

# A system dynamics approach for urban water reuse planning: a case study from the Great Lakes region

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**Abstract** Water reclamation and reuse practices are recently receiving growing attention due to increasing water scarcity, concerns about the effect of wastewater discharges on receiving water, and availability of high-performing and cost-effective water reuse technologies. However, incorporation of water reuse schemes into water/wastewater infrastructure systems is a complex decision making process, involving various economical, technological, and environmental criteria. System dynamics (SD) allows modeling of complex systems and provides information about the temporal and feedback behavior of the system. In this sense, a SD model of the existing water/wastewater system in

Kalamazoo-Michigan, an urban area in the Great Lakes region, was created with the hypothetical incorporation of water reuse. The model simulates and optimizes the overall water system cost (including water, wastewater and water reuse components), accounting for future scenarios of population, economic growth and climate change. Results indicate significant levels of water reuse after an infrastructure build delay. The model also indicates that a decision to implement water reuse yields remarkably lower water withdrawals and lower water treatment costs even in a location with a relatively abundant water supply like Kalamazoo. This study emphasizes the fact that a true understanding of the practice of water reuse cannot be achieved without taking regional and climatic parameters into account.

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## 1 Introduction

Water scarcity defined as imbalance between water availability and demand is becoming a major challenge for many jurisdictions around the globe (UNESCO 2009). Increasing population along with land-use and climatic changes will steadily deteriorate the quantity and quality of the earth's fresh water resources (Zimmerman et al. 2008). Although there have been substantial developments in increasing access to fresh water resources through technology innovation and more effective water resources management, higher global living standards combined with population growth still threaten the sustainability of water resources and ecosystems. Moreover, climate change presents another threat to global water sustainability by

disturbing precipitation patterns and increasing evapotranspiration. Currently, one-third of the world's population is affected by water scarcity (UNESCO 2009).

To minimize water scarcity, a series of measures have been pursued to reduce water demand and/or increase water supply capacities. Desalination and water conservation and reuse are the most common approaches. Currently global desalination capacity is 12 billion gallons of water per day with an expected global growth of 120 % by 2016 (Kranhold 2008; GWI 2009). Unfortunately, desalination is a process that is energy-intensive and expensive, with potential adverse environmental impacts through the release of brine to marine habitats and receiving waters. These challenges have persuaded many locations to invest in water conservation and reuse programs, with an emphasis on wastewater reclamation (Exall et al. 2004; GWI 2009).

Water reuse is associated with several benefits. Reclaimed water can be used in agricultural and landscape irrigation, industrial processes, groundwater recharge, and for recreational purposes, thereby preserving valuable fresh water resources for potable applications. Water reuse is also associated with materials and energy recovery, and the reduction of life-cycle carbon emissions in the water supply process (Strutt et al. 2008; Guest et al. 2009; Leewongtanawit and Kim 2009; Mo et al. 2010; Li and Huang 2011). As a result of these benefits and increasing public awareness, there is a growing demand for reclaimed water to address two primary challenges: (1) increasing urban water scarcity (leading to water-reusing markets), and (2) decreasing water quality as a result of wastewater discharge. Also, in the past decade, high-grade water reclamation technologies such as ultra-filtration, reverse osmosis, and ultraviolet disinfection have become more economically favorable and more effective (Asano et al. 2007). It is expected that water reuse capacities increase globally with an expected growth of 180 % by 2016 (GWI 2009).

To address issues related to water reclamation and reuse, a wide range of studies have been carried out in recent years. These issues include financing of water reuse projects (Starkl et al. 2009); reclaimed water pricing (Cuthbert and Hajnosz 1999); risk, performance and environmental impact assessment (Nilsson and Bergstrom 1995; Balkema et al. 2002; Benedetti et al. 2008); water reclamation and reuse infrastructure design and planning (De Melo and Cfimara 1994; Jodicke et al. 2001); choice of treatment system such as on-site, central plant, clustering, and use of natural or constructed wetlands (Orona et al. 1999; Verhoeven, and Meuleman 1999; Chung et al. 2008); choice of treatment technology in wastewater treatment plants (with aerobic, activated sludge, filtering, and disinfection processes) and optimal control of treatment operations (Lessard and Beck 1991; Andrews 1994; Alvarez-Vazquez et al. 2008); and water reuse and wastewater treatment

locations analysis and capacity planning (Vasiloglou et al. 2008; Almasri and McNeill 2009).

The multitude of information presented in the above studies suggests that water reclamation and reuse decision making, within an integrated water resources management framework, is a complex process comprised of societal, technological, economical and environmental criteria (Li et al. 2009; Liu and Tong 2011; Deviney et al. 2012). This approach is linked to water quantity, quality and pricing aspects with benefits ranging from water conservation to energy and material efficiency. This highlights the importance of adopting a more comprehensive approach to analyze water reuse planning and management. The approach of system dynamics (SD) modeling offers advantages in understanding and addressing nonlinear behavior of socio-economic-environmental systems and assessing policy implications with controls, feedbacks, and delays in built systems (Khan et al. 2009; Winz et al. 2009). As a component of urban water systems, water reuse, however, has rarely been included in any SD research (Chung et al. 2008; Li and Huang 2012).

As such, a SD framework is applied to model and analyze water reclamation and reuse decisions considering future scenarios of population, economic growth, and climate change. This study aims to capture the influence of various drivers (such as population, climate, water price, and system cost) on water reuse as well as the (feedback) impacts of water reclamation and reuse decisions on some of these drivers. It emphasizes the fact that a true understanding of water reuse practice cannot be achieved without incorporating regional and climatic parameters.

The paper is structured as follows. First, we explore the rationale behind SD modeling and how an SD model is formulated. We introduce the equations governing a water reclamation and reuse decision problem as implemented in an SD framework. This paves the path to present the model as a whole, with its parameters, decision variables, scenario elements, and their interrelationships. The applicability and usefulness of the proposed approach is then investigated through a case study in Kalamazoo County, Michigan, an urban area served by a public water system. This is followed by Sect. 3 to discuss the findings and to perform a sensitivity analysis. We will conclude by highlighting the advantages of the proposed model with indication of future research avenues to address the limitations of this study.

## 2 SD approach

### 2.1 Problem definition

SD is a modeling approach emphasizing controls, feedbacks, and delays that has been used for analyzing and

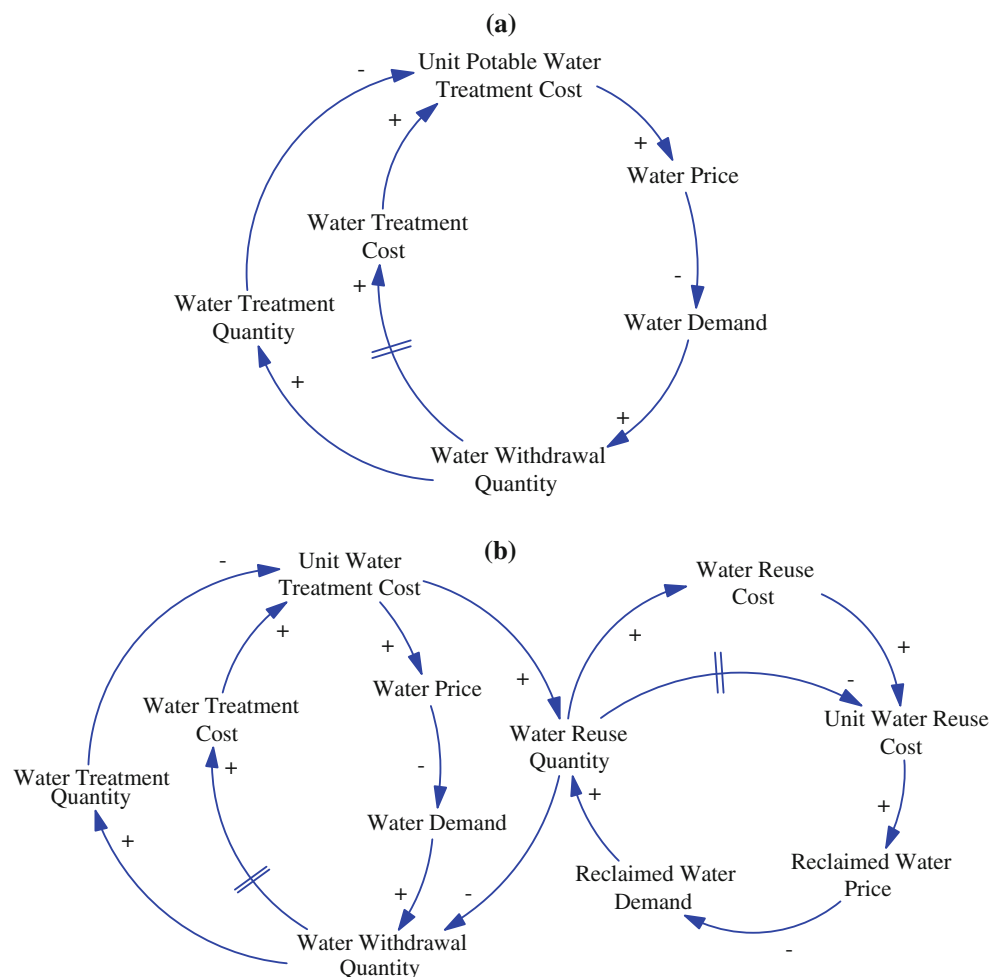
simulating the behavior of complex problems with a focus on policy analysis and design (Khan et al. 2009; Huang and Cao 2011). Causal loop diagrams (CLDs), as the foundation of SD models, are used to identify the relationships between individual system components and to depict feedback loops that affect system regulation. Feedback loops can either be reinforcing or balancing depending on the relationships between the variables constituting the loop.

The CLDs in Fig. 1 represent the critical component differences of a water reclamation-reuse system as compared to conventional water/wastewater infrastructure. Common CLD notation applies where a “+” sign indicates a reinforcing relationship between two variables. An increase in the arrow tail variable causes an increase in the arrow head variable. A “-” sign indicates a balancing relationship between two variables. An increase in the arrow tail variable causes a decrease in the arrow head variable. The double hash mark indicates a time delay in the cause and effect relationship between two variables.

Figure 1a depicts a CLD of the water demand-water treatment system without water reuse. This system consists of two causal (feedback) loops, as two pathways drive the

Unit Potable Water Treatment Cost. If Water Withdrawal Quantity increases, the Water Treatment Cost increases which leads to an increase in the Unit Potable Water Treatment Cost. A delay is depicted between Water Withdrawal Quantity and Water Treatment Cost to represent the time required to increase capacity/capital to manage the higher levels of water withdrawal. On the other hand, increased Water Withdrawal Quantity requires an increase in Water Treatment Quantity. Economies of scale dictate that this increased quantity drives down the Unit Potable Water Treatment Cost. Thus the pathway through Water Treatment Cost tends to increase the Unit Potable Water Treatment Cost, while the pathway through Water Treatment Quantity tends to decrease the Unit Potable Water Treatment Cost. In this way, the loop through water treatment quantity is reinforcing and the loop through water treatment cost is balancing. The Unit Potable Water Treatment Cost drives the (consumer) Water Price that in turn influences the total Water Demand. In the model without water reuse, the total Water Demand alone drives the Water Withdrawal Quantity since water demand can only be satisfied by withdrawals from ground or surface water.

**Fig. 1** A CLD of critical system components for a water supply system **a** without water reuse, **b** with water reuse



Now, consider the water system with a water reuse process (Fig. 1b). In this case, Water Withdrawal Quantity is influenced by Water Reuse Quantity in addition to the total Water Demand. In other words, the total Water Demand can now be partially satisfied (assuming non-potable applications) by reclaimed water:

$$\text{Water withdrawal quantity} = \text{total water demand} - \text{water reuse quantity}.$$

Thus, if water reuse is introduced to the system, the water withdrawal quantity decreases. Similar to the Water Treatment and Water Treatment Cost pathways described above, the Unit Water Reuse Cost is driven by Water Reuse Quantity via two pathways. Firstly, Water Reuse Quantity tends to increase the Water Reuse Cost since more water needs to be reclaimed and capacity needs to be increased. Secondly, the increase in Water Reuse Quantity itself tends to decrease the Unit Water Reuse Cost due to economies of scale. In general, the Unit Water Reuse Cost directly affects the Reclaimed Water Price (set by the utilities), which will drive the Reclaimed Water Demand. The Reclaimed Water Demand (which represents the influence from the demand side) and the Unit Water Treatment Cost (which represents the influence from the supply side) will drive the rates of water reuse.

A total of six feedback loops are created by the addition of the water reuse process. Two loops are related to the water reuse component of the model; a balancing loop through water reuse cost and a reinforcing loop along the pathway from Water Reuse Quantity to Unit Water Reuse Cost. Additionally, two loops are created by the interaction of water reuse with the typical water supply system. A balancing loop is created from Water Reuse Quantity to Water Withdrawal Quantity through Water Treatment Cost. A reinforcing loop is created from Water Reuse Quantity to Water Withdrawal Quantity through Water Treatment Quantity.

### 2.2 Equations

To implement water reuse schemes, reclamation capacities are to be created on the basis of demand for recycled water, the associated costs, and pricing mechanism. Water reuse costs are associated with the need for increased treatment and secondary distribution. In this sense, if the reclaimed water price is set based on associated costs, it is expected to be priced higher than the potable water (AWWA 2008). Thus, to encourage consumers to use more reclaimed water, the price is usually set much lower, taking into account the indirect savings and benefits associated with water reuse (i.e. a decreased cost of water treatment, water efficiency, etc.) (AWWA 2008). The cost recovery is also an issue when it comes to water/reclaimed water pricing, as the water/reclaimed water selling revenue is usually not enough to compensate all

treatment-supply costs, and utilities need to rely on municipal, regional, or federal subsidies (AWWA 2008).

In this sense, a cost-minimizing public water utility has to decide on water and reclaimed water prices (often expressed as a ratio), while also setting a target on the reclaimed water quantity. In doing so, the utility is looking for the optimal cost compromise between treatment and reuse options. Increasing water reuse capacities decreases water withdrawal, which, in turn, reduces (potable) water treatment costs. This solution can be identified through an optimization model, which determines reclaimed water quantities and prices that correspond to a minimum total cost of water supply.

The optimal solution to water/reclaimed water system capacities and pricing is a minimum overall net present cost:

$$\text{Minimize } \pi = \int_{t_0}^T \beta(t) \cdot [c_w(t) + c_r(t)] dt \tag{1}$$

where  $\pi$  is the net present total cost of water treatment-reuse system (\$1,000),  $T$  is the planning scope (year),  $t_0$  is the initial time (year),  $c_w(t)$  is the water treatment cost at year ‘ $t$ ’ (\$1,000/year),  $c_r(t)$  is the water reuse cost at year ‘ $t$ ’ (\$1,000/year),  $\beta(t)$  is the Discount factor for year ‘ $t$ ’ (where  $\beta(t) = \frac{1}{(1+i_n)^t}$ , for an average nominal interest rate of  $i_n$ ).

By introducing all cost elements as functions of time, we can capture periodical variations in capital and operational costs due to creation of new capacities or degradation of the existing ones. Water treatment cost ( $c_w(t)$ ) is the sum of associated capital, operational and overload (to meet excess demand with external sources) costs. It is a function of created capacities and quantity of treated water. Water reuse cost ( $c_r(t)$ ) is the sum of water reuse capital (capacity building) and operational (pumping, transport, etc.) costs, which are functions of water reuse capacity and reclaimed water quantity, respectively. In this sense, we have:

$$c_w(t) = C_w^{(C)}(t) \cdot I_w(t) + C_w^{(O)}(t) \cdot x_w(t) + C_w^{(L)}(t) \cdot L_w(t) \tag{2}$$

$$c_r(t) = C_r^{(C)}(t) \cdot I_r(t) + C_r^{(O)}(t) \cdot x_r(t) \tag{3}$$

where  $C_w^{(C)}(t)$  is the unit capital cost of water treatment capacity development at year ‘ $t$ ’ (\$1,000/million gallons),  $I_w(t)$  is the water treatment capacity added at year ‘ $t$ ’ (million gallons/year),  $C_w^{(O)}(t)$  is the unit operation cost of water treatment at year ‘ $t$ ’ (\$1,000/million gallons),  $x_w(t)$  is the quantity of water treated at year ‘ $t$ ’ (million gallons/year),  $C_w^{(L)}(t)$  is the unit water treatment overload cost at year ‘ $t$ ’ (\$1,000/million gallons),  $L_w(t)$  is the quantity of water treatment overload at year ‘ $t$ ’ (million gallons/year),  $C_r^{(C)}(t)$  is the unit capital cost of water reuse applications capacity development at year ‘ $t$ ’ (\$1,000/million gallons),

$I_r(t)$  is the water reuse applications capacity added at year ‘ $t$ ’ (million gallons/year),  $C_r^{(O)}(t)$  is the unit operation cost of water reuse applications at year ‘ $t$ ’ (\$1,000/million gallons),  $x_r(t)$  is the quantity of water reused at year ‘ $t$ ’ (million gallons/year), for  $C_w^{(C)}(t) = C_w^{(C)}(t_0)(1 + i_p)^t$ ;  $C_w^{(O)}(t) = C_w^{(O)}(t_0)(1 + i_p)^t$ ;  $C_w^{(L)}(t) = C_w^{(L)}(t_0)(1 + i_p)^t$ ;  $C_r^{(C)}(t) = C_r^{(C)}(t_0)(1 + i_p)^t$ ;  $C_r^{(O)}(t) = C_r^{(O)}(t_0)(1 + i_p)^t$ ; where  $i_p$  is the average inflation rate.

Assuming that there is an obligation to treat all received wastewater regardless of the source (fresh or reclaimed), the ongoing cost of the wastewater treatment system does not influence the decision regarding the quantity of reclaimed water applications and water/water reuse cost recovery ratios. Thus, these ongoing costs are excluded from  $\pi$ . Minimizing (1) identifies the optimal tradeoff between (potable) water treatment costs (which decreases as a result of water reuse) and water reuse (application) costs (comprised of non-potable treatment and redistribution costs). In doing so, water treatment and reuse quantity and capacity levels (i.e.  $I_w(t)$ ,  $x_w(t)$ ,  $L_w(t)$ ,  $I_r(t)$ , and  $x_r(t)$ ) are determined through (4)–(8):

$$I_w(t) = \text{Max}\{[e(t) \cdot (1 + \mu_w) - X_w(t)]/T_w, s_w(t)\} \tag{4}$$

(i.e. the water treatment capacity is developed to meet the increasing demand for water withdrawals and to offset the capacity depreciations)

$$x_w(t) = \text{Min}\{X_w(t), e(t)\} \tag{5}$$

(i.e. the actual water treatment quantity is constrained by water treatment capacities and has to meet water withdrawal needs)

$$L_w(t) = e(t) - x_w(t) \tag{6}$$

(i.e. water treatment overload occurs when water withdrawal exceeds water treatment, and the excess demand is met through the excess treatment capacities of other suppliers in the region) where  $e(t)$  is the water extraction at year ‘ $t$ ’ (million gallons/year),  $\mu_w$  is the water treatment capacity reserve ratio,  $X_w(t)$  is the water treatment capacity at year ‘ $t$ ’ (million gallons),  $T_w$  is the water treatment capacity development delay (year),  $s_w(t)$  is the water treatment capacity retired/depreciated at year ‘ $t$ ’ (million gallons/year),

and

$$I_r(t) = \text{Max}\{[\alpha \cdot x_{ww}(t) - X_r(t)]/T_r, s_r(t)\} \tag{7}$$

(i.e. water reuse capacity is developed to maintain the water reclamation capacities in line with an optimally-targeted share of wastewater quantity, and to also offset capacity depreciations)

$$x_r(t) = \text{Min}\{x_{ww}(t), X_r(t), r(t)\} \tag{8}$$

(i.e. water reuse is constrained by reclaimed water demand and supply (wastewater treatment quantity) and water reuse capacity) where  $0 < \alpha \leq \alpha_{\text{max}}$  is the target water reuse quantity ratio (as a portion of total reclaimed water), which is a decision variable, where  $\alpha_{\text{max}}$  corresponds to the maximum (technically feasible) water reuse quantity (as percentage of wastewater quantity),  $x_{ww}(t)$  is the quantity of wastewater treated at year ‘ $t$ ’ (million gallons/year),  $X_r(t)$  is the water reuse applications capacity at year ‘ $t$ ’ (million gallons),  $T_r$  is the water reuse capacity development delay (year),  $s_r(t)$  is the water reuse applications capacity retired/depreciated at year ‘ $t$ ’ (million gallons/year),  $r(t)$  is the potential demand for reclaimed water (water reuse) at year ‘ $t$ ’ (million gallons/year).

The time-dependent elements used in (4)–(8) are identified as follows:

$$e(t) = d(t) - x_r(t) \tag{9}$$

(i.e. water reuse offsets parts of water demand and consequently reduces water withdrawals)

$$X_w(t) = X_w(t_0) + \int_{t_0}^t (I_w(t) - s_w(t))dt \tag{10}$$

(i.e. water treatment capacity increases when capacity developments exceed depreciations)

$$s_w(t) = s_w \cdot X_w(t) \tag{11}$$

(i.e. a fixed asset depreciation (degradation) rate is assumed for water treatment capacities)

$$x_{ww}(t) = \text{Min}\{X_{ww}(t), \omega(t) \cdot d(t)\} \tag{12}$$

(i.e. the actual wastewater treatment is constrained by total generated wastewater and wastewater treatment capacity)

$$X_r(t) = X_r(t_0) + \int_{t_0}^t (I_r(t) - s_r(t))dt \tag{13}$$

(i.e. water reuse capacity increases when capacity developments exceed periodic depreciations)

$$s_r(t) = s_r \cdot X_r(t) \tag{14}$$

(i.e. a fixed asset depreciation (degradation) rate is assumed for water reuse capacities)

$$r(t) = \text{Max}\left\{\gamma \cdot d(t) \cdot \left(1 - [p_r(t)/p_w(t)]^k\right), 0\right\} \tag{15}$$

(i.e. a continuous interpretation of reclaimed water demand-price relationship ( $r(t)$ ,  $p_r(t)$ ), with boundary points of  $(0, p_w(t))$  and  $(\gamma \cdot d(t), 0)$ , where  $\gamma$  is a cap ratio for reclaimed water demand taking into account the targeted uses of reclaimed water (excluding all potable water demands) and  $k$  is a price elasticity factor which captures

the responsiveness of reclaimed water demand to changes in reclaimed water price. Because of a public resistance to the idea of water reuse where consumers clearly have a cost-effective substitute, it is expected that  $k \leq 1$  (Dolnicar and Hurlimann 2010) where  $d(t)$  is the water demand at year ‘ $t$ ’ (million gallons/year),  $X_{ww}(t)$  is the wastewater treatment capacity at year ‘ $t$ ’ (million gallons),  $\omega(t)$  is the wastewater (generation) ratio at year ‘ $t$ ’,  $s_w$  is the average water treatment capacity retirement/depreciation rate (1/year),  $s_r$  is the average water reuse applications capacity retirement/depreciation rate (1/year),  $\gamma$  is the upper bound ratio for reclaimed water demand (i.e. a percentage of total water demand),  $p_r(t)$  is the average potable water price at year ‘ $t$ ’ (\$1,000/million gallons),  $p_w(t)$  is the average reclaimed water price at year ‘ $t$ ’ (\$1,000/million gallons),  $k$  is the reclaimed water price elasticity factor.

Wastewater treatment capacity  $X_{ww}(t)$ , which is used in Eq. 12 to identify actual wastewater treatment quantity, is also a stock variable that grows when capacity development exceeds depreciations:

$$X_{ww}(t) = X_{ww}(t_0) + \int_{t_0}^t (I_{ww}(t) - s_{ww}(t))dt \tag{16}$$

where  $I_{ww}(t)$  is the wastewater treatment capacity added at year ‘ $t$ ’ (million gallons/year),  $s_{ww}(t)$  is the wastewater treatment capacity retired/depreciated at year ‘ $t$ ’ (million gallons/year).

We calculate water demand using its per capita estimation:

$$d(t) = n(t) \cdot d^{(pc)}(t) \tag{17}$$

where  $n(t)$  is the population served by utility at year ‘ $t$ ’ (person),  $d^{(pc)}(t)$  is the per capita water demand at year ‘ $t$ ’ (million gallons/(person  $\times$  year))

The per capita water demand ( $d^{(pc)}(t)$ ) is estimated using the state-level per capita daily water demand regression model (Eq. 18) developed by US Geological Survey (2002) as follows:

$$d^{(pc)}(t) = \frac{365}{10^6} [107.173 - 4.726\bar{p}(t) + 2.43GSP^{(pc)}(t) - 1.299ASP(t) + 0.777AST(t)] \tag{18}$$

where  $\bar{p}(t)$  is the perceived water price at year ‘ $t$ ’ (\$1,000/million gallons) (i.e. the price consumers pay for water in average),  $GSP^{(pc)}(t)$  is the gross state product per capita at year ‘ $t$ ’ (\$1,000/person),  $ASP(t)$  is the average total summer (June–July–August) Precipitation at year ‘ $t$ ’ (in.),  $AST(t)$  is the average summer temperature at year ‘ $t$ ’ (Fahrenheit).

The numbers in the above regression equation are determined by US Geological Survey using data of the past

50 years for each US state. We have used the ones suggested for the state of Michigan (USGS 2002).

When consumers have a choice between water and reclaimed water, the perceived water price is computed as the medium of average water and reclaimed water prices:

$$\bar{p}(t) = \frac{\int_{t_0}^t e(t)dt}{\int_{t_0}^t d(t)dt} \cdot p_w(t) + \frac{\int_{t_0}^t x_r(t)dt}{\int_{t_0}^t d(t)dt} \cdot p_r(t) \tag{19}$$

With average water and reclaimed water prices calculated in line with the associated costs:

$$p_w(t) = \lambda_w \cdot (\bar{C}_w(t) + \bar{C}_{ww}(t)) \tag{20}$$

$$p_r(t) = \lambda_r \cdot (\bar{C}_r(t) + \bar{C}_{ww}(t)) \tag{21}$$

(i.e. in public water/reclaimed water systems, the price partially recovers the associated costs, and the uncovered portion of costs has to be compensated through municipal, regional and/or federal subsidies) where  $\lambda^{\min} \leq \lambda_w \leq 1$  is the water cost recovery ratio, which is a decision variable (with a minimum cost recovery target of  $\lambda^{\min}$ ),  $\lambda^{\min} \leq \lambda_r \leq 1$  is the water reuse cost recovery ratio, which is a decision variable (with a minimum cost recovery target of  $\lambda^{\min}$ ),  $\bar{C}_w(t)$  is the average-per-unit water system cost at year ‘ $t$ ’ (\$1,000/million gallons),  $\bar{C}_{ww}(t)$  is the average-per-unit wastewater system cost at year ‘ $t$ ’ (\$1,000/million gallons),  $\bar{C}_r(t)$  is the average-per-unit water reuse applications cost at year ‘ $t$ ’ (\$1,000/million gallons).

Development and depreciation of wastewater treatment capacity are directed by the following equations:

$$I_{ww}(t) = \text{Max}\{[\omega(t) \cdot d(t) \cdot (1 + \mu_{ww}) - X_{ww}(t)]/T_{ww}, s_{ww}(t)\} \tag{22}$$

(i.e. wastewater treatment capacity is developed to keep treatment capacities in balance with wastewater generation, and to offset capacity depreciations)

$$s_{ww}(t) = s_{ww} \cdot X_{ww}(t) \tag{23}$$

(i.e. a fixed asset depreciation (degradation) rate is assumed for wastewater treatment capacities) where  $\mu_{ww}$  is the wastewater treatment capacity reserve ratio,  $T_{ww}$  is the wastewater treatment capacity development delay (year),  $s_{ww}$  is the wastewater treatment capacity retirement/depreciation rate (1/year).

The average-per-unit costs used in (20) and (21) are computed as:

$$\bar{C}_w(t) = \frac{\int_{t_0}^t c_w(t)dt}{\int_{t_0}^t e(t)dt} \tag{24}$$

$$\bar{C}_{ww}(t) = \frac{\int_{t_0}^t c_{ww}(t)dt}{\int_{t_0}^t d(t)dt} \tag{25}$$

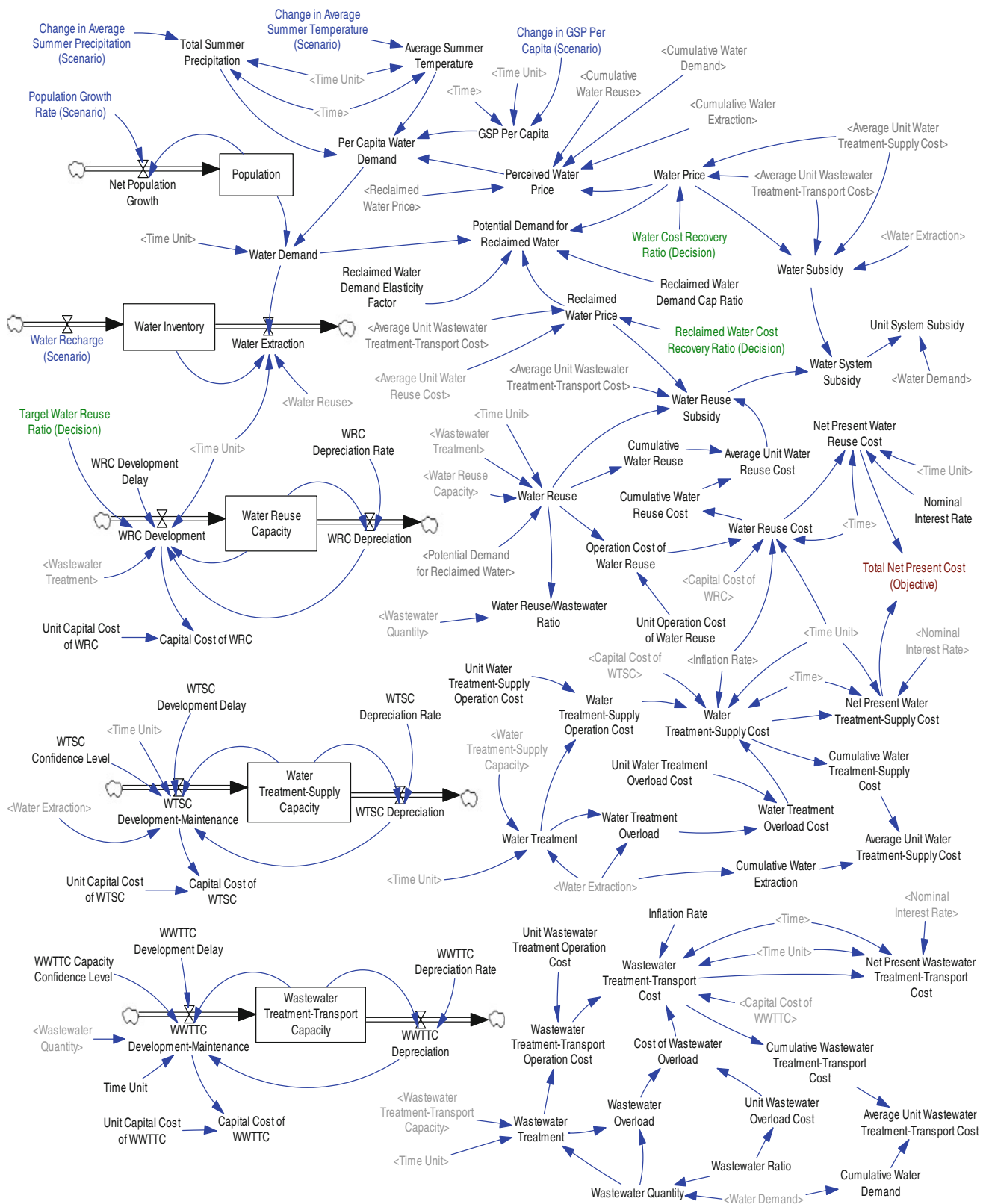
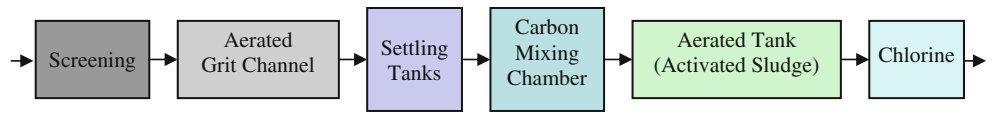


Fig. 2 Water reuse planning SD model

**Fig. 3** Kalamazoo wastewater treatment process



$$\bar{C}_r(t) = \frac{\int_{t_0}^t c_r(t) dt}{\int_{t_0}^t x_r(t) dt} \tag{26}$$

where  $c_{ww}(t)$  is the wastewater treatment cost at year ‘ $t$ ’ (\$1,000/year).

Wastewater treatment cost ( $c_{ww}(t)$ ) is comprised of capital (capacity building), operational (collection, process, etc.), and overload costs:

$$c_{ww}(t) = C_{ww}^{(C)}(t) \cdot I_{ww}(t) + C_{ww}^{(O)}(t) \cdot x_{ww}(t) + C_{ww}^{(L)}(t) \cdot L_{ww}(t) \tag{27}$$

where  $C_{ww}^{(C)}(t)$  is the unit capital cost of wastewater treatment capacity development at year ‘ $t$ ’ (\$1,000/million gallons),  $C_{ww}^{(O)}(t)$  is the unit operation cost of wastewater treatment at year ‘ $t$ ’ (\$1,000/million gallons),  $C_{ww}^{(L)}(t)$  is the unit wastewater treatment overload cost at year ‘ $t$ ’ (\$1,000/million gallons),  $L_{ww}(t)$  is the quantity of wastewater treatment overload at year ‘ $t$ ’ (million gallons/year)

and

$$L_{ww}(t) = \omega(t)d(t) - x_{ww}(t) \tag{28}$$

(i.e. wastewater treatment overload occurs when wastewater generation exceeds wastewater treatment, and the excess wastewater is treated through the excess treatment capacities of other wastewater treatment facilities in the region)

$$\text{for } C_{ww}^{(C)}(t) = C_{ww}^{(C)}(t_0)(1 + i_p)^t; \quad C_{ww}^{(O)}(t) = C_{ww}^{(O)}(t_0)(1 + i_p)^t; \quad C_{ww}^{(L)}(t) = C_{ww}^{(L)}(t_0)(1 + i_p)^t$$

Similar to average water/wastewater treatment costs, average water reuse application costs, and the associated prices of water and reclaimed water, the average amount of financial assistance required by water utility to compensate un-recovered costs can be estimated by:

$$\bar{y}(t) = \text{Max} \{ [\bar{C}_w(t) + \bar{C}_{ww}(t) - p_w(t)] \cdot e(t) + [\bar{C}_r(t) + \bar{C}_{ww}(t) - p_r(t)] \cdot x_r(t), 0 \} \tag{29}$$

where  $\bar{y}(t)$  is the average required financial assistance at year ‘ $t$ ’ (\$1,000/year)

This amount could be compensated either indirectly by municipalities and government (through subsidies) or directly through increased water/reclaimed water prices. In the second case, the utility will basically compute a “per unit water reuse charge” and incorporate it into water/reclaimed water prices as a tariff:

$$\bar{Y}(t) = \frac{\bar{y}(t)}{d(t)} \tag{30}$$

where  $\bar{Y}(t)$  is the per unit financial assistance required at year ‘ $t$ ’ (\$1,000//million gallons)

### 2.3 Model

Based on the CLDs (Fig. 1) and the above governing equations, a SD model (as shown in Fig. 2) using Vensim Professional simulation software (2010), which is equipped with optimization and sensitivity analysis capabilities, was developed. The performance of water/wastewater systems with a water reuse component is simulated to identify the optimal water/reclaimed water cost recovery ratios along with the optimal quantity targeted for water reuse applications (as a percentage of the total wastewater generated). These decision variables, along side water demand, drive the policies of water–wastewater treatment/water reuse capacity development for public water systems.

Estimating the per capita water demand, the model takes into account future variations in influencing climatic and economic factors such as temperature, precipitation, population, water recharge, and per capita GSP over the planning timescale. Pessimistic and optimistic scenarios are used to populate these parameters. Other techno-economic parameters to consider are interest rate, capital and operational costs, and depreciation rates (to account for maintenance and replacements). The state (or level) variables to monitor are population, inventory of water resources, and water/wastewater treatment-water reuse capacities.

Per capita water demand is forecasted by Eq. 18 using 2008 baseline population and water demand, as an indicator of current water treatment capacity and wastewater quantity. The wastewater quantity defines the maximum volume for reclaimed water applications. Having this upper bound in place (according to Eq. 8), the balance between potential water treatment savings and water reuse costs

**Table 1** Scenario elements and their optimistic and pessimistic growth rates

Scenario element	Annual growth	
	Optimistic	Pessimistic
Average summer temperature (%)	0.07	0.13
Average summer precipitation (%)	0.34	0.18
Per capita GSP (%)	−1.50	0.60
Population (%)	0.09	0.38
Groundwater inventory <sup>a</sup>	98,000	73,000

<sup>a</sup> Unit: million gallons/year

**Table 2** Parameters for Kalamazoo, Michigan case study SD simulation (in alphabetical order)

Parameter	Value	Unit
Current average total summer precipitation ( $ASP(t_0)$ )	11.33	Inches
Current average summer temperature ( $AST(t_0)$ )	69°	Fahrenheit
Current gross state product per capita ( $GSP^{(pc)}(t_0)$ )	32.612	\$1,000/person
Current population ( $n(t_0)$ )	248,407	Person
Current water reuse capacity ( $X_r(t_0)$ )	0	Million gallons
Current water treatment capacity ( $X_w(t_0)$ )	$55 \times 365 = 20,075$	Million gallons
Current wastewater treatment capacity ( $X_{ww}(t_0)$ )	$28 \times 365 = 10,220$	Million gallons
Initial time ( $t_0$ )	2008	–
Inflation rate ( $i_p$ )	0.012	–
Minimum cost recovery ratio ( $\lambda^{\min}$ )	100 %	–
Nominal interest rate ( $i_n$ )	0.05	–
Planning scope ( $T$ )	100	Year
Reclaimed water price elasticity factor ( $k$ )	1	–
Unit capital cost of water reuse capacity development ( $C_r^{(C)}(t_0)$ )	0.20	\$1,000/ Million gallons
Unit capital cost of water treatment capacity development ( $C_w^{(C)}(t_0)$ )	0.2259	\$1,000/ Million gallons
Unit capital cost of wastewater treatment capacity development ( $C_{ww}^{(C)}(t_0)$ )	0.2036	\$1,000/ Million gallons
Unit operation cost of water reuse ( $C_r^{(O)}(t_0)$ )	0.10	\$1,000/ Million gallons
Unit operation cost of water treatment ( $C_w^{(O)}(t_0)$ )	0.3502	\$1,000/ Million gallons
Unit operation cost of wastewater treatment ( $C_{ww}^{(O)}(t_0)$ )	1.3364	\$1,000/ Million gallons
Upper bound ratio for reclaimed water demand ( $\gamma$ )	80 %	–
Water reuse capacity development delay ( $T_r$ )	5	Year
Water reuse capacity retirement/ depreciation rate ( $s_r$ )	2 %	1/Year
Water treatment capacity development delay ( $T_w$ )	2	Year
Water treatment capacity reserve ratio ( $\mu_w$ )	10 %	–
Water treatment capacity retirement/depreciation rate ( $s_w$ )	2 %	1/Year

**Table 2** continued

Parameter	Value	Unit
Wastewater (generation) ratio ( $\omega(t)$ )	$28/55 = 0.5091$	–
Wastewater treatment capacity development delay ( $T_{ww}$ )	2	Year
Wastewater treatment capacity reserve ratio ( $\mu_{ww}$ )	10 %	–
Wastewater capacity retirement/ depreciation rate ( $s_{ww}$ )	10 %	1/Year

provides the optimal values for decision variables (water reuse quantity and cost recovery ratios) according to Eq. 1.

It should be mentioned that, in reality, treatment and reuse capacities are maintained with minor upgrades of pumps, valves, replacement of tanks, etc. to keep their capacity close to the design capacity, for quite a long time. But to do so, asset degradations should be compensated by new investments and maintenance. By considering three different depreciation rates for water, wastewater, and water reuse capacities in our model (Eqs. 11, 14, and 23), we are capturing various rates of degradations and the equivalent capacities that should be created to counter these degradations. This is not a capacity increase but rather a capacity balancing.

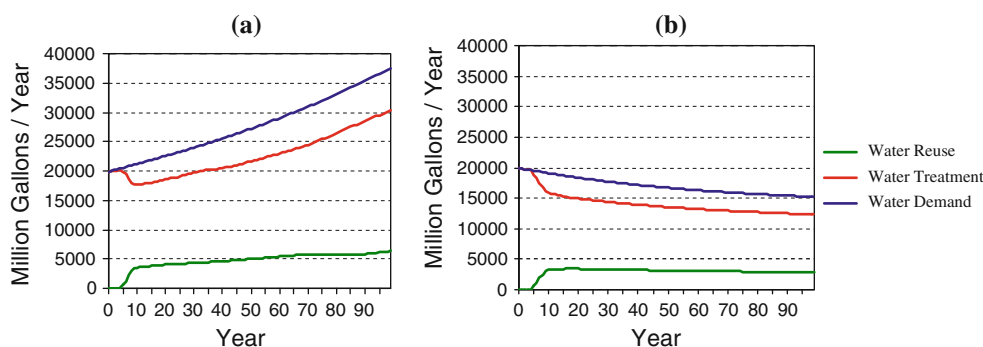
### 3 Case study

A small number of public water supply systems are identified as “very large” (serving greater than 100,000 people) and provide water to about 44 % of the population served by public water supply systems (EPA 2002). The Kalamazoo, Michigan public water supply system represents a “very large” water supply system in Great Lakes region. Kalamazoo County gets an average 34–36 in. of rain annually with groundwater recharge capacity estimated at 73–98 billion gallons per year (with approximately 65 % of rain lost through evapotranspiration and 10 % as run-off to surface water) (Kalamazoo 2011a). Given the scale and groundwater dependence, this public water supply system is used to investigate the optimal water reuse capabilities (from quantity and cost perspectives) with respect to population, climate, and economic development scenarios over the next 100 years (as climate scenarios are typically developed for 100 years).

The Kalamazoo public water supply system supplies about 55 million gallons per day while the Kalamazoo wastewater treatment system (2011a, b), operating at a 53 % hydraulic capacity, is currently receiving a flow of approximately 28 million gallons per day. The wastewater

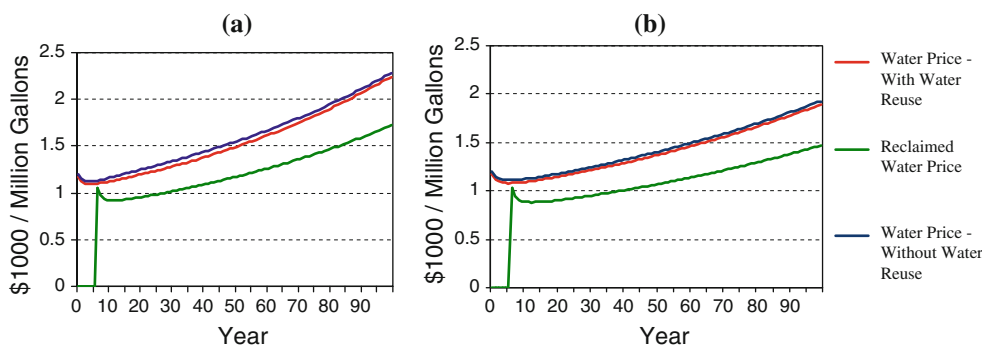
**Table 3** Decision variables and their scenario-based optimal values

Scenarios	Minimum cost recovery target (%)	Decision variables			Objective function
		Target water reuse quantity ratio, $\alpha^*$ (%)	Water cost recovery ratio, $\lambda_w^*$ (%)	Water reuse cost recovery ratio, $\lambda_r^*$ (%)	Net present total cost of water treatment-reuse per \$1,000 ( $\pi$ )
Pessimistic	100	39	100	100	217,200
	90	58	100	90	207,894
	80	91	100	80	199,810
	70	100	100	70	191,510
Optimistic	100	32	100	100	171,499
	90	53	100	90	166,090
	80	85	100	80	160,782
	70	100	100	70	155,397

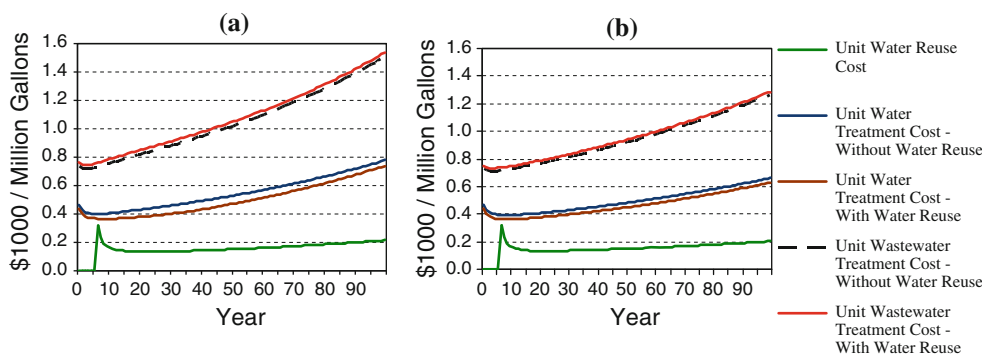


**Fig. 4** Water demand, treatment, and reuse quantities estimated for **a** pessimistic and **b** optimistic scenarios

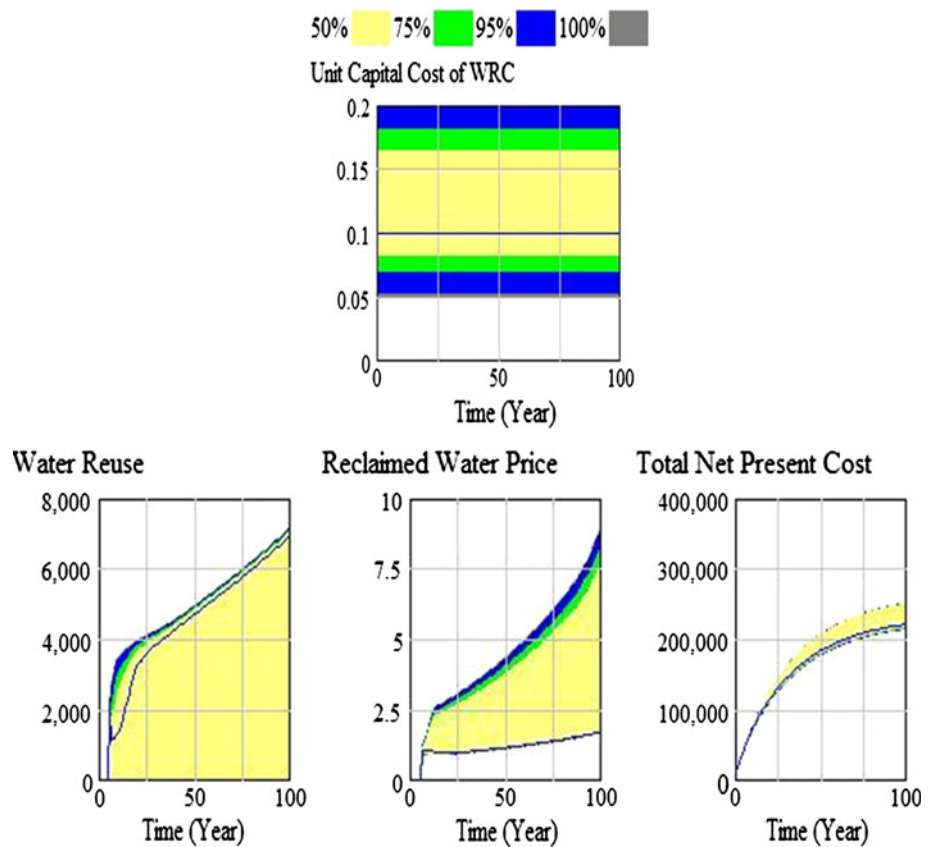
**Fig. 5** Water and reclaimed water prices estimated for **a** pessimistic and **b** optimistic scenarios



**Fig. 6** Unit water treatment, unit wastewater treatment, and unit water reuse costs estimated for **a** pessimistic and **b** optimistic scenarios



**Fig. 7** Sensitivity of water reuse quantities, prices, and total system cost to unit capital cost of water reuse (\$1,000/million gallons)



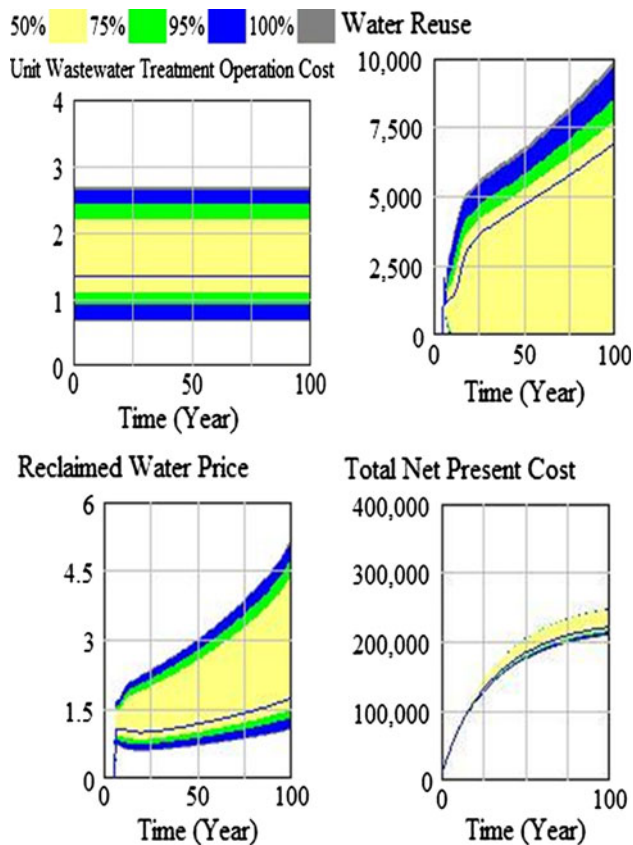
treatment plant uses an activated sludge (bugs) processing system, with a powdered activated carbon mechanism to protect the bugs from strong toxins and to help dissolved chemicals settle. Figure 3 is a representation of the process followed in Kalamazoo wastewater treatment plant (2011b).

Based on this baseline information and considering future scenarios of population growth, climatic change (in terms of temperature and precipitation) and economic growth (in terms of per capita GSP) as presented in Table 1 (Easterling and Karl 2001; NCSL 2008; BEA 2009; TWC 2011; USCB 2011), as well as capital and operational information (Kalamazoo 2008, 2009, 2010a, b, c), the parameters of the water reuse planning SD model for a 100-year simulation are presented in Table 2 (also see the Appendix section for further details about Vensim software command lines, initial values and settings).

The pessimistic and optimistic scenarios represent the boundaries that exist on forecasts for water resource associated parameters in Kalamazoo County over the next century. A pessimistic scenario, from a water resources perspective, is associated with the highest forecasts on population growth, economic development, and temperature rise (with reinforcing impacts on water demand) and the lowest predictions for precipitation. In an optimistic

scenario, the parameters are set to reflect the least pressure on water resources from both supply and demand perspectives. Table 3 presents the simulation results; minimizing “Total Net Present Water Treatment/Reuse Costs” with respect to “Target Water Reuse Ratio”, “Water Cost Recovery Ratio”, and “Reclaimed Water Cost Recovery Ratio”, as decision variables, for different minimum cost recovery targets. Figures 4, 5, and 6 show the optimal simulated trends of water reuse quantities, water/reclaimed water prices, and the associated unit costs for a full cost recovery target in both pessimistic and optimistic scenarios, respectively.

In summary, the results indicate a significant level of water reuse in Kalamazoo after an infrastructure build delay. Findings also reveal that a decision to implement water reuse can yield remarkably lower water withdrawals in Kalamazoo. In addition, recovering and reusing over a third of generated wastewater will pose almost no cost burden on this public water supply system and the costs are fully compensated by an equivalent reduction of water treatment and wastewater transport costs. In the following section, we will further explore and discuss these findings and will perform a sensitivity analysis to identify key influencing parameters in implementation of water reuse schemes in the study area.



**Fig. 8** Sensitivity of water reuse quantities, prices, and total system cost to unit operation cost of wastewater treatment (\$1,000/million gallons)

#### 4 Result analysis

Reviewing Table 3 and Figs. 4, 5, and 6 reveals a number of key findings. Water reuse capacity in Kalamazoo water system at a targeted level of 32–39 % can be achieved with a full cost recovery without increasing current prices. Also, under any cost recovery target, the system would be able to fully recover water treatment costs through water prices (unless the prices are constrained by an upper bound rather than unit cost). Water/reclaimed water prices in Fig. 5 (as a ratio of unit costs) include an annual inflation rate of 1.2 %. Given inflation, these prices (and unit costs) are actually decreasing over time. This is due to the fact that Eq. 1 ensures that capacities being optimally developed align with water treatment/reuse needs (increasing the productivity of capacities and thus reducing the unit water/reclaimed water treatment costs).

There is a clear trade-off between the amount of water reuse and minimum cost recovery target. Higher (than the above-mentioned) targets for water reuse require external financial assistance in the form of subsidies and/or tariffs because reclaimed water prices cannot fully recover the

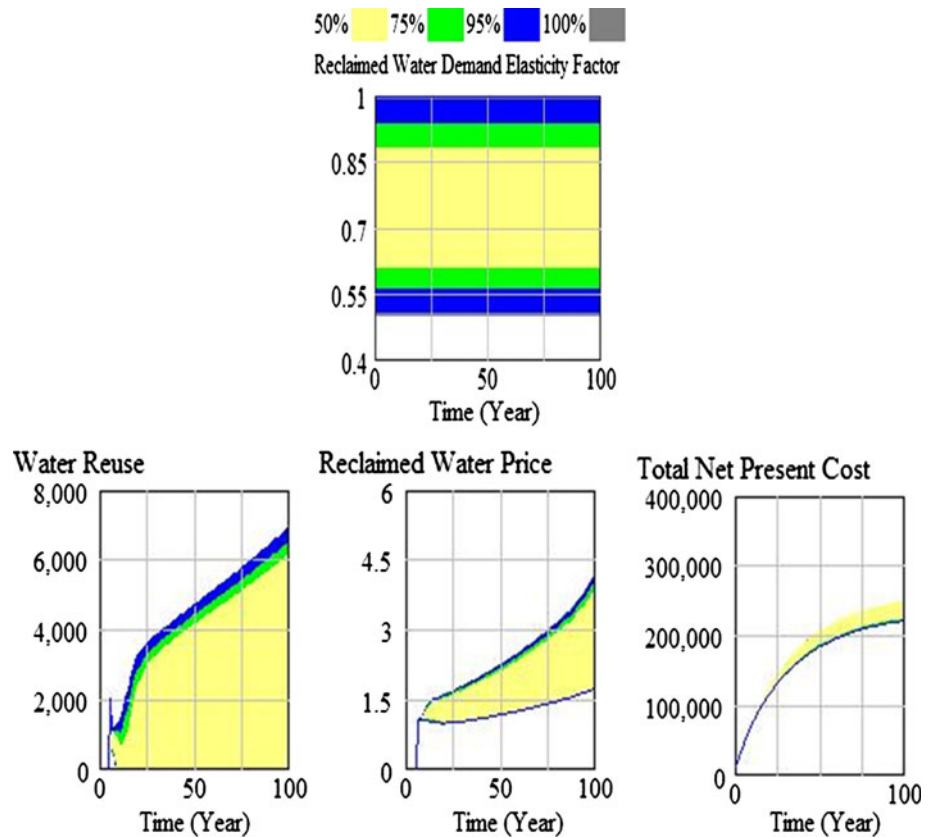
unit costs associated with water reclamation. This clearly reflects the feedback structure presented in Fig. 1b. Although an increase in reclaimed water quantities reduces water treatment costs, it increases reclaimed water treatment costs. In this sense, higher targets for water reuse lead to an overall increase in total cost of the system reducing its cost recovery capability. In an optimal setting, due to the cost advantage expressed in Eq. 1, water reuse capacities grow to a point where the sum of water reclamation capital and operational costs equals water treatment cost savings. At that point, a constant portion of water demand can be met with reclaimed water (as shown in Fig. 4).

A higher demand for water in a pessimistic scenario triggers a higher demand for reclaimed water compared with the optimistic scenario. This yields a higher overall system cost as more capacities for water reuse have to be built to meet this elevated demand. This consequently imposes higher prices for water/reclaimed water (Fig. 5), which in turn limits the demand for reclaimed water according to price-demand feedbacks captured in Fig. 1b. As revealed from Table 3, in an optimal (cost) setting, the reclaimed water prices are matching the minimum cost recoveries. This is due to the fact that the system is to achieve a minimum cost recovery (target) while maintaining a competitive price for reclaimed water.

To further analyze the above outcomes, we assess the sensitivity of the results obtained with respect to non-scenario parameters listed in Table 2 (rows 9–29). Utilizing Vensim software’s toolbox for sensitivity analysis, the values of these parameters were varied uniformly, within  $\pm 50\%$  of their model values (noting that from Eq. 15, we have “reclaimed water elasticity factor  $\leq 1$ ”). From this analysis, Unit Water Reuse Capital Cost (in \$1,000/million gallons), Unit Wastewater Treatment Operational Cost (in \$1,000/million gallons), and Reclaimed Water Price Elasticity Factor are identified as the most sensitive parameters of the model. Figures 7, 8, and 9 capture the impact of these sensitivities on recycled water quantity (in million gallons/Year), reclaimed water price (in \$1,000/million gallons), and net present water system cost (in \$1,000) for the pessimistic scenario, respectively. The analysis performed for various confidence levels, as shown in the first column of these figures, reveals that the sensitivities grow over time. This is a natural consequence of employing an objective function based on net present values. It is worth mentioning that the area under the sensitivity graphs could capture the extent of change while the share of yellow area (50 % confidence level) could represent the speed of change.

Decisions on reclaimed water quantity and price are more sensitive to water reuse capital costs (as shown in Fig. 7) than to operational costs. This is an expected outcome, considering the present value of these costs, as the capital costs are upfront costs, while operating costs are

**Fig. 9** Sensitivity of water reuse quantities, prices, and total system cost to reclaimed water demand elasticity factor



on-going. Also, wastewater treatment operational costs are more sensitive than water reuse operational costs because this cost is remarkably higher than both water treatment and water reuse operational costs and is included in both water and reclaimed water prices. Thus, an increasing unit wastewater treatment cost will decrease the relative difference between these prices, reducing the demand for reclaimed water (as presented in Fig. 8). To have a steady quantity of reclaimed water in water supply, a steady (or decreasing) level of the above-mentioned unit costs must be maintained. This requirement could be related to the expected improvements in performance of water reuse/wastewater treatment technologies along with the expansion of water reuse markets globally (economy of scale).

The reclaimed water price elasticity factor reflects consumers’ behavior toward reclaimed water and water reuse programs. As presented in Fig. 9, an increasing elasticity factor is associated with a decreasing public dislike for reclaimed water, which triggers a higher demand for water reuse (Dolnicar and Hurlimann 2010).

It should be mentioned that other parameters of the model, which are associated with lower sensitivities and variations in our case study, could behave differently if we shift to a different jurisdiction. For example, there could be volatilities in GDP (captured through water demand

function), interest and inflation rates (used in cost estimations), subsidies and incentives (reflected in total cost), wastewater generation trends (captured by a ratio), and energy/carbon prices as part of unit cost estimations (Mo et al. 2010) that can impose a significant challenge for water reclamation projects.

### 5 Conclusions

This study developed a framework for water reclamation-reuse planning and management. A SD approach was utilized to capture this complex decision making process with many temporal and feedback components, involving various economical, technological, and environmental criteria. The reclaimed water quantities and prices are identified over a planning horizon by minimizing total net present cost of the system. This decision problem was modeled and analyzed with respect to future population, economic and climate scenarios and was implemented in a case study in Kalamazoo County, Michigan. It was revealed that a decision to incorporate water reuse capabilities could yield remarkably lower water withdrawals in Kalamazoo with recovery of over a third of wastewater at almost no additional cost. Increasing the share of water reuse beyond this

threshold requires external financial assistance in the form of subsidies and/or tariffs as reclaimed water prices cannot fully recover the unit costs associated with water reclamation. The main finding of this study was that a decision regarding water reclamation and reuse is a case-specific one and needs to be addressed through an integrated water–wastewater system optimization model given the future scenarios of climate change, population, and other regional and technological factors. We should emphasize the fact that the uncertainties and stochastic behavior were admitted in scenario parameters of the model. In this sense, it would be interesting to admit some degrees of uncertainty in definition of non-scenario parameters of the model. For instance, capacity development delays and inflation and/or interest rates could be treated as stochastic parameters reflecting the technical uncertainty and economic volatility that could exist within the scope of planning. In addition, this model can be applied to assess water reuse decision making in other jurisdictions such as areas with water scarcity, a more receptive population, or where desalination is or will be an option for increasing water supply. There might be additional costs of using reused water in some regions. For instance, salts tend to accumulate in the system as more and more water is reused. It is not a problem where water is low in salts. However, in areas with high salt contamination in water, this would be a major issue creating additional maintenance costs. Finally, the proposed model can be expanded to incorporate other potential benefits of water reuse, including reduction in energy consumption and GHG emissions as well as energy-materials recovery.

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#### Appendix: glossary of system equations as defined in Vensim (in alphabetical order)

Average Summer Temperature =  $69 * (1 + \text{"Change in Average Summer Temperature (Scenario)"})^{\text{(Time/Time Unit)}}$

“Average Unit Wastewater Treatment – Transport Cost” =  $\text{"Cumulative Wastewater Treatment – Transport Cost"}/\text{Cumulative Water Demand}$

Average Unit Water Reuse Cost = IF THEN ELSE (Cumulative Water Reuse > 0, Cumulative Water Reuse Cost/Cumulative Water Reuse, 0)

“Average Unit Water Treatment – Supply Cost” =  $\text{"Cumulative Water Treatment – Supply Cost"}/\text{Cumulative Water Extraction}$

Capital Cost of WRC = Unit Capital Cost of WRC \* WRC Development

Capital Cost of WTSC = ACTIVE INITIAL (Unit Capital Cost of WTSC \* “WTSC Development – Maintenance”, 0)

Capital Cost of WWTC = Unit Capital Cost of WWTC \* “WWTC Development – Maintenance”

“Change in Average Summer Precipitation (Scenario)” = 0.0018

“Change in Average Summer Temperature (Scenario)” = 0.0013

“Change in GSP Per Capita (Scenario)” = 0.006

Cost of Wastewater Overload = Unit Wastewater Overload Cost \* Wastewater Overload

“Cumulative Wastewater Treatment – Transport Cost” = INTEG (“Wastewater Treatment – Transport Cost”, 15738.1)

Cumulative Water Demand = INTEG (Water Demand, 20075)

Cumulative Water Extraction = INTEG (Water Extraction, 20075)

Cumulative Water Reuse = INTEG (Water Reuse, 0)

Cumulative Water Reuse Cost = INTEG (Water Reuse Cost, 0)

“Cumulative Water Treatment – Supply Cost” = INTEG (“Water Treatment – Supply Cost”, 11563.8)

GSP Per Capita =  $32.6123 * (1 + \text{"Change in GSP Per Capita (Scenario)"})^{\text{(Time/Time Unit)}}$

Inflation Rate = 0.012

Net Population Growth = Population \* “Population Growth Rate (Scenario)”

“Net Present Wastewater Treatment – Transport Cost” = INTEG (“Wastewater Treatment – Transport Cost”/(1 + Nominal Interest Rate)<sup>(Time/Time Unit)</sup>, 15738.1)

Net Present Water Reuse Cost = INTEG (Water Reuse Cost/(1 + Nominal Interest Rate)<sup>(Time/Time Unit)</sup>, 0)

“Net Present Water Treatment – Supply Cost” = INTEG (“Water Treatment – Supply Cost”/(1 + Nominal Interest Rate)<sup>(Time/Time Unit)</sup>, 11563.8)

Nominal Interest Rate = 0.05

Operation Cost of Water Reuse = Unit Operation Cost of Water Reuse \* Water Reuse

Per Capita Water Demand = ACTIVE INITIAL (365 \* (90.659 – 4.726 \* Perceived Water Price + 2.43 \* GSP Per Capita – 1.299 \* Total Summer Precipitation + 0.777 \* Average Summer Temperature + 16.514)/1e+006, 0.0808)

Perceived Water Price = (Cumulative Water Extraction \* Water Price + Cumulative Water Reuse + Reclaimed Water Price)/Cumulative Water Demand

Population = INTEG (Net Population Growth, 248407)  
 “Population Growth Rate (Scenario)” = 0.0038  
 Potential Demand for Reclaimed Water = MAX  
 (Reclaimed Water Demand Cap Ratio \* Water Demand  
 \* (1 - (Reclaimed Water Price/Water Price)^Reclaimed  
 Water Demand Elasticity Factor), 0)  
 “Reclaimed Water Cost Recovery Ratio (Deci-  
 sion)” = 1 (Initial)  
 Reclaimed Water Demand Cap Ratio = 0.8  
 Reclaimed Water Demand Elasticity Factor = 1  
 Reclaimed Water Price = IF THEN ELSE (Average  
 Unit Water Reuse Cost > 0, “Reclaimed Water Cost  
 Recovery Ratio (Decision)” \* (Average Unit Water  
 Reuse Cost + “Average Unit Wastewater Treat-  
 ment - Transport Cost”), 0)  
 “Target Water Reuse Ratio (Decision)” = 1  
 “Total Net Present Cost (Objective)” = Net Present  
 Water Reuse Cost + “Net Present Water Treatment  
 - Supply Cost”  
 Total Summer Precipitation = 11.33 \* (1 + “Change  
 in Average Summer Precipitation (Scenario)”^(Time/  
 Time Unit))  
 Unit Capital Cost of WRC = 0.1  
 Unit Capital Cost of WTSC = 0.2259  
 Unit Capital Cost of WWTTC = 0.2036  
 Unit Operation Cost of Water Reuse = 0.1  
 Unit System Subsidy = Water System Subsidy/Water  
 Demand  
 Unit Wastewater Overload Cost = 2.866/Wastewater  
 Ratio  
 Unit Wastewater Treatment Operation Cost = 1.336  
 Unit Water Treatment Overload Cost = 1.3476  
 “Unit Water Treatment - Supply Operation Cost” =  
 0.3502  
 Wastewater Overload = IF THEN ELSE (Wastewater  
 Quantity > Wastewater Treatment, Wastewater Quan-  
 tity - Wastewater Treatment, 0)  
 Wastewater Quantity = Wastewater Ratio \* Water Demand  
 Wastewater Ratio = 28/55  
 Wastewater Treatment = MIN(Wastewater Quantity,  
 “Wastewater Treatment - Transport Capacity”/Time Unit)  
 “Wastewater Treatment - Transport Capacity” = INTEG  
 (“WWTTC Development - Maintenance” - WWTTC  
 Depreciation, 10220)  
 “Wastewater Treatment - Transport Cost” = (Capital  
 Cost of WWTTC + Cost of Wastewater Over-  
 load + “Wastewater Treatment - Transport Operation  
 Cost”) \* (1 + Inflation Rate)^(Time/Time Unit)  
 “Wastewater Treatment - Transport Operation Cos-  
 t” = Unit Wastewater Treatment Operation Cost \*  
 Wastewater Treatment  
 “Water Cost Recovery Ratio (Decision)” = 1

Water Demand = DELAY FIXED (Per Capita Water  
 Demand \* Population, Time Unit, 20075)  
 Water Extraction = ACTIVE INITIAL (IF THEN  
 ELSE (Water Inventory > 0, MIN(Water Demand -  
 Water Reuse, Water Inventory/Time Unit), 0), 20075)  
 Water Inventory = INTEG (“Water Recharge (Sce-  
 nario)” - Water Extraction, 850000)  
 Water Price = ACTIVE INITIAL (“Water Cost Recov-  
 ery Ratio (Decision)” \* (“Average Unit Wastewater  
 Treatment - Transport Cost” + “Average Unit Water  
 Treatment - Supply Cost”), 0.197 \* (1000/264.17))  
 “Water Recharge (Scenario)” = 73000  
 Water Reuse = MIN(Potential Demand for Reclaimed  
 Water, MIN(Water Reuse Capacity/Time Unit, Waste-  
 water Treatment))  
 Water Reuse Capacity = INTEG (WRC Develop-  
 ment - WRC Depreciation, 0)  
 Water Reuse Cost = (Capital Cost of WRC + Opera-  
 tion Cost of Water Reuse) \* (1 + Inflation Rate)^(Time/  
 Time Unit)  
 Water Reuse Subsidy = MAX ((Average Unit Water  
 Reuse Cost + “Average Unit Wastewater Treatment -  
 Transport Cost” - Reclaimed Water Price) \* Water  
 Reuse, 0)  
 “Water Reuse/Wastewater Ratio” = Water Reuse/Waste-  
 water Quantity  
 Water Subsidy = MAX((“Average Unit Wastewater  
 Treatment - Transport Cost” + “Average Unit Water  
 Treatment - Supply Cost” - Water Price) \* Water  
 Extraction, 0)  
 Water System Subsidy = Water Reuse Subsidy + Water  
 Subsidy  
 Water Treatment = MIN(Water Extraction, “Water  
 Treatment - Supply Capacity”/Time Unit)  
 Water Treatment Overload = ACTIVE INITIAL (IF  
 THEN ELSE (Water Extraction > Water Treatment,  
 Water Extraction - Water Treatment, 0), 0)  
 Water Treatment Overload Cost = Unit Water Treat-  
 ment Overload Cost \* Water Treatment Overload  
 “Water Treatment - Supply Capacity” = INTEG (“WTSC  
 Development - Maintenance” - WTSC Depreciation,  
 20075)  
 “Water Treatment - Supply Cost” = ACTIVE INITIAL  
 ((Capital Cost of WTSC + Water Treatment Overload  
 Cost + “Water Treatment - Supply Operation Cost”) \*  
 (1 + Inflation Rate)^(Time/Time Unit), 7120)  
 “Water Treatment - Supply Operation Cost” = “Unit  
 Water Treatment - Supply Operation Cost” \* Water  
 Treatment  
 WRC Depreciation = Water Reuse Capacity \* WRC  
 Depreciation Rate  
 WRC Depreciation Rate = 0.02

$WRC \text{ Development} = \text{DELAY FIXED} (\text{MAX}(\text{"Target Water Reuse Ratio (Decision)" * Wastewater Treatment * Time Unit} - \text{Water Reuse Capacity}) / \text{WRC Development Delay, WRC Depreciation}), \text{WRC Development Delay, WRC Depreciation})$   
 $WRC \text{ Development Delay} = 5$   
 $WTSC \text{ Confidence Level} = 0.1$   
 $WTSC \text{ Depreciation} = \text{"Water Treatment} - \text{Supply Capacity"} * \text{WTSC Depreciation Rate}$   
 $WTSC \text{ Depreciation Rate} = 0.02$   
 $WTSC \text{ Development Delay} = 5$   
 $\text{"WTSC Development} - \text{Maintenance"} = \text{ACTIVE INITIAL} (\text{MAX}(\text{Water Extraction * Time Unit * (1 + WTSC Confidence Level)} - \text{"Water Treatment} - \text{Supply Capacity"})) / \text{WTSC Development Delay, WTSC Depreciation}, 0)$   
 $WWTTC \text{ Capacity Confidence Level} = 0.1$   
 $WWTTC \text{ Depreciation} = \text{WWTTC Depreciation Rate} * \text{"Wastewater Treatment} - \text{Transport Capacity"}$   
 $WWTTC \text{ Depreciation Rate} = 0.02$   
 $WWTTC \text{ Development Delay} = 5$   
 $\text{"WWTTC Development} - \text{Maintenance"} = \text{MAX} (\text{Wastewater Quantity * Time Unit * (1 + WWTTC Capacity Confidence Level)} - \text{"Wastewater Treatment} - \text{Transport Capacity"})) / \text{WWTTC Development Delay, WWTTC Depreciation})$

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