A multi-criteria sustainability assessment of water reuse applications: A case study in Lakeland, Florida

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Water impact statement:

Using the proposed multi-criteria analysis framework, sustainability of different alternatives for water reuse were evaluated through a holistic sustainability perspective that accounted for environmental, economic, and social dimensions. This study provides stakeholders with a decision-making support tool in reverse logistics application in water systems and formation of closed-loop water supply chains, as an alternative to withdrawals from natural water resources.

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ABSTRACT

Water shortage and water contamination necessitate adopting a reverse logistics and a closed-loop supply chain approach, which is the process of moving wastewater from its typical final destination back to the water supply chain with different levels of treatment for reuse. Hence, the incorporation of sustainability concepts through life cycle assessments for selecting reclaimed water applications considering reverse logistics and closed-loop systems is receiving more attention. However, no prior studies have evaluated the trade-off between the reclaimed water quality and corresponding costs, environmental impacts and social benefits for different types of water reuse. The aim of this study is therefore to design possible scenarios for water reuse based on water reuse guidelines and evaluate the different types of end use based on the three dimensions of sustainability (i.e., economic, environmental and social aspects) simultaneously. The different reuse types considered include unrestricted urban reuse, agricultural reuse, indirect potable reuse (IPR), direct potable reuse (DPR), distributed unrestricted urban reuse, as well as some degree of decentralization of treatment plants for distributed unrestricted urban reuse. The trade-off investigation and decision-making framework are demonstrated in a case study and a regret-based model is adopted as the support tool for multi-criteria decision-making. This study revealed that although increasing the degree of treatment for water reuse increases the implementation and operation and maintenance (O&M) costs of the design, it increases the value of resource recovery significantly, such that it can offset the capital and O&M costs associated with the treatment and distribution for DPR. Improving the reclaimed water quality also reduces the environmental footprint (eutrophication) to almost 50% for DPR compared to the other reuse scenarios. This study revealed that the distance between the water reclamation facility and the end use plays a significant role in economic and environmental (carbon footprint) indicators.

Keywords: Life Cycle Assessment; Reverse Logistics; Reclaimed Water; Water Infrastructure, Sustainability, Water Reuse

Nomenclature

Abbreviations			
ANPV	Annualized net present value	*P*	Phosphorus
ASNPV	Annualized specific net present value	*PV*	Present value
CAS	Conventional activated sludge	*US*	Unites States
CFP	Carbon footprint	*VRR*	Value of resource recovery
DPR	Direct potable reuse	*WHO*	World Health Organization
EPA	Environmental Protection Agency	*WTP*	Water treatment plant
EU	Eutrophication	*WWTP*	Wastewater treatment plant
FDEP	Florida Department of Environmental Protection	Variables	
FV	Future value	i	Annual discount rate
IPR	Indirect potable reuse	n	Number of years for design's lifetime
ISO	International Organization for Standardization	P_t	Water demand
LCA	Life cycle assessment	T_p	Planning horizon
LCCA	Life cycle cost analysis	w	Weighting factor
N	Nitrogen	Outputs	
NPV	Net present value	NR	Normalized regret score
O&M	Operation and maintenance	R	Regret score
		$\bar{R}$	Final regret score

1. Introduction

The increasing demand, scarcity, and contamination of water resources, accompanied by the likely impacts of climate change, have made complex challenges for sustainable water and wastewater management, demonstrating the need for the integrated management of wastewater systems that facilitates and promotes resource recovery (Zheng et al., 2016). Traditionally, the main function of a wastewater treatment plant was defined as the removal of contaminants to safely release it back to natural water bodies (Hospido et al., 2004; Gallego et al., 2008). The traditional approach for wastewater management primarily relies on centralized treatment systems and reduces the negative impacts of wastewater on the environment and natural ecosystems (Morera et al., 2016). However, this is achieved at the expense of high energy and chemical consumption by these treatment plants (Godin et al., 2012). In order to maintain and improve the sustainability of current systems, a paradigm shift must occur in wastewater management that emphasizes resource recovery (e.g., water, energy, and nutrients) over treatment (Capodaglio, 2017). This paradigm shift not only offsets some portion of required energy for treatment, but also reduces the need for freshwater withdrawals by supplementing the water supply chain with reclaimed water.

Supply chain network design is receiving growing attention for solving production and demand problems in a variety of research fields (Ramezani et al., 2013). Traditional supply chain designs rely primarily on forward networks to manufacture products using raw materials. The reverse logistics network, also known as a backward or recovery network, is the process of returning used products to the collection and repair centers in order to be remanufactured and become qualified for reuse. The same notion can be applied to water production: wastewater can be diverted back to decentralized, satellite, or centralized wastewater treatment systems such that it is treated to a water quality level that permits water reclamation (see Figure 1). A study conducted by Fleischmann et al. (2001) analyzed the impacts of product recovery on logistics networks. They showed that the product recovery impacts such as economic benefits, environmentally conscious customers and regulations, are context-dependent and require an individually comprehensive approach for redesigning any type of industrial production activity in an integral way.

One primary challenge in realizing such a closed-loop water system can be the lack of a planning and design framework to evaluate and identify the most sustainable application for reclaimed water. During the last decade, the emerging challenges in water systems such as water shortage, increasing water demand, and water pollution, have motivated researchers to evaluate and improve the sustainability of water systems by focusing on water reclamation and reuse. There have also been several Life Cycle Assessment (LCA) studies, as a standard method (ISO, 2006a; ISO, 2006b), in recent decades to determine the impacts resulting from water treatment, water distribution, and/or wastewater treatment for reclaimed water use. In combination or parallel with LCA, multi-criteria analysis has been widely used to evaluate the available alternatives according to a defined set of measurable criteria (Figueria et al., 2005). These approaches are broadly used to help decision-makers choose the most appropriate solutions in achieving particular goals according to the evaluation criteria. However, lack of environmental dimensions in the evaluation criteria for decision-making has led to tremendous problems in the past century (e.g. fog, acid rain, and red tide), necessitating a transition in allocation of the evaluation criteria for decision-making. The transition needs to provide the insights with respect to economic, environmental, and social impacts, amongst which trade-offs may arise, to be supported by the decision-makers in both private and public sector. In addition, decision-makers may have to deal with unknowns and uncertainties, which are characteristics of investing in new designs and models (Linder and Williander, 2015). The bottom line is that the criteria (definition and quantification algorithm) and assessment method (data collection and visualization pattern) are highly influenced by the decision-making framework, which is selected initially based on the case-specific parameters and the study's goal (Guarini et al., 2018).Amores et al. (2013) evaluated the environmental impacts of reclaimed water use for non-potable purposes such as irrigation in Spain. They showed that this scenario reduces the freshwater consumption due to net water savings, but it didn't make a significant improvement to the environmental impacts due to the additional resources required for tertiary treatment. Pasqualino et al. (2011) studied the environmental profile of four wastewater treatment plants for different water reuse scenarios and revealed that using the reclaimed water for potable purposes not only preserves freshwater resources, but also result in higher environmental impacts due to the additional required treatment processes. Munoz et al. (2009) designed four bench-scale treatment systems to evaluate the environmental impacts of wastewater treatment for reuse via irrigation. The results showed that wastewater reuse for irrigation with any of the studied tertiary treatment systems had lower ecotoxicity impacts than those without tertiary treatment. Meneses at al. (2010) used LCA methods to evaluate the environmental advantages and disadvantages of reclaimed water use for non-potable applications. The results showed that replacing desalinated water with reclaimed water for non-potable purposes is beneficial when there is a scarcity of freshwater.

Other studies analyzed the environmental impacts of urban water systems that mainly focus on treatment technologies (e.g. Beavis and Lundie, 2003; Metcalf et al., 2007; Lim and Park, 2008). The latter revealed that as the degree of treatment increases, the cost and the negative environmental impacts associated with the treatment increases, although they offset a portion of the freshwater needed. There are also few studies that apply multi-criteria analysis in the design and evaluation of water systems. Ren and Liang (2017) developed a group multi-attribute decision analysis (MADA), with economic, environmental, and society-politic evaluation criteria, to assess the sustainability of four treatment processes for water reclamation in China. The developed MADA analysis consisted of: 1) Determining the relative performances of the treatment processes regarding the evaluation criteria (extreme poor, very poor, poor, medium poor, fair, medium good, good, very good, and extreme good); 2) Weights determination for the evaluation criteria; 3) Establishing the aggregated decision-making matrix; and 4) Determining the priority sequences of the alternatives and comparing their relative priorities. The results revealed that with the selected weighting strategy, anaerobic single-ditch oxidation obtained the best score among the treatment technologies; however, the selection was highly dependent on the weighting strategy. Benedetti et al. (2010) developed a Monte Carlo simulation and multi-criteria analysis to achieve the optimal configuration in the operation phase of a wastewater treatment plant in Belgium. The evaluation criteria consisted of effluent quality (weighted sum of contaminants load in the effluent), the fraction time during which the effluent fails to meet the water quality limit, and costs (capital and O&M). The proposed framework was based on the optimization of impact categories in the defined evaluation criteria. The results revealed a significant improvement in terms of economic (total costs and operation costs) and environmental (total nitrogen) impact assessments. They also showed that the anoxic fraction of reactor volume and the volume of primary clarifier played a significant role in system's performance. Flores-Alsina et al. (2008) also developed a multi-criteria analysis to evaluate the operation configuration of six wastewater treatment plants under uncertainty, using a Monte Carlo simulation. The evaluation criteria consisted of environmental, economic, legal, and technical aspects. The evaluation procedure consisted of normalization of systems performance (best=1; worst=0), weighting the evaluation criteria, and summation of weighted normalized factors to obtain the final score for each treatment alternative. The results revealed that the selected configuration showed a relatively better performance in almost all of the selected impact categories, and helped reduce the risk of system failure. Nonetheless, no prior studies evaluated treatment requirements and different types of water reuse applications in a holistic (i.e., economic, environmental and social) sustainability assessment. Therefore, the goal of this study is to evaluate the trade-off between reclaimed water quality and corresponding costs, environmental impacts and social benefits for different types of water reuse applications. This trade-off analysis paired with a regret-based model can help decision-makers identify the degree of treatment needed to produce reclaimed water as well as the type of reuse applications to initiate.

2. Materials and methods

In this study, a multi-criteria analysis framework was developed and used to compare the water reuse alternatives in terms of economic, environmental, and social impacts. The study was conducted in the City of Lakeland, Florida, where the water service area is experiencing a rapid growth in terms of population. The methodology used in this study is described in this section.

2.1. Study area

The trade-off evaluation for different types of reclaimed water applications was conducted for the City of Lakeland, which is located on the western side of Polk County, Florida. The city is within the Southwest Florida Water Management District (SWFWMD) boundary (REISS Engineering, 2009), and has a total population of 106,420 and a population growth rate of 9.3% (US Census, 2016). Figure 2 shows the summary of current water, wastewater, and reclaimed water systems in the City of Lakeland and a map showing the location of the primary water and wastewater infrastructure can be found in the supplementary material (Figure S1). The source water for the city's water supply is groundwater withdrawn from the Floridian aquifer using 19 wells, and the water is conveyed to two water treatment facilities via an 8.74 mile pipeline (City of Lakeland, 2017). T.B. Williams is the larger water treatment facility with a design capacity of 51 mgd located in the west-central part of the city and C.W. Combee is the smaller plant with a design capacity of 8 mgd located in the northern part of the city. The water distribution system incorporates a service pipeline with approximately 998 miles of total length to deliver the treated water to more than 54,000 active customers (City of Lakeland, 2017). Based on the city's report, water use is characterized as residential (65%), commercial and industrial (26.3%), aesthetic and recreational (2.3%), fire flow (0.3%), and the remaining portion was unaccounted for.

The city's sewer collection system covers approximately 40,000 square miles of service area and encompasses 50 miles of forced sewer and 300 miles of gravity mains. The system is being used to convey raw wastewater to two wastewater treatment plants (City of Lakeland, 2017). The Glendale WWTP is the larger treatment facility with a design capacity of 13.7 mgd located in the southern part of the city and the Northside plant is the smaller plant with a design capacity of 8 mgd, covering the northern part of Lakeland (REISS Engineering, 2009). Both wastewater treatment plants consist of primary treatment and secondary treatment (conventional activated sludge [CAS]) followed by disinfection (chlorination). The City of Lakeland's current reclaimed water infrastructure provides 5.11 mgd of reclaimed water to the McIntosh power generation facility where the water is used as cooling make-up water. The other portion of treated wastewater effluent receives further treatment in the Lakeland artificial wetlands. From there, the water is pumped by the TECO power generation plant.

Although Lakeland's water system is suitable for present-day water demand and treatment requirements, the City of Lakeland is undergoing rapid growth in the southwest and northeast regions of the service area, which makes it challenging to satisfy future water demand. The amount of water that the City of Lakeland can withdraw from the Floridian aquifer has been limited to an annual average daily demand (AADD) of 35.03 mgd and a monthly average maximum of 42.04 mgd. The city's water use permit is issued by SWFWMD and is valid through December 16, 2028 (REISS Engineering, 2009). Since the service area and the population in the City of Lakeland are growing quickly, it has been predicted that in 2026 the city will have a population of approximately 242,000 and a water demand projection of 35.03 mgd. Based on the city's existing permit and current water system capacity, meeting the water demand will be challenging in a few years (See Figure S2 in supplementary material). Different types of water reuse options, which can satisfy the future water demand projection, were designed, evaluated and compared based on economic and environmental criteria. Ultimately, a decision-making tool that can be used by stakeholders to evaluate the trade-offs between water reuse types, degree of treatment and sustainability constraints was also introduced. The effluent from the Glendale water reclamation facility and Lakeland's artificial wetland were considered for reuse scenarios, or as the influent for the additional treatment, when needed. The effluent water quality reports were obtained from the facilities, which were reported based on an annual average basis (2017). More information regarding the water quality and water quality requirements (reuse standards) used for the design of additional treatments can be found in the supplementary materials (Table S1).

2.2. Scenario generation and design

A supply chain network that contains a forward and backward network is known as a closed-loop supply chain network (Ramezani et al., 2013). US EPA (2012) guidelines for water reuse were used to design seven scenarios that can potentially improve the sustainability of the current water network in the City of Lakeland and meet future demand. The alternatives in this study consisted of: 1) urban reuse (unrestricted), 2) agricultural reuse (food crops), 3) indirect potable reuse (IPR), 4) direct potable reuse (DPR), 5) distributed unrestricted urban reuse, 6) centralized treatment for distributed unrestricted urban reuse and 7) decentralized treatment for distributed unrestricted urban reuse (US EPA, 2012). The last two scenarios were designed to also further evaluate the impacts of a degree of decentralization of treatment plants to the water systems. For most reuse types, there are US guidelines, regulations and quality standards that the reclaimed water has to meet. These guidelines were primarily based on the US EPA and Florida Department of Environmental Protection (FDEP) for water reuse in the state of Florida (US EPA, 2012; Florida DEP, 2017).Although US EPA water reuse guidelines lacks the quality requirements and regulatory for DPR, it is recommended that water quality should meet the drinking water quality for this reuse scenario. Additional treatment processes were added to the Glendale WWTP's existing treatment train when the effluent's water quality did not meet the quality requirements for water reuse (i.e., scenario 3 and scenario 4, see Table S1 in the supplementary material). Specifically, the WateReuse Treatment Train Toolbox IT^{3}PR and the guideline manual developed by WateReuse Research Foundation (Trussell et al., 2015) were used for these scenarios. The WateReuse Treatment Train Toolbox IT^{3}PR considers US EPA water quality requirements in its database for the design of additional treatment with the underlying assumption that the reclaimed water becomes source water for a water treatment plant.

First, the best location for implementation of each reuse scenario was identified based on various considerations such as available lands with the minimum distance from the reclaimed water production's location, land price in the City of Lakeland, the stakeholders and the city officials' preferences and the US EPA guidelines (e.g., requirement for the minimum water travel distance between injection point and extraction wells for IPR). The different locations were evaluated and discussed during several meetings with the city officials and also based upon the US EPA guidelines. In fact, the potential locations for reuse were fairly restricted. For reuse scenarios 1 and 2, the golf courses and strawberry farmlands already existed in the city, and for DPR, the water treatment plant (between the two existing plants), which had available design capacity to receive the reclaimed water, was selected. For IPR, the nearest location for injection of reclaimed water, based on the minimum water travel distance required by EPA, was chosen. In the next step, considering the amount of available reclaimed water for each scenario, reclaimed water quality at different points of generation and the quality requirements, the best facility for providing the water needed for each reuse design was selected. The effluent water quality in each facility (e.g., Glendale WWTP, Glendale pond, and artificial wetland) was compared to the water quality requirements for each reuse scenario and the facility that required fewer (additional) treatment processes, was selected. The major pipelines were designed (i.e., diameter and length) to convey the reclaimed water from the source of generation to the reuse scenario's location; they accounted for the required water flow rate and the expected water velocity. For the minor pipelines, the same approach was adopted and the junctions and fittings were selected based on the space limitations (where needed).

To calculate the pumping power required for each scenario (major and minor pumps), the Darcy-Weisbach Pressure and Head Loss Equation was used. To obtain the Reynolds number, Darcy's friction factor, skin friction coefficients and pressure drops for pipe fittings, the Moody diagram and Fundamentals of Engineering Reference Handbook were used (Moody, 1944; NCEES, 2013). For the selection of the pumps, pipeline materials, pipeline fittings and the other equipment needed for designing each scenario, the process equipment cost estimation manual (Loh et. al., 2002) and the McMaster-CARR website and manuals were used. For the calculation of the pipelines' length needed for reuse scenarios 5, 6, and 7, which require extensive pipelines for unrestricted decentralized urban reuse, as well as for the energy requirements for reclaimed water distribution, Bentley WaterGEMS CONNECT Software Edition [10.00.00.50] was used. The GIS data and the water network and sewer system files were obtained from the City of Lakeland's Water Utilities Department.

The first reuse scenario (unrestricted urban reuse) evaluated the use of reclaimed water for the irrigation of golf courses. With a total of 1,103 golf courses and 524 golf communities, golf in the state of Florida is a critical industry contributing to the state economy (SRI International, 2015). On average, irrigation of each golf course in Florida requires 0.26 mgd of water (Florida DEP, 2016). In this scenario, 2.83 mgd of reclaimed water was taken from the Glendale WWTP's pond and conveyed to 10 different golf courses around the City of Lakeland using 12-3/4" O.D. pipelines with a total length of 30.26 miles. Since the water quality of Glendale WWTP's effluent met the requirement for the irrigation of golf courses, no additional treatment was needed.

Scenario 2 considered agricultural water reuse for irrigating strawberries – one of Florida's major food crops. Four major pipelines (12-3/4" O.D.) conveyed 4.6 mgd to 170 acres of farmland over a total length of 18,406 ft. No additional wastewater treatment was required for this scenario (Jeong et al., 2016) and drip irrigation was assumed for dispersal.

For scenario 3 (IPR), 2.83 mgd of reclaimed water was taken from the artificial wetlands and was injected into two 750-ft injection wells (1.5 mgd capacity each). Ultraviolet (UV) disinfection was added to the treatment train to meet the total number of fecal coliforms requirement (Cotton et al., 2001; US EPA, 2003), and the reclaimed water was conveyed over 11.68 miles by a major pipeline (24" O.D.) from the wetlands to the injection site.

In direct potable reuse, reclaimed water serves as the influent for water treatment plants. Although this type of reuse is rare, it has been receiving more attention during the last decade. Regulations and guidelines for this type of reuse are non-existent in the U.S.; however, drinking water quality standards are recommended (US EPA, 2012). For scenario 4, the reclaimed water was conveyed 7.98 miles by a major pipeline (24" O.D.) from the artificial wetlands to the T.B. Williams water treatment facility, which had the available capacity to receive the extra influent. Additional filtration and disinfection processes were added to the treatment train to satisfy drinking water quality guidelines (see Table 1 and Figure S7 in the supplementary material). Figures showing the location and pipeline required to implement each scenario can be found in the supplementary material (see Figures S3, S4, S5, S6, and S8).

In reuse scenario 5, a total of 2.83 mgd of treated wastewater from Glendale WWTP was distributed using an extensive "purple" pipeline for non-potable urban reuse purposes such as backyard irrigation, landscaping, and carwashes.

As it was mentioned before, the last two scenarios were designed to also evaluate the impacts of some degree of decentralization for wastewater treatment plants. In scenario 6, one centralized medium-scale WWTPs with a capacity of 3.00 mgd was designed to treat 2.83 mgd of household wastewater. The reclaimed water was distributed using an extensive purple pipeline for non-potable urban reuse. In scenario 7, the City of Lakeland was divided into five different clusters and five decentralized medium-scale WWTPs with a capacity of 0.7 mgd were designed to treat 2.83 mgd of household wastewaters in total (see Figure S9 in the supplementary material). The reclaimed water was distributed using an extensive purple pipeline, again for non-potable urban reuse. Construction data from existing and decommissioned WWTPs in the City of Lakeland were used to model the centralized as well as the five decentralized plants. Details about this and other scenarios (e.g., the location of the WWTPs, pipelines, etc.) can be found in the supplementary material (Tables S3-S9).

Figure 3 shows the overview of the scenarios considered in the study and the summary of information related to each scenario can be seen in Table 1.

2.3. Indicator description and quantification

In order to evaluate different feasible scenarios and provide a decision-making support tool for stakeholders, multi-criteria evaluation was used. The criteria selected in this study consisted of an economic indicator, environmental impacts and the value of resource recovery (VRR) as social impacts.

2.3.1. Economic indicator

In this study, capital costs and operation and maintenance (O&M) costs were considered for each design. For the added treatment processes, the capital costs included land purchase, pipelines, pumps, construction of pipelines and wells, and equipment and materials. The O&M costs included pumping energy, pipeline maintenance, labor, chemicals, overhead and management, energy consumed for the added treatment processes, repairs and material consumption. Data were mainly collected from stakeholders, the primary power companies in the state of Florida (TECO and Duke Energy) and engineering handbook manuals (e.g. NCEES, 2013). The data used to calculate capital and O&M costs for each scenario can be found in the supplementary material (Table S2 and Tables S10-S16). The cost data obtained from the City of Lakeland are converted to 2017 dollars using Unites States historical cost indexes (RSMeans, 2017) to estimate the costs associated with the new design scenarios. A lifespan of 33 years was considered for the added treatment processes, however, maintenance and part replacements were needed to meet this lifespan. For some processes, such as UV disinfection and ultrafiltration, maintenance and part replacements were more frequent, resulting in consideration of higher O&M costs for these processes.

In order to combine capital and O&M costs for all the scenarios, annualized specific net present value (ASNPV) was calculated (Maurer, 2009). First, the net present value (NPV) was calculated, which consisted of the present value of capital and O&M expenditures. The O&M

expenses ($C_{O\&M}$) for each year (n = 1, 2, 3, …, 33) were converted to present values (PV) and the annualized specific net present value (ASNPV) was calculated using equation 1 for an average interest rate, *i*, of 5%, lifespan, T_p, of 33 years, and demand (P_t) at time *t* for each component. More details about the cost calculations can be found in the supplementary material (Equations S1-S4 and Table S17).

$$ASNPV = \frac{NPV_{\text{Capital}} + \sum_{1}^{33} C_{O\&M} \frac{1}{(1+\mathrm{i})^{n}}}{\frac{1}{T_P}\int_{0}^{T_P} P_t.dt} \quad (1)$$

2.3.2. Environmental indicators

Environmental footprints of the designs are becoming increasingly important in the construction of new infrastructures due to increasing environmental awareness (Sinha et al., 2016; Qi and Chang, 2013; Du et al., 2011; Phillips et al., 2013). Carbon footprint and eutrophication were used as environmental indicators in this study.

Carbon footprint (CFP) is an abstract environmental sustainability indicator (ESI) to globally characterize the impact on climate change (Qi and Chang, 2013). It is an estimate of total greenhouse gas (GHG) emissions from a defined activity over a specific time frame or over the product/project's life cycle, typically expressed as carbon dioxide equivalents (CO_2-eq). Carbon footprint is highly influenced by the electricity consumption of the processes (Byrne et al., 2017). Since previous LCA studies have revealed that CFP in water and wastewater industries is dominated by the electricity consumption during the processes (Loubet et al., 2014; Pintilie et al., 2016), electricity consumption by the pumps and processes was selected to calculate CFP for this case. In this study, greenhouse gas equivalencies for electricity consumption were calculated based on eGRID data (US EPA, 2017). Electricity consumption data were collected from the individual treatment plants in the City of Lakeland. Additionally, the pumping electricity was estimated based on the types of pumps assumed for each scenario and engineering handbooks (NCEES, 2013).

Water eutrophication (EU) refers to the nutrient enrichment (nitrogen and phosphorus) of aquatic environments and is becoming one of the biggest challenges in aquatic environmental protection around the world (Heisler et al., 2008). Since the degree of eutrophication is largely determined by the magnitude of external nitrogen (N) and phosphorus (P) loads (Valiela et al., 2016), the concentration of those elements in the final reclaimed water was considered for this environmental indicator expressed as PO_4-equivalent. Depending on the level of treatment and the source of reclaimed water used for each scenario, the concentration of these two elements and the corresponding environmental impacts varied for each design. Moreover, for urban reuse (golf course irrigation), agricultural reuse (strawberry irrigation) and distributed unrestricted urban reuse (e.g., lawn irrigation), since nutrient uptake by the plants offsets a portion of eutrophication potential of the reclaimed water, it was included in the calculation of the eutrophication potential associated with these reuse scenarios. For agricultural reuse, drip irrigation was assumed for dispersal and the design of the irrigation system (plants, irrigation lands, and water requirement) for the calculation of nutrient uptake, were based on the studies of strawberry production in the state of Florida (e.g. Peres at al., 2011). For calculation of nutrient uptake by golf course grass, strawberry plant and lawn irrigation, the required data was obtained from previous studies (i.e., Kumar and Dey, 2011; Palmer at al., 2014; Vanhoutte at al., 2017). As a rough estimation, 12%, 9% and 10% nutrient uptake from the reclaimed water for grass surface irrigation, strawberry drip irrigation and non-potable urban reuse (~80% for lawn irrigation) was assumed, respectively. Water quality information was obtained mainly from stakeholders, the water and wastewater treatment plants' water quality data sheets, the artificial wetlands' influent and effluent water quality data and the water quality reports from the City of Lakeland.

2.3.3. Social indicator

The value of resource recovery (the willingness to pay) was used as the social indicator for the evaluation of each scenario. The value of resource recovery was collected from Polk County and Hillsborough County's reclaimed water prices (Hillsborough County, 2017; Polk County, 2017), considering the fact that as the value of the recovered resource increases, the willingness to pay by the reclaimed water end users increases. For urban reuse, the monthly flat rate of the reclaimed water for irrigation purposes (based on a 12" pipeline) was used. For agricultural reuse, the selling price of reclaimed water to the farmers in the State of Florida was used. For IPR and DPR, the price of drinking water was used for calculating the value of the reclaimed water, considering the price deduction due to the additional processes (water extraction, conveyance and treatment for IPR and water treatment for DPR) needed in these reuse scenarios before the water became qualified to be sold to the customers. The data related to costs for water treatment was obtained from the T.B. Williams water treatment facility in the City of Lakeland. Finally, for distributed unrestricted urban reuse, the monthly charge for the reclaimed water network (purple pipeline) in Hillsborough County was used as the value of resource recovery (Hillsborough County, 2017).

2.4. Scenario evaluation

According to the technical literature on multi-criteria assessment and decision-making, there are a variety of evaluation methods (e.g., TOPSIS, regret, ELECTRE, AHP, PROMETHEE, and WSM) with application in different situations (e.g., number of evaluation elements, typology of indicators, expected solutions, type of decision-making problem, and solution approach). However, selection of the most appropriate method for a specific problem and field of application has not been investigated previously (Guarini et al., 2018). Although there are advantages and disadvantages associated with each assessment method, the selection depends on the case-specific parameters in the case study (e.g., number of evaluation elements, typology of indicators, expected solutions, type of decision-making problem, and solution approach) and the decision-makers preferences. The results of different decision-making methods are not often equal. This is mainly because the selected weighting schemes, the chosen scale of the scores, and the resulting distribution of the scores within the evaluation criteria, do not have the same impact in all of the evaluation models (Tscheikner-Gratl et al., 2017).

The complex decision-making models, such as AHP, ELECTRE, PROMETHEE, and TOPSIS, have been widely used in urban planning (Behzadian et al., 2010; Gervásio; Kabir et al., 2014; Simões da Silva, 2012 and Tscheikner-Gratl et al., 2017) and they provide the ability to use both qualitative and quantitative criteria in the evaluation process. However, the potential compensation effects between lower scores on some criteria and higher scores on others, inability to identify the most preferred solution based on the defined criteria, change in the final ranking of alternatives when a new alternative is added, complexity in implementation, and time-consuming procedure are some of the disadvantages associated with these methods, which lower the popularity of them among available methods (Kabir et al., 2014; Macharis et al., 2004 and

Pires et al., 2011). These methods are being used mainly for strategic decisions, while a vector normalization for multi-dimensional problems is needed (Huang et al., 2011).

For single dimensional problems, when there is only one network with limited number of alternatives during the design process, WSM and regret models can be used to find the optimal alternatives based on the defined evaluation criteria. Although these methods are relatively simpler than other multi-criteria decision-making methods, they still provide a wide range of applicability, with similar results compared to methods that are more sophisticated (Kabir et al., 2014; Kolios et al., 2016; Sabzi and King, n.d.). The concept of WSM is to find the closest alternative to the “best” value and the concept of regret (opportunity loss) is to make decision recommendations on mutually exclusive strategies (Casal-Campos et al., 2018). When the dataset is not large, it would be rational to use the simpler evaluation methods such as WSM, which require less external knowledge and provide the decision-makers with better understanding of the problem and recommended solutions (Tscheikner-Gratl et al., 2017). In this study, in order to evaluate each reuse scenario and investigate the trade-offs, a regret-based model was used based on the minimax regret criterion. The minimax regret model, also known as the savage model, is an approach to decision-making under uncertainty. For instance, when the likelihood of the possible outcomes is not known with sufficient precision to use the classical expected value criteria, the regret-based model can be used as a support tool for the decision-making process (Loulou and Kanudia, 1999). Moreover, when there is a discrete number of choices, such as different possible real world scenarios, the minimax regret strategy is a useful tool for risk-neutral decision-making. The minimax regret model also provides decision-makers with the ability to normalize the evaluation criteria when there is unit diversity and uncertainty in the defined criteria. This technique minimizes the risk of making the wrong decision in selecting among the possible alternatives. Although there are a variety of alternatives for decision-making and a comparison to other models can be made, it was outside of the scope of this study. In this study, a symmetric formulation was obtained for a decision-making problem stated in terms of a specific constraint to minimize (negative) or maximize (positive) impacts. If $P_{i,j}$ is defined as the performance of strategy $i \in S$ (reuse scenario) for indicator $j \in F$ (defined criteria and constraints), the regret ($R_{i,j}$) is defined as the difference between the impact incurred and the optimum achievable (Loulou and Kanudia, 1999), i.e.:

$$R_{i,j} = \left| \underset{i \in S}{opt}(P_{i,j}) - P_{i,j} \right| \quad (2)$$

S: scenarios (1, 2, 3, 4, 5, 6, 7) and F: indicators (1, 2, 3, 4)

The optimum achievable is the optimum value (maximum or minimum) in each impact category across reuse alternatives. In order to make the comparison across indicators, the normalized regret scores (NR) can be calculated by:

$$NR_{i,j} = \frac{R_{i,j}}{\max_{i \in S}[R_{i,j}]} \quad (3)$$

And the final regret score ($\bar{R}$) for each scenario can be calculated by assigning weighting factors, w_j, for each indicator:

$$\bar{R}_i = \sum_j \left(w_j \cdot NR_{i,j}\right) \quad (4)$$

$$\text{Where } \sum_j w_j = 1$$

The results were reported based on individual indicators and a multi-criteria analysis; in the latter case, weighting schemes were assigned such that equal weighting was applied to each indicator (the base case), as well as weighting schemes that were cost-centered and environmentally-centered. The weighting factors for cost- and environmentally-centered results were based on stakeholder preferences, where cost-centered assigned 55% weight for the economic indicator and 15% for the other indicators and environmentally-centered assigned 35% weight for each environmental indicator and 15% for the remaining indicators.

2.5. Location and treatment analysis for DPR

In this study, the minimum treatment requirement for DPR was considered. In other cases, DPR can include more extensive treatment due to lower reclaimed water quality and/or higher water quality requirements, which result in higher impacts. Moreover, this reuse scenario usually receives less interest from stakeholders due to the complexity of treatment processes and some other challenges such as social acceptance. In this scenario, the reuse location is also highly restricted by the location of water treatment facilities in the area and it reduces the flexibility of the end-use location for DPR. Hence, a sensitivity analysis was conducted to evaluate the impact of increasing the distance to the end use location, in addition to increasing the ASNPV to accommodate additional treatment requirements. In both instances, the variable in question was increased in increments of 10% and the resulting regret scores (for the base case) were evaluated.

3. Results and discussion

In this study, different water reuse alternatives were designed to fill the gap between available water resources and projected water demand in the City of Lakeland, Florida. A multi-criteria analysis framework was developed to compare the water reuse alternatives and provide the insights to the factors with the highest impacts. Moreover, a sensitivity analysis of parameters that had a significant contribution to the impact categories was conducted.

3.1. Trade-offs for water reuse management

Based on the results of this study, it was evident that there were trade-offs between the degree of treatment for water reuse, water reuse type and location, and the economic, environmental and social impacts of the reuse scenarios. For instance, the urban reuse and agricultural reuse scenarios had the same treatment scheme, but the longer distance to the point of urban reuse resulted in a much higher ASNPV (1,667 vs. 413 $/MG) as is shown in Figure 4. Moreover, although the scenarios had similar eutrophication impacts because of the similarities in water quality and nutrient uptake, the carbon footprint was much higher for urban reuse than agricultural reuse (8,684 vs. 1,781 kg CO_2-eq/MG) because of higher energy requirements for reclaimed water transfer and distribution. Agricultural reuse not only had lower ASNPV compared to urban reuse, it also obtained a higher VRR due to the higher value of reclaimed water for this reuse type. Since the selling price of the reclaimed water to the farmers for agricultural purposes was much higher than the selling price for urban reuse, with the same degree of treatment, agricultural reuse had a higher value of resource recovery, as much as $1,394 higher per million gallons of reclaimed water, compared to the urban reuse ($173/MG). Although agricultural reuse was the most preferable option across most indicators (i.e., ASNPV, VRR and carbon footprint), this reuse scenario had the highest eutrophication (see Figure 5) among all the scenarios, which was mainly due to the high level of nutrients remaining in the reclaimed water for irrigation purposes (Metcalf et al., 2007).

Primary and secondary treatment (conventional activated sludge [CAS] in this case) plays a significant role in the cost of the treatment trains and it was common among all scenarios for water reuse due to the minimum water quality requirements. Hence, the cost evaluation excluded the common processes and only included the processes that were different for different reuse scenarios. The results revealed that the implementation and operation of additional treatment processes was not a significant contributor to the economic indicator compared to the capital and O&M costs associated with the distribution of the reclaimed water (e.g., pipeline construction, reclaimed water pumping). On the other hand, as the reclaimed water quality increases, the value of resource recovery increases accordingly and the environmental impacts of water reclamation (eutrophication) decreases due to greater nutrient removal. As it can be seen in Figure 4, although improving the reclaimed water quality from urban reuse to IPR and DPR had little impact on ASNPV (considering the costs associated with the water conveyance), it resulted in a significant increase to the VRR (173 vs. 3,500 \$/MG for urban reuse and IPR, respectively). As the result also showed, increasing the degree of treatment after CAS from agricultural reuse to IPR and DPR did not increase the carbon footprint significantly, due to the low energy requirements of the additional treatment processes (i.e. ultra-filtration, UV disinfection and additional chlorination). Most of the previous studies have also shown that the operation phase in treatment process and water transfer are responsible for approximately 40% and 50% of GHG emissions associated with water systems, respectively (e.g., Amores et al., 2013; Barjoveanu et al., 2014; Lemos et al., 2013; Opher and Friedler 2016; Risch et al., 2015; Slagstad and Brattebø, 2014). Wastewater treatment and disposal (reclaimed water quality) were also the significant contributors (~91%) to the freshwater eutrophication potential.

As Figure 4 also shows, distributed urban reuse (scenario 5) increased the ASNPV significantly. Distributed urban reuse for non-potable purposes (e.g., lawn irrigation and carwashes) required an extensive pipeline for distribution of the reclaimed water to the households (purple pipeline) and it increased the capital costs associated with this scenario and the ASNPV accordingly. Although distributed urban reuse had the highest ASNPV among all reuse scenarios, this type of reuse reduces the cost associated with withdrawal, treatment and distribution of water to the distributed end users (households) by replacing the potable water with the reclaimed water for non-potable purposes, to a greater level than other reuse scenarios. These considerations were outside the scope of this study since the amount of water offset was similar across scenarios. The summary of different costs associated with each scenario and more details about the capital costs, O&M costs and the value of resource recovery for reuse scenarios, can be found in the supplementary material (Table S17).

3.2. Decentralized vs. centralized reuse and treatment

As it was mentioned before, two scenarios were designed to evaluate the impacts of some degree of decentralization for the water systems. The results for these reuse scenarios can be seen with the last two scenarios in Figure 4 and Figure 5. For both reuse scenarios, ASNPV increased significantly due to the extensive pipeline requirements for distributed urban reuse. Accordingly, these reuse scenarios obtained the highest carbon footprint among the different scenarios, which is mainly due to the high electricity consumption by the major pumps for distribution of reclaimed water to the final customers. Previous LCA studies have also revealed that the collection and distribution of wastewater and reclaimed water, compared to the other steps in the process, consume the highest amount of electricity in urban water and wastewater infrastructure (Lyons et al., 2009). The higher degree of decentralization in scenario 7 resulted in higher ASNPV due to the need for multiple medium-scale wastewater treatment plants and higher O&M costs (per unit volume of wastewater) associated with them; however, the costs and energy requirements for distribution of the reclaimed water to the final users (households) and associated CFP were reduced significantly for this reuse scenario (see Tables S8, S9, S15 and S16 in the supplementary material). In addition, increasing the degree of decentralization has some advantages such as more flexibility in operation, reliability and better management in case of natural disasters or terrorist events (Diagger, 2009). Therefore, the trade-offs have to be carefully evaluated for the given context when considering the degree of decentralization. Prior literature has also shown that decentralization of wastewater treatment facilities improves the environmental and economic impacts associated with water systems (e.g., Chung et al., 2008; Gardels et al., 2011; Glick and Guggemos, 2013; Lam et al., 2015), while other studies revealed that centralized systems show better performances (e.g., Matos et al., 2014; Shehabi et al., 2012; Thibodeau et al., 2014). Some believe that the decision to decentralize plants strongly depends on local conditions (e.g., population density) and a framework is required to evaluate the study area and make the final decision (Chung et al., 2008; Lehtoranta et al., 2014). The results of this study revealed that decentralization of treatment facilities increased the capital costs associated with treatment and decreased the O&M costs associated with the entire water system significantly (i.e., water transfer costs). In this case, the decrease in O&M costs could not offset the increase in the capital costs associated with treatment and the final ASNPV for decentralized systems was higher than centralized treatment option. However, decentralization of treatment facilities decreased the carbon footprint associated with the water system by up to 45% by reducing the energy required for the water distribution network.

3.3. Multi-criteria Decision-making

The results for the regret-based analysis are shown in Table 2. This table shows the normalized regret score (NR) for each reuse scenario within each criterion and the final regret score ($\overline{\mathrm{R}}$) based on different weighting strategies. Based on the definition of the regret-based model, the reuse scenarios with regret scores closer to zero obtained better values for the corresponding criteria.

The preferred scenario, with respect to the normalized regret score, changed as different individual impacts were considered. For example, agricultural reuse had the lowest normalized regret score for the economic (NR_ASNPV) and carbon footprint indicators (NR_CFP) (see Table 2), although there is only a small difference between the agricultural reuse scenario and the urban reuse, IPR and DPR scenarios in the case of the economic indicator. The lower regret scores could be attributed to the lower infrastructure requirements for water transfer pipelines and treatment (i.e., agricultural reuse, urban reuse, or IPR). Accordingly, the scenarios that required more water transfer and distribution (as was the case with distributed reuse) had a significantly higher NR_CFP. This was due to the higher consumption of pumping energy for reclaimed water distribution. Interestingly enough, however, the second most preferred option for the carbon footprint indicator (NR_CFP) was the implementation of decentralized treatment plants with distributed urban reuse (Scenario 7). The savings in energy consumption from the local distribution of reclaimed water were enough to lead to significant reductions in this indicator relative to all centralized treatment options (excluding the most preferred option, agricultural reuse). Since the water distribution infrastructure and pumping energy had a significant influence on the preferred scenario, sensitivity to the distance to the end user and the type of terrain (hilly versus flat) are expected. Moreover, the better reclaimed water quality for

IPR and DPR resulted in significantly lower social (NR_VRR) and environmental (NR_EU) impacts.

From Table 2, it is evident that when the weighting strategy transitioned from the base case to cost-centered, scenarios with a shorter distance between reclaimed water production and end use locations, and/or lower complexity in design implementation and treatment, obtained better final regret scores. Although increasing the distance from agricultural reuse to IPR and DPR increased the ASNPV and CFP significantly, the lower environmental impact (EU) and the higher social indicator (VRR) decreased the final regret scores (both cost- and environmentally-centered) associated with these two scenarios. Moreover, changing the weighting strategy to environmentally-centered improved the final regret score of scenarios with higher reclaimed water quality (IPR and DPR). Accordingly, DPR obtained the best cumulative regret score across the three weighting strategies. The sensitivity to the distance of the treatment plant and treatment costs for the DPR scenario will be examined further in Section 3.4.

The results also revealed that the additional treatment needed after CAS results in a relatively small increase in the economic indicator due to the simplicity of the design and the low-cost treatment processes. However, the additional treatment increased the VRR significantly (enough to offset all the capital and O&M costs associated with the reuse scenarios). Currently, the major driver for implementation of DPR is severe drought due to the lack of enough regulations and guidelines for DPR and the social acceptance concerns. This study showed that DPR for the studied area is one of the best alternatives for supplementing water supply, based on different dimensions of sustainability.

3.4. Sensitivity analysis for DPR

Although DPR obtained the best regret score among reuse scenarios, increasing the distance between the water reclamation facility and water treatment location, as well as increasing the complexity of the additional treatment requirements had a significant influence on the regret score of this reuse scenario. These two parameters not only affected the final capital and O&M costs (ASNPV), they also affected the CFP associated with this reuse type.

Among different reuse scenarios, the selection of reuse location for DPR is highly restricted by the location of water treatment plants and the flexibility of reuse location is usually much higher for other reuse types. As Figure 6 shows, if the distance between water reclamation and water treatment plant increases by 6.17 miles, DPR will not be the best reuse scenario based on the base case regret score and IPR will become the best reuse type. Moreover, in some cases (for instance when the quality requirements for DPR are higher and/or the reclaimed water has lower quality), the treatment trains for DPR become more complex and it increases the associated cost with the additional treatments significantly. As it can be seen in Figure 6, if the ASNPV associated with the additional treatment processes increases form 1,712 $/MG to 26,809 $/MG, IPR will be a better option than DPR. If the ASNPV of the additional treatment increases to $43,869/MG, agricultural reuse will also obtain a better base case regret score than DPR. Although a 6.17 miles increase in the distance between water reclamation and water treatment facilities is possible, a 26,809 $/MG increase in ASNPV for additional treatments doesn’t seem realistic. According to the City of San Diego’s report, in case of implementing an additional advanced water purification facility for IPR and DPR, consisting of membrane filtration, reverse osmosis, UV disinfection, and advanced oxidation, the ASNPV does not exceed $4,010/MG (City of San Diego, 2013).

3.5. Limitations and future work

One limitation of this study is the treatment process considered for DPR. For this scenario, only a few additional treatment processes were added after secondary treatment and treatment by artificial wetlands (i.e., ultra-filtration, UV/H_2O_2, and chlorination). DPR treatment can include more extensive treatment, which would result in different (likely higher) impacts. Accordingly, future work can consider a sustainability evaluation of existing DPR treatment trains.

Further investigations can be conducted to evaluate the influence of the degree of decentralization on water reuse options. The last two scenarios offered insight about decentralizing treatment to some extent, however, the analysis does not reflect the full spectrum of decentralization that can be considered (e.g., at the household- or building-level to large-scale WWT). Moreover, the effects of decentralization of water reuse and wastewater treatment on the economic and environmental impacts of the entire water system (e.g., including the freshwater withdrawn, water treatment and its distribution) was outside of the scope of this study.

Although most of the data used for the design of reuse scenarios was obtained from the previous construction projects in Polk County and the practical feedback from the City of Lakeland's officials, there were assumptions when the real data was missing (e.g. additional treatments for DPR). However, the conducted sensitivity analyses addressed some aspects of the uncertainty by showing robustness of the recommended solutions. An uncertainty analysis could be conducted to further address this limitation, which was outside the scope of this study.

4. Conclusion

This paper presented a multi-criteria evaluation of the sustainability of water reuse scenarios, in which the City of Lakeland in Florida was used as a case study to design the city's integrated water system. The results of this study revealed that the distance between the water reclamation facility and the end use played a significant role in economic and environmental indicators. Increasing the average distance from 0.9 miles to 6.5 miles, with the same degree of treatment for urban reuse and agricultural reuse, increased the CFP from 1,781 kg CO_2-eq/MG to 8,684 kg CO_2-eq/MG, while it increased the ASNPV from $413 to $1,667 respectively. The higher reclaimed water quality required an increase in the complexity of the treatment processes, and consequently increased the economic impact (ASNPV) and CFP. Higher water quality, however, improved the EU of water reuse as well as the value of resource recovery significantly, and it increased the final regret score. The higher value of resource recovery could also offset all the capital and O&M costs associated with the treatment and distribution for DPR in the case study. Considering this fact, DPR obtained the best regret score among the five alternatives, but the lack of existing regulations and guidelines for its implementation, high water quality requirements, as well as challenges with social acceptance, led stakeholders and officials to lose interest in this water reuse scenario. Moreover, the sensitivity analysis revealed that if the distance between water reclamation and water treatment plants increased by 6.17 miles, or the ASNPV associated with the additional treatment requirements increased by 25,097 $/MG, DPR would not be the best reuse scenario. Agricultural reuse obtained the best score in terms of both the individual economic and environmental impact (i.e., CFP). Due to its ease of implementation, less complexity in design and more flexibility in the end-use locations, this scenario received more attention from stakeholders. Although the results of this study are case-specific, the factors that impact the sustainability indicators, the trade-off analysis, as well as the proposed regret-based decision making approach can be applied for water reuse scenario analysis in other cases. The results of this study showed the importance and influence of bringing environmental and social aspects into account, in addition to adopting different weighting strategies that depends on the stakeholders' preferences. The concept of regret model provided a useful tool in the comparative assessment of water reuse alternatives, in which the differences in nature and scale of criteria often makes the evaluation, normalization, and comparison more challenging. Although the investigated case study was in the context of a city in the US, the findings of this study can be broadly applicable to other cases. The results presented in this study demonstrated that increasing the reclaimed water quality for reuse applications not only decreases the negative impacts of water reuse on the environment, but also increases the value of resource recovery significantly, as far as it can offset the costs and environmental footprints associated with the additional required treatments. The results also showed that reducing the distance between reclaimed water generation point (treatment facilities) and reuse location, dramatically reduces the costs and environmental impacts associated with the reuse scenario, and it is mainly because water transfer was the most responsible in the majority of the impact categories (i.e., ASNPV and CFP).While conventional secondary wastewater treatment plants are regulated with respect to the water quality of the effluent discharged to water bodies and, more specifically, the nutrient concentrations of the effluent, water reuse guidelines typically do not regulate nutrients. However, as was shown by the results of scenarios 1 and 2 on the eutrophication potential considering the relatively small amount of nutrient uptake by crops (9-11%), nutrients are still released into the environment during water reuse scenarios and can pose a potential threat to the environment. Although the nutrient concentrations and runoff are likely lower than that from excess fertilizer on farmlands, in the future, policy makers may consider limiting the nutrients in reclaimed water applied to land and specify limits specific to particular crops considering the variation in uptake or impose seasonal application rates as is done with fertilizer in Florida.

Moreover, regulating and implementing the reuse scenarios with higher water quality requirement (e.g., DPR) not only reduces the negative impacts of the reclaimed water on the environment but also increases the revenue from the wastewater significantly, as far as it can offset the majority of costs associated with the additional treatments. Since the energy consumption during the treatment processes plays a significant role in the carbon footprint associated with the water reuse scenarios, consideration of treatment trains with lower energy requirements for implementation helps further reduce the water reuse impacts on the future of climate change.

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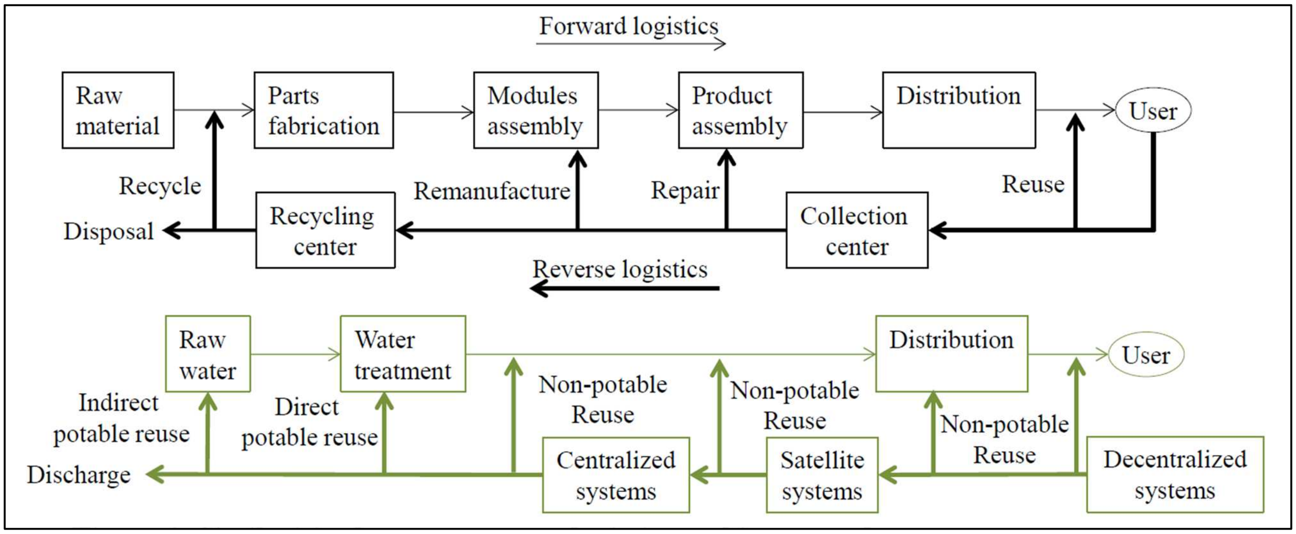
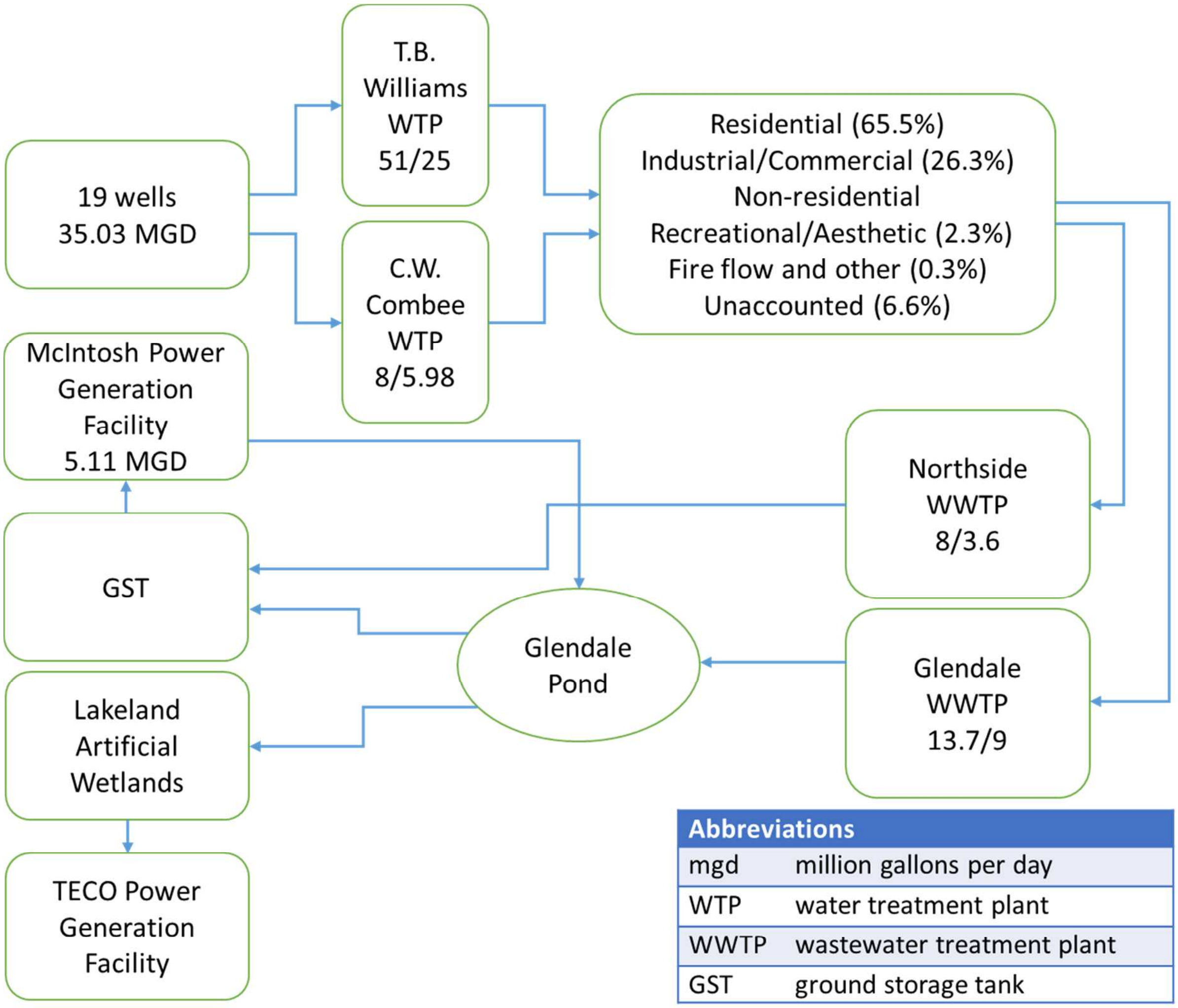


Figure 1. Conventional reverse logistics compared to its application for integrated wastewater management.



Abbreviations	
mgd	million gallons per day
WTP	water treatment plant
WWTP	wastewater treatment plant
GST	ground storage tank

Figure 2. Summary of the current water, wastewater and reclaimed water cycle in the City of Lakeland, Florida. The water usage is shown in percentage and the design capacity/operation capacity for the plants is shown in mgd.

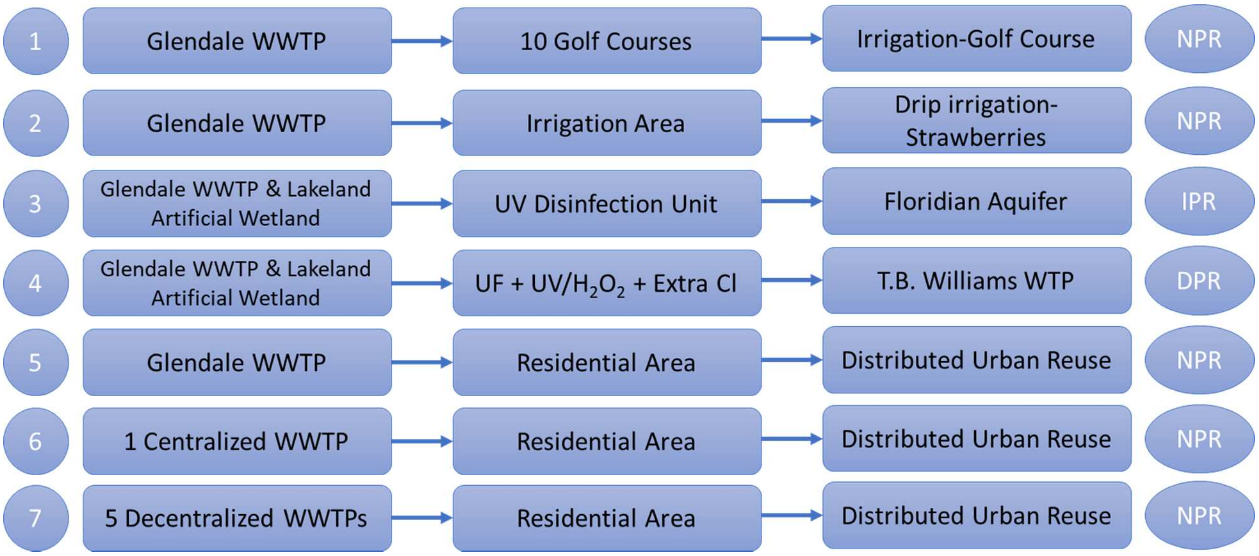


Figure 3. Overview of the scenarios considered in the study.
Abbreviations: UV: ultraviolet; UF: ultra-filtration; WTP: water treatment plant; WWTP: wastewater treatment plant; Cl: chlorination; NPR: non-potable reuse; IPR: indirect potable reuse; DPR: direct potable reuse

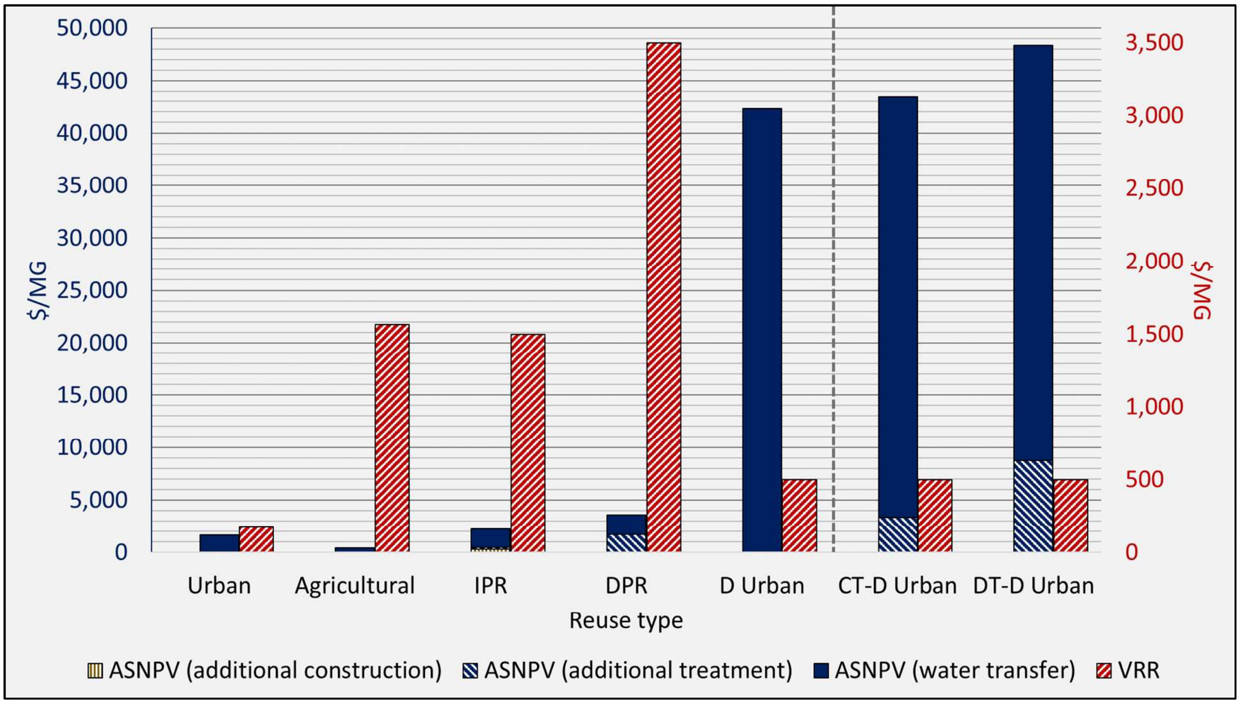


Figure 4. Annualized specific net present value (ASNPV) and value of resource recovery (VRR) for different reuse scenarios, based on a design life time of 33 years.
Abbreviations: IPR: indirect potable reuse; DPR: direct potable reuse; D: distributed; CT: centralized treatment; DT: decentralized treatment; MG: million gallon

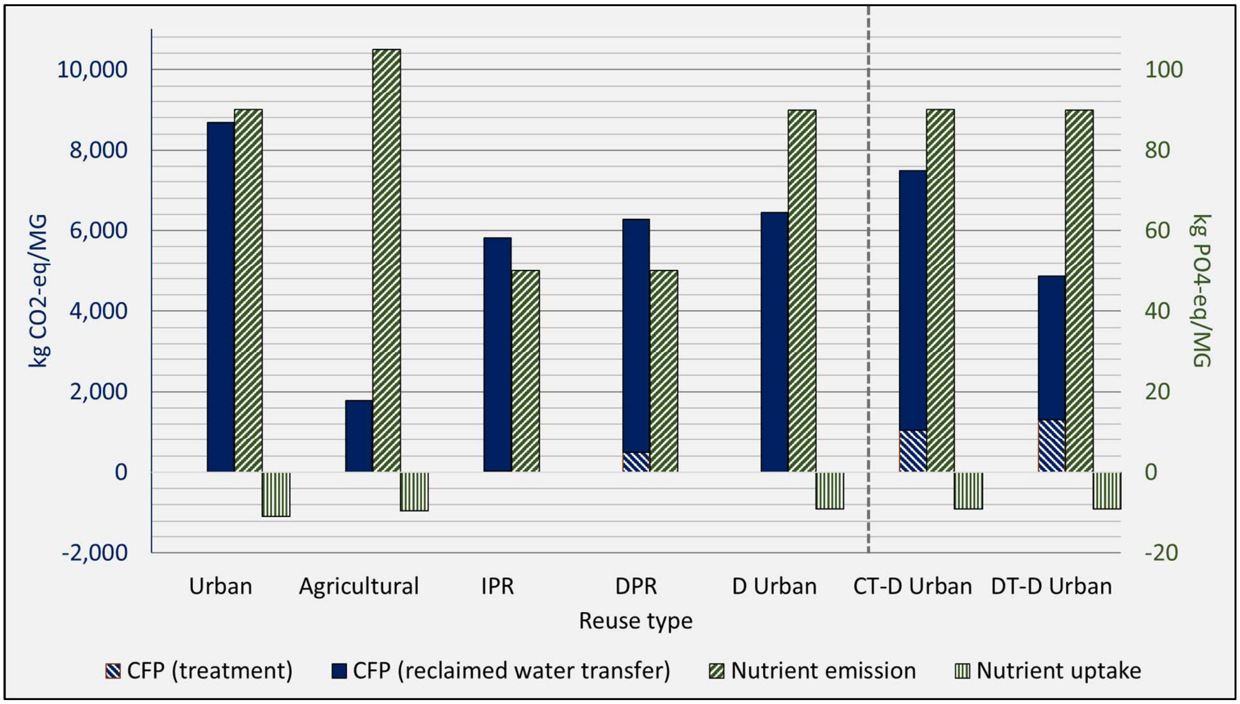


Figure 5. Environmental impacts (carbon footprint [CFP] and eutrophication [EU]) associated with different reuse scenarios.

Abbreviations: IPR: indirect potable reuse; DPR: direct potable reuse; D: distributed; CT: centralized treatment; DT: decentralized treatment; MG: million gallon

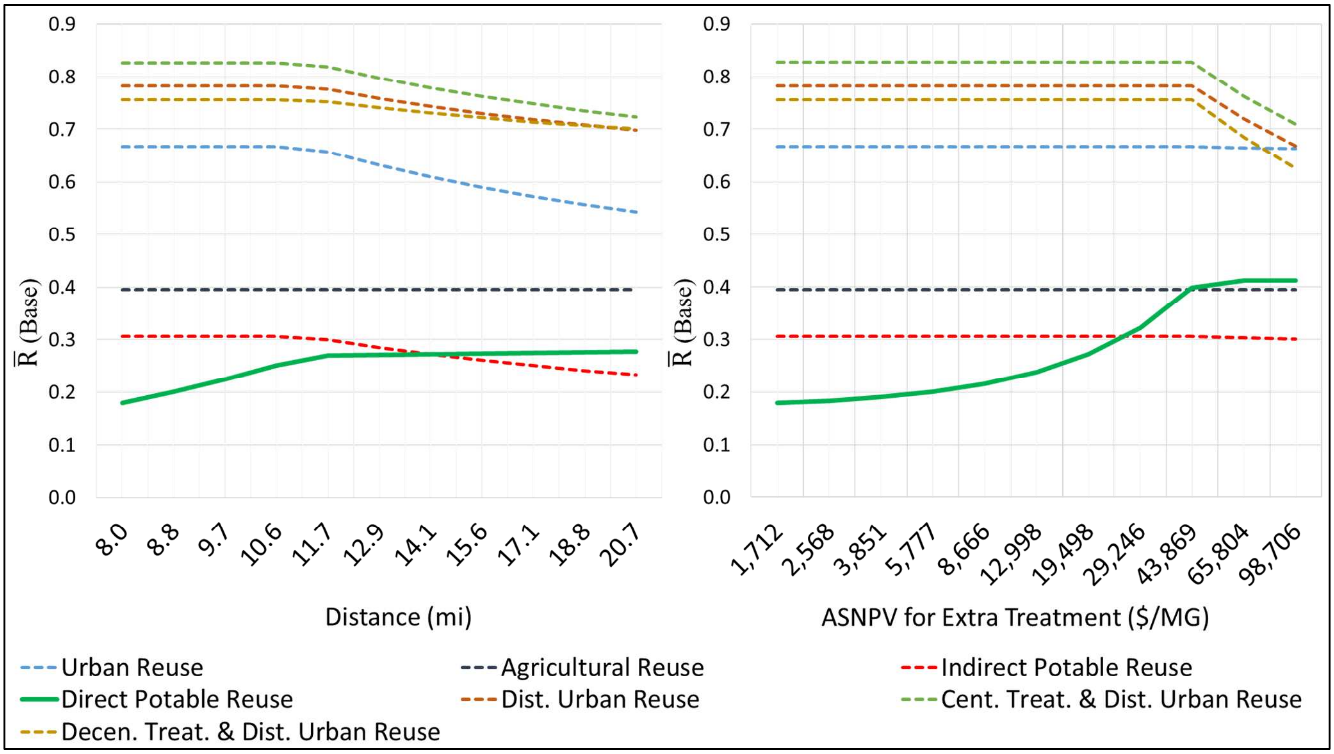


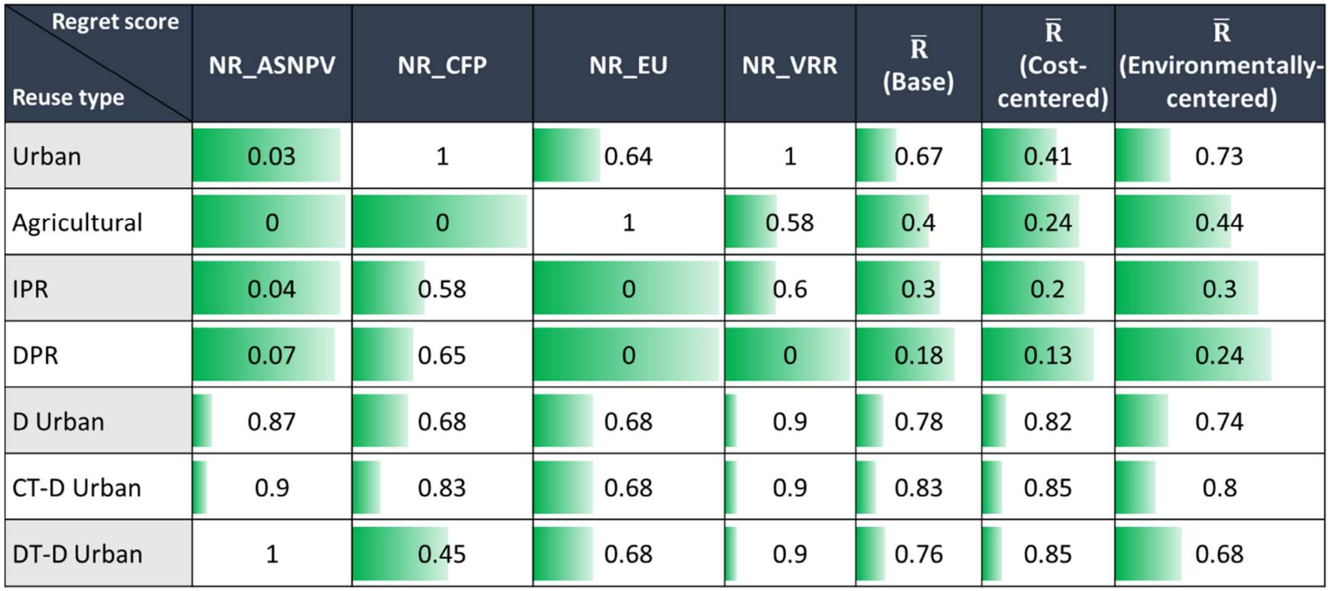
Figure 6. The location and treatment analysis for direct potable reuse (DPR) scenario.

Table 1. The summary of information related to each scenario in this study

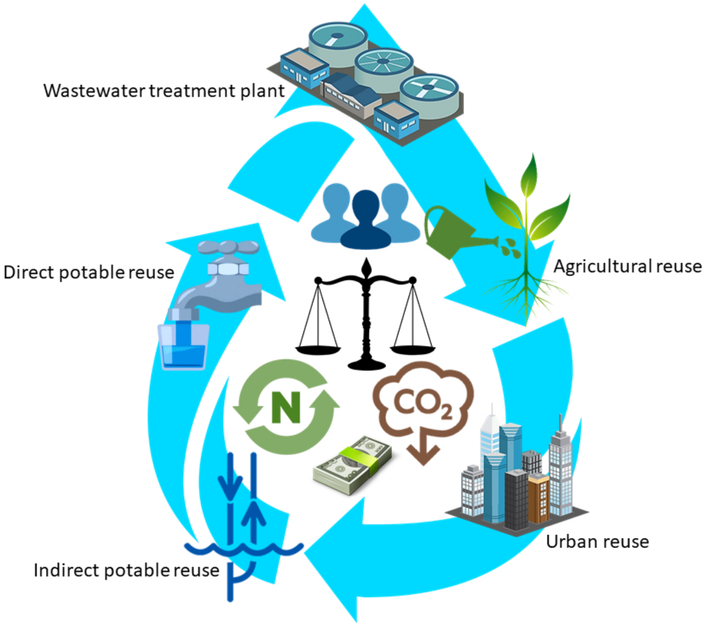
	Description	Recommended treatment	Additional treatment required	Pipeline required	Pumping requirement	Energy consumption by additional treatment	Nitrogen and Phosphorus concentration in the effluent
Scenario 1	Urban reuse	Secondary treatment-Filtration-Disinfection	-	30.26 mi 12-3/4" O.D.	48,000 KWh/day	0 KWh/day	15.01 (mg TN/l) 5.7 (mg TP/l)
Scenario 2	Agricultural reuse	Secondary treatment-Filtration-Disinfection	-	3.49 mi 12-3/4" O.D.	16,000 KWh/day	0 KWh/day	15.01 (mg TN/l) 5.7 (mg TP/l)
Scenario 3	Indirect potable reuse	Secondary treatment-Filtration-Disinfection - Multiple barriers for pathogen and organics removal (Advanced)	UV disinfection	11.68 mi 24" O.D.	32,486 KWh/day	298 KWh/day	1.54 (mg TN/l) 4.1 (mg TP/l)
Scenario 4	Direct potable reuse	No defined standard	Ultra-filtration-UV/H_2O_2-additional Chlorination	7.98 mi 24" O.D.	31,937 KWh/day	2,678 KWh/day	1.0 (mg TN/l) 4.1 (mg TP/l)
Scenario 5	Distributed urban reuse	Secondary treatment-Filtration-Disinfection	-	569.17 mi Varying diameter	35,635 KWh/day	0 KWh/day	15.01 (mg TN/l) 5.7 (mg TP/l)
Scenario 6	Centralized treatment for distributed urban reuse	Secondary treatment-Filtration-Disinfection	1 medium-scale CAS system	569.17 mi Varying diameter	35,635 KWh/day	5,818 KWh/day	15.01 (mg TN/l) 5.7 (mg TP/l)
Scenario 7	Decentralized treatment for distributed urban reuse	Secondary treatment-Filtration-Disinfection	5 medium-scale CAS systems	569.17 mi Varying diameter	19,599 KWh/day	7,263 KWh/day	15.01 (mg TN/l) 5.7 (mg TP/l)

Table 2. The results for the regret-based model and the calculated regret score for each scenario

Abbreviations: IPR: indirect potable reuse; DPR: direct potable reuse; D: distributed; CT: centralized treatment; DT: decentralized treatment; ANPV: annualized net present value; CFP: carbon footprint; EU: eutrophication; VRR: value of resource recovery



Regret score / Reuse type	NR_ASNPV	NR_CFP	NR_EU	NR_VRR	$\bar{R}$ (Base)	$\bar{R}$ (Cost-centered)	$\bar{R}$ (Environmentally-centered)
Urban	0.03	1	0.64	1	0.67	0.41	0.73
Agricultural	0	0	1	0.58	0.4	0.24	0.44
IPR	0.04	0.58	0	0.6	0.3	0.2	0.3
DPR	0.07	0.65	0	0	0.18	0.13	0.24
D Urban	0.87	0.68	0.68	0.9	0.78	0.82	0.74
CT-D Urban	0.9	0.83	0.68	0.9	0.83	0.85	0.8
DT-D Urban	1	0.45	0.68	0.9	0.76	0.85	0.68



Alternative water reuse applications were evaluated while considering a holistic sustainability perspective that accounted for environmental, economic, and social dimensions.