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Decision support toolkit for integrated analysis and design of reclaimed water infrastructure

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A B S T R A C T

Planning of water reuse systems is a complex endeavor. We have developed a software toolkit, IRIPT (**I**ntegrated Urban **R**eclaimed Water **I**nfrastructure **P**lanning **T**oolkit) that facilitates planning and design of reclaimed water infrastructure for both centralized and hybrid configurations that incorporate satellite treatment plants (STPs). The toolkit includes a *Pipeline Designer* (*PRODOT*) that optimizes routing and sizing of pipelines for wastewater capture and reclaimed water distribution, a *Selector* (*SelWTP*) that assembles and optimizes wastewater treatment trains, and a *Calculator* (*CalcBenefit*) that estimates fees, revenues, and subsidies of alternative designs. For hybrid configurations, a *Locator* (*LocSTP*) optimizes siting of STPs and associated wastewater diversions by identifying manhole locations where the flowrates are sufficient to ensure that wastewater extracted and treated at an adjacent STP can generate the revenue needed to pay for treatment and delivery to customers. Practical local constraints are also applied to screen and identify STP locations. Once suitable sites are selected, *System Integrator* (*ToolIntegrator*) identifies a set of centralized and hybrid configurations that: (1) maximize reclaimed water supply, (2) maximize reclaimed water supply while also ensuring a financial benefit for the system, and (3) maximize the net financial benefit for the system. The resulting configurations are then evaluated by an *Analyst* (*SANNA*) that uses monetary and non-monetary criteria, with weights assigned to appropriate metrics by a decision-maker, to identify a preferred configuration. To illustrate the structure, assumptions, and use of IRIPT, we apply it to a case study for the city of Golden, CO. The criteria weightings provided by a local decision-maker lead to a preference for a centralized configuration in this case. The Golden case study demonstrates that IRIPT can efficiently analyze centralized and hybrid water reuse configurations and rank them according to decision-makers' preferences.

1. Introduction and background

Demand for reclaimed water and for reclaimed water infrastructure is increasing in regions susceptible to drought and water shortage. Drivers include population and economic growth, accompanied by increased water demand and increased pressure on local water supplies (USEPA, 2012, 2004); increased risk of drought and water scarcity due to climate change (Diffenbaugh et al., 2015); the need to mitigate, decrease, or eliminate environmental impacts resulting from water diversions and wastewater discharges (USEPA, 2005); and potential for financial savings and revenue from the sale of reclaimed water (Ring et al., 2016). The intelligent planning needed to develop infrastructure that can meet local demands for reclaimed water requires site-specific assessment of a wide range of system configurations that capture and treat wastewater and distribute it to customers, while also satisfying a diverse set of technological, environmental, social, and economic constraints (Woods et al., 2013).

The appropriate scale of water reclamation is a critical design variable. Typically, wastewater is captured at the scale of a *catchment*, the service area of a centralized wastewater treatment plant (CTP), but it can also be captured at the scale of a *cluster*, a subdivision of a catchment, in which case it can be treated at one or more satellite treatment plants (STPs) (Lee et al., 2013). Reclaimed water systems may also be “nested”, with small water reuse systems

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contained within a larger water reuse boundary, or with provisions for export of water to locations outside the catchment. Changes in the service area of a treatment plant affect plant sizing, pipeline routes and sizes, and pump sizes and locations. Because these design elements are linked and interactive and because treatment plants at different locations can be combined with service areas of differing size, an enormous number of water reuse configurations and design combinations are possible, even for seemingly small systems. Decision support tools (DSTs) are needed to effectively and systematically integrate design elements and to assist decision-makers in evaluating a wide range of configurations across scale.

Commercial DSTs are already available to assist with conceptual design of stormwater management systems. MUSIC (Model for Urban Stormwater Improvement Conceptualisation), a DST developed by eWater Solutions, enables conceptual design of urban stormwater management systems, with capabilities for simulation of stormwater flows and water quality at differing scales (Wong et al., 2002). Urban Developer, another eWater Solutions DST, ensures water balances and simulates water transportation networks for all elements of the water cycle, including potable water, stormwater, and wastewater (Hardy et al., 2011). Both MUSIC and Urban Developer can simulate various water management scenarios and assist in the evaluation of specified system configurations, but many design details (e.g., pipe diameters, lengths, and slopes) must be specified *a priori.*

Integrated DSTs have also been developed for planning of reclaimed water systems. Like the DSTs for stormwater management, these systems require a large number of *a priori* design decisions as input data (e.g., pipeline routes; distances and elevations between treatment plants and customers; and locations for pumps, treatment plants, and storage tanks) (Joksimovic et al., 2008; Stephen Davis, 2009). Recently, Gikas et al. (2015) developed software that optimizes water reuse infrastructure regionally by minimizing annualized total capital and operating costs. Their analysis does not consider local reclaimed water distribution and wastewater collection systems. Input data include *a priori* specification of pairwise pumping distances and elevations based on the given locations of potential treatment plants and population centers. Guo and Englehardt (2015) also used modeling to scale distributed direct potable reuse systems with the goal of minimizing treatment and conveyance costs. The design process is simplified by connecting sources to demands based on straight-line distances from one building to the next without considering practical constraints, such as rights-of-way. To date, no tool for reclaimed water planning has integrated siting and design of STPs and wastewater diversions; design of pipeline networks; selection of wastewater treatment trains; analysis of fees, revenues, and subsidies; and other important considerations, such as different facility ownership scenarios.

In this work, we introduce an integrated package of decision support tools termed IRIPT (**I**ntegrated Urban **R**eclaimed Water **I**nfrastructure **P**lanning **T**oolkit) for the design of urban reclaimed water infrastructure. IRIPT analyzes both centralized configurations, where a single CTP delivers reclaimed water to the entire service area, and hybrid configurations, where reclaimed water is delivered from a CTP and one or more STPs or from STPs alone. These configurations are then ranked using decision-maker weights across a set of criteria, both monetary and non-monetary. The toolkit includes provisions for design of system elements that, in previous DSTs, required *a priori* definition by the toolkit user, such as siting and design of STPs and associated wastewater diversions, and routing of wastewater and reclaimed water pipeline networks. Configurations are identified that: (1) maximize reclaimed water supply from the available wastewater flow, (2) maximize reclaimed water supply from the available wastewater flow while ensuring a financial benefit for the system, and (3) maximize the financial net benefit for the system. System configurations are then ranked in accord with decision-maker weightings across multiple performance criteria.

In order to identify attractive reuse configurations, IRIPT addresses the following questions: (1) which customers should receive reclaimed water when delivery of water to all potential customers is not economically justified or feasible? (i.e., which customers should be included and which should be excluded for a given configuration?), (2) for hybrid configurations, how should customers be grouped to ensure that each customer is supplied with reclaimed water from a treatment plant?, and (3) how can the numerous design factors be integrated to achieve an optimal spatial configuration?

To test the utility of IRIPT, we apply it to a case study (City of Golden, CO) and demonstrate that it enhances the decision-making process by comprehensively and automatically assessing various design options and identifying a water reuse configuration that satisfies decision-maker priorities. All steps are transparent to the toolkit user: intermediate design results and performance metrics used for multi-criteria decision analysis (MCDA) are readily accessible. The user can also access data used for computation of performance metrics, including capital and O&M costs for each design element, energy usage and savings, and supplies of reclaimed water.

2. Implementation of decision support software tools

Fig. 1 is an overview of the decision-making tools implemented in IRIPT for planning of water reuse infrastructure. Inputs include criteria and metrics for evaluation of different reclaimed water configurations, weights for each criterion/metric, and the choice of a multi-criteria decision methodology for ranking and selecting a preferred configuration. Additional detailed data requirements include locations and flowrates for the CTP, wastewater flowrates throughout the sewer network, customer locations, and projected reclaimed water demands. Four tools developed by us (red boxes) are used to site satellite treatment plants and associated wastewater diversions (*LocSTP*), select appropriate treatment trains (*SelWTP*), optimize pipeline routes and designs for wastewater capture and reclaimed water distribution (*PRODOT*), and calculate fees, revenues, and subsidies

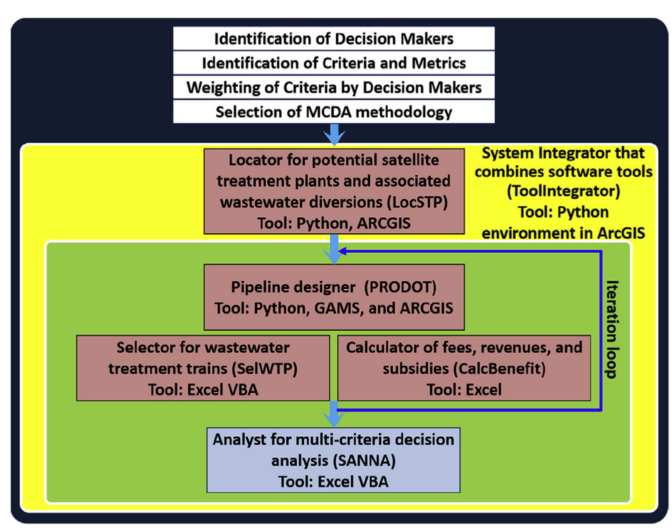


Fig. 1. An overview of decision-making tools implemented in IRIPT for planning of water reuse infrastructure.

(*CalcBenefit*). The configurations identified by these tools are inputs to a MCDA tool developed by a third party (blue box, Jablonský, 2009). All five tools are nested within a System Integrator (*ToolIntegrator*). The sections that follow describe the capabilities and implementation of each of these tools.

2.1. Locator for satellite treatment plants and associated wastewater diversions (LocSTP)

Treatment systems are designed with local conditions in mind. A GIS-based methodology can help system designers decide on potential locations for STPs with different local requirements. A key concept implemented in *LocSTP* is the idea of a threshold STP capacity required for economic viability, referred to here as a "breakeven reclaimed water flowrate" (BRWF), defined as follows:

$$Q_b = \frac{C_{ts} + C_{st} + C_p + C_{omts} + C_{mp}}{(R + S - F - A_{cp} - A_{mp}) \cdot \Delta t_{op}} \qquad (1)$$

Equation (1) is derived from a balance on unit costs and unit benefits for an STP, where Q_b = breakeven reclaimed water flowrate (BRWF) = flowrate of reclaimed water (m^3/d) that must be treated and delivered so that the revenue covers the cost of treatment and delivery; C_{ts} = amortized capital cost of treatment system [\$/yr]; C_{st} = amortized capital cost of storage tank [\$/yr]; C_p = amortized capital cost of pumps for wastewater diversion and reclaimed water distribution [\$/yr]; C_{omts} = annual O&M costs of treatment system [\$/yr]; C_{mp} = annual maintenance cost for pump system [\$/yr]; R = unit revenue from sale of reclaimed water [\$/m^3] or, equivalently, the unit price of reclaimed water [\$/m^3] (see Section 2.4); S = unit subsidy for use of reclaimed water (see Section 2.4) [\$/m^3]; F = unit costs for all fees (see Section 2.4) [\$/m^3]; A_{cp} = unit capital costs of the pipe networks for the wastewater diversion and reclaimed water delivery [\$/m^3]; A_{mp} = unit maintenance costs of the pipe networks for the wastewater diversion and reclaimed water delivery [\$/m^3]; and Δt_{op} = annual duration of operation [days/yr].

In equation (1), the numerator terms for treatment system costs have units of \$/year and are obtained from *SelWTP* (Fig. 1 and Section 2.3). The amortized capital cost of pumps C_p is a nonlinear function of flowrate ($a \cdot Q_b^c$) and is calculated by *ToolIntegrator* (Fig. 1), where a = a parameter calibrated to local pump station costs and c = a parameter set by empirical or statistical data. A factor in the denominator, Δt_{op}, accounts for the number of days of operation per year, and the remaining terms in the denominator have units of \$/m^3.

The BRWF calculation assumes one pump station per STP for distribution of reclaimed water. It also assumes that some costs with high uncertainty are much smaller than the major system costs and can be neglected. These costs include installation and O&M costs for diversion pipes that convey wastewater to STPs and O&M costs for reclaimed water distribution systems.

As shown in Fig. 2, *LocSTP* identifies candidate locations for STPs and associated wastewater diversions. The algorithm is executed as follows: 1) wastewater and organic mass flows for the sewer network are estimated; 2) sewer manholes with sufficient wastewater flow to meet the BRWF (Eq. (1)) are identified; 3) unacceptable STP locations based on user-supplied geographic criteria (Table 1) are excluded; 4) user-defined STP locations for exclusion and inclusion are added; 5) STP location closest to each reclaimed water (RW) customer are identified; 6) potential STP locations closest to each sewer manhole selected in Step 2 are identified; and 7) each STP location is paired with the closest sewer manhole.

2.2. Pipeline designer (PRODOT)

Pipeline design is accomplished using a tool, Pipeline ROuting and Design Optimization Tool (*PRODOT)*, described in detail elsewhere (Lee et al., 2016). Briefly, *PRODOT* identifies near-minimum-cost pipeline routes using a Minimum Steiner Tree algorithm accounting for existing infrastructure, environmental and safety concerns, trade-offs in pipeline length, installation method, and traffic congestion during construction. *PRODOT* also optimizes pump station locations, pumping energy, pipe diameters, and pressure classes using mixed-integer non-linear programming (MINLP) to minimize the sum of amortized pipe and pump capital costs and annual pumping energy cost. One *PRODOT* feature added for integration within IRIPT is flexible weighting of capital and O&M costs using non-negative weights α and β in the pipeline design optimization function of Eq. (2):

Minimize ($\alpha \cdot$Amortized capital cost + $\beta \cdot$Annual pumping energy cost),

$$\text{where } 0 \le \alpha, \beta \le 1, \text{ and } \alpha + \beta = 1 \qquad (2)$$

A second capacity added to *PRODOT* is code that computes the fraction of total flow within each pipe segment allocated to each reclaimed water customer (Fig. S1). This fraction is used to estimate the incremental capital cost of the pipeline network for each potential customer. More details are provided in section S1 of the Supplemental Material (SM).

2.3. Selector for wastewater treatment process (SelWTP)

The *SelWTP* tool is a modification of the Coalbed Methane Produced Water Treatment and Beneficial Use Screening Tool (Plumlee et al., 2014). This DST was originally developed for selection of process trains for treatment and reuse of produced water generated by the upstream oil and gas industry (RPSEA, 2010). In the original tool, simple additive weighting was used to select treatment trains for beneficial reuse. *SelWTP* uses a multi-objective optimization for selection of treatment trains and includes a database of *treatment methods* that are applicable to municipal wastewater reclamation. The treatment methods include both individual technologies and commonly bundled technologies that constitute small standardized treatment trains (e.g., coagulation/flocculation/sedimentation). *SelWTP* distinguishes between desalination technologies and conventional technologies that can also serve as pre-treatment or post-treatment to the desalination technologies.

SelWTP first compares influent water quality to the target effluent quality for specific reuse applications (e.g., indirect potable use, crop irrigation, stream flow augmentation, livestock watering) and then generates an internal roster of constituents that require removal and their required percent removal. An expert-defined matrix was created in *SelWTP* that assigns percent removals of multiple constituents to each treatment technology or bundle of technologies. The expert-defined database also includes cost curves for each technology that correlates unit cost of treatment (\$/m^3) and unit chemical demand (monetized, \$/m^3) to size/capacity of system (m^3/day).

SelWTP then uses a set of objective functions to assemble optimized treatment trains that will first achieve the treatment goal, and then comply with economic (i.e., capital and annual O&M costs) and technical (i.e., ability to automate operation, flexibility, footprint, current commercial status, mobility, modularity, robustness, waste management, and ability to recover energy and nutrients) criteria. While the *SelWTP* always searches for the least expensive treatment solution, user-assigned weights, ranging from 1 (lowest importance) to 5 (highest importance), dictate selection

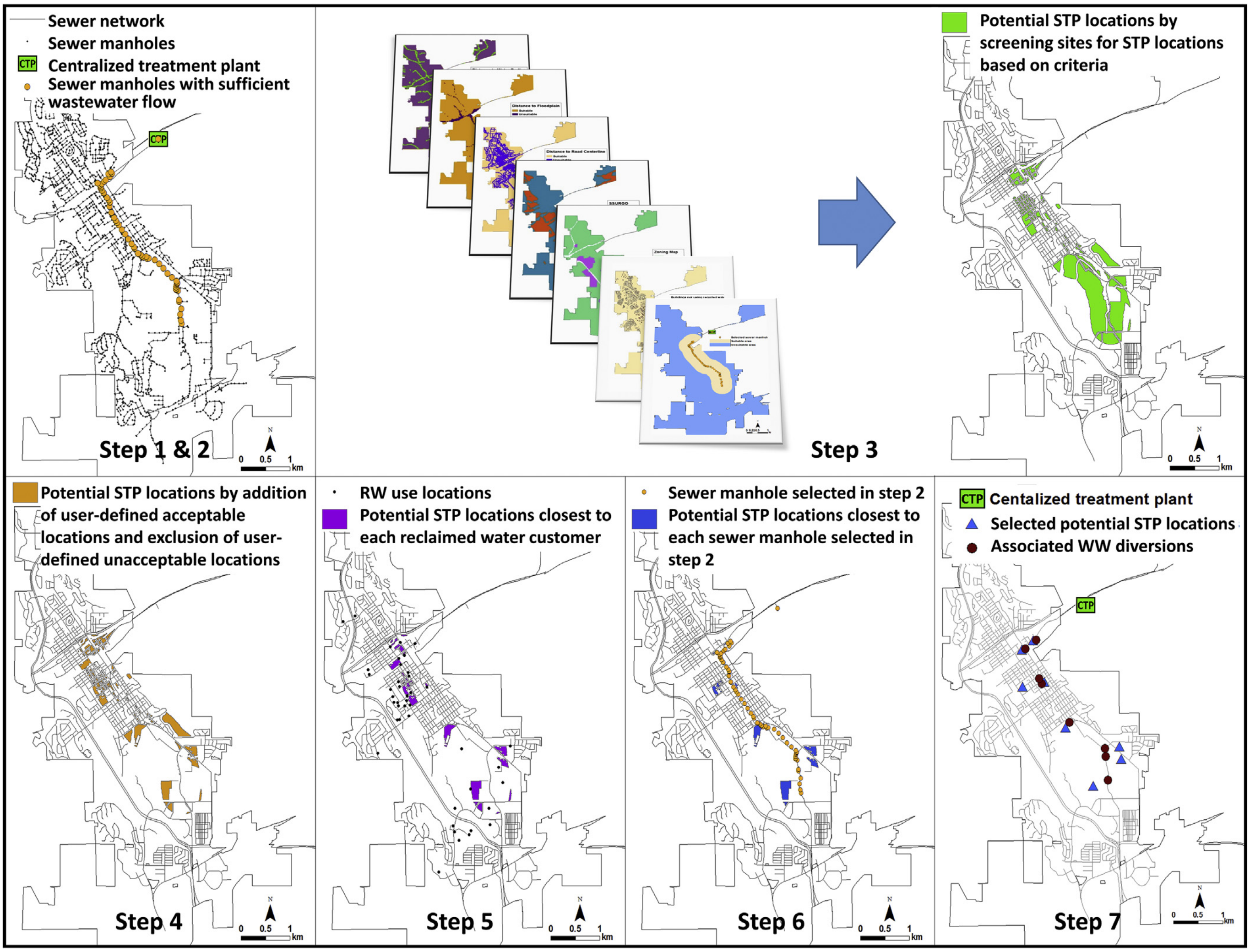


Fig. 2. Steps for *LocSTP*. Steps 1 & 2 estimate wastewater and organic mass flows throughout the sewer network and identify sewer manholes with sufficient wastewater flow to meet the BRWF. Step 3 screens out unacceptable STP locations using geographic criteria. Step 4 adds user-defined acceptable STP locations and excludes user-defined unacceptable locations. Step 5 selects potential STP locations closest to each RW customer. Step 6 selects potential STP locations closest to each sewer manhole selected in Step 1. Step 7 pairs each STP location with the closest sewer manhole.

Table 1
Geographic criteria used in the screening (Step 3) of unacceptable satellite treatment plant (STP) locations.

Criteria
• Restricted zoning districts • Soil properties • User-defined upper bound for proximity to sewer manholes identified by the BRWF analysis • Regions avoided due to the presence of existing road networks • User-defined lower bounds for proximity to waterbodies • User-defined lower bounds for proximity to high hazard areas, such as floodplains or earthquake zones

of processes with the desired levels of the technical criteria listed above. The user can also specifically dictate inclusion or exclusion of one or more technologies from the process trains that will be assembled by *SelWTP*.

The conceptual flowchart of *SelWTP* is illustrated in Fig. 3. *SelWTP* automatically assembles treatment methods into treatment trains and scores the treatment trains. The score for each treatment train is the sumproduct of user weighting and expert ranking for each treatment method within the train. A non-linear optimization is then used to select a final treatment train from among the constructed treatment trains. Additional details are provided in section S2 of the SM.

As outputs, *SelWTP* sizes and estimates the costs of storage tanks at the treatment site based on a user-defined time requirement for storage. For STPs, it calculates flowrates and concentrations of residual biosolids returned to the sewer network. Energy recovery at the STPs is computed assuming anaerobic digestion, which may be followed by sidestream nitrogen management options.

2.4. Calculator of fees, revenues, and subsidies (CalcBenefit)

Fig. 4 illustrates the monetary exchanges assumed by *CalcBenefit*

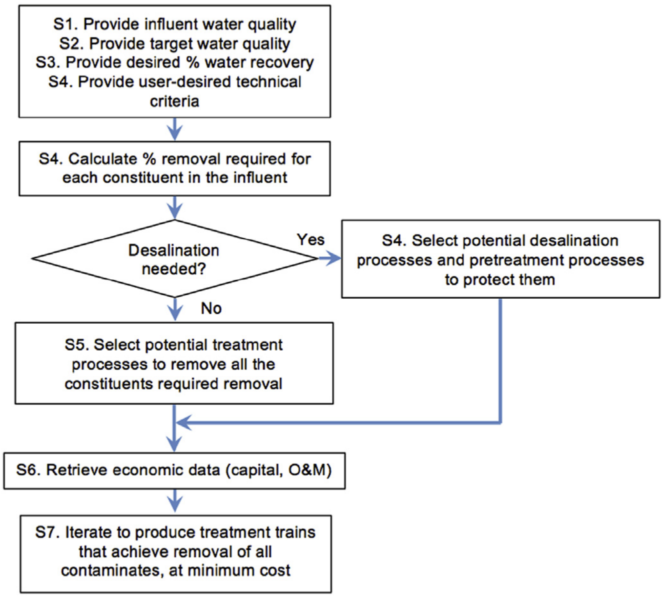


Fig. 3. *SelWTP* conceptual flowchart.

for a system containing a single CTP and a variable number of STPs (could be zero). *CalcBenefit* considers three different facility owner scenarios for water reclamation facilities. Fig. 4(a) shows the case in which all wastewater treatment and water reclamation facilities are owned and operated by a single entity. We assume that the revenues for the owner come from: (1) fees collected from wastewater generators for the conveyance of wastewater to and its treatment at the existing CTP (CTP_{WW}) and STPs; (2) revenue from the sale of reclaimed water produced at the centralized water reclamation facility for advanced treatment (CTP_{RW}) and STPs and delivered to CTP_{RW} and STP customers; and (3) subsidies from a government or other sources to promote water reuse.

Fig. 4(b) shows the case in which the owner of the water reclamation facilities does not own the CTP_{WW}, but does own a CTP_{RW} that upgrades CTP_{WW} effluent to the water quality standards required for reuse, the reclaimed water distribution system, and all STP water reclamation facilities. We assume that the revenues for this owner come from: (1) fees collected from wastewater generators for conveyance of wastewater to and its treatment at the STPs; (2) revenue from the sale of reclaimed water produced at the CTP_{RW} and STPs and delivered to CTP_{RW} and STP customers; and (3) subsidies from governmental and other sources to promote water reuse. Also, we assume that the owner of the water reclamation facilities (CTP_{RW} and STPs) pays (1) fees for residual management at the CTP_{WW} caused by the STPs; and (2) fees for reduction in wastewater flow to the CTP_{WW} caused by the STPs. We assume that the fees collected from wastewater generators connected to the CTP_{WW} are unchanged by the reuse system.

Fig. 4(c) shows the case in which one entity owns all CTP water reclamation facilities (CTP_{WW} and CTP_{RW}) and another entity owns all STP water reclamation facilities. We assume that the revenues for the former entity come from: (1) fees collected from wastewater generators for conveyance of wastewater to and its treatment at the CTP_{WW}; (2) revenue from the sale of reclaimed water produced at the CTP_{RW} and delivered to CTP_{RW} customers; (3) subsidies from governmental and other sources to promote water reuse; (4) fees for residual management at the CTP_{WW} caused by the STPs; and (5) fees for reduction in wastewater flow to the CTP_{WW} caused by the STPs. And we assume that the revenues for the STP entity come from: (1) fees collected from wastewater generators for conveyance of wastewater to and its treatment at the STPs; (2) revenue from the sale of reclaimed water produced at the STPs and delivered to STP customers; and (3) subsidies from governmental and other sources to promote water reuse. Also, we assume that the STP owner pays (1) fees for residual management at the CTP_{WW}; and (2) fees for reduction in wastewater flow to the CTP_{WW}.

We also compute, as a separate indicator, potential cost savings to customers resulting from replacement of potable water with reclaimed water (i.e., the cost of avoided potable water minus the

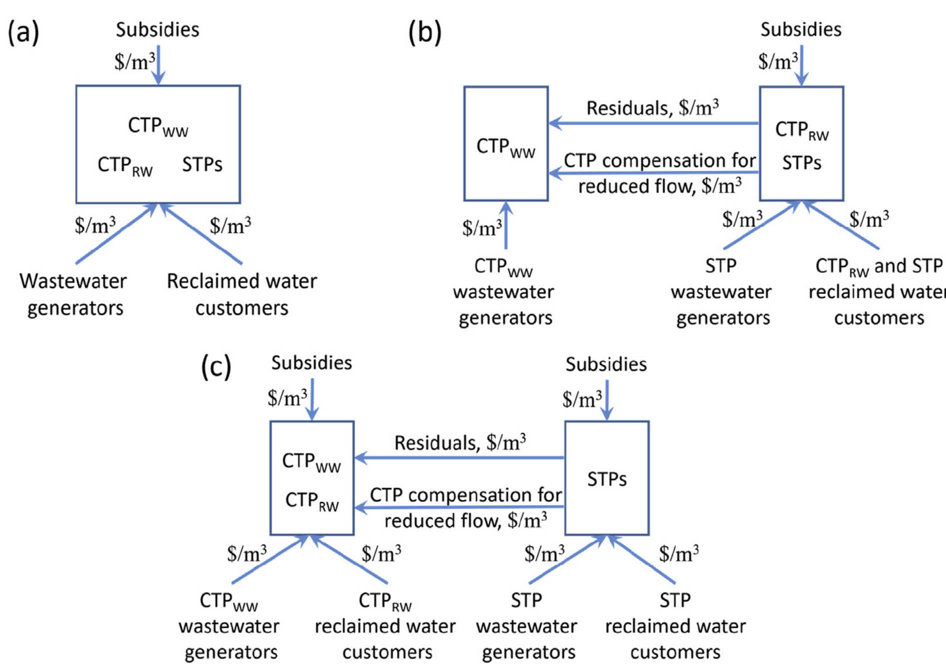


Fig. 4. The monetary exchanges assumed by *CalcBenefit* for a system containing a single CTP and a variable number of STPs (CTP_{WW} is an existing centralized wastewater treatment facility; CTP_{RW} is a centralized water reclamation facility, including an advanced treatment. Boxes represent administrative/operational entities.).

cost of reclaimed water). More details are provided in section S3 of the SM.

2.5. Analyst for multi-criteria decision analysis (SANNA)

Planning of reclaimed water infrastructure typically requires consideration of multiple criteria, some of which may conflict. To implement multi-criteria decision analysis (MCDA), we use the System for ANalysis of Alternatives (*SANNA*), developed by Josef Jablonský, (2009). We choose this tool because it is available on-line and supports several MCDA methods (e.g., Electre (Roy, 1968), PROMETHEE (Brans, 1982), and TOPSIS (Hwang and Yoon, 1981)) that are widely used for real-world problems. The current IRIPT version uses PROMETHEE to compare criteria that have incomparable or incommensurate metrics because of, e.g., different measurement scales, such as monetary and nonmonetary metrics (Linkov, 2005). Key steps of PROMETHEE are as follows (Lee et al., 2013): Step 1) Configurations are compared in pairs for each criterion and a preference function score for each comparison is calculated using the usual preference function. A preference score of 1 is given to a configuration alternative if its performance is superior to the paired alternative, and a score of 0 is given otherwise. Step 2) Each score is multiplied by a normalized weight assigned to the corresponding criterion. The weighted scores are summed across the criteria and comparisons for each configuration and divided by the number of alternative configurations to obtain the “positive outranking flows” and “negative outranking flows”. Step 3) The final ranking is determined by the net outranking flows, which are defined as the “positive outranking flow” minus the “negative outranking flow” and range between -1 and +1. These steps are performed by SANNA, which is a tool for MCDA of IRIPT.

2.6. Applications used for tool implementation

LocSTP was developed using Python and geoprocessing tools in ArcGIS. *PRODOT* was developed using Python, General Algebraic Modeling System (GAMS), and ArcGIS (Lee et al., 2016). *CalcBenefit* was developed using Microsoft Excel. *SelWTP* and *SANNA* were developed using VBA (Visual Basic for Applications) in Microsoft Excel.

3. Integration of decision support software tools

Each of the component tools described in Section 2 has unique functionalities with rich features and can be run independently as a stand-alone tool. However, the decision-making process involves more than simply executing each tool sequentially. Careful integration and iteration between tools are necessary to generate wastewater reuse configurations that satisfy the design requirements. Thus, an integrated DST that considers a number of critical factors in the decision-making process, and orchestrates the tools accordingly, is essential.

The components described above are integrated into IRIPT using the Python environment within ArcGIS. IRIPT directly controls dataflow between tools and generates recommendations based on user input. A third-party Python extension package (pywin32) interacts with Microsoft Windows and launches external software applications.

4. Structure of decision-making process applied to IRIPT

This section describes the decision-making process used to identify optimal centralized and hybrid water reuse configurations for three different cases. In Case 1, the objective is to maximize the volume of reclaimed water supplied to customers. In Case 2, the objective is to maximize reclaimed water supplied to customers, while ensuring a positive system net benefit. In Case 3, the objective is to maximize the system net benefit.

Fig. 5 illustrates the algorithm used to identify centralized configurations that maximize the reclaimed water supplied to customers (Case 1). In Step 1.1, *SelWTP* identifies supplemental treatment methods needed at the CTP to meet water quality standards for a specified beneficial use, and the sizes and costs of storage tanks are computed. A user-defined storage time is used to compute storage volumes. *PRODOT* then creates an optimized reclaimed water distribution network (pipeline routing, pump station locations, and pipe sizes) designed to serve all reclaimed water customers. In Step 1.2, *CalcBenefit* computes revenues from the sale of reclaimed water based upon a user-specified unit price ($\$/m^3$). These unit prices are assumed uniform for all customers. *CalcBenefit* also computes subsidies and potential savings to customers. Using these steps, the toolkit user can identify the configuration that maximizes reclaimed water supplied to customers given the assumed unit prices and subsidies. An IRIPT algorithm calculates system net benefit using data from Table S2 to determine subsequent execution of the program—if negative, IRIPT proceeds to Case 2, and if positive, IRIPT proceeds to Case 3.

Fig. 6 illustrates the algorithm used to identify the centralized water reuse configuration that maximizes reclaimed water supply for the available wastewater flow, while also providing a positive net benefit for the reclaimed water system (Case 2). This involves *trimming* (Steps 2.1–2.3) followed by *checking* (Steps 2.4–2.6). *ToolIntegrator* sorts all customers in order of their unit net benefit ($\$/m^3$), from smallest to largest, then systematically eliminates the set of customers with the smallest unit net benefits (Step 2.1). The unit net benefit for a given customer ($\$/m^3$) is defined as the incremental system net benefit ($\Delta\$$ for the system) that results when a known volume of reclaimed water (m^3) is delivered to that customer. As customers are removed, *SelWTP* upgrades the CTP, *PRODOT* optimizes pipeline design, and *CalcBenefit* calculates fees, revenues, subsidies, and potential savings for the remaining customers (Steps 2.2–2.3). Steps 2.1–2.3 iterate until the configuration system net benefit is positive. At each iteration, the toolkit reports the breakeven price of reclaimed water ($\$/m^3$) for each system configuration that results in zero net benefits. This information gives insight into the impacts of reclaimed water pricing on system size (i. e., volume of reclaimed water supplied, no. customers).

After IRIPT has identified a configuration with a positive system net benefit, it checks customers that were excluded in the last trimming step to determine whether they can be added back into the system while still enabling positive net benefits. The customer with the least negative net benefit will be added back in first. Steps 2.4–2.6 are repeated until the system net benefit is negative. The checking process stops when the system net benefit is negative after a customer is added back in, and the final selected configuration is the configuration obtained before addition of that customer.

Fig. 7 illustrates trimming for a simple example. IRIPT first removes the two customers who have the lowest unit net benefits. The toolkit user controls this process by initially multiplying the system net benefit resulting from the final configuration of the previous case (-100) by a user-selected trimming factor (0.3). The trimming factor enables rapid exclusion of customers based upon economic considerations and avoids exhaustive enumeration. IRIPT optimizes the system design for the remaining customers, resulting in a new configuration and a new system net benefit. If the system net benefit after this optimization is positive (+3, in this example), no more customers are excluded. If system net benefit remains negative, additional trimming is required, and Steps 2.1–2.3 are repeated. If this trimming eliminates all customers, then water

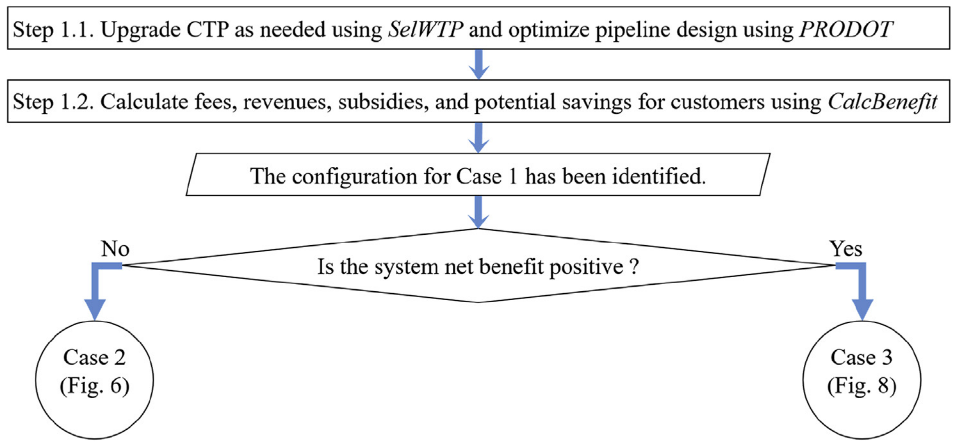


Fig. 5. Case 1 of centralized configuration (optimization with all customers served).

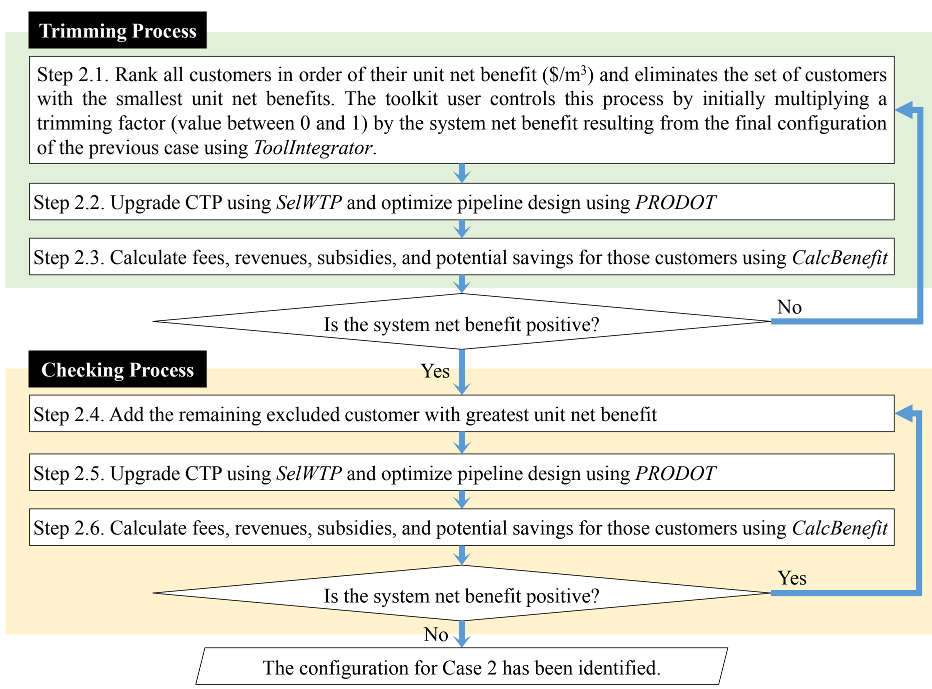


Fig. 6. Case 2 of centralized configuration (seek positive system net benefit by excluding customers).

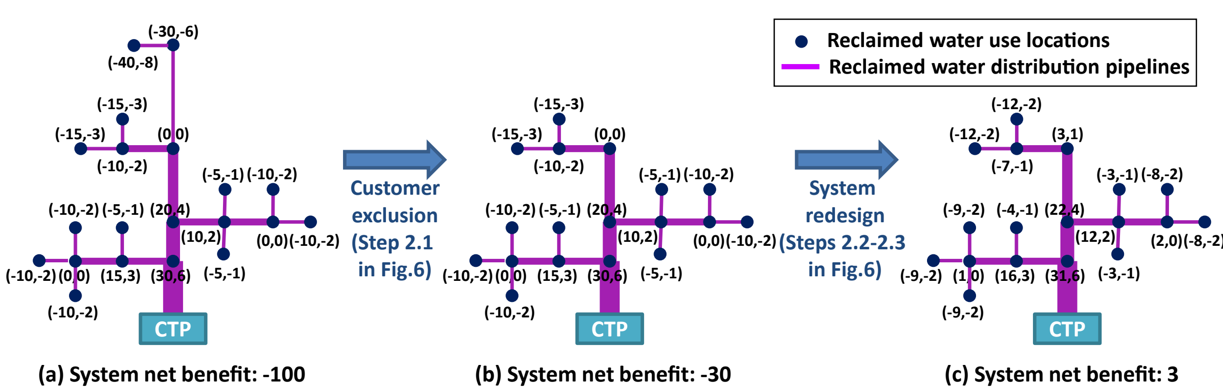


Fig. 7. Simplified example illustrating the trimming process used by IRIPT to exclude consumers that have the lowest unit net benefits. The pairs of numbers in this figure are (system net benefit incremented by including a customer ($), unit net benefit incremented by including a customer ($/m^3)).

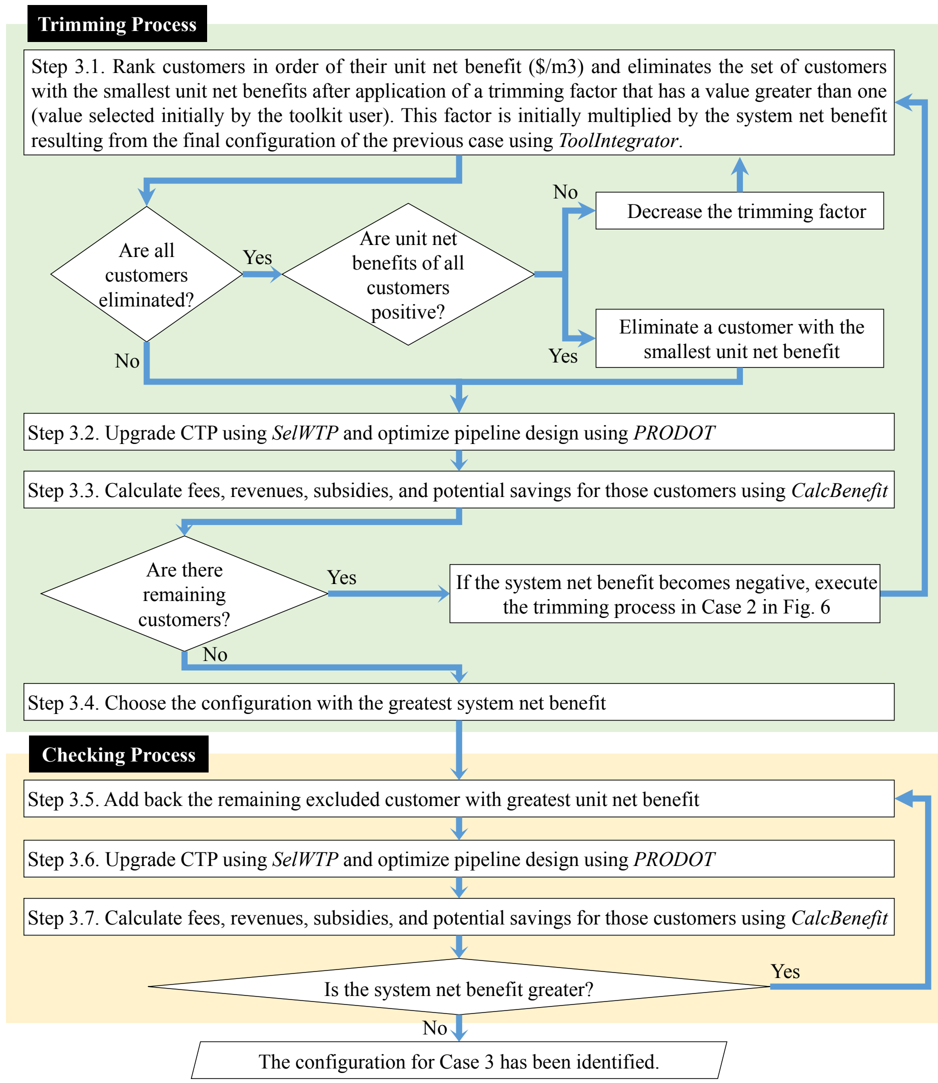


Fig. 8. Case 3 of centralized configuration (attempt to maximize positive system net benefit by excluding customers).

reuse is deemed infeasible for the assumed unit price of reclaimed water.

Fig. 8 illustrates the algorithm used to identify centralized water reuse configurations that maximize the system net benefit (Case 3). As before, we use *trimming* (Steps 3.1–3.4) followed by *checking* (Steps 3.5–3.7). Step 3.1 ranks customers in order of their unit net benefit ($/m^3) and eliminates the set of customers with the smallest unit net benefits after application of a trimming factor that has a value *greater than one* (value selected initially by the toolkit user). This factor is initially multiplied by the system net benefit resulting from the final configuration of the previous case. If all customers are eliminated by trimming and one or more of the eliminated customers have negative unit net benefits, IRIPT automatically decreases the trimming factor and repeats Step 3.1. If all the eliminated customers have positive unit net benefits, IRIPT eliminates the customer with the smallest unit net benefit. If customers remain after trimming, *SelWTP* upgrades the CTP, *PRODOT* optimizes pipeline design, and *CalcBenefit* calculates fees, revenues, subsidies, and potential savings for the remaining customers in Steps 3.2–3.3. If there are remaining customers but the system net benefit becomes negative, IRIPT executes the trimming process of Case 2 in Fig. 6 until a configuration with a positive system net benefit is obtained. Iteration of steps 3.1–3.3 continues until there are no remaining customers. This results in a series of intermediate configurations. IRIPT compares these intermediate configurations and selects the configuration with the greatest system net benefit (Step 3.4) for further analysis in the *checking* step. IRIPT checks the most promising intermediate configuration by adding back customers that were excluded in the trimming step that resulted in the most promising intermediate configuration, beginning with the customer with the largest unit net benefit. After addition of this customer, *SelWTP* upgrades the CTP, *PRODOT* optimizes pipeline design, and *CalcBenefit* computes fees, revenues, subsidies, and potential savings for those customers. IRIPT uses all of this information to determine the system net benefit that results from inclusion of this customer. If the system net benefit increases, the process is repeated with the customer that has the next largest unit net benefit, and so on. The checking process stops when the system net benefit decreases after a customer is added back in, and the final selected configuration is the configuration obtained before addition of that customer.

Fig. 9 illustrates the algorithm used to identify hybrid water reuse configurations that maximize reclaimed water supply (Case 1H); reclaimed water supply while also providing a positive net

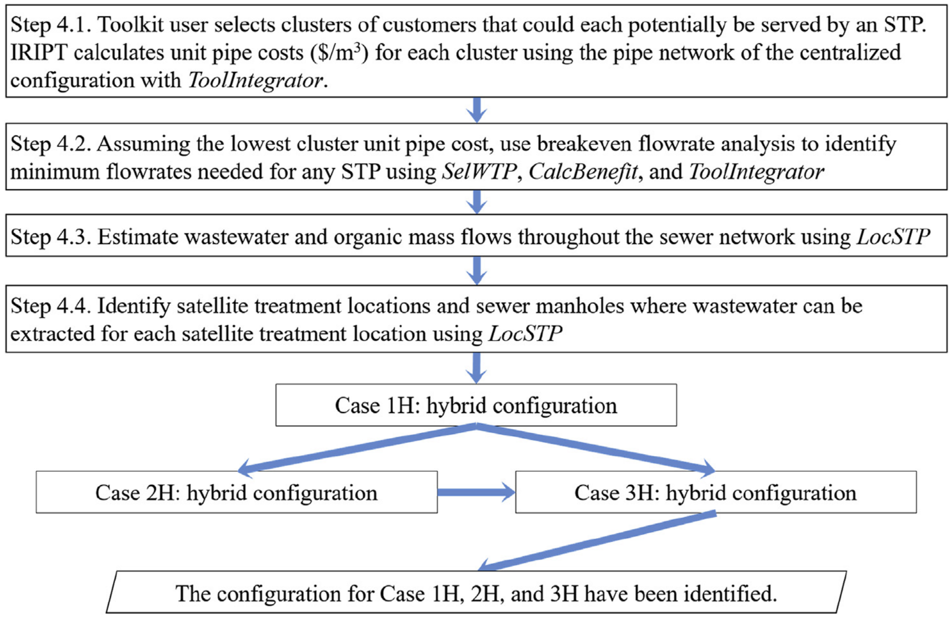


Fig. 9. Integrated decision-making process for planning of hybrid water reuse infrastructure.

benefit (Case 2H); and system net benefit (Case 3H).

Steps 4.1–4.4 in Fig. 9 summarize the initialization steps used to analyze a hybrid configuration. In Step 4.1, the toolkit user selects clusters of customers that could be served by a single STP. This step is enabled by a pause in the execution of the program. *ToolIntegrator* then calculates unit pipe costs ($\$/m^3$) for each cluster using the pipe network of the centralized configuration created in Step 1.1 of Fig. 5. Three such clusters are illustrated in Fig. 10. *ToolIntegrator* then selects the cluster with the lowest unit pipe cost ($\$0.40/m^3$ in this example). This value is calculated by dividing the amortized pipeline cost by the annual reclaimed water flow to the cluster. Using the lowest unit pipe cost (Step 4.1) and data from *SelWTP* and *CalcBenefit, ToolIntegrator* performs a breakeven flowrate analysis

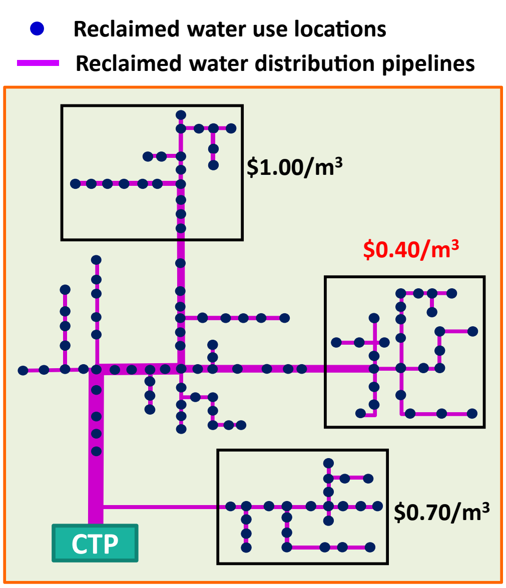


Fig. 10. IRIPT uses pipeline subsets within the CTP distribution system to estimate the costs of water distribution pipelines that could potentially connect to an STP. For calculation of the BRWF, the lowest unit pipe cost ($\$0.40/m^3$) is selected.

(Eq. (1)) to identify the minimum flowrates needed for an STP (Step 4.2).

In Step 4.3, *LocSTP* estimates baseline wastewater and contaminant mass flows in the direction of the wastewater flow by summing mass flows throughout the sewer network. This is the minimum flowrate for each pipeline in the sewer network, i.e., the flowrate that is available at all times. *LocSTP* then identifies potential STP and wastewater diversion locations as described in Section 2.1 (Step 4.4).

The algorithm used to configure hybrid systems (Case 1H, 2H, and 3H) is similar to the algorithm used to configure centralized systems (Figs. 5, 6, and 8) with two important differences: (1) hybrid configurations allow for monetary exchanges between a CTP and STPs (Section 2.4) and (2) customers are divided into non-overlapping STP and CTP configurations that ensure service to all potential customers and adequate flow to the STP. This is accomplished in the “matching step” (Fig. 11). As shown in Fig. 11(a), IRIPT initially generates reuse configurations for each treatment plant in which each plant is assumed to serve all customers. Unit net benefits ($\$/m^3$) are then compared for each customer and for each configuration (Fig. 11(a1)-(a3)). Customers with negative unit net benefits for all of the treatment plant locations are assigned to the treatment plant with the least negative unit net benefit and the customers with positive unit net benefits for one or more of the treatment plant locations are assigned to all the treatment plants with positive unit net benefits.

After assignment of all customers to treatment plants, flowrates are checked throughout the system to ensure that reclaimed water can be recovered economically. STPs with flows that are less than the BRWF are excluded (e.g., STP1 in Fig. 11(a2)). IRIPT then automatically redesigns the system to enable new connections between each treatment plant and its prospective consumers based on prior assignments (Fig. 11(b1 and b2)). For customers connected to more than one treatment plant, unit net benefits ($\$/m^3$) are compared for each treatment plant, and each customer is assigned to the plant that results in the largest unit net benefit. IRIPT then redesigns the system yielding a non-overlapping configuration of STP- and CTP-customers, where each treatment plant serves the customers

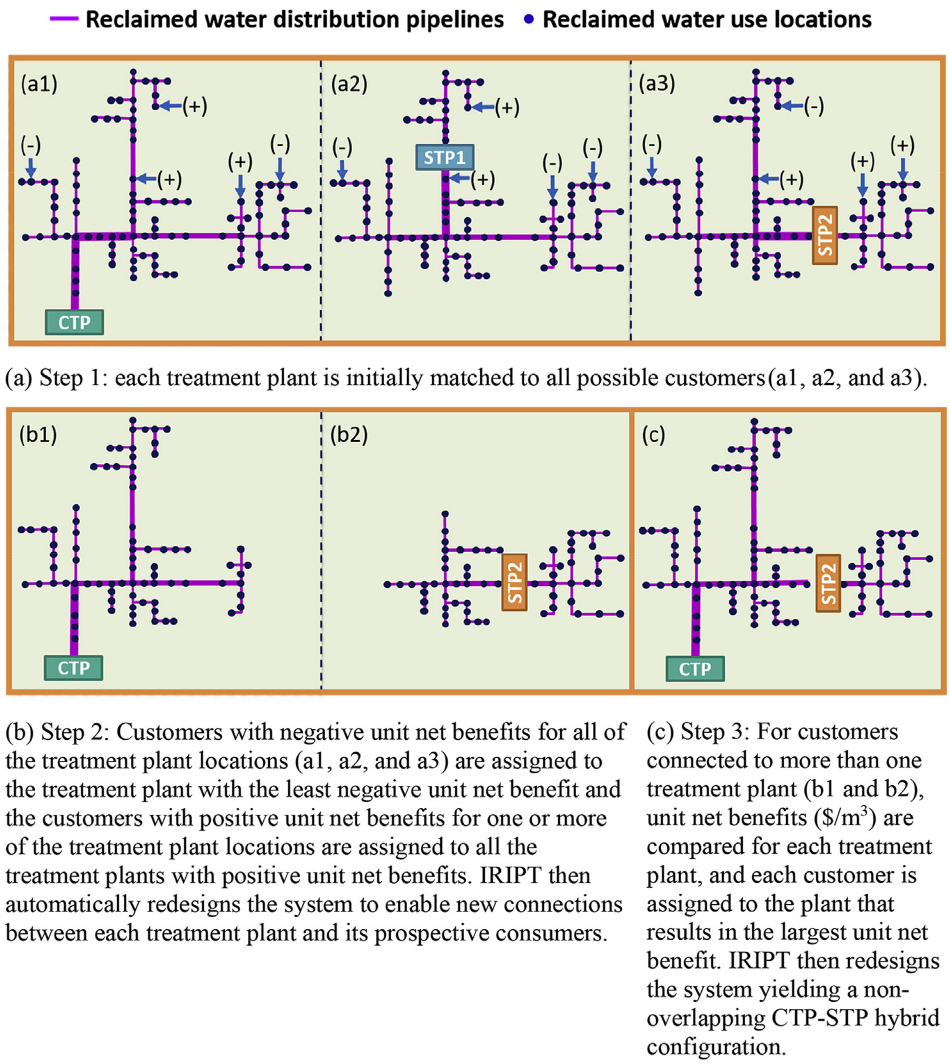


Fig. 11. Three sub-steps in the matching step to yield the non-overlapping configuration that serve all potential customers in the process of identifying the optimal hybrid configuration. (+) or (-) indicate the positive or negative unit net benefit of each potential customer. Only reclaimed water distribution pipelines are shown.

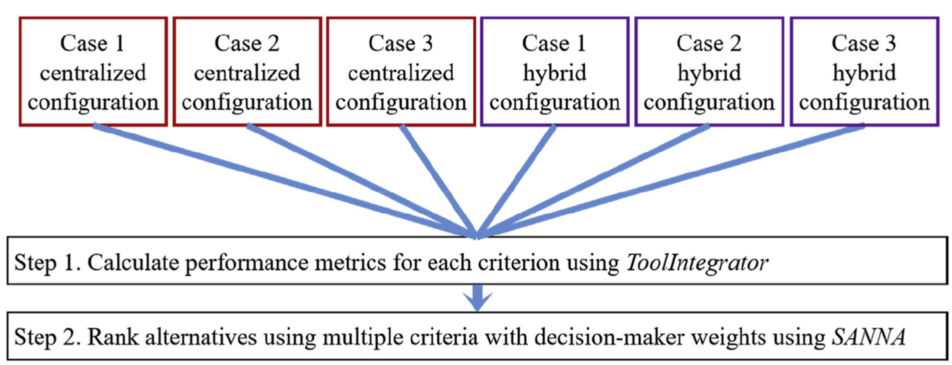


Fig. 12. Decision-making process for ranking of all water reuse infrastructure.

with the largest unit net benefits. This configuration serves all potential customers given the wastewater available for diversion to STPs (Fig. 11(c)).

Fig. 12 illustrates use of MCDA to select the final preferred configuration. *ToolIntegrator* calculates performance metrics for each of the three centralized configurations and for each of the three hybrid configurations. *SANNA* then ranks these six configurations using calculated performance metrics and weights assigned by decision-makers. *CalcBenefit* also calculates the cost savings to the reclaimed water customer, i.e., the cost of avoided potable water purchase minus the cost of reclaimed water.

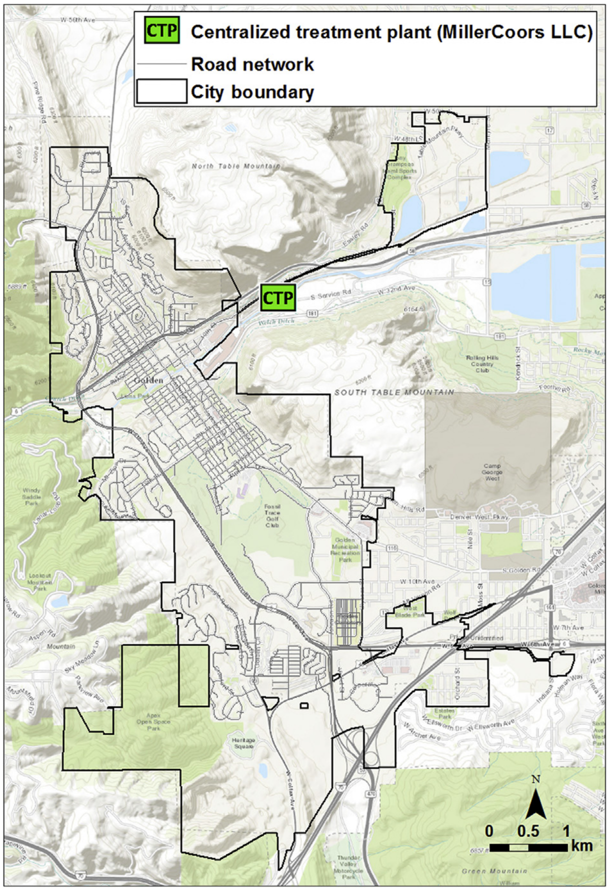


Fig. 13. Map of the city of Golden, Colorado.

5. Case study

5.1. Background

The City of Golden is located in Jefferson County, Colorado. The city does not operate its own CTP, relying instead on a treatment plant operated by MillerCoors LLC (Fig. 13). The effluent from the treatment plant discharges to Clear Creek. Because Golden's existing contract with MillerCoors does not include provisions for water reuse, a new contract would be needed with provisions for Golden to install and operate a reclaimed water distribution system upstream of the MillerCoors treatment plant along with one or more STPs. The City of Golden would likely be required to compensate MillerCoors for the reduction in treatment plant inflow (personal communication with Ms. Anne Beierle, Deputy Director/Water & Utilities, City of Golden). Fig. 4(b) illustrates the monetary exchanges of the Golden case study, where the owner of CTP_{WW} is MillerCoors and the owner of both the CTP_{RW} and the STPs is assumed to be the City of Golden.

Golden is located in a semi-arid region (City of Golden, 2015) with an irrigation season normally extending from April through October (personal communication with Mr. Les Major, Utilities Superintendent, City of Golden). At present, Golden does not use reclaimed water. We chose Golden for this case study because of the city's expressed interest in water reuse and their willingness to share water infrastructure data. For the following analysis, we assume that the current reclaimed water regulations in Colorado apply. Reclaimed water reuse currently allowed under Colorado Reclaimed Water Control Regulation 84 includes landscape irrigation and various commercial and industrial uses, such as cooling, street cleaning, fire protection, and zoo operations (CO Water Quality Control Commission, 2013). Direct potable reuse is not considered in this analysis.

5.2. Application of IRIPT integrated decision-making

5.2.1. Input data

5.2.1.1. Inputs for MCDA. The Golden case study demonstrates how IRIPT improves the decision-making process by incorporating user input into selection of a single preferred infrastructure configuration that satisfies decision-maker priorities. This case study identifies and ranks water reuse infrastructure configurations at different geographic scales, while considering the sensitivity to different design parameters (e.g., the unit price of reclaimed water, subsidy rate, and CTP compensation for reduced flow). Criteria and metrics for MCDA are summarized in Table 2.

The PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluations) I and II methods are used for the MCDA in the same way as in Lee et al. (2013). Ms. Anne Beierle of the City of

Table 2
Criteria and metrics.

Criteria	Definitions & Metrics
1. Investment Cost	Estimated initial expenses, including construction cost, engineering and construction management costs, with contingencies. ($ x 10^6)
2. O&M Cost[a]	Present value of operation and maintenance costs and CTP compensation for reduced flow. ($ x 10^6)
3. System Revenue[a]	Present value of revenues to the water reuse system generated by reclaimed water sales, wastewater treatment fees at STPs, and other revenues, such as subsidies. ($ x 10^6)
4. System Net Benefit[a]	Present value of benefits minus present value of costs. ($ x 10^6)
5. Annual Energy Requirement	Energy required for wastewater treatment and pumping for wastewater capture and reclaimed water distribution. (MWh/yr)
6. Resilience to Water Stress	Fraction of nonpotable water use met by reclaimed water. We assume that a reduction in fresh water diversions enhances resilience to water stress. (%)

[a] Costs and benefits for criteria 2, 3, and 4 assume 30 yr time period and 3.5% discount rate, and are incremental with respect to the existing system.

Table 3
Weights, 0 (lowest) to 10 (highest), used for ranking of alternatives.

	Decision-making Criteria					
	Investment Cost ($ x10^6)	O&M Cost ($ x10^6)	System Revenue ($ x10^6)	System Net Benefit ($ x10^6)	Annual Energy Requirement (MWh/yr)	Resilience to Water Stress (%)
Weights	6	6	3	8	7	8

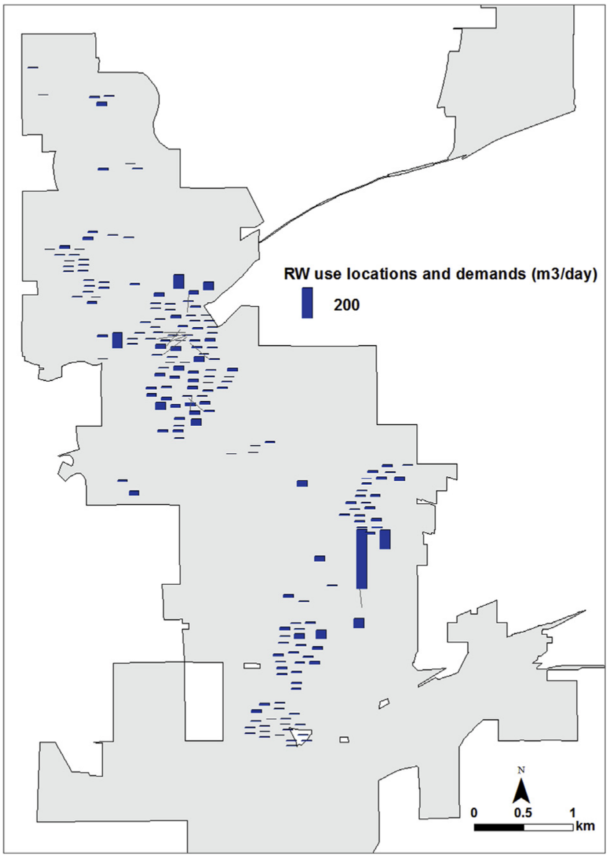


Fig. 14. Reclaimed water (RW) use locations and demands in Golden, Colorado.

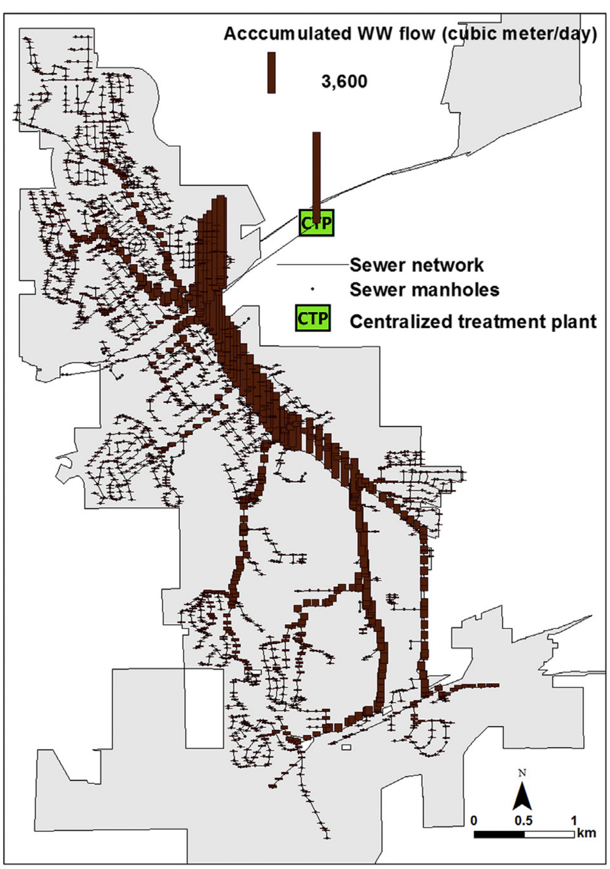


Fig. 15. Estimated winter baseline flowrates at manholes throughout the sewer network in Golden, Colorado.

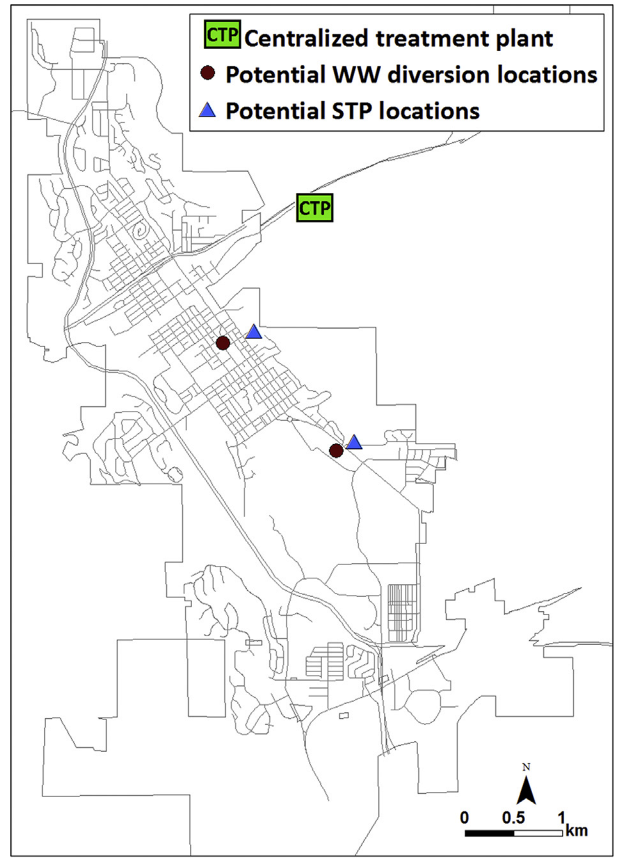


Fig. 16. Potential locations for satellite treatment plants (STPs) and associated wastewater diversions in Golden, Colorado.

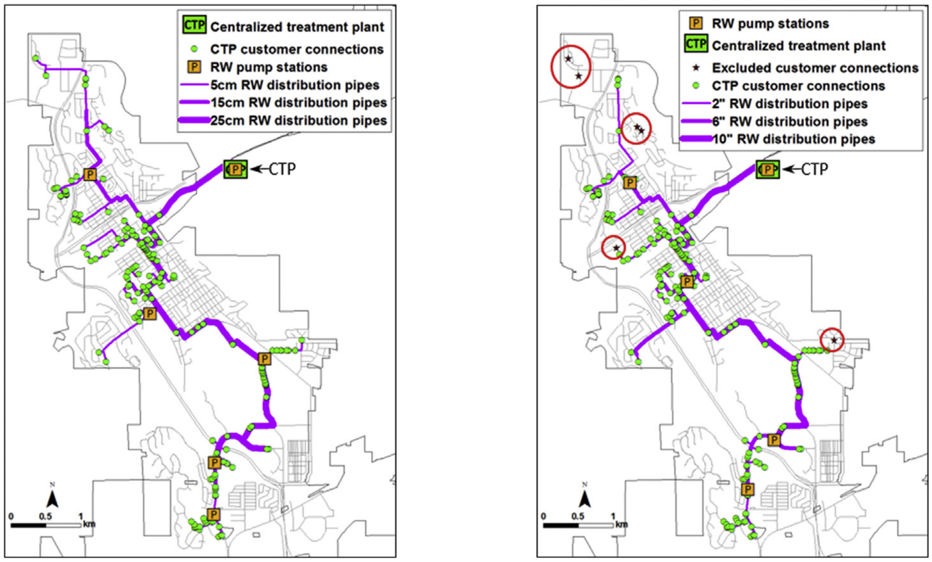
Golden provided weights for each of the criteria in Table 3, using a scale of 0 (lowest preference) to 10 (highest preference).

5.2.1.2. Reclaimed water demand and customer locations. We assume that reclaimed water usage in Golden will be limited to outdoor irrigation, including both unrestricted-access landscape irrigation with a high degree of public contact and resident-controlled landscape irrigation on residential property. Both uses require secondary treatment with filtration and disinfection according to Colorado reclaimed water control regulations (CO Water Quality Control Commission, 2013). Local public parks, currently irrigated with river water, were selected as the primary set of potential reclaimed water customers. Residential, commercial, and industrial customers with relatively high landscape water demands (>3.5 m^3/d) are a second potential customer group. We selected the subset of such customers located between Golden's existing CTP and the parks. More details are available in section S4 of the SM.

During the landscape irrigation season (April to October), the total potential reclaimed water demand for all of the potential customers is 2730 m^3/day (0.72 MGD). We assume that reclaimed water facilities would only be operated during this period of time, eliminating the need for inter-seasonal or inter-annual carryover storage. We assume that irrigation is carried out from 6 p.m. to 10 a.m. (Denver Water, 2017), with pumps and pipes sized for peak hour. The locations of potential reclaimed water customers and their demands are shown in Fig. 14; the height of the bar at each location indicates the potential daily reclaimed water demand.

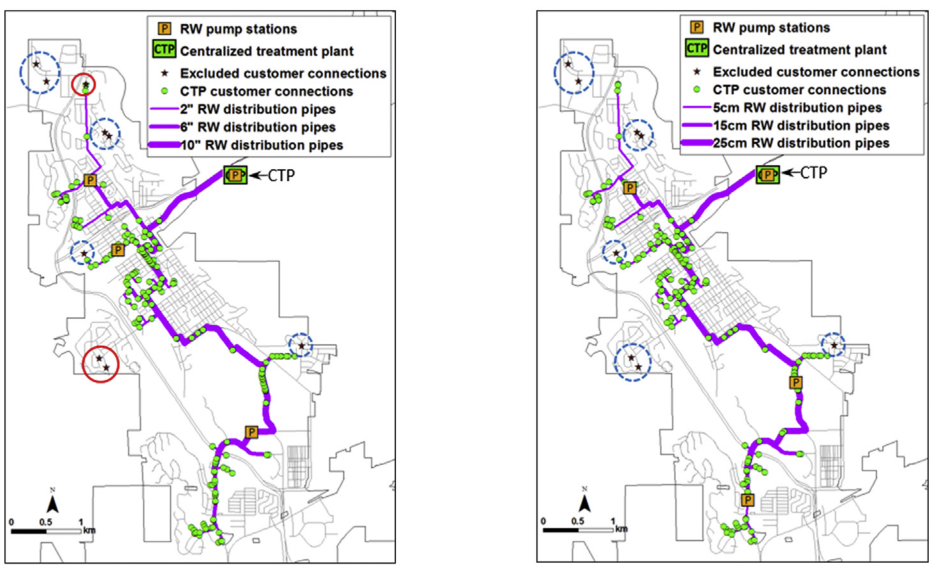
5.2.2. Baseline wastewater flowrates throughout the sewer network

To estimate baseline wastewater flowrates throughout the sewer network, we assume that February water use is non-



(a) System for delivery to all users (2730 m^3/d) with annual system net benefit less than zero ($-108K)

(b) Redesigned system (2700 m^3/d) with annual system net benefit less than zero ($-41K)



(c) Redesigned system (2660 m^3/d) with annual system net benefit greater than zero ($50K)

(d) Redesigned final system (2670 m^3/d) with annual system net benefit greater than zero ($35K)

Fig. 17. IRIPT results for four centralized configurations: (a) Case 1 configuration that maximizes reclaimed water supply to customers; (b) intermediate Case 2 configuration obtained by trimming, where the system net benefit remains negative; (c) intermediate Case 2 configuration after more trimming, with a positive system net benefit; and (d) final Case 2 configuration obtained after checking, where the annual system net benefit is decreased but remains positive, and an additional customer receives service. Solid circles are customers newly excluded in every iteration and dotted circles are customers excluded in the previous iterations.

consumptive and therefore available for wastewater capture in any month. Each year, Golden establishes its sewer billing for the year based upon water use during the month of February (personal communication with Ms. Kim Soulliere, GIS Coordinator, City of Golden). This value is multiplied by 3 for quarterly billings. Using the February flowrate data, *LocSTP* performs a series of mass balances to estimate winter season baseline flowrates (m^3/d) at manholes throughout the sewer system (Fig. 15).

5.2.3. Breakeven reclaimed water flowrate

Using the methodology of Sections 2.1 and 4, the calculated BRWF for a STP providing reclaimed water to a cluster of customers in Golden is 1240 m^3/day (0.33 MGD). This assumes an unit pipe cost of \$0.50/m^3 for the reclaimed water distribution pipelines. For individual customers, the BRWF for an onsite water reuse system is 500 m^3/day (0.13 MGD), but the maximum reclaimed water demand is only 400 m^3/day (0.1 MGD). This implies that onsite water reuse is not economically viable.

5.2.4. Identify locations for satellite treatment plants and associated wastewater diversions

Using the methodology described in Sections 2.1 and 4, *LocSTP* identifies two potential locations for STPs and their associated wastewater diversion points. The results are illustrated in Fig. 16.

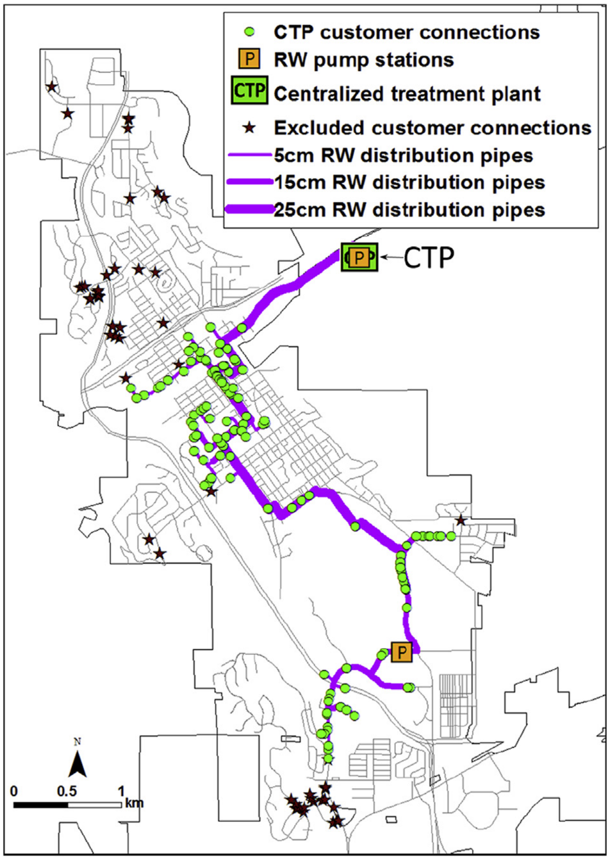


Fig. 18. The centralized configuration with the maximum system net benefit.

5.2.5. Select wastewater treatment and energy recovery processes

Because the only use of reclaimed water is landscaping, *SelWTP* selects a wastewater treatment train consisting of screening, grit removal, microscreen filtration, aerobic biological treatment in a sequencing batch reactor, microfiltration, and chemical disinfection. This treatment train selection is based upon expert rankings included in *SelWTP* and default weights assigned for domestic wastewater treatment. This expected effluent satisfies reclaimed water control regulations of the State of Colorado (CO Water Quality Control Commission, 2013). *SelWTP* also assesses the feasibility of energy recovery during wastewater treatment. For the case of Golden, treatment trains without energy recovery process are chosen because systems with energy recovery incur high capital and O&M costs and because the default weights assigned to capital and O&M costs are higher than the default weight assigned to ability to recover energy. Therefore, all STP residuals are returned to the wastewater collection system for digestion at the CTP. The existing centralized wastewater treatment processes consist of a bar screen, a grit collection system, equalization surge tanks, primary clarifiers, an activated sludge system, secondary clarifiers, sand filters, a post-aeration basin, and chlorination (personal communication, Mr. Chris Naber, Environmental Specialist, City of Golden). We assume that no additional treatment process is needed at the CTP. We also assume that all storage tanks have a two-day residence time.

5.2.6. Select pipeline route and optimize pipe and pump systems

As shown in Fig. 16, there are 2 potential STP locations in Golden. Using *PRODOT*, near-optimal pipeline routes are identified that capture wastewater and deliver reclaimed water from each treatment plant, including the CTP, to customers served by that plant. Pump locations and pipe sizes are optimized for each pipeline system. Pumps are sized to deliver reclaimed water to customer connections at delivery pressures of 390–1240 kPa (57–180 psi) (RMC Water and Environment, 2008; USEPA, 2004).

5.2.7. Economically favorable water reuse configurations for the City of Golden

Figs. 17 and 18 illustrate how centralized water reuse configurations are identified by IRIPT. These configurations all assume a unit price of reclaimed water of $1.32/m^3 ($5/1000gal) and a subsidy of $0.20/m^3 ($0.75/1000gal) over 30 years. We assume that competitive pricing of reclaimed water requires sale of reclaimed water at a value less than the potable water price, $1.39/m^3 ($5.26/1000gal). Also, we assume that a subsidy provider would provide financial support to enable installation and operation of centralized and hybrid systems with positive system net benefits.

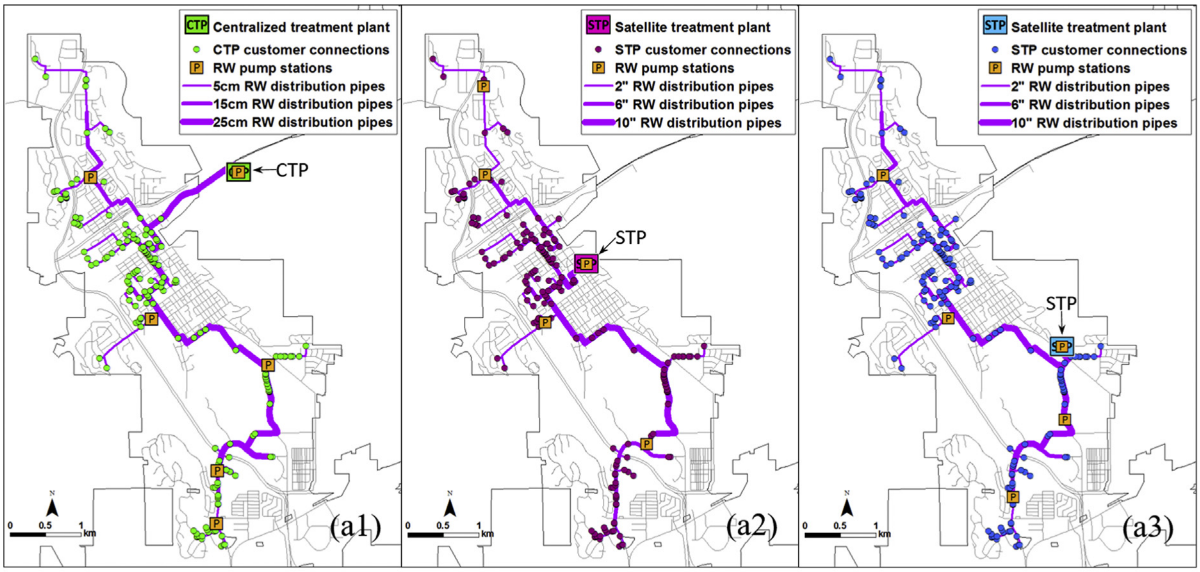
When reclaimed water is delivered to all potential customers, thereby maximizing reclaimed water supply for the available wastewater, IRIPT recommends the configuration of Fig. 17(a). The annual system net benefit for this configuration is −$108K, implying that this design is not economically viable. In order to achieve a positive net benefit, the reclaimed water rate must be increased to $1.51/m^3 ($5.72/1000gal), a value that exceeds the current potable water rate of $1.39/m^3 ($5.26/1000gal) for Golden. Alternatively, the external subsidy must be increased by $0.39/m^3 ($1.47/1000gal). If a higher water rate is not acceptable, IRIPT can be used to eliminate a set of customers that have the lowest unit net benefits. Customers within the solid circles of Fig. 17(b) are excluded, and a new system is recommended. The annual system net benefit decreases from -$108K to -$41K, but is still less than zero. In order to achieve a positive net benefit with this configuration, the reclaimed water rate would need to be $1.39/m^3 ($5.26/1000gal), the current potable water rate in Golden, or the external subsidy must be increased to $0.27/m^3 ($1.01/1000gal). With one additional iteration removing the lowest-unit-net-benefit customers, the annual system net benefit becomes greater than zero ($50K) (Fig. 17(c)). As expected, excluded customers tend to be farther away from the CTP, at locations with relatively small water demand near the ends of pipeline branches.

Because this removal algorithm is heuristic, IRIPT rechecks customers excluded in the steps leading to Fig. 17(c) to determine whether they can be added back into the system while still maintaining a positive system net benefit. In this case, one of the previously excluded customers can be re-incorporated, yielding a annual system net benefit greater than zero ($35K), but less than the annual system net benefit of Fig. 17(c). This configuration supplies 2670 m^3/day to 183 reclaimed water customers and excludes 8 customers whose total demand is 60 m^3/day (Fig. 17(d)). Table S3 provides the detailed IRIPT output for each configuration of Fig. 17.

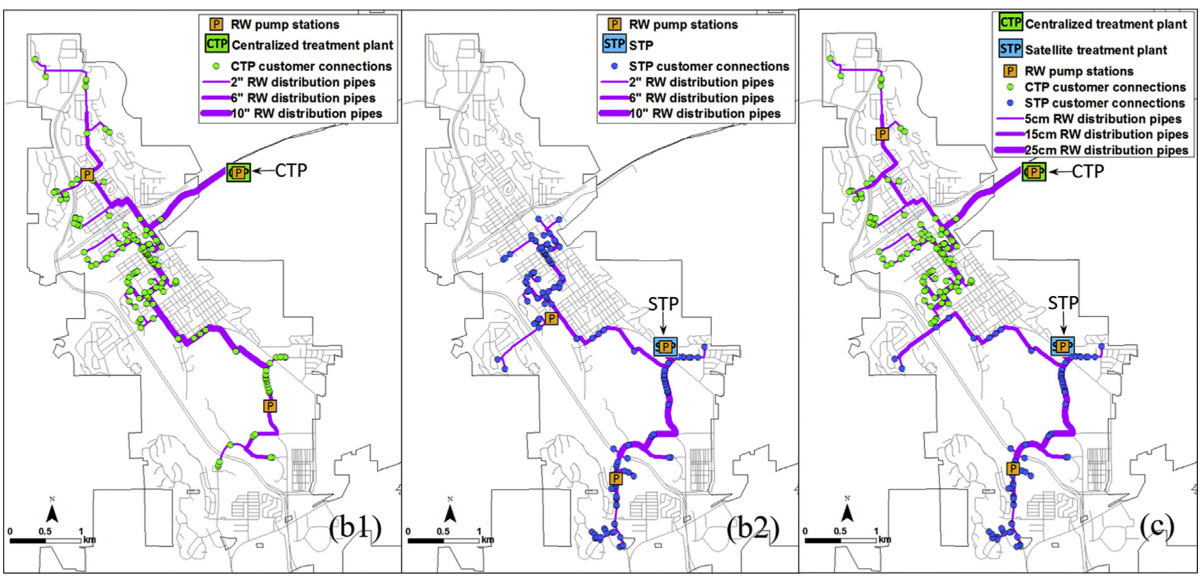
After generating the optimal configuration for Case 2, IRIPT proceeds to Case 3 by trimming customers until no customers remain and selects the centralized configuration that has the largest system net benefit. IRIPT also checks to determine whether customers should be added back in. Fig. 18 is the configuration that maximizes the system net benefit.

Figs. 19–21 illustrate hybrid water reuse configurations identified by IRIPT. In addition to the assumptions implemented for the centralized configuration, we assume that 10% of the current wastewater volume charge is paid to the CTP for diversion of wastewater to an STP.

Beginning with a set of potential STP and sewer capture locations (Fig. 16) and a database of locations and reclaimed water demands for all potential customers, IRIPT creates non-overlapping



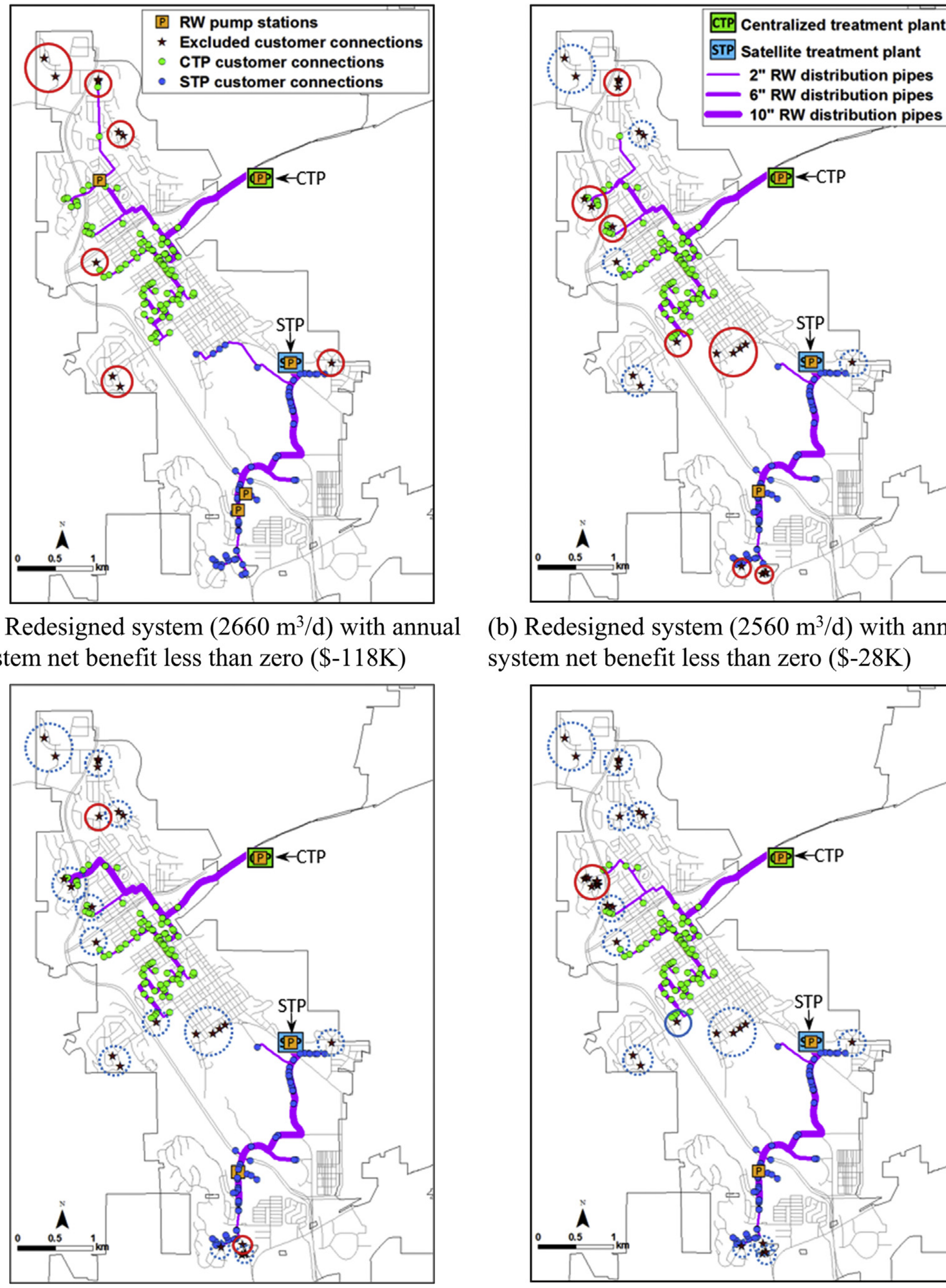
(a) Step 1: each treatment plant is initially matched to all possible customers (a1, a2, and a3).



(b) Step 2: Customers with negative unit net benefits for all of the treatment plant locations (a1, a2, and a3) are assigned to the treatment plant with the least negative unit net benefit and the customers with positive unit net benefits for one or more of the treatment plant locations are assigned to all the treatment plants with positive unit net benefits. IRIPT then automatically redesigns the system to enable new connections between each treatment plant and its prospective consumers.

(c) Step 3: For customers connected to more than one treatment plant (b1 and b2), unit net benefits ($\$/m^3$) are compared for each treatment plant, and each customer is assigned to the plant that results in the largest unit net benefit. IRIPT then redesigns the system yielding a non-overlapping CTP-STP hybrid configuration.

Fig. 19. Matching step for case 1 of the hybrid configuration showing how customers are assigned to groups served by a CTP and STP in order to supply reclaimed water to all customers.



(a) Redesigned system (2660 m³/d) with annual system net benefit less than zero ($-118K)

(b) Redesigned system (2560 m³/d) with annual system net benefit less than zero ($-28K)

(c) Redesigned system (2550 m³/d) with annual system net benefit less than zero ($-17K)

(d) Redesigned final system (2490 m³/d) with annual system net benefit greater than zero ($1K)

Fig. 20. IRIPT results for four hybrid configurations: (a)-(c) intermediate Case 2 configuration obtained by trimming, where the annual system net benefit remains negative; and (d) final Case 2 configuration after trimming, where the annual system net benefit is positive. Solid circles are customers newly excluded in every iteration and dotted circles are customers excluded in the previous iterations.

subsystems, which in combination serve all potential customers, i.e., maximizing reclaimed water supply for the available wastewater. Fig. 19(a) shows the set of water reuse configurations resulting from the assumption that each treatment plant (CTP or STP) serves all potential customers in the system. Fig. 19(b) then illustrates the redesigned system, where customers with negative unit net benefits for all of the treatment plant locations (a1, a2, and a3) are assigned to the treatment plant with the least negative unit net benefit, and the customers with positive unit net benefits for one or more of the treatment plant locations are assigned to all the treatment plants with positive unit net benefits. In this process, the STP in Fig. 19(a2) is excluded because it has insufficient reclaimed water flow (i.e., less than the BRWF). Fig. 19(c) shows the non-overlapping configuration of STP- and CTP- customers where each treatment plant serves the customers with the largest unit net benefits. This configuration serves all potential customers given the wastewater flow available for diversion to STPs. If the total demand of the customers assigned to an STP (Fig. 19(b2)) exceeds the

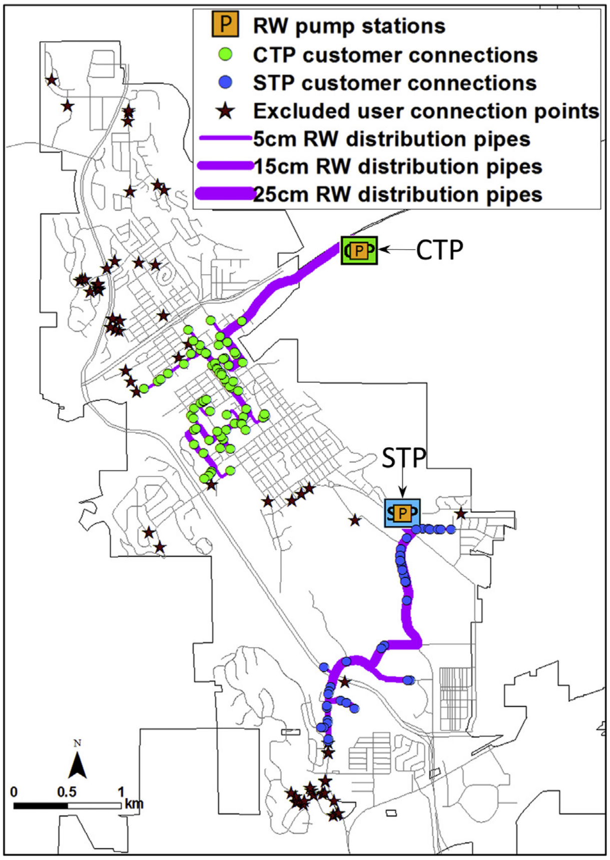


Fig. 21. The hybrid configuration with the maximum system net benefit.

capacity of the STP, customers initially assigned to the STP are reassigned to the CTP starting with the customer with the shortest pipeline distance to the CTP. This re-assignment ensures that the demand at the STP is less than its capacity and results in a separation of service areas for the CTP and STP (Fig. 19(c)).

Additional iterations are next used to trim the non-overlapping service areas to ensure positive net benefits for the system while maximizing water delivery to customers. Fig. 20 illustrates how IRIPT uses additional iterations to trim customers and to identify the optimal hybrid water reuse configuration. Beginning with the configuration from Fig. 19(c), IRIPT trims the network through seven more iterations, removing customers with the lowest unit net benefits, and ultimately enabling maximizing reclaimed water use and ensuring a positive system net benefit (a checking step is not required in this case because the final iteration excludes one customer). Fig. 20(a)-(d) illustrate three intermediate configurations (a-c) and the final configuration (d) from these further iterations. Isolated customers located far from the source of reclaimed water are excluded, as are low-demand customers located at or near the end of a pipeline and far from a treatment plant. The net result is an increase in the annual system net benefit from −$165K (Fig. 19(c)) to +$1K (Fig. 20(d)). Details of the changes in system configuration during the trimming process are summarized in Table S4.

After generating the optimal configuration for Case 2, IRIPT proceeds to Case 3 by trimming customers until no customers remain and selects the hybrid configuration that has the largest system net benefit. IRIPT also checks to determine whether customers should be added back in. Fig. 21 is the configuration that maximizes the system net benefit.

5.2.8. Performance metrics for each configuration

Table 4 summarizes performance metrics for six configurations, three for a centralized and three for a hybrid system, where the objectives are to: (1) maximize reclaimed water supply; (2) maximize reclaimed water supply while ensuring a positive system net benefit; and (3) maximize system net benefit. Values of the performance metrics in Table 4 are readily understood, but the low O&M cost for the centralized configuration needs explanation. These low costs are due to the fact that system net benefits are computed for the owner of the reclaimed water facility, which, in this case, is the City of Golden. Because the City of Golden does not own and operate the CTP, O&M costs to the city for CTP treatment are zero, but the costs of O&M for the reclaimed water distribution system are not zero. Expansion of the CTP could potentially incur O&M costs for Golden, if needed to meet water quality standards. However, in this case this is not required.

5.2.9. Ranking of alternatives

Implementing the MCDA algorithm described earlier, the centralized configuration shown in Fig. 18 receives the highest rank (Table 4). This is primarily because of the high weighting of the System Net Benefit criterion, where it scores highest in terms of performance, and also because of its relatively low investment and O&M costs and low Annual Energy Requirement. The three hybrid configurations ranked lower than the three centralized configurations. This was because of the poor performance of the hybrid system with respect to O&M Costs and Annual Energy requirements.

5.2.10. Sensitivity analyses

To assess the relative importance of unit prices of reclaimed water, subsidy rates, and CTP compensation for lower wastewater revenues due to the diversion and treatment of wastewater at STPs, we carried out a sensitivity analysis in which we varied each of these factors one at a time and evaluated the resulting changes in relative ranking of alternative configurations. The results are summarized in section S5 of the SM.

6. Results and discussion

For the City of Golden case study, IRIPT shows that, under a set of realistic assumptions, a centralized configuration is preferred over a hybrid configuration. The results also suggest why a centralized configuration may be a better choice for Golden—the localization advantages of a satellite system are diminished because Golden is a relatively small city, and the distance from the CTP to the farthest water reuse locations is only 3–4 km. This factor affects the pipe length requirements and energy for pumping. For hybrid configurations, this results in pipe costs that are not sufficiently low to offset the costs of multiple treatment plants.

The case study also demonstrates that IRIPT can automatically generate water reuse configurations using user-specified site-specific data that are commonly available for urban populations. The reasons why a certain configuration may be preferred over another are made transparent to the toolkit user. The short turn-around time for analysis of different configurations allows on-the-fly adjustments of input data, enabling the toolkit user to explore the consequences of such changes. Also, calculation of the breakeven reclaimed water price at each iteration enables toolkit users to understand how water pricing impacts the size of the system and number of reclaimed water consumers.

The tools developed through this research have produced reasonable results and useful insights for reclaimed water infrastructure planning, but obtaining input data in a digitized format is a significant challenge. Our experience shows that some

Table 4
Performance data for centralized and hybrid configurations (see definitions in Table 2).

Configuration		Investment Cost ($ x10^6)	O&M Cost ($ x10^6)	System Revenue ($ x10^6)	System Net Benefit ($ x10^6)	Annual Energy Requirement (MWh/yr)	Resilience to Water Stress (%)	Rank
Centralized water reuse	[a] Fig. 17(a)	17.4	0.6	16.0	−2.0	262	28.0	3
	[b] Fig. 17(d)	14.4	0.6	15.7	0.7	252	27.4	2
	[c] Fig. 18	9.7	0.5	13.7	3.5	216	23.9	1
Hybrid water reuse	[a] Fig. 19(c)	18.8	4.4	20.1	−3.1	552	28.0	6
	[b] Fig. 20(d)	13.7	4.1	18.3	0.5	499	25.5	5
	[c] Fig. 21	10.9	3.9	16.3	1.5	425	22.8	4
Weights		6	6	3	8	7	8	

[a] Configuration to maximize reclaimed water supply.
[b] Configuration to maximize reclaimed water supply while also providing a positive system net benefit.
[c] Configuration to maximize system net benefit.

assumptions may be needed in the absence of data. In the case of Golden, for example, the limited number of sewer flow meters within the sewer system made it necessary for us to use potable water usage data as a surrogate for wastewater flows.

7. Conclusion

- An integrated decision support toolkit, IRIPT, developed for planning of water reuse infrastructure, supports a diverse range of design functions, including siting of STPs and associated wastewater diversions, optimal pipeline routing and sizing, selection of wastewater treatment processes, and calculation of fees, revenues, subsidies, and potential savings for customers.
- IRIPT identifies centralized and hybrid water reuse configurations that meet three potential planning objectives: (1) maximizing reclaimed water supply; (2) maximizing reclaimed water supply while ensuring a positive system net benefit; and (3) maximizing system net benefit. The resulting configurations include critical design details that satisfy diverse technological, environmental, social, and economic constraints. The toolkit also ranks configurations using multiple criteria and input from decision-makers.
- We expect that the IPIPT toolkit will give decision-makers the ability to analyze many configurations across a wide range of scales, facilitating more transparent decisions, engaging stakeholders, and increasing chances of socially acceptable and equitable solutions that satisfy many needs simultaneously.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.watres.2018.01.037.

Abbreviations

BRWF	Breakeven reclaimed water flowrate
CalcBenefit	Calculator of fees, revenues, and subsidies
DST	Decision support tool
IRIPT	Integrated Urban Reclaimed Water Infrastructure Planning Toolkit
LocSTP	Locator for satellite treatment plants and associated wastewater diversions
MCDA	Multi-criteria decision analysis
PRODOT	Pipeline ROuting and Design Optimization Tool
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
SANNA	System for ANalysis of Alternatives
SelWTP	Selector for wastewater preatment process
STP	Satellite treatment plants

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