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Life cycle assessment of small-scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia

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ABSTRACT

This study examines a hybrid system (HS) that combines a greywater reclamation system with the centralized water system. Greywater is collected from laundry, showers, faucets and dishwashing and is reclaimed for non-potable on-site purposes (i.e., irrigation and toilet flushing) by using submerged membrane bioreactors (MBRs). This technology can reduce the burden of the conventional system (CS), defined as the water supply and wastewater treatment systems within the City of Atlanta. We conducted a life cycle assessment (LCA) comparison of the HS and CS using TRACI v2.1, which simulates ten impacts related to the ecosystem, human health and natural resources. We simulated the technology feasibility for nine residential zones, including five single-family house zones (SFZs) and four multi-family apartment building zones (MFZs) that vary by land use and population density (0.4–62.2 persons per 1000 m^2). The greywater reclamation system reduces non-potable water demand in SFZs (by 17–49%) and MFZs (by 6–32%) while simultaneously reducing electricity consumption by 17–49% and 32–41% for SFZs and MFZs, respectively. Moreover, the LCA score of the CS is 20–41% lower than that of the HS. However, the sensitivity analysis indicates that energy sources in electricity generation play a critical role in reducing and stabilizing life cycle impacts. The results indicate that the LCA scores stabilize at higher population densities. Therefore, once the greywater reclamation capacity is exhausted, municipalities can further decrease the life cycle impacts related to water infrastructure through improvements in the electricity generation infrastructure.

1. Introduction

Large-scale centralized water systems provide the essential functions of supplying drinking water, treating wastewater and managing stormwater runoff. Centralized water supply systems typically withdraw 100% of the water supply from the environment and treat it to potable standards regardless of the water's end use. Afterward, wastewater is collected and treated according to municipal standards prior to discharge into the environment. Accordingly, the centralized water infrastructure is an open-loop system that is dependent on the water availability from selected reservoirs.

The average percentage of generated wastewater that undergoes treatment varies regionally in North America (75%), Europe (71%), the Middle East and N. Africa (51%), Asia (32%), the Russian Federation and ex-Soviet States (28%), and Latin America (20%); however a majority of the wastewater goes untreated in Sub-Saharan Africa (Sato et al., 2013). Similarly, the percentage of reused wastewater varies between countries and regions. For instance, developed countries tend to have rigorous regulation when it comes to the discharge of treated wastewater. This tends to limit crop irrigation (i.e., agriculture and lawns) as the primary use for treated wastewater, especially in water stressed areas (Sato et al., 2013). Developing countries, on the other hand, have a higher percentage of direct untreated wastewater reuse for crop irrigation due to lower water costs, energy costs, fertilizer costs,

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and limited water access (Sato et al., 2013).

To accommodate population growth and urbanization, wastewater discharge standards under the Clean Water Act have become stringent in order to protect the water environment from increasing water withdrawal and use. Furthermore, climate change is driving changes to global hydrology through extreme precipitation or drought patterns (United Nations World Water Assessment Programme, 2016). Coupled with population growth, cities have higher risks of resource depletion and degradation will increase as well (McDonald et al., 2014, 2011). On average, approximately 80% of the energy for the centralized water supply system is used to transport water from surface water bodies to residential areas (Goldstein et al., 2002). Approximately 4% of the total electricity consumption in the U.S. can be attributed to water and wastewater treatment and transportation (Daw et al., 2012). With limited energy and water resources, the conventional system (CS) cannot be sustained.

Rainwater harvesting, xeriscaping, dry toilets (i.e., composting and urine diverting toilets), and wastewater reclamation have been investigated as alternatives to mitigate freshwater withdrawal and energy consumption resulting from the CS. Harvested rainwater and reclaimed wastewater can be used for non-potable demand such as toilet flushing and outdoor irrigation which account for approximately 17% and 30% of US domestic water demand (US Environmental Protection Agency, 2017; Water Research Foundation, 2016). Xeriscaping – the use of native vegetation or low-water plants for landscaping – is expected to reduce approximately 50% of irrigation water in comparison to lawns (Jeong et al., 2016); however, this is dependent on the local climate, precipitation patterns, and plant types. Depending on the model and format, dry toilets can reduce between 10 and 30% of household water use (Schuetze and Santiago-Fandiño, 2013) and approximately 32% of the water and energy use associated with toilet flushing (Sullivan and Horwitz-Bennet, 2009).

Large- and small-scale wastewater reclamation systems have also been studied as one of the alternatives to supply water and treat wastewater (Mo et al., 2014; Pintilie et al., 2016). The life cycle environmental impacts of water and wastewater treatment systems primarily result from electricity consumption. Within conventional water treatment, the electricity demand mainly comes from the pumping and distribution systems (Crittenden et al., 2012). On the other hand, the energy demand in wastewater treatment plants is dependent on the nutrient loads and the required microbial demands for treatment (i.e., aeration biological treatment of substrates and nitrification) (Rittman and McCarty, 2001). LCA studies for water reclamation have demonstrated that large-scale systems have a smaller environmental impact than long-distance water importation and desalination (Meneses et al., 2010; Pasqualino et al., 2010; Stokes and Horvath, 2009). The Orange County Groundwater Replenishment System (California) has produced up to 70 mgd (0.26 million m^3 per day)—the equivalent of 600,000 residents' water demand—to recharge groundwater for indirect potable reuse and seawater intrusion prevention (Dunivin et al., 2011). Similarly, the city of Tampa (Florida) has reclaimed 35 mgd (0.13 million m^3 per day) of wastewater for irrigation, a significant fraction of the anticipated water demand for 2030 (111 mgd, or 0.42 million m^3 per day), and replaces 5 mgd (0.02 million m^3 per day) of annual well withdrawal (CDM et al., 2009).

Small-scale wastewater reclamation systems using membrane bioreactors (MBRs) may serve as decentralized alternatives to supply water and treat wastewater. MBRs function similar to activated sludge systems, in which membrane filters replace the secondary clarifier. Despite being susceptible to unexpected flows, wastewater strength and domestic products (i.e., bleach, caustic soda, perfume, vegetable oil, and washing powder)—all of which may be toxic to biomass—several studies have confirmed that MBRs properly treat wastewater to non-potable uses. (Jefferson et al., 2001, 1999; Melin et al., 2006; Meuler et al., 2008; Paris and Schlapp, 2010; Pidou et al., 2007). Moreover, separating greywater (i.e., faucet, shower, bath, dishwashers and laundry) from blackwater (i.e., water containing human waste) is also helpful to produce reclaimed water that is safe for non-potable use.

In their study, Meuler et al. (2008) assess the effluent quality of greywater reclaimed from a small-scale MBR system within an office building in Germany. Similarly, Paris and Schlapp (2010) tested the HUBER GreyUse® system to treat greywater from a dormitory building in Vietnam without adequate wastewater treatment infrastructure. Accordingly, both studies determined that the effluent quality produced by small-scale MBRs met the standards of the German Association for Rainwater Harvesting and Water Recycling (FBR) and was adequate for toilet flushing, laundry and irrigation (Meuler et al., 2008; Paris and Schlapp, 2010). Similar to the FBR on-site water-reuse standards, both the NSF International Standard/American National Standard for on-site residential and commercial water reuse treatment systems (NSF/ANSI 350) and the standard of Queensland Department of Infrastructure and Planning for water reuse are available and presented in Table 1 (Meuler et al., 2008; U.S. Environmental Protection Agency, 2012a).

Although MBRs effectively produce non-potable water, electricity consumption for small-scale MBR operation was crucial in assessing the life cycle environmental impacts (Hospido et al., 2012; Memon et al., 2007). Prevention of both biological and non-biological fouling on the membrane surface accounts for more than 50% of the electricity consumption of submerged MBRs' operation in aeration tanks (Gil et al., 2010; Krzeminski et al., 2012). Moreover, electricity consumption increases with decreasing treatment scale (Abegglen and Siegrist, 2006; Boehler et al., 2007; Fenu et al., 2010; Krzeminski et al., 2012). Thus, further study is required to determine the energy-saving treatment capacity of greywater reclamation compared to the CS (Abegglen and Siegrist, 2006).

This study serves as a continuation of two companion works: 1) an LCA of Atlanta's centralized water system (Jeong et al., 2015); and 2) an LCA of low impact development (LID) technologies (i.e., rainwater harvesting, xeriscaping, and bioretention systems) combined with Atlanta's centralized water systems (Jeong et al., 2016). Accordingly, we continue the theme of decentralized water systems to meet non-potable demands by expanding the analysis to greywater reclamation.

In this study, we simulate the water and electricity consumption of a hybrid system (HS) composed of small-scale greywater reclamation technologies working in conjunction with the CS and evaluate the life cycle environmental impacts of replacing potable water demand with reclaimed water for non-potable uses. The non-potable uses include restricted indoor use (i.e., toilet flushing) and unrestricted outdoor use (i.e., irrigation) regulated in NSF/ANSI standard 350 (Table 1). We assess the impacts for a variety of residential communities in the City of Atlanta, Georgia that vary with land use and population density. The scope is restricted to the city boundaries, and does not extend to the Atlanta metropolitan area. The CS is defined as the centralized water, wastewater and stormwater management systems within Atlanta. Greywater is reclaimed for non-potable purposes using an MBR system that is composed of preliminary filtration, biological degradation, and membrane filtration. The reclaimed water is distributed using a pump and piping system. LCA scores are estimated as percentages compared to the annual US average environmental impacts on a per capita basis. Accordingly, we compared the LCA single scores of the CS and HS for each community. In addition, our study demonstrates which communities benefit more from reclaiming greywater to the water