DISSERTATION

A COLLABORATIVE PLANNING FRAMEWORK FOR INTEGRATED URBAN WATER MANAGEMENT WITH AN APPLICATION IN DUAL WATER SUPPLY: A CASE STUDY IN FORT COLLINS, COLORADO

Submitted by

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ABSTRACT

A COLLABORATIVE PLANNING FRAMEWORK FOR INTEGRATED URBAN WATER MANAGEMENT WITH AN APPLICATION IN DUAL WATER SUPPLY: A CASE STUDY IN FORT COLLINS, COLORADO

Urban water management is essential to our quality of life. As much of our urban water supply infrastructure reaches the end of its useful life, water managers are using the opportunity to explore alternative strategies that may enable them to better meet modern urban water challenges. Water managers must navigate the labyrinth of balancing stakeholder needs, considering all costs and benefits, reducing decision risk, and, most importantly, ensuring public health and protecting the environment. Innovative water managers need guidance and tools to help manage this complex decision space. This dissertation proposes a collaborative, risk-informed, triple bottom line, multi-criteria decision analysis (CRTM) planning framework for integrated urban water management decisions. The CRTM framework emerged from the obstacles and stakeholder needs encountered during a study evaluating alternative dual water supply strategies in Fort Collins, Colorado. The study evaluated four strategies for the dual supply of raw and treated water including centralized and decentralized water treatment, varying distribution system scales, and integration of existing irrigation ditches with raw water landscape irrigation systems. The results suggest that while the alternative dual water supply strategies offer many social and environmental benefits, the optimal strategies are dependent on local conditions and stakeholder priorities. The sensitivity analysis revealed the key parameters driving uncertainty in alternative performance were regulatory and political reinforcing the importance of participation from a wide variety of stakeholders. Evaluation of the decision process suggests the CRTM framework increased knowledge sharing between study participants. Stakeholder contributions enabled a comprehensive evaluation of the option space while examining the financial, social and environmental benefits and trade-offs of the alternatives. Most importantly, evolving the framework successfully maintained stakeholder participation throughout the study.

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DEDICATION

This is dedicated to my husband, Jason Cole, whose visions for the future and optimism in humankind's capacity to embrace change always inspire me to participate in creating solutions for our future.

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CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Urban water supply infrastructure in the United States is at a critical juncture. As much of the current infrastructure reaches the end of its useful life [1], water managers question whether maintaining a conventional water supply system is the best approach for the future. Infrastructure renewal offers an opportunity to explore alternative urban water management strategies that might better address the challenges of climate change, changing urban populations and development, and lack of funding and public support for capital improvements [1, 2, 3]. However, this is no easy feat as managers are often required to find solutions that satisfy many competing interests and goals. They must provide safe, reliable delivery of drinking water by financing replacement of aging infrastructure; implement full-cost pricing, while maintaining universal access to water through affordable rates; provide better quality drinking water, often from poorer quality source water, while reducing greenhouse gas emissions; meet future water demands of a growing urban population in over appropriated river basins, with limited storage, and an increasingly uncertain future water supply due to climate change; and support urban development without negatively effecting the environment or local industry dependent on shared water resources [1, 3, 4].

Historically, the urban water system has been managed by separate water supply, wastewater, and stormwater entities with little integration. Utilities are attempting to remove these departmental barriers, facilitate collaboration, and move toward an integrated urban water management strategy. Integrating water sectors and other urban sectors can create a more efficient, resilient, and adaptable urban water system [5, 6]. With limited new water resources, water managers are also focusing on alternative strategies to meet future demand of a growing population. These strategies include urban development focused on smart growth [7, 8, 9], demand side management [10, 11, 12, 13] and using alternative sources of supply that are local and more reliable, such as reclaimed water, graywater, seawater, rainwater, and stormwater [14, 15, 16, 17]. The alternative strategies considered by a utility depend on many local and regional factors, including the quality of available water sources, scarcity of supply, municipal end uses of water, water use governance and municipal water rights, and geographical features such as elevation, land use, climate, vegetation, and population.

Strategies focusing on more efficient use of water resources, especially local non-conventional sources, often incorporate the use of a dual distribution system. Dual distribution systems allow for the separate distribution of potable and non-potable water, enabling a fit-for-purpose approach to match water quality with the intended use, thus reserving higher quality source water for potable uses [18]. Dual distribution strategies can also reduce water or wastewater treatment, improve water quality of receiving water bodies, and create a more resilient infrastructure.

The dual distribution of reclaimed and potable water is now common in water scarce areas in the western United States, as well as areas in the southeastern United States subject to drought and limited storage capacity [14]. However, in areas where water use is governed by the Doctrine of Prior Appropriation, the volume of water utilities can recycle may be limited by water rights. For this reason, many utilities and new developments located near headwaters in the western United States have considered the dual distribution of raw water for irrigation and treated water for all other municipal uses. Landscape irrigation water demand in these areas can range up to 55 to 67% of total demand [19, 20].

Once a utility has decided to consider alternative approaches to urban water management, deciding on the best urban water management strategy for the future is a complex problem.

Identifying the most financially efficient solution is no longer the only concern. Consideration must also be given to the social and environmental impacts, balancing all the benefits and trade-offs of alternative solutions [5, 21]. More holistic approaches require expanding the circle of stakeholders in the decision making process and increased public engagement. Integrated Urban Water Management (IUWM) proposes using adaptive, iterative processes to align urban development and basin management by engaging local communities in solving problems through the efficient integration of water sources, water use sectors and water services at different scales [5]. This is challenging as these decisions often include a mix of incommensurable and intangible criteria, long planning horizons due to the long lifetimes of water infrastructure, performance uncertainty over the planning period, collaboration among a large group of diverse stakeholders often with competing objectives and attitudes toward risk, and a lack of public support [1, 22, 23, 24].

This research builds upon a two-year study conducted for the City of Fort Collins, Colorado comparing alternative centralized and decentralized strategies for the dual supply of raw and treated water with the existing conventional system [25]. In agreement with IUWM principles, the study attempted to balance the triple bottom line of financial, social, and environmental performance (TBL) and support a flexible transdisciplinary approach to decision making. Involving multidisciplinary experts and stakeholders in a complex decision process created a labyrinth of increasing problem complexity, competing stakeholder interests and decision risk. The results of the study favored the centralized alternatives, but neither of them were dominant as they each offered trade-offs. Stakeholder participation and collaboration across city departments was essential for success, but it led to a more complex decision problem. Uncertainty and sensitivity analyses were not conducted as part of the initial case study leading to several limitations including: a lack of confidence in decision results due to the decision analysis method; lack of confidence in long-term performance due to input uncertainty and variable stakeholder preferences; and a lack of visibility into the inputs driving uncertainty in alternative performance. An understanding of key parameters in the decision models is a critical component to improve the decision process and understand how this research might be applied to other locations.

Without a framework for navigating the labyrinth created from integrating TBL, competing stakeholder interests, and uncertainty, the team initially created a linear, technocratic decision model. Using the method, the team encountered several obstacles common to IUWM decision making including stakeholder requests for higher levels of participation and omitting performance indicators important to the community. Adapting the method in response to stakeholder concerns and addressing the limitations, opens the possibility of creating a formalized framework for evaluating IUWM alternatives.

1.2 Research Questions

The questions addressed in this research are:

1. Is the dual supply of raw and treated water an effective alternative to a traditional urban water supply system? What are the unique benefits and obstacles of centralized and decentralized dual water supply strategies?
2. How can the approach used in the case study be extended to improve stakeholder confidence in the long-term results of the dual water supply alternative strategies and provide transparency into inputs driving uncertainty in the performance of the alternatives to inform the next level of analysis?

3. How do the obstacles faced in the case study compare to the obstacles to IUWM implementation in the literature? Can the approach taken in the original case study and lessons learned be used to create a decision framework that addresses IUWM obstacles?

1.3 Research Objectives & Hypotheses

The case study was extended through the following objectives to address the research goals:

Objective 1: Assess if the financial, social, and environmental rankings of the dual supply alternatives are dependent on the MCDA technique used in the analysis.

> H1.1 The financial performance ranking of the alternatives will vary marginally, but the alternatives with the top financial performance will remain the same (Central/Dual, Conventional, Separated Irrigation) regardless of MCDA technique.
>
> H1.2 Central/Dual will remain the top ranked alternative in social performance regardless of MCDA technique.
>
> H1.3 Separated Irrigation will remain the top ranked alternative in environmental performance regardless of MCDA technique.

Objective 2: Examine the reliability of the models' predictions of the dual supply system alternatives' long-term financial, social, and environmental performance given the uncertainty in model inputs over time and variability in stakeholder preferences.

> H2.1 Central/Dual, followed by Separated Irrigation, will have the best and most reliable overall performance given input uncertainty and stakeholder preference variability.

Objective 3: Assess if there are any priority financial, social, and environmental performance inputs driving the uncertainty in the alternatives' performance and/or if models can be simplified.

H3.1 Uncertainty in financial, social, and environmental performance of the dual supply system alternatives will be driven by a small number of key inputs.

H3.2 The financial, social and environmental models will have non-influential inputs that can be set to a constant value to simplify the models.

Objective 4: Explore how the obstacles faced in the dual water supply study compare to obstacles to IUWM implementation found in the literature and assess how well the proposed framework worked to overcome those barriers.

H4.1 The proposed framework fosters interdepartmental collaboration allowing for a more holistic approach to the analysis.

H4.2 The stakeholder driven decision process provides a more comprehensive consideration of the alternatives′ financial, social, and environmental performance over the approach originally proposed in the case study.

Objectives 1, 2 and 3 use multiple MCDA methods, uncertainty analysis and sensitivity analysis to confirm the findings of the original case study and elucidate the benefits and trade-offs of the dual water supply strategies (Research Question 1). Objectives 2 and 3 use uncertainty and sensitivity analyses to improve stakeholder confidence in results and transparency into the inputs driving uncertainty in alternative financial, social, and environmental performance (Research Question 2). Objective 4 proposes a collaborative planning framework for IUWM decision making and shows how it helped overcome obstacles faced in the case study (Research Question 3).

1.4 Dissertation Structure & Benefits

This is a multipart dissertation where each part is considered separately. It is organized into three papers, which address the objectives identified above.

1. Centralized and decentralized strategies for dual water supply (Objective 1)
2. Confronting uncertainty in the evaluation of dual water supply strategies (Objectives 2 & 3)
3. Collaborative planning framework for integrated urban water management (Objective 4)

The first paper extends the current body of literature on dual water supply systems by evaluating benefits and trade-offs of centralized and decentralized water treatment approaches, varying distribution system scales, and integration of existing irrigation ditches with raw water landscape irrigation systems. It goes beyond technical performance metrics to include a comprehensive financial, social and environmental evaluation of the alternatives, including regulatory and political risks and opportunities, and criteria important to stakeholders. The second paper uses uncertainty and sensitivity analyses to elucidate the benefits and trade-offs of dual water supply systems and identify critical uncertainties that need to be addressed. Finally, the third paper proposes a collaborative planning framework that integrates different methods from the literature to address common obstacles encountered in IUWM and shows how it helped overcome the obstacles encountered in a case study evaluating dual water supply alternatives in Fort Collins, Colorado.

CHAPTER 2: CENTRALIZED AND DECENTRALIZED STRATEGIES FOR DUAL WATER SUPPLY [1]

2.1 Summary

Dual water systems are becoming an important urban water management strategy as more utilities adopt increasingly integrated approaches that enable matching source water quality to the intended use, more efficient use of resources, use of non-traditional local water sources, and more resilient systems. Four alternative strategies for the dual supply of raw water for non-potable municipal uses (e.g. landscape irrigation and fire supply) and treated water for potable uses were evaluated in this study. The alternative strategies included centralized and decentralized water treatment approaches, varying distribution system scales, and integration of existing irrigation ditches with raw water landscape irrigation systems. Multiple Criteria Decision Analysis (MCDA) was used to conduct a Triple Bottom Line (TBL) evaluation of the alternative strategies versus maintaining a conventional water supply system. This methodology allowed for the inclusion of incommensurable performance indicators and stakeholder preferences in the decision process, which was instrumental in garnering stakeholder support. The study found that the alternative strategies provide many social and environmental benefits versus a conventional system that may justify initial capital costs; a predominately gravity fed distribution system favored centralized water treatment alternatives to decentralized options; the use of existing irrigation canals for municipal use provides unique social and environmental benefits important to the community; and the optimum strategies are dependent on local conditions and community priorities.

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[1] This chapter is adapted from: Cole J, Sharvelle S, Fourness, D, Grigg, N, Roesner, L, & Haukaas, J. (2018). “Centralized and Decentralized Strategies for Dual Water Supply: Case Study”. J Water Resour Plann Manage 144(1):05017017-1-11

2.2 Introduction

The conventional approach to municipal water supply, where water for all end uses is treated to the same standard at a centralized facility and distributed via a single distribution system, may no longer be suitable for the future [2, 26]. Urban water managers must confront the challenges of changing urban populations, ensuring future water supply, protecting the environment, supporting local industry, and decreasing energy and water footprints [3, 4, 27] without compromising safety, reliability, affordability and regulatory compliance [27]. As the nation's water infrastructure reaches the end of its useful life [28], replacement offers utilities a unique opportunity to implement alternative strategies. Water managers from Fort Collins, Colorado recognized the planned renewal of their water supply infrastructure as an opportunity to re-evaluate their long-term urban water management strategy. Similar to many cities in the Western U.S., approximately 40 to 50% of Fort Collins' municipal demand is used for landscape irrigation and use of alternative water sources is limited by complex water rights [25, 29]. Using potable water to meet irrigation demand triples the required water treatment plant capacity, increasing energy use and process chemicals used for water treatment. In this forward-looking case study, the authors' used an innovative methodology to conduct a comprehensive triple bottom line evaluation of alternative strategies for the dual supply of raw and treated water for municipal use with consideration of centralized and decentralized systems.

Dual water systems date back to the Roman Empire, where lower quality water was used for marine circuses and landscape irrigation to save higher quality water for potable uses [18]. More recently, utility managed dual water supply systems in the U.S. have primarily focused on the distribution of potable and recycled water to conserve scarce potable supplies and find an alternative use for reclaimed water to reduce surface water pollution and avoid costs from increased regulations on wastewater discharges [14, 30, 31]. In areas where water rights limit the quantity of water utilities can recycle, utilities have considered dual distribution of raw water for landscape irrigation and treated water for all other municipal uses [32, 33]. Despite the potential for improving potable water quality by moving fire supply to non-potable distribution systems and using smaller diameter pipes to distribute potable water [18, 34, 35], there are no large scale implementations of this practice in the United States [14].

Considering alternative strategies for water supply creates opportunities to consider decentralized water supply (e.g. point-of-entry and neighborhood systems). Research on economies of scale of water supply systems [36, 37], centralized versus decentralized water reclamation facilities with the dual supply of recycled and treated water [38], and multiple scale urban water systems that consider several alternative water sources [39] provide insight into local circumstances that may make decentralized water treatment more favorable for dual water systems. Research efforts have evaluated a wide range of dual water system implementation scales [38, 40, 41, 42, 43], however the focus has been on non-potable facilities. To the best of the authors' knowledge there are no studies that consider decentralized water treatment with dual water supply systems.

The American Water Works Association, United States Environmental Protection Agency and American Society of Civil Engineers all promote the use of Triple Bottom Line (TBL) objectives (economic, social, and environmental) to promote future sustainable development. Due to the incommensurable and often competing criteria found in water management decisions, several approaches have been used to evaluate water management alternatives within the TBL framework. Chen and Wang [44] conducted a TBL cost benefit analysis of water reuse alternatives by monetizing social and environmental benefits. Liner and deMonsabert [45], Kang and Lansey

[35] and Newman et al. [39] all propose optimization approaches to multi-objective water infrastructure decisions to demonstrate the trade-offs between TBL objectives. While monetizing social and environmental benefits and multi-objective optimization techniques provide approaches for evaluating TBL objectives, they do not address stakeholder engagement. This is a motivation for the application of Multi-Criteria Decision Analysis (MCDA) in water resource decision problems as it provides a framework for integrating stakeholder preferences and incommensurable criteria into the decision process [46]. While MCDA problems can include financial, social, and environmental criteria, the end result is a ranking of alternatives based on an aggregate score. As new water management strategies are considered, tools are needed to assess TBL objectives quantitatively that facilitate stakeholder engagement.

The goal of this research was to evaluate the financial, social, and environmental benefits and trade-offs of alternative strategies for the dual supply of raw and treated water. The alternative strategies included centralized versus decentralized water treatment, varying scales of dual distribution, and the use of existing irrigation ditches throughout the service area. The research examines whether a dual water supply system better meets the city’s goals than the existing conventional system; assesses the benefits and trade-offs of decentralized water treatment systems compared to the conventional centralized water treatment facility; and explores the unique impacts of integrating city water corridors with seasonal raw water irrigation systems. An early stage, high level analysis of the strategies was conducted with collaboration among many participants and a large number of stakeholder-identified criteria, rendering MCDA appropriate. A novel methodology, integrating MCDA and TBL analysis, facilitated a comprehensive evaluation of the alternatives from each lens of sustainability (financial, social, and environmental). The approach promoted interdepartmental collaboration, stakeholder participation, and enabled a comparison of the alternatives' overall financial, social, and environmental performance using a combination of quantitative and qualitative performance indicators.

2.3 Approach / Methodology

The two-year study involved a project team, which included technical experts from the City of Fort Collins Utilities and Colorado State University, and a diverse group of city stakeholders to ensure alignment with city goals and community representation. The study used a hybrid TBL-MCDA approach to analyze alternative strategies to select the most promising for further evaluation. The evaluation required the collaboration of multiple stakeholders, which led to the inclusion of many incommensurable and intangible criteria. MCDA facilitated the decision analysis by providing a computational framework for analyzing alternatives while facilitating transparency and accountability [46]. The hybrid methodology used MCDA to generate a ranking of the alternatives for each bottom line.

The overall approach taken in this study involved five main steps (Figure 2.1). The most important phase of MCDA is structuring the problem and populating the decision matrix [22, 47]. Substantial time was spent with technical experts and stakeholders on steps 2 and 3 (Figure 2.1) to define a separate financial, social, and environmental decision matrix for three sample neighborhoods in the utility service area.

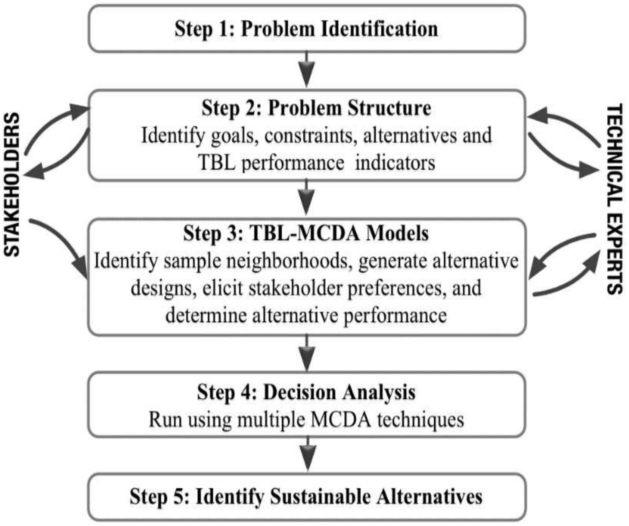

Figure 2.1: Overall Approach

Step 1: Problem Identification

Fort Collins' ongoing renewal of their aging water supply infrastructure provided an opportunity to evaluate alternative approaches to meeting the city's future water needs and sustainability goals. The city desires to more efficiently use existing and future water resources to continue to provide safe, affordable, reliable, high quality drinking water in the face of future population growth and urban development. The challenges of the future combined with complex water rights limiting use of recycled water and stormwater led to the utility's interest in the dual supply of raw and treated water to municipal customers.

Step 2: Problem Structure

A flexible and iterative approach integrated expert knowledge and fostered participation among the technical team and stakeholders to define the city goals, constraints, alternatives for consideration, and key criteria for the evaluation of alternatives. Given the diverse group of stakeholders involved, it was crucial to facilitate stakeholder engagement and provide transparency into the feasibility, impacts, and trade-offs associated with the alternatives and existing conventional system.

Stakeholders included the project team and members from city departments comprising the Nature in the City Group. This group conducts public outreach to preserve and enhance the quality of life in Fort Collins; reflect the priorities of the community; and achieve the sustainability goals of improving community access to nature, improving quality of natural spaces and land stewardship [48]. This group represented the diverse needs of the community for the purposes of this feasibility study. More extensive community involvement is recommended for future phases of the project but was not possible at this early stage.

Project Goals

The project goals were to improve drinking water quality and safety of supply; reduce energy use and greenhouse gas emissions; facilitate more effective use of the city's water resources; improve operational efficiency of urban water supply; enhance the city's water corridors and the natural habitats they support; improve community and neighborhood livability with more resilient water supply infrastructure able to accommodate future growth; and facilitate collaboration with neighboring water utilities and local agriculture in the future.

Project Constraints

The city's complex water rights, which limit the use of recycled water or stormwater, were the main driver in selecting dual supply of raw and treated water alternatives for consideration. Other challenges identified by the team included coordinating municipal and agriculture demand with environmental flows, future population growth with a corresponding increase in higher density mixed use development, availability of future supply, and the impact of changing water rates on future demand.

Alternatives considered

The study evaluated four alternatives for the dual supply of raw and treated water, along with the current conventional system, as defined below:

1. *Conventional* - currently Fort Collins is supplied by two main surface water sources that are blended and treated at a centralized conventional water treatment facility where finished water is then distributed to the end user via a predominately gravity fed potable water distribution system for all municipal uses.
2. *Central/Dual Alternative* - drinking water treatment continues at the central facility; the existing distribution system is used to distribute raw water for fire and irrigation demand; and

a new potable distribution system is used to distribute drinking water for indoor use. Both distribution systems remain gravity fed.

3. *Neighborhood Alternative* - raw water is conveyed to neighborhoods via the existing transmission mains; raw water for fire and irrigation demand continues to be distributed via the existing neighborhood distribution system; water for indoor demand is treated to drinking water standards at new satellite neighborhood water treatment facilities and then distributed via a new potable distribution system. The non-potable distribution system remains gravity-fed and the new neighborhood potable distribution systems require pumping.
4. *Point-of-Entry Alternative* - raw water is distributed through the existing gravity fed transmission and distribution mains to the service connection; at the service connection, raw water is diverted to the irrigation system and water for indoor use is treated to drinking water standards at a point-of-entry water treatment system, thereby removing the need for a dual distribution system.
5. *Separated Irrigation Alternative* – utilizes the existing network of irrigation ditches as an alternative to dual transmission mains; water for fire and indoor demand continues to be treated at the central water treatment facility and distributed to the end user via the existing distribution system; new neighborhood raw water irrigation systems will be installed to withdraw raw water directly from the network of irrigation ditches in the city. The potable distribution system remains gravity-fed and the new non-potable irrigation systems require pumping.

TBL Performance Indicators

The project team and stakeholders identified a set of main criteria and one to three financial, social, and environmental performance indicators, which defined how the alternatives performed on each criterion from each lens of sustainability. It was important to stakeholders to conduct a comprehensive TBL analysis of the alternatives. To accomplish this, a mix of quantitative and qualitative performance indicators were used in the analysis (Table 2.1; Appendix A, Tables A.1 through A.3). Quantitative performance indicators, such as capital and operations and maintenance (O&M) costs (Appendix A, Tables A.4 and A.7), were calculated using data from the utility, manufacturer specifications and literature (Table 2.1). Qualitative performance indicators used ordinal scales for qualitative assessment or indirect quantitative metrics, as designated in Table 2.1. These were deemed enough information for this feasibility level comparison of the alternatives. Additional details on performance indicators can be found in Cole et al. [25] or in Appendix A (Tables A.1 through A.8).

Table 2.1: Summary of the main criteria and TBL performance indicators used in the analysis (refer to [25] and Appendix A for additional information)

Main Criteria	Financial Indicator Summary	Social Indicator Summary	Environmental Indicator Summary
1. Impact of new infrastructure	1.1 Cost of new infrastructure (US $) - transmission & distribution mains, raw water filtration & meters, backflow prevention, water treatment facilities 1.2 Net replacement costs (US $) - 70-year lifetime in 2014 constant $ [real discount rate 3.375%[1], real escalation rate 0%][2]	1.1 Disruption from construction (US $)– AWWARF Asset Failure Cost Model to calculate access impairment, travel delay, customer outage, substitution[3] 1.2 Increase in temporary employment (US $)[4] [proportional to new infrastructure capital costs]	1.1 Greenhouse gas (GHG) emissions from transport of materials, equipment, and embodied energy associated with manufacturing. (US $)[4, 5] Assumption: capital costs provide an indirect comparison 1.2 Temporary stormwater pollution (ft^2)[4]- footprint of new construction
2. Energy use	2.1 Annual energy costs (kWh/yr)[4] – water treatment and distribution pumping (EPANET2)	2.1 Health impacts associated with air pollution due to GHG emissions from energy production – (kWh/yr)[4, 5]	2.1 Annual GHG emissions (CO_2e/yr) [Fort Collins' 2012 emission factor]
3. Routine maintenance	3.1 Annual operations & maintenance (O&M) costs (US $/yr) – chemicals, media, filters, and repairs/maintenance for water treatment and distribution systems	3.1 Disruption to community from maintenance (US $/yr) - AWWARF Asset Failure Cost Model used to calculate access impairment, travel delay, customer outage, substitution[3]	3.1 GHG emissions due to maintenance vehicles/equipment (Ordinal) [indicators - # of water treatment facilities & miles pipe] 3.2 Chemical consumables (Tons/yr) – chlorine, aluminum sulfate, calcium hydroxide, fluoride, & carbon dioxide
4. Staffing	4.1 Full time employees (FTE) needed for water treatment and distribution operations (FTE) 4.2 Training costs needed for new technologies (Ordinal)	4.1 Employment and job security – FTE/neighborhood normalized by max FTE/neighborhood [more FTE needed, the more employment & job security] 4.2 Increased earning potential (Ordinal) [increase in workforce skillset results in higher earning potential]	4.1 Employee transport GHG emissions (FTE)[4, 5] [proportional to FTE]
5. Consumer water quality	5.1 Disinfection byproducts (DBP) exposure health care costs (hr)[4] – [proportional to Social 5.1] 5.2 Cross-connection costs (Ordinal) – [separation between potable & non-potable systems, fire and irrigation services on potable system, max elevation difference in system affect risks] 5.3 Source water contamination event costs (Ordinal) Assumption: travel, supplies, and number of locations affect response	5.1 Drinking water quality (hr)[5] – EPANET2 used to conduct water age analysis [water age in distribution system indicator of water quality] 5.2 Potential health risk from cross-connection failure (Ordinal)[5] 5.3 Level of adaptability to health risks associated with source water contamination event (Ordinal) [travel time, supplies, and number of treatment locations]	5.1 Water quality receiving water bodies (Ordinal) – based on chlorine and coagulant addition
6. Environmental flows	NA – unable to determine without more detailed water rights analysis	6.1 Enhancement of natural areas and benefits to local ditch companies (Ordinal)[7]	6.1 Benefits to species and natural systems from increased in-stream flows (Ordinal)[6,7]
7. Supply risk	7.1 Costs of alternative supplies due to limited supply or disruption to supply (Ordinal) 7.2 Risk of obsolete infrastructure (Ordinal)	7.1 Resiliency of infrastructure to changes in supply due to limited supply or disruption to supply (Ordinal)[5]	7.1 Risk level for variable supply effects on city water corridors (Ordinal)
8. Rate risk	8.1 Confidence in O&M projection (Ordinal) [Rate changes dependent on O&M costs]	8.1 Affordability of monthly water bill for low or fixed income households ($/yr) [Rate changes depend on O&M costs]	8.1 Changes in irrigation water demand due to rate changes (US $)[4] [proportional to O&M changes; demand elasticity]
9. Alternative source opportunity	9.1 Savings to later using alternative non-potable sources (LF)[4] - based on scale of dual distribution system	9.1 Being an innovative community and potential to increase in-stream flows for recreational uses (LF)[4,5]	9.1 Improvements to water corridors from using alternative sources of non-potable water (LF)[4, 5]
10. Revenue opportunity	10.1 Wholesale water revenue (Gal/yr)[4]– revenue from using spare capacity to sell water to adjacent communities	10.1 Improve water security in neighboring communities and increasing jobs in Fort Collins (Gal/yr)[4, 5]	10.1 Environmental benefits from decreasing need for water treatment facility expansion and construction (Gal/yr)[4,5]
11.Regulatory/ Political risk	11.1 New regulation costs (Ordinal) – risk of costs for mitigating new regulations 11.2 Public relations costs (Ordinal) – costs associated with increase in communication	11.1 Public acceptance (Ordinal) [public perception based on level of deviation from current conventional system]	11.1 Negative environmental impacts from mitigation required for additional regulatory requirements for water quality monitoring and compliance (Ordinal)

[1][49]; [2]Assumptions in []; [3][50]; [4]Indirect quantitative metric used; [5] Uses same calculation as respective financial indicator; [6]Uses same calculation as respective social indicator; [7]Only applies to Separated Irrigation alternative.

Step 3: TBL-MCDA Models

Identification of Sample Neighborhoods

Rather than model all the alternatives for the entire service area, three sample neighborhoods representative of the utility service area were selected using geographic information system (GIS) land use data to model the impact of each alternative (Appendix A, Figure A.1). Fort Collins is dominated by low density development, but each neighborhood represents three different development eras, which affect land use type, homeowner association (HOA) presence, and distribution system characteristics (Appendix A, Table A.9). A separate TBL-MCDA model was conducted for each sample neighborhood to determine if the feasible alternative strategies differ by development type.

Design for Alternative Scenarios

Hypothetical systems representative of each alternative in each neighborhood were designed to estimate the alternatives' performance on the indicators. Topography in Fort Collins allows for a majority of the city's existing transmission and distribution systems to be gravity fed. The Central/Dual and Point-of-Entry alternatives still benefit from having gravity fed systems, but the Neighborhood and Separated Irrigation alternatives require pumping. Neighborhood requires pumping from the satellite treatment facilities to distribute potable water and Separated Irrigation requires pumping for the new raw water irrigation systems. EPANET 2, public domain software used for modeling water movement and quality within pressurized pipe networks [51], was used to model water age and estimate pumping energy requirements for non-gravity fed alternatives (Appendix A, Figure A.2 provides neighborhood network layouts and Tables A.10 & A.11 provide additional information on EPANET 2 models). Monthly demand data from 2001 to 2013 was used to estimate the average base and irrigation water demand for each service type for each land use type (Appendix A, Figure A.1). Utility data was used to create the neighborhood network layouts and provide the pipe diameters used in the existing system. All other information, such as node and water treatment facility distance from the neighborhood, does not necessarily represent the existing system. The systems were also modeled in isolation from the citywide network, and with the assumption that the dual distribution systems would run parallel to the existing distribution system for all alternatives. This was deemed sufficient for this high level analysis as the same network layout was used for all the alternatives.

Five water treatment technologies were considered for each decentralized alternative and a simple MCDA was used to evaluate these alternatives based on five equally weighted main criteria: cost, energy use, maintenance requirements, performance, and implementation (more detail in [25]). For the Neighborhood alternative, the five technologies considered included conventional, conventional with high-level process automation, ultrafiltration, direct filtration, and up-flow adsorption-clarification with dual-media filtration. All systems considered also included chlorine disinfection. The Ultrafiltration Membrane System was selected for the Neighborhood alternative due to its high performance on maintenance requirements, performance, and implementation (Appendix A, Figs. A.3 & A.4).

The technologies evaluated for the Point-of-Entry alternative included reverse osmosis, activated carbon / kinetic degradation fluxion (KDF) media, ultrafiltration, reverse osmosis with activated carbon, and activated carbon/KDF and ion exchange. The Activated Carbon/KDF package was selected for the Point-of-Entry alternative due to its low capital costs, simplistic operation, low energy requirements and smaller system size (Appendix A, Figs. A.5 & A.6). Ultraviolet (UV) light was selected for disinfection for the Point-of-Entry alternative due to its common use with point-of-entry treatment systems and its effectiveness against cryptosporidium and giardia lamblia.

Alternative TBL Performance

Performances of the alternatives for financial, social, and environmental performance indicators were estimated. A summary of the methodology used to calculate each performance indicator from Table 2.1 is included in [25].

Elicitation of Stakeholder Preferences

A 5-point scale was used to elicit stakeholder preferences on the importance of the main criteria to the financial, social, and environmental bottom lines, consistent with studies that have found 5 to 7 point scales with midpoints to have the best validity and reliability [52]. The relative importance factors were normalized and used to define a weight vector for each bottom line for each stakeholder.

Step 4: Decision Analysis

The team conducted the decision analysis using two MCDA techniques, the Weighted Sum Method (WSM) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) II. Recent studies comparing results of water resources decision problems using different techniques found little variation in the top ranked alternatives [22, 53]. However, Hajkowicz and Higgins [22] found a slightly larger risk of differences in alternative’s ranks with different techniques when a mix of quantitative and qualitative criteria were used. To mitigate this risk two alternative MCDA techniques were used to ensure the robustness of the results.

The WSM was used because its simplicity facilitates user acceptance and buy-in [47, 54, 55]. It is a simple value based method (Eqn. 2.1) where the total value of each alternative is equal to the sum of the products as shown below, with the highest score representing the best performance [24].

$$A^*_{WSM-Score} = max_i \sum_{j=1}^{n} a_{ij}\, w_j,\ \ for\ i = 1,2,3\ \ldots.,m \qquad (2.1)$$

Where: $A^*_{WSM-Score}$ is the score of the best alternative in a decision matrix with m alternatives and n criteria, a_{ij} is the value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.

The WSM is governed by the additive utility assumption [24]. Application is simple for criteria with the same units but does not hold with incommensurable criteria. The alternatives' performance data were converted to a common 1 to 5 scale (using linear interpolation or ordinal scales), where 1 represents the worst performance and 5 represents the best performance. One of the concerns with these transformations is the assumption that the normalized ratings have the same value for all the criteria, which might not be a true representation of alternative performance. Another concern is applying cardinal properties to ordinal data when a mix of qualitative and quantitative metrics are used in an analysis [24].

The decision analysis was also run using an outranking technique better suited for a mix of cardinal and ordinal data. The PROMETHEE II method provides a complete ranking of alternatives using a preference structure based on pairwise comparisons between all the alternatives for each criterion [56]. Brans and Mareschal's [56] simplest preference function ($P_j\left[d_j(i,i')\right]$) was used, due to the number of performance indicators and the difficulty in determining appropriate threshold values for each performance indicator (Eqn. 2.2):

$$P_j\left[d_j(i,i')\right] = \begin{cases} 0 \text{ when } d_j(i,i') \le 0 \\ 1 \text{ when } d_j(i,i') > 0 \end{cases} \qquad (2.2)$$

Where the difference in performance between alternatives i and i' on criterion j is defined as $d_j(i,i') = a_{ij} - a_{i'j}$.

An aggregated preference index is used to combine the preference function results with the criteria weights assigned by stakeholders and a positive (Eqn. 2.3) and negative (Eqn. 2.4) outranking flow ($\phi^+(i), \phi^-(i)$) for each alternative compared to (m-1) other alternatives is then calculated by:

$$\phi^+(i) = \frac{1}{m-1}\sum_{i'=1}^{m} \pi(i,i') \qquad (2.3)$$

$$\phi^-(i) = \frac{1}{m-1}\sum_{i'=1}^{m} \pi(i',i) \qquad (2.4)$$

Where: $\pi(i,i')=\sum_{j=1}^{n} P_j(i,i')w_j \text{ and } \pi(i',i)=\sum_{j=1}^{n} P_j(i',i)w_j$

The net outranking flow ($\phi(i)$) represents the overall score for each alternative and ranges between -1 and 1, where 1 represents the best performance (Eqn. 2.5):

$$\phi(i) = \phi^+(i) - \phi^-(i) \qquad (2.5)$$

For each sample neighborhood, a separate decision matrix for financial, social, and environmental performance was used to rank the alternatives from each TBL perspective for a total of 9 decision matrices. Each decision matrix was run using 18 different weight vectors, one assuming equal weighting of all criteria and the remaining representing the priorities of the 17 stakeholders. Finally, the decision matrices were run using both the WSM and PROMETHEE II methods for a total of 324 MCDA runs.

Step 5: Identify Sustainable Alternatives

No aggregate function was used to combine the financial, social, and environmental bottom lines, as it was the stakeholder's preference to show the TBL results separately. The results of the three bottom lines for each neighborhood were used to identify the top alternatives for further consideration and determine whether the different neighborhoods favored similar alternatives. Kendall's coefficient of concordance [57] was calculated for each bottom line, weight vector, and MCDA method to determine the level of agreement on the rank order of the five alternatives for the three neighborhoods.

2.4 Results

Despite neighborhood differences, Kendall's coefficient of concordance was greater than 0.8 for 95% of the neighborhood MCDA ranking results (critical values for 0.05 and 0.01 levels of significance are 0.716 and 0.840 respectively [57]). Due to the high level of agreement (Appendix A, Table A.12), and for the purposes of clarity, results for the first neighborhood are discussed as representative for the entire service area.

Financial Performance

As anticipated from other findings [14, 30], the conventional system performs well on a majority of the financial performance indicators (Figure 2.2, Table 2.2). However, Central/Dual's high overall financial performance was unexpected (Table 2.2: Overall Financial). While Central/Dual requires a high initial investment and more maintenance, it offers the greatest savings in water treatment costs by reducing the volume of water treated, eliminating peak potable demand in summer months, and allowing the city to save higher quality water resources for potable needs (Figure 2.2 & Table 2.2: Financial A. Costs). Central/Dual also increases opportunities to use alternative non-potable sources in the future (depending on water rights) (Figure 2.2: Financial

B.2) and creates an opportunity to generate revenue from the excess water treatment facility capacity to offset implementation costs (Figure 2.2: Financial B.1).

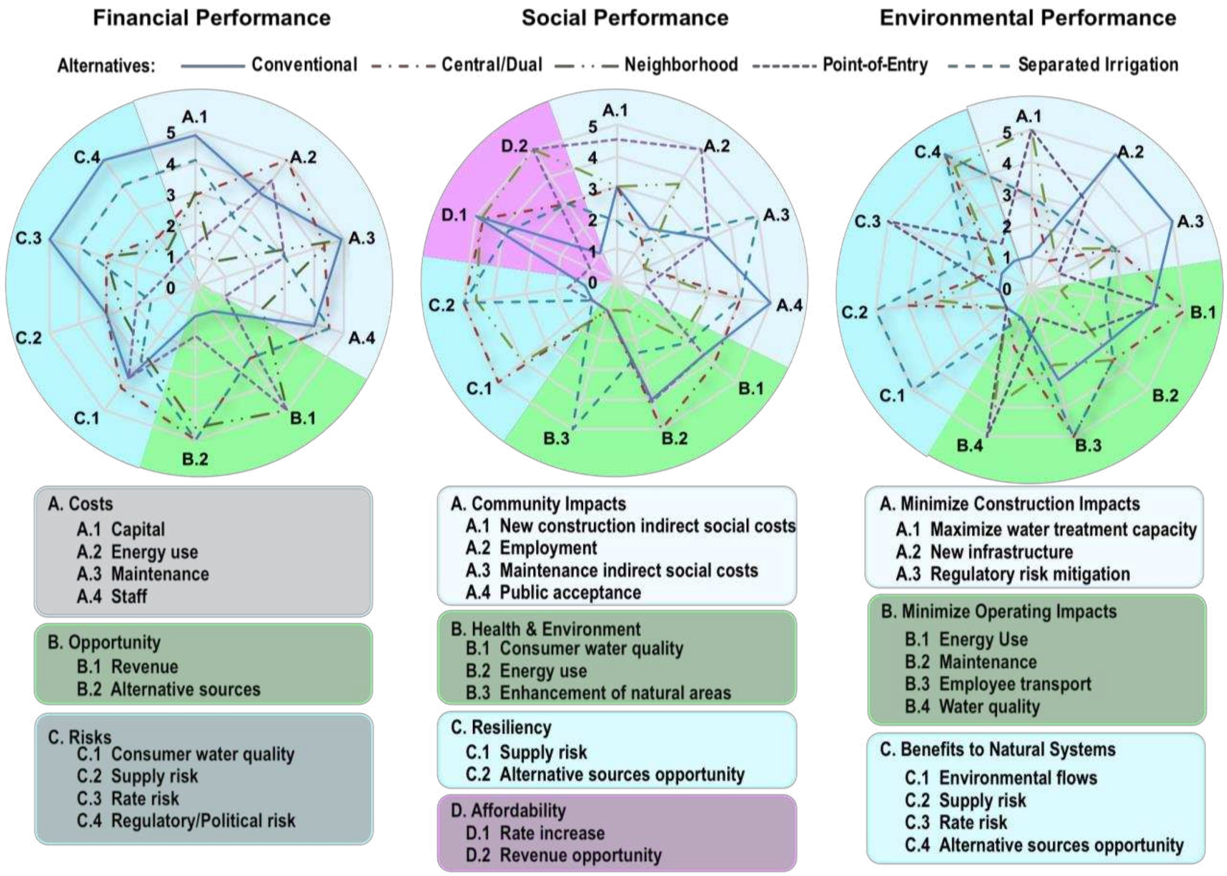

Figure 2.2: Alternatives' Performance on Financial, Social, and Environmental Performance Indicators

Table 2.2: Alternative average financial, social, and environmental ratings by category (equally weighted) Rating of 5 represents the best performance.

Alternatives	Conventional	Central/Dual	Neighborhood	Point-of-Entry	Separated Irrigation
			Financial Category		
A. Costs	4.4	4.2	2.7	2.4	3.5
B. Opportunity	1.0	4.0	4.8	3.3	4.0
C. Risks	4.2	3.0	2.4	1.9	3.1
Overall Financial Rating	3.6	3.7	3.0	2.4	3.4
			Social Category		
A. Community Impacts	3.3	2.4	2.7	3.4	3.1
B. Health & Environment	2.9	3.4	1.6	2.9	3.5
C. Resiliency	1.0	5.0	4.3	1.3	3.0
D. Affordability	3.0	3.8	4.9	3.0	3.4
Overall Social Rating	2.7	3.4	3.1	2.8	3.2
			Environmental Category		
A. Minimize Construction Impacts	3.7	2.3	3.1	3.1	2.8
B. Minimize Operating Impacts	2.8	3.9	2.8	3.1	3.0
C. Benefits to Natural Systems	1.0	2.8	2.4	2.2	4.3
Overall Environmental Rating	2.4	3.1	2.7	2.7	3.4

Centralized water treatment alternatives outperformed decentralized water treatment alternatives financially for several reasons (Figure 2.2 & Table 2.2). Local topography allows for a gravity fed potable distribution system from the existing centralized water treatment facility. The separate dual distribution system provided by Central/Dual and Separated Irrigation allows the city to use higher quality water sources for treatment [58]; conserve reservoir water through the use of surplus tributary water rights during the spring runoff season; and use of alternative non-potable water sources in the future (Figure 2.2: Financial B.2).

Social Performance

The social performance indicators suggest that in aggregate, dual supply alternatives offer more benefits to the community, with the centralized water treatment alternatives performing better overall (Figure 2.2; Table 2.2: Overall Social). Central/Dual provides the best consumer water quality and lowest energy use (Figure 2.2: Social B.1 & B.2). It also offers the most resiliency to disruptions in supply through more finished water storage, access to multiple sources of water, and conserving more reservoir water resources (Figure 2.2 & Table 2.2: Social C. Resiliency). By increasing flows in the urban water corridors, Separated Irrigation offers unique enhancements to the natural areas supported by these corridors, improving community aesthetics, access to nature, and recreation (Figure 2.2: Social B.3).

Consumer water quality was an important public health criterion and included three performance indicators (water age in potable distribution system, risk of potential cross-connections, and risk associated with a source water contamination event) (Figure 2.2: Social B.1). Central/Dual and Neighborhood improve potable water quality by reducing time in the potable distribution system by approximately 75%, similar to Digiano et al. [34] and Kang and Lansey [35]. Point-of-Entry had the best water age performance by eliminating the potable distribution system. Separated Irrigation was the only alternative that did not move fire supply to the non-potable system, resulting in potable demand reduction and increased residence time in the potable distribution system. Conventional performed well due to the inclusion of cross-connection and source water contamination risks in the consumer water quality criterion. For the purposes of this study, cross-connection and source water contamination risks were estimated using qualitative metrics and further analysis should attempt to quantify these risks and further refine mitigation strategies. However, further information is needed to characterize source water contamination events.

Environmental Performance

The dual supply alternatives all offer environmental benefits over the conventional system (Figure 2.2, Table 2.2). Central/Dual leads the alternatives in minimizing operating impacts to the environment (Figure 2.2 & Table 2.2: Environmental B. Minimize Operating Impacts). Separated Irrigation offers the most benefits to natural systems (Table 2.2: Environmental C. Benefits to Natural Systems), as it is the only alternative that increases environmental flows, which influences two of the criteria in this category (Figure 2.2: Environmental C.1 & C.2), setting it apart from the other alternatives.

Central/Dual is the only alternative that uses less energy than Conventional (Figure 2.2: Environmental B.1) by treating less water and using a gravity fed dual distribution system. The water treatment technologies used in the decentralized alternatives use more energy per unit of water treated. This did not result in a net increase in energy use, however, because they treat less water. The pumping required for the neighborhood potable distribution system from the satellite water treatment facilities in the Neighborhood alternative and the raw water pump station for the Separated Irrigation alternative resulted in 2 and 1.6 times the annual energy use for Central/Dual.

Stakeholder Preferences

Seventeen stakeholders rated the relative importance of the criteria from financial, social, and environmental perspectives (Figure 2.3). The stakeholders rated capital costs of new infrastructure, annual energy costs, and operations and maintenance costs, followed by financial risks associated with a compromise to consumer water quality as the most important financial criteria. From a social perspective, stakeholders' most important criteria were consumer water quality followed by environmental flows. The top two environmental criteria ranked by stakeholders were environmental flows and consumer water quality. The next most important environmental criteria were greenhouse gas emissions from energy use and the ability to use dual distribution systems for alternative non-potable sources in the future. Note that environmental flows, which only apply to the Separated Irrigation alternative, were a top priority for stakeholders from both the social and environmental perspective, as the community values the riparian ecosystem for its natural, aesthetic and recreational benefits.

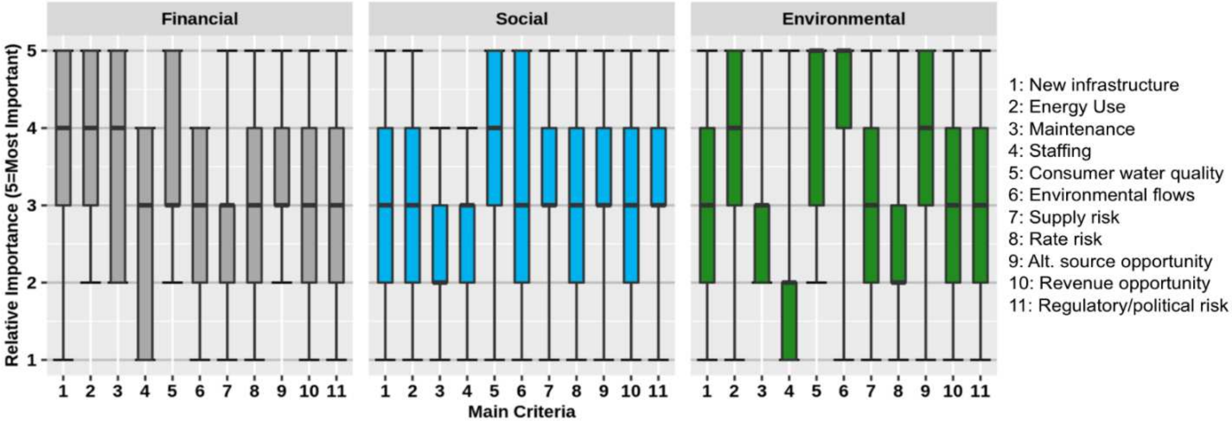

Figure 2.3: Box Plots of Stakeholder Relative Importance Results (n=17). Box plots provide the minimum, 25th percentile, median, 75th percentile, and maximum relative importance ratings assigned by stakeholders

MCDA Results

Both WSM and PROMETHEE II MCDA methods preferred the same top alternative(s) from the financial, social, and environmental perspectives (Figure 2.4). The social bottom line results show the greatest difference in the performance of the lower ranked alternatives. This is not unexpected, as previous studies show that while multiple techniques yield the same top alternative, several found the lower ranked alternatives varied by method [22, 53].

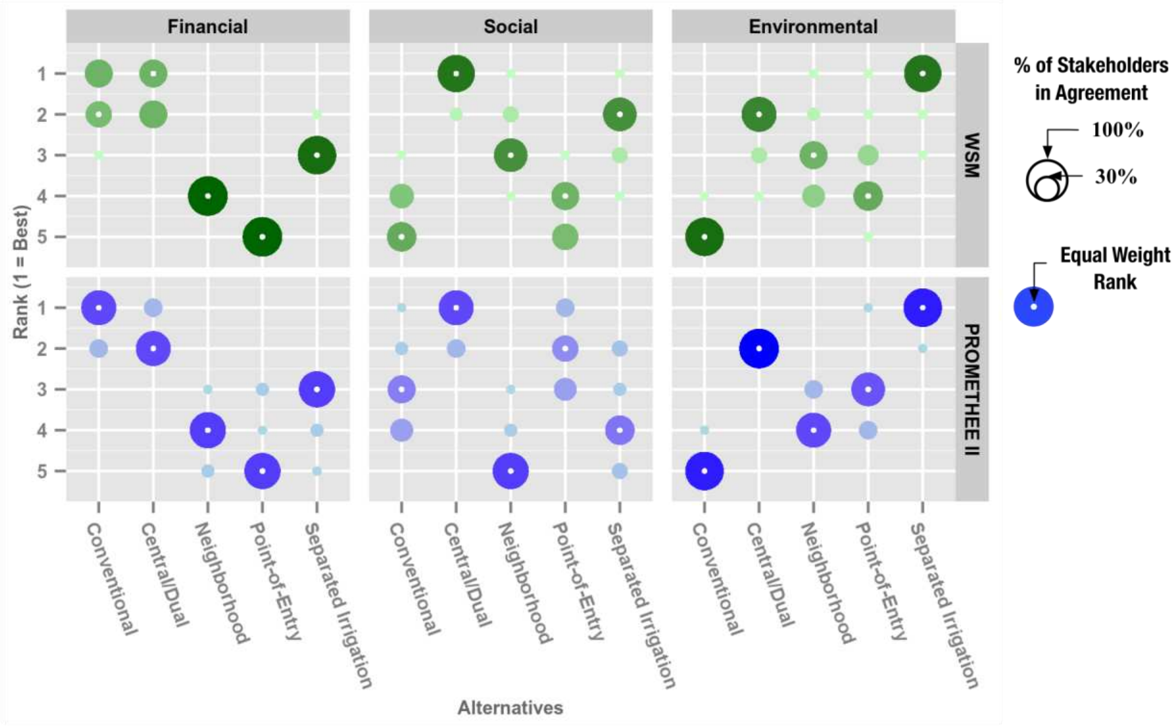

Figure 2.4: WSM & PROMETHEE II MCDA Stakeholder Ranking Results for Neighborhood 1 (n=17). Size of bubble is indicative of stakeholder agreement (see legend)

The financial results for both methods show that most stakeholders agree Conventional and Central/Dual are the top two ranked alternatives, followed by Separated Irrigation and the decentralized alternatives. However, there is disagreement between the methods and less agreement among stakeholders on whether Conventional or Central/Dual is the top ranked alternative from a financial perspective, which is unsurprising given their close overall financial performance (Table 2.2: Overall Financial).

Stakeholders agreed Central/Dual was the highest ranked alternative from the social bottom line using both MCDA methods. It performed well on eight of the eleven social criteria and it had the best performance in consumer water quality, which was the top social priority for stakeholders. However, there was little consensus among stakeholders and methods on the ranking of the remaining alternatives. The discrepancies between the two methods in the social bottom line (Figure 2.4) are a result of the way the overall score is calculated. In the WSM, the common scale used has a direct effect on the overall score, whereas PROMETHEE II is only concerned with whether an alternative has a better performance, not with the degree of that performance.

Both methods, and majority of stakeholders, agree that Separated Irrigation has the top environmental performance followed by Central/Dual, and that Conventional has the lowest environmental performance. In both the social and environmental bottom lines, the criterion associated with environmental flows only applies to the Separated Irrigation alternative. This could explain why Separated Irrigation has the best environmental performance and contributes to the discrepancy between the WSM and PROMETHEE II social results. Separated Irrigation's increased environmental flows also play a role in its performance on the environmental effects of the limited supply indicator within the environmental bottom line (Figure 2.2: Environmental C.2).

Overall, the alternatives with centralized water treatment performed the best with lower performance and stakeholder consensus on the performance of the decentralized alternatives reflecting the number of social and environmental trade-offs associated with these alternatives.

2.5 Discussion

The results are dependent on local conditions and community priorities. Fort Collins Utilities benefits from high elevation changes that allow for gravity fed transmission to the existing water treatment facility, a predominately gravity fed treatment process and a gravity fed distribution system to the end user. The service area has very good source water quality, and multiple surface water sources with different seasonal variations in water quality. Growth restrictions and spare infrastructure capacity in the service area eliminates the need for additional infrastructure to meet future growth. These factors led to a financial preference for the centralized water treatment alternatives (Conventional, Central/Dual, Separated Irrigation). Additionally, stakeholder priorities and the high value they placed on the ecosystems surrounding the urban water corridors influenced the criteria weights used in the MCDA, the alternatives considered, and the criteria used to compare alternative performance. The importance of urban water corridors led to the addition of the Separated Irrigation alternative and the environmental flows criterion in the social and environmental bottom lines.

The financial performance, and the potential for net economies of scale in water supply systems, depends on the number of connections, water treatment technology, the distances and elevation changes in the service area, and the existing capacity of water supply infrastructure to meet future demands [36, 37, 38, 59]. The ideal strategy optimizes the trade-offs between economies of scale found in water treatment and the diseconomies of scale found in distribution [37, 38, 59]. Given that two thirds of water supply costs are related to the distribution system and more advanced treatment processes do not have the economies of scale found in conventional treatment, net economies of scale in water supply can be difficult to achieve [36, 60]. Areas without Fort Collins' advantages may find decentralized alternatives more financially viable. However, decentralized alternatives need to address water quality monitoring and drinking water regulatory barriers, including disinfection residual requirements and the requirement for public water systems to maintain oversight for all responsibilities.

The top social priority for stakeholders was consumer water quality. Early proponents of dual water systems focused on the potential for improving potable water quality by conserving better quality sources for potable demand and moving fire supply to the non-potable distribution system [18, 61]. These considerations both favored the Central/Dual alternative in this study. Separated Irrigation offered the unique benefit of improving the natural areas supported by the urban water corridors. However, the use of irrigation canals in Fort Collins is restricted to seasonal use due to the cold winter climate, which prevented the use of the raw water system for fire supply and realizing benefits to potable water quality. This would not be a limiting factor in warmer climates where these systems could operate year round, making them even more attractive.

Energy use has become an important focus for water utilities [62, 63] as cities look to decrease their carbon footprint. Local conditions, like source water quality and elevation changes, and water treatment technology have a large impact on water supply energy use. The average energy use for water supply utilities ranges between 0.08 kWh/m^3 to 0.62 kWh/m^3 (average of top & bottom 10 utilities found in [63]). Fort Collins' water supply energy use ranged between 0.06 to 0.19 kWh/m^3 from 2004 to 2012 because of their predominately gravity fed treatment and distribution combined with high quality source water. Central/Dual was the only alternative that had lower energy use than the existing conventional system by treating less water. The other alternatives all treated less water, but more energy intensive water treatment technologies and additional pumping requirements increased energy demand. However, areas that require more energy intensive water treatment and pumping to distribute water will likely see more energy benefits in the decentralized alternatives than Fort Collins.

This was a high level decision analysis study to evaluate which alternative urban water supply strategies should be considered in future planning based on community priorities and local factors. It was important to the utility to take a participatory approach throughout the decision process, including problem structuring. This led to a complex decision space with over forty performance indicators, consisting of some well-defined quantitative indicators with other more qualitative indicators. However, the approach was crucial to garnering stakeholder support and further participation in the process, while improving institutional capacity for implementing sustainable alternative urban water strategies in the future. In this context, MCDA provided a useful tool for structuring the decision-making process. In later analyses, multi-objective optimization [35, 39, 64, 65, 66] can be used to more closely evaluate optimal combinations of alternative water supply strategies that provide the best balance between TBL objectives most important to stakeholders.

2.6 Conclusions

This collaborative effort involving multiple city departments, technical experts, and stakeholders, evaluated potential strategies to implement dual water supply systems in Fort Collins, Colorado. The approach resulted in a comprehensive TBL evaluation of the alternatives through several iterations of the methodology based on participant feedback, utilizing interdisciplinary knowledge and community priorities. Dual water supply alternatives could provide many social and environmental benefits for the community compared to the conventional water supply system. The centralized dual water supply alternatives, Central/Dual and Separated Irrigation, were favored over the decentralized alternatives because of community priorities and regional factors. Central/Dual was financially competitive with the conventional system and had the most social benefits, whereas Separated Irrigation provided the greatest environmental benefits.

Limitations of the study included the use of several qualitative and indirect quantitative performance indicators, a lack of uncertainty and sensitivity analysis, and simplistic distribution system design. Future work should include more diverse community involvement to help garner community acceptance and support. The addition of uncertainty and global sensitivity analysis to the decision framework will help increase decision makers' confidence in the results [67] and help identify the input parameters and criteria driving the decision [68].

The participatory approach presented here provides a crucial first step to increasing institutional capacity for implementing a more sustainable alternative urban water strategy. Extending the methodology to include community participation, uncertainty analysis and design optimization will provide a robust TBL decision framework for water utility managers to evaluate the best solutions to meet their cities' needs both today and in the future.

CHAPTER 3: CONFRONTING UNCERTAINTY IN THE EVALUATION OF DUAL WATER SUPPLY STRATEGIES[2]

3.1 Summary

As much of our urban water supply infrastructure reaches the end of its useful life, water managers are using the opportunity to explore alternative strategies that enable them to also utilize alternative local water sources. However, evaluating alternative strategies is challenging as water managers are required to balance the needs of multiple stakeholders, consider all the costs and benefits, reduce risks and, most importantly, ensure public health and protect the environment. Here, a recent study that evaluated alternatives for the dual supply of raw and treated water, which resulted in a complex decision process involving 45 performance indicators and 17 stakeholders, is extended. Uncertainty and global sensitivity analyses were applied to the study's decision models to assess the reliability of the results given long-term uncertainty, improve transparency in the decision process and elucidate the benefits and trade-offs of alternatives for the dual supply of raw and treated water. The results improved confidence and provided more clarity into the top performing alternative by allowing the alternatives to be considered across the full range of plausible uncertainty. The key drivers of model variance were regulatory and political, depending on access to alternative non-potable water sources in the future, ability to sell potable water to adjacent utilities, the possibility of cost savings by avoiding the need for water rights conversion, and stakeholder priorities. The key drivers were not originally predicted by the project team and were only revealed through global sensitivity analysis. The results highlight the importance of including local, regional and regulatory stakeholders in the decision process.

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[2] This chapter is adapted from a prepared journal article to be submitted for publication: Cole J, Sharvelle S, Arabi, M (2018). "Confronting Uncertainty in the Evaluation of Dual Water Supply Strategies".

3.2 Introduction

Managers of urban water supply infrastructure face many challenges including climate change, urban population changes, environmental degradation, public understanding of water systems, ‘lock-in’ effects of legacy systems, and financing replacement of aging infrastructure [1, 2]. In addition, they are also asked to make infrastructure decisions based on financial, social and environmental costs and benefits, and conflicting stakeholder priorities [46, 69]. As conventional water supply systems reach the end of their useful life, water managers are considering alternative water supply strategies. Many of these strategies use alternative local sources of water, such as stormwater, graywater, reclaimed water, seawater or untreated raw water [14, 17], and a ‘fit-for-purpose’ approach that matches water quality with the intended use. These strategies often incorporate the use of dual water supply systems for the separate supply of potable and non-potable water.

Although there are several implementations of the dual supply of reclaimed or raw water for non-potable uses and treated water for potable uses [14], there is still long-term uncertainty regarding the adoption of these strategies. Uncertainties can include limited information on the costs and benefits of these systems, lack of or changing regulatory frameworks, uncertainty in long-term performance and conflicting stakeholder priorities [17, 68]. Stakeholder inclusivity, performance under long-term uncertainty and visibility into the decision parameters driving uncertainty is essential for reducing decision risk and gaining the support needed for adoption. This paper applies uncertainty and global sensitivity analyses to a recent case study that evaluated centralized and decentralized strategies for the dual supply of raw and treated water to meet these needs [70].

Uncertainty analysis quantifies uncertainty in model output, while sensitivity analysis determines how uncertainty in the model output can be allocated to variation in the model inputs [71]. Most MCDA analyses in the water resources planning and management field use one-at-a-time or local sensitivity analysis and primarily focus on the sensitivity of the criteria weights [68, 72]. However, long infrastructure lifetimes and the potential for significant interaction effects between inputs makes a global sensitivity analysis a better choice when evaluating water supply infrastructure alternatives. Global sensitivity analysis considers the entire decision space by simultaneously evaluating inputs over the entire range of each input [71].

Cole et al. [70] extended the previous research on dual water supply by considering the benefits and trade-offs of centralized and decentralized water treatment strategies, varying scales of dual distribution, and the use of existing irrigation ditches throughout the service area. Using a hybrid triple bottom line - multi-criteria decision analysis (TBL-MCDA) methodology and a participatory approach, Cole et al. [70] aimed to empower stakeholders in the decision process, increase transparency into the financial, social and environmental benefits and trade-offs of the alternatives considered, and not allow TBL costs and benefits to compensate for each other on a single bottom line.

Inclusion of stakeholders in a participatory decision process led to the addition of more social and environmental criteria important to the community. Cole et al. [70] discussed the decision’s dependency on local conditions and stakeholder priorities and the intangibility of many of the social and environmental benefits important to stakeholders, which led to several questions. How can the approach used in the study be extended to improve stakeholder confidence in the results given long-term uncertainties, such as changes to current regulations, indoor and outdoor demand, and stakeholders' priorities? How can water managers improve visibility into the inputs driving model uncertainty and inform the next level of analysis?

This research applies uncertainty and global sensitivity analyses to the TBL-MCDA models to evaluate the reliability of the results, identify key inputs driving uncertainty in the alternatives' financial, social, and environmental performance, explore possibilities for model simplification, and elucidate the benefits and trade-offs of alternative strategies for the dual supply of raw and treated water. The uncertainty analysis examines the robustness of the alternatives' long-term performance given uncertainty in model inputs over time and the range of stakeholder criteria weights. The sensitivity analysis helps identify which uncertain inputs decision makers should focus on in future analysis to reduce uncertainty in the alternatives' performance, and which inputs are not contributing to performance uncertainty for model simplification.

3.3 Approach

Cole et al. [70] evaluated the benefits and trade-offs of four alternative strategies for the dual supply of raw and treated water in Fort Collins, Colorado. Using integrated urban water management (IUWM) principles, the study attempted to balance financial, social, and environmental performance and support a flexible transdisciplinary approach to decision making involving multidisciplinary experts and stakeholders. Four alternatives for the dual supply of raw and treated water were evaluated along with maintaining the existing conventional water supply system *(Conventional)*: 1*) Central Dual* continued drinking water treatment at the existing conventional central water treatment facility, used the existing distribution system to distribute raw water for fire and irrigation demand, and installed a new potable distribution system to distribute drinking water for indoor use; 2) *Neighborhood* conveyed raw water to neighborhoods using the existing distribution system. Water for indoor demand was treated at new satellite neighborhood water treatment facilities (ultrafiltration membrane systems) and then distributed via new neighborhood potable distribution systems; 3) *Point-of-Entry* conveyed raw water to the service connection using the existing distribution system. Water for indoor demand was treated on-site at point-of-entry water treatment systems (activated carbon and kinetic degradation fluxion media with ultraviolet disinfection); 4) *Separated Irrigation* used the existing central water treatment facility and distribution system to treat and distribute drinking water for indoor and fire protection use. The network of irrigation ditches throughout the city would distribute raw water to neighborhood separated irrigation systems for landscape irrigation.

The TBL-MCDA method used in the study [70] resulted in the project team and stakeholders defining a combination of quantitative and qualitative performance indicators for the main criteria, for each bottom line, to ensure the TBL objectives important to the community were represented in the analysis. This resulted in a complex decision problem involving 11 main criteria evaluated by a mix of 45 qualitative and quantitative performance indicators, weighted by 17 stakeholders with different priorities. While the results were dependent on local conditions and stakeholder priorities, the study found the Conventional and Central Dual alternatives had the best financial performance, Central Dual had the best social performance and Separated Irrigation the best environmental performance. The limitations of the study addressed here included a lack of confidence in long-term performance due to input uncertainty and variable stakeholder preferences; and difficulty in identifying the inputs driving uncertainty due to the large number of performance indicators and stakeholders. Uncertainty due to the structure of the TBL-MCDA models is not addressed here.

Uncertainty and sensitivity analyses were applied to the TBL-MCDA models from Cole et al. [70] to improve confidence in the results and identify which inputs were driving performance uncertainty (Figure 3.1).

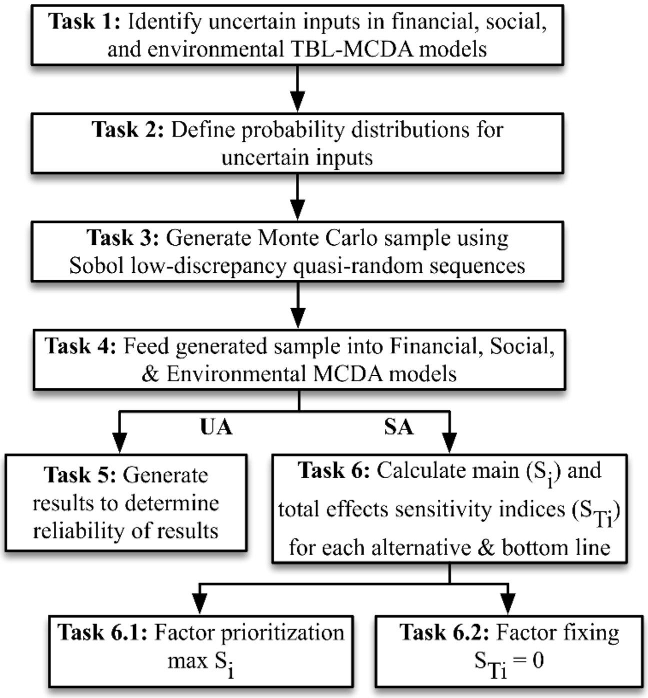

Figure 3.1: Uncertainty and Sensitivity Analysis Approach

Tasks 1-3: Define uncertain inputs & generate Monte Carlo samples

The uncertain inputs used to calculate the alternatives' performance in the performance indicators for the TBL-MCDA models were identified (Table 3.1; Figure 3.1, Task 1). Probability distributions were defined for each uncertain input (Figure 3.1, Task 2; Appendix B, Table B.1). The inputs used to calculate the quantitative performance indicators were defined as uniform or triangular probability density functions based on utility data and/or literature review (Table 3.1; Appendix B, Table B.1; [70]). The inputs used in the assessment of qualitative indicators use a mix of probability mass and probability density functions.

For the qualitative indicators, the inputs are the factors evaluated to compare the alternatives. For example, the "resiliency of infrastructure to limited supply" performance indicator (Table 3.1, Social 7.1) considered two scenarios, seasonal shortages in supply and a short term service disruption. Five binary factors were considered when assessing alternative performance: 1. Whether the alternative has access to multiple raw water sources (LSms); 2. Whether the alternative has a dual distribution system that would allow for the use of alternative non-potable sources in the future (LAS); 3. Whether the alternative increases finished water storage (LSs); 4. Whether the alternative has access to backup water treatment systems (LSb); 5. Whether the alternative reduces the number of customers that would be affected in the event of a service disruption (LSpop). The alternative with the most points received the best rating. Not all the alternatives had uncertainty around these inputs. For example, the city has access to two raw water sources. However, the non-potable irrigation systems in Separated Irrigation only have access to river sources, which may result in a shortage later in the summer.

There were also some performance indicators where it was apparent the uncertain inputs would have no impact on the alternatives' performance in relation to one another and would not change the MCDA results (Table 3.1). For example, public relations costs (Table 3.1, Financial 11.2) assumed that the further the alternatives deviated from the conventional system customers were used to, the higher the public relations costs would be for that alternative. In this case, alternatives closer to the conventional system will always rank better, with no change to MCDA results.

Table 3.1: Main criteria, performance indicators and (uncertain inputs) used in the calculation of the alternative performance on that indicator (ordinal identifies the qualitative indicators). Additional information on uncertain inputs provided in Appendix B, Table B.4

Main Criteria	Financial Performance Indicators	Social Performance Indicators	Environmental Performance Indicators
1. Impact of new infrastructure	1.1 Cost of new infrastructure (Cds, Ct, Cbfp, Csis, Cpoe, Di)	1.1 Disruption from construction [c]	1.1 GHG emissions construction (Cds, Ct, Cbfp, Di, Cpoe, Csis) [a]
	1.2 Net replacement costs (Cds, Ct, Csis, Cpoe, Ltm, Lds, Cwtf, RLcwt, Lcwt, Lnwt, Lpoe, i, Di, Do)	1.2 Increase in temporary employment (Cds, Ct, Cbfp, Di, Cpoe, Csis) [a]	1.2 Temporary stormwater pollution [a]
2. Energy use	2.1 Annual energy costs (CEwt, CEvar, PEpot, PEnon, NEwt, POEEwt, Di, Do)	2.1 Health impacts associated with GHG emissions from energy production (Di, Do, CEvar, CEwt, Newt, PEpot, POEEwt, PEnon) [a]	2.1 Annual GHG emission (Di, Do, CEvar, CEwt, Newt, PEpot, POEEwt)
3. Routine Maintenance (excluding energy)	3.1 Annual operations & maintenance costs for water treatment (Di, Do, ECwtom, ACwtom, Nwtom, POEwtom)	3.1 Disruption to community from maintenance	3.1 GHG emission maintenance (GHGdds, GHGnwt)
	3.2 Annual operations & maintenance costs for distribution (DSpotom, TMpotom, SISom)		3.2 Chemical consumables (Di, Do, Clc, Al2SO43, CaOH2, F, CO2, Cln)

4. Staffing	4.1 Full-time employees (Brate, FS, FTEpoewt, Bno, Di, Do)	4.1 Employment (Bno, Brate, FS, Di, Do, FTEpoewt)	4.1 Employee transport GHG emissions (Bno, Brate, FS, FTEpoewt, Di, Do) [a]
	4.2 Training costs for new technologies (Tdd, Twt, Tno) *ordinal*	4.2 Increased earning potential (Tdd, Twt, Tno) *ordinal*	
5. Consumer water quality	5.1 DBP exposure health care costs [a, c]	5.1 Water age in potable distribution system [c]	5.1 Water quality receiving water bodies *ordinal*
	5.2 Cross-connection costs (RFpdd, RFsdd, RFp, RFfi) *ordinal*	5.2 Health risks from cross-connections (RFfi, RFpdd, RFp, RFsdd) *ordinal*	
	5.3 Source water contamination event costs (Sn, Spoe) *ordinal*	5.3 Level of adaptability to source water contamination event (Sn, Spoe) *ordinal*	
6. Environmental flows	6.1 Avoided transaction costs [b] (ATC) *ordinal*	6.1 Enhancement of natural areas & benefits to canal companies (ATC) *ordinal*	6.1 Benefits to species and natural systems from increasing ISFs (ATC) *ordinal*
7. Supply risk	7.1 Cost of alternative supplies (LSms, LAS, LSs, LSb, LSpop) *ordinal*	7.1 Resiliency of infrastructure to limited supply (LAS, LSs,LSb, LSpop, LSms) *ordinal*	7.1 Variable supply effects on water corridors (LAS) *ordinal*
	7.2 Risk of obsolete infrastructure (ROc, ROn, ROpoe, ROsis) *ordinal*		
8. Rate risk	8.1 Confidence in O&M projections (Rdd, Rn, Rsis) *ordinal*	8.1 Affordability (ECwtom, Di, Do, ACtwom, Nwtom, POEwtom, DSpotom, TMpotom, SISom	8.1 Changes in water demand (ECwtom, Di, Do, Nwtom, POEwtom, ACwtom, DSpotom, TMpotom, SISom) [a]
9. Alternative source opportunity	9.1 Savings from later using alternative non-potable sources [a] (LAS)	9.1 Being an innovative community and improving natural areas (LAS)	9.1 Improvements to water corridor ecosystems (LAS)
10. Revenue opportunity	10.1 Wholesale water revenue [a] (Rev)	10.1 Improve regional water security in adjacent communities (Rev) [a]	10.1 Environmental benefits from decreasing need for new WTF to meet growth (Rev) [a]
11. Regulatory of political risk	11.1 New regulation costs *ordinal*	11.1 Public acceptance (PAdd, PAnwt) *ordinal*	11.1 Negative environmental impacts from mitigation required for new regulatory requirements (RRcwt, RRraw, RRnwt, RRpoe)
	11.2 Public relations costs *ordinal*		

[a] Uses an indirect quantitative metric; [b] Not included in original study [70] due to lack of water rights information; [c] The relative performance of the alternatives to each other do not change with uncertainty

The correlations between the 11 main criteria weights given by the 17 stakeholders for each bottom line were evaluated using the Pearson product-moment correlation coefficient (Test 28 in [57]). The analysis indicated 24%, 9%, and 44% of the $r_{.05}$ values exceeded the critical value in the financial, social, and environmental decision models respectively (Appendix B, Tables B.1-B.3). The results suggest some correlation between stakeholders' criteria weights. Rather than use a separate input for each criteria weight, a dummy variable was created to represent the criteria weight vectors in the financial, social, and environmental MCDAs to ensure stakeholder perspectives were preserved and avoid non-orthogonal inputs. Then a uniform probability mass function was used to represent the probability distribution for the 17 stakeholders.

A Monte Carlo sample of the uncertain inputs used in the financial, social, and environmental MCDA models was generated for each model using Sobol low-discrepancy quasi-random sequences, from the R Random Toolbox Package, with a modification to allow probability mass functions for the discrete inputs (Figure 3.1, Task 3; [73]). Low-discrepancy sampling sequences allow for more uniform sampling of the entire sample space and reduce the number of samples needed for the analysis [74, 75].

Tasks 4-5: TBL-MCDA model runs

The generated samples were run through the separate financial, social, and environmental MCDA models from Cole et al. [70] using the weighted sum method (WSM), from the R MCDA Package [76], and the Preference Ranking Organization Method for Enrichment of Evaluation II (PROMTHEE II) [56]. The simplest preference function was used with PROMETHEE II, due to the large number of performance indicators and difficulty defining appropriate threshold values for the qualitative indicators [70].

The WSM has several limitations when evaluating a mix of quantitative and qualitative criteria because it assumes additive utility [24]. It requires converting incommensurate criteria to a common rating scale. To address this issue, the performance data was transformed to a common rating scale using local scaling to convert the alternatives' performance on the performance indicators to a common 1-to-5 scale, where 1 represents the worst performance and 5 represents the best performance [70]. In local scaling the maximum and minimum performance values set the lower (1) and upper (5) boundaries of the transformation [77]. This results in applying cardinal properties to ordinal data for qualitative criteria and the assumption that the normalized performance ratings have the same value for all the performance indicators [70]. This can exaggerate the differences in alternative performance and allows for high performance on one indicator to compensate for low performance on another, which might not be a true representation of alternative performance [78, 79]. The Monte Carlo simulation results did reveal similar results for the top performing alternatives for both methods, like other studies that compared MCDA methods [22, 53]. However, in the WSM models the sensitivity results did show compensability effects where there were fewer sensitive inputs and they tended to be the inputs that resulted in an extreme performance rating of a 1 or 5 (results not shown).

Outranking techniques are better suited than the WSM when considering a mix of cardinal and ordinal data [78]. Rather than assuming additive utility to calculate the overall value of an alternative, the outranking method's goal is to determine if there is enough information to say one alternative is at least as good as another alternative. This makes it better suited to decisions that involve incomplete performance value information, which is common when considering long-term social and environmental performance. For these reasons and the compensability effects observed, only the results for the PROMETHEE II method are shown and discussed (Figure 3.1, Tasks 4, 5).

Task 6: Sensitivity Analysis

A variance based sensitivity analysis, which decomposes the variance of the model output into fractions that can be attributed to individual inputs, was selected for several reasons. Variance based methods are model independent, consider the entire variation range of model inputs, can determine the main and interaction effects between input factors on model output variance, and can be used to handle groups of inputs and correlated inputs [71, 74]. The Sobol method was selected because of its robustness [80]. The Sobol method is based on the decomposition of the variance of the model output ($V(Y)$) into terms of increasing dimensionality (Eqn. 3.1), for the case where all model inputs are orthogonal [74]:

$$V(Y) = \sum_i V_i + \sum_i \sum_{j>i} V_{ij} + \cdots + V_{12\ldots k} \qquad (3.1)$$

Where the conditional variance V_i is the first order effect of input X_i on $V(Y)$, V_{ij} represents the second order interaction effects of inputs X_i and X_j on $V(Y)$, and k *represents* the number of input factors. The inputs (X) included the inputs used to calculate the alternatives' performance on the performance indicators (Table 3.1) and the dummy criteria weight variable in each bottom line.

The first order (main effects) sensitivity index represents the main effect contribution of each input to the output variance [71] and is represented by the normalized conditional variance V_i (Eqn. 3.2) [74].

$$S_i = \frac{V(E(Y|X_i))}{V(Y)} \qquad (3.2)$$

The total effects indices are used to determine the interaction effects that are not captured by the main effects indices [71]. For the calculation of the total effects sensitivity index, Homma and Saltelli [81] introduce the conditional variance, $V(E(Y|X_{-i})$, which represents the impact on output variance due to everything except X_i. Then, the difference between the output variance and the new term represents the total of all terms in the variance decomposition that include X_i. The total effects sensitivity index can be calculated using Eqn. 3.3 [74].

$$S_{T_i} = \frac{V(Y)-V(E(Y|X_{-i})}{V(Y)} = \frac{E(V(Y|X_{-i}))}{V(Y)} \qquad (3.3)$$

Sobol's decomposition of variance is based on the assumption that all inputs are orthogonal, and therefore, $S_{T_i} \geq S_i$ and $S_{T_i} - S_i = Interaction\ effects\ for\ X_i$. However, this does not hold true for correlated inputs where the input variance also affects other input factors, in which case the sum of the conditional variances can be higher than the output variance and the assumptions based on orthogonal inputs mentioned above are no longer true [74]. This was one of the reasons a dummy variable was created to represent the stakeholder criteria weight vectors.

The R Sensitivity Analysis Package [82] provides several methods for the Monte Carlo estimation of Sobol' indices with independent inputs. The 'sobolEff' method, based on Janon-Monod [83], was selected as it provided the most consistent results and is good for large first order indices [83]. All first order indices or all total effect indices are estimated at a cost of N(p+1) model simulations [83]. A base sample size (N) of 1,100 was used in the analysis. Bootstrapping was used to obtain the 95% confidence intervals of the sensitivity indices due to the large number of uncertain inputs [84]. This technique resamples, with replacement, the Monte Carlo samples B times (eliminating the need for further model evaluations), then at each stage and for each input the sensitivity indices are calculated to estimate the sampling distribution of the indices [84]. A B value of 10,000 was used in the analysis.

Factor prioritization identifies key inputs for future analysis (Figure 3.1, Task 6.1) by identifying model inputs that, when fixed, result in the greatest reduction to output variance [71]. It assumes that inputs are fixed one at a time and therefore is only concerned with first order effects and not with higher order (interaction) effects [74]. The total effects sensitivity indices were also calculated to provide overall visibility into the inputs driving the output variance, the amount that is due to main effects versus interaction effects, and for factor fixing (Figure 3.1, Task 6.3). Factor fixing allows for model simplification by identifying non-influential inputs ($S_{Ti} \sim 0$) that can be fixed to a nominal value for future analysis [74].

TBL Weighting Analysis

The main benefit of the TBL-MCDA approach taken in Cole et al. [70] was to elucidate the TBL benefits and trade-offs between the alternatives considered. Although financial, social and environmental performance are not interchangeable, meaning high performance in one cannot compensate for low performance in another, it may be useful for decision makers to simulate stakeholder weights for each bottom line to determine the range of values where the overall top alternative may change when considering total performance. An exploratory TBL analysis was conducted to assess variability of results based on the importance stakeholders place on financial, social and environmental performance. The analysis of the weights stakeholders place on the importance of financial (W_{FIN}), social (W_{SOC}) and environmental (W_{ENV}) performance on the top ranked alternative if the bottom lines were aggregated to a single total bottom line was determined using Eqn. 3.4:

$$Overall\ Performance_j = W_{FIN}P_{FINi} + W_{SOC}P_{SOCi} + W_{ENV}P_{ENVi} \qquad (3.4)$$

Where: j = bottom line; i = alternative

$W_{FIN} = 1 - W_{SOC} - W_{ENV} \quad (0.1 \leq W_{SOC} \leq 0.5 \; and \; 0.1 \leq W_{SOC} \leq 0.5\,)$

P_{FINi}, P_{SOCi}, P_{ENVi} represent the mean performance from the uncertainty results

3.4 Results

Uncertainty Analysis Results

The uncertainty analysis supports the original findings that the centralized water treatment alternatives generally outperform the decentralized alternatives (Figure 3.2). The utility's ability to use gravity fed distribution, spare capacity in the existing water treatment facility, and multiple raw water sources with different seasonal variations in water quality all favored these alternatives

[70]. There is overlap in financial performance between the existing conventional system, Central Dual and Separated Irrigation. Central Dual offers the most social benefits, while Separated Irrigation offers the most environmental benefits (Figure 3.2). In the original study, there was not enough information to confirm Separated Irrigation offered water rights savings over the alternatives and that criterion was removed from the financial analysis (Table 3.1: Financial 6.1; [70]). However, this uncertainty could be modeled in the uncertainty analysis and its inclusion improved Separated Irrigation's financial performance.

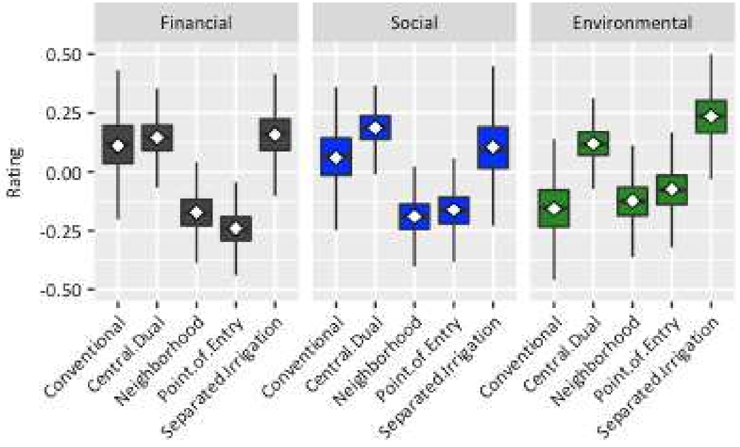

Figure 3.2: Uncertainty analysis results of financial, social, and environmental performance (PROMETHEE II MCDA method was used where +1 represents best performance and -1 worst performance; box plot represents minimum, 25%, median, 75%, maximum performance ratings, dot = mean)

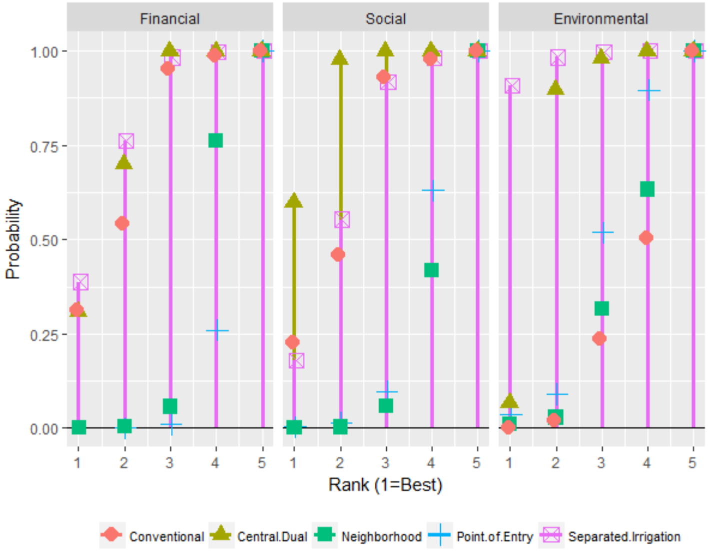

Figure 3.3: Cumulative distribution function of the alternatives' financial, social and environmental rankings (1=Best, 5=Worst)

The uncertainty analysis shows Conventional, Central Dual and Separated Irrigation each the top ranked alternative about a third of the time in the financial bottom line (Figure 3.3: Financial). In the social bottom line, Central Dual is the top ranked alternative about 60% of the time, with the remainder split between Conventional and Separated Irrigation (Figure 3.3:

Social). In the environmental bottom line, Separated Irrigation is the top ranked alternative followed by Central Dual about 90% of the time (Figure 3.3: Environmental). The decentralized alternatives (Neighborhood, and Point-of-Entry) have the lowest financial and social performance and are in the bottom three in environmental performance.

The uncertainty results suggest more information is needed to distinguish between the financial performance of the top three alternatives. There is more distinction between the top alternatives in the other bottom lines, but there is still some overlap. Overall, the uncertainty analysis results show Separated Irrigation, followed by Central Dual, has the best performance but there is still some overlap between Conventional, Central Dual, Separated Irrigation, which presents decision risk. The sensitivity analysis can help identify the inputs driving the variance in performance. This enables stakeholders to focus on reducing the uncertainty in those inputs to more clearly understand the alternatives' relative performance.

Sensitivity Analysis Results

The total effects sensitivity indices provide visibility into the inputs driving the uncertainty in the TBL-MCDA model results (Figure 3.4). The sum of the total effects sensitivity indices for all the alternatives in the financial, social, and environmental models were greater than 1 (Figure 3.4), indicating higher order interaction effects between the inputs (Figure 3.5 patterned bar), confirming the need for a global sensitivity analysis. The main effects indices (Figure 3.5 solid bar) were used to identify the inputs where stakeholders should focus future research efforts. Because the uncertainty analysis results show that the decentralized alternatives have the lowest financial, social, and environmental performance despite input uncertainty and there is overlap in the performance between the three centralized water treatment alternatives (Figure 3.2), the top priorities are inputs that will reduce uncertainty between the Conventional, Central Dual and Separated Irrigation performance.

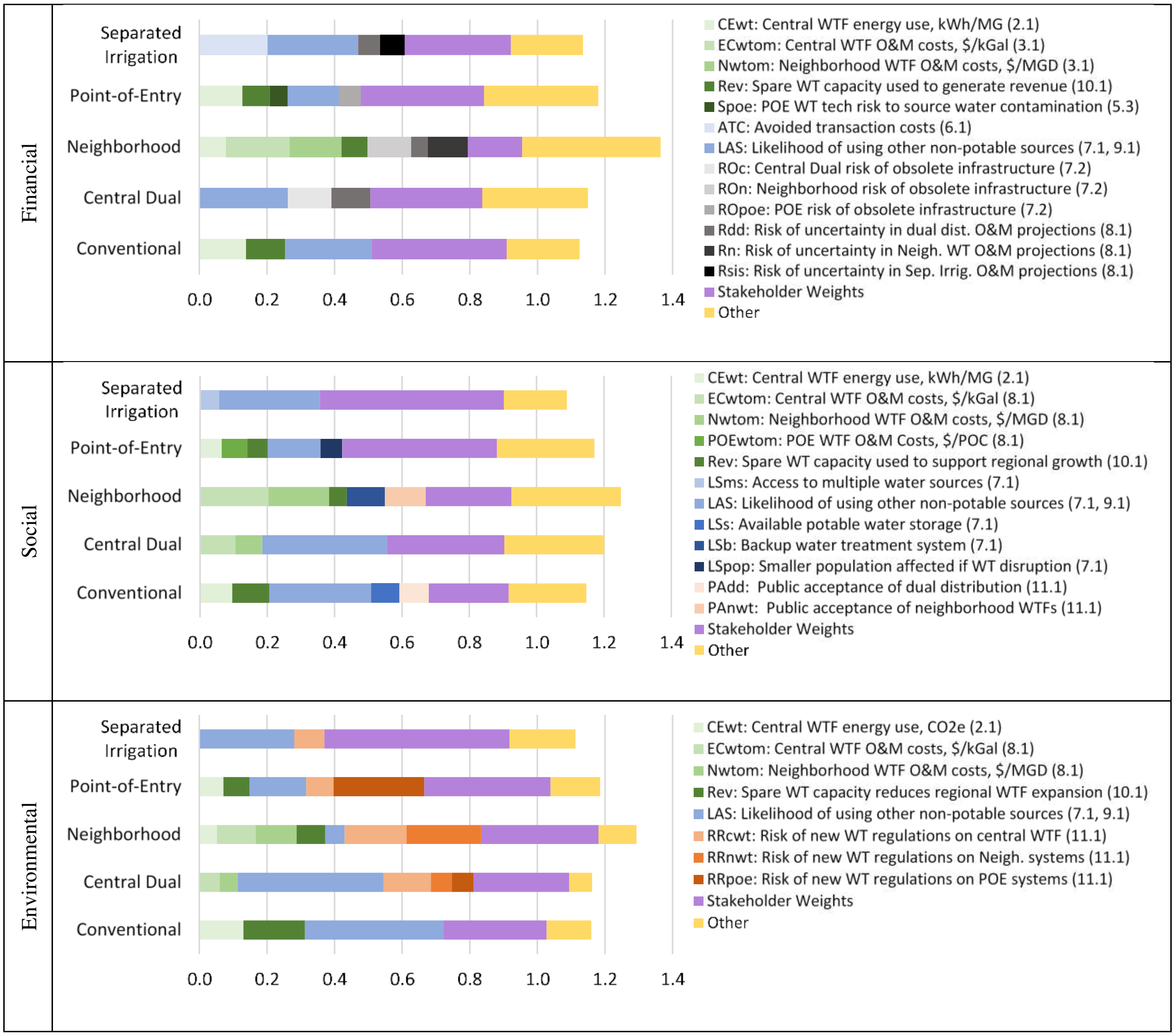

Figure 3.4: Uncertain inputs with total effects sensitivity indices > 0.05 in financial, social, and environmental bottom lines (performance indicator(s) in which input is used (Table 3.1))

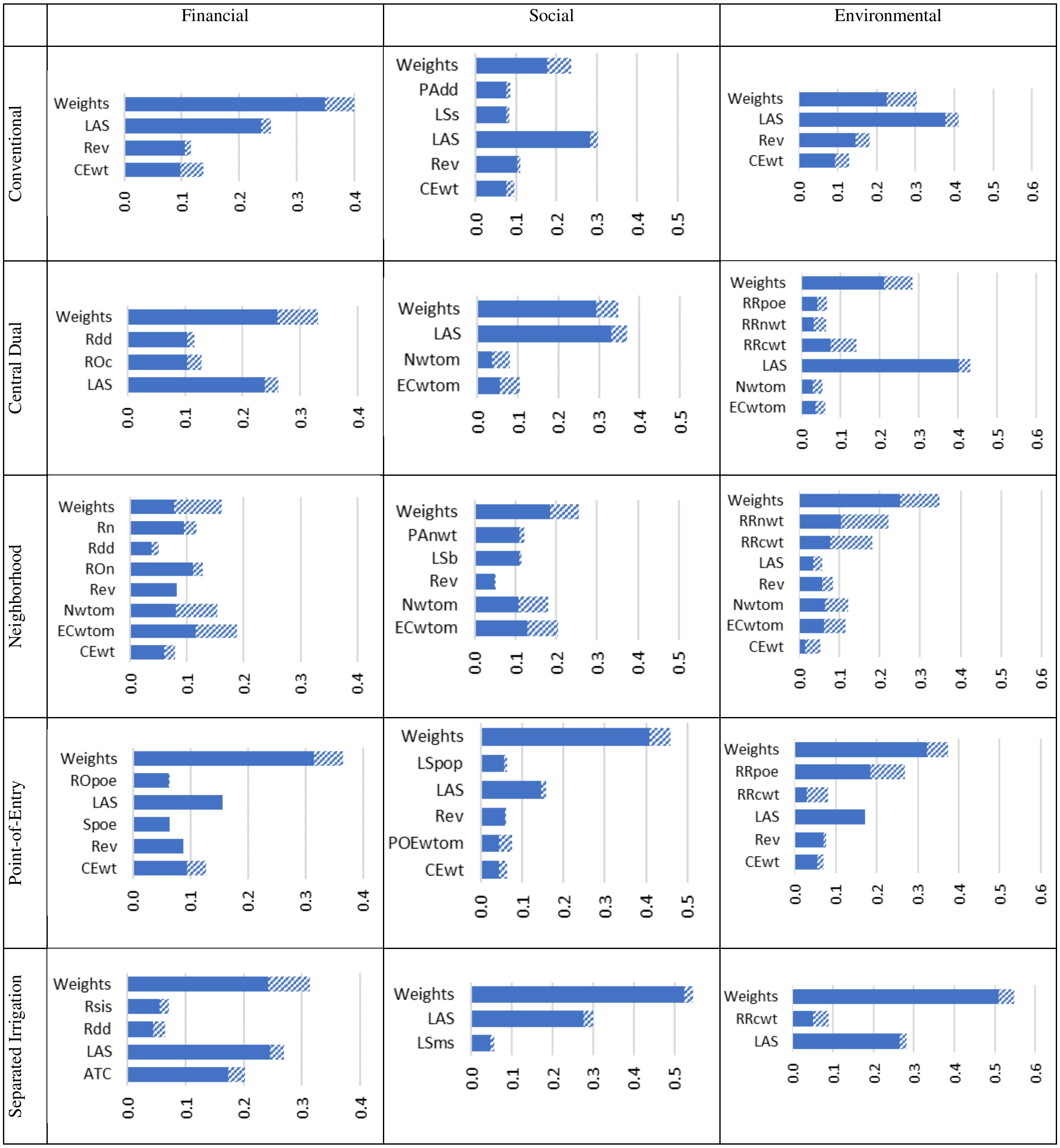

Figure 3.5: Main and Interaction Effects Sensitivity Indices > 0.05, main effects are represented by solid bar and interaction effects are represented by pattern bar

The main effects sensitivity indices for the stakeholder weights contribute between 16% and 48% of the total variance for Conventional, Central Dual, and Separated Irrigation performance (Figure 3.5: Stakeholder Weights). Stakeholder input is particularly important for the Separated Irrigation alternative because it accounts for 48% (social) and 46% (environmental) of its variance. This is not surprising given Separated Irrigation's performance on the social and environmental indicators under criterion 6 (Table 3.1: 6. Environmental Flows). Separated Irrigation always outperforms the other alternatives in this criterion, making it sensitive to whether stakeholders rate the importance of this criterion high. The results' sensitivity to disagreement among stakeholders (Figure 3.4: Stakeholder Weights) is not surprising given its focus in other studies [68, 72] and its impact on all criteria. This impact and the correlation between weights demonstrates the importance of engaging stakeholders throughout the entire decision process and ensuring their perspectives are maintained when conducting the sensitivity analysis.

The likelihood the utility can use alternative non-potable water sources (e.g. recycled water, gray water, stormwater) in the future (Figures 3.4 & 3.5: LAS) gives the alternatives with dual distribution systems (Central Dual, Neighborhood, Separated Irrigation) advantages over the single distribution system alternatives (Conventional, Point-of-Entry) as a large part of the infrastructure needed is already in place. Focusing on securing the right to use alternative non-potable sources in the future (Figure 3.5: LAS) and a more in-depth water rights analysis (Figure 3.5: ATC) would have the largest impact on minimizing financial uncertainty. LAS financial main effects contribute around 20% of the total variance for all three top alternatives and ATC contributes another 15% for Separated Irrigation. Reducing uncertainty about whether the utility will be able to use alternative supplies would also reduce uncertainty in the social and environmental bottom lines, where the LAS input's main effects contribute between 24% to 35% of the total variance for Conventional, Central Dual, and Separated Irrigation.

Avoided transaction costs (Figure 3.4: ATC) and using the spare capacity at the existing water treatment facility to generate revenue (Figure 3.4: Rev) both offer ways to offset the costs of implementing the alternatives. Separated Irrigation results are sensitive to ATC because it is the only alternative that allows the city to use their water rights still designated for irrigation use for municipal irrigation. However, these savings are difficult to assess as they depend on the success of the water right conversion process.

All the dual water supply alternatives free up capacity at the water treatment facility, with the decentralized alternatives freeing up the most. This creates an opportunity to generate revenue selling treated water to adjacent utilities that may not have capacity to meet growing demand (Figures 3.4 & 3.5: Rev). Wholesale revenue could be used to offset alternative implementation costs and provide social and environmental benefits to the region by reducing the need to augment existing regional water treatment facilities to meet demands from a growing population. However, these benefits are dependent on demand from adjacent utilities and the ability to negotiate a collaborative agreement with regional water utilities.

Uncertainty in performance (Figures 3.4 & 3.5: CEwt, Spoe) and operating and maintenance (O&M) costs (Figures 3.4 & 3.5: ECwtom, Nwtom, POEwtom) inputs associated with the three water treatment technologies considered in the alternatives also contributed to output uncertainty. Energy use at the central water treatment facility was influential because there is overlap in energy use performance between Conventional and Point-of-Entry (Figure 3.5 CEwt; [25]). There was also overlap in performance between the O&M costs of the central and neighborhood water treatment facilities with the difference in the average annual O&M costs only being $1,300 [25].

Other inputs driving uncertainty in the financial results included those associated with rate stability risks (Figures 3.4 & 3.5: Rdd, Rn, Rsis) and risk of new infrastructure strategies becoming obsolete from a large reduction to non-potable demand or change in water treatment requirements

(Figures 3.4 & 3.5: ROc, ROn, ROpoe). Other inputs driving uncertainty in the social results included public acceptance of alternative strategies (Figures 3.4 & 3.5: PAdd, PAnwt) and the alternatives' resiliency to limited supply (Figures 3.4 & 3.5: LSms, LAS, LSs, LSb, LSpop). Other inputs driving uncertainty in the environmental results included uncertainty that future water treatment regulations would require augmentation to water treatment facilities and result in environmental impacts (Figures 3.4 & 3.5: RRnwt, RRpoe, RRcwt).

The total effects sensitivity indices were used to identify inputs that did not contribute to the output variance of any alternative and can be fixed to their nominal values in the future. The analysis showed that 29%, 26%, and 48% of the financial, social, and environmental inputs respectively can be fixed to simplify models for future analysis.

TBL Weighting Analysis Results

The results of the exploratory TBL analysis show the boundary where the top ranked alternative (Separated Irrigation or Central Dual) changes (Fig. 3.6). The results show that if environmental performance is weighted at least 0.33, then Separated Irrigation is the favored alternative regardless of the social and financial weights. Central Dual is favored as the social weight increases and environmental weight decreases. Overall, Separated Irrigation is the top alternative. However, if stakeholders place a higher importance on social and financial performance, the top alternative can change stressing the importance of including stakeholders in the entire decision process.

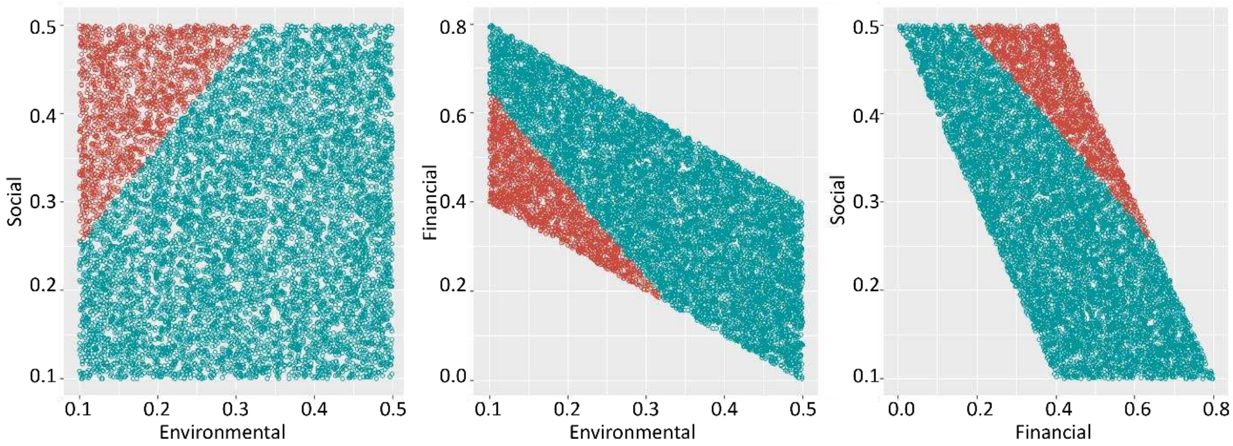

Figure 3.6: TBL Preference Weights When Top Ranked Alternative Changes (Red = Central Dual, Blue = Separated Irrigation)

3.5 Discussion

The results of this analysis are case specific, and every location will have different local conditions, drivers, constraints, evaluation criteria and stakeholder priorities. However, this study provides more insight into the benefits and trade-offs of dual water supply systems and the critical uncertainties limiting adoption of dual water supply strategies. The key inputs driving the variance in the alternatives' TBL performance can be categorized as regulatory, political and technical performance. The critical uncertainties in the analysis were regulatory and political rather than technical, highlighting the need to address these issues.

Regulatory

Several of the inputs driving uncertainty in the model outputs were related to regulatory and legal issues (Figure 3.5: LAS, ATC, RRnwt, RRpoe, RRcwt). Of these, the most important was a utility's right to use alternative sources in the future, such as reclaimed, graywater, rainwater or stormwater (Figure 3.5: LAS). Most of the large scale dual water supply implementations in the United States focus on the dual supply of reclaimed and treated water [14]. The main drivers for these systems are wastewater discharge requirements, savings on potable water treatment and conserving potable supply [14, 30, 31]. The ability to use alternative sources in the future is important when considering dual water supply systems, even for utilities whose water rights currently restrict its use, because it offers more flexibility in the future should regulations or water rights change. The current regulatory and legal framework around the use of new technologies and strategies that allow for use of alternative sources is rapidly changing [17], which provides hope for utilities currently restricted in the use of these sources. Some states have recently passed legislation regarding the use of alternative sources making these strategies more available but there is still uncertainty around legal rights and future regulatory changes [17].

The utility in this study is close to the headwaters with more senior water right holders downstream and is restricted in the amount of reclaimed or stormwater it can use. However, future legislation or a change in the utility's water rights portfolio may change the availability of these sources. This represented a critical uncertainty in consideration of the dual water supply alternatives, as alternatives with dual distribution systems will already have infrastructure in place to distribute non-potable water from alternative non-potable sources should they become available, offering an advantage over single distribution system alternatives.

Political

The Separated Irrigation alternative has the best overall performance (Figure 2) and potentially benefits both urban and agricultural interests. Separated irrigation systems, where raw water historically used for agricultural irrigation is used for landscape irrigation, are common in the western U.S. [33]. These systems can benefit agricultural producers by compensating for non-pass through costs associated with urbanization around canals [32]. They also provide value to the urban community by improving the urban green spaces supported by these waterways, which was not considered in previous studies evaluating separate irrigation systems [32, 33]. Urban green spaces contribute to the livability of a city by improving air and water quality; reducing urban heat island effects; enhancing physical and psychological wellbeing; and providing opportunities for social connection and recreation [85, 86]. However, Separated Irrigation's success is linked to the success of local irrigation districts and canal companies, making cooperation between them and the utility critical. Equally important is understanding the urban community's willingness to pay for the benefits of maintaining the current canal system. This is important because those benefits may be in opposition to modernization goals of canal companies. For example, if canal improvements in the utility service area include lining canals [33] or replacing canals with pressurized systems [87], the benefits valued by the urban community would diminish. This stress the importance of collaboration with regional agricultural stakeholders to confirm the feasibility of the Separated Irrigation alternative.

Wholesale revenue was a key uncertainty because the city's existing water treatment facility has spare capacity to accommodate future population growth and other utilities in the region may not have the capacity to meet future growth. This offers an opportunity to optimize regional water treatment but requires collaboration between multiple water utilities. Other cities may not have spare capacity in their existing water supply systems. In cities where this is the case, the utility may find savings from decreasing potable demand and reducing the need to augment current infrastructure to meet future demand.

Without the ability to use alternative non-potable water sources, generate wholesale revenue to offset implementation costs, and create water right conversion savings, the Central Dual and Separated Irrigation alternatives may not be financially feasible and result in fewer social and environmental benefits. Creating the regulatory and political agreements necessary for successful implementation of an alternative dual water supply strategy will require expanding the circle of participants in the planning process to include state regulators, water rights specialists, regional irrigation districts and canal companies, regional utilities and utility customers.

Stakeholder perspectives and priorities had a large impact on the financial, social and environmental output variance making them integral to the planning process. Efforts to improve consensus among stakeholders would reduce output variance and clarify the relative performance of the alternatives. It is also important to ensure stakeholder perspectives are preserved in the decision models since the results showed a correlation between stakeholder weights. Otherwise, there is a risk of preference models that do not represent actual stakeholder priorities.

Uncertainty in the political and regulatory inputs, and the importance of differing stakeholder opinion on the results, emphasizes the need to expand the stakeholder group to include regional stakeholders, regulators, and the public. Stakeholder engagement should begin early and include frequent engagement throughout the decision process. Stakeholders can bring to light drivers not previously considered, provide more insight into the problem to reduce uncertainty and identify areas of future conflict or collaboration.

Technical

The inputs most influential to the uncertainty of the results were unexpected. For example, it was hypothesized that indoor and outdoor demand would be the most influential inputs as they were used in the calculation of several performance indicators. While these had total sensitivity indices, ranging from 0.01 to 0.04, other inputs had a larger impact on output uncertainty. The Neighborhood and Conventional alternatives were most sensitive to indoor and outdoor demand and approximately 50% of the sensitivity was due to higher order interaction effects.

The Neighborhood decentralized alternative did not perform well relative to the central water treatment alternatives. However, it was comparable in performance on some of the key technical indicators that may make it a more favorable alternative in areas without a gravity fed water distribution system. The O&M costs and water treatment energy use were comparable to the central water treatment facility. However, the need to add pumping for distribution gave the Neighborhood alternative the lowest energy rating. This would likely change in areas with non-gravity fed distribution systems.

The alternatives considered in this study had differences that decreased the importance of uncertainty in technical inputs to the alternatives' relative performance. For example, there was little uncertainty in relative performance due to distribution system metrics, such as water age in the distribution system, because the main drivers of alternative performance were not uncertain in this analysis. Water age decreased with the decentralization of water treatment and moving fire supply to the non-potable distribution system. These inputs were important in comparing alternative performance, but were not influential in result uncertainty.

Technical and financial performance are important in evaluating any alternative infrastructure strategy. However, it is frequently the political and regulatory uncertainty that prevents adoption of new alternative infrastructure strategies [17] and this was supported here. The purpose of Cole et al. [70] was to identify feasible water supply infrastructure strategies for the future and, in doing so, found that the regulatory and political inputs were the most important to improving confidence in their feasibility. It may not be possible to diminish this uncertainty. However, an informed decision process requires these risks be investigated in more depth and the stakeholder group be expanded to include regional utilities, canal companies, regulators and the public so all the benefits, trade-offs, and risks are made transparent to decision makers and stakeholders.

Future analysis may be needed to evaluate structural and stakeholder uncertainty. Structural uncertainty, uncertainty resulting from the decision models' structure, can be addressed by evaluating the models with different architectures [88]. A variance based sensitivity analysis for non-orthogonal inputs can be used to measure stakeholder preferences' impact on specific criteria [74]. The decision problem and stakeholder priorities will evolve in the future. As more information is obtained and stakeholders have a better understanding of the benefits and trade-offs, drivers may change, other alternatives may be considered, and more constraints identified. Adopting new infrastructure strategies involves an iterative decision process and long implementation timelines.

Making Final Decisions

The purpose of considering alternative urban water supply strategies is to improve the public's quality of life. Therefore, engaging the public in the future planning process is essential. Water managers need to understand the public's acceptance of alternative strategies and have a clear understanding of their priorities. The benefits and trade-offs of existing systems and the alternatives under consideration should be transparent to the public, so they can make an informed decision on which benefits they are willing to pay for and their willingness to bear increased rates or taxes.

The approach used in the analysis maintained separation between the bottom lines, rather than aggregating results to a single bottom line, with the view that financial, social, and environmental costs and benefits are not interchangeable. So how do decision makers ultimately make their final decision when no alternative outperforms all the others on all bottom lines?

Historically, financial performance has been the driver, but sustainable urban water management solutions require a triple bottom line approach.

The TBL weighting analysis results showed Separated Irrigation as the top overall alternative. However, caution should be used for only using an aggregated bottom line for the final decision as it allows for Separated Irrigation's high environmental performance to compensate for its lower social performance. This information, along with an assessment of the value stakeholders place on the social and environmental benefits, can help water managers make a more informed decision, but should be considered in conjunction with the benefits and trade-offs elucidated in the TBL-MCDA analysis.

3.6 Conclusions

Here, a recent study on the benefits and trade-offs of four alternative centralized and decentralized strategies for the dual supply of raw and treated water [70] was extended using uncertainty and sensitivity analyses to address decision risk, improve transparency in the decision process, and provide insight into the benefits and trade-offs of alternative strategies. Uncertainty analysis improved confidence in decision results by allowing decision makers to consider alternative performance over the full range of plausible inputs and identify the most robust alternative over the entire range. The key drivers of model variance were regulatory and political in nature, which was not originally predicted by the project team and were only revealed through the sensitivity analysis.

The uncertainty analysis results found the Separated Irrigation alternative to have the best overall performance when the alternatives are considered across the range of plausible uncertainty. However, the sensitivity analysis identified a few key drivers that should be addressed to reduce decision risk in the future. These include uncertainties that are more regulatory and political in nature rather than technical. Stakeholder priorities had the most influence followed by the utility's access to alternative non-potable water sources in the future, ability to sell potable water to adjacent utilities, and possibility of cost savings by avoiding the need for water rights conversion. Resolving these issues depends on collaboration between the stakeholders from the initial study, state regulators, regional utilities, and local irrigation districts and canal companies.

Community preferences, gravity fed distribution and spare infrastructure capacity to meet increasing water demand favored the centralized water treatment alternatives over the decentralized alternatives in this study [70]. However, the decentralized alternatives should not be ruled out in other locations. The Neighborhood alternative offers many benefits, comparable water treatment energy use and O&M costs to conventional systems and modular solutions for areas that may not have capacity to accommodate future growth.

The participatory decision process used in the study resulted in a large number of qualitative and indirect quantitative performance indicators that require more information to characterize alternatives' performance [70]. Sensitivity analysis provided valuable insight for prioritizing which inputs to focus on in the future and which inputs would not have much impact on performance. The results of any strategic decision making process regarding urban water infrastructure will depend on local conditions and stakeholder priorities. Uncertainty and sensitivity analysis help provide confidence in the results and visibility into key uncertain inputs that require more attention in future analysis.

CHAPTER 4: COLLABORATIVE PLANNING FRAMEWORK FOR INTEGRATED URBAN WATER MANAGEMENT[3]

4.1 Summary

The historical division of water management into different sectors, with financially and technologically driven decision processes, make taking a more holistic approach to finding sustainable solutions for urban water management difficult. Here, a planning framework for Integrated Urban Water Management (IUWM) that evolved during a 2-year study evaluating alternative strategies for urban water supply within a local government context is described. The planning framework was developed to overcome the obstacles that surfaced over the course of the study. It provides a structured approach to strategic decision making that integrates triple bottom line (TBL), multi-criteria decision analysis (MCDA), uncertainty and sensitivity analyses, and participatory decision making into an exploration of water supply alternatives. TBL assured stakeholders that the decisions considered financial, social, and environmental performance. MCDA provided visibility into the benefits and trade-offs of the alternatives by providing a quantitative method for comparing alternatives that incorporates incommensurate performance indicators and priorities of multiple stakeholders. Uncertainty and sensitivity analyses addressed concerns regarding decision risk and improved transparency into inputs driving uncertainty in the analysis. Finally, a flexible participatory process helped circumvent socio-institutional barriers by adapting the methodology and increasing cooperation among stakeholders and multidisciplinary experts. The resulting collaborative risk informed TBL-MCDA (CRTM) planning framework helps refine the feasible set of alternatives by providing more transparency into the drivers, technologies and stakeholders influencing the decision. The planning framework increased the

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[3] This chapter is adapted from a prepared journal article to be submitted for publication: Cole J, Sharvelle S, Grigg N, Pivo G, Haukaas J (2018). "Collaborative Planning Framework for Integrated Urban Water Management".

number of participants involved in the study, increased interaction between participants, changed the structure of the decision problem, increased the number of performance indicators considered and improved stakeholder cooperation in the decision process.

4.2 Introduction

Urban water management is a critical component of urban livability providing sanitation, safe drinking water, urban drainage and protection from flooding, urban agriculture, aesthetics and recreation, and protection of the environment and water sources [89]. Water system maintenance is challenged by difficulties in financing the replacement of aging water infrastructure, climate change, changing populations, urban consolidation, environmental degradation, and public understanding of the value of water systems and services [2, 3, 27]. To respond, managers need a new approach which includes integrated urban water systems and distributed systems strategies; considers financial, social, and environmental costs and benefits; and employs an adaptive, participatory approach to decision making [26, 90, 91]. This paper describes the development of a planning framework for urban water infrastructure decision making with these elements that evolved during a study to assess dual water supply systems for the City of Fort Collins, Colorado. The large number of study participants from diverse city departments made a collaborative and flexible approach essential. The initial decision methodology was adapted to address obstacles and participants' needs encountered during the study. The resulting planning framework provides a structured approach to high-level strategic decision making through the integration of triple bottom line (TBL), multi-criteria decision analysis (MCDA), uncertainty and sensitivity analyses, and participatory decision making.

The last century's financially-driven, technocratic water management methods resulted in the separation of technological solutions into different water sectors, isolating them from their social and environmental contexts, and from broader urban planning [5]. The unintended consequences of these methods include inefficient use of water, poor nutrient control, wasted energy, and insufficient institutional capacity to adapt to the complexity of social-ecological systems with new technological solutions [2, 92, 93].

Integrated urban water management (IUWM) offers an adaptive and iterative process to overcome these limitations, and align urban development and basin management, by engaging local communities in solving problems through efficient integration of water sources, water use sectors and water services at different scales [5]. Like similar frameworks, including sustainable urban water management, total water management, and One Water, IUWM attempts to [2, 5, 94, 95]:

- Balance economic development, social equity, and environmental sustainability.
- Support a flexible, transdisciplinary approach involving multiple stakeholders and public engagement.
- Cultivate a holistic view that recognizes relationships among the water, land use, real estate, and energy sectors.
- Create a more natural water cycle that addresses urban water way disconnections.
- Increase flexibility and resiliency of urban water systems.
- Enhance water security through local source diversification with non-traditional water sources.
- Implement a fit-for-purpose approach that matches water quality with the intended use.
- Use water, energy and nutrient resources efficiently.

Despite initiatives to adopt IUWM, few successful implementations have been reported. Key obstacles include lock-in effects from legacy systems, a risk-averse culture with little tolerance for uncertainty, increased complexity, biases toward technocratic solutions, financially driven decisions, decreasing government budgets, vertical and horizontal institutional fragmentation, and a lack of collaborative governance and community participation [2, 26, 92, 96]. Marlow et al. [2] identified two feedback loops, a hard loop focused on asset management metrics and soft loop driven by stakeholder perceptions of responsibilities, values, risk tolerance, and willingness to pay, driving investment decisions. The soft loop is likely responsible for the low level of adoption of alternative strategies [2] and highlights the need for methodologies to improve stakeholder visibility into all the costs and benefits of competing strategies. This soft feedback loop concept introduced by Marlow et al. [2] is used throughout this chapter.

Researchers have offered several conceptual frameworks to address obstacles to IUWM. The American Water Works Association (AWWA), United States Environmental Protection Agency (USEPA), and American Society of Civil Engineers (ASCE) promote TBL analysis for water infrastructure decision making to encourage more sustainable practices [69, 97, 98]. TBL structures the decision problem into economic, social, and environmental dimensions and maintains separate bottom lines to include all costs and benefits [99]. Several studies have used MCDA, which provides a computational method for analyzing a set of decision alternatives (discrete decision space) over incommensurable criteria with different weights of importance [24], in water resources management decision problems [23, 46, 53, 54, 100, 101]. Hyde et al. [72] and Scholten et al. [68] applied uncertainty analysis to address decision risk due to future uncertainty in a water resource development problem and a water supply infrastructure problem. Scholten et al. [68] and Karaca et al. [100] address uncertainty with MCDA and alternative future scenarios.

Other authors have applied social learning frameworks to address socio-institutional barriers to IUWM [93, 102, 103].

Marlow et al. [2] shows how the ‘option space’, a sub-set of feasible alternatives, is influenced by actors (participants involved in the water infrastructure decision process), technology (solutions available and the confidence in performance) and drivers (goals, constraints and other factors) in IUWM decision making. This concept of option space is used throughout this chapter. More guidance is needed for water managers in how to overcome obstacles to IUWM when defining the option space. This paper discusses how several of the previously referenced obstacles were encountered during a 2-year study exploring alternative strategies for dual water supply within a local government context. A collaborative, risk informed, TBL-MCDA (CRTM) planning framework for IUWM evolved through the integration of various strategies suggested in the literature for overcoming obstacles to water resources and environmental decision making. The CRTM framework addresses the challenges of organizational fragmentation and bias toward technocratic solutions with a flexible transdisciplinary process involving multidisciplinary experts and stakeholders. It uses a hybrid TBL-MCDA approach to decision making that seeks to fully consider and provide transparency into the financial, social, and environmental benefits and trade-offs of the alternatives considered. Finally, it uses uncertainty and global sensitivity analyses to address decision risk and problem complexity by evaluating the reliability of the results under uncertainty and improving transparency into the inputs driving uncertainty in the results.

4.3 Study to Assess Alternatives for Dual Water Supply

The City of Fort Collins is committed to sustainability in their approach to planning for the future, which involves a dynamic process that includes systems thinking, continuous improvement, and TBL analysis [104]. Water managers at the utility saw replacement of their aging water supply distribution system as an opportunity to improve the water supply infrastructure to better meet the city's future water needs and sustainability goals. These goals included improving drinking water quality, promoting more efficient use of water and energy resources, enhancing the city's water corridors, improving community livability, and facilitating sustainable regional benefits [70, 104]. The Water Engineering and Field Services Operations Manager discussed ideas for separate water supply via dual distribution systems with Colorado State University (CSU) faculty, which led to a 2-year study where Fort Collins Utilities commissioned CSU to explore the topic further [70]. The study evaluated four alternatives for the dual supply of raw and treated water, in addition to maintaining the existing conventional system. The first three alternatives used the existing distribution system to supply raw water for irrigation and fire supply but considered varying scales of decentralized water treatment and new potable distribution (centralized water treatment and dual distribution, neighborhood scale water treatment and neighborhood dual distribution, and point-of-entry water treatment with single distribution of raw water). The fourth alternative utilized the existing network of irrigation ditches throughout the city to supply raw water for seasonal irrigation (separated irrigation systems).

The study participants were comprised of four main groups, the project team, internal and external experts, and the stakeholder group. The initial interdisciplinary project team was comprised of managers from three departments within the utility (water engineering & field services, water treatment, and water resources) and researchers from the Civil & Environmental Engineering Department at CSU. Internal experts were experts outside the initial project team from different city or CSU departments. External experts were the other experts consulted who did not work for the city or the university. The stakeholder group included the project team and representatives from multiple city departments comprising the Nature in the City Group (NICG).

This group has direct engagement with residents, community and business partners, the Mayor, and City Councilmembers through participation in a project that focuses on improving the community's access to nature. The NICG focuses on how to enhance the city's natural areas to support more diverse social and ecological opportunities [105].

Although the city is committed to collaborative governance and sustainability in future planning, there is no standard method for incorporating systems thinking, TBL analysis, and continuous improvement in a collaborative decision process. Like other cities, departments are organized by technical specialty and tend to work independent of one another. This posed a methodological problem for the project team. How could it foster collaboration among departments needed for systems thinking and continuous improvement and conduct a quantitative, reproducible triple bottom line analysis of the alternatives?

Original Methodology

The original methodology proposed for the study incorporated TBL and MCDA in the analysis, but took a linear, technocratic approach driven by the project team, with limited opportunity for stakeholder participation (Figure 4.1). The project team was responsible for identifying alternatives and structuring the problem; expert consultation was intended to guide alternative designs; and stakeholder input was limited to weighting the criteria used in the decision analysis.

The City of Fort Collins uses TBL for future planning and decision making to ensure a comprehensive consideration of all the benefits and trade-offs associated with a project from an economic, human, and environmental perspective [104]. Evaluating alternative urban water strategies through TBL is not new. Chen and Wang [44] conducted a TBL cost-benefit analysis by monetizing social and environmental benefits, and Kang and Lansey [35] and Liner and deMonsabert [45] applied optimization methods to multi-objective water supply problems to demonstrate the trade-offs between TBL objectives. Karaca et al. [100] conducted a qualitative TBL analysis of water and energy infrastructure using MCDA and scenario planning. These studies provide insight into criteria and methodologies that can aid decision makers by improving transparency into the benefits and trade-offs between economic, social, and environmental objectives. However, they do not address the inclusion of competing stakeholder priorities in the decision-making process.

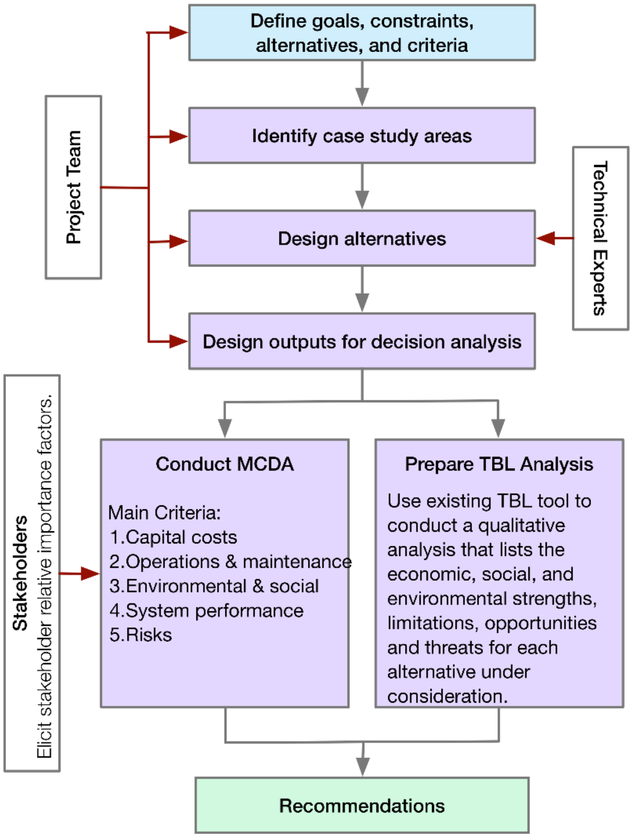


Figure 4.1: Original Approach

Hajkowicz and Collins [46] suggest using MCDA in water resources decision problems to provide transparency and accountability in the decision process; include and facilitate conflict resolution among multiple stakeholders; provide a logical and robust framework for decision making; and allow for inclusion of important non-financial factors (e.g. water quality, greenhouse gas emissions, improvements to urban natural areas, affordability) in the decision-making process. Using MCDA in this way provides a structured methodology for exploring the option space and narrows the field of feasible alternatives.

The original methodology proposed using MCDA to evaluate the alternatives' performance on the criteria identified by the project team with the results aggregated to provide a single bottom line (Figure 4.1). Independent of the MCDA, the city's existing TBL tool, based off the City of Olympia and Evergreen State Sustainability Action Map [106, 107], was used to complete a TBL analysis for each alternative (Figure 4.1). It is a qualitative tool that provides a list of an alternative's strengths, limitations, and opportunities from an economic, social, and environmental perspective but does not provide a method for computing the bottom lines. The MCDA results and TBL lists would have been used to make recommendations for future strategies.

Stakeholder and Project Team Identified Needs for Project Success

The decisions made in the study could have affected several other departments within the utility, the city, and the broader region, making collaboration essential to the study's success. Collaboration was pursued through a transparent, cooperative, and adaptive process focused on improving participant knowledge, understanding the problem from multiple perspectives, and remaining open to stakeholder feedback to ensure alignment with city goals and community priorities. Engaging in this process surfaced several additional needs for project success.

Need for more inclusive participation

Due to the exploratory nature of the study, consultation with utility experts led to the identification of other experts to consult, ideas for other alternatives to consider, and a larger perspective of the problem. The original approach (Figure 4.1) needed to be more agile to accommodate a continuously evolving problem structure as a larger, more diverse group of experts were consulted.

The first stakeholder meeting with the NICG sought to explain and validate the project, methods, alternatives, evaluation criteria, and elicit stakeholder preferences. The project team arrived with a set of highly technical criteria that also included a small number of social and environmental criteria. The original criteria were grouped under five main criteria: capital costs, operations and maintenance, social and environmental, system performance, and risks (Figure 4.1). However, during and after the first stakeholder workshop, it was clear that stakeholders wanted more meaningful participation. They felt the original criteria did not adequately address ecological and social concerns. They identified several missing criteria and felt their involvement in defining the criteria used to evaluate the option space was important to ensure a comprehensive analysis of the alternatives.

The initial technocratic approach did not fully consider the soft feedback loop and the need to integrate a wide variety of stakeholder values, interests and priorities in the identification and analysis of alternative strategies. It assumed the non-technical stakeholders (NICG) would be satisfied with a level of participation typical to other MCDA studies where they rate the relative importance of the performance metrics defined by experts. The result was stakeholders did not feel empowered in the decision process and were unwilling to participate further if changes were not made.

Comprehensive TBL approach

The NICG also believed the decision methodology deviated too far from the TBL approach city staff had become accustomed to using. They were unclear how the proposed decision analysis methods would interface with TBL in the final decision. Their other concern was that since social and environmental performance indicators were all included under one of the five main criteria (Figure 4.1), financial, social, and environmental performance did not have equal standing in the decision analysis. This reflects the non-compensability issue brought up in the literature in the ‘strong’ versus ‘weak’ sustainability debate where there is disagreement on whether human-made capital assets can substitute natural capital assets as long as the aggregated income does not decrease over time (weak sustainability) [108]. Strong sustainability advocates stress these are not interchangeable as natural capital must be protected to ensure success of future generations [108].

Uncertainty and decision risk

Enabling a larger group of experts and stakeholders from different backgrounds to define the problem structure increased the complexity of the decision problem. How would decision risk from uncertainty in the applied MCDA methodology, stakeholder preferences, and inputs used to assess alternative performance be dealt with in the decision analysis? How could the project team identify key inputs driving uncertainty in alternative performance and simplify the decision model for future analysis? Finally, how should major future changes that could alter the structure of the decision problem be addressed?

4.3 CRTM Planning Framework

The unanticipated stakeholder and project team concerns and reluctance of stakeholders to participate further without changes led the project team to re-evaluate the methodology. Several modifications were made to address concerns and regain stakeholder commitment to the study. The CRTM planning framework (Figure 4.2) evolved from the needs identified for project success. The new framework addressed the methodological concerns by integrating the three pillars of sustainability into the decision model with a new hybrid TBL-MCDA approach, decreased decision risk with the inclusion of uncertainty and sensitivity analyses and scenario planning, and included a more flexible participatory approach throughout the decision process. The hybrid TBL-MCDA provided structure for complex IUWM decision problems by ensuring the financial, social, and environmental bottom lines have equal representation in the final decision. Inclusion of uncertainty and sensitivity analysis using Monte Carlo and variance-based methods provided insight into performance under future uncertainty and transparency into the model inputs driving the decision process. Scenario planning would enable the evaluation of extreme future scenarios that cannot be addressed with uncertainty analysis. Finally, including the NICG, multidisciplinary experts, and managers throughout the process enabled a holistic transdisciplinary approach to urban water management decision-making, fostered better alignment with city goals, and identified conflicts and opportunities for collaboration with other city departments.

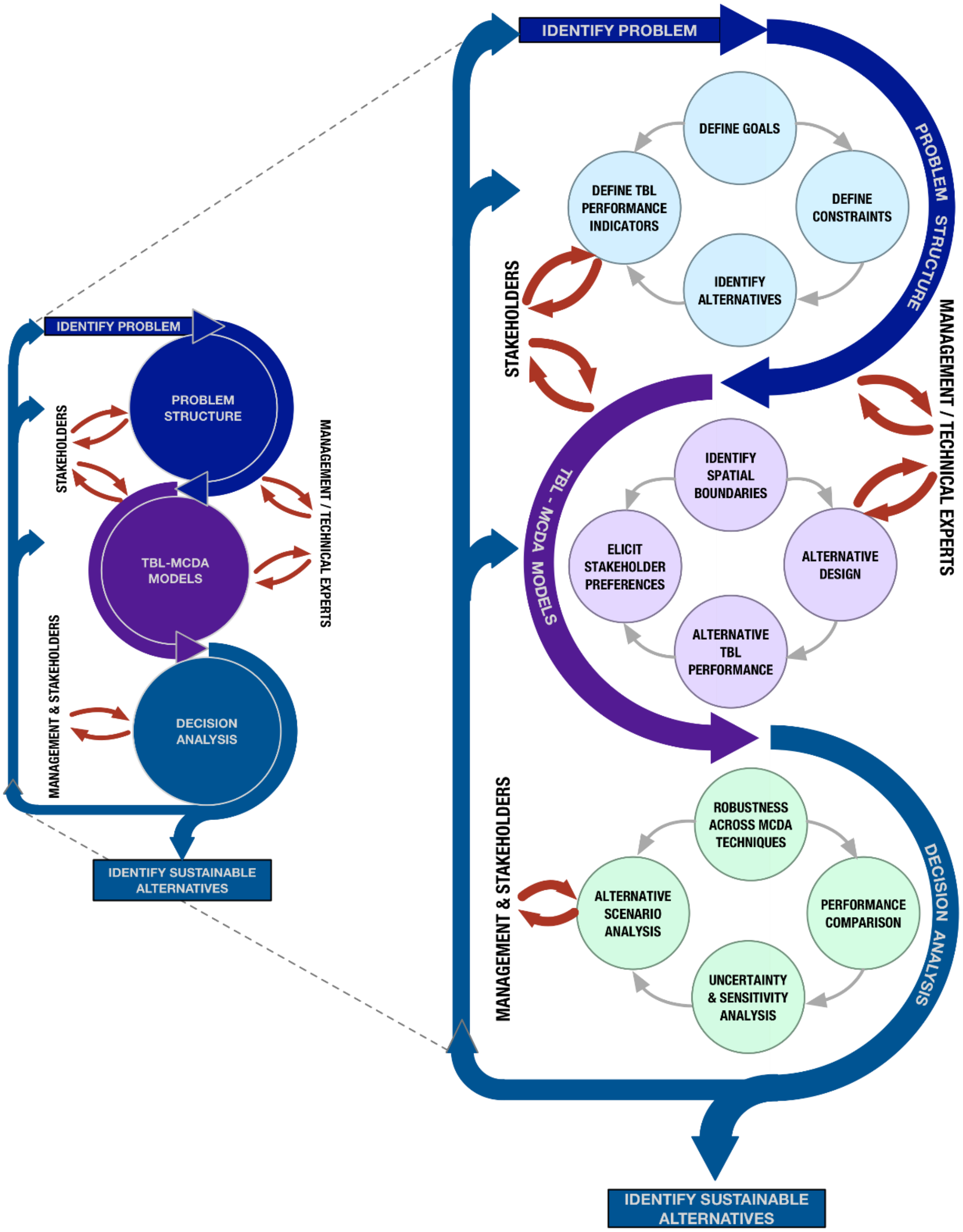


Figure 4.2: CRTM Planning Framework

Hybrid TBL-MCDA Approach

In a study evaluating sustainability in asset management in the Australian water sector, water professionals agreed water authorities needed to embed sustainability into decision tools and move away from thinking of sustainability as a ‘bolt-on issue’ to be successful [109]. The NICG in the dual water supply study expressed the same sentiment. The original approach, like other studies that applied MCDA to evaluate water management alternatives, used a combination of financial, social, and environmental criteria to calculate one aggregate score rather than a score in each bottom line [110, 111]. However, in Fort Collins, visibility of alternatives’ performance on each bottom line was important to stakeholders. The CRTM framework took a new hybrid TBL-MCDA approach (Figure 4.3), which integrated TBL into the MCDA and maintained separation between financial, social, and environmental performance. The main criteria were evaluated through each TBL lens to ensure comprehensive consideration of the impacts and ensured the three dimensions of sustainability had equal representation in the decision process.

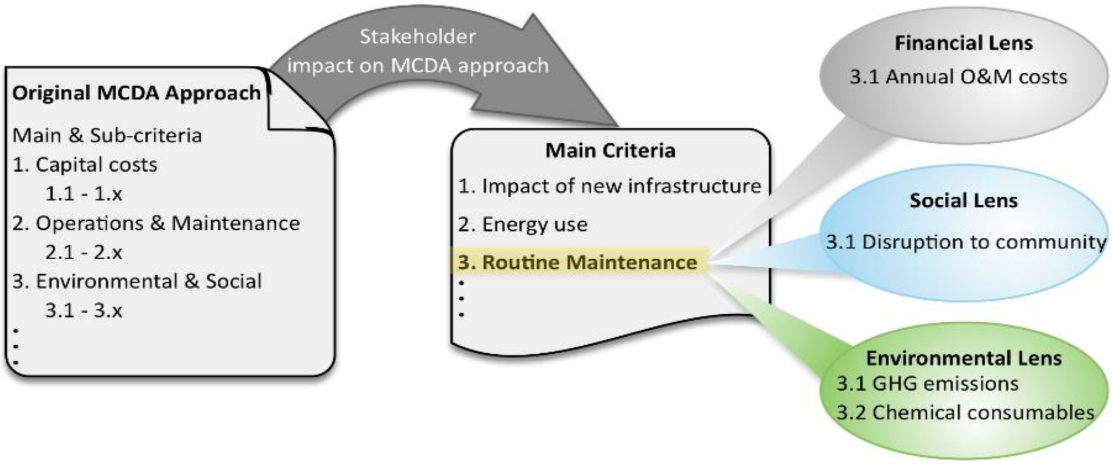


Figure 4.3: Hybrid MCDA-TBL Approach

The criteria used in the MCDAs were developed by defining the main criteria for the evaluation of the alternatives, then evaluating the main criteria from each dimension of sustainability to define the performance indicators used to measure the performance of the alternatives on each bottom line [70]. The new criteria and performance indicators were defined by the project team based on the original criteria and feedback from the NICG. Then, stakeholder preferences on the relative importance of the main criteria for each bottom line were elicited using a direct rating method [112]. This ensured each bottom line had equal standing in the final decision and allowed stakeholders to decide how important each criterion was to financial, social, and environmental performance. Outputs were developed to enable participants to readily assess performance from each TBL lens for each alternative based on average scores using stakeholder preferences in each TBL category (Figure 4.4; refer to [70] for study methodology and results).

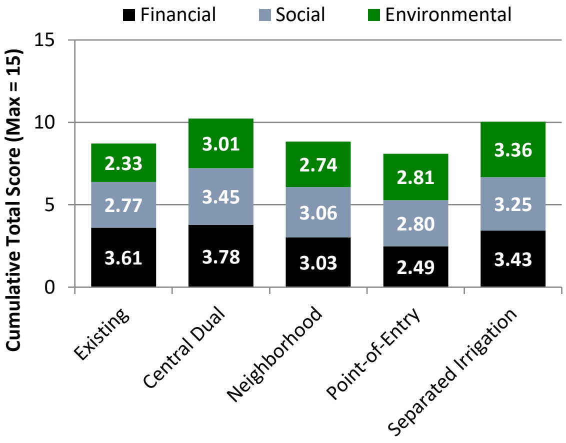


Figure 4.4: TBL-MCDA average stakeholder results for sample neighborhood 1 (Best score for each bottom line = 5 & Best cumulative score = 15) (From [25])

Addressing Decision Risk

Decision risk concerns included increasing complexity due to a larger, more diverse group of participants defining the problem structure, the MCDA technique selected, uncertainty regarding model inputs, and uncertainty in assumptions made about the future when defining the problem. The project team also wanted to improve transparency in the decision process by identifying key inputs driving uncertainty in the decision analysis results.

Robustness across MCDA methods

The most commonly used MCDA methods in water resources planning and management decision problems are compromise programming, analytical hierarchy process, the preference ranking organization method for enrichment evaluation (PROMETHEE) and elimination and choice expressing reality (ELECTRE) outranking methods, and the weighted sum method (WSM) [46, 112, 113]. Recent water resources and environmental studies compared the results of several

MCDA techniques on the same problem and found that regardless of the technique applied, the alternative rankings only vary slightly and there is rarely a change in the top ranked alternative [22, 53, 113]. However, Hajkowicz and Higgins [22] found a slightly larger risk of change in alternative ranking with analyses that include a mix of quantitative and qualitative criteria. Stakeholder involvement in defining the criteria used in this study increased the number of criteria in the decision analysis, as well as the number of qualitative criteria. Therefore, there was a need to confirm the decision results using more than one MCDA technique.

Analytical hierarchy process and outranking methods are better suited for a mix of qualitative and quantitative data, but they are more complex and less transparent to stakeholders [112, 114]. Howard [47], Janssen [54] and Zanakis et al. [55] all found methods that are easy for stakeholders to understand, such as the weighted sum method, facilitate user acceptance and buy-in in the decision-making process. Belton and Stewart [114] recommend using a simpler method with stakeholders, to avoid stakeholder confusion, and doing a comparison analysis using other techniques later in the analysis stage for comparison of results. As a result, the WSM was used initially and then compared to an analysis using an outranking method (PROMETHEE II) to confirm decision results [70].

Other criticisms of MCDA include poor problem structuring that omits important criteria or alternatives, valuation and scaling effects from reducing multi-dimensional problems to a single dimension for aggregation, difficulty in accounting for uncertainties in model inputs, and failure to account for extreme future scenarios in the analysis [112, 115]. Integrating a participatory approach throughout the decision process helped reduce omission risk. Using multiple MCDA techniques helped address uncertainty due to the valuation and scaling techniques applied in the weighted sum MCDA technique. The remaining issues were addressed later with the integration of uncertainty and sensitivity analyses and scenario planning into the framework.

Uncertainty and Sensitivity Analyses

Services from water infrastructure may be relied upon for 100 years or more. Therefore, decisions about planning and management of urban water supply infrastructure are made under deep uncertainty [151]. Public sector decisions are conducted under a high degree of public scrutiny, and uncertainty must be acknowledged, rigorously quantified, and considered in any decision process. Uncertainty and sensitivity analyses can decrease decision risk and improve transparency into the key inputs driving the decisions. Therefore, these approaches are essential for robust decision making and evaluation of alternatives under future uncertainty [152]. Uncertainty and sensitivity analyses improve decision analysis by examining the reliability of the MCDA results given uncertainty in criteria weights and performance indicator input factors, identifying key inputs driving uncertainty in the decision model results and identifying options for model simplification [68, 71, 72].

Most MCDA sensitivity analyses in the water resources planning and management field use one-at-a-time, or local sensitivity analysis [68, 72]. However, the potential for significant highly nonlinear interactions between parameters makes variance-based global sensitivity analysis a more appropriate choice when comparing IUWM alternatives. Variance-based sensitivity analysis measures the contribution of uncertainty in the model inputs to the output model variance by varying inputs according to a given probability distribution, simultaneously evaluating the contribution from each individual input and the interactions between inputs [68, 71, 75].

Cole and colleagues [116] performed an uncertainty analysis using a Monte Carlo-based approach to determine the reliability of financial, social, and environmental performance of IUWM alternatives. That analysis was followed by a variance-based sensitivity analysis to calculate first order (main) and total sensitivity indices for each input. Main sensitivity indices were used to prioritize inputs that had the most influence on alternative performance uncertainty. Total sensitivity indices were used to identify non-influential inputs that could be fixed in future iterations for model simplification. But how does the IUWM decision hold up if assumptions about the future environment change?

Scenarios of Alternative Futures

Contextual uncertainty, extreme changes in the utility's operating environment, which may result in a change to the drivers, actors and technologies defining the option space, cannot be addressed with uncertainty analysis. Scenario planning can address this limitation by providing a process for considering plausible alternative future scenarios [68, 100, 117]. The purpose of scenario planning is to identify uncertain and uncontrollable factors that may impact the consequences of a decision [118]. Benefits of scenario planning include enhancement of an institution's capacity to perceive, interpret and respond to change, as well as facilitate social learning [119].

In the CRTM planning framework the scenario planning process is used to identify critical uncertainties that affect water infrastructure to obtain a matrix of extreme alternative future scenarios. These scenarios are then used to "wind tunnel test" [100] the option space. The scenarios may shift the option space by changing the drivers, technologies under consideration, and the priorities of the actors. There are two levels of analysis that can then be done to address contextual uncertainty. First, the scenarios and TBL-MCDA models can be used to evaluate the performance of the alternatives in the future scenarios, focusing on the most influential inputs identified in the sensitivity analysis. Second, the scenarios can be used to examine whether the option space and factors used to evaluate the option space would change in each possible future.

MCDA, uncertainty analysis, and sensitivity analysis provide the structure for complex decision analysis, but do not address the socio-institutional barriers to taking a flexible, transdisciplinary approach needed for IUWM. A process was needed to accommodate feedback from many diverse participants throughout the study.

Participatory Process

Urban water management problems are influenced by local and regional conditions, planning decisions, regulations, water rights, geography and community priorities. Participants of IUWM projects can include representatives from the different water sectors, local customers, city departments, regional interests, and regulators (Figure 4.5). This makes a collaborative, participatory process essential for success. A participatory approach to decision making improves understanding and respect for other perspectives resulting in better technical and contextual understanding of complex problems, an increase in ownership of the outcome, the potential to address water justice issues, and establishment of the social network needed to support long-term organizational adaptive capacity [93, 120, 121]. However, lack of inclusiveness, empowerment, transparency, and clear goals can lead to a poor participation process with negative outcomes, including lack of cooperation, support and consideration for minority viewpoints [121].

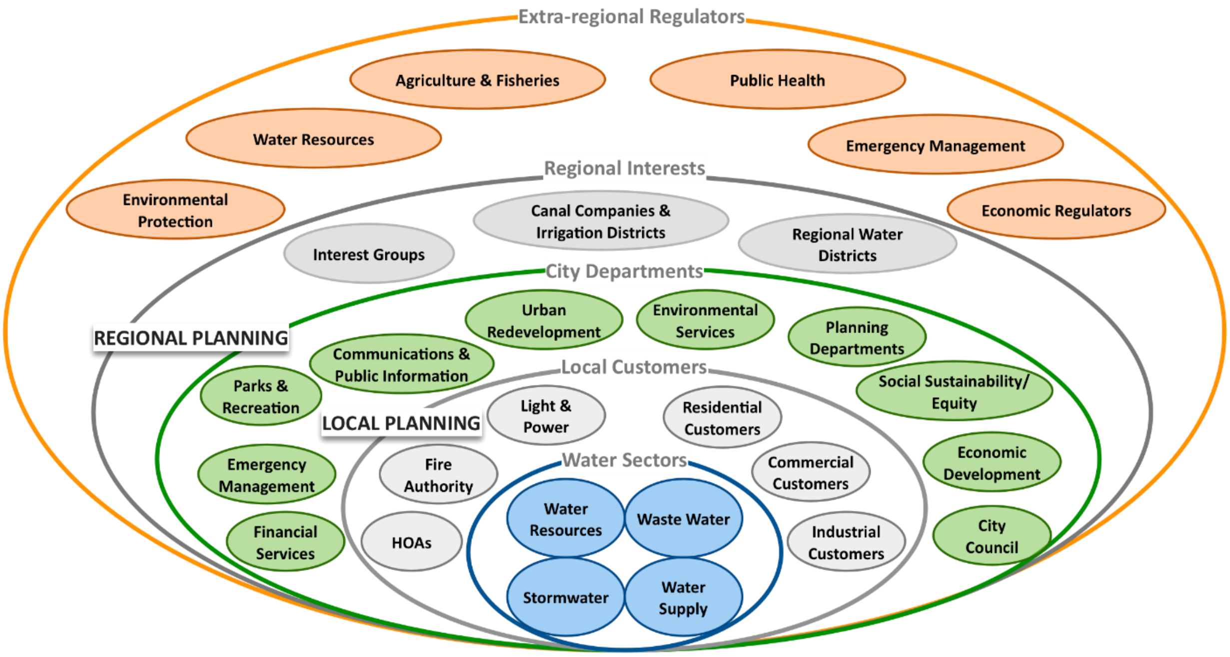


Figure 4.5: IUWM Participants

The CRTM planning framework enables continuous feedback loops between the project team, internal and external experts, and stakeholders (Figure 4.6). In the study, it included a wider range of participants, encouraged knowledge sharing among participants, and created a more agile approach. Formal meetings with utility and city department managers, as well as participation from managers in monthly progress meetings, facilitated interdepartmental collaboration. Two formal stakeholder workshops allowed the NICG to identify missing decision criteria and methodological concerns early in the study. Later, the NICG validated the revised methods and performance indicators and assigned weights to the criteria used in the decision

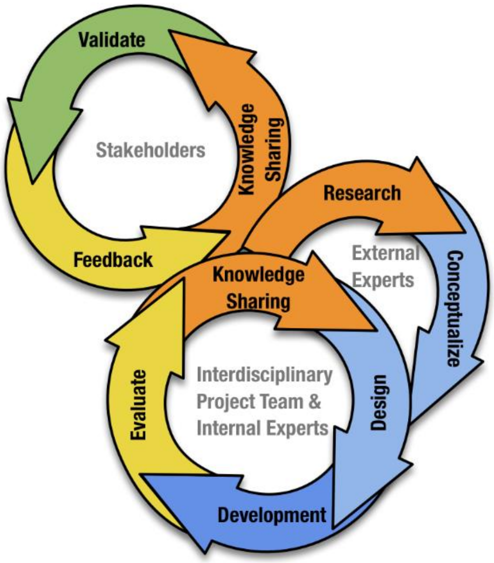


Figure 4.6: Participatory Approach

analysis. This iterative process facilitated a soft feedback loop and allowed the option space to evolve as the team consulted and presented progress to participants and received feedback to incorporate into future versions.

While each of the four components of the CRTM framework - TBL, MCDA, uncertainty and sensitivity analyses, and participatory decision making - provide a critical piece of the puzzle, merging the components into a single framework, enables practitioners to address a wider range of IUWM barriers. The CRTM planning framework builds on previous studies by integrating all four concepts to address the barriers to IUWM. The methodology provides further refinement of the option space (feasible infrastructure solutions) by providing more transparency into the factors (actors, technology, drivers) influencing the option space [2]. An iterative and participatory approach throughout the decision process provides insight into stakeholder priorities and attitudes toward risk, performance and cost of new technical solutions considered, and constraints and goals. MCDA and TBL help to provide the structure and process for facilitating complex multidimensional decision problems between multiple stakeholders and facilitate stakeholder understanding of the benefits and trade-offs associated with alternative strategies. Uncertainty and sensitivity analyses ensure better understanding of complex problems and reduce decision risk. Any long-term infrastructure decision will require several iterations of the framework as decision makers' understanding of the problem evolves or environmental conditions and stakeholder preferences change.

4.4 Impacts of the CRTM Planning Framework

This section explains how the CRTM planning framework (Figure 4.2) changed the factors influencing the option space in the study. It changed the decision models used to evaluate the option space, improved visibility into the decision process with uncertainty and sensitivity analyses, expanded the number of participants, increased communication between participants, and facilitated NICG cooperation.

TBL-MCDA Models

Changing the decision models to preserve the complimentary lenses of sustainability and including the NICG in defining the criteria and performance indicators used to evaluate the alternatives resulted in more meaningful stakeholder participation and regained their support in the study. In addition, quantitative scores in each TBL category further enhanced the capacity to assess the decision.

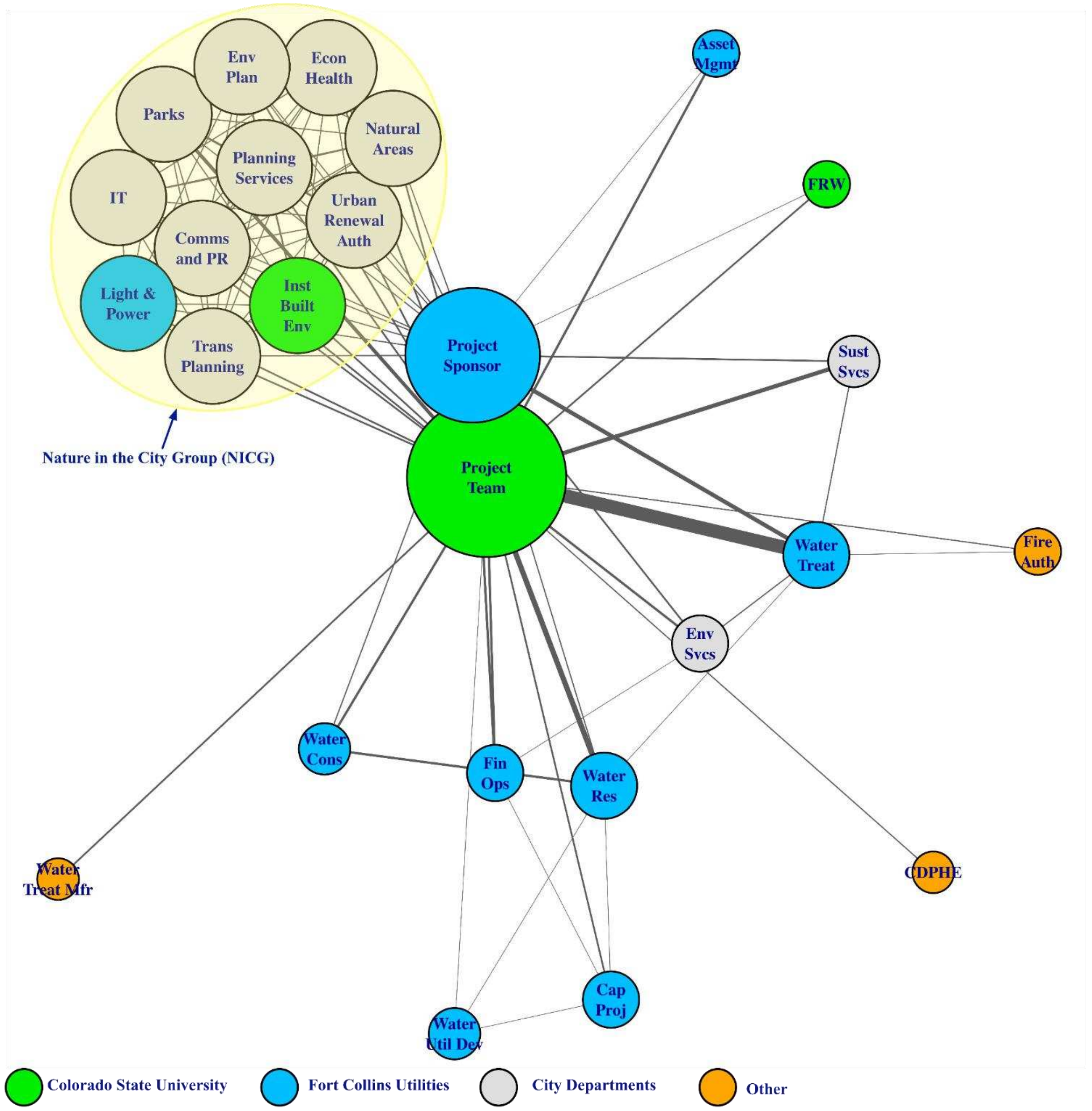
Originally, there were 25 performance indicators organized under 5 main criteria. The revised approach increased the number of main criteria to 11 and evaluating those criteria from each bottom line resulted in a total of 17 financial, 15 social and 13 environmental performance indicators [70]. Of particular interest to the group were how alternatives would affect the natural areas supported by the urban water corridors. This resulted in addition of a criterion that favored the fourth alternative (separated irrigation systems).

Addressing uncertainty

The results of the uncertainty analysis helped refine the option space by confirming that, even with the uncertainty in the model inputs and different stakeholder priorities, the centralized water treatment alternatives outperformed the decentralized alternatives on every bottom line [116]. They also showed overlap in the financial performance of the top alternatives identifying this as an important area for future analysis. The sensitivity analysis results showed that the key factors driving uncertainty in the alternatives' financial, social, and environmental performance were regulatory and political in nature rather than technical [116]. Scenario planning was added to the methodology to evaluate extreme future uncertainties that cannot be addressed with uncertainty analysis but was not done as part of the dual water systems study.

Expanding Participatory Decision Making

Initially, the project participants consisted of 8 participants from 3 departments. However, snowball sampling expanded the number of participants and departments involved as the team's understanding of the problem and people affected by the decision improved. Ultimately, the study included 41 participants representing 26 departments from the university, city, region, state, and water technology providers (Figure 4.7). Collaborating among a large group of participants made integrating a more iterative participatory process throughout the study essential.



Departments

Project Team: Civil & Environmental Engineering
Project Sponsor: Water Engineering & Field Services
Water Treat: Water Production
Water Cons: Water Conservation
Water Res: Water Resources
Water Util Dev: Water Utility Development
Fin Ops: Financial Operations
Asset Mgmt: Asset Management
Cap Proj: Capital Projects
Inst Built Env: Institute for the Built Environment
Sust Svcs: Sustainability Services
Env Svcs: Environmental Services
Econ Health: Economic Health
Urban Renewal Auth: Urban Renewal Authority
IT: Information Technology
Trans Planning: Transportation Planning
Planning Services
Comms and PR: Communications & Public Involvement
Fire Auth: Poudre Fire Authority
CDPHE: Colorado Public Health & Environment
Water Process Equipment Manufacturers
FRW: Forest, Rangeland and Watershed Stewardship
Env Plan: Environmental Planning
Parks
Natural Areas
Light & Power

Figure 4.7: Knowledge sharing among study participants

Force-directed graph using Fruchterman & Reingold algorithm. Nodes represent the 26 departments/organizations involved in the study. Node size represents the number of shortest paths going through that department (betweenness centrality) (igraph R package). Connections represent knowledge sharing communications. Thickness of connections represent the number of communications. Meetings, workshops, and phone conversations were represented as reciprocal communications and emails as unidirectional communication.

Stakeholders included in this study were representatives from city departments (Figure 4.7: NICG). While local government participants are key stakeholders, implementation of IUWM requires additional buy-in from customers, other stakeholders and regulators. These groups were not included in this initial study but are discussed further in the Discussion Section.

Engaging in a soft feedback loop process resulted in several important changes. Participant feedback expanded the evaluation factors and the option space as stakeholders shared community values and priorities, other city managers shared departmental goals, and multidisciplinary experts revealed financial, technical, regulatory or political constraints. It gave study participants a more holistic view of the problem and a better understanding of different stakeholders' attitudes toward risk.

The participatory approach (Figure 4.6) taken in the CRTM framework used in the dual water systems study led to a greater level of interaction among study participants. The original methodology would have resulted in a star shaped social network graph of communication among participants with all communication flowing to and from the project team. Instead there were more communication connections between participants than originally anticipated (Figure 4.7). The exchange of knowledge between the project team, utility, and other city departments led to a better understanding of how the project would affect the objectives of other city departments, how it fits into the city's overall goals, and the priorities of the local community.

4.5 Discussion

The original methodology in the dual water systems study led to the confrontation of several challenges to IUWM identified in previous studies. However, more inclusive participation throughout the study and maintaining a cooperative approach allowed for the identification of obstacles to project success and the adaptation of a decision framework to address those obstacles.

The resulting CRTM planning framework was successful in overcoming some of the identified barriers to IUWM but did not address ‘lock-in effects of legacy systems’ [2] or regulatory hurdles which need to be considered in future work. This framework stresses the importance of involving stakeholders and experts from the beginning of a project in an iterative process to ensure contextual and technical understanding of the problem, empower stakeholders, and garner support. The importance of integrating a hybrid TBL-MCDA approach to provide structure for the decision analysis, ensure problems are evaluated from the three lenses of sustainability, and make transparent to stakeholders the benefits and trade-offs involved with alternatives. It also addresses the need for the inclusion of techniques, such as uncertainty analysis, scenario planning, and sensitivity analysis, that account for future uncertainty and provide a better understanding of the increasingly complex problems water managers are asked to solve. The focus of this study was on IUWM decision making in a public utility context. However, the CRTM concepts could potentially be applied to other contexts as the challenges faced by IUWM decision makers are similar to other public infrastructure decisions involving complex systems and multiple stakeholders.

Addressing IUWM Barriers

The CRTM planning framework (Figure 4.2) integrates TBL, MCDA, uncertainty and sensitivity analyses, scenario planning, and a participatory process to address obstacles to IUWM planning. Limitations of the original methodology and the participant needs identified for project success arose from several of the IUWM barriers previously identified in the introduction section. Several researchers have combined more than one method to increase the effectiveness of their approach. Hyde et al. [72] and Sapkota et al. [110] both proposed frameworks that utilize MCDA and uncertainty analysis to evaluate sustainable water alternatives. Scholten et al. [68] took this a step further and applied MCDA, uncertainty analysis, and global sensitivity analysis to water supply infrastructure planning. Scholten et al. [23] and Karaca et al. [100] both use MCDA and scenario planning to evaluate water infrastructure decisions. Ultimately, the synergy created from integrating these different methods in a single planning framework enables decision makers to overcome many IUWM barriers (Table 4.1).

Table 4.1: How the CRTM planning framework addressed barriers to IUWM decision making

IUWM barriers encountered	How the CRTM planning framework addressed barriers
Lack of collaborative governance	Addressed institutional obstacles to collaboration through an informal, flexible, participatory process that included multiple stakeholder groups, water sectors, and city departments. Revised methodology regained stakeholder support and further participation in the study.
Risk averse culture	Stakeholder participation was key to understanding different types of risk and attitudes towards those risks. Uncertainty and sensitivity analyses, and scenario planning provide a structured methodology for addressing decision risk.
Bias toward technocratic solutions	Inclusion of stakeholders in a collaborative, iterative approach throughout the project allowed for better contextual understanding of the human, technological and ecological dimensions. TBL-MCDA allowed for inclusion of more subjective criteria important to stakeholders in the decision analysis.
Vertical & horizontal fragmentation	Managers from different "silos" were included through informal meetings, inclusive monthly progress meetings, and stakeholder workshops. This participation facilitated the identification of areas of alignment and conflict, which allowed for a more holistic approach.
Lack of information and/or appropriate tools	Stakeholder and expert involvement in an iterative, participatory process allowed for knowledge sharing between participants resulting in a comprehensive approach to the problem. TBL-MCDA, uncertainty analysis and sensitivity analysis provided a structural framework for the decision process.
Increased complexity	Integration of a participatory process increased understanding of the problem from multiple perspectives. Sensitivity analysis can help identify key inputs driving the uncertainty in the decision results and simplify the decision problem for future iterations.
Decisions driven by financial metrics	Hybrid TBL-MCDA approach provided transparency into all costs and benefits by analyzing the decision problem through the three pillars of sustainability and including incommensurable and intangible performance criteria in a quantitative manner.

The project identified two feasible dual water supply alternatives for the city to consider in future planning, centralized water treatment with dual distribution and separated irrigation systems. The revised approach garnered buy-in from stakeholders and water managers would like to implement a pilot study. However, 'lock-in effects of legacy systems' [2] still pose an obstacle to implementation. In a built out urban area, implementing alternative solutions is less difficult in redevelopment or new development areas on the fringe of the service area. There is interest in a neighborhood planned for redevelopment located close to the central water treatment facility for implementation, but this remains in the preliminary discussion phase. Marlow et al. [2] point out that implementation of new solutions will likely happen incrementally over time. Maintaining momentum to implement new strategies will require concerted effort and ongoing community engagement.

Community Values

Several water utility sustainable practices and technical solutions exist, but there is a gap in adoption of these systems by local governments. Landis [122] found that less than half of the 125 US water utilities surveyed are using sustainability practices or technologies and only 21% had a sustainability plan or policy approved by the local government. Fort Collins is a progressive city with a Sustainability Services Department and has adopted sustainability and climate action plans. The local community has a history of innovation and investment in its future focused on ecological and social values [123, 124]. Smithsonian Lemelson Center for the Study of Invention and Innovation recognized Fort Collins as a place of invention due to its “overarching character of collaboration” between the Colorado State University, city government and local businesses [124]. Residents have approved sales tax increases to create open space and land conservation enabling the preservation of 39 natural areas [123]. The Fort Collins’ community focus on the environmental and social benefits of nurturing these natural areas had a significant effect on the option space and the key drivers included to evaluate alternative performance. This demonstrates how community values and the presence of a local university committed to community engagement can shape the option space further reinforcing the need for early engagement with the community.

Next steps involve decision makers consulting the public on the benefits they value the most to inform the decision process. Choice experiments, which are commonly used to measure individual preferences regarding ecosystem services [125, 126, 127], can be applied to assess the value the public places on the benefits of the alternatives.

Institutional Obstacles to Collaborative Decision Making

Implementation of IUWM may require fundamental changes in the structure and regulatory control of water services. The study discussed here focused mainly on water supply, but IUWM can involve wastewater, stormwater and recycled water, as well as associated issues of green infrastructure. Obtaining approvals and buy-ins from customers, other stakeholders and regulators can involve lengthy and conflictual processes involving law, politics, finance and public opinion.

As they undertake their work duties, stakeholders within a local government represent the public in part, but planners and managers are often surprised by the extent of public resistance to change, funding increases and perceived risk. To confront possible barriers, it is good practice to consider customers and ratepayers, the broader public and regulators as other stakeholders. Understanding how customers view the risks, benefits, and possible changing roles and responsibilities associated with alternative strategies is essential to understanding the full context of the problem, different stakeholder biases and customer adoption [115, 128]. Engaging the broader public early in the soft loop process helps inform the public, build trust, and prevent misinformation that could lead to public rejection of alternative strategies [92, 128, 129]. Even with broad public acceptance, risk-averse regulatory bodies have little incentive to change long-standing practices designed to avoid past failures. For example, even while homeowners have been enthusiastic to use graywater or roof runoff for irrigation, regulatory bodies have often prohibited the practice [17].

Ultimately, gaining approval from local government stakeholders within an organization is a necessary first step, but the most that can be gained at that stage is development of an initial plan. This must then be converted into an action program that includes planned public participation at different stages [130]. Even then, the public may not take interest until a definite issue, such as a rate or tax increase, is in front of them. Opposition can surface at any stage and must be anticipated.

Long-term Action Program

Implementation of alternative strategies occurs over time. As time passes, external conditions change, new technologies become available, and stakeholder opinions and objectives change. The CRTM framework addresses this with future iterations of the framework. However, integrating the CRTM framework with a dynamic adaptive policy plan [131] will provide a roadmap for identifying when water managers should engage in the next CRTM cycle. As current strategies reach a tipping point, “conditions under which an action no longer meets the clearly specified objectives” [131], the CRTM framework can be used to re-evaluate the option space.

4.6 Conclusions

This manuscript details the CRTM planning framework that evolved from a study evaluating alternative water supply strategies for a utility in Colorado. The original linear, technocratic decision process was limited in facilitating ongoing input from a diverse group of participants, evaluating alternatives from the TBL, and quantifying and evaluating decision risk. These limitations ultimately led to resistance from stakeholders. In response to these challenges a new framework evolved that provided a structured methodology for integrating TBL into MCDA, incorporated uncertainty and sensitivity analyses, and provided a more agile participatory approach to the problem. The framework addresses barriers to IUWM decision making by building institutional capacity through a more flexible and participatory approach; integrating the three pillars of sustainability, incommensurate criteria, and stakeholder preferences; reducing decision risk and improving transparency and considering extreme futures. The CRTM framework could potentially be more broadly applied to other complex public infrastructure decisions.

The CRTM framework was successful in regaining stakeholder support. Stakeholder feedback was not only the impetus for the CRTM framework, but it also impacted the criteria used to refine the option space. The TBL-MCDA models ensured a better balance between financial, social, and environmental performance in the decision analysis. The agile participatory process increased the number and diversity of participants involved in the study and increased knowledge sharing among participants. This allowed for a more holistic approach to the decision process, more collaboration between city departments and better alignment with community values.

Problem complexity was addressed with uncertainty and global sensitivity analyses. Uncertainty analysis helped refine the option space by showing how uncertainty in decision model inputs affected performance of the alternatives. Global sensitivity analysis provided more transparency for model simplification and identification of key inputs for future analysis.

There were some key lessons learned from the study that practitioners should keep in mind when applying the CRTM planning framework. Involving stakeholders early in the process and taking a flexible, adaptive approach provides local context to the problem, avoids a technocratic approach and facilitates stakeholder participation and buy-in. In addition to coordinating across city departments, addressing issues of long-term uncertainty and risk requires integrating tools like uncertainty analysis, global sensitivity analysis, and future scenario planning into the planning framework. Determining the level of detail appropriate for the type of analysis being conducted and remaining inclusive without creating needless complexity is challenging and a method for minimizing problem complexity is essential. Finally, maintaining momentum for IUWM projects is difficult due to long planning horizons. A project timeline that includes well timed, cyclic inclusion of stakeholders throughout the process can help maintain public interest and organizational momentum.

Future work should focus on strengthening linkages with external stakeholders. This study attempted to overcome institutional barriers by focusing on horizontal collaboration at the city governance level. However, the study lacked direct public participation and vertical collaboration between local and more regional interests. Groups representing the public, utility customers, regional water utilities, canal companies, irrigation districts, and other regional interest groups should be included in future consideration of the feasible alternatives and policies for future implementation of the alternative strategies.

CHAPTER 5: CONCLUSIONS

5.1 Dual Water Supply Systems

The research presented here sought to examine whether the dual supply of raw and treated water for municipal use offers a better water supply strategy for the future; identify the unique benefits and trade-offs of centralized and decentralized dual water supply strategies; and identify key inputs driving uncertainty in the performance of these alternatives strategies. Previous research on dual water supply systems has predominately focused on the dual supply of reclaimed and treated water [14, 30, 31] or, in formerly irrigated agriculture areas where reclaimed water is restricted, separate raw water irrigation systems [32, 33]. Some considered centralized and decentralized reclamation facilities [38] and others considered the benefits to potable water quality from moving fire supply to non-potable distribution systems [34, 35]. This research extended this body of research to focus on the benefits and trade-offs of centralized versus decentralized water treatment approaches and varying distribution scales compared to separate raw water irrigation systems or conventional water supply. Although the findings were site specific, they suggest the following key findings regarding strategies for the dual supply of raw and treated water:

- The optimum strategy depends on stakeholder priorities, community goals and local conditions (e.g., topography, climate, the number, quality and location of fresh water sources, spare capacity in existing water supply infrastructure, extent of service area build out, population growth projections, the number of service connections, and whether water rights and regulations restrict the use of alternative non-potable sources).
- Dual water supply systems can result in several water treatment benefits: a reduction in capital costs, O&M costs and energy use by reducing volume of water treated and peak

demands in summer months, saving better quality source water for potable uses, and reducing the water treatment capacity required to meet potable demand.

- Dual distribution systems enable the use of alternative non-potable water sources, allow the use of lower quality fresh water sources for non-potable uses extending better quality supplies, and improve potable water quality when fire supply is moved to the non-potable distribution system, thus reducing time in the distribution system.
- Decentralized water treatment alternatives can offer some benefits over centralized alternatives: they improve drinking water quality by moving treatment closer to the point of use and they can provide backup systems in the case of short-term supply disruptions. Satellite neighborhood water treatment facilities can offer these benefits without substantially increasing water treatment energy use or O&M costs.
- Centralized water treatment alternatives are favored over decentralized alternatives when high elevations in a service area allow for gravity fed distribution systems.
- Regulatory barriers to decentralized water treatment strategies include: water quality monitoring requirements, disinfection residual requirements, and the requirement for public water systems to maintain oversight for all responsibilities.
- Separate raw water irrigation systems that integrate the use of existing urban irrigation ditches offer unique social and environmental benefits to the community by enhancing urban green spaces.
- Technical and financial performance are important in evaluating alternative dual water supply strategies, but regulatory and political considerations can represent larger obstacles in the decision making process.

- Creating the regulatory and political agreements necessary for successful implementation of alternative dual water supply strategies requires including regulators, water rights specialists, and local agriculture and regional utility stakeholders.
- Stakeholders should be included early and involved in frequent engagement throughout the decision process as conflicting stakeholder opinions have a large impact on the results and stakeholders can bring to light other alternatives, drivers and constraints.

5.2 CRTM Planning Framework

The other goal of this research was to create a planning framework to address obstacles to IUWM decision making based on the lessons learned and obstacles faced in the case study in Fort Collins. Analysis of the decision process suggests the CRTM planning framework:

- Helped refine the option space by providing transparency into the actors, drivers and technology shaping the decision.
- Enabled a collaborative process that expanded the number of participants and increased knowledge sharing through feedback loops between the project team and the diverse groups of stakeholders.
- Provided a structured TBL-MCDA process that ensured a balance between the three lenses of sustainability and included stakeholder priorities.
- Decreased decision risk and improved transparency into a complex decision process through uncertainty and sensitivity analysis.

5.3 Research Hypotheses

This section briefly summarizes whether the research findings supported the original hypotheses. While these results cannot be generalized beyond the case study, they suggest areas for consideration for other utilities evaluating similar strategies.

H1.1 The financial performance ranking of the alternatives will vary marginally, but the alternatives with the top financial performance will remain the same (Central/Dual, Conventional, Separated Irrigation) regardless of MCDA technique.

Conventional, Central Dual and Separated Irrigation remained the top three alternatives. However, the WSM slightly favored Central Dual and PROMETHEE II slightly favored Conventional as the top alternative from a financial perspective. Both methods ranked Separated Irrigation as the third best alternative.

H1.2 Central Dual will remain the top ranked alternative in social performance regardless of MCDA technique.

Central Dual remained the top ranked alternative for both MCDA methods. However, there was little agreement between methods or stakeholders on the rank of the remaining alternatives mainly due to the compensatory effects of the WSM.

H1.3 Separated Irrigation will remain the top ranked alternative in environmental performance regardless of MCDA technique.

This was supported by the MCDA results. Both methods and most stakeholders ranked Separated Irrigation followed by Central Dual as the top alternatives from an environmental perspective.

H2.1 Central/Dual, followed by Separated Irrigation, will have the best and most reliable overall performance given input uncertainty and stakeholder preference variability.

This was not supported by the uncertainty analysis results. The reverse was found to be true. When alternative performance was evaluated across the full range of input uncertainty Separated Irrigation had the best overall performance followed by Central Dual.

H3.1 Uncertainty in financial, social, and environmental performance of the dual supply system alternatives will be driven by a small number of key inputs.

This was supported by the sensitivity analysis results. However, the inputs which were the most important were unexpected. The key inputs driving uncertainty in the results were regulatory and political in nature (e.g. likelihood of using alternative non-potable sources in the future) rather than technical (e.g. indoor and outdoor demand).

H3.2 The financial, social and environmental models will have non-influential inputs that can be set to a constant value to simplify the models.

This was supported by the sensitivity analysis results. The analysis showed that 29%, 26%, and 48% of the financial, social, and environmental inputs respectively can be fixed to simplify models for future analysis.

H4.1 The proposed framework fosters interdepartmental collaboration allowing for a more holistic approach to the analysis.

This was supported by the results of the social network analysis. The analysis showed that rather than all communication flowing to and from the project team as would be expected in the original approach, there was more communication connections between participants than originally anticipated.

H4.2 The stakeholder driven decision process provides a more comprehensive consideration of the alternatives' financial, social, and environmental performance over the decision process originally proposed in the case study.

This was supported by a comparison of the original performance indicators considered and aggregated single bottom line and the resulting problem structure that almost doubled the number of performance indicators and maintained separation between the three lenses of sustainability.

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APPENDIX A: SUPPLEMENTAL INFORMATION FOR CHAPTER 2

A.1 Introduction

The supplemental information provides additional detail on the triple bottom line performance indicators, neighborhood selection, distribution system designs, information on the selection of the water treatment technologies used in the two decentralized alternatives, and comparison of neighborhood performance.

A.2 Triple Bottom Line Performance Indicators Supplemental Information

Table A.1: Summary of main criteria and financial performance indicators used in the financial bottom line analysis. Additional information on the performance indicators can be found in the final report [25].

Main Criterion	Performance Indicator	Qualitative/ Quantitative	Min/ Max	Unit	Description of performance indicator
1. Impact of new infrastructure	1.1 Cost of new infrastructure	Quantitative	Min	$	Includes costs of new transmission & distribution mains, raw water meters, backflow prevention devices, water treatment facilities, pumps, storage, and raw water filtration. EPANET2 used to determine pipe diameters & lengths. Refer to Table A.4 for unit cost data & assumptions.
	1.2 Net replacement costs	Quantitative	Min	$	Calculated for 70-year period, in 2014 constant dollars (real discount rate 3.375%[1], real escalation rate 0%). Refer to Table A.5 for lifetime assumptions.
2. Energy use	2.1 Annual energy costs	Quantitative[2]	Min	KWh/ yr	▪ Annual energy used for comparison. Includes energy use for water treatment and distribution system pumping (EPANET2). Excludes water treatment energy use met with 100 kW solar array. ▪ Water treatment calculations: Conventional used total demand, all other alternatives used base demand. Refer to Table A.6 for details. ▪ Existing distribution system gravity fed. Pumping only required for Neighborhood potable distribution (base demand) and Separated Irrigation non-potable distribution (irrigation demand).[3]
3. Routine maintenance	3.1 Water treatment O&M costs	Quantitative	Min	$/yr	Annual costs include chemicals, media, filters and repairs/maintenance for water treatment excluding energy use in 2.1. Refer to Table A.7 for details.
	3.2 Distribution system O&M costs	Quantitative	Min	$/yr	Annual costs include surveying, flushing, pipe repairs, and fixed overhead costs. Excludes energy use in 2.1. Refer to Table A.7 for details.
4. Staffing	4.1 Full time employees (FTE)	Quantitative	Min	FTE	▪ FTE needed for water treatment and distribution operations. ▪ FTE is defined as 1,920 hrs/yr, 48 wk/hr ▪ Distribution operations based on utility data on pipe leak repairs, surveying & flushing. ▪ Conventional water treatment based on current FTE and normalized by % of total demand. Other treatment uses manufacturer data.
	4.2 Training costs	Qualitative	Min	-	Training costs for new technologies and cross connection prevention. Assigns a qualitative assessment that considers how different the treatment technologies are from the conventional system, how many employees must be trained, and whether additional cross-connection training is required.
5. Consumer water quality	5.1 Health care costs due to disinfection byproducts (DBP) exposure	Quantitative[2]	Min	hr	▪ Average water age in distribution system was used for indirect comparison. ▪ Assumed water age in distribution is proportional to health care costs associated with DBP exposure. ▪ Water quality analysis run using EPANET2.
	5.2 Cross-connection event costs	Qualitative	Min	-	▪ A qualitative assessment of the risk of a cross-connection failure was used as an indirect comparison of the costs associated with cross-connection failure.

					▪ Physical conditions considered in assessing risk: separation between potable and non-potable systems, fire and irrigation services connected to potable system, max elevation difference in system. ▪ Assumes all garden hoses, irrigation systems, and fire sprinkler systems are hooked up to the non-potable system.
	5.3 Source water contamination event	Qualitative	Min	-	▪ A qualitative assessment of the cost to the utility as a result of a water contamination event. ▪ Assumed probability of event same for all alternatives. ▪ Assessments were based on travel for correction & supplies, and the number of locations affected.
6. Environmental flows	NA	-	-	-	Unable to determine without more detailed water rights analysis
7. Supply risk	7.1 Cost of alternative supplies	Qualitative	Min	-	▪ Cost of alternative supplies due to limited supply or supply disruption. ▪ Assumed the more resilient the alternative was to water shortage, the lower the costs of acquiring additional water supply.
	7.2 Risk of obsolete infrastructure	Qualitative	Min	-	▪ Risk of that infrastructure becomes unnecessary due to decrease in non-potable demand or change in water treatment requirements.
8. Rate risk	8.1 Confidence in O&M projections	Qualitative	Max	-	▪ Financial risk of incorrect revenue and O&M projections. ▪ Assumed rate revenue covers annual O&M costs.
9. Alternative source opportunity	9.1 Savings to later use of alternative non-potable sources	Quantitative[2]	Max	LF	▪ Scale of dual distribution system, in linear feet, is used for indirect comparison. ▪ Assumed the more extensive the dual distribution system, the less cost involved in implementing use of alternative sources; and alternative sources only used for non-potable uses.
10. Revenue opportunity	10.1 Wholesale water revenue	Quantitative[2]	Max	Gal/yr	▪ Additional revenue that could be generated from using spare capacity at existing water treatment facility to sell water wholesale to neighboring water districts. ▪ Spare capacity at existing water treatment facility was used for comparison.
11. Regulatory/ Political risk	11.1 New regulation costs	Qualitative	Min	-	▪ Mitigation costs for new regulations. ▪ Assumed the more alternatives deviate from conventional system, the higher the risk.
	11.2 Public relation costs	Qualitative	Min	-	Costs associated with increase in communication and managing public perception with implementation of alternative strategy.

[1] [49]; [2] Indirect quantitative metric used for comparison of alternatives; [3] Demand based on 2001-2013 monthly data (see section A.4 Alternatives Design for details).

Table A.2: Summary of main criteria and social performance indicators used in the social bottom line analysis. Additional information on the performance indicators can be found in the final report [25].

Main Criterion	Performance Indicator	Qualitative/ Quantitative	Min/ Max	Unit	Description of performance indicator
1. Impact of new infrastructure	1.1 Disruption to community	Quantitative[1]	Min	$	Social costs to community from new construction. AWWARF Asset Failure Cost Model[1] used to calculate routine social costs of access impairment, travel delay, customer outage, substitution.
	1.2 Temporary employment	Quantitative[2]	Max	-	Assumed temporary employment proportional to capital costs of project.
2. Energy use	2.1 Air pollution impacts	Quantitative[2]	Min	kWh/yr	Health impacts associated with air pollution due to emissions from energy production.[3]
3. Routine maintenance	3.1 Disruption to community	Quantitative[1]	Min	$/yr	Social costs to community from routine maintenance. AWWARF Asset Failure Cost Model[1] used to calculate routine social costs of access impairment, travel delay, customer outage, substitution.
4. Staffing	4.1 Employment/Job Security	Quantitative	Max	-	The more FTE required, the more employment and job security for community.
	4.2 Earning potential	Qualitative	Max	-	An increase in skillset of workforce results in higher earning potential.
5. Consumer water quality	5.1 Drinking water quality	Quantitative[3]	Min	hr	▪ EPANET2 used to conduct water quality analysis. ▪ Assumed water age in distribution system is an indicator of water quality.
	5.2 Cross-connection health risk	Qualitative[3]	Min	-	▪ Potential health risk from cross-connection failure. ▪ Assumed every cross-connection failure is a potential health risk.
	5.3 Adaptability to source water contamination	Qualitative	Min	-	▪ Qualitative assessment of the level of adaptability to health risks associated with source water contamination event.

					▪ Assessments based on response period due to travel time for correction and supplies and the number of locations affected.
6. Environmental flows	6.1 Natural areas 6.2 Benefits to local ditch companies	Qualitative Qualitative	Max Max	- -	▪ Merged 6.1 and 6.2. This only applies to the Separated Irrigation alternative; therefore, a quantitative assessment was not need for comparison. ▪ Separated Irrigation increases instream flows in city water corridors, which enhances the natural areas supported by irrigation ditches. ▪ Separated Irrigation also shares in O&M costs of maintaining ditches with irrigation or ditch companies.
7. Supply risk	7.1 Resiliency to supply risks	Qualitative	Max	-	Resiliency of infrastructure to limited supply or supply disruption.[3]
8. Rate risk	8.1 Affordability	Quantitative	Max	$	▪ Affordability of monthly water bill for low/fixed income households. Reflects the rate change based on change in O&M costs from existing. ▪ Assumes rate changes based on O&M costs.
9. Alternative source opportunity	9.1 Innovative community	Quantitative[2,3]	Max	LF	Being an innovative community and potential to increase in stream flows for recreational uses by later using alternative sources.
10. Revenue opportunity	10.1 Improve community water security	Quantitative[2,3]	Max	Gal/yr	Improves water security in neighboring water districts that lack spare water treatment capacity for to meet population growth projections.
11. Regulatory/ Political risk	11.1 Public acceptance	Qualitative	Max	-	Assumed public perception based on level of deviation from conventional system.

[1] [50]; [2] Indirect quantitative metric used for comparison of alternatives; [3] Uses financial performance indicator for comparison.

Table A.3: Summary of main criteria and environmental performance indicators used in the environmental bottom line analysis. Additional information on the performance indicators can be found in the final report [25].

Main Criterion	Performance Indicator	Qualitative/ Quantitative	Min/ Max	Unit	Description of performance indicator
1. Impact of new infrastructure	1.1 Greenhouse gas (GHG) emissions	Quantitative[1,2]	Min	$	▪ GHG emissions of new construction from transport of materials, equipment, and embodied energy. ▪ Assumed capital costs provide and indirect comparison.[2]
	1.2 Temporary storm water pollution	Quantitative[1]	Min	SF	▪ Footprint of new construction was used for comparison. ▪ Assumes the larger the construction footprint, the more temporary sediment pollution of storm water
2. Energy use	2.1 GHG emission in CO_2e	Quantitative	Min	lbs CO_2e /yr	Used Fort Collin's 2012 emission factor for electricity (1,672 lbs CO_2e/MWh) to convert annual energy use.
3. Routine maintenance	3.1 GHG emissions	Qualitative	Min	-	▪ GHG emissions due to maintenance vehicles/equipment. ▪ Assumed number of water treatment facilities and miles of pipe indicators of GHG due to maintenance. (Excluded 2.1 energy use).
	3.2 Chemical consumables for water treatment	Quantitative	Min	Tons/yr	Annual tons of chlorine, aluminum sulfate, calcium hydroxide, fluoride, and carbon dioxide used in water treatment.
4. Staffing	4.1 Commute GHG emissions	Quantitative[1,2]	Min	FTE	Assumed commute emissions proportional to number of FTE.
5. Consumer water quality	5.1 Water quality of receiving water bodies	Qualitative	Max	-	▪ Effects chemical addition during water treatment has on water quality of receiving water bodies. ▪ Largest environmental concerns were DBPs from chlorination and dissolved monomeric aluminum from coagulant addition.
6. Environmental flows	6.1 Ecosystem benefits	Qualitative	Max	-	▪ Similar to Social 6.1, only applies to Separated Irrigation. ▪ Increase in instream flows benefits species and natural systems.
7. Supply risk	7.1 Effects on water corridors	Qualitative	Min	-	Assigns a risk level to the potential effects variable supply could have on the city's water corridors. The existing system (Conventional) acts as a baseline for comparison of the alternatives.
8. Rate risk	8.1 Water demand	Quantitative[1]	Min	$	▪ Potential changes in irrigation water demand due to rate changes. ▪ Assumed rate changes proportional to O&M changes and irrigation water demand sensitive to price.
9. Alternative source opportunity	9.1 Improvements to water corridors	Quantitative[1,2]	Max	LF	▪ Improvements to water corridors from using alternative sources of non-potable water.[2]

					▪ Assumed the more extensive the dual distribution system, the less work involved in implementing alternative sources of supply. ▪ Assumed that alternatives sources of supply will increase instream flows in the Cache la Poudre River.
10. Revenue opportunity	10.1 Avoided construction benefits	Quantitative[1, 2]	Max	Gal/yr	Environmental benefits from decreasing the need for water treatment facility expansion and regional construction.[2]
11. Regulatory/ Political risk	11.1 Environmental impacts of new regulations	Qualitative	Min	-	Negative environmental impacts from mitigation required to meet additional or new regulatory requirements for water quality monitoring and compliance.

[1] Indirect quantitative metric used for comparison of alternatives; [2] Uses financial performance indicator for comparison

Table A.4: Summary of New Infrastructure Unit Costs

Distribution System Capital Costs	
Item	**Assumptions/Notes**
Water main with service connections: (\$/LF) = 4.35 (f_p) + 104.60 Water main without service connections: \$/LF = 3.33 (f_p) + 69.95 (f_p=6 to 12-in) \$/LF =11.59 (f_p) – 8.11 (f_p=16 to 60-in) Where: f_p = pipe diameter (in)	▪ 2014 utility unit costs ▪ Utility shares traffic control and road repair costs with another city department for 50% of new pipe installation. ▪ PVC (polyvinyl chloride) C909 up to 16-in, PC150 DIP (ductile iron pipe) for 18 to 30-in, 150 psi steel for 36 to 60-in ▪ Central/Dual: Transmission mains to neighborhoods not included in EPANET2 modeling. Assumed citywide network of transmission mains shared equally across the service area. Assumed ½ f_p existing needed for new potable transmission mains. This was deemed conservative since fire demand and seasonal irrigation demand would continue to be provided by the existing transmission mains.
Additional non-potable connection costs \$120 / non-potable connection	▪ Includes centralized raw water filtration to 80-mm ▪ Includes Fluidic-oscillation-type meters ▪ Unit costs from [132], adjusted for 2014 using ENR CCI (Engineering News-Record's Construction Cost Index)
Additional potable connection costs \$707 / potable connection	▪ Includes backflow prevention device for potable service lines ▪ Unit cost from [133], adjusted for 2014 using ENR CCI
Raw water irrigation system for Separated Irrigation Alternative \$3,510 / non-potable connection	▪ Unit cost from [32], adjusted for 2014 using ENR CCI ▪ Includes pumps, filtration, pipes, and storage. ▪ Seasonal use with pipe burial depth 24 to 30-in
Neighborhood alternative distribution pumps \$12,000 / pump	▪ 50-hp pumps with VFDs (variable-frequency drive) from [134]
Water Treatment Capital Costs	
Item	**Assumptions/Notes**
Neighborhood treatment includes: Ultrafiltration package plant (\$) = 0.0003(x^3) - 0.8109(x^2) + 2,016.9(x) + 38,246; Where: x = capacity in gal/min Chlorine Disinfection (\$) = 3x10^{-6}(x^3) – 0.423(x^2) + 267.76(x) + 29,368; Where: x = capacity in gal/min Clearwell storage = 4x10-6(x3) – 0.0636(x2) + 585.7(x) + 86,890 Where: x = capacity in 1000 gal Land acquisition range \$47,000 to \$180,000 / lot	▪ 1.0 MGD ultrafiltration package plant with chlorine disinfection and clearwell storage. ▪ Ultrafiltration, chlorine disinfection, clearwell storage costs from [135], adjusted for 2014. ▪ Average lot size and costs per sf determined for each sample neighborhood using Fort Collins geographic information system (GIS) data and local listings on Zillow.com.
Point-of-entry treatment includes: KDF/GAC Whole House Filters Single family = \$1,499/connection Duplex = \$2,185/connection Multi-family/Commercial = \$2,869/connection UV Disinfection Single family = \$1,775/connection Duplex = \$2,109/connection Multi-family/Commercial = \$5,115/connection Enclosure for treatment system Single family = \$500/connection Duplex, Multi, Commercial = \$800/connection Additional costs = \$1,524 / connection mechanical warning system/auto shut-off, installation, initial monitoring, and indirect costs	▪ Activated Carbon/KDF (kinetic degradation fluxion) with a sediment pre-filter and UV disinfection package ▪ KDF/GAC (granular activated carbon) single family from [136] ▪ KDF/GAC duplex, multi-family/commercial from www.waterinc.com/products/hosuepure ▪ UV (ultraviolet) disinfection from [137] ▪ Enclosure for treatment system from Koester Metals (www.kmienclosures.com) ▪ Mechanical warning system/auto shut-off: SEOH Hanna HI983307, EC/TDS (electrical conductivity / total dissolved solids) meter with visual alarm ▪ Indirect costs include permitting, pilot testing, legal, engineering, and contingency estimated using EPA Cost Estimating Tool [138] ▪ Installation and initial year monitoring estimated using EPA Cost Estimating Tool [138] ▪ Additional costs include mechanical warning system/auto shut-off, installation, initial monitoring, and indirect costs

Table A.5: Lifetime Assumptions for Replacement Costs

Distribution System Lifetime Assumptions

Item	Lifetime (yrs)	Notes/Assumptions
Pipe material:		• Service lifetimes from AWWA's Buried No Longer Report [139]. • FCU Pipe failure history (1997-2013) used to determine if a shorter than average, average, or longer than average lifetime was anticipated for each neighborhood. Average = 0.25 breaks/mile/year [140]. • New pipe material assumptions: PVC C909 up to 16-in, PC150 DIP for 18 to 30-in, 150 psi steel for 36 to 60-in • The costs per neighborhood for centralized water treatment and network of transmission mains were normalized by % of total service area.
PVC (polyvinyl chloride)	70	
CIP (cast iron pipe)	115	
DIP (ductile iron pipe)	72.5 to 110	
Concrete	75	
Steel	95	

Water Treatment Lifetime Assumptions

Item	Lifetime	Notes
Conventional water treatment facility	50 years	▪ Central and neighborhood lifetimes from [97] ▪ Point-of-Entry lifetime from [141]
Neighborhood water treatment facility	50 years	
Point-of-Entry treatment systems	20 years	

Table A.6: Water treatment energy use

Item	Energy Use	Notes
Conventional centralized water treatment facility	321 kWh/MG	▪ Based on average energy consumption from 2008 to 2012 ▪ 44% of energy use proportional to volume of water treated
Neighborhood water treatment:		
Ultrafiltration membrane system	474 kWh/MG	[142]
Chlorine	100 kWh/MG	(60-250 kWh/MG from [143])
Point-of-Entry water treatment:		
Filter backwash	364 kWh/MG	[144]
UV disinfection	100 kWh/MG	[145]
Mechanical warning	205 kWh/MG	Hanna HI983307/Sarco LC1350
Retained central functions for neighborhood and POE water treatment	14 kWh/MG	Includes flouridation, alkalinity & pH adjustment, pressure dissipation, exhaust fans (from Utility data 2008 to 2012)

Table A.7: O&M Unit Costs

Distribution System O&M Costs	
Item	**Assumptions/Notes**
Distribution system: Fixed costs = $0.20 / l.f. Variable costs = $0.69 / l.f.	▪ Fixed and variable costs estimated from 2013-2014 utility costs. ▪ New potable distribution systems used PVC pipe, therefore costs for these systems were adjusted using failure history data (1997-2013) to determine % of pipe failures due to electrolysis holes for each sample neighborhood. Random sample (n=20) of cost data for electrolysis hole repair used to estimate cost savings by eliminating electrolysis hole failures.
Raw water irrigation system: $75 / non-potable service connection	▪ From [32], adjusted for 2014. ▪ Only applies to the Separated Irrigation alternative

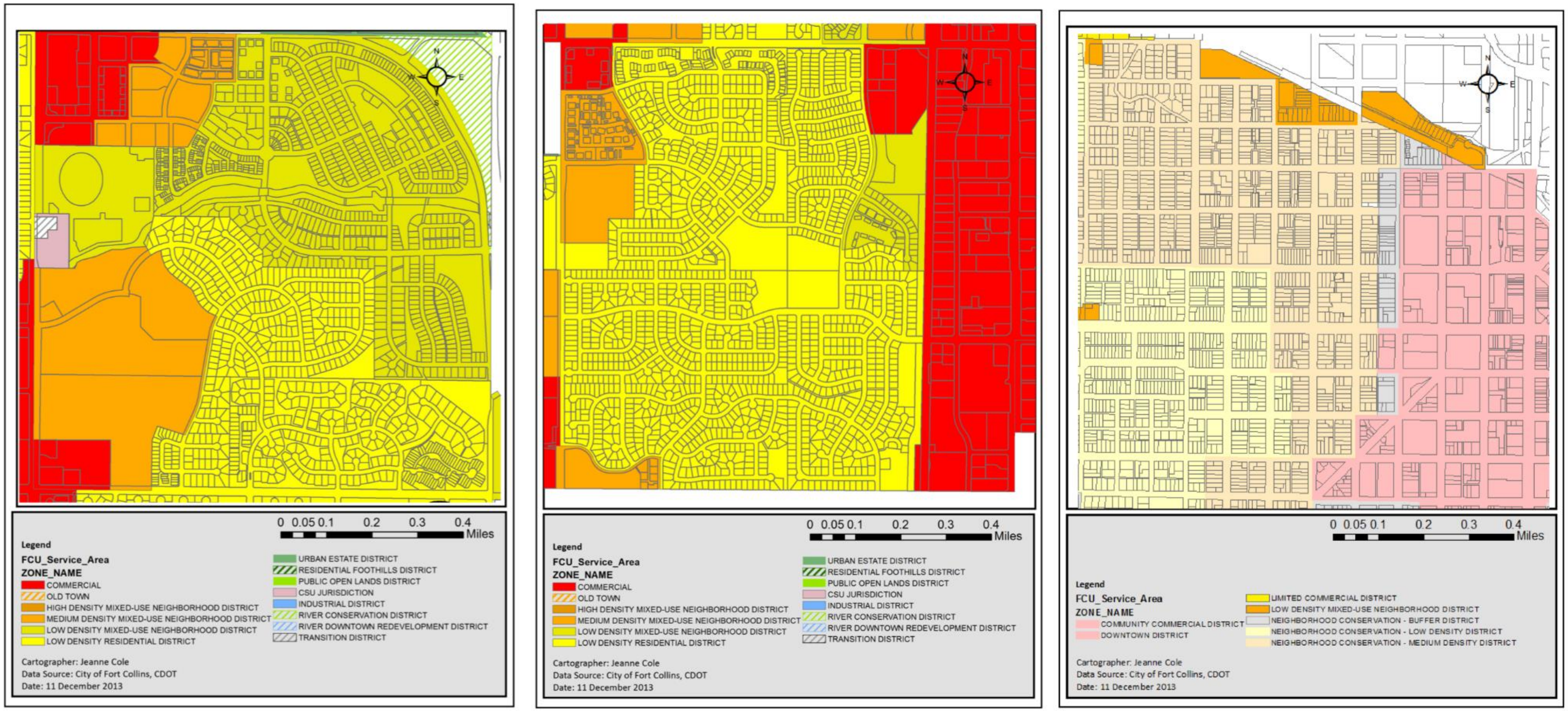
Water Treatment O&M Costs	
Item	**Assumptions/Notes**
Central water treatment: Based on utility cost data	▪ Neighborhood costs proportional to water production volume. ▪ Total demand used for Conventional and base demand used for Central/Dual and Separated Irrigation.
Neighborhood water treatment: Ultrafiltration w/ chlorine disinfection O&M = 241.28(x) + 17,092	▪ [135] ▪ Energy costs subtracted – Assumed 12% of O&M costs for energy ▪ Where: x is capacity in gpm (base demand)
Point-of-Entry water treatment: Range $4.48 to $5.24 / 1,000 gal	▪ POE based on EPA Cost Estimating Tool [138] and additional added for chronic suite testing. ▪ Base demand used to estimate costs

Table A.8: Average Water Age in Potable Distribution Systems (hours)

Alternative	Neighborhood 1	Neighborhood 2	Neighborhood 3
Conventional	16.2	11.2	8.8
Central/Dual	4.2	3.8	6.4
Neighborhood	3.9	3.2	4.5
Separated Irrigation	22.1	18.4	18.5

***POE does not have a potable distribution system**

A.3 Neighborhood Selection



Neighborhood 1 developed mid 1990s+

Neighborhood 2 developed 1970s to 1990

Neighborhood 3 developed 1890 to 1950

Figure A.1: Sample Neighborhoods Used in MCDA

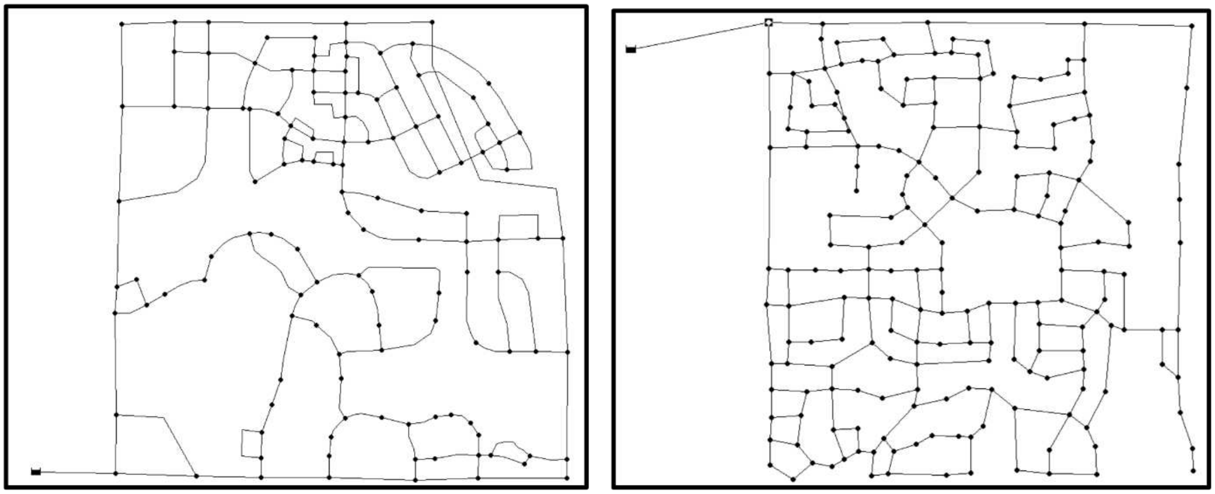
Table A.9: Summary of sample neighborhood characteristics

Characteristic Type	Neighborhood 1	Neighborhood 2	Neighborhood 3
Development era[1]	Mid 1990s +	1970s to 1990	1890 to 1950
Land use type[2]	50% low/medium density mixed use and remaining low density residential and commercial	Mainly low density residential, with commercial corridor along eastern border, and pockets of medium density mixed use	Original town center comprised of downtown commercial and low/medium density conservation
HOAs[3]	2/3 have HOAs	1/4 have HOAs	No HOAs
Distribution system information[4]	16.4 miles pipe 95% DIP[5], 5% PVC[6] High failure rate[8]	17.1 miles pipe 95% DIP, 5% PVC Average failure rate	18.5 miles pipe 75% CIP[7], 22% DIP, 3% other Low failure rate

[1] The sample neighborhoods each covered a 1-mi^2 area and represent the three main development eras in Fort Collins; [2] The sample neighborhoods represent 80% of the land use types in the service area. Another 13% are represented by CSU and Public Open Lands, which are already predominately irrigated with raw water; [3] It was important to include neighborhoods with homeowner associations (HOAs), as they tend to be large water users for the irrigation of green spaces; [4] Distribution system information was used with calculating replacement costs and maintenance performance indicators for the existing distribution system; [5] Ductile Iron Pipe; [6] Polyvinyl Chloride; [7] Cast Iron Pipe; [8] Failure rates are in reference to national average = 0.25 [140].

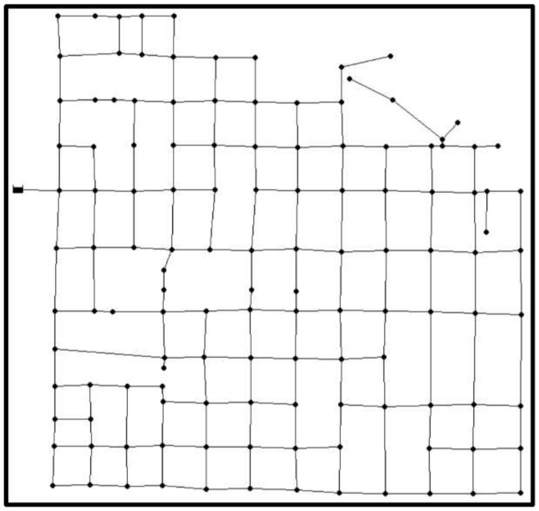
A.4 Alternative Designs

Distribution System Modeling



Neighborhood 1 network layout

Neighborhood 2 network layout



Neighborhood 3 network layout

Figure A.2: Neighborhood network layouts created in EPANET2

Utility information was used to create the layout and provide the diameters used in the existing system. All other information, such as node and water treatment facility distance from the neighborhood, does not necessarily represent the existing system. The systems were also modeled in isolation from the citywide network. It was assumed that the dual distribution systems would run in parallel to the existing distribution system allowing for the use of the same neighborhood network layout for all alternatives.

Table A.10: EPANET2 Model Scenarios

Alternative	Model Scenarios[1]
Conventional *Summary:* *- Existing central water treatment facility treats total demand* *- Existing transmission and distribution lines for potable water distribution to meet indoor, irrigation, and fire demand*	1. Model water age in existing single potable distribution system using average total demand and diurnal pattern for total water use. (Note: Average annual total demand is used, which means water age in summer will be less than that in winter because of irrigation demand in summer months.)
Central/Dual – Central water treatment and dual distribution of potable and raw water *Summary:* *- Existing central water treatment facility treats indoor demand only* *- Existing transmission and distribution lines for raw water distribution to meet irrigation and fire demand* *- New potable only transmission and distribution lines for potable water distribution to meet indoor demand*	1. Design new potable only distribution system using base demand and a peak factor of 2.5.[2] 2. Model water age in new potable distribution system using base demand and diurnal pattern for indoor use.
Neighborhood – satellite water treatment and neighborhood dual distribution of potable and raw water *Summary:* *- New neighborhood water treatment facility treats indoor demand* *- Existing transmission and distribution lines for raw water distribution to meet irrigation and fire demand* *- New potable only neighborhood distribution lines for potable distribution from neighborhood water treatment facility*	1. Design new potable only distribution system and pump sizing using base demand and a peak factor of 2.5.[2] 2. Model water age and pumping energy in new potable distribution system using base demand and diurnal pattern for indoor use.
Point-of-Entry – Single raw water distribution system with POE water treatment	No EPANET modeling required because it does not include a dual distribution system and potable water treatment occurs at the customer service connection
Separated Irrigation – Addition of irrigation only distribution system from irrigation ditch network *Summary:* *- Existing central water treatment facility treats indoor and fire demand* *- Existing transmission and distribution lines for potable water distribution for indoor and fire demand* *- New raw water distribution system from irrigation ditch for irrigation demand*	1. Model water age in existing distribution system with base demand and diurnal pattern for indoor use. 2. Design new raw water irrigation only distribution system using irrigation demand and a peak factor of 6.0.[2] 3. Model pumping energy in raw water irrigation system based on diurnal pattern for outdoor use.

[1] Monthly demand data from 2001 to 2013 was used to estimate the average base, irrigation, and total demand for each service type. December to February data was used to estimate average base demand. There is little fluctuation from base demand in March and November. Average irrigation demand used April to November average (minus base demand).

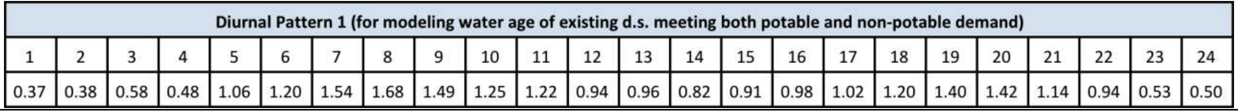
[2] A trial and error approach was used for design.

Table A.11: Distribution System Design Requirements/Assumptions

Operating pressures [146, 147]	○ Minimum pressure, without fire flow, in potable distribution system = 40 psi ○ Optimum pressure between 40 to 80 psi ○ Pressure reducer valves required on all service where pressure is greater than 80 psi ○ Separated Irrigation Alternative: Minimum = 25 psi; Optimum between 25 to 50 psi
Peak factors [148, 149]	○ Peak factor of 2.5 was used for design based on the Water Supply and Demand Management Policy ○ Separated Irrigation Alternative peak factor 6.0 based on water-wise watering suggestions
Maximum velocity Minimum diameter New pressure pipe [104, 150]	5 ft/s Residential = 2-inches; Commercial = 6-inches AWWA C900 or C909 PVC Pressure Pipe or equivalent

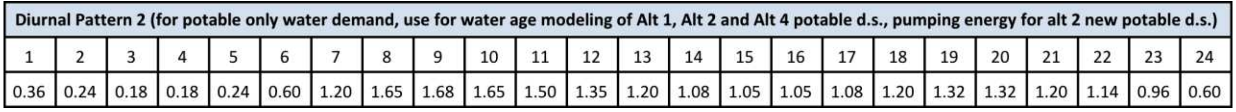
Diurnal demands used for water age and energy modeling:

Total water use diurnal demand [19]



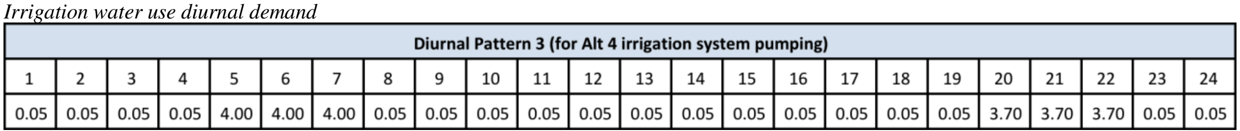
Diurnal Pattern 1 (for modeling water age of existing d.s. meeting both potable and non-potable demand)																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.37	0.38	0.58	0.48	1.06	1.20	1.54	1.68	1.49	1.25	1.22	0.94	0.96	0.82	0.91	0.98	1.02	1.20	1.40	1.42	1.14	0.94	0.53	0.50

Indoor water use diurnal demand [19]



Diurnal Pattern 2 (for potable only water demand, use for water age modeling of Alt 1, Alt 2 and Alt 4 potable d.s., pumping energy for alt 2 new potable d.s.)																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.36	0.24	0.18	0.18	0.24	0.60	1.20	1.65	1.68	1.65	1.50	1.35	1.20	1.08	1.05	1.05	1.08	1.20	1.32	1.32	1.20	1.14	0.96	0.60

Irrigation water use diurnal demand



Diurnal Pattern 3 (for Alt 4 irrigation system pumping)																							
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
0.05	0.05	0.05	0.05	4.00	4.00	4.00	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	3.70	3.70	3.70	0.05	0.05

A.5 Neighborhood Water Treatment System Selection

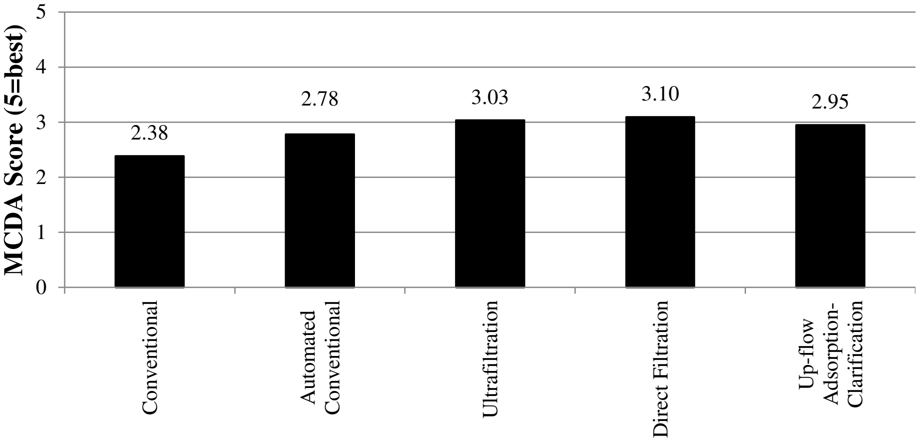


Figure A.3: Total score (WSM) for Neighborhood system selection (Max Score = 5)

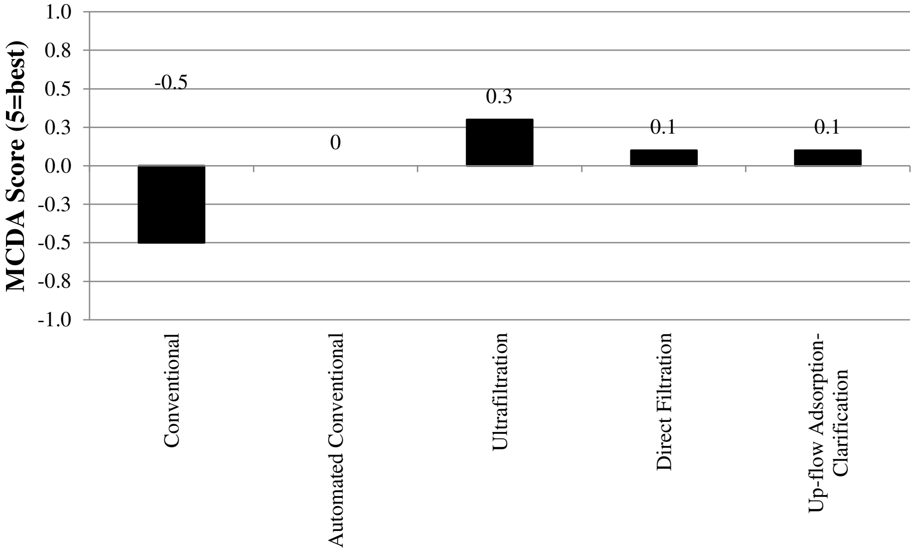


Figure A.4: Total score (PROMETHEE II) for Neighborhood system selection (Max Score = 1)

A.6 Point-of-Entry Water Treatment System Selection

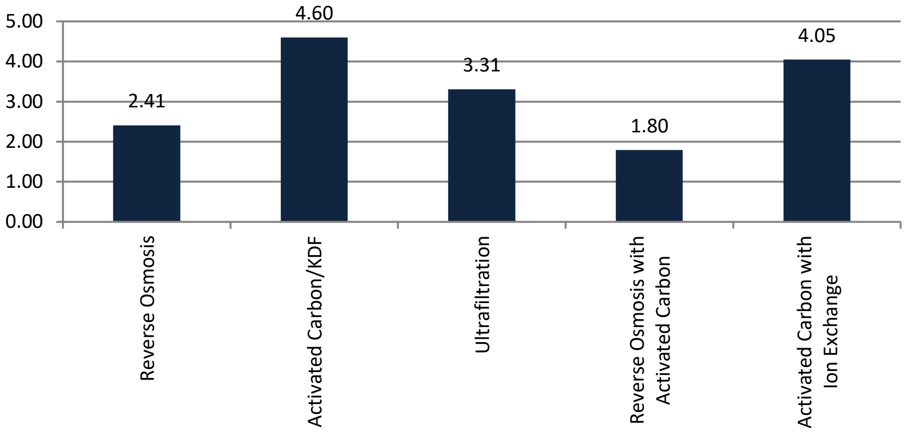


Figure A.5: Total score (WSM) for POE system selection (Max Score=5)

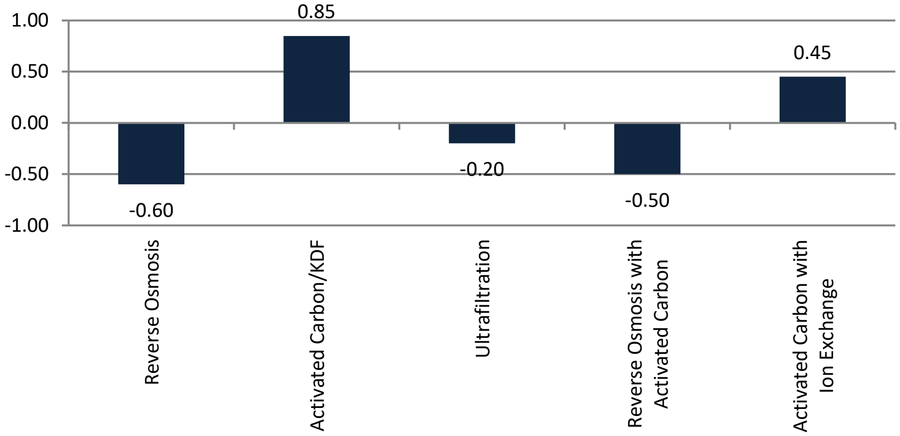


Figure A.6: Total score (PROMETHEE II) for POE system selection

A.7 TBL Performance

Table A.12: Summary of Kendall's coefficient of concordance results measuring the similarity of the neighborhood MCDA rankings. Values represent % of stakeholder results that have the same ranking of alternatives for all three neighborhoods exceeding the critical values for 0.05 and 0.01 levels of significance.

Level of Significance	WSM			PROMETHEE II		
	Financial	Social	Environmental	Financial	Social	Environmental
0.05	100%	94%	100%	100%	89%	94%
0.01	100%	83%	94%	100%	83%	89%

APPENDIX B: SUPPLEMENTAL INFORMATION FOR CHAPTER 3

B.1 Pearson Correlation Coefficients for Stakeholder Criteria Weights

Pearson product-moment correlation coefficients for the 11 criteria weights for the 17 stakeholders in the financial, social, and environmental MCDA models (Test 28 in [57]).

Table B.1: Financial bottom line Pearson product-moment correlation coefficients ($r_{.05}$=.482, Table A16 in [57])

	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11
W1	1.00										
W2	0.22	1.00									
W3	0.38	0.28	1.00								
W4	0.46	0.17	0.48	1.00							
W5	0.32	0.20	0.33	0.42	1.00						
W6	0.03	0.77	0.06	-0.09	0.09	1.00					
W7	0.00	0.31	0.39	0.22	0.54	0.34	1.00				
W8	0.52	0.22	0.31	0.62	0.62	0.06	0.03	1.00			
W9	0.09	0.59	0.34	0.07	0.00	0.69	0.21	0.05	1.00		
W10	0.40	0.35	0.58	0.52	0.38	0.15	0.63	0.19	-0.05	1.00	
W11	0.43	0.68	0.30	-0.08	0.13	0.57	0.19	0.15	0.59	0.17	1.00

Table B.2: Social bottom line Pearson product-moment correlation coefficients ($r_{.05}$=.482, Table A16 in [57])

	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11
W1	1.00										
W2	0.01	1.00									
W3	0.34	0.40	1.00								
W4	0.25	0.35	0.47	1.00							
W5	0.33	-0.56	0.03	0.27	1.00						
W6	-0.25	0.57	0.01	0.37	-0.27	1.00					
W7	-0.22	-0.44	-0.15	0.08	0.48	0.20	1.00				
W8	0.69	0.15	0.34	0.33	0.42	-0.10	-0.07	1.00			
W9	-0.19	0.42	0.20	0.54	-0.19	0.60	-0.02	-0.02	1.00		
W10	0.36	0.56	-0.02	0.25	-0.11	0.44	-0.22	0.43	0.21	1.00	
W11	0.40	-0.41	-0.14	-0.50	0.27	-0.57	-0.02	0.28	-0.46	-0.12	1.00

Table B.3: Environmental bottom line Pearson product-moment correlation coefficients ($r_{.05}$=.482, Table A16 in [57])

	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11
W1	1.00										
W2	0.79	1.00									
W3	0.46	0.59	1.00								
W4	0.62	0.61	0.79	1.00							
W5	0.01	0.14	0.14	0.31	1.00						
W6	0.64	0.79	0.52	0.49	0.33	1.00					
W7	0.09	0.31	0.43	0.59	0.65	0.55	1.00				
W8	0.19	0.34	0.36	0.51	0.21	0.37	0.67	1.00			
W9	0.59	0.67	0.53	0.55	0.11	0.80	0.36	0.22	1.00		
W10	-0.37	-0.21	-0.02	0.26	0.24	-0.28	0.41	0.53	-0.20	1.00	
W11	0.20	0.17	0.26	0.61	0.50	0.37	0.72	0.52	0.15	0.39	1.00

B.2 Additional Information on Uncertain Inputs

Table B.4: Uncertain input description, performance indicators the inputs are used in, probability distribution information

		Performance Indicators that use input			Probability Distribution	
Input	Description	Financial	Social	Environ-mental	Distribution Type PDF/PMF uniform/triangle	Distribution boundaries (Notes)
Cds	Weighted Unit Cost potable only D.S. ($/lf)	1.1, 1.2	1.2	1.1	PDF, Triangle	a=67; b=178; c=109 (2014 utility unit costs)
Ct	Weighted Unit Cost potable only Transmission mains ($/lf)	1.1, 1.2	1.2	1.1	PDF, Triangle	a=83; b=146; c=136 (2014 utility unit costs)
Cbfp	Backflow preventer unit cost ($/poc)	1.1	1.2	1.1	PDF, Uniform	min=700; max=1250 (Weighted unit cost based on service connection type; minimum unit cost from [133] and commercial/multi-family range from https://home.costhelper.com/backflow-preventers.html)
Csis	Separated Irrigation System unit cost ($/poc)	1.1, 1.2	1.2	1.1	PDF, Uniform	min=2800; max=4200 [32]
Cpoe	POE unit cost ($/poc)	1.1, 1.2	1.2	1.1	PDF, Triangle	a=5660; b=8900; c=6118 [70]
Ltm	New potable TM service lifetime assumption (yr)	1.2			PDF, Uniform	min=54; max=102 [70; 139]
Lds	New potable DS service lifetime assumption (yr)	1.2			PDF, Uniform	min=55; max=100 [70; 139]
Cwtf	Unit replacement cost central WTF ($/MGD)	1.2			PDF, Triangle	a=430,460; b=3,197,701; c=1,229,885 (2014 utility costs; Range +30%, -15% [153])

RLcwt	Remain. service life assumption of central WTF (yr)	1.2			PDF, Triangle	a=20; b,c=40 (2014 utility data)
Lcwt	Convention WTF service life assumption (yr)	1.2			PDF, Triangle	a=40; b=70; c=50 [154]
Lnwt	Neighborhood WTF service life assumption (yr)	1.2			PDF, Triangle	a=40; b=70; c=50 [154]
Lpoe	POE service life assumption (yr)	1.2			PDF, Triangle	a=15; b=25; c=20 [154]
i	Real discount rate (%)	1.2			PDF, Triangle	a=2; b=10; c=3.375 [70; 155]
CEwt	Energy use central water treatment kWh/MG	2.1	2.1	2.1	PDF, Triangle	a=145; b=730; c=321 (2008 – 2012 utility energy use data; Range +30%, -15% [153])
CEvar	Central WTF variable energy use (%)	2.1	2.1	2.1	PDF, Triangle	a=22; b=80; c=44 [25]
PEpot	Potable ds pumping kWh/MG	2.1	2.1	2.1	PDF, Uniform	min=315; max=460 ([25]; assumed 65 – 95% efficiency range)
PEnon	non-potable ds pumping kWh/MG	2.1	2.1	2.1	PDF, Uniform	min=265; max=390 ([25]; assumed 65 – 95% efficiency range)
NEwt	Neighborhood WT energy kWh/MG	2.1	2.1	2.1	PDF, Triangle	a=490; b=750; c=574 ([70]; Range +30%, -15% [153])
POEEwt	POE WT energy kWh/MG	2.1	2.1	2.1	PDF, Triangle	a=460; b=890; c=670 ([70]; Range +30%, -15% [153])
Di	Indoor demand (MG/yr)	1.1, 1.2, 2.1, 3.1, 4.1	1.2, 2.1, 4.1, 8.1	1.1, 2.1, 3.2, 4.1, 8.1	PDF, Triangle	a=66; b=131; c=112 (2004-2012 utility demand data; [156])
Do	Outdoor demand (MG/yr)	1.2, 2.1, 3.1, 4.1	2.1, 4.1, 8.1	2.1, 3.2, 4.1, 8.1	PDF, Triangle	a=56; b=115; c=102 (2004-2012 utility demand data; [156])
ECwtom	unit O&M cost existing central WT ($/kGal)	3.1	8.1	8.1	PDF, Triangle	a=.25; b=1.85; c=.70 ([70]; Range +30%, -15% [153])
ACwtom	unit adjustment for alternatives using central WT ($/kGal)	3.1	8.1	8.1	PDF, Triangle	a=.03; b=.25; c=.09 ([70]; Range +30%, -15% [153])
Nwtom	Avg. unit O&M cost neighborhood WT ($/MGD Capacity)	3.1	8.1	8.1	PDF, Triangle	a=64,100; b=476,175; c=183,145 ([70]; Range +30%, -15% [153])
POEwtom	Avg. unit O&M cost POE WT ($/kGal)	3.1	8.1	8.1	PDF, Triangle	a=1.65; b=12.20; c=4.70 ([70]; Range +30%, -15% [153])
DSpotom	Annual O&M cost of N1 potable DS ($)	3.2	8.1	8.1	PDF, Triangle	a=11,630; b=86,395; c=33,229 (2014 utility data)
TMpotom	Annual O&M cost of N1 potable TM ($)	3.2	8.1	8.1	PDF, Triangle	a=2,725; b=20,250; c=7,789 (2014 utility data)
SISom	O&M unit cost for SIS ($/POC)	3.2	8.1	8.1	PDF, Triangle	a=37; b=274; c=105.30 [32]
Brate	repairs hours/break	4.1	4.1	4.1	PDF, Triangle	a=13.5; b=75; c=30.7 (from 1996 - 2013 utility pipe failure history [25])
FS	flushing & surveying hours/yr	4.1	4.1	4.1	PDF, Triangle	a=170; b=680; c=340 (from 1996 – 2013 utility work order data [25])
FTEpoewt	# of FTE required to maintain POE systems	4.1	4.1	4.1	PDF, Triangle	a=1.39; b=2.05; c=1.51 (2 -3 hr/connection/yr [25])
Bno	# Breaks/yr new d.s.	4.1	4.1	4.1	PMF, Uniform	n=0:5,prob=c(.16,.17,.17,.17,.17,.16) (from 1996 - 2013 utility pipe failure history, adjusted for pipe material [25])
Tdd	Dual distribution training	4.2	4.2		PMF, Triangle	n=-2:0,prob=c(.5,.3,.2) (Raw water irrigation systems already in use in service area. Represents uncertainty dual distribution requires additional training.)

Twt	New treatment technology training	4.2	4.2		PMF, Triangle	n=-2:0,prob=c(.3,.5,.2) (Conventional may later require new technology training too. Represents uncertainty Neighborhood and POE require more training than Conventional.)
Tno	More WT operators require training	4.2	4.2		PMF, Triangle	n=-2:0,prob=c(.5,.3,.2) (Represents uncertainty in number of operators required for POE.)
RFpdd	Risk Factor for parallel dual distribution	5.2	5.2		PDF, Uniform	min=1; max=3 (Central Dual & Neighborhood increase risk factor for parallel dual distribution [157; 158; 159].)
RFsdd	Risk factor for dual distribution, not parallel (SIS)	5.2	5.2		PDF, Uniform	min=1; max=2 (Separated Irrigation risk factor for dual distribution, risk range less than RFpdd because distribution systems are not parallel.)
RFp	Risk factor for pressure in non-potable distribution system being higher than pressure in potable distribution systems	5.2	5.2		PDF, Uniform	min=1; max=3 (Increase risk when pressure in non-potable distribution system > potable distribution system [133; 160])
RFfi	Risk factor for fire & irrigation on potable line	5.2	5.2		PDF, Uniform	min=1; max=3 (Increase risk at point-of-use for irrigation and fire suppression systems [133])
Sn	Neighborhood WT tech risk	5.3	5.3		PMF, Uniform	n=3:5,prob=c(.33,.33,.34) (Represents uncertainty in whether decentralizing water treatment to the neighborhood level increases risk due to longer response times.)
Spoe	POE WT tech risk	5.3	5.3		PMF, Uniform	n=1:5,prob=c(.2,.2,.2,.2,.2) (Represents uncertainty in whether decentralizing water treatment to the POE increases risk due to longer response times. Assumes higher risk because of higher level of decentralization.)
ATC	Avoided transaction costs	6.1	6.1	6.1	PMF, Uniform	n=1:2,prob=c(.5,.5) (Represents uncertainty Separated Irrigation will result in water right conversion savings, over all the other alternatives, because rights designated for irrigation can still be used for landscape irrigation.)
LSms	Use of multiple existing sources	7.1	7.1		PMF, Uniform	n=0:1,prob=c(.5,.5) (Represents uncertainty of the benefit for Separated Irrigation. FCU does not use all available river sources in runoff season due to high treatment costs [58]. Central Dual's and Separated Irrigation's dual distribution system allows for conservation of reservoir water through use of surplus tributary water rights during the spring runoff season. However, Separated Irrigation does not have access to reservoir sources for irrigation later in the season.)
LAS	Likelihood of using alternative non-potable sources	7.1, 9.1	7.1, 9.1	7.1, 9.1	PMF, Uniform	n=0:1,prob=c(.5,.5) (Represents uncertainty in whether the utility will have the rights to use alternative sources in the future. Central Dual's and Separated Irrigation's dual distribution system would allow for use of alternative non-potable sources if permitted by water rights.)

LSs	Increase finished water storage	7.1	7.1		PMF, Uniform	n=0:1,prob=c(.5,.5) (Central Dual and Separated Irrigation increase potable storage but Existing could benefit from increase storage if banned irrigation use. Represents the uncertainty in Central Dual and Separated Irrigation's benefit of increased potable storage over the existing system.)
LSb	Backup treatment systems	7.1	7.1		PMF, Uniform	n=0:1,prob=c(.5,.5) (Represents uncertainty in whether Neighborhood water treatment facilities could offer backup systems.)
LSpop	Smaller population affected in case of outage	7.1	7.1		PMF, Uniform	n=0:1,prob=c(.5,.5) (Represents uncertainty in benefit decentralized water treatment offers because of fewer people affected.)
ROc	Risk of obsolete infrastructure for Central Dual alternative	7.2			PMF, Uniform	n=1:5,prob=c(.2,.2,.2,.2,.2) (Represents risk that Central Dual infrastructure becomes unnecessary due to decrease in non-potable demand or change in regulations.)
ROn	Risk of obsolete infrastructure for Neighborhood alternative	7.2			PMF, Uniform	n=1:5,prob=c(.2,.2,.2,.2,.2) (Represents risk that Neighborhood infrastructure becomes unnecessary due to decrease in non-potable demand or change in regulations.)
ROpoe	Risk of obsolete infrastructure for POE alternative	7.2			PMF, Uniform	n=3:5,prob=c(.33,.33,.34) (Represents risk that POE infrastructure becomes unnecessary due to change regulations. Higher risk assumed because lack of information and regulations for large scale implementations.)
ROsis	Risk of obsolete infrastructure for SIS alternative	7.2			PMF, Uniform	n=2:4,prob=c(.33,.33,.34) (Represents risk that Separated Irrigation infrastructure becomes unnecessary due to decrease in non-potable demand, change in regulations or change in agreements with irrigation & ditch companies.)
Rdd	Confidence in O&M projections for dual distribution	8.1			PMF, Uniform	(8.1 Assumes the most confidence in Conventional because it's the existing system and least confidence in POE due to no existing large scale implementations.) Rdd: n=0:2,prob=c(.33,.33,.34) (Represents risk of uncertainty in O&M projections for dual distribution.) Rn: n=0:2,prob=c(.33,.33,.34) (Represents risk of uncertainty in O&M projections for neighborhood water treatment.) Rsis: n=0:1,prob=c(.5,.5) (Represents risk of uncertainty in O&M projections for separated irrigation systems. Assumes less risk than dual distribution because raw water irrigation systems already exist in public parks.)
Rn	Confidence in O&M projections for neighborhood WT	8.1			PMF, Uniform	
Rsis	Confidence in O&M projections for SIS	8.1			PMF, Uniform	
Rev	Rev - amount of spare capacity used to generate revenue (MG)	10.1	10.1	10.1	PDF, Uniform	min=0; max=907 (Represents uncertainty in how much revenue can be generated through selling water wholesale to neighboring water districts.)

PAdd	Public acceptance of dual distribution		11.1		PMF, Uniform	(Assumes Conventional has highest public acceptance (5) because it's the existing system and POE has the least public acceptance (1) because it represents the largest disruption to status quo.) PAdd: n=-1:0,prob=c(.5,.5) (Represents uncertainty of the public's acceptance of dual distribution systems. Dual distribution is common in the state so public acceptance may already exist (n=0).) PAnwt: n=-1:0,prob=c(.5,.5) (Represents uncertainty of the public's acceptance of the decentralized neighborhood water treatment systems.)
PAnwt	Public acceptance of neighborhood WT		11.1		PMF, Uniform	
GHGdds	GHG due to additional maintenance equip/vehicles for dual d.s.			3.1	PDF, Uniform	(Assumes Conventional has the highest performance (5) and POE has the lowest performance (1).) GHGdds: min=-2; max=0 (Represents uncertainty in additional GHG emissions due to maintenance of dual distribution systems (excludes energy use (2.1).) GHGnwt: min=-1; max=0 (Represents uncertainty in additional GHG emissions due to maintenance of neighborhood water treatment systems (excludes energy use (2.1).)
GHGnwt	GHG due to additional travel to multiple WT sites			3.1	PDF, Uniform	
Clc	Central WTF Chlorine lb/MG			3.2	PDF, Uniform	min=11; max=14 (2000 – 2012 utility chemical use data)
Al2SO43	Central Aluminum Sulfate lb/MG			3.2	PDF, Uniform	min=132; max=203 (2000 – 2012 utility chemical use data)
CaOH2	Calcium Hydroxide lb/MG			3.2	PDF, Uniform	min=143; max=200 (2000 – 2012 utility chemical use data)
F	Fluoride lb/MG			3.2	PDF, Uniform	min=27; max=49 (2000 – 2012 utility chemical use data)
CO2	Carbon Dioxide lb/MG			3.2	PDF, Uniform	min=65; max=119 (2000 – 2012 utility chemical use data)
Cln	Neighborhood Chlorine lb/MG			3.2	PDF, Uniform	min=18; max=23 (2000 – 2012 utility chemical use data)
RRcwt	Risk of new WT regs. resulting in changes to central WTF			11.1	PDF, Uniform	min=-1; max=0 (Represents uncertainty in risk of new regulations requiring change to Conventional water treatment.)
RRnwt	Risk of new WT regs. resulting in changes to neighborhood WTF			11.1	PDF, Uniform	min=-1; max=0 (Represents uncertainty in risk of new regulations requiring change to Neighborhood water treatment.)
RRpoe	Risk of new WT regs. resulting in changes to POE systems			11.1	PDF, Uniform	min=-2; max=0 (Represents uncertainty in risk of new regulations requiring change to POE water treatment.)
RRraw	Risk of new WT regs. for raw water use resulting in changes to infrastructure			11.1	PDF, Uniform	min=-2; max=0 (Represents uncertainty in risk of new regulations for raw water use requiring change to infrastructure.)