THESIS

# ASSESSING BENEFITS AND CONSEQUENCES OF WATER CONSERVATION AND FIT FOR PURPOSE WATER SYSTEMS

Submitted by

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ABSTRACT

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Rising population accompanied with urbanization is increasingly challenging the resilience and capacity of traditional water management system. The migration of the human population to urban areas has given birth to sprawling new developments and re-developments which poses serious challenges to conserve and manage water. Water managers and policy makers are faced with an arduous task to enhance conventional water management systems by implementing Integrated Urban Water Management and hybrid centralized-decentralized systems. To enable informed decisions on water demand management strategies based on water demand reduction, cost, energy savings, etc., understanding benefits and consequences is of utmost importance. Benefits and consequences of water conservation and reuse are seldom considered while making quantitative decisions, mainly due to lack of supporting data or methodology. This research fills this knowledge gap by providing methodology on identifying, developing and quantifying a set of indicators that measure performance for water demand reduction strategies including conservation strategies and use of alternate water sources (i.e., fit for purpose water) in triple bottom line (TBL) categories. Literature review, triple bottom line (TBL) evaluation, and Multi-Criteria Decision Analyses (MCDA) were used to develop a set of indicators to assess water demand reduction strategies. To demonstrate the use of indicators to inform water management decisions, TBL indicator analysis was performed on Globeville-Elyria-Swansea (GES) community in Denver, Colorado using Integrated Urban Water Model (IUWM). The results from TBL indicator analysis suggests that use of stormwater performed well across all indicator categories, it achieved high water demand reduction, was energy efficient and also publicly accepted. Further cost comparison and MCDA scores revealed, Stormwater for Potable & Irrigation as the top performing end use. Use of stormwater as a supply has potential for large reduction in demand for traditional supplies and

also offers notable social and environmental benefits. Water rights issues and costs remain barriers for adoption of this practice that need to be overcome to realize the benefits.

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# Chapter 1: Introduction

## 1.1 Research Motivation

People across the world are experiencing severe water scarcity due to urbanization and rapid population growth. Increase in global population directly relates to increase in urban population. With globally over 50 percent of the population living in urban areas, it is estimated that by 2045 the world's urban population will increase to 6 billion (World Bank, 2020), skyrocketing urban development. While the migration of the human population to urban areas has significant positive impacts on economic growth, the risks involved with lack of proper urban services can jeopardize economic and social development (Global Water Partnership, 2012). The sprawling urban new developments and redevelopments further put pressure on urban utilities to meet the needs of communities' freshwater demand.

In many places, the lack of predictability of extreme events is threatening to increase water demand while shrinking the water supply (EPA, 2008). By 2030, water demand in developing countries is estimated to increase by 50 percent while 40 percent freshwater supply shortage is predicted worldwide (UNESCO, 2018). A variety of factors including climate change, production and consumption of water- intensive foods like meat, unsustainable irrigation and ageing water infrastructure further escalate pressure on freshwater sources. Therefore, water managers must think creatively to ensure a reliable supply that meets social equity, economic efficiency, and environmental sustainability (World Bank, 2020).

With a scarce freshwater supply to meet burgeoning water demand, water managers are now focusing on moving towards an integrated urban water system which is sustainable, efficient and adaptable. Contrasting to existing water management system where water supply, wastewater and stormwater are compartmentalized, Integrated Urban Water Management is a holistic approach for managing all sources of urban water to meet different water needs. IUWM reduces urban freshwater demand by using demand-side management techniques, that include education and optimization of water use efficiency, and use of alternate water sources like stormwater, graywater, wastewater and roof runoff. IUWM is also referred to as One Water in the US, signifying the interconnectedness between all water. The One Water approach considers the water cycle as an integrated system. It recognizes that all water has value and therefore it must be managed carefully to achieve multiple benefits (Water Research Foundation, 2017).

While IUWM provides policy makers with a framework to make informed decisions, use of innovative technology and efficient practices helps reinvent urban water management. A myriad range of urban water solutions are being implemented under IUWM. Significant potable water savings are achieved through water reuse and conservation strategies. In addition to water demand reduction several other side benefits and consequences like energy savings, water security, health impacts, etc. are also obtained through use of these strategies which go unaccounted while making decisions. These benefits and consequences are added outcomes and not directly targeted by policy makers but go above and beyond the direct benefits of water conservation. However, these are seldom considered while making quantitative decisions, mainly due to lack of supporting data or methodology. Including the indicator analysis in the decision-making process will aid in taking a comprehensive decision.

## 1.2 Background

### 1.2.1 Water in Urbanization

Urbanization is one of the major stressors of water today. In the coming years, urban areas around the world are expected to absorb all the population growth which is usually caused due to rural- urban migration, natural urban population increase or through reclassification of rural areas as urban areas (WWAP, 2017). This urban population rise is especially causing disadvantaged populations to live in blighted neighborhoods and informal settlements without safe access to water and sanitation generating negative impacts on human health and environment (Global Water Partnership, 2012). Urbanization and its impact to the environment are distinct in scale and have potential to pose adverse challenges. Urban planners are struggling to keep pace with the growth of cities both in size and population, with regards to infrastructure facilities and their development. At this critical juncture, rethinking the way urban spaces are planned and redeveloped is not an option but an imperative. Achieving sustainable development by integrating water in urban planning is essential (United Nations, 2016).

Water is a connector between various sectors in the city. As cities expand and existing areas are redeveloped, energy consumption associated with water supply, distribution and wastewater treatment also increase (Sattenspeil et al. 2009). The increase in total municipal water demand is not just driven by increase in urban population, but also by economic development with more industries producing, manufacturing and packaging goods. In addition, economic development also increases per- capita water use in residences as new technologies such as showers, washing machines and dishwashers are being used extensively (McDonald et al. 2014). This leads to highly concentrated effluent flow downstream, negatively impacting the aquatic habitat (Mitchell, 2006). Furthermore, the ageing water infrastructure exacerbates the conventional water management system. As a result, centralized municipal water systems are challenged to meet the needs of future populations, protect the environment and decrease energy and water footprints. The same standard water treatment for all end uses at a centralized facility may no longer be suitable to meet future needs. Using potable water for irrigation triples the required water treatment plant capacity, in turn increasing energy and chemicals used for the treatment (Cole at al. 2018a).

According to Water Research Foundation, an average American family utilizes 58.6 gallons per capita per day in indoor uses (REU2016). The outdoor water use varied with geographic location and climatic diversity. Outdoor usage was found higher for homes in warmer climates where irrigation continues through winter months (DeOreo et al. 2016). The figure below illustrates areas and proportion of indoor water, of which shower, faucet and clothes washer require potable water.

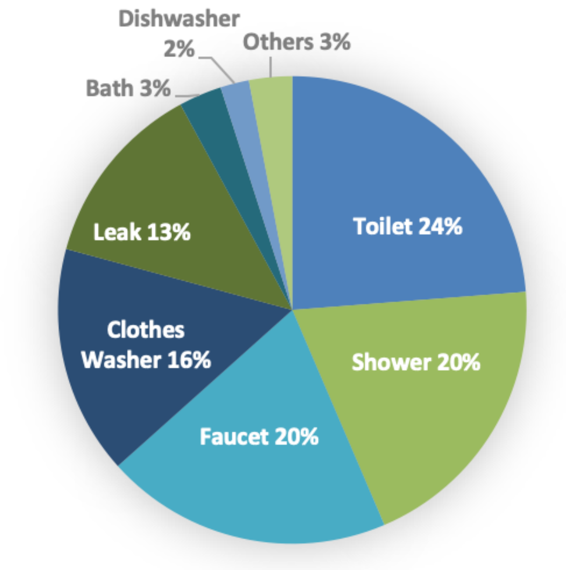



*Figure 1: Indoor Water Use in America*
*The Others category includes evaporative cooling, humidification, water softening, and other uncategorized indoor uses (REU2016).*

Residential indoor water conservation plays a vital role in reducing overall water demand. Almost a fourth of the pie chart represents toilet that could be satisfied using non-potable water supply. A 15.4% decrease in average annual indoor water use from 69.3gpcd to 58.6gpcd was seen from REU1999 to REU2016 as old washers and toilets wear out and were replaced with new ones (Mayer et al. 1999; DeOreo et al. 2016). Further reduction to 36.7gpcd is expected when homeowners switch to more efficient appliances and fixtures with automated metering and leak alert programs (DeOreo, 2011).

In addition, most of the outdoor urban water demands including landscape irrigation, car washing, street cleaning, fire suppression, fountains, wetland and, building cooling and heat exchange can also be met using non-potable water. By classifying water uses into potable and non-potable and matching water quality to its intended use (i.e., fit for purpose water), IUWM helps achieve sustainable water use through alternative supplies and water reuse. Fit for purpose water reduces wastewater generation as well as freshwater demand in turn reducing the need to expand water facilities with growing population (7).

1.2.2 Use of Alternate Water Sources: Reduction in Water Demand for Traditional Supplies

Given the inevitable population growth, use of alternate water is the best way to bring a sustainable balance between water demand and supply. Neale et al. (2020) found that use of alternate water notably reduced demand for traditional water supplies across Denver, Tucson and Miami. Use of stormwater for irrigation achieved maximum demand reduction of 17%, 33% and 16% for Denver, Tuscon and Miami respectively. While there was a limited potential for demand reduction from roof runoff due to low storage capacity (200 gal/household). In addition, wastewater reuse strategies reduced wastewater generation by 25 percent for each of the three cities.

Steffen et al. (2013) studied the potential residential water- savings and stormwater management benefits in 23 cities across seven climatic regions in the US. A water balance approach was applied at a daily time step for various rainwater cistern sizes to determine water saving efficiency. The results showed that water saving efficiency was dependent on the cistern size and climatic pattern. In most US regions, rainwater harvested from a residential parcel using a 50-gallon rain barrel achieved 50 percent water savings for non-potable uses but in arid regions of West and Southwest US, less than 30 percent water savings were observed.

Luthy et al. (2018) reinforced that utilizing urban stormwater runoff can help reduce water scarcity in semi-arid regions. The study illustrated various examples in the US and Australia that achieved significant water demand reduction through large scale urban stormwater capture for direct beneficial use and groundwater recharge. The National Park at Washington DC captures 3800 $m^3$ of stormwater off the Mall's turf and walkways. This water is treated using 25µm microscreens followed by ultraviolet disinfection and is primarily used for irrigation. Adelaide city in Australia plans to accommodate half its water demand in 2050 by increasing the amount of urban stormwater harvesting threefold to 60M $m^3$/year. After the Millennium Drought in Australia, a desalination plant was initiated in Adelaide, but it was found that utilizing stormwater in place of desalinated water reduces significant costs for potable and non-potable uses. The study concluded with a new paradigm of viewing stormwater not just as a flood or pollution problem but as a water source with multiple beneficial uses to overcome water scarcity.

López Zavala et al. (2016) saw a 48 percent reduction in potable water consumption and 59 percent reduction in wastewater generation when roof runoff harvesting was integrated with graywater reuse in Monterrey Campus, Mexico. In addition, implementation of these systems generated important economic benefits for the institution.

Residential indoor water conservation plays a vital role in reducing overall water demand. DeOreo at al. 2016 conducted in an assessment of water use for 1000 single family residences across 23 study sites located in US and Canada (REU2016). The study sites were diverse in geographic location and climate resulting in a large variation in average annual water use per household when considering indoor and outdoor water user. This study is subsequent to Residential End Uses of Water (REU1999) by Mayer et al. (1999). A 15.4% decrease in average annual indoor water use from 69.3gpcd to 58.6gpcd was seen from REU1999 to REU2016 as old washers and toilets wear out and were replaced with new ones. Further reduction to 36.7gpcd is expected when homeowners switch to more efficient appliances and fixtures with automated metering and leak alert programs (DeOreo at al. 2011). A 16 percent drop in average outdoor use was also anticipated when excess irrigators use irrigation controllers and climate appropriate landscape to be more water efficient.

Yushiou et al. (2011) found similar results from controlled experiments in Ipswich watershed, Massachusetts. The study assessed impacts on water use from implementation of water use strategies. It was found that installation of weather-sensitive irrigation controller switches (WSICS) substantially reduced water use in residences and municipal athletic fields. The installation of rainwater harvesting systems in residences with high irrigation demand experienced a significant demand reduction with WSICS compared to low water users. In addition, the study led two outreach programs to provide free home indoor water use audits and water fixture retrofit kits and gave rebates for low-water-demand toilets and washing machines. Both outreach programs resulted in significant water savings. In first four years of program execution, 9.2 percent of the town's households participated in one or both of the outreach programs which resulted in 3950$m^3$/quarter of water savings for the town.

Several Life Cycle Assessment (LCA) studies have been conducted to evaluate water demand reduction strategies. Jeong et al. (2016) conducted a LCA study of low impact development (LID) technologies, including bioretention area, rainwater harvesting and xeriscape for the City of Atlanta, Georgia to control stormwater runoff, supply non- potable water and irrigate landscapes. LCA was performed for five single-family and four multi-family residences. The results showed reduction in potable water use by 50 percent in single-family zones and 25 percent in multi-family zones. It showed that water savings decreased in high population density zones due to decreased surface area available for LIDs.

Jeong et al. (2018) conducted another LCA study to assess water conservation from small- scale graywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. Graywater was assumed to be collected using submerged membrane bioreactors for non-potable uses like toilet flushing and irrigation. It was found that the graywater hybrid system reduced non-potable water demand by 17-49 percent in single-family zones and 6-32 percent in multi-family zones.

Wiltshire at al. (2005) studied Australian Government policy frameworks and guidelines for graywater reuse in urban areas. The study concluded that graywater reuse for irrigation and toilet flushing reduced 41 percent potable water demand, usually varying between 30-70 percent in urban households.

### 1.2.3 Benefits and Consequences with Water Conservation and Use of Alternate Supplies

The recent shift in thinking towards IUWM can have substantial payoffs resulting in building resilient and sustainable cities while also maximizing the use of water, energy and other materials. In addition to water demand reduction, use of water conservation and fit for purpose water has a variety of indirect benefits to increase urban livability while also promoting a healthy ecosystem. The National Academies of Science Committee conducted a study to identify risks, costs, and benefits of using graywater and stormwater to enhance local water supplies (NAP, 2016). The study showed that graywater and stormwater systems have potential to reduce potable water demand while providing additional benefits such as energy efficiency, stormwater pollution reduction and water supply diversification. The study concluded that stormwater and roof runoff capture were a function of the frequency and volume of precipitation events, and available storage capacity. In arid areas with low precipitation, graywater can be reliably used for irrigating native landscapes. It was also inferred that graywater and stormwater systems will achieve maximum water demand reduction when used at a neighborhood scale, however significant costs from storage, treatment and dual distribution will be incurred.

The study by Steffen et al. (2013) utilized U.S Environmental Protection Agency Storm Water Management Model (EPASWMM) to quantify stormwater management benefits. It was observed that rainwater harvesting reduced stormwater runoff volume up to 20 percent in semi-arid regions of the US. The study concluded that cities can benefit through rainwater harvesting not just as a stormwater control measure but also as an alternate source of water.

The LCA study by Jeong et al. (2016) for the City of Atlanta, Georgia used TRACI 2.1 (tool by US EPA for reduction and assessment of chemical and other environmental impacts) to stimulate impacts on ecosystem, human health, and natural resources. It was found that rainwater harvesting, and xeriscaping have lesser carcinogenic impact than conventional water supply and maintaining lawn. However, at a community level, use of xeriscape and bioretention areas in single-family zones have higher carcinogenic impact in a hybrid system (i.e., combination of LID technology with conventional system) than the conventional system alone due to extensive installation of PVC pipes. The researchers used a freshwater ecosystem impact (FEI) indicator to note any ecosystem impacts. It was found that use of hybrid system reduced freshwater ecosystem impacts by 55 percent in single family zones and 74 percent in multi-family zones as compared to conventional system.

Jeong et al. (2018) also used TRACI 2.1 to simulate impacts on ecosystem, human health, and natural resources. The study showed that within the graywater reclamation, treatment energy was the largest contributor to acidification, ecotoxicity and carcinogenic impacts for a total of about 30 percent. The impacts were found to be larger for single-family zones as landscape irrigation increased with per capita water demand. It was concluded that use of membrane bioreactors was effective in reducing water demand without increasing the impacts on environment.

In addition to water demand reduction, Wiltshire at al. (2005) concluded that graywater reuse offered many indirect benefits that were largely unquantifiable like benefits to public infrastructure in the form of reduced sewerage flows, reduction in treatment plant size and smaller distribution systems.

The literature is rich in studies focused on the impacts of water conservation and use of alternate water sources on demand for traditional supplies. However, limited literature identifies the multiple other benefits that are achieved in addition to water demand reduction. In spite of knowing that benefits and consequences for water conservation and use of alternate water supplies exist, policy makers remain uncertain of it, due to lack of study and proper documentation.

### 1.2.4 Indicators for Urban Water Systems

Use of co-benefits for system analysis is extensively used for climate change mitigation studies, but only more recently for urban water systems. The term co-benefit was first used in academic literature in the 1990s by the Intergovernmental Panel on Climate Change (IPCC). The IPCC defined co-benefits as the unintended positive side effects of a policy. Since then, various studies and journal articles have been published on co-benefits of climate action (Jiang et al. 2013; Thompson et al. 2014). However, co-benefits are seldom considered while making quantitative decisions, mainly due to lack of supporting data or methodology.

Indicators play a major role in evaluating progress towards goals and assessing co-benefits of alternate strategies. They clearly define complex co-benefits and/or terms amongst stakeholders with diverse interests. Recently, a wide range of sustainability indicators have been developed to assess water-related issues at various scales of use. However, very few indicators are actually put to practice. The Cooperative Research Center for Water Sensitive Cities (CRCWSC) to overcome this issue, developed the Water Sensitive Cities (WSC) Index to aid governments to assess their cities' urban water management (Chesterfield et al. 2016). The WSC Index is designed to define key attributes of a water sensitive city, track problems to achieve city wide water sensitive goals, and assist decision makers to prioritize action. The WSC Index contains 34 indicators (Table 1) that represent important attributes of a water sensitive city across social, economic and environmental domains. The attributes include improved livability, sustainability, resilience and productivity (Chesterfield et al. 2016).

*Table 1: 7 goals and 34 indicators of a water sensitive city by Chesterfield et al. (2016)*

| ***1.Ensure good sensitive governance*** | ***2.Increase community capital*** | ***3.Achieve equity of essential services*** | ***4.Improve productivity and resource efficiency*** | ***5.Improve ecological health*** | ***6.Ensure quality urban space*** | ***7.Promote adaptive infrastructure*** |
|---|---|---|---|---|---|---|
| **1.1** Knowledge, skills and organizational capacity | **2.1** Water literacy | **3.1** Equitable access to safe and secure water supply | **4.1** Benefits across other sectors because of water-related services | **5.1** Healthy and biodiverse habitat | **6.1** Activating connected urban green and blue space | **7.1** Diverse fit-for-purpose water supply system |
| **1.2** Water is key element in city planning and design | **2.2** Connection with water | **3.2** Equitable access to safe and reliable sanitation | **4.2** Low GHG emissions in water sector | **5.2** Surface water quality and flows | **6.2** Urban elements functioning as part of the urban water system | **7.2** Multi-functional water system infrastructure |
| **1.3** Cross-sector institutional arrangements and processes | **2.3** Shared ownership, management and responsibility of water assets | **3.3** Equitable access to flood protection | **4.3** Low end-user potable water demand | **5.3** Groundwater quality and replenishment | **6.3** Vegetation coverage | **7.3** Integration and intelligent control |
| **1.4** Public engagement participation and transparency | **2.4** Community preparedness and response to extreme events | **3.4** Equitable and affordable access to amenity values of water-related assets | **4.4** Water-related commercial and economic opportunities | **5.4** Protect existing areas of high ecological value | | **7.4** Robust infrastructure |
| **1.5** Leadership, long-term vision and commitment | **2.5** Indigenous involvement in water planning | | | | | **7.5** Infrastructure and ownership at multiple scales |

| | | | | | | |
|---|---|---|---|---|---|---|
| **1.6** Water resourcing and funding to deliver broad societal value | | | | | | **7.6** Adequate maintenance |
| **1.7** Equitable representation of perspectives | | | | | | |

Cole et al. (2018a) developed a list of triple bottom line performance indicators for water supply systems. The study evaluated four strategies for dual distribution of raw water for non-potable demand and potable water for indoor demand in the City of Fort Collins. MCDA was utilized to compare alternative dual water systems against the existing system used by the city from a triple bottom line perspective. An extensive list of triple bottom line performance indicators, including impact of new infrastructure, consumer water quality, supply risk, etc., were developed to clearly quantify the data and aid stakeholder decision making.

1.2.5 Globeville, Elysia – Swansea Community

Globeville, Elyria – Swansea (GES) is one of the oldest communities in Denver with a population of 10,924 making up 2 percent of Denver's total population today. In the 1800s, railroad yards and heavy industries attracted Central and Eastern Europeans for jobs, followed by Hispanic settlers who worked in the meat packing industries (DEH, 2014). Today, the neighborhood is characterized by a strong Hispanic culture and influence, with many families with young children. According to 2010 US census, 70 percent of all residents in GES are Hispanics as compared to Denver where 30 percent of all population represent Hispanics. As can be seen in the demographic (Table 2), the poverty rate (i.e., characterized by lack of income to ensure sustainable livelihood and other basic services) and, the number of people living in a household is higher compared to Denver while the average annual income and education (i.e., high school and above) are lower.

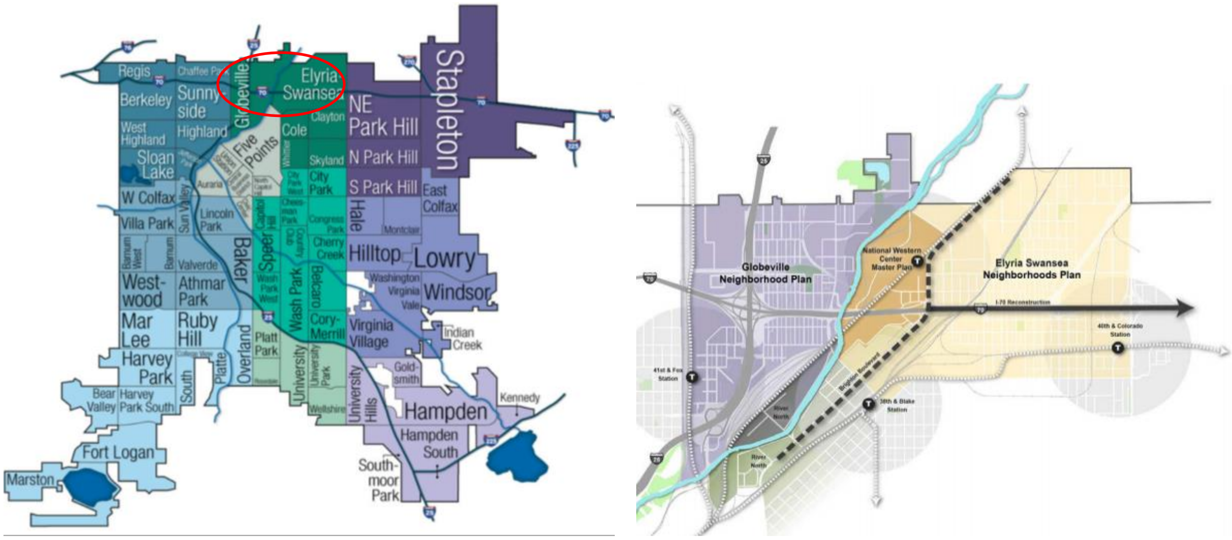



*Figure 2: Globeville, Elyria- Swansea Community in Denver, Colorado*

*Table 2: Demographics for Denver and Globeville, Elyria- Swansea (2010 US censes)*

| *Categories* | *Denver* | *Globeville, Elyria- Swansea* |
|---|---|---|
| *Population* | 600,158 | 10,924 |
| *Households* | 285,797 | 10,088 |
| *Average Household Size* | 2 | 4 |
| *Average Annual Income ($)* | 60,098 | 48,125 |
| *Education (Percent)* | 86.70 | 65.50 |
| *Poverty (Percent)* | 24.60 | 15.10 |

A report by Denver Environmental Health (DEH, 2014), summarized the issues faced in GES community from neighborhood planning. The heavy industries in GES, in addition to creating jobs, produced an exceedingly large amount of negative impacts on air quality, water and soil. The community consistently experiences noise, odors and periodic poor air quality from industries, heavy traffic and freight trains. GES has also observed a spike in vehicular air pollution since the construction of Interstates 70 and 25. In addition, the scarcity of trees and green infrastructure in the community further affect the air quality and result into urban heat islands. The construction of freeways and railroad tracks limit connectivity, making it hard to get to the neighborhood parks. There is only one separate bike lane in the whole neighborhood and over half of the public streets lack sidewalks. This has not only impacted the residents' mobility, but it also has negative impacts on opportunities for physical activities and recreation. Furthermore, lack of a full-service grocery store in the community has made it even more challenging for residents to be healthy. All of this has led to serious mental and physical health issues among residents. Obesity is one of the common results of unhealthy eating and lack of exercise, which in turn increases the likelihood of diabetes and cardiovascular diseases. More than half of adults in District 9, containing GES, are obese. GES and a number of other neighborhoods in Denver have higher rates of cardiovascular diseases than Denver as a whole. Besides, strong odors and noise from the industries affect residents' mental health and also cause respiratory diseases such as asthma.

Nelson et al. (2017) lead a health assessment study specific to GES community to identify resource gaps and need of GES residents to achieve healthy living before the redevelopment of the community begins. The survey had a 12.4% response rate with 480 total residents filling out the survey. From the survey, it was found that 15.5% GES residents had diabetes while that for all of Denver County was 8.1% (figure 3). The study also found that cost of fresh fruits and vegetables, and lack of grocery store nearby were the top reasons that made it difficult for the residents to eat healthy. While 80 percent of the residents reported feeling safe in the neighborhoods during the day, nearly half reported not feeling safe at night or on trails. In addition, 14% respondents reported frequent mental distress (i.e., 14 or more days of feeling stressed, depressed or having emotional problems in the last 30 days).

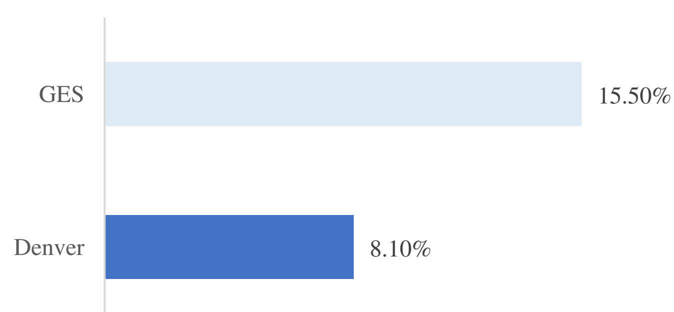



*Figure 3: Cases of diabetes in Denver and GES community by Nelson et al. (2017).*

It is observed that the GES residents scarcely irrigate on their property. As can be seen in figure 4, the indoor water demand for GES community is nearly the same as that of Denver but it drops sharply for outdoor demand.

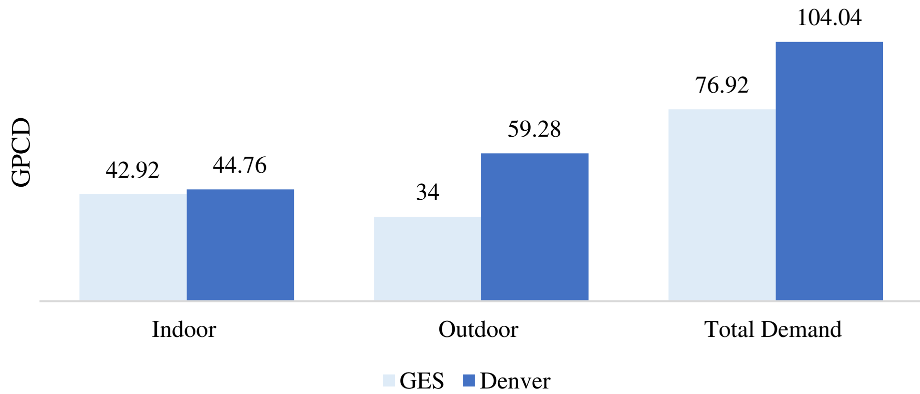



*Figure 4:Water Demand in Denver and GES community*

The South Platte River dividing Globeville from Elyria- Swansea, and the Heron Pond located in Globeville are the most significant water features in GES, monitored by the Denver Department of Environmental Health (DEH). The water quality of South Platte River passing through GES is worse than anywhere else in the city since the area is located just downstream of Denver's urban core. This generates highly polluted stormwater runoff carrying oils, chemicals, pesticides, debri and sediments. Levels of phosphorus, E. coli, nitrate and arsenic in the river are above permissible limits strictly prohibiting swimming and wandering in the river. Heron pond, on the other hand, has high concentrations of manganese, cadmium and iron. These metals found their way into the pond by runoff from metal refining smelters. This also polluted the groundwater. Colorado Department of Public Health and Environment undertook the remediation and monitored the cadmium groundwater plume to meet surface water standards before it merged with the South Platte River. (DEH, 2014)

Increase in urbanization has caused a substantial rise in stormwater runoffs throughout Denver. The city's stormwater drainage system built in 1990 is inadequate to handle stormwater. Stormwater infrastructure in Globeville is only able to support a 2-year storm event, which is considered a very small event (Globeville

Stormwater Systems Study, 2018). During a rainfall event, water naturally drains to the South Platte River. During major storms, the GES community experiences significant flooding; endangering lives and causing damage to pipelines, roads, properties, businesses and other utilities. Therefore, to overcome these challenges of flooding, air and noise pollution, and health, the GES community was chosen as a case study. An interactive GIS map was created using eRams to summarize the water and health data in the GES community (figure 5).

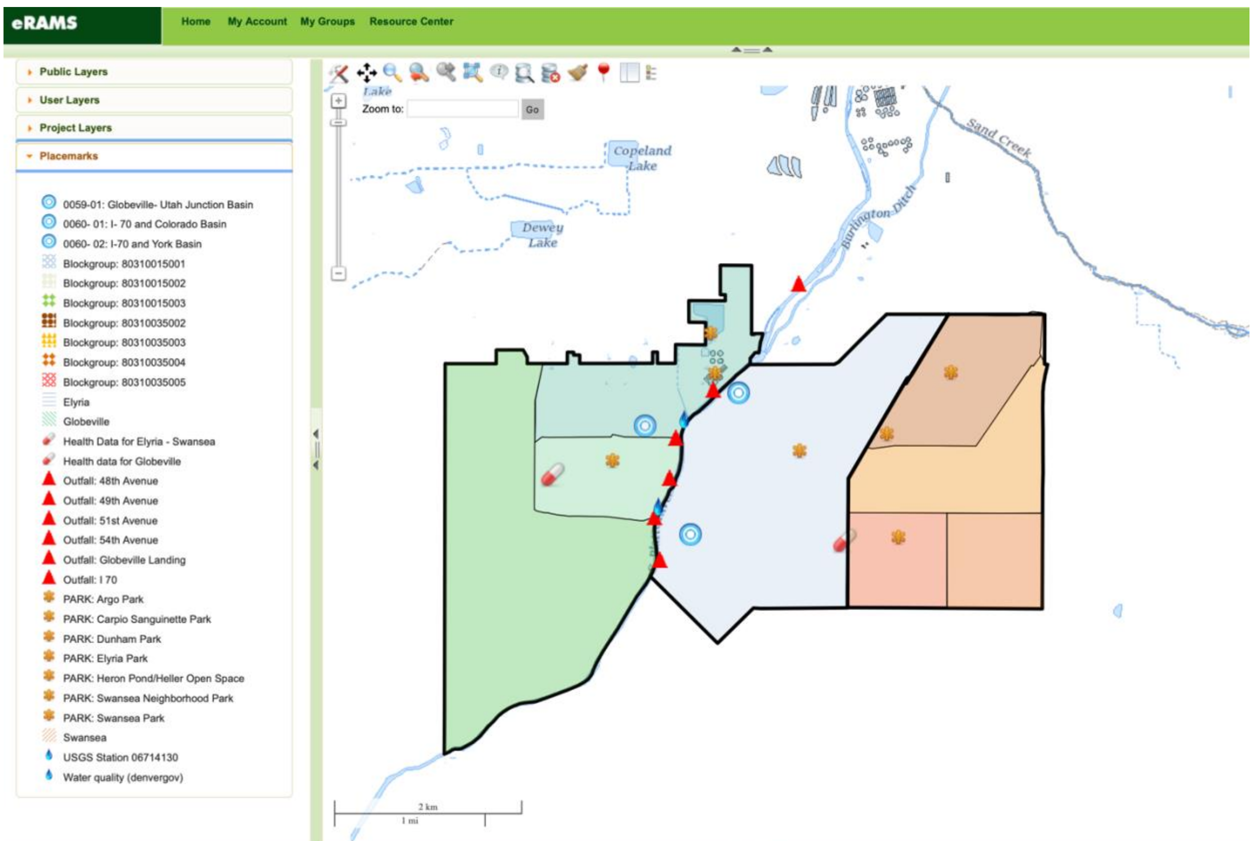



*Figure 5: GES eRams Project*

Implementing use of alternate water systems has the potential to reduce freshwater demand, especially in new and redevelopment areas, like the GES community. Redevelopment of community spaces provides an opportunity to rethink urban water systems. Integrating water in urban planning can achieve a resilient, sustainable, progressive and healthy community. Using fit for purpose water can overcome challenges of stormwater flooding, increased water demand, energy & water bills, etc. and increase livability.

### 1.2.6 Summary

Abundant research has been done surrounding water conservation and use of alternate water sources and corresponding direct benefits, i.e. demand reduction for traditional water supplies. Studies (NAP, 2016; Zhang et al. 2009) that have evaluated water demand reduction through use of different strategies, lack comparative assessment of all alternate water use and water conservation strategies. There remains a lack of studies that identify, acknowledge and document the benefits and consequences that come with water demand reduction strategies. While LCA studies have contributed important findings related to broader benefits and considerations for water demand reduction strategies (Jeong et al. 2016, 2018), those studies have not included comprehensive assessment including all triple bottom line categories.

Use of indicator analysis to evaluate alternate water supply strategies can be very useful for implementation in new and redevelopment areas thereby increasing livelihood and sustainability. Each community is different and therefore indicator analysis along with TBL evaluation has the potential to enhance decision makers' understanding on how and why certain strategies work better than others.

## 1.3 Objectives

This study seeks to assess water demand reduction through use of water conservation and alternate water supply strategies. The objective of the study is to provide a framework to assess benefits and consequences of integrated urban water system through indicator analysis. The Integrated Urban Water Model (IUWM) (Sharvelle et al. 2017) is utilized to simulate indoor and outdoor water demand for residential and commercial, industrial & institutional (CII) sectors. A combination of four water conservation strategies and four alternate water supply strategies are evaluated using hybrid approach of indicator analysis along with MCDA and TBL evaluation, similar to the approach described by Cole et al. (2018b). This research uses the indicator analysis to enable informed decisions on water demand management strategies like water security, cost, energy savings, health impacts, etc. using TBL criteria. It provides methodology for identifying, developing and quantifying indicators associated with water demand reduction strategies including water conservation and use of alternate water sources. The water conservation (end use efficiency) strategies include Indoor Conservation (IC), Climate Appropriate Landscape (CAL), Efficient Irrigation Systems (EIS), Advanced Irrigation Systems (AIS) ; and alternate water supplies include Graywater (GW), Stormwater (SW), Roof Runoff (RR) and Wastewater (WW) for end uses such as Toilet Flushing (TF), Irrigation (I), and Potable (P). A comparative assessment of water demand reduction along with its various benefits and consequences for all the strategies is performed. In addition, an annualized cost comparison and cost savings from water use is conducted for top performing strategies. Globeville, Elyria- Swansea community in Denver, CO is used as a case study to assess benefits and tradeoffs associated with water conservations and use of alternate supplies.

## Chapter 2: Methodology

The methodology used to achieve the objectives of this study consisted of developing a set of indicators (category) through literature review by thoroughly defining the indicator and metric for each of them. Next, observed data of water use for the GES was obtained to calibrate and test the IUWM. A calibration process consistent with Neale et al. (2020) was used to determine the best fitting parameters that match observed water use to set a baseline condition. Indoor and outdoor water use was then obtained by running IUWM's water demand reduction strategies for each of the eight blockgroups making up the GES community. Indicator analysis was then performed followed by MCDA and TBL analysis to identify effective water use strategy for the GES community.

### 2.1 Development of Indicators and Metrics

The indicator analysis aims to provide a comprehensive perspective to ensure water security while engaging the community to promote sustainable water use. This study used a combination of qualitative and quantitative methods to develop indicator for integrated urban water systems. Qualitative research included documenting information from literature review while quantitative research involved assessment of data obtained from various surveys and performing TBL evaluation and MCDA.

Based on the literature reviewed in the section above (Chesterfield et al. 2016; Cole et al. 2018a) a list of indicators was developed to specifically address water demand reduction strategies. Indicators and metrics were defined for each category of benefits and considerations in TBL categories of Social, Economic and Environmental. To ensure a thorough research, indicators corresponding to each co-benefit are linked to the WSC Index indicators in Table 3.

*Table 3: Connections between developed indicators and WSC Index indicators*
*Note: Indicators numbered in parenthesis ( ) represent developed indicators for this research (summarized in Table 4).*

| ***1.Ensure good sensitive governance*** | ***2.Increase community capital*** | ***3.Achieve equity of essential services*** | ***4.Improve productivity and resource efficiency*** | ***5.Improve ecological health*** | ***6.Ensure quality urban space*** | ***7.Promote adaptive infrastructure*** |
|---|---|---|---|---|---|---|
| ***(1.6)*** Public Acceptance | (***1.8)*** Public Awareness | ***(1.2)*** Potential risk from unintended exposures | (***1.3)*** Health outcomes resulting from decreased emissions | (***3.1)*** Ecosystem benefits from water left in natural system | (***1.9a)*** Physical and mental wellbeing | (***2.5)*** Risk of CSO violation |
| (***1.8)*** Public Awareness | | (***1.4)*** Impact on water available downstream | (***1.1)*** Water Security | (***3.4)*** Impacts to aquatic life downstream | (***1.9b)*** Thermal Comfort | |
| | | | ***(1.7)*** Employment Opportunities | (***3.5)*** Impacts on ecosystem downstream | | |
| | | | (***2.4)*** Impacts to recreation, agriculture and industry downstream | (***3.9)*** *Biodiversity* | | |
| | | | (***2.7)*** Income | | | |
| | | | (***2.9)*** Increased property values in the neighborhood | | | |
| | | | (***3.3)*** Emissions resulting from energy use | | | |

Table 4 summarizes the list of developed indicator categories against their respective indicators and metrics, and notes whether each metric was minimized or maximized. Each parameter was either minimized or maximized to achieve a high MCDA score, as discussed below (section 2.4). MCDA helps evaluate multiple conflicting parameters to reach a decision. Achieving a high MCDA score is better.

While indicators describe the indicator category, a metric is unit of measurement for performance for that indicator. After thorough reasoning and evaluation, irrelevant and inconsequential indicator categories were eliminated from necessary TBL categories. For example, public perception of using fit for purpose water is only categorized an indicator under Social, while it is eliminated from Economic and Environmental categories due to irrelevance. In addition, life cycle costs and water cost savings are not included in the indicator analysis since those are included in life cycle costs as described by Neale et al. (2020).

*Table 4: Benefits and Consequences for each TBL category.*
*Each TBL is numbered (1-3) and indicator categories are numbered (1 – 9) to develop a specific number notation for each indicator. Parameter minimized or maximized is noted for each indicator. Irrelevant indicator for a TBL category is represented by N/A.*

| Indicator Category | 1. Social | | 2. Economic | | 3. Environmental | |
|---|---|---|---|---|---|---|
| | Indicator | Metrics | Indicator | Metrics | Indicator | Metrics |
| **1. Reduced Demand for Traditional Water Supplies** | (***1.1)*** Water Security | Demand for traditional supply (gal/year) *[Min]* | Cost savings considered separately | N/A | (***3.1)*** Ecosystem benefits from water left in natural system | Decreased demand for traditional supply (gal/year) *[Min]* |
| **2. Health Impacts** | (***1.2)*** Potential risk from unintended exposures | LRTs *[Min]* See table 5 | N/A | N/A | N/A | N/A |
| **3. Energy Efficiency** | (***1.3)*** Health outcomes resulting from decreased emissions | Water Demand (gal/year) *[Min]*<br>Wastewater Outflow (gal/year) *[Min]*<br>Water treatment (LRTs) *[Min]* | Already included in costs | N/A | (***3.3)*** Emissions resulting from energy use | Water Demand (gal/year) *[Min]*<br>Wastewater Outflow (gal/year) *[Min]*<br>Water treatment (LRTs) *[Min]* |
| **4. Potential for Reduced Flow Downstream** | (***1.4)*** Impact on water available downstream | Wastewater effluent discharge *[Max]*; Stormwater volume diverted (gal/year) *[Min]* | (***2.4)*** Impacts to recreation, agriculture and industry downstream | Wastewater effluent discharge *[Max]*; Stormwater volume diverted (gal/year) *[Min]* | (***3.4)*** Downstream ecosystem Impacts | Wastewater effluent discharge *[Max]*; Stormwater volume diverted (gal/year) *[Min]* |

| | | | | | | |
|---|---|---|---|---|---|---|
| **5. Potential for Combined Sewer Overflow** | N/A | N/A | (***2.5)*** Risk of CSO violation | Wastewater discharge to sewer *[Min]*; Stormwater volume diverted *[Max]* (gal/year) | (***3.5)*** Impact on downstream ecosystem | Wastewater discharge to sewer *[Min]*; Stormwater volume diverted (gal/year) *[Max]* |
| **6. Public Perception** | (***1.6)*** Public Acceptance | See table 6 *[Max]* | N/A | N/A | N/A | N/A |
| **7. Employment Opportunity** | (***1.7)*** Social Mobility | Capital Cost; Maintenance Cost *[Max]* (See table 7) | (***2.7)*** Income | Capital Cost; Maintenance Cost *[Max]* (See table 5) | N/A | N/A |
| **8. Awareness of Efficient Water Use** | (***1.8)*** Public Awareness | Change in current practice (yes-1; no-0) *[Max]* | N/A | N/A | N/A | N/A |
| **9. Green Space** | (***1.9a)*** Physical and mental wellbeing | Area of green space added per acre *[Max]* | (***2.9)*** Increased property values in the neighborhood | Area of green space added per acre *[Max]* | (***3.9)*** Biodiversity | Area of green space per acre *[Max]* |
| | (***1.9b)*** Thermal Comfort | TBD | | | | |

1. Reduced Demand for Traditional Water Supplies

With increasing population and climate change, water shortage is inevitable. According to United Nations, today, more than 1 in every 10 people on the planet is affected by the global water crisis, struggling to access quality and quantity of water they need. Therefore, efficient water management is cornerstone for our survival. Diversifying the water sources by replacing freshwater with stormwater, roof runoff, graywater or wastewater for potable and non- potable uses may not only reduce the pressure off water utilities but also will also increase water security. In addition, reduced reliance on freshwater would promote a healthy ecosystem. Knowledge of total water demand for the area under study is necessary to achieve water security. Hence the total water demand, i.e., a combination of indoor and outdoor water demand is used here to represent this co-benefit.

2. Health Impacts

Implementing use of alternate water supply sources requires rigorous planning and management to avoid negative health impacts from cross connections, treatment process malfunctions, and unintended exposures to non- potable water. The risk to public health increases with increasing scale, complexity and number of applications systems, and variability in source water microbial quality $Log_{10}$ pathogen Reduction Target (LRT) values (Sharvelle et al. 2017; Schoen et al. 2017) are used inform treatment requirements based on source water end use combinations (Table 3). Quantitative Microbial Risk Assessment (QMRA) was utilized to derive the pathogen log reduction targets (LRT) which corresponds to an infection risk of $10^{-4}$ per person per year (ppy) at the 95$^{th}$ percentile confidence interval. Recommended LRTs do not reflect industrial wastewater targets as those source waters may pose a higher risk for specific chemical contaminants Source water end use combinations with a higher LRT require more extensive treatment to meet public health standards. For the purpose of identifying a metric to estimate potential health impacts resulting from human exposure to pathogens, the LRT for the source water end use combinations is used with a higher LRT required for treatment indicating more risk associated with treatment failures that could result in an unintended exposure. To reduce complexity, an average of $LRT_{10}$ values for enteric bacteria, virus and protozoa has been used (Table 5).

*Table 5: 95$^{th}$ Percentile Log10 Pathogen Reduction Targets ($LRT_{10}$) to meet $10^{-4}$ (infection) ppy Benchmarks for Healthy Adults*
*Note: $LRT_{10}$ values summarized in table reflect an average of bacteria, virus and protozoa*

| | ***Roof Runoff*** | ***Greywater*** | ***Stormwater*** | ***Wastewater*** |
|---|---|---|---|---|
| ***Toilet Flushing*** | 3.5 | 4.5 | 5.5 | 7 |
| ***Irrigation*** | 3.5 | 4.5 | 4.5 | 7 |
| ***Potable Uses (laundry, shower, faucet, dish, leak)*** | 7.5 | 8.75 | 8.5 | 10.6 |
| ***Toilet Flushing and Irrigation*** | 3.5 | 4.5 | 5.5 | 7 |
| ***Potable Use and Irrigation*** | 7.5 | 9 | 8.5 | 10.6 |

3. Energy Efficiency

Water Systems including drinking water and wastewater systems are large consumers of energy, accounting for 30 to 40 percent of total energy consumed (EPA, 2019). Energy consumption only for water transportation is currently estimated between 3 and 6 percent (Gomez et al. 2018). Water systems not only account for 2 percent of total energy consumed in the United States, but also add over 45 million tons of greenhouse gases annually (EPA, 2019). By incorporating water conservation and use alternate water strategies a lot of energy can be saved, reducing utility bills and greenhouse gas emissions. In this research, the energy efficiency is represented by an estimation of three metrics. The energy efficiency was estimated based on three sub-criteria:

- *Energy consumption for treatment*: $LRT_{10}$ values from table 4 were used where higher $LRT_{10}$ value corresponds to a higher amount of energy consumed. [*Min*]
- *Energy Savings from Water Supply*: This describes reduced energy for water treatment and was estimated by the demand for traditional supplies. [*Min*]
- *Energy Savings from Wastewater Treatment*: This measures energy for treatment of domestic wastewater and was estimated by average wastewater effluent discharge at the municipal WWTF

(gal/yr). [*Min*]. Note that when treated wastewater is recycled, the energy for treatment of that water is accounted for by the *energy consumption for treatment* category described above.

Energy efficiency is not included as an Economic co-benefit since these costs are included in the operations and maintenance cost to install alternate water systems (Neale et al. 2020)

4. Potential for Reduced Flow Downstream

This indicator was aimed for cities in compliance with Municipal Separate Storm Sewer System (MS4) where maintaining flow for downstream uses is important. There is a risk of lower flows and higher waste concentrations when using fit for purpose water (Hodgson et al. 2018), which might affect the quality and quantity of water flowing downstream. In addition, a part of stormwater or roof runoff when used for outdoor irrigation is also diverted to downstream flows. The decline in water flow downstream may have a negative impact on recreation activities, agriculture and aquatic ecosystem downstream. To estimate the potential for this risk, average annual wastewater effluent discharge and stormwater diverted were used. Minimizing these parameters was considered to decrease potential risk for downstream flow impacts.

5. Potential for Combined Sewer Overflow

This indicator category was aimed for cities with Combined Sewer Overflow Systems (CSO). There is a risk of overflowing, which can have a negative impact on the residents and aquatic ecosystem downstream. This can be overcome by regulating amount of wastewater discharged to the sewer and diverting stormwater from the sewer system. Thus, the metrics used to develop a score for potential for CSO, wastewater discharge to sewer and stormwater volume diverted are maximized and minimized respectively to achieve a high MCDA score and measured in gallons per year.

6. Public Perception

Use of alternate water sources is of increasing relevance for water- stressed regions but is often considered a contentious option as public perception plays a major barrier for fit-for-purpose water. From a literature review on public perception of using alternate water sources, it was found that majority of studies focused on perceptions of using recycled wastewater. However, the findings were consistent, that acceptance of municipal recycled wastewater progressively decreases with increase in personal contact (Muthukumaran et al. 2011; Rock et al. 2012; Marks, 2004). Even though studies on other alternate water sources are scarce, a similar pattern is observed for roof runoff, stormwater and graywater. While outdoor irrigation is strongly accepted, the support drops as the use involves closer personal contact, e.g. toilet flushing and potable use (Marks, 2004; Keremane et al. 2011). Rock et al. (2012) surveyed public perception of using recycled water for a range of uses from watering non-edible crops, toilet flushing to laundry, cooking and drinking. This along with other studies demonstrate that public acceptance for non-potable uses is far more than potable or drinking water purposes (Marks, 2006). Consistent with these studies, here the public perception for using roof runoff is ranked 5 which is the highest, followed by stormwater while graywater and wastewater are ranked the least (Schoen et al. 2017; Jahne et al. 2016). Similarly, among non- potable uses outdoor irrigation is rated the highest, i.e., 5, followed by toilet flushing and lastly potable uses. A weighted Average was then applied to estimate a score for each source water end use combination (Table 6).

*Table 6: Public Perception of different source water end use combination using Weighted Average*

| Source water end use combinations | **Score for each End Use** | Roof Runoff | Stormwater | Graywater | Wastewater |
|---|---|---|---|---|---|
| **Score for each source water** | | 5 | 2.5 | 1 | 1 |
| Irrigation | 5 | 5 | 3.75 | 3 | 3 |
| Toilet Flushing | 2.5 | 3.75 | 2.5 | 1.75 | 1.75 |
| All Potable Uses (Laundry, Shower, Faucet, Dish, Leak) | 1 | 3 | 1.75 | 1 | 1 |
| Toilet Flushing & Irrigation | 1[a] | 3.75 | 2.5 | 1.75 | 1.75 |
| Potable & Irrigation | 1[a] | 3 | 1.75 | 1 | 1 |

a: Lowest score among the two end uses take priority for each end use.

7. Employment Opportunities

Adoption of IUWM will create job opportunities in several sectors, including trained artisans with installation and plumbing skills. Due to lack of studies and uncertainty in number of jobs created, a binary system was used to denote when potential jobs are created (Table 7). Here, the employment opportunities are classified under two categories- jobs for installation and jobs for maintenance activities.

*Table 7: Employment Opportunity Scoring*
*Note: 0 – no potential for increased person-hours; 1 – potential for increased person-hours*

| **Strategies** | **Jobs for Installation** | **Jobs for Maintenance Activities** |
|---|---|---|
| **Indoor Conservation** | 0 | 0 |
| **Climate Appropriate Landscape** | 1 | 0 |
| **Advanced and Efficient Irrigation Systems** | 0 | 0 |
| **Graywater Indoor - Toilet Flushing & Potable Uses** | 1 | 1 |
| **Graywater Outdoor - Irrigation** | 1 | 0 |
| **Stormwater Indoor -Toilet Flushing & Potable Uses** | 1 | 1 |
| **Stormwater Outdoor - Irrigation** | 1 | 1 |
| **Roof Runoff Potable Uses** | 1 | 1 |
| **Roof Runoff Toilet Flushing & Irrigation** | 0 | 0 |
| **Wastewater Indoor - Toilet Flushing & Potable Uses** | 1 | 1 |
| **Wastewater Outdoor - Irrigation** | 1 | 1 |

8. Awareness of Efficient Water Use

In today's age, public awareness of water conservation through use of efficient water technology and fit for purpose water is of utmost importance. Contrary to the belief that raising awareness is telling people what they are supposed to do, raising awareness is to define issues and educate people so that they can make their own, informed decisions (Global Water Partnership, 2012). Raising public awareness for water issues means having a general level of understanding of water issues and to create shared values on managing water use. Awareness can be raised through a variety of channels including launching water campaigns through local and mass media, organizing exhibits, workshops, displays and via putting posters, billboards and brochures. Studies indicate that spreading awareness on use of efficient water not only increases public participation but also public acceptance on using alternate water sources (Priest et al. 2003; Alsaluli et al. 2015). For this indicator, use of any one or more alternate water or energy efficient technology it is considered to have spread awareness.

9. Green Space

Green spaces such as parks, community gardens, schoolyards as well as wetlands and meadows are slowly shrinking as, globally, more than 50 percent of the population become urban dwellers (WHO, 2011). City life provides good sanitation, access to health care, nutrition and education but is also associated with adverse health impacts like anxiety, mood disorders, schizophrenia and higher risk of infections (Engemann et al. 2019). In recent years, lower exposure to green spaces has been linked to these various health and mental outcomes. A study by World Health Organization (WHO) showed that 3.3 percent of global deaths occurred due to physical inactivity linked to poor walkability and lack of access to recreational areas (WHO, 2011). Urban parks and gardens facilitate physical activity, social interaction, recreation and relaxation. In addition, trees filter out noise and air pollution, and increase urban livability by cooling the cities. Various studies have found that properties situated near a green space are valued at a higher price than other comparable properties in the neighborhood (Voicu & Been, 2008; Yengué & Mirza, 2015). Furthermore, green spaces are a vital part of the ecosystem and also help reduce stormwater flooding. Here, only newly added green spaces per acre of area are considered as a co-benefit.

Area of green space is often used as a metric for mental and physical well-being associated with urban environment (Jones et al. 2017). Thermal comfort is a benefit of increased green space in urban areas (Gonçalves et al. 2019). We are currently working with Elie Bou- Zeid from Department of Civil and Environmental Engineering at Princeton University to develop a model that estimate thermal comfort benefits from adding green space and increasing irrigation to convert dead landscape areas to healthy grass. Area of green space is also directly correlated to property values (Ward et al. 2008; Lutzenhiser et al. 2001;

Shultz & Schmitz, 2008). Addition of greenspace and diverse species also relates to ecosystem benefits and biodiversity (Shultz & Schmitz, 2008).

## 2.2 Integrated Urban Water Model

The Integrated Urban Water Model (IUWM) is a GIS enabled process-based water balance model that quantifies residential, commercial and outdoor water demands. IUWM has explicit functionalities to evaluate the potential for water conservation and use of source water end uses combinations. Source waters including stormwater, roof runoff, graywater and wastewater in combination with uses like toilet flushing, irrigation and potable use. In addition, the model is designed such that it can be used for a range of water use scale from block group to city scale (Sharvelle et al. 2017).

The GES community was used as a case study area. The community is 2128.6 acres and characterized by mostly high-density land use (Table 8). Water use data for the GES community was spatially collected by U.S. census block groups for ten years starting from 2008 to 2018 from Denver Water. The analysis includes all residential indoor and outdoor water use within the GES community boundaries, including 8 block groups.

*Table 8: GES data summary*

| **Blockgroup** | **Area (acre)** | **Households** | **Population** | **Area of High, Medium, Low Density Developments** | | | |
|---|---|---|---|---|---|---|---|
| | | | | High density Area (acre) | Medium density Area (acre) | Low density Area (acre) | Open Space (acre) |
| **80310015001** | 299 | 239 | 831 | 78.22 | 85.15 | 90.73 | 23.02 |
| **80310015002** | 185 | 349 | 1229 | 39.56 | 60.34 | 68.83 | 12.96 |
| **80310015003** | 823 | 452 | 1627 | 426.42 | 253.21 | 103.02 | 27.27 |
| **80310035002** | 24 | 400 | 1449 | 89.17 | 82.24 | 62.35 | 8.94 |
| **80310035003** | 267 | 379 | 1455 | 100.12 | 92.08 | 68.39 | 1.34 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **80310035004** | 152 | 168 | 625 | 58.55 | 56.32 | 35.09 | 0.45 |
| **80310035005** | 160 | 423 | 1723 | 31.06 | 64.36 | 61.68 | 2.46 |

Outdoor water use for commercial and industrial (CII) was included to account for irrigation of parks and open spaces. Outdoor irrigation is included in calibration as IUWM estimates outdoor demand using land cover and does not distinguish between residential and non- residential (Sharvelle et al. 2017). Calibration was performed to evaluate the best performing set of parameters to obtain estimates of water use that closely match observed water use data (Sharvelle et al. 2017). The same calibration procedure used by Neale et al. (2020) was utilized here. As shown in table 6, the parameters were realistic in range. For GES community, the parameters calibrated were plant factor, net irrigation requirement ($k_i^{met}$), fraction of precipitation events responded to ($k_i^{pcp}$) and percent irrigated area of each NLCD category. Neale at al. (2020) applied a plant factor ($k_i^{pf}$) of 0.8 and percentage of irrigation requirement met ($k_i^{met}$) of 45% calibration of outdoor water use in Denver. Because outdoor water use was observed to be different in the GES community compared to Denver (Figure X), those values were not applied here, and were instead calibrated. Parameter estimates for irrigation efficiency ($k_i^{eff}$) and threshold temperature ($T_i^{irr}$) were assumed to be consistent with Denver (Table 7; Neale et al. 2020). Calibrated and Applied values for each blockgroup can be found at Appendix A.

*Table 9: Calibrated and Applied parameter values*

| IUWM Parameter | Description | Calibration Range | Calibrated and Applied Values |
|---|---|---|---|
| $\alpha$ | Indoor Demand Profile Alpha | 40-100 | 76.74 |
| $\beta$ | Indoor Demand Profile Beta | 0.5- 0.99 | 0.57 |
| $k_i^{met}$ (%) | Net irrigation requirement met | 20-100 | 14-19 |
| $k_i^{pcp}$ (%) | Precipitation events responded to | 20-80 | |
| $k_i^{eff}$ | Irrigation application efficiency | - | 0.71 |
| $T_i^{irr}$ (°C) | Threshold Temperature | - | 5° C |
| $k_i^{pf}$ | Plant factor | 0.5 – 0.9 | 0.65 (0.4 - 0.8) |
| $A_{i,c}$ (%) Open Space | Open space area irrigated | 30 - 90 | 13.2 (0.4 - 29.3) |
| $A_{i,c}$ (%) Low Density | Low density area irrigated | 30 - 90 | 72.9 (35.1 – 103) |

| | | | |
|---|---|---|---|
| $A_{i,c}$ (%) Medium Density | Medium density area irrigated | 10 - 70 | 121.9 (56.3 – 281.8) |
| $A_{i,c}$ (%) High Density | High density area irrigated | 2 - 30 | 156.8 (31 – 100) |

The calibrated values were used to compare observed and modeled data for the study area. Indoor and outdoor water demands for one blockgroup located in Globeville is shown in figure 6, similar data was collected for all eight blockgroups making up the GES community.

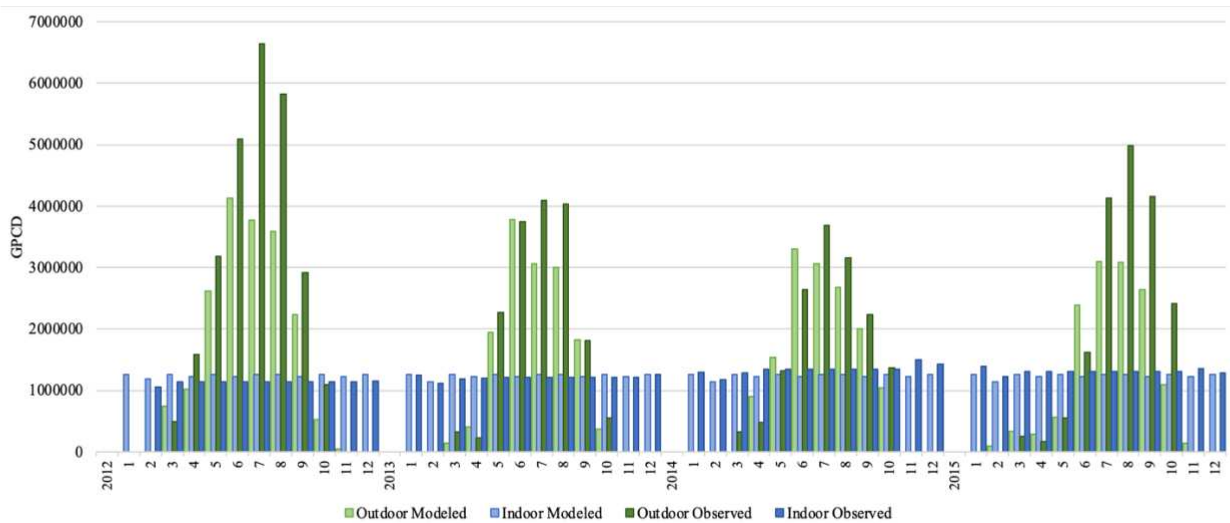



*Figure 6: Monthly observed vs modeled indoor and outdoor demand in GPCD*

A blockgroup from the study area had dominant industrial water use as it has high concentration of industries and was therefore eliminated due to huge error between observed and modeled data, and because the focus of this study is on residential water use and outdoor CII water use (indoor CII excluded). Calibration for rest of the blockgroups in the study area performed well (Table 10). Negative MRE values indicate model overestimation. The model performance was also tested using error statics; mean relative error (MRE), bias fraction (BIAS) and Nash- Sutcliffe of Efficiency (NSCE) (Sharvelle, 2017).

*Table 10: Calibrated Values for GES Study Area*

| *Use* | *NSCE* | *MRE* | *BIAS* |
|---|---|---|---|
| *Residential Indoor* | 0.945 | -0.02 | -0.004 |

| | | | |
|---|---|---|---|
| *Outdoor* | 0.813 | -0.04 | 0.160 |

## 2.3 Strategies to Reduce Demand for Traditional Supplies

The calibrated parameters obtained above were used to develop the baseline scenario. All the other water conservation and reuse scenarios are based off these calibrated parameters. Distinct source water end use combination scenarios were created to evaluate the most promising water conservation or reuse technique for GES community. The four alternate water sources supply four end uses including Toilet Flushing, Irrigation, and two combined end use strategies; Toilet Flushing & Irrigation and Potable & Irrigation. This research used identical adoption strategy for water conservation and reuse strategies as Neale et al. (2020; Table X). Strategies 1 to 4, i.e., Indoor Conservation, Climate Appropriate Landscape (Xeriscape), Advanced Irrigation and Efficient Irrigation Systems are categorized as water conversation strategies. while strategies 5-8, i.e., Graywater, Stormwater, Roof Runoff and Wastewater for all end uses are categorized as use of alternate water sources.

*Indoor Conservation (IC)* in IUWM uses predefined household profile function for High Efficiency New Homes (HENH) as defined in the Residential End Use study (DeOreo et al. 2016; Sharvelle et al. 2017). *Climate appropriate landscape (CAL)* reduces outdoor demand by decreasing or eliminating the need for supplemental water for irrigation. This strategy is modelled in IUWM by minimizing the calibrated evapotranspiration plant factor to 0.5. While *Advanced Irrigation Systems (AIS)* stimulates installation of weather-based irrigation controllers in households with existing sprinkler systems, *Efficient Irrigation System (EIS)* reduces irrigation demand through installation of high efficiency sprinkler heads and use of smart water meters. Graywater systems include laundry, bath and non- kitchen sink water as supplies for end uses. *Stormwater* supply for all end uses is collected from the neighborhood (small to medium urban watershed) and is stored in a large tank or detention basin before treatment and distribution. *Roof Runoff* for all end uses utilizes a household roof to collect roof runoff with a 200 gal per household storage capacity. Wastewater systems include wastewater use after being treated to meet the standards for all end uses. Different alternate waters are treated to different standards for fit-for-purpose use (Neale et al. 2020).

*Table 11: IUWM Strategy Parameter Values*

| Strategies | Key Parameter | Value | Percent Adoption | Storage (gal/house hold) |
|---|---|---|---|---|
| **1.Indoor Conservation** | REUS high efficiency $\alpha$ and $\beta$ | - | 50% | - |
| **2.Climate Appropriate Landscape** | Plant factor | 0.5 | - | - |
| **3.Advanced Irrigation Systems** | Percent reduction in irrigation demand | 10% | - | - |
| **4.Efficient Irrigation Systems** | Irrigation efficiency | 0.85 | - | - |
| **5.Graywater Use for end uses** | Available graywater for end use | - | 30% | 200 |
| **6.Stormwater collection for end uses** | Available stormwater for end use | 40% | 100% | 3000 |
| **7.Roof Runoff for end uses** | Roof area – fraction of impervious area | 0.2 | 30% | 200 |
| **8.Wastewater for end uses** | Available wastewater for end use | 25% | 100% | - |

## 2.4 Multi-criteria Decision Analysis to Assess TBL Performance of Water Demand Reduction Strategies

Rather than analyzing performance of each water use strategy for each of the TBL category to obtain MCDA scoring, a hybrid approach involving the indicators, TBL categories and MCDA was used to identify the best performing strategies for the community. This approach was preferred since it is a comprehensive approach and analyzes the performance of each of the strategies against all indicator and TBL categories.

Three different MCDA models, one for each of the TBL categories, i.e., Social, Economic and Environmental categories was developed. The social MCDA model included all developed indicator categories that were relevant in the social category. Each of the indicators weighed equally. No preference was given to one from another. A similar process was used to set up the Economic and Environmental models. And MCDA was performed using two methods, Weighted Average Method (WAM) and Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) II for all scenarios. Raju et al. 2000 found a little difference in the top-ranked alternative when comparing results using various MCDA methods while Hajkowicz and Higgins, 2008 found a slightly big difference when a combination of subjective and objective criteria was used. To avoid inconsistency two MCDA methods were used to determine the most effective alternative.

WAM is the most popular method because of its ease of understanding and computation. This method computes a weighted average of each criterion's score for each alternative (Giove et al. 2009)

$$V(a) = \sum_{i} w_i * v_i(a)$$

Where V(a) is the summation of each alternative a; $w_i$ represents the weight linked to the $i^{th}$ criterion (as selected by the stakeholder).

PROMETHEE is an outranking technique best suited to analyze a mix of quantitative and qualitative data. This method performs a pairwise comparison between all the alternatives for each criterion. The very same (PROMETHEE II) method as described by Cole et al. (2018b) was utilized here.

## 2.5 Green Space

This is an important indicator category that takes into consideration water demand for increasing green spaces and atmospheric conditions to determine thermal comfort. This indicator category is a part of the future work. In this research, water use strategies that could be used in GES to meet the increase in water demand were identified. As seen in figure 3, outdoor water demand is considerably lower in GES than in Denver. Hence, there is a potential to increase green spaces in GES by increasing outdoor irrigation. This increase is proposed to be met by use of alternate water for outdoor irrigation.

Addition of new green spaces in the community will increase the community's outdoor water demand. By adding green spaces, the outdoor water demand for GES was increased from 34 GPCD to 60 GPCD, i.e., equivalent to that of Denver's outdoor demand. This increase was achieved by increasing the net irrigation requirement ($k_i^{met}$ ) shown in table 9 to 40 percent for each blockgroup in the study area. It was aimed to be met by use of stormwater or wastewater since both these alternate water strategies were able to achieve maximum water demand reduction in the community.

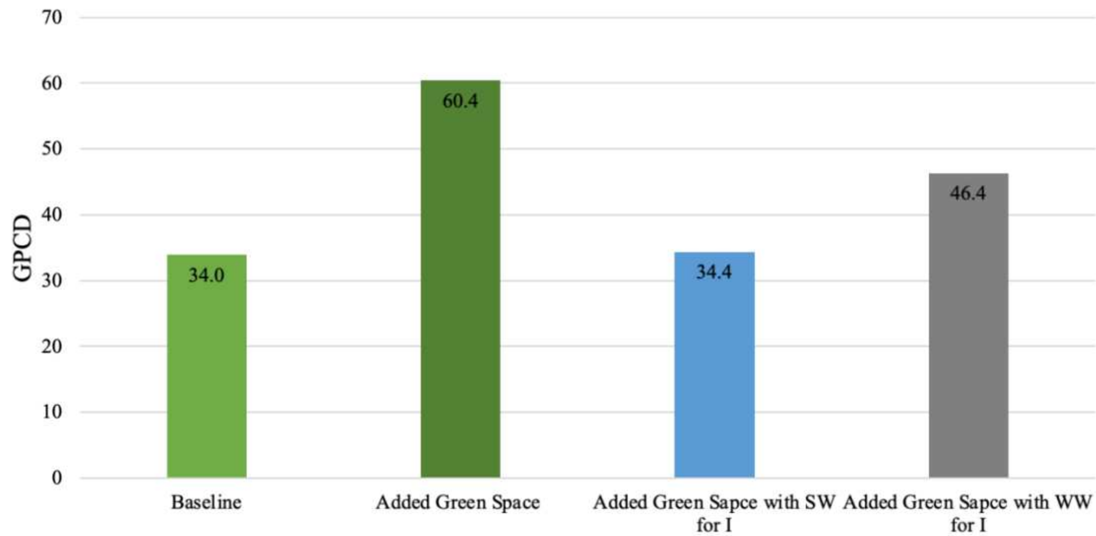



*Figure 7: Outdoor Water Demand with Added Green Space*
*SW=Stormwater; WW=Wastewater; End Use: I=Irrigation*

It is observed from figure 14 that the increase in outdoor irrigation demand is met when 55 percent stormwater is available for capture at 3000 gallons storage capacity. On the other hand, wastewater still falls short of 12 gallons to meet the increase in outdoor demand when 99 percent was available for capture.

## Chapter 3: Results and Discussion

### 3.1 Annual Water Demand Reduction

Water demand reduction in this study refers to reduced demand for traditional supplies as described in Neale et al. (2020). Figures 7-8 display solutions of annual water demand reduction for GES community in gallons per capita per day (GPCD) and percent reduction in water demand from the baseline scenario (figure 2). The baseline outdoor and indoor demand for GES community is 34 GPCD and 42.9 GPCD respectively. Comparing different water conservation and alternate water strategies over a 10-year period will help us determine an appropriate strategy to reduce water demand in the GES community.

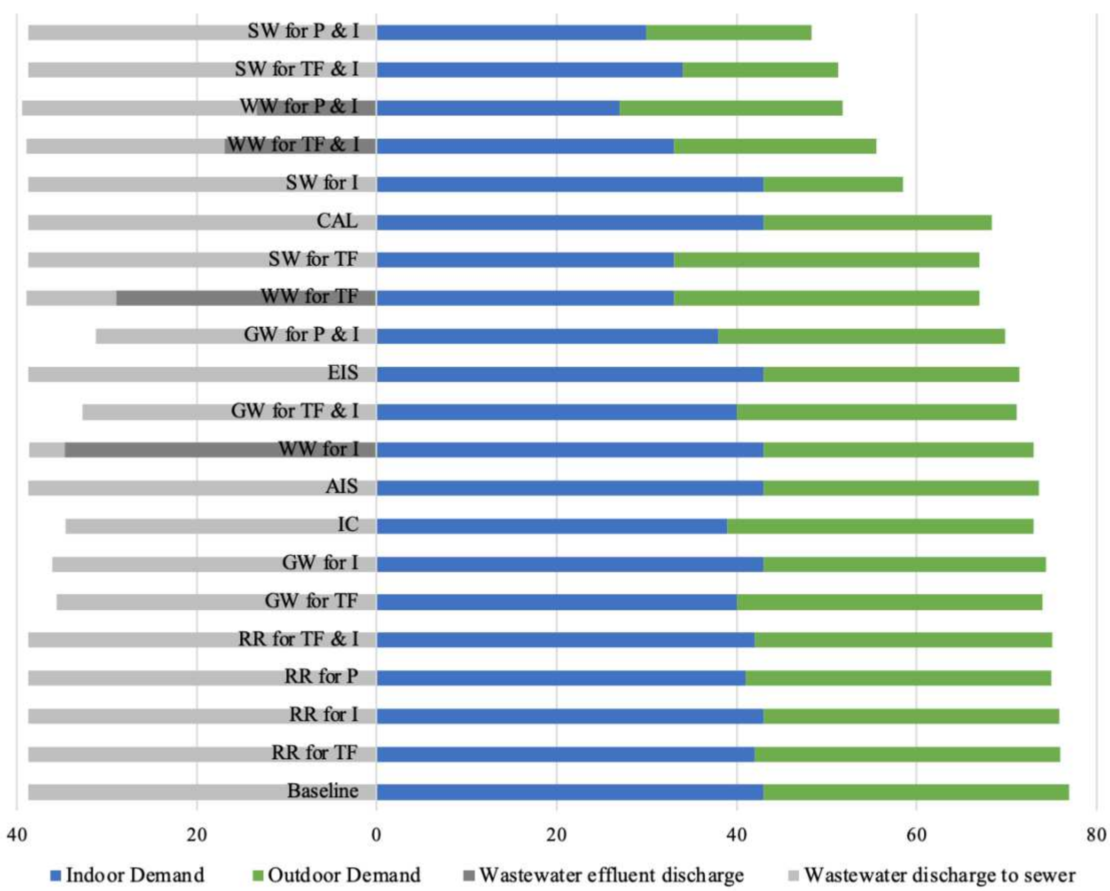



*Figure 8: Water Demand Reduction in GPCD in GES community*
*IC = Indoor Conservation; CAL=Climate Appropriate Landscape; EIS=Efficient Irrigation Systems; AIS=Advanced Irrigation Systems; GW=Greywater; SW=Stormwater; R=Roof Runoff; WW= Wastewater; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*

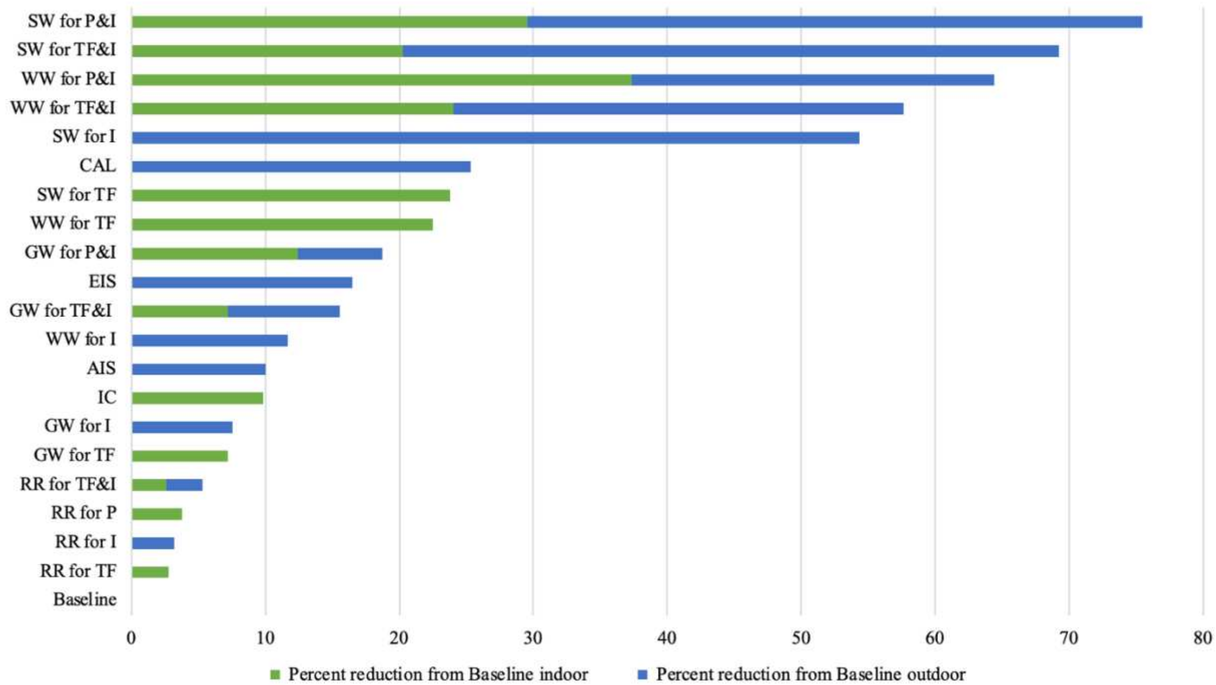



*Figure 9: Percent Water Demand Reduction from Baseline*
*IC = Indoor Conservation; CAL=Climate Appropriate Landscape; EIS=Efficient Irrigation Systems; AIS=Advanced Irrigation Systems; GW=Greywater; SW=Stormwater; R=Roof Runoff; WW= Wastewater; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*

*Outdoor Demand Reduction Strategies*

Outdoor demand reduction strategies include Climate Appropriate Landscape, Advanced Irrigation Systems, and Efficient Irrigation Systems. A 25% reduction in outdoor water demand is observed in the GES community when landscape is converted to Climate Appropriate Landscape. This strategy is effective in the community as irrigated turf grass landscape is easily seen in the area. Water consumption of turf grass is quite high and therefore the calibrated plant factor of 0.8 was used. A high plant factor corresponds to higher plant water requirement. Efficient Irrigation Systems also significantly reduces outdoor irrigation demand followed by Advanced Irrigation Systems. Overall higher water demand reductions are observed in GES community than Denver (as calculated by Neale et al. 2020) due to very low outdoor water use in the GES community.

*Indoor Demand Reduction Strategies*

Indoor Conservation decreases water demand in the community by 10% at the adoption levels studied here (Table 11). The reduction in water demand is markedly higher in GES than that of Denver which was observed to be 2% (Michael et al. 2020). The average number of people residing in one household in GES versus that in Denver overall (table 1) accounts for this difference. Since the indoor water demand is higher than that of Denver, it provides more opportunity to achieve demand reduction via indoor conservation fixtures.

*Alternate Water Strategies*

Among the four alternate water supply strategies, stormwater supply has the maximum potential to reduce indoor as well as outdoor water demand. Use of stormwater for irrigation reduces outdoor demand by 54% while 29% reduction in indoor demand is achieved when stormwater is utilized for potable & irrigation. This is a representative that GES community receives a good amount of precipitation. However, the area does not usually experience rainfall events during the peak summer months when the irrigation demand is highest, but it gets rainfall during spring and early summer months.

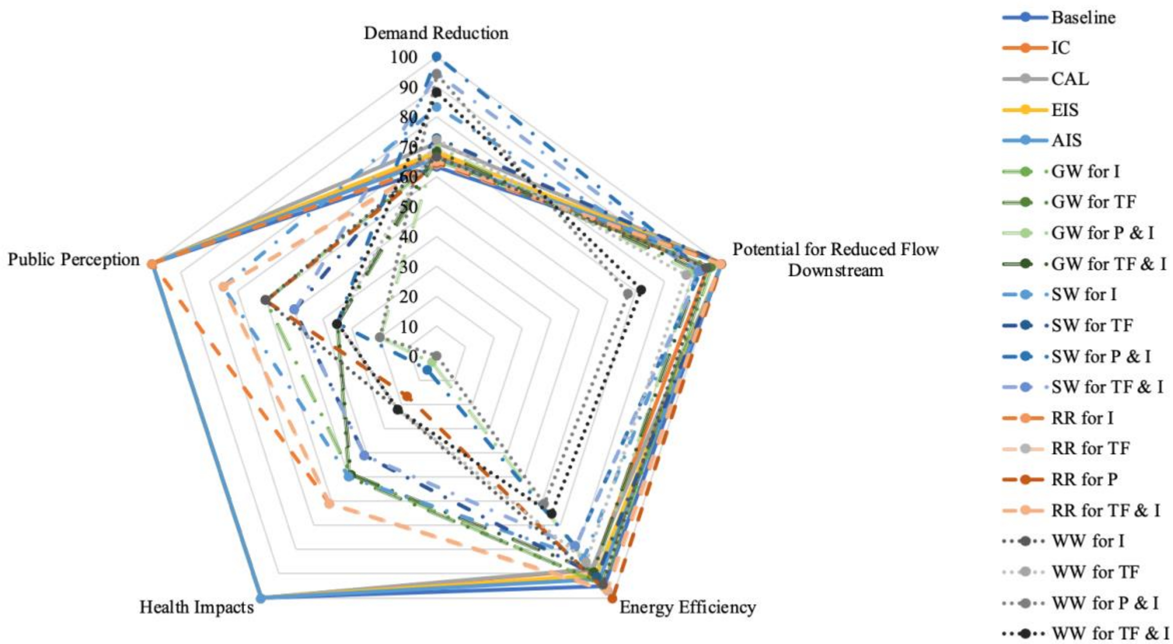
After stormwater use, wastewater reuse in the community can considerably reduce water demand. Maximum outdoor and indoor water demand reduction was achieved by wastewater for toilet flushing & irrigation (34%) and wastewater for potable & irrigation (37%) respectively. A high volume of wastewater is produced in the community due to presence of manufacturing plants and heavy industries accounting for this trend.

Graywater performs relatively poor. Less than 20% demand reduction is generally observed for all end uses with Graywater. However, use of graywater reduces wastewater discharge to the sewer with possible benefits to the WWTF. The lowest demand reduction is achieved by use of Roof Runoff.

## 3.2 Analysis of Indicator Performance

Figure 8 shows the percent performance of each strategy with regards to various indicators for GES community. From the eight indicators developed in this research, only five are shown in this graph. Since

Increased Awareness of Efficient Water Use is scored hundred percent for each strategy except that of baseline; Jobs are divided into capital cost and maintenance cost and hence from table 5, each strategy scores zero, fifty or hundred percent for this co-benefit; Increased green space is analyzed separately further. Hence, these three indicator categories are not displayed in the spider plot below (figure 10).



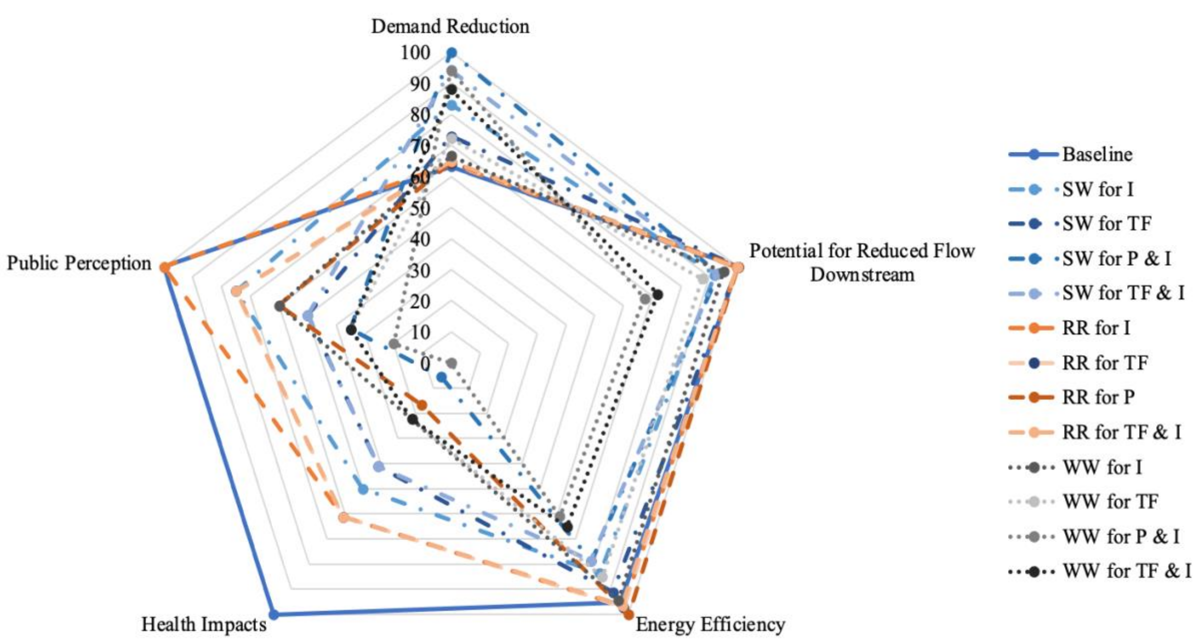



*Figure 10: Indicator Analysis for all end uses*
*IC = Indoor Conservation; CAL=Climate Appropriate Landscape; EIS=Efficient Irrigation Systems; AIS=Advanced Irrigation Systems; GW=Greywater; SW=Stormwater; R=Roof Runoff; WW= Wastewater; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*

*End Use Efficiency Strategies*

All end use efficiency strategies including Indoor Conservation, Climate Appropriate Landscape, Efficient Irrigation Systems and Advanced Irrigation Systems are highlighted with a bold line. These follow a similar trend across the five indicators. They get a perfect score for Health Impacts, Public Perception and Potential for Reduced Flow Downstream since these pose no potential health risks, are highly publicly accepted and does not reduce the volume of flow downstream. All the four strategies achieve more than 85 percent energy efficiency. However, they are some of the least performing strategies for Water Security or Resilience to Water Shortage as they totally rely on freshwater supply. Among the four water conservation strategies, Climate Appropriate Landscape performs well in GES community, achieving 71 percent water security.

*Alternate Water Supply Strategies*

Stormwater end uses are represented by shades of blue on the graph. All stormwater end uses perform differently for each co-benefit. Performance of different stormwater end uses for Resilience to Water Shortage, Potential for Reduced Flow Downstream and Energy Efficiency depend on the volume of water demand, water discharge and energy required to treat it respectively. Among the four end uses, stormwater for Potable & Irrigation achieves a 100 percent water security but it has very high potential for health risk and is also least favored end use by public. Stormwater for Toilet Flushing, on the other hand, returns all water downstream after use hence scores 100 percent for Potential for Reduced Flow and it also performs competitively with other stormwater end uses. Stormwater for Irrigation and Stormwater for Toilet Flushing & Irrigation also perform very well as compared to all the other alternate water.

Followed by stormwater, Wastewater for Potable & Irrigation (94%) and Wastewater for Toilet Flushing & Irrigation (88%) also achieve high water security. Conversely, Wastewater for Irrigation and Wastewater for Toilet Flushing perform well in Potential for Reduced Flow Downstream (i.e., all wastewater after use is retuned downstream) and Energy Efficiency. Nevertheless, all wastewater end uses, some more than others, are least publicly favored and also pose a high potential health risk.

Similar to wastewater, graywater is also least ranked water reuse strategy by public even though it has lesser potential for health risk than wastewater. All graywater end uses are Energy Efficient and also score well for Potential for Reduced Flow Downstream. But in comparison with other alternate water and water conservation strategies they perform average for all the other indicator categories.

Among all the other alternate water strategies, roof runoff is the most publicly accepted. Roof Runoff for Irrigation achieves 100 percent public acceptance similar to all water conservation strategies. Roof Runoff for Potable use achieves a perfect score for Potential for Reduced Flow Downstream and Energy Efficiency. However, it has a very high potential for Health Impacts. Roof Runoff for Toilet Flushing & Irrigation and Roof Runoff for Toilet Flushing score very competitively among all the other alternate water strategies, for all indicator except for Resilience to Water Shortage. All Roof Runoff end uses achieve least water security since the volume of roof runoff captured is the least among other strategies.

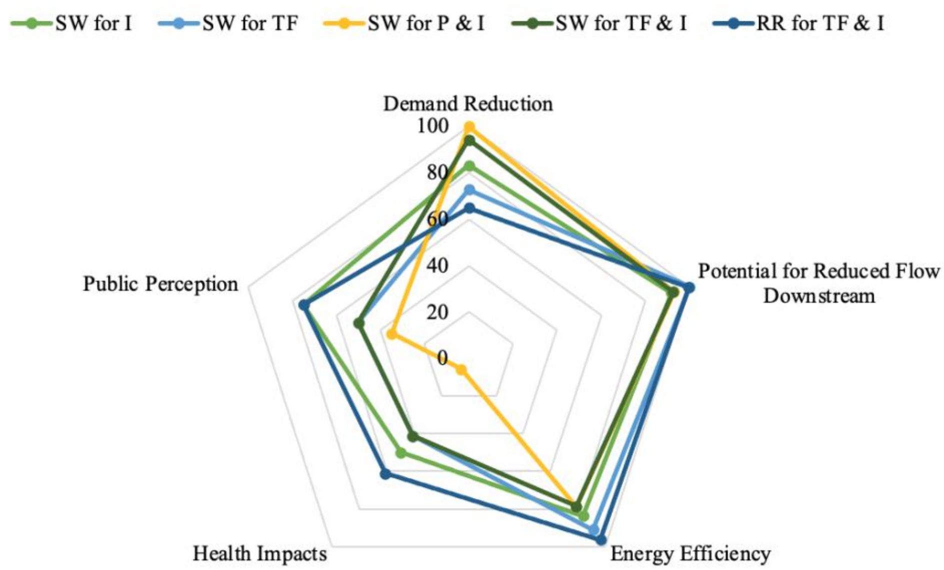



*Figure 11: Top 5 performing strategies*
*SW=Stormwater; R=Roof Runoff; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*

Further, top five performing water strategies were identified through indicator analysis and MCDA scores described in detail in section 3.3. A strategy was considered a top performing strategy if it achieved a high score in all three TBL categories in Promethee MCDA. An indicator analysis of the five top performing strategies included all stormwater end uses and Roof Runoff for Toilet Flushing & Irrigation as shown in figure 11.

## 3.3 MCDA Results & Discussion

While IUWM provides policy makers with framework to take improved decisions on urban water management, MCDA facilitates the decision analysis by providing a computational framework for analyzing alternate water strategies, increasing transparency and accountability.

A ranking of the alternative for each TBL category was generated using the hybrid method. MCDA was performed using Weighted Average Method (WAM) and Preference Ranking Organization Method for Enrichment of Evaluations (Promethee) II for all scenarios.

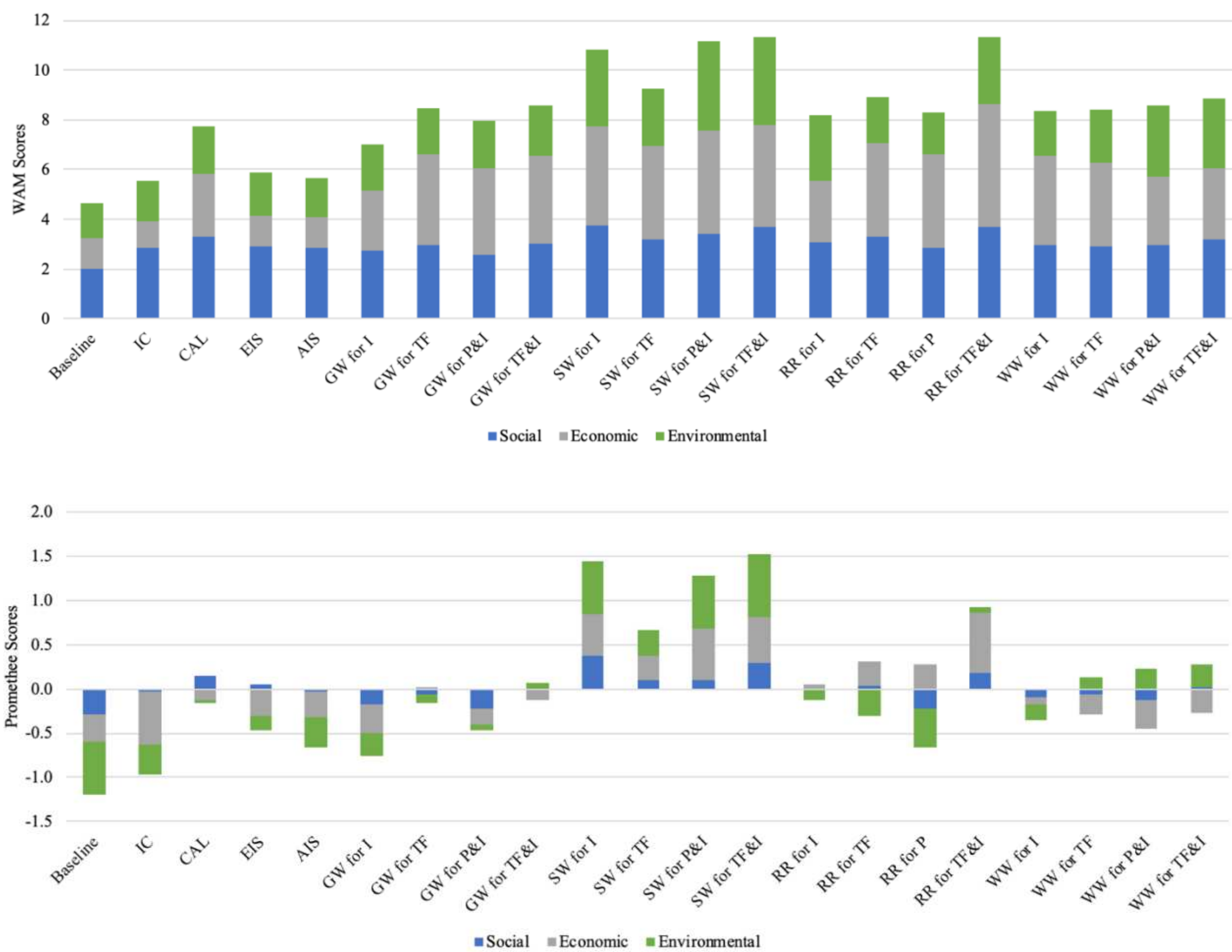



*Figure 12: MCDA scores using Weighted Average Method (WAM) and Promethee*

*IC = Indoor Conservation; CAL=Climate Appropriate Landscape; EIS=Efficient Irrigation Systems; AIS=Advanced Irrigation Systems; GW=Greywater; SW=Stormwater; R=Roof Runoff; WW= Wastewater; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*


*Figure 13: MCDA scores using Weighted Average Method (WAM) and Promethee Spider Plots*

*IC = Indoor Conservation; CAL=Climate Appropriate Landscape; EIS=Efficient Irrigation Systems; AIS=Advanced Irrigation Systems; GW=Greywater; SW=Stormwater; R=Roof Runoff; WW= Wastewater; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*

As seen in the figure 12, both WAM and Promethee methods showed best performance for the same alternatives from economic and social categories, i.e., Roof runoff for Toilet Flushing & Irrigation in economic and Stormwater for Irrigation in social categories. However, Stormwater for Potable Use & Irrigation in WAM and Stormwater for Toilet Flushing & Irrigation in Promethee scored best from Environmental category. In both the models, the baseline scenario has the least overall score. But overall, a lot of variation is observed when the MCDA model is simulated using WAM and Promethee. In social category, it is observed that all the strategies in WAM relatively score higher than Promethee. In general, WAM scores are more spread out than Promethee scores. In particular, wide variation is observed in Promethee in the economic performance for stormwater and graywater, while WAM results are very consistent (Figure 13). This variation between the two MCDA models can be explained by how WAM and Promethee estimate each indicator metric. WAM compares one indicator with all the others and provides the best performing strategy with perfect score. Promethee, on the other hand, uses a pair-wise comparison, i.e., it accounts for so many other indicators that perform similarly and therefore this method does not give a maximized score but a relative score considering all indicator categories.

The indicators, Potential for Reduced Flow Downstream and Energy Efficiency, for the sturdy area utilizes same numerical values of wastewater effluent discharge for most of the water conservation and alternate water strategies (Table 12). For this indicator, WAM provides a high score to all strategies with like values. In this particular example, for many of the strategies, there is not an impact to wastewater effluent discharge (i.e., outdoor water use efficiency and all strategies that use stormwater and roof runoff; Table 12). In the WAM, all of these strategies would receive a score of 5, while the pairwise comparison applied by Promethee does not apply a higher score when the metric is the same for an indicator. This explains the high score with low variation for stormwater use and outdoor water efficiency observed when the WAM was applied, particularly for the economic and social categories (Figure 13). Here, the pairwise comparison by Promethee better explains differences among performance of water demand reduction strategies. Therefore, Promethee was selected for better representation for this research.

*Table 12: Wastewater effluent discharge values for Potential for Reduced flow downstream*
*IC = Indoor Conservation; CAL=Climate Appropriate Landscape; EIS=Efficient Irrigation Systems; AIS=Advanced Irrigation Systems; GW=Greywater; SW=Stormwater; R=Roof Runoff; WW= Wastewater; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*

| Water Use Strategies | Baseline | IC | CAL | EIS | AIS | GW for I | GW for TF | GW for P&I | GW for TF&I | SW for I | SW for TF | SW for P&I | SW for TF&I | RR for I | RR for TF | RR for P | RR for TF&I | WW for I | WW for TF | WW for P&I | WW for TF&I |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wastewater effluent discharge (GPCD) | 38.6 | 34.8 | 38.6 | 38.6 | 38.6 | 36.1 | 35.5 | 31.2 | 32.7 | 38.6 | 38.6 | 38.6 | 38.6 | 38.6 | 38.6 | 38.6 | 38.6 | 34.7 | 29.0 | 13.4 | 16.9 |

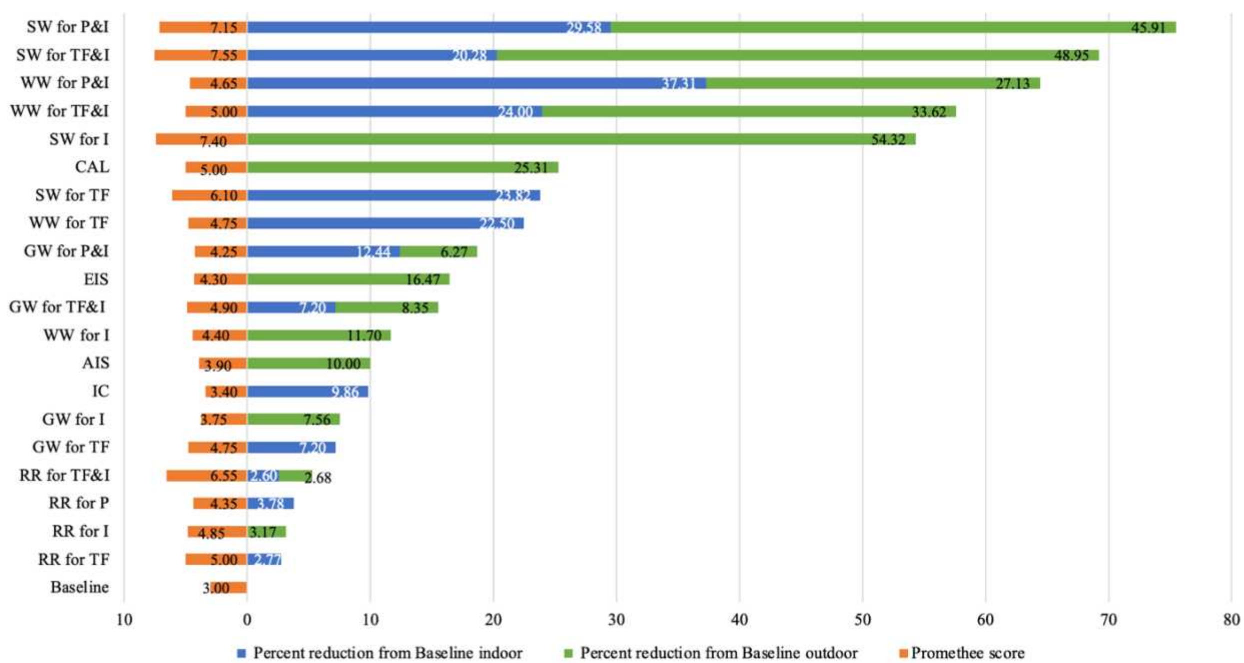



*Figure 14: Promethee score vs. Percent Demand Reduction*
*For purposes of clear visualization Promethee scores are scaled from zero to ten (rather than -1 to 1 as output by Promethee model).*
*IC = Indoor Conservation; CAL=Climate Appropriate Landscape; EIS=Efficient Irrigation Systems; AIS=Advanced Irrigation Systems; GW=Greywater; SW=Stormwater; R=Roof Runoff; WW= Wastewater; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable*

Figure 14 shows a comparison between Promethee score and percent demand reduction for each strategy. It shows an average Promethee score obtained from all TBL categories scaled from -1 to +1 to 0 to 10 for better visualization, where 0 represents the least score while 10 represents the highest score. It is observed that Stormwater for Potable & Irrigation achieves maximum annual demand reduction in the community with 75 percent reduction in overall water demand. However, Stormwater for Toilet Flushing & Irrigation gets a higher score from Promethee. This is because Promethee takes into consideration performance of each source water end use combination and weighs it against each indicator category before assigning a score. So, figure 14 aids our understanding in identifying the strategies that perform well overall for the community. Wastewater for Potable & Irrigation also achieves high demand reduction but gets a negative Promethee score. Roof Runoff for Toilet Flushing & Irrigation achieves less than 5 percent demand reduction yet achieves a Promethee score of 0.31 that is because Roof Runoff for Toilet Flushing & Irrigation performed better than all the other alternatives in economic category in the MCDA model. This shows that the MCDA scoring did not just consider demand reduction but all the indicators to give a comprehensive score.

### 3.3 Assessing Tradeoffs for Strategies

Assessing tradeoffs while selecting a strategy for implementation is of utmost importance. Tradeoffs help achieve a balanced selection between two desirable but incompatible outcomes. As seen in Figure 15, among the top 5 performing strategies, not all strategies get a high MCDA score (PROMOETHEE) for all the three TBL categories. While Roof Runoff for Toilet flushing and Irrigation gets a high score in Economic category, it scores very poorly in Environmental category as compared to other top performing strategies. Stormwater for Potable & Irrigation scores very well for Economic and Environmental while it scores poorly for Social. Stormwater for Toilet Flushing & Irrigation and Stormwater for Irrigation comparatively score well for all TBL categories. On the other hand, Stormwater for Toilet Flushing scores low for all TBL categories compared to other top strategies.

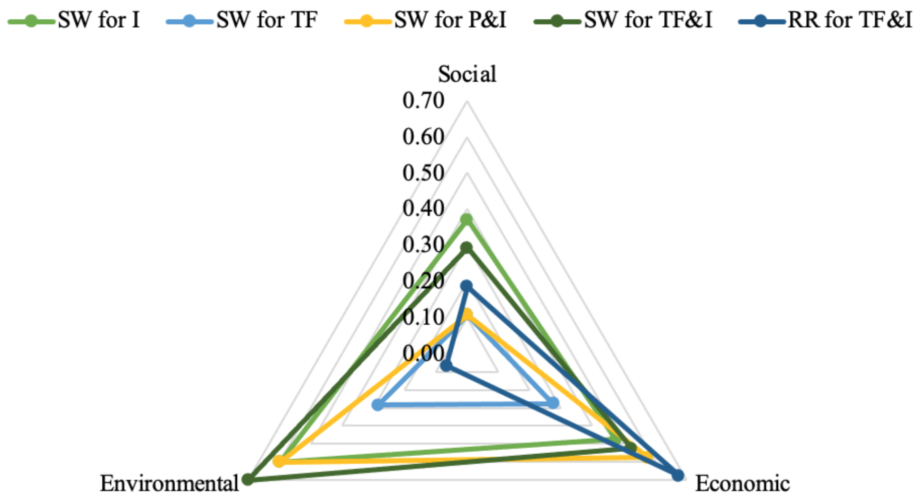



*Figure 15: TBL- MCDA evaluation for top five strategies*
*SW=Stormwater; R=Roof Runoff; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable (Cost and Water Cost Savings were annualized costs per 1000 gallons and were normalized together)*

The top five performing strategies identified for the GES community were compared with their respective Promethee scores, percent reduction from baseline, water cost savings (Denver Water, 2020) and annualized cost normalized from 0 to 100 (figure 16). Table 13 shows the system type and total annualized cost incurred for the use of these strategies in Denver as calculated by Neale et al. (2020). The water cost savings were obtained from Denver Water, 2020 for Single -Family Residential Customers per 1000 gallons volume. Treated Water Volume Rates for Tier I for 0 to average winter consumption were utilized here. Annual water cost savings were then calculated for each blockgroup.

*Table 13: Annualized cost for top 5 water use strategies as calculated by Neale et al. (2020)*

| **Strategy** | **Total Annualized Cost in Denver** | **System Type** |
|---|---|---|
| **Stormwater for Irrigation** | $ 19, 000, 000 | Centralized |
| **Stormwater for Toilet Flushing** | $ 62, 000, 000 | Neighborhood-Subregional |
| **Stormwater for Toilet Flushing & Irrigation** | $128, 000, 000 | Neighborhood-Subregional |

| | | |
|---|---|---|
| **Stormwater for Potable & Irrigation** | $ 55, 000, 000 | Centralized Direct Potable Reuse |
| **Roof Runoff for Toilet Flushing and Irrigation** | $ 2, 000, 000 | Single Family Residence |

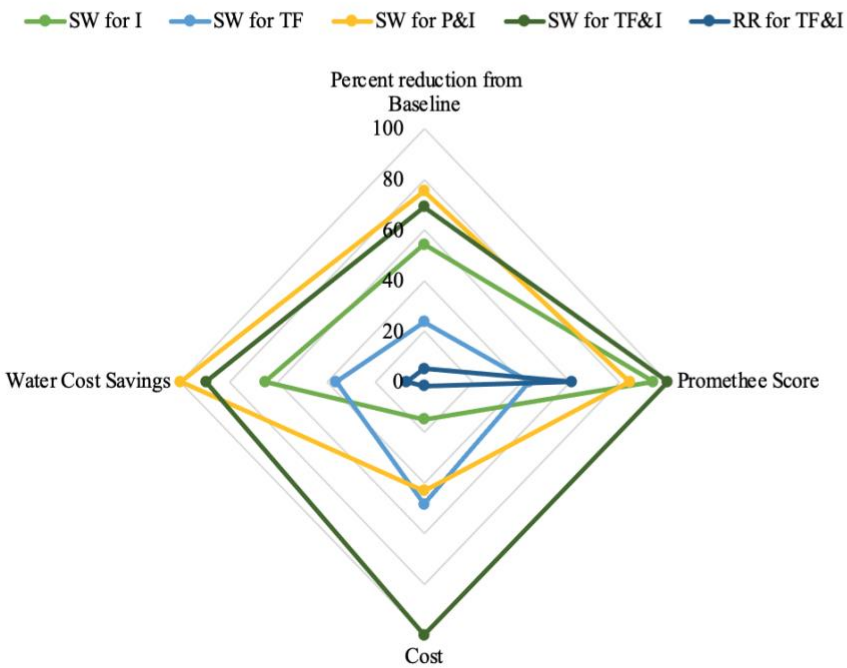



*Figure 16: Four – Way Comparison with Top Five Performing strategies*
*SW=Stormwater; R=Roof Runoff; End Uses: I=Irrigation; T =Toilet Flushing; P=Potable (Cost and Water Cost Savings were annualized costs per 1000 gallons and were normalized together)*

It is observed that Stormwater for Toilet Flushing & Irrigation achieves 70 percent annual water demand reduction, gets the best Promethee score and also saves approximately 90 percent in water charges, but it is the most expensive stormwater end use. Stormwater for Potable & Irrigation and Stormwater for Irrigation closely compete each other. While Stormwater for Potable & Irrigation achieves the highest annual demand reduction (75%) and water cost savings (100%), Stormwater for Irrigation achieves a higher for Promethee score and is way more cost efficient than Stormwater for Potable & Irrigation. In addition, Stormwater for Irrigation also achieves more than 50 percent annual water demand reduction. Roof Runoff for Toilet

Flushing & Irrigation is the most inexpensive alternate strategy that could be considered but it achieves only about 5 percent of water demand reduction which is not feasible for the community.

### 3.5 Conclusion

This study provides a framework to evaluate various water conservation and alternate water supply strategies using an approach to assess performance indicators for potential implementation in the Globeville, Elyria- Swansea community in Denver, Colorado. The study also identifies the unique benefits and trade-offs of using these water strategies. The approach resulted in a comprehensive evaluation of the water strategies through MCDA including TBL evaluation. The alternate water strategies that exceled when only demand reduction was considered were Stormwater and Wastewater. Nevertheless, these strategies did not necessarily score the best for all the indicator categories and therefore assessing trade-offs is of utmost importance for decision making.

Top five performing strategies from indicator analysis included all Stormwater End Uses and Roof Runoff for Toilet Flushing & Irrigation. From MCDA analysis, these strategies performed well for all the indicators and TBL categories over others. The top performing strategy for GES community in terms of demand reduction, indicator analysis, water cost savings (Denver Water,2020) and cost efficiency (Michael et al., 2020) were Stormwater for Potable & Irrigation and Stormwater for Irrigation. Use of Stormwater for Irrigation was also fully able to meet the increase in outdoor demand stimulated by Addition of Green Spaces in the GES community. Overall, Stormwater for Irrigation performed better than all the other strategies considered in this study for GES community, but was found to come at a high cost.

However, the study by Michael et al. 2020 clearly showed that Stormwater use is one of the most expensive alternate water strategies. From various studies it is observed that stormwater systems are costly not because it is a complex system or needs extensive treatment but there is no standard of practice in place for it. For every new project, a custom design is created to capture stormwater for beneficial use, which costs a ton each time. In response to citizen interest on implementing stormwater use, 10 states in the US have developed specific regulations on stormwater capture and use which widely vary in complexity and use.

While some states provide basic guidelines for design and permitting stormwater capture systems, others are much more detailed but not legally enforceable. Colorado on the other have regulations that restrict stormwater capture altogether (NAP, 2016).

In addition, Colorado follows the doctrine of Prior Appropriation, i.e., the system of water allocation is based on the historical order in which water rights were acquired. Under this law, it becomes all the more difficult to use alternate water when a downstream water right holder exists. Capturing alternate water could result in reduced water flow downstream affecting the water rights holder as well the aquatic life downstream. In general, expanding use of alternate water is tricky since each state follows different water rights doctrines. There is no federal guidance that addresses this issue. This provides an opportunity for policy makers to think creatively about standards of use of decentralized infrastructure for alternate water, especially stormwater.

Future work on the research should include indicator analysis for a combination of two or more alternate water strategies for implementation. It could also look into implementing multiple water sources at one time. The addition of indicators in diverse fit-for purpose water systems supply system and multi-functional water system will help decision makers' confidence in the results and increase robustness.

The approach presented here provides a pivotal first step to a sustainable alternate urban water use. Extending the methodology to identify and develop relevant indicators will aid decision making to meet the demands of a fast-paced urban growth

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## Appendix

Calibrated and Applied values for each blockgroup for input to IUWM.

| Blockgroup | Plant Factor | Percent area irrigated in developments with | | | | Area irrigated (acre) in developments with | | | | Net irrigation met |
|---|---|---|---|---|---|---|---|---|---|---|
| | | High density | Medium density | Low density | Open Spaces | High density | Medium Density | Low Density | Open Spaces | |
| **80310015001** | 0.76 | 25 | 12 | 37 | 51 | 19.55 | 10.22 | 33.57 | 11.74 | 19 |
| **80310015002** | 0.56 | 10 | 42 | 70 | 43 | 3.96 | 25.34 | 48.18 | 5.57 | 19 |
| **80310015003** | 0.76 | 25 | 12 | 37 | 37 | 106.60 | 30.38 | 38.12 | 10.09 | 19 |
| **80310035001** | Blockgroup eliminated | | | | | | | | | |
| **80310035002** | 0.76 | 25 | 12 | 37 | 37 | 22.29 | 9.87 | 23.07 | 3.31 | 19 |
| **80310035003** | 0.6 | 16 | 46 | 72 | 32 | 16.02 | 42.35 | 49.24 | 49.24 | 14 |
| **80310035004** | 0.68 | 2 | 34 | 49 | 90 | 1.17 | 19.15 | 17.19 | 17.19 | 16 |
| **80310035005** | 0.43 | 17 | 64 | 84 | 95 | 5.28 | 41.19 | 51.81 | 51.81 | 19 |