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Conceptual Framework for Decentralized Green Water-Infrastructure Systems

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Abstract

We present a model for a Decentralized Green Water-Infrastructure System (DGWIS) based on a new conceptual framework that optimizes the use of captured rainwater, recycled wastewater and renewable energy resources. DGWIS is designed for building-scale localized water supply systems that utilize rainwater and greywater and incorporate advanced small-scale water treatment systems and renewable local energy sources such as solar and wind. Several constraints are considered: i) available renewable energy; ii) greywater production rate; iii) potential captured rainwater; iv) water demand; v) water storage volumes required to accommodate greywater, harvested rainwater, and separate water/ energy supplies from the city; and vi) water treatment capacities. The proposed DGWIS optimization framework demonstrates proof-of-concept and provides a solid foundation for an innovative paradigm shift toward water and energy sustainability.

Keywords: Decentralized Green Water-Infrastructure System (DGWIS), greywater, optimization framework, rainwater harvesting, renewable energy

Introduction

Increased urbanization and population growth have created a significant demand for expanding and enhancing our water infrastructure based on the principles of sustainability (Larsen *et al* 2016), with critical and emerging issues including water scarcity, promoting water use efficiency, improving water quality, repair or replacement of deteriorating water infrastructure, and reducing water-related energy use (NRC 2008; Dallman and Piechota 2010; Ruberto *et al* 2013). Conventional urban water infrastructure systems typically involve centralized, large networks serving large populations; a dependency on imported water supplies; an increasing demand for wastewater generation and treatment due to population increases; an increased level of impervious cover leading to greater stormwater runoff; and a myriad of pipe networks for delivering potable water to consumers and transporting wastewater and stormwater runoff away from urban areas (Dallman *et al* 2016). At present, more than 52,000 conventional or centralized potable water treatment and distribution systems operate in the US, with most being powered by conventional energy distribution systems (USEPA 2009a). In 2009, the electricity consumed by the nation's public drinking water and wastewater utilities for pumping, conveyance, treatment, distribution, and discharge amounted to 56.6 billion kWh (CRS 2013; Sanders and Webber 2012).

In 1998, the U.S. Green Building Council (USGBC) developed a new Green Building Rating System, Leadership in Energy and Environmental Design (LEED), to encourage the ~~worldwide~~ nationwide adoption of sustainable green building development practices (USGBC 2006). Recent studies have shown that LEED certified buildings consume an average of 25 to 50% less energy than comparable conventional office, commercial, and government buildings (Turner and Frankel 2008; Matisoff *et al* 2014). However, more than 65% of the high-quality potable water that the utilities produce is actually consumed for non-potable uses such as flushing toilets, washing cars, and landscape irrigation (DeOreo *et al* 2016). Green building design could significantly ameliorate this adverse impact by incorporating practices that improve the efficient use of water in buildings through implementing better design, operation, and maintenance across a building's entire lifecycle (Cassidy 2003; USGBC 2006; Corbett and Muthulingam 2007).

In this ~~article~~paper, we present a conceptual framework for a *Decentralized Green Water-Infrastructure System (DGWIS)* for buildings (industrial, commercial, government, and office) that integrates locally available water sources (i.e. rainwater and greywater) with renewable local energy sources (i.e. solar and wind) to support water treatment and distribution. Rainwater harvesting and greywater recycling have long been identified as alternative water sources for the sustainable management of water resources (Dixon *et al* 1999; Pidou *et al* 2007; Agudelo-Vera *et al* 2011, 2012 a, b; Walsh *et al* 2014; Dallman *et al* 2016; Tavakol-Davani *et al* 2016) and the general characteristics of greywater and rainwater harvesting systems have been studied by many researchers (Pidou *et al* 2007; Eriksson *et al* 2009; Li *et al* 2009; Malinowski *et al* 2015; NRWI 2015). DGWIS will incorporate advanced small-scale water treatment technologies based on patterns of anticipated water use. The production and consumption of energy at the individual building level for harvesting and treating water on site are expected to increase service reliability and technical efficiency and reduce environmental impacts by decreasing the energy required. An added benefit would be that decentralized systems should also improve the Levels-of-Service (LOS) by reducing service interruptions in the transmission and distribution networks.

The optimization framework for DGWIS developed in this study quantifies the energy and water potentially saved based on the assumption that the supplemental water supplies provided by DGWIS replace conventional tap water supplies and do not just increase demand. Our hypothesis is that alternative technologies, specifically DGWIS, can provide a partial solution to the water/energy supply and water quality challenges facing communities in the US and around the world. The potential contributions of self-sufficiency and wastewater recovery rate for sustainable water resource management have been highlighted in several recent studies (Rygaard *et al* 2011; Agudelo-Vera *et al* 2011, 2012a); we therefore sought to chart a new paradigm shift in urban water/energy management by evaluating and optimizing the capture and reuse of rainwater/greywater to augment domestic water supplies while at the same time reducing water-related energy usage by adopting renewable energy technologies in buildings. In the following sections, the general characteristics of rainwater harvesting, small-scale water treatment and renewable energy sources are explored in more detail.

Background

Significant opportunities exist for rainwater capture and use in buildings. In the absence of a rainwater harvesting system, the rainwater ~~from urban rooftops~~ is usually discharged to stormwater drainage systems, comprising a major source of surface water pollution (Younos 2011; Campisano and Modica 2016; Dallman *et al* 2016). It is, however, possible for up to 80% of the rainwater falling on urban rooftops (after initial abstractions such as depression storage, evaporation and splash) to be captured and available for various indoor and outdoor uses (Younos 2011). Younos (2014) noted that recent technological advances in pre-filtration, firstflush design, and the availability of small-scale water treatment units mean that captured rainwater could be more widely used as a potable water source. Advances in small-scale and packaged water treatment technologies such as reverse osmosis, carbon filter, and UV disinfection devices allows small-scale decentralized water production systems to be installed as satellite systems within buildings to treat and use locally available water sources, including captured rainwater and reclaimed greywater. A typical small-scale packaged water treatment system with a capacity of up to 50,000 liters per day can easily be configured as a water treatment unit at the individual building level in urban areas (Younos 2014).

At present, solar and wind energy have considerable potential for utilizing renewable energy in water and wastewater treatment for domestic water systems. For example, photovoltaics (PV) can be used to power pumps to transport water to where it is needed (Al-Smairan 2012). The New Jersey American Water Canal Road Water Treatment Plant (WTP) has a PV solar array that currently provides approximately 20% of the Canal Road WTP’s peak energy usage (Lelby and Burke 2011) and the Washington Suburban Sanitary Commission (WSSC) uses wind energy to power one-third of WSSC’s water and wastewater operations (Lelby and Burke 2011). The Commonwealth of Massachusetts has launched a pilot program to increase energy efficiency statewide for drinking and wastewater facilities using both solar and wind energy. So far, the area served includes 21 water and wastewater facilities, 14 pilot sites, and 7 identified green sites (USEPA 2009b). The next potential applications include water source treatment (captured rainwater and wastewater) and water distribution within buildings. To the best of the authors’ knowledge, these renewable energy technologies have not been applied as yet to small-scale, decentralized water infrastructure elements. The proposed DGWIS would thus be a significant step toward sustainable water/energy use in urban environments.

Optimization Framework

In this section, the optimization framework of the proposed DGWIS is presented. Greywater recycling and rainwater harvesting are considered alternative sources that can be used for toilet flushing and other non-potable purposes and renewable energy sources are used to operate pump and water treatment facilities wherever possible. It is critical to understand the full details of the process dynamics of the system for optimal management of both the water and renewable energy resources. Several constraints are taken into account: i) the renewable energy available – in particular, solar and wind energy being generated at time *t;* ii) the greywater production rate and amount available at time *t*; iii) the available rainfall and potential harvested rainfall at time *t*; iv) variations in water demand over time; v) the availability of sufficient water storage volumes to accommodate greywater and harvested rainwater, in addition to that for the water supplied from city mains; and vi) treatment capacities. Available renewable energy, greywater production rate, available rainfall, and water demand are stochastic by nature and thus require uncertainty analysis.

The limits of a building's premises constitute the boundary of the system of interest here when considering inflows (water supplied from city systems and electricity from the grid), outflows (to sewer systems) and water recycling, subject to the unique constraints of each system (Figure 1). Wastewater from showering/washing, cooking, and laundry represents a potential source for water recycling (R_t). Rainwater capture potential (P_t) is evaluated by taking into account the various storage tank sizes and treatment capacities as a function of time; two separate and variable tank sizes (S_p, S_r) are used for rainwater harvesting and greywater, respectively. Depending on treatment capacity, the volume of a treatment unit can be defined in terms of its hydraulic residence time. The objective of the DGWIS model is to minimize consumption of the water supplied by the city (I_t) and electricity from the grid ($E_{c,t}$). This performance goal can be accomplished by implementing water efficient technologies, and maximizing water recycling rates and/or rainwater harvesting use rates.

[INSERT FIGURE 1 ABOUT HERE]

The objective (1) of the optimization framework is to minimize the net consumption of water supplied from the mains and energy from the grid in terms of cost. Constraint (2) requires that the electricity (demand) used for the water treatment and pump operation ($E_{1,t}$, $E_{2,t}$, $E_{3,t}$) cannot exceed the electricity harvested from solar panels and/or wind turbines ($E_{r,t}$) and supplied by the city ($E_{c,t}$). Constraints (3) and (4) are, respectively, the water supply restrictions for the two types of water demand depicted in Figure 1. For instance, Constraint (3) ensures that the water consumption amounts for toilet use and landscape irrigation cannot be greater than the total available from rainwater harvesting (P_t), recycled water (R_t) and the water mains (I_t). Constraints (5)-(7) show functional relationships (g) regarding energy requirements (for treatment and pumping) as a function of P_t and R_t. Water amounts in conjunction with characteristics are converted and quantified into water pressure variations in Constraint (8), and Constraints (9), (10), and (11) ensure that the hydraulic parameters including water pressure, velocity, and water quality inside the plumbing system remain within specified ranges. In addition, water quality parameters such as disinfectant concentrations, DBP, THMs, water age, temperature, pH, TOC, heavy metal concentration, microbiological quality, and turbidity all need to be within the allowable range (USEPA 2017). The parameters used in this model also require detailed information on solar panel efficiency, the hours of available sunlight, energy transmission rates from solar panel/ wind turbine to pump, treatment facilities, and the operational characteristics of the pump. All variables with a '*t*' subscript have a time varying stochastic nature. The current model considers the situation at the individual building level; the economies of scale for more widespread implementation impacts (Cornejo *et al* 2016) are outside the scope of this paper. The notations used in the mathematical formulation are provided in the Appendix.

Objective Function: Minimize $\alpha\,(I_{1,t} + I_{2,t}) + \beta E_{c,t}$ (1)

Subject to the following constraints:

$$E_{c,t} + E_{r,t} \geq E_{1,t} + E_{2,t} + E_{3,t} \quad (2)$$

$$P_t + R_t + I_{2,t} \geq D_{2,t} \quad (3)$$

$$I_{1,t} \geq D_{1,t} \quad (4)$$

$$E_{1,t} = g_1(P_t) \quad (5)$$

$$E_{2,t} = g_2(R_t) \quad (6)$$

$$E_{3,t} = g_3(R_t) \quad (7)$$

$$PR_t = f_1\,(I_t, P_t, R_t, \text{pump characteristics}) \quad (8)$$

$$PR_{min} \leq PR_t \leq PR_{max} \quad (9)$$

$$V_{min} \leq V_t \leq V_{max} \quad (10)$$

$$C_{min} \leq C_t \leq C_{max} \tag{11}$$

Decision Variables:

$I_{1,t}$: water main supply to $D_{1,t}$.

$I_{2,t}$: water main supply to $D_{2,t}$.

$E_{c,t}$: electricity supply from the power grid.

Procedure

To implement the newly developed optimization framework for a real case, a simulation model that incorporates both discrete event simulation (DES) and system dynamics (SD) can be utilized. DES generates discretized stochastic availability/ demand per unit time *t*, sampling from a distribution of the best fit, and is thus a computational and analytical tool that allows not only the stochastic characteristics within a complex system to be modeled, subject to variability, but also makes it possible to test a number of different hypothetical ("what if") scenarios, for example by changing the treatment capacity over time, to identify the best case scenario among various alternatives. As two separate tanks (S_p and S_r) control the rates of the water inflows and outflows, the use of an SD technique facilitates modeling a system that continuously changes from one state to another by applying differential equations to measure changes in the rates of state variables over time. To solve this optimization problem, an evolutionary algorithm (in this case, a genetic algorithm) that conducts a random search while exploring a feasible region and exploiting good solutions can be considered (Holland 1992). Given an initial set of solutions, the algorithm evaluates these solutions via a simulation model and then applies genetic operations such as crossover and mutation to produce a new solution, which it then includes in the set of updated solutions. The string of values for decision variables represents each point in the solution space.

The mathematical formulation of the proposed DGWIS model balances two different performance metrics - usage of water and electricity - in the objective function by scaling each required supply amount to its respective cost. Alternatively, given the inverse relationship between water mains supply and demand for toilets and irrigation ($I_{2,t}$) and the amount of electricity supplied by the city ($E_{c,t}$), a corresponding Pareto frontier can be constructed to analyze further trade-offs between the two. Moreover, regarding the constraints that include nonlinear functions, namely Energy Constraints 1-3 and the Pressure requirement, the Reformulation-Linearization Technique (RLT) (Sherali and Adams 1994) can be applied to generate a class of valid inequalities with which to restructure the model formulation and, consequently, enhance the model's solvability. RLT allows a constraint to be linearized by substituting for nonlinear terms, thereby tightening the model representation with bound constraints and reducing its complexity, resulting in a mixed (linear) integer program model. The solution approach described here integrates simulation and metaheuristic search procedures while utilizing a mixed integer programming solver, thus enhancing the quality of each solution generated during the search process. The outcomes of this research can be used to develop short-term optimal operation guidelines for the DGWIS as well as a prescriptive decision support tool for addressing strategic long-term planning and management problems.

Conclusions

(1) This article proposes a new model, DGWIS, based on a mathematical framework for optimizing the use of captured rainwater, recycled wastewater and renewable energy resources. DGWIS is defined as a building-scale localized water supply system that utilizes rainwater and greywater and integrates advanced small-scale water treatment systems and renewable local energy sources such as solar and wind for water treatment and distribution in buildings.

(2) The dynamics and complex interactions among the elements of the defined systems are described. Based on the newly developed framework, the optimized theoretical input (I_t) and output (O_t) and the maximum recycling rate (P_t plus R_t) can be calculated for the selected sites. Furthermore, the resulting model can be integrated into a smart water grid (SWG), a high-efficiency water management system that integrates information and communication technologies (ICT).

(3) The proposed DGWIS optimization framework is ~~confidently~~ expected to demonstrate proof-of-concept via computational results using large-scale real data (work currently ongoing), thus providing a ~~firm~~ foundation for future research to develop an innovative paradigm shift toward greater water and energy sustainability.

Appendix

Parameters:

α: penalty coefficient for the use of mains water.

β: penalty coefficient for the use of electricity supplied by the grid.

~~$E_{r,t}$: harvested renewable energy.~~

~~P_t: potential harvested rainwater.~~

~~R_t: potential water recycling.~~

~~$E_{1,t}$: energy required to treat harvested rainwater; a function of P_t.~~

~~$E_{2,t}$: energy required energy to treat greywater (from showering, washing, cooking and laundry); a function of R_t~~

~~$E_{3,t}$: energy required to operate the pump; a function of R_t.~~

~~$D_{1,t}$: water demand for showering/washing, cooking, and laundry.~~

~~$D_{2,t}$: water demand for toilet and irrigation.~~

PR_{min}: minimum required pressure inside plumbing system.

~~PR_t: actual pressure inside the plumbing system.~~

PR_{max}: maximum required pressure inside plumbing system.

C_{min}: minimum concentration for water quality parameters.

~~C_t: concentration of water quality parameters.~~

C_{max}: maximum concentration for water quality parameters.

Variables:

$E_{r,t}$: harvested renewable energy.

P_t: potential harvested rainwater.

R_t: potential water recycling.

$E_{1,t}$: energy required to treat harvested rainwater; a function of P_t.

$E_{2,t}$: energy required energy to treat greywater (from showering, washing, cooking and laundry); a function of R_t

$E_{3,t}$: energy required to operate the pump; a function of R_t.

$D_{1,t}$: water demand for showering/washing, cooking, and laundry.

$D_{2,t}$: water demand for toilet and irrigation.

PR_t: actual pressure inside the plumbing system.

C_t: concentration of water quality parameters.

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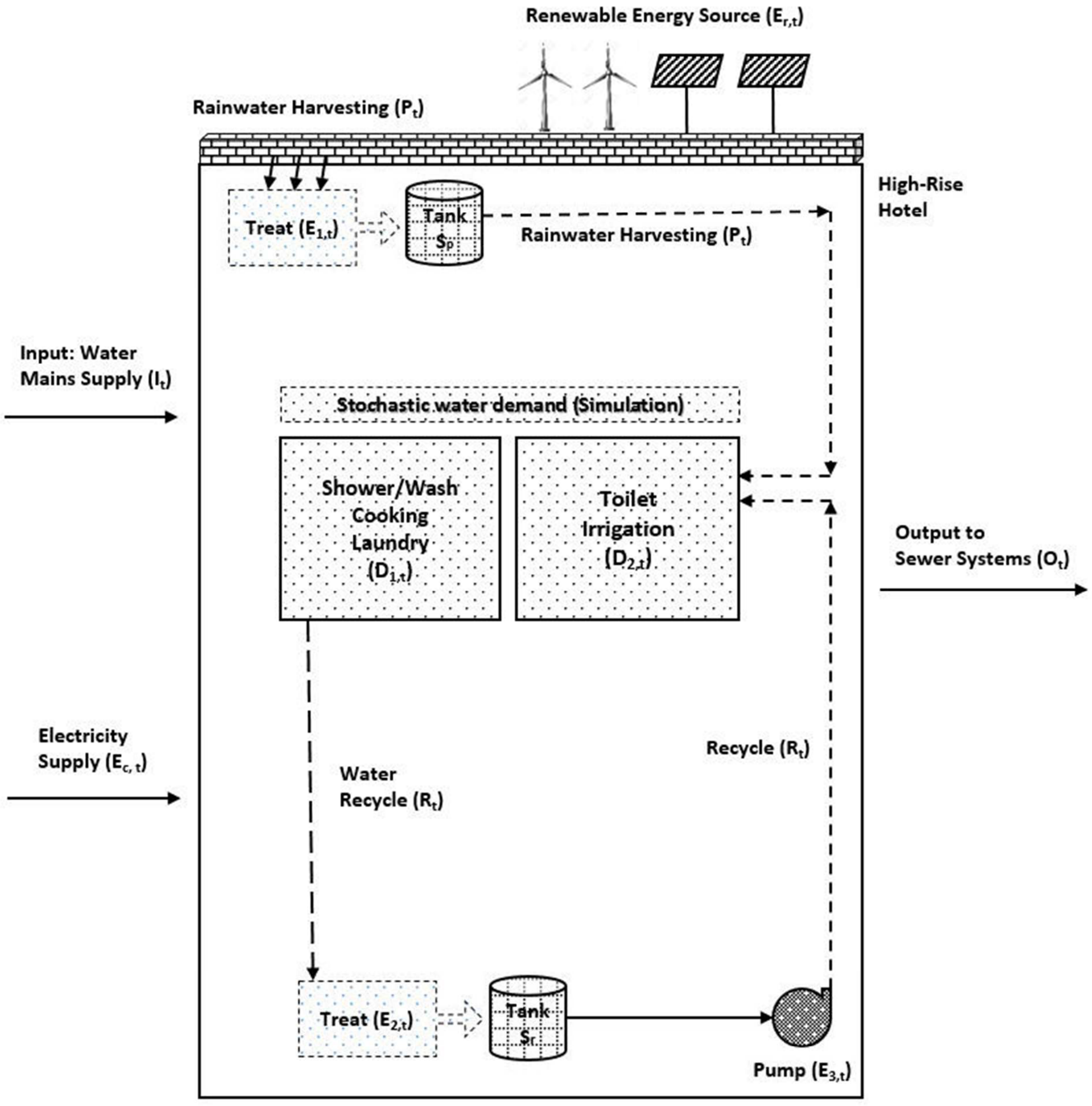

Figure 1 Configuration of the Decentralized Green Water-Infrastructure System