pipe Water Distribution System.” Water Resource Conservation, Education and Public Policy.

East Bay Municipal Utility District (EBMUD). (2008). “East Bayshore Recycled Water Project.”

Elmund, K., Strong, S. and Hamdan, B. (2013). “2012 City of Fort Collins Lower Cache la Poudre River & Urban Creek Water Quality Report.” Fort Collins Utilities, Fort Collins, CO.

Evoqua Water Technologies. (2014). “Memcor XS Submerged Membrane System.” [*Product Literature]*, < http://www.evoqua.com/en/products/membrane_filtration_separation/ microfiltration_membrane_systems> (March 10, 2014).

Fluytec. (2013). “Ultrafiltration Standard Systems.” [*Product Literature]*, Erandio-Vizcaya, Spain.

General Electric. (2013). “Packaged Systems for Water and Wastewater Treatment.” [*Product Literature], GE Water & Process Technologies.* Downloadable brochure. (March 19, 2014). Phone conversation, March 22, 2014 (281-727-9306).

Godman, R. & Kuyk, D. (1997). “A Dual Water System for Cap Coral.” American Water Works Association, July 1997.

Golstein, R. and Smith, W. (2002). “Water & Sustainability: U.S. Electricity Consumption for Water Supply and Treatment – The Next Half Century.” *Topical Report Volume 4*, Electric Power Research Institute, Palo Alto, CA.

Gumerman, R. C., Culp, R. L., and Hansen, S. P. (1979). "Estimating Water Treatment Costs." Rep. No. EPA-600/2-79-162a-d, Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio 45268.

Haukaas, J. (2013). “FCU Dual Water Systems Project Kickoff Meeting.”

James, W., Craik, S., Molla, S., Suarez, A. (2012). “Direct Filtration: A Tale of Two Winters.” *AWWA Opflow*, January 2012.

Jones, R., Allen, P., Garland, J. and Wang, Z. (2008). “Evaluation of Package Water Treatment Plants for Severe Drought Conditions for City of Raleigh, NC.” *Hazen and Sawyer, P.C.*

KDF Fluid Treatment (2014) Point-of-Entry or Point-of-Use Water Treatment Systems. *KDF Fluid Treatment Description,* <http://www.kdfft.com> (September 14, 2014).

Kirmeyer, G., L. Kirby, B., Murphy, P., Noran, K., Martel, T., Lund, T., Anderson, J. and Medhurst, R. (1999). “Maintaining and Operating Finished Water Storage Facilities.” Denver, Colo.: AWWA and AWWARF.

Lenntech.Water Treatment Solutions (2014). “Ultrafiltration membrane Technology.” [*Product Literature]*, < http://www.lenntech.com/library/ultrafiltration/ultrafiltration.htm> (May 8, 2014)

Mayer, P., D'Audney, L. and Bode, D. (2009). “Water Conservation Plan. Ft. Collins, CO.” City of Fort Collins Utilities.

McKenzie, C. (2005). “Wastewater Reuse Conserves Water and Protects Waterways.” On Tap. Winter 2005: 46-51.

National Drinking Water Clearinghouse. (1997). “Package Plants.” *Tech Brief: A National Drinking Water Clearinghouse Fact Sheet #6*.

National Research Council. (1997). “Safe Water From Every Tap: Improving Water Service to Small Communities.” Table 3-4 p 64-65. *Committee on Small Water Supply Systems, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources.* Washington, D.C.

New Hampshire Drinking and Groundwater Bureau. (2012). “Surface Water Treatment Plants in New Hampshire.” *Environmental Fact Sheet.*

Okun, D. (1997). “Distributing reclaimed water through dual systems.” *Journal American Water Works Association*, 89(11), 52-64.

Pelican Water Systems. (2014). “Sediment Pre-filter Water System.” [*Product Literature]*, <http://www.pelicanwater.com/pre-sediment-filter-systems.php> (June 11, 2014).

Peter-Varbanets M., Zurbrugg C., Swartz, C. and Pronk W. (2009). “Decentralized systems for potable water and the potential of membrane technology.” Water Res 43: 245–265.

Plappally, A. and Lienhard, J. (2012). “Energy requirements for water production, treatment, end use, reclamation, and disposal.” *Renewable & Sustainable Energy Reviews*, 16(7), 4818-4848. doi: 10.1016/j.rser.2012.05.022

PureEarth Technologies, Inc. (2014). “How Our Filters Work (what’s KDF and GAC?),” [*Product Literature]*, <http://www.pure-earth.com/how.html> (October 31, 2013).

Rossman, L. (2000). "EPANET2 User's Manual." *(W. S. a. W. R. Division, Trans.).* Cincinnati, OH: National Risk Management Research Laboratory, United States Environmental Protection Agency.

Schowalter, L. (2006). "Development of UV-based water purification systems for point of use/point of entry." *Critical National Need Idea*, submitted by Crystal IS, Inc. to National Institute of Standards and Technology (NIST).

Sharma, R. (2010). Development of a Preliminary Cost Estimation Method for Water Treatment Plants. University of Texas – Arlington

State of Colorado. (2011). "Clarification about log removal credits granted to package plants with upflow clarification for meeting the removal requirements for Giardia lamblia, virus, and Cryptosporidium." [Letter from Gov. John Hickenlooper to Colorado Public Water Systems, July 4, 2011].

Tonka Water. (2014). "Packaged Treatment Systems." [*Product literature],* <http://www.tonkawater.com/package.cfm> (February 15, 2014). Phone conversation February 23, 2014 (763-252-0905).

Town of Cary, NC. (2013). "Town of Cary Reclaimed Water Master Plan Update." Prepared by CDM Smith, July 2013.

U.S. Army Corps of Engineers. (1999). "Design of Small Water Systems." Washington, D.C.

U.S. EPA. (1979). "Estimating Water Treatment Costs." EPA-600/2-79-162b

U.S. EPA. (1980). “Package Water Treatment Plants.” Vol. 2 A Cost Evaluation. *Municipal Environmental Research Laboratory*, Cincinnati, OH.

U.S. EPA. (1991). “Technologies for Upgrading Existing or Designing New Drinking Water Treatment Facilities.” CRC Press.

U.S. EPA. (1997). “Small System Compliance Technology List for the Surface Water Treatment Rule.”

U.S. EPA. (1997). “Water on Tap: A Consumer’s Guide to the Nation’s Drinking Water.” EPA/815/K-97/002. July 1997.

U.S. EPA. (2001). “Low-Pressure Membrane Filtration for Pathogen Removal: Application, Implementation, and Regulatory Issues,” United State Environmental Protection Agency, Office of Water.

U.S. EPA. (2002). “Guidance for Implementing a Point-of-Use or Point-of-Entry Treatment Strategy for Compliance with the Safe Drinking Water Act,” United States Environmental Protection Agency, Office of Water.

U.S. EPA. (2003). “Small Drinking Water Systems Handbook – A Guide to ‘Packaged’ Filtration and Disinfection Technologies with Remote Monitoring and Control Tools,” United States Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Water Supply and Water Resources Division.

U.S. EPA. (2007). “Cost Evaluation of Point-of-Use and Point-of-Entry Treatment Units for Small Systems: Cost Estimating Tool and User Guide,” United State Environmental Protection Agency, Office of Water.

U.S. EPA. (2008). “Costs and Benefits of Complete Water Treatment Plant Automation.” AwwaRF

U.S. EPA. (2008). “Evaluation of Dynamic Energy Consumption of Advanced Water and Wastewater Treatment Technologies.” AwwaRF.

U.S. EPA. (2013). “Energy Efficiency in Water and Wastewater Facilities.” State and Local Climate and Energy Program.

U.S. EPA. (2014). “Conventional Treatment.” *Water Treatability Database,* <http://iaspub.epa.gov/tdb/pages/treatment/treatmentOverview> (March 10, 2014).

U.S. EPA. (2014). “Direct Filtration.” *Water Treatability Database,* < http://iaspub.epa.gov/tdb/ pages/treatment/treatmentOverview > (March 21, 2014).

U.S. Filter. (2000). “Unique Recovery Services for Industrial Wastes and Wastewater.” <http://www.idaho-maryland.com/i/pdf/PD-May29-2007/Appen-C_WaterTreatmentSystemDescription.pdf> (April 11, 2014).

U.S. Fire Administration. (2008) Water Supply Systems and Evaluation Methods. Volume II: Water Supply Evaluation Methods. FEMA.

Wang, P., Ma, J., Wang, Z., Shi, F. and Liu, Q. (2012). “Enhanced Separation Performance of PVDF/PVP- -MMT Nanocomposite Ultrafiltration Membrane Based on the NVP-Grafted Polymerization Modification of Montmorillonite (MMT).” Langmuir 2012, 28, 4776−4786.

WesTech. (2014). “Product Specifications for AltaFilter Ultrafiltration Membrane System and Trident Package Treatment System.” Proposal obtained for the City of Fort Collins, July 9, 2014.

APPENDIX A: NEIGHBORHOOD-SCALE TREATMENT SYSTEM SELECTION

MCDA Basic Data

			A-1	A-2	A-3	A-4	A-5
Criteria	**Sub-Criteria**	**Max/ Min**	**Conventional**	**Conventional w/ Complete Automation**	**Ultrafiltration**	**Direct Filtration**	**Up-flow Adsorption-Clarification**
Cost							
	Capital cost	Min	$1,470,000	$1,505,000	$1,545,000	$1,385,000	$1,030,000
	Operations cost	Min	$200,000	$170,000	$186,400	$110,000	$196,000
Energy Usage							
	Treatment energy usage (kWh/day)	Min	1483	1112	1788	1200	1500
	Percent recovery (%)	Max	95%	95%	85%	95%	90%
Maintenance Requirements							
	Employee time required (hrs/wk)	Min	20	10	10	15	15
	System lifetime	Max	20	18	15	20	20
	Operational complexity	Min	High	Med	Low	Med	Med
	Chemical requirements	Min	Very High	Very High	Very Low	Med	Med
	Sludge production	Min	100%	100%	60%	55%	50%
Performance							
	Removal of *Giardia lamblia* (log)	Max	2.5	2.5	4	2	2
	Removal of *Cryptosporidium* (log)	Max	2.5	3	4	2.5	2.5
	Removal of viruses (log)	Max	2	2	3.5	1	1
	Influent turbidity limit (NTU)	Max	100	100	30	10	50
Implementation							
	System size (ft^2)	Min	600	650	145	400	300
	Opportunity for expansion	Max	Poor	Very Poor	Very Good	Poor	Very Good
	Availability	Max	Good	Very Poor	Very Good	Poor	Good
	Community disturbance	Min	High	High	Low	Low	Low
	Remote Monitoring Amenability	Max	1.5	2	3.5	1.5	1.5

Word Scales

Word Scales (5=best)

Word	Rating
Very Good	5
Good	4
Fair	3
Poor	2
Very Poor	1
Very Small	5
Small	4
Medium	3
Large	2
Very Large	1
Very Low	5
Low	4
Med	3
High	2
Very High	1

Input Data and Sources

Conventional

Criterion	Value	Source
Capital cost ($ 2014)	$1,470,000	U.S. EPA, 1980 and Sharma, 2010
Operations cost ($ 2014)	$199,736	Sharma, 2010
Total energy use (kWh/day)	1483	Electric Power Research Institute, 2002
Sludge production	100%	*Relative percent to base other technologies
Employee time required (hrs/wk)	20	Tonka, 2014 (763-252-0905)
System lifetime	20	Tonka, 2014 (763-252-0905)
Operational complexity	High	National Research Council, 1997
Percent recovery	95%	Tonka, 2014 (763-252-0905)
Removal of Giardia lamblia (log)	2.5	Colorado Primary Drinking Water Regulations, Article 7
Removal of Cryptosporidium (log)	3	Colorado Primary Drinking Water Regulations, Article 7
Removal of viruses (log)	2	Colorado Primary Drinking Water Regulations, Article 7
Chemical requirements	Very High	Jones et. al, 2008
Influent turbidity limit (NTU)	100	U.S. EPA, 1991
System size (ft^2)	600	Jones et. al, 2008
Opportunity for add-ons	Poor	
Availability	Good	
Community disturbance	High	*Based on sludge production

Automated Conventional

Criterion	Value	Source
Capital cost ($ 2014)	$1,505,000	Small Drinking Water Systems Handbook (EPA, 2003)
Operations cost ($ 2014)	$169,776	Sharma, 2010
Total energy use (kWh/day)	1112	U.S. EPA, 2013
Sludge production	100%	*Relative percent to base other technologies
Employee time required (hrs/wk)	10	Tonka, 2014 (763-252-0905)
System lifetime	18	Tonka, 2014 (763-252-0905)
Operational complexity	Med	National Research Council, 1997
Percent recovery	95%	Tonka, 2014 (763-252-0905)
Removal of Giardia lamblia (log)	2.5	Colorado Primary Drinking Water Regulations, Article 7
Removal of Cryptosporidium (log)	3	Colorado Primary Drinking Water Regulations, Article 7
Removal of viruses (log)	2	Colorado Primary Drinking Water Regulations, Article 7
Chemical requirements	Very High	Jones et. al, 2008
Influent turbidity limit (NTU)	100	U.S. EPA, 1991
System size (ft^2)	650	Jones et. al, 2008
Opportunity for add-ons	Very Poor	
Availability	Very Poor	
Community disturbance	High	*Based on sludge production

Ultrafiltration

Criterion	Value	Source
Capital cost ($ 2014)	$1,545,000	Sharma, 2010
Operations cost ($ 2014)	$186,400	Sharma, 2010
Total energy use (kWh/day)	1788	WesTech, 2014
Sludge production	60%	Wang et al, 2012
Employee time required (hrs/wk)	10	General Electric, 2013 (281-727-9306)
System lifetime	15	Tonka, 2014 (763-252-0905)
Operational complexity	Low	National Research Council, 1997
Percent recovery	85%	General Electric 281-727-9306
Removal of Giardia lamblia (log)	4	U.S. EPA, 2001
Removal of Cryptosporidium (log)	4	U.S. EPA, 2001
Removal of viruses (log)	3.5	U.S. EPA, 2001
Chemical requirements	Very Low	National Drinking Water Clearinghouse, 1999
Influent turbidity limit (NTU)	30	U.S. EPA, 1991
System size (ft^2)	145	Evoqua, 2014
Opportunity for add-ons	Very Good	
Availability	Very Good	
Community disturbance	Low	*Based on sludge production

Direct Filtration		
Criterion	Value	Source
Capital cost ($ 2014)	$1,385,000	Logsdon et al, 1980
Operations cost ($ 2014)	$110,000	Logsdon et al, 1980
Total energy use (kWh/day)	1200	Conservative estimate
Sludge production	55.00%	James et. al, 2012
Employee time required (hrs/wk)	15	Corix, 2013 (604-455-3500)
System lifetime	20	Corix, 2013 (604-455-3500)
Operational complexity	Med	National Research Council, 1997
Percent recovery	95%	Corix, 2013 (604-455-3500)
Removal of Giardia lamblia (log)	2	Colorado Primary Drinking Water Regulations, Article 7
Removal of Cryptosporidium (log)	2.5	Colorado Primary Drinking Water Regulations, Article 7
Removal of viruses (log)	1	Colorado Primary Drinking Water Regulations, Article 7
Chemical requirements	Med	James et. al, 2012
Influent turbidity limit (NTU)	10	U.S. EPA, 1997 - Small Systems Treatment Rule
System size (ft^2)	400	Corix, 2013 (604-455-3500)
Opportunity for add-ons	Poor	
Availability	Poor	
Community disturbance	Low	*Based on sludge production

Up-flow Adsorption-Clarification		
Criterion	Value	Source
Capital cost ($ 2014)	$1,030,000	U.S. Filter, 2000
Operations cost ($ 2014)	$195,830	Sharma, 2010
Total energy use (kWh/day)	1500	Conservative estimate
Sludge production	50.00%	WesTech, 2014
Employee time required (hrs/wk)	15	Corix, 2013 (604-455-3500)
System lifetime	20	Corix, 2013 (604-455-3500)
Operational complexity	Med	National Research Council, 1997
Percent recovery	90%	Corix, 2013 (604-455-3500)
Removal of Giardia lamblia (log)	2	Colorado Primary Drinking Water Regulations, Article 7
Removal of Cryptosporidium (log)	2.5	Colorado Primary Drinking Water Regulations, Article 7
Removal of viruses (log)	1	Colorado Primary Drinking Water Regulations, Article 7
Chemical requirements	Med	Fluytec, 2013
Influent turbidity limit (NTU)	50	Fluytec, 2013
System size (ft^2)	300	Corix, 2013 (604-455-3500)
Opportunity for add-ons	Very Good	
Availability	Good	
Community disturbance	Low	*Based on sludge production

WAM Scores

Neighborhood Level Treatment System Selection

Resource Criteria	**Relative Importance**	**Normalized Weights**	**Attribute Normalized Weights**	**ALTERNATIVES**				
				1	**2**	**3**	**4**	**5**
Cost	1	0.200						
Capital cost			0.500	1.58	1.31	1.00	2.24	5.00
Operations cost			0.500	1.00	2.33	1.60	5.00	1.18
			1	1.29	1.82	1.30	3.62	3.09
Energy Usage	1	0.200						
Treatment energy usage (kWh/day)			0.500	2.81	5.00	1.00	4.48	2.71
Percent recovery (%)			0.500	5.00	5.00	1.00	5.00	3.00
			1.000	3.90	5.00	1.00	4.74	2.85
Maintenance Requirements	1	0.200						
Employee time required (hrs/wk)			0.200	1.00	5.00	5.00	3.00	3.00
System lifetime			0.200	5.00	3.40	1.00	5.00	5.00
Operational complexity			0.200	2.00	3.00	4.00	3.00	3.00
Chemical requirements			0.200	1.00	1.00	5.00	3.00	3.00
Sludge production			0.200	1.00	1.00	4.20	4.60	5.00
			1	2.00	2.68	3.84	3.72	3.80
Performance	1	0.200						
Removal of Giardia lamblia (log)			0.250	2.00	2.00	5.00	1.00	1.00
Removal of Cryptosporidium (log)			0.250	1.00	2.33	5.00	1.00	1.00
Removal of viruses (log)			0.250	2.60	2.60	5.00	1.00	1.00
Influent turbidity limit (NTU)			0.250	5.00	5.00	1.89	1.00	2.78
			1.000	2.65	2.98	4.22	1.00	1.44
Implementation	1	0.200						
System size (ft^2)			0.200	1.40	1.00	5.00	2.98	3.77
Opportunity for expansion			0.200	2.00	1.00	5.00	2.00	5.00
Availability			0.200	4.00	1.00	5.00	2.00	4.00
Community disturbance			0.200	2.00	2.00	4.00	4.00	4.00
Remote Monitoring Amenability			0.200	1.00	2.00	5.00	1.00	1.00
			1.000	2.08	1.40	4.80	2.40	3.55
	5		**Overall**	2.385	2.777	3.033	3.096	2.948
			Rank	***5***	***4***	***2***	***1***	***3***

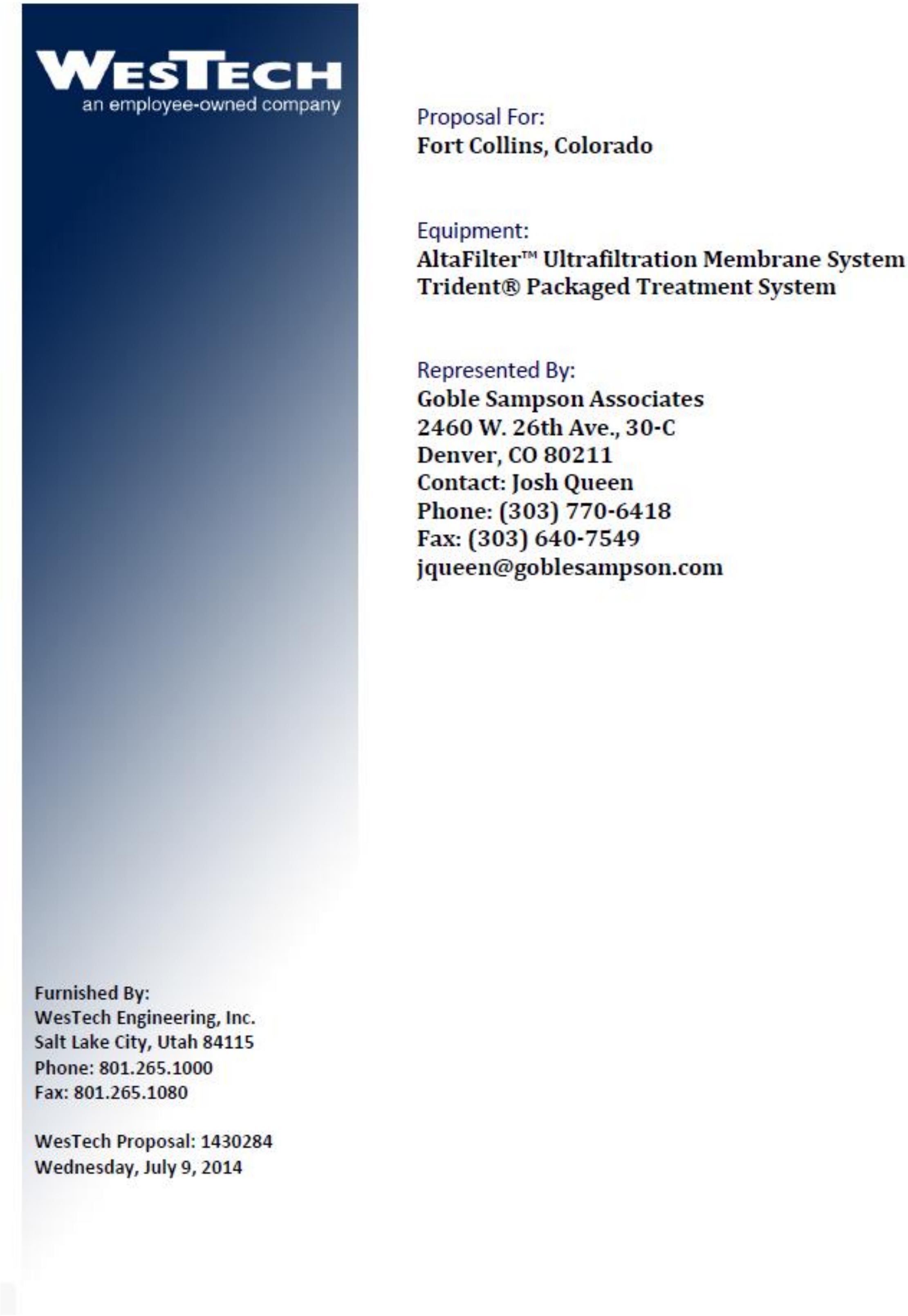
Promethee Scores

	Conventional	Automated Conventional	Ultrafiltration	Direct Filtration	Up-flow Adsorption Clarification	f+
A-1	0	0.20	0.20	0.20	0.40	0.25
A-2	0.80	0	0.40	0.40	0.40	0.50
A-3	0.80	0.60	0	0.60	0.60	0.65
A-4	0.80	0.60	0.40	0	0.40	0.55
A-5	0.60	0.60	0.40	0.60	0	0.55
f-	0.75	0.50	0.35	0.45	0.45	
f =f+ - f-	-0.50	0.00	0.30	0.10	0.10	
Ranking	**5**	**4**	**1**	**2**	**2**	

Assumptions

- Required system capacity: 1 MGD (694 gpm)
- 2014 ENR CCI: 9749.51

WesTech Proposal



WESTECH
an employee-owned company

Proposal For:
Fort Collins, Colorado

Equipment:
AltaFilter™ Ultrafiltration Membrane System
Trident® Packaged Treatment System

Represented By:
Goble Sampson Associates
2460 W. 26th Ave., 30-C
Denver, CO 80211
Contact: Josh Queen
Phone: (303) 770-6418
Fax: (303) 640-7549
jqueen@goblesampson.com

Furnished By:
WesTech Engineering, Inc.
Salt Lake City, Utah 84115
Phone: 801.265.1000
Fax: 801.265.1080

WesTech Proposal: 1430284
Wednesday, July 9, 2014

ITEM "A" - AltaFilter™ Ultrafiltration Membrane System

We are pleased to offer the following information on the WesTech AltaFilter™ Ultrafiltration Membrane System. To achieve 1.0 MGD treated production, WesTech recommends using two (2) AltaFilter™ skids each containing twenty (20) hollow fiber ultrafiltration modules. This 2 x 50% design allows for operating redundancy when one skid is offline during cleaning or maintenance.

The compact AltaFilter™ ultrafiltration (UF) skid is fully functional, easy to use, and simple to install. The system includes Toray™ hollow-fiber UF membrane modules, pumps, piping, valves, a clean-in-place system, instrumentation and controls required for a complete and functional system with reliable and simple operation. The Toray HFU-2020N ultrafiltration hollow fiber modules are certified for a minimum of 4-log removal for Cryptosporidium and Giardia through independent evaluation in the State of California. A small nominal pore size of 0.01 micron classifies the membrane as an ultrafilter.

The proposed AltaFilter™ ultrafiltration system has been designed to ensure reliable and simple operation and is completely automated, including start/stop operation, backwashing, and daily integrity checks. WesTech has designed the system using the concept of a skid mounted package to minimize field assembly. The skid assembly is completely tested in WesTech's shop prior to transportation to the job-site, ensuring that installation and commissioning activities are efficient.

GENERAL OPERATION

Influent water is pumped from the source into the feed tank. The influent water is then fed by the off-skid feed pumps to the inlet of the pre-filter and screened to remove any debris larger than 200 micron that could damage the hollow fiber membrane. The screened raw water flows through the ultrafiltration modules in an outside/in flow pattern to effectively remove particulates and pathogens from the water.

The feed pump speed is adjusted by the VFD to maintain the flow rate set point as particulates are removed by the membranes. Periodic backwashing, typically at 30 minute intervals, is used to remove accumulated matter from the membranes and flush the modules. An included backwash pump draws from the treated water storage tank. A semi-automatic chemical Clean-In-Place (CIP) is initiated when membrane permeability reaches a specified value. Fully-automated maintenance cleans are performed periodically to maintain the permeability of the membranes between more extensive CIP cleans. Sodium hypochlorite and citric acid are used for cleaning.

Pneumatically-actuated valves, using compressed air, are used as part of the automated system to execute the various operational states. Membrane integrity testing is conducted automatically at least once every 24 hours. The pressure decay test (PDT) was designed for modular installations and is capable of detecting a single fiber break.

PROCESS DESIGN

The system is designed utilizing the following water quality data, desired treated water quality, and membrane process design parameters.

UF Inlet Water Quality – Cache la Poudre River and Colorado-Big Thompson Project Surface Water*

Parameter	Value
Minimum Temperature	5º C
Turbidity	< 3 NTU average
Total Organic Carbon (TOC)	< 3 mg/l average
Iron (Fe)	<0.3 mg/L average
Manganese (Mn)	<0.05 mg/L average
pH	6.5 – 8.5
Total Suspended Solids	< 3 mg/l average

* Values are assumed and should be verified. Deviation from stated values may require modification of design.

Typical Ultrafiltration Effluent Water Quality

Parameter	Value
Turbidity	< 0.1 NTU 99% of the time
Silt Density Index	< 2
Giardia Percent Removal*	> 99.9999%
Cryptosporidium Percent Removal*	> 99.9999%
Virus Removal*	1.5 log removal

* The Toray HFS-2020 module has certification from the California Department of Public Health for 4-log removal of *Giardia* and *Cryptosporidium* through independent evaluation. Typical removal levels are often on the order of 6-log. Additionally, Toray HFU-2020N membranes achieve 1.5 log removals of viruses, though virus removal certification only recognized to 1.0 log by CDPH.

UF Design Summary: Two Trains in Operation

Parameter	**1.0 MGD (5°C)**	
Total Membrane Modules	40	
Banks	2	
Installed Modules per Bank	20	
Total Module Capacity per Bank	20	
Membrane Area per Module	775	ft^2
Membrane Area per System	31,000	ft^2
Design Temperature	5	°C
Flux at Design Temperature	37.28	gfd
Normalized Flux (20°C) at Design Temperature	56.77	gfd
Approx. Flow Rates		
Instantaneous	802.6	gal/min
Average Gross	726.6	gal/min
Average Net Permeate	694.4	gal/min
Instantaneous Backwash Rate	441.4	gal/min
Approx. Net Permeate Production per Day	999,997.4	MGD
Backwash Waste Volume per Day	19,447	gal/day
Influent Used for Rinsing/Draining per Day	26,827	gal/day
Water Recovery at Design Conditions	95.6	%
Estimated MC Frequency	1 – 7	per week
Estimated CIP Frequency*	> 30	Days

*CIP frequency is conservatively estimated at once every 30 days. Assuming that inlet water quality meets or exceeds the specified values, the CIP frequency may be as high as once every four months.

STANDARD FEATURES

The skid-mounted system shall be supplied shop assembled with all required piping, wiring, instruments and controls for a complete and operable system.

Each of the two (2) ultrafiltration skids will be supplied with the following components:

- One (1) powder coated, welded steel skid
- Twenty (20) Toray HFU-2020N ultrafiltration modules with 0.01 micron pore size
- One (1) feed / backwash magnetic flow meter w/ transmitter (Siemens 5100)
- Pneumatically-actuated and manual valves (Bray)
- One (1) Hach 1720E permeate turbidimeter with sc200 controller
- Schedule 80 PVC piping
- Local electrical I/O Junction Box which communicates with the main PLC via Ethernet

One (1) *clean-in-place (CIP)* system will be supplied with the following components:

- One (1) powder coated, welded steel skid
- One (1) HDPE CIP tank / neutralization tank w/ lid
- Two (2) chemical metering pumps for NaOCl and citric acid (Prominent)
- One (1) CIP pump w/ premium efficiency motor (MDM or equal)
- One (1) pH sensor (GF Signet)
- One (1) temperature sensor (Dwyer)
- One (1) heater (Chromalox)

The following will be *supplied and shipped loose* with the filtration skids:

- Two (2) feed pumps w/ premium efficiency motor (Goulds or equal)
- One (1) backwash supply pump w/ premium efficiency motor (Goulds or equal)
- Two (2) 200 micron, automatic backwashing pre-strainer (VAF or equal)
- One (1) compressed air system consisting of air compressor, receiver, filter and dryer (Atlas Copco)
- One (1) UL 508 listed, NEMA 4 electrical control panel wired to receive three phase 480 volt (40 amps) power and including the following:
    i. PLC – Allen Bradley
    ii. Door mounted, 10" color touchscreen
    iii. Feed and Backwash pump VFDs – Square D Altivar
    iv. Contactors – ABB
    v. Solenoid valve block
    vi. Ethernet switch

ON-SITE TECHNICAL ASSISTANCE AND TRAINING

Not included. WesTech recommends field service during construction, pre-commissioning and start-up to ensure the equipment is installed and commissioned per WesTech and sub-suppliers requirements.

ADDITIONAL INFORMATION

- **Advantages:** There are several advantages of WesTech's ultrafiltration membrane system.
    - Membrane filtration uses an absolute barrier for consistent production of high quality permeate. In contrast, media filtration is a depth filtration process. This means, for example, that a spike in the inlet turbidity to a media filter will lead to higher turbidity in the filtered product. UF will produce consistent treated water quality in spite of fluctuations in raw water quality. Guaranteed water quality is the primary advantage for UF.
    - Compared to media filtration, UF is able to achieve greater log-removal credits for *Cryptosporidium oocysts* and *Giardia*. UF is also preferred as pretreatment to reverse osmosis systems. Media filtration can be more cost effective, depending on the application.
    - UF will consistently remove turbidity and suspended solids without coagulant addition, possibly saving operating costs associated with chemical consumption.

  - Because the system is skid-mounted and undergoes factory testing, installation activities are extremely efficient for the UF equipment, reducing overall construction costs.
- **Operating Costs:**
  - **Electrical:** Annual electrical consumption for the UF equipment is approximately 173,000 kw-hr/year. At the U.S. average electricity cost of $0.08/kw-hr, costs would be approximately $13,900 / year.
  - **Chemical:** Annual chemical consmpution for citric acid and sodium hypochlorite associated with membrane cleaning is approximately $7,800 / year.
- **Waste Disposal:** The UF system is >95% efficient, meaning 5% of the total treated influent is sent to waste. Waste is frequently sent to a standard wastewater system or evaporative ponds. Chemical waste from the cleaning cycles can be neutralized and disposed of in the same manner.
- **Operations:** WesTech has several plants where 1 – 2 operators operate the systems. Operators are required to maintain reports sent to state regulator agencies and perform routine monitoring and maintenance on the equipment.

NOTE: ANY ITEM NOT LISTED ABOVE TO BE FURNISHED BY OTHERS.

ITEMS NOT BY WESTECH: Electrical wiring, conduit or electrical equipment, piping, valves, or fittings, lubricating oil or grease, shop or field painting, field welding, erection, detail shop fabrication drawings, performance testing, unloading, storage, concrete work, field service, (except as specifically noted).

These proposal sections have been reviewed for accuracy and approved for issue:
By: Lindsay Housley Date: July 9, 2014

ITEM: "B" - Trident® Packaged Treatment System

We are proposing a Trident Packaged Treatment System for this project. This system is designed as follows:

Design Flow Rate to System:	700 gpm (1.0 MGD)
Trident Model:	TR-210A
Design Flow Rate per Tank:	350 gpm
Number of Tanks per System:	2
Tank Length:	14 ft.-6 in.
Tank Width:	8 ft.-11 in.
Tank Height:	8 ft.-5 in.
AC Loading at design flow:	10 gpm/ft2
Filter Loading at design flow:	5.0 gpm/ft2
Material of Construction:	Carbon Steel
Turbidity:	NTU
Color:	Cu
Other:	ppm

Technical Description:

The Trident Packaged Treatment System combines a unique upflow Adsorption Clarifier® System with a downflow mixed media filter bed for high rate water treatment. The Adsorption Clarifier system includes a buoyant media for increased capture of contaminants with ease of flushing from the system. The mixed media filter combines different sized filter materials to capture decreasing sized particles through the depth of the filter bed. This package design provides reduced footprint and lower capital costs from conventional systems. The Trident system is capable of removing turbidity, suspended solids, color, iron, manganese, odor, taste and parasites such as Giardia lamblia and Cryptosporidium. The Aquaritrol® III automatic process controller automatically adjusts chemical feed rates to changing water quality to dose the proper amount of chemicals. All materials in contact with potable water are NSF 61 approved. The system is modular for easy expansion for future needs.

Key Features and Benefits

- Reduces capital costs and footprints by using high rate, packaged treatment
- Simplifies operator interface with automatic control
- Removes the bulk of contaminants in the adsorption clarifier to increase filter run time
- Optimizes chemical dosing by the Aquaritrol III automatic process controller
- Eases future expansion with modular design

The following budget pricing includes:

Painted steel tanks with all necessary tank internals including, Adsorption Clarifier buoyant media, MULTIBLOCK® underdrain with Laser Shield™ media retainer, and mixed media filter materials. Also includes inlet flow control with adjustable setpoint, pneumatically operated butterfly valves, two chemical feed packages (normally alum and polyelectrolyte), the Aquaritrol® III automatic process control PLC program, effluent turbidimeter, two air blowers, and PLC control system, freight to the jobsite, and startup.

Trident Web Page

NOTE: ANY ITEM NOT LISTED ABOVE TO BE FURNISHED BY OTHERS.

ITEMS NOT BY WESTECH
Electrical wiring, conduit or electrical equipment, piping, valves, or fittings, lubricating oil or grease, shop or field painting, field welding, erection, detail shop fabrication drawings, performance testing, bonds, unloading, storage, concrete work, field service, (except as specifically noted).

This proposal section has been reviewed for accuracy and approved for issue:
By: Gerry Baker Date: July 9, 2014

BUDGET PRICING

ITEM	EQUIPMENT	PRICE (U.S.)
"A"	1.0 MGD AltaFilter™ Ultrafiltration Membrane System	$730,000
"B"	Trident Packaged Treatment System	$380,000

The above mentioned equipment was designed according to the information which we received. The dimensions may vary slightly depending on the plant's actual design parameters. Assumed values may have been used, therefore, all information shall be verified by the Engineer.

Unless otherwise indicated, prices listed are for equipment only. All optional items will be offered with the purchase of the scoped equipment only. No optional items will be sold separately.

Prices are for a period not to exceed 30 days from date of proposal.

Warranty: A written supplier's warranty will be provided for the equipment specified in this section. The warranty will be for a minimum period of (1) year from start-up or 18 months from time of equipment shipment, whichever comes first. Such warranty will cover all defects or failures of materials or workmanship which occurs as the result of normal operation and service except for normal wear parts (i.e. squeegees, skimmer wipers, etc.).

Terms: Terms for equipment are 15 percent payment of the purchase price with submittal drawings, 35 percent upon receipt of major material in shop, and 50 percent net 30 days from shipment. Retentions are not allowed.

Sales Tax: No sales taxes, use taxes, or duties have been included in our pricing.

Freight: Prices quoted are **F.O.B. shipping point** with freight allowed to a readily accessible location nearest to jobsite. All claims for damage or loss in shipment shall be initiated by purchaser.

Submittals: Submittals will be made approximately **6 to 8 weeks** after purchase order is received in our office.

Shipment: Estimated shipment time is **16 to 18 weeks** after approved submittal drawings are received in our office.

Field Service: Prices do not include field service unless noted in equipment description. Additional field service is available at $960.00 per day plus expenses.

Paint: If your equipment has paint included in the price, please take note of the following. Primer paints are designed to provide only a minimal protection from the time of application (usually for a period not to exceed 30 days). Therefore, it is imperative that the finish coat be applied within 30 days of shipment on all shop primed surfaces. Without the protection of the final coatings, primer degradation may occur after this period, which in turn may require renewed surface preparation and coating. If it is impractical or impossible to coat primed surfaces within the suggested time frame, WesTech strongly recommends the supply of bare metal, with surface preparation and coating performed in the field. All field surface preparation, field paint, touch-up and repair to shop painted surfaces are not by WesTech.

APPENDIX B: POINT-OF-ENTRY TREATMENT SYSTEM SELECTION

MCDA Basic Data

			A-1	**A-2**	**A-3**	**A-4**	**A-5**
Criteria	**Sub-Criteria**	**Max/Min**	**Reverse Osmosis**	**Activated Carbon/KDF**	**Ultrafiltration**	**Reverse Osmosis with Activated Carbon**	**Activated Carbon with Ion Exchange**
Cost							
	Capital cost	Min	$ 5,000.00	$ 1,299.00	$ 2,700.00	$ 6,800.00	$ 2,500.00
	Operations cost	Min	$ 240.00	$ 120.00	$ 240.00	$ 280.00	$ 150.00
Energy Use							
	Process energy use (kWh/MG)	Min	2015	364	1000	2378	1164
	Min pressure requirement (psi)	Min	35	20	30	35	25
	Recovery efficiency	Max	45%	99%	85%	73%	90%
Maintenance Requirements							
	Operational complexity	Min	High	Low	Med	Very High	Low
	Component replacement frequency	Min	2.5	2.14	2.20	2.83	2.43
	Waste produced	Min	Very High	Low	Med	Very High	Low
Performance							
	Virus removal	Max	Very Good	Poor	Good	Very Good	Poor
	Influent turbidity limit (NTU)	Max	1	20	15	10	20
	Organic contaminant removal	Max	Good	Very Good	Fair	Very Good	Very Good
	Inorganic contaminant removal	Max	Very Good	Fair	Good	Very Good	Good
Implementation							
	System size (cu. ft.)	Min	38.0	12.5	6.4	44.2	16.5
	Availability (NSF Certified Systems)	Max	5	5	3	3	5

Word Scales

Word Scales (5=best)	
Word	Rating
Very Good	5
Good	4
Fair	3
Poor	2
Very Poor	1
Very Small	5
Small	4
Medium	3
Large	2
Very Large	1
Very Low	5
Low	4
Med	3
High	2
Very High	1

Input Data and Sources

Reverse Osmosis

	Value	Source
Capital cost	$ 5,000.00	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Operations cost	$ 240.00	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Total energy use (kWh/MG)	2015	Lazarova et. Al, 2012. *Water-energy Interactions in Water Reuse p. 188*
Operational complexity	High	USEPA, 2006. *Point-of-Use or Point-of-Entry Treatment Options for Small Drinking Water Systems*
Component replacement frequency	2.5	USEPA, 2007. *Cost evaluation of POU/POE treatment units for small systems: cost esimating tool and user guide. p. 14*
Waste stream produced	Very High	
Virus removal	Very Good	CDC, 2008. *Drinking Water Treatment Technologies for Household Use [Fact Sheet]*
Turbidity limit (NTU)	1	Paul et. Al, 1990. *Reverse Osmosis Membrane Fouling - The Final Frontier*
Organic contaminant removal	Good	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Inorganic contaminant removal	Very Good	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Recovery efficiency	45%	Manufacturer Data: CrystalQuest, Watts, OsmoTec, 2013.

System size (cu. ft.)	38	Watts/Alamo R12 1200 GPD unit
Availability	5	Manufacturer search, National Sanitary Foundation (NSF)
Min pressure requirement (psi)	35	Pure Water Freedom, 2014. http://purewaterfreedom.com/pwf/index.php/fluoride-filters/whole-house/500-gpd-whole-house-reverse-osmosis-system.html

Activated Carbon/KDF

	Value	Source
Capital cost	$ 1,299.00	Manufacturer Data: Pure Earth WH-EXL-CC
Operations cost	$ 120.00	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Total energy use (kWh/MG)	363.85	Chowdhury, 2013. *Activated Carbon: Solutions for Improving Water Quality p. 283*
Operational complexity	Low	Nowicki et al, 2012. *Monitoring activated carbon drinking water filters*
Component replacement frequency	2.14	Malley et al, 1993. *Point of Entry treatment for petroleum contaminated water supplies*
Waste stream produced	Low	
Virus removal	Poor	Dvorark & Skipton, 2013. *Drinking Water Treatment: Activated Carbon Filtration*
Turbidity limit (NTU)	20	KDF Fluid Treatment, Inc., 2003
Organic contaminant removal	Very Good	Premier Water Systems, 2013
Inorganic contaminant removal	Fair	Premier Water Systems, 2013
Recovery efficiency	99%	US Bureau of Reclamation, 2014. *Granular Activated Carbon (GAC)*
System size (cu. ft.)	12.5	Minnesota Department of Health, 2013
Availability	5	Manufacturer search, National Sanitary Foundation (NSF)
Min pressure requirement (psi)	20	Manufacturer Data: Pure Earth WH-EXL-CC

Ultrafiltration

	Value	Source
Capital cost	$ 2,700.00	Martin, 2010 and Manufacturer Data: Pentek
Operations cost	$ 240.00	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Total energy use (kWh/MG)	1000	Young, 2008. *American Water - Energy Management & Alternative Energy Use in the Water Sector*
Operational complexity	Med	USEPA, 2003. *Small drinking water systems handbook.*
Component replacement frequency	2.20	
Waste stream produced	Med	
Virus removal	Good	CDC, 2008. *Drinking Water Treatment Technologies for Household Use [Fact Sheet]*
Turbidity limit (NTU)	15	Gray et al, 2007. *Point of Entry/Use Treatment for Delivery of Potable Water*
Organic contaminant removal	Fair	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Inorganic contaminant removal	Good	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*

Recovery efficiency	85%	US Bureau of Reclamation, 2010. *Microfiltration (MF) and Ultrafiltration (UF)*
System size (cu. ft.)	6.4	Pentek FreshPoint U440 Ultrafiltration System
Availability	3	Manufacturer search, National Sanitary Foundation (NSF)
Min pressure requirement (psi)	30	General Electric, Homespring Water System

Reverse Osmosis with Activated Carbon

	Value	Source
Capital cost	$ 6,800.00	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Operations cost	$ 280.00	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Total energy use (kWh/MG)	2378.35	Add RO and GAC
Operational complexity	Very High	USEPA, 2006. *Point-of-Use or Point-of-Entry Treatment Options for Small Drinking Water Systems*
Component replacement frequency	2.83	USEPA, 2007. *Cost evaluation of POU/POE treatment units for small systems: cost esimating tool and user guide. p. 14*
Waste stream produced	Very High	
Virus removal	Very Good	CDC, 2008. *Drinking Water Treatment Technologies for Household Use [Fact Sheet]*
Turbidity limit (NTU)	10	KDF Fluid Treatment, Inc., 2003
Organic contaminant removal	Very Good	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Inorganic contaminant removal	Very Good	USEPA, 2006. *Investigation of POU/POE Treatment Devices as a Means of Security*
Recovery efficiency	73%	Heijman et al, 2007. *Zero liquid discharge: Heading for 99% recovery in nanofiltration and reverse osmosis*
System size (cu. ft.)	44.2	Manufacturer Data: Watts & US Water RO + GAC single tank w/ 300 gal storage (35" dia, 81" height)
Availability	3	Manufacturer search, National Sanitary Foundation (NSF)
Min pressure requirement (psi)	35	http://purewaterfreedom.com/pwf/index.php/fluoride-filters/whole-house/500-gpd-whole-house-reverse-osmosis-system.html

Activated Carbon with Ion Exchange

	Value	Source
Capital cost	$ 2,500.00	Manufacturer Data: Pelican Water Systems, Aquasana
Operations cost	$ 150.00	USEPA, 2006. Point-of-Use or Point-of-Entry System Design and Costs (POE Cation Exchange)
Total energy use (kWh/MG)	1163.85	Exergy Technologies Corp. - 0.8 to 1.6 kwh/1000 gal
Operational complexity	Low	Nowicki et al, 2012. *Monitoring activated carbon drinking water filters*
Component replacement frequency	2.43	Malley et al, 1993. *Point of Entry treatment for petroleum contaminated water supplies*
Waste stream produced	Low	

Virus removal	Poor	Dvorark & Skipton, 2013. *Drinking Water Treatment: Activated Carbon Filtration*
Turbidity limit (NTU)	20	
Organic contaminant removal	Very Good	
Inorganic contaminant removal	Good	
Recovery efficiency	90%	California Energy Commission, 2007. End-Use Efficient, Environmentally Friendly Water-Softening Device
System size (cu. ft.)	16.53	Aquasana, 2014. Rhino Whole House Filter System
Availability	5	Manufacturer search, National Sanitary Foundation (NSF)
Min pressure requirement (psi)	25	APEC Water, 2014. 25-100 psi required.

WAM Scores

Point-of-Entry Treatment System Selection

Resource Criteria	**Relative Importance**	**Normalized Weights**	**Attribute Normalized Weights**	**ALTERNATIVES**				
				1	**2**	**3**	**4**	**5**
Cost	1	0.200						
Capital cost			0.500	2.31	5.00	3.98	1.00	4.13
Operations cost			0.500	2.00	5.00	2.00	1.00	4.25
			1	2.15	5.00	2.99	1.00	4.19
Energy Use	1	0.200						
Process energy use (kWh/MG)			0.333	1.72	5.00	3.74	1.00	3.41
Min pressure requirement (psi)			0.333	1.00	5.00	2.33	1.00	3.67
Recovery efficiency			0.333	1.00	5.00	3.96	3.04	4.33
			1.000	1.24	5.00	3.34	1.68	3.80
Maintenance Requirements	1	0.200						
Operational complexity			0.333	2.00	4.00	3.00	1.00	4.00
Component replacement frequency			0.333	2.93	5.00	4.67	1.00	3.32
Waste produced			0.333	1.00	4.00	3.00	1.00	4.00
			1	1.98	4.33	3.56	1.00	3.77
Performance	1	0.200						
Virus removal			0.333	5.00	2.00	4.00	5.00	2.00
Influent turbidity limit (NTU)			0.333	1.00	5.00	3.95	2.89	5.00
Organic contaminant removal			0.333	4.00	5.00	3.00	5.00	5.00
Inorganic contaminant removal			0.000	5.00	3.00	4.00	5.00	4.00
			1.000	3.33	4.00	3.65	4.30	4.00
Implementation	1	0.200						
System size (cu. ft.)			0.500	1.66	4.36	5.00	1.00	3.93
Availability (NSF Certified Systems)			0.500	5.00	5.00	1.00	1.00	5.00
			1.000	3.33	4.68	3.00	1.00	4.47
	5		**Overall**	2.407	4.603	3.308	1.795	4.046
			Rank	**4**	**1**	**3**	**5**	**2**

Promethee Scores

	A-1	**A-2**	**A-3**	**A-4**	**A-5**	**f+**
A-1	0.00	0.00	0.20	0.60	0.00	0.20
A-2	1.00	0.00	1.00	0.80	0.80	0.90
A-3	0.80	0.00	0.00	0.80	0.00	0.40
A-4	0.40	0.20	0.20	0.00	0.20	0.25
A-5	1.00	0.00	1.00	0.80	0.00	0.70
f-	0.80	0.05	0.60	0.75	0.25	
f =f+ - f-	-0.60	0.85	-0.20	-0.50	0.45	
Ranking	**5**	**1**	**3**	**4**	**2**	

Neighborhood Demand and Connections

Connection Type	Number
Single	1,355
Duplex	12
Multi-Family	9
Commercial	211
Total	1,587

Source Water Quality Contaminants of Concern

- Upper Cache la Poudre River
    - Concerns: Dissolved Selenium, Copper, E. Coli
- Lower Cache la Poudre River
    - Concerns: Dissolved Selenium, Temperature, Copper, E. Coli
- Horsetooth Reservoir
    - Concerns: Total Coliform, E. Coli, Arsenic, Copper, Selenium

Data obtained from Fort Collins Utilities Horsetooth Water Quality Monitoring Reports (2009-2010), Lower CLP Water Quality Monitoring Reports (2008-2012), Upper CLP Water Quality Monitoring Reports (2008-2011)

Component Replacement Frequency

Component	Lifetime	Source
Reverse Osmosis		
Prefilter	6-12 months	PureTec (http://puretecwater.com/reverse-osmosis.html)
Membrane	2-5 years	PureTec (http://puretecwater.com/reverse-osmosis.html)
Activated Carbon/KDF		
Prefilter	6-12 months	Pelican Water Systems (http://www.pelicanwater.com/)
Media	3-5 years	Pelican Water Systems (http://www.pelicanwater.com/)
Ion Exchange (Salt-free)		
Media	10 years	Pelican Water Systems (http://www.pelicanwater.com/)
Ultrafiltration		
Prefilter	6-12 months	Jantzen (http://www.jantzen.com.my/products.html)
Membrane	5 years	Jantzen (http://www.jantzen.com.my/products.html)
KDF		
Media	7 years	Pure-Earth (http://www.pure-earth.com/PDF/kdf-2.pdf)

APPENDIX C: MCDA CRITERIA AND RESULTS

MCDA Basic Data

Economic Input

ECONOMIC PERFORMANCE METRIC INPUTS

			ALTERNATIVES				
			A-1	**A-2**	**A-3**	**A-4**	**A-5**
Criteria	**Performance Metrics**	**Max/ Min**	**Existing**	**Central & Dual**	**Neighborhood**	**Point-of-Entry**	**Separated Irrigation**
Impacts of New Infrastructure							
	Capital costs for new infrastructure	Min	$0.00	$15,791,135.00	$15,528,633.00	$10,374,388.00	$6,973,727.00
	Replacement Costs 70yr Lifetime (Existing = 50, Neighborhood= 50, POE = 20, Existing WDS = 70, PVC=70)	Min	$3,999,541	$3,598,983	$3,519,757	$12,308,238	$3,606,592
Energy Use							
	Total energy use in WT & Distribution	Min	70,685	57,933	121,412	78,504	92,712
	Return on renewable energy at WTF	Max	7.67%	9.36%	5.21%	8.06%	6.82%
	Revenue from selling carbon credits	Max	0	12,752	-50,727	-7,819	-22,028
Routine Maintenance							
	Chem, media, filters, repairs for water treatment	Min	$237,483.00	$146,908.00	$179,773.00	$716,961.00	$146,908.00
	Distribution system O&M	Min	$100,812.00	$173,356.00	$165,567.00	$100,812.00	$270,561.00
Staffing							
	FTE equivalent for WT & DS operations	Min	1.4	1.15	1.52	2.15	1.15
	Cost of workforce transitional training	Min	Lowest	Low	High	Highest	Low
Consumer Water Quality							

	Health care costs associated with exposure to DBPs (proportional to water age)	Min	8.8	6.4	4.5	0	18.5
	Costs associated with potential cross-connection failure	Min	Low Risk	Moderate Risk	Highest Risk	Lowest Risk	Moderate Risk
	Costs associated with a source water contamination event	Min	Lowest	Lowest	Medium	Highest	Lowest
Use of city water corridors							
	Avoided transaction costs (currently not used - requires more information regarding water rights)	Max	NA	NA	NA	NA	NA
Risk of limited supply							
	Cost of alternative water supplies.	Min	Highest	Lowest	Low	Highest	Highest
	Risk of obsolete infrastructure.	Min	Lowest Risk	Highest Risk	Highest Risk	Moderate Risk	High Risk
Risk of rate changes							
	Confidence in O&M projections.	Max	Very Good	Average	Average	Very Poor	Good
Opportunity for new water management strategies							
	Savings on later implementing alternative sources of supply	Max	0	126,759	112,844	24,180	126,759
Revenue opportunities							
	Sell treated water to neighboring communities	Max	687,084,097	781,170,838	907,285,714	907,285,714	781,170,838
Regulatory/Political Risk							
	Costs associated with changing alternative back to existing or to make changes needed to meet new regulations.	Min	Lowest Risk	Highest Risk	Highest Risk	Highest Risk	Low Risk
	The costs associated with increase in communication and managing public perception	Min	Lowest Risk	Moderate Risk	High Risk	Highest Risk	Low Risk

Social Input

SOCIAL PERFORMANCE METRIC INPUTS

			ALTERNATIVES				
			A-1	A-2	A-3	A-4	A-5
Criteria	Performance Metrics	Max/Min	Existing	Central & Dual	Neighborhood	Point-of-Entry	Separated Irrigation
Impacts of New Infrastructure							
	Disruption to community	Min	$0.00	$166,300.00	$166,300.00	$8,000.00	$158,300.00
	Temporary Employment	Max	0.0	1.0	1.0	0.7	0.4
Energy Use							
	Health impacts associated with air pollution	Min	70,685	57,933	121,412	78,504	92,712
Routine Maintenance							
	Disruption to community	Min	$67,500.00	$170,500.00	$170,500.00	$67,500.00	$136,400.00
Staffing							
	Employment and job security	Max	1.4	1.15	1.52	2.15	1.15
	Increased earning potential for a higher skilled workforce	Max	None	Some	More	Most	Some
Consumer Water Quality							
	Water age	Min	8.8	6.4	4.5	0	18.5
	Potential health risk from a cross-connection failure	Min	Low Risk	Moderate Risk	Highest Risk	Lowest Risk	Moderate Risk
	Potential health risk from a source water contamination event	Min	Very Good	Very Good	Average	Very Poor	Very Good
Use of city water corridors							
	Enhancement of water corridors	Max	None	None	None	None	Most
	Benefits to local ditch companies	Max	None	None	None	None	Most
Risk of limited supply							
	Resiliency of infrastructure to changes in supply	Max	Least Resilient	Most Resilient	Resilient	Least Resilient	Least Resilient
Risk of rate changes							
	Affordability of monthly water bill for low or fixed income households.	Max	$0.00	$18,030.71	($7,044.79)	($479,478.36)	($79,174.02)
Opportunity for new water management strategies							

	Being an innovative community and potential to increase ISFs for recreational uses	Max	0	126,759	112,844	24,180	126,759
Revenue opportunities							
	Improving water security of regional community and increasing jobs in Fort Collins	Max	687,084,097	781,170,838	907,285,714	907,285,714	781,170,838
Regulatory/Political Risk							
	Public acceptance of the alternatives	Max	Very Good	Good	Average	Very Poor	Good

Environmental Input

ENVIRONMENTAL PERFORMANCE METRIC INPUTS

Criteria	Performance Metrics	Max/Min	ALTERNATIVES				
			A-1	A-2	A-3	A-4	A-5
			Existing	Central & Dual	Neighborhood	Point-of-Entry	Separated Irrigation
Impacts of New Infrastructure							
	GHG emissions (proportional to capital costs)	Min	$0.00	$15,791,135.00	$15,528,633.00	$10,374,388.00	$6,973,727.00
	Temporary stormwater pollution	Min	0	286,569	242,276	8,937	224,743
Energy Use							
	GHG emissions in CO2e	Min	118,185	96,864	203,000	131,258	155,015
Routine Maintenance							
	GHG emissions in CO2e	Min	Lowest	Medium	High	Highest	Medium
	Chemical consumables for WT	Min	51.66	29.59	19.15	31.24	29.59
Staffing							
	Employee Transport GHG emissions CO2e	Min	1.4	1.15	1.52	2.15	1.15
Consumer Water Quality							
	Water quality of receiving water bodies	Max	No Change	Limited Benefit	Some Benefit	More Benefit	Most Benefit
Use of city water corridors							
	Benefits to species and natural systems	Max	None	None	None	None	Most
Risk of limited supply							
	Effects variable supply could have on the city's water corridors.	Max	Highest Risk	Moderate Risk	Moderate Risk	Moderate Risk	Lowest Risk
Risk of rate changes							
	Potential changes in irrigation water demand due to rate changes.	Min	$0.00	$18,030.71	($7,044.79)	($479,478.36)	($79,174.02)
Opportunity for new water management strategies							
	Potential benefit to species and natural systems by increasing ISFs by using alt. sources	Max	0	126,759	112,844	24,180	126,759
Revenue opportunities							

Regulatory/Political Risk	Decreasing need for new WTF construction in the regional community	Max	687,084,097	781,170,838	907,285,714	907,285,714	781,170,838
	Loss of environmental benefits	Min	Lowest Risk	Moderate Risk	Moderate Risk	Highest Risk	Moderate Risk

WAM Results

Equal Weighting

	Existing	Central & Dual	Neighborhood	Point-of-Entry	Separated Irrigation
Economic	3.70	3.62	3.02	2.38	3.45
Social	2.87	3.37	3.02	2.95	3.04
Environmental	2.49	2.92	2.74	2.85	3.75

Stakeholder Average

	Existing	Central & Dual	Neighborhood	Point-of-Entry	Separated Irrigation
Economic	3.70	3.72	3.02	2.47	3.46
Social	2.91	3.44	3.02	2.88	3.10
Environmental	2.43	2.88	2.69	2.87	3.77

Criteria Ratings

Criteria	Economic					Social					Environmental				
	Existing	**Central/ Dual**	**Neighborhood**	**POE**	**Separated Irrigation**	**Existing**	**Central/ Dual**	**Neighborhood**	**POE**	**Separated Irrigation**	**Existing**	**Central/ Dual**	**Neighborhood**	**POE**	**Separated Irrigation**
Impacts of new infrastructure	4.89	2.98	3.03	1.69	4.10	3.00	3.00	3.00	4.30	1.90	5.00	1.00	1.34	3.62	2.55
Energy use	3.92	5.00	1.00	3.72	2.72	4.20	5.00	1.00	3.70	2.81	4.20	5.00	1.00	3.70	2.81
Routine maintenance	4.68	4.15	4.12	3.00	3.00	5.00	1.00	1.00	5.00	2.32	3.00	3.36	3.50	2.26	3.36
Staffing	4.50	4.50	2.76	1.00	4.50	1.50	1.50	3.24	5.00	1.50	4.00	5.00	3.52	1.00	5.00
Consumer water quality	4.03	3.87	2.68	3.67	3.00	4.03	3.87	2.68	3.67	3.00	1.00	2.00	3.00	4.00	5.00
Use of city water corridors	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	5.00	1.00	1.00	1.00	1.00	5.00
Risk of limited supply	3.00	3.00	2.50	2.00	1.50	1.00	5.00	4.00	1.00	1.00	1.00	3.00	3.00	3.00	5.00
Risk of rate changes	5.00	3.00	3.00	1.00	4.00	4.86	5.00	4.80	1.00	4.22	1.14	1.00	1.20	5.00	1.78
Opportunity for new water management strategies	1.00	5.00	4.56	1.76	5.00	1.00	5.00	4.56	1.76	5.00	1.00	5.00	4.56	1.76	5.00
Revenue opportunities	1.00	2.71	5.00	5.00	2.71	1.00	2.71	5.00	5.00	2.71	1.00	2.71	5.00	5.00	2.71
Regulatory/Political risk	5.00	2.00	1.50	1.00	4.00	5.00	4.00	3.00	1.00	4.00	5.00	3.00	3.00	1.00	3.00
Overall	3.703	3.621	3.015	2.383	3.453	2.871	3.371	3.025	2.949	3.041	2.486	2.915	2.739	2.850	3.746
Rank	**1**	**2**	**4**	**5**	**3**	**5**	**1**	**3**	**4**	**2**	**5**	**2**	**4**	**3**	**1**

Economic Performance Ratings

ECONOMIC								
Resource Criteria	**Relative Importance**	**Normalized Weights**	**Attribute Normalized Weights**	**ALTERNATIVES**				
				1	**2**	**3**	**4**	**5**
Impacts of New Infrastructure	1.000	0.100						
Capital costs for new infrastructure			0.500	5.00	1.00	1.07	2.37	3.23
Replacement Costs 70yr Lifetime (Existing = 50, Neighborhood= 50, POE = 20, Existing WDS = 70, PVC=70)			0.500	4.78	4.96	5.00	1.00	4.96
			1.000	4.89	2.98	3.03	1.69	4.10
Energy Use	1.000	0.100						
Total energy use in WT & Distribution			0.333	4.20	5.00	1.00	3.70	2.81
Return on renewable energy at WTF			0.333	3.37	5.00	1.00	3.75	2.55
Revenue from selling carbon credits			0.333	4.20	5.00	1.00	3.70	2.81
			1.000	3.92	5.00	1.00	3.72	2.72
Routine Maintenance	1.000	0.100						
Chem, media, filters, repairs for water treatment			0.500	4.36	5.00	4.77	1.00	5.00
Distribution system O&M			0.500	5.00	3.29	3.47	5.00	1.00
			1.000	4.68	4.15	4.12	3.00	3.00
Staffing	1.000	0.100						
FTE equivalent for WT & DS operations			0.500	4.00	5.00	3.52	1.00	5.00
Cost of workforce transitional training			0.500	5.00	4.00	2.00	1.00	4.00
			1.000	4.50	4.50	2.76	1.00	4.50
Consumer Water Quality	1.000	0.100						
Health care costs associated with exposure to DBPs (proportional to water age)			0.333	3.10	3.62	4.03	5.00	1.00
Costs associated with potential cross-connection failure			0.333	4.00	3.00	1.00	5.00	3.00
Costs associated with a source water contamination event			0.333	5.00	5.00	3.00	1.00	5.00
			1.000	4.03	3.87	2.68	3.67	3.00
Use of city water corridors	1.000	0.000						
Avoided transaction costs (currently not used -			1.000	1.00	1.00	1.00	1.00	1.00

requires more information regarding water rights)								
			1.000	1.00	1.00	1.00	1.00	1.00
Risk of limited supply	1.000	0.100						
Cost of alternative water supplies.			0.500	1.00	5.00	4.00	1.00	1.00
Risk of obsolete infrastructure.			0.500	5.00	1.00	1.00	3.00	2.00
			1.000	3.00	3.00	2.50	2.00	1.50
Risk of rate changes	1.000	0.100						
Confidence in O&M projections.			1.000	5.00	3.00	3.00	1.00	4.00
			1.000	5.00	3.00	3.00	1.00	4.00
Opportunity for new water management strategies	1.000	0.100						
Savings on later implementing alternative sources of supply			1.000	1.00	5.00	4.56	1.76	5.00
			1.000	1.00	5.00	4.56	1.76	5.00
Revenue opportunities	1.000	0.100						
Sell treated water to neighboring communities			1.000	1.00	2.71	5.00	5.00	2.71
			1.000	1.00	2.71	5.00	5.00	2.71
Regulatory/Political Risk	1.000	0.100						
Costs associated with changing alternative back to existing or to make changes needed to meet new regulations.			0.500	5.00	1.00	1.00	1.00	4.00
The costs associated with increase in communication and managing public perception			0.500	5.00	3.00	2.00	1.00	4.00
			1.000	5.00	2.00	1.50	1.00	4.00
	11.000	1.000	**Overall**	3.703	3.621	3.015	2.383	3.453
			Rank	**1**	**2**	**4**	**5**	**3**

Social Performance Ratings

SOCIAL								
Resource Criteria	Relative Importance	Normalized Weights	Attribute Normalized Weights	ALTERNATIVES				
				1	2	3	4	5
Impacts of New Infrastructure	1.000	0.091						
Disruption to community			0.500	5.00	1.00	1.00	4.81	1.19
Temporary Employment			0.500	1.00	5.00	5.00	3.80	2.60
			1.000	3.00	3.00	3.00	4.30	1.90
Energy Use	1.000	0.091						
Health impacts associated with air pollution			1.000	4.20	5.00	1.00	3.70	2.81
			1.000	4.20	5.00	1.00	3.70	2.81
Routine Maintenance	1.000	0.091						
Disruption to community			1.000	5.00	1.00	1.00	5.00	2.32
			1.000	5.00	1.00	1.00	5.00	2.32
Staffing	1.000	0.091						
Employment and job security			0.500	2.00	1.00	2.48	5.00	1.00
Increased earning potential for a higher skilled workforce			0.500	1.00	2.00	4.00	5.00	2.00
			1.000	1.50	1.50	3.24	5.00	1.50
Consumer Water Quality	1.000	0.091						
Water age			0.333	3.10	3.62	4.03	5.00	1.00
Potential health risk from a cross-connection failure			0.333	4.00	3.00	1.00	5.00	3.00
Potential health risk from a source water contamination event			0.333	5.00	5.00	3.00	1.00	5.00
			1.000	4.03	3.87	2.68	3.67	3.00
Use of city water corridors	1.000	0.091						
Enhancement of water corridors			0.500	1.00	1.00	1.00	1.00	5.00
Benefits to local ditch companies			0.500	1.00	1.00	1.00	1.00	5.00
			1.000	1.00	1.00	1.00	1.00	5.00
Risk of limited supply	1.000	0.091						
Resiliency of infrastructure to changes in supply			1.000	1.00	5.00	4.00	1.00	1.00
			1.000	1.00	5.00	4.00	1.00	1.00
Risk of rate changes	1.000	0.091						

Affordability of monthly water bill for low or fixed income households.			1.000	4.86	5.00	4.80	1.00	4.22
			1.000	4.86	5.00	4.80	1.00	4.22
Opportunity for new water management strategies	1.000	0.091						
Being an innovative community and potential to increase ISFs for recreational uses			1.000	1.00	5.00	4.56	1.76	5.00
			1.000	1.00	5.00	4.56	1.76	5.00
Revenue opportunities	1.000	0.091						
Improving water security of regional community and increasing jobs in Fort Collins			1.000	1.00	2.71	5.00	5.00	2.71
			1.000	1.00	2.71	5.00	5.00	2.71
Regulatory/Political Risk	1.000	0.091						
Public acceptance of the alternatives			1.000	5.00	4.00	3.00	1.00	4.00
			1.000	5.00	4.00	3.00	1.00	4.00
	11.000	1.000	**Overall**	2.871	3.371	3.025	2.949	3.041
			Rank	**5**	**1**	**3**	**4**	**2**

Environmental Performance Ratings

ENVIRONMENTAL

Resource Criteria	Relative Importance	Normalized Weights	Attribute Normalized Weights	ALTERNATIVES				
				1	2	3	4	5
Impacts of New Infrastructure	1.000	0.091						
GHG emissions (proportional to capital costs)			0.500	5.00	1.00	1.07	2.37	3.23
Temporary stormwater pollution			0.500	5.00	1.00	1.62	4.88	1.86
			1.000	5.00	1.00	1.34	3.62	2.55
Energy Use	1.000	0.091						
GHG emissions in CO2e			1.000	4.20	5.00	1.00	3.70	2.81
			1.000	4.20	5.00	1.00	3.70	2.81
Routine Maintenance	1.000	0.091						
GHG emissions in CO2e			0.500	5.00	3.00	2.00	1.00	3.00
Chemical consumables for WT			0.500	1.00	3.72	5.00	3.51	3.72
			1.000	3.00	3.36	3.50	2.26	3.36
Staffing	1.000	0.091						
Employee Transport GHG emissions CO2e			1.000	4.00	5.00	3.52	1.00	5.00
			1.000	4.00	5.00	3.52	1.00	5.00
Consumer Water Quality	1.000	0.091						
Water quality of receiving water bodies			1.000	1.00	2.00	3.00	4.00	5.00
			1.000	1.00	2.00	3.00	4.00	5.00
Use of city water corridors	1.000	0.091						
Benefits to species and natural systems			1.000	1.00	1.00	1.00	1.00	5.00
			1.000	1.00	1.00	1.00	1.00	5.00
Risk of limited supply	1.000	0.091						
Effects variable supply could have on the city's water corridors.			1.000	1.00	3.00	3.00	3.00	5.00
			1.000	1.00	3.00	3.00	3.00	5.00
Risk of rate changes	1.000	0.091						

Potential changes in irrigation water demand due to rate changes.			1.000	1.14	1.00	1.20	5.00	1.78
			1.000	1.14	1.00	1.20	5.00	1.78
Opportunity for new water management strategies	1.000	0.091						
Potential benefit to species and natural systems by increasing ISFs by using alt. sources			1.000	1.00	5.00	4.56	1.76	5.00
			1.000	1.00	5.00	4.56	1.76	5.00
Revenue opportunities	1.000	0.091						
Decreasing need for new WTF construction in the regional community			1.000	1.00	2.71	5.00	5.00	2.71
			1.000	1.00	2.71	5.00	5.00	2.71
Regulatory/Political Risk	1.000	0.091						
Loss of environmental benefits			1.000	5.00	3.00	3.00	1.00	3.00
			1.000	5.00	3.00	3.00	1.00	3.00
	11.000	1.000	**Overall**	2.486	2.915	2.739	2.850	3.746
			Rank	**5**	**2**	**4**	**3**	**1**