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Evaluation of Implementation Strategies of On-site Water Conserving Technologies in Three Urban Neighborhoods

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Abstract: This paper addresses a knowledge gap that exists for city- or neighborhood-wide applications of on-site water-conserving technologies, such as rainwater and gray-water systems. We develop a framework for evaluating policies requiring on-site rainwater and gray-water systems in residential units. Our framework incorporates housing stock dynamics, fixture retrofitting, and water demand models. It assesses costs and benefits of policy implementation strategies for three urban neighborhoods selected according to their built environment and socio-economic characteristics. Evaluation results identify a potential 5.4 to 37.2 percent reduction in future neighborhoods' water demand. With the most cost-efficient water-conserving technologies, a household is expected to save \$160 – \$393 from their annual water bills. The cost-benefit analyses indicate substantial variation in water-saving potential and the cost-efficiency of on-site water-conserving technologies across neighborhoods. Our findings present that to maximize effectiveness, the specific choice of water conserving technology and implementation strategy needs to account for local conditions of land-use characteristics, household structure, and water fixture conditions.

Keywords: Sustainable urban water management, On-site water-conserving technology, Water demand projection, Rainwater harvesting, Grey-water recycling, Cost-benefit analysis, Water affordability

Introduction

Current urban water management predominantly uses a linear approach that is also described as the take, make, waste approach (Daigger 2009). Conventional urban water systems contain extended collection and distribution networks, as well as functionally specialized infrastructure that leads to the loss of valuable resources such as water, energy, and nutrients (Wong and Brown 2009; Younos 2011). Also, the system lacks the flexibility necessary for efficient reconfiguration in response to changing operational conditions (Brown et al. 2011; Schramm and Felmeden 2012). A variety of factors ranging from slow or declining population growth, deteriorating infrastructure, tighter regulatory controls, and climate variability, places increasing pressure on water prices (Baird 2010; Leigh and Lee 2019). At the same time, urban water systems may be unable to ensure water affordability due to requirements of high capital investment and long depreciation times (Schramm and Felmeden 2012). Consequently, 11.9 percent of U.S. households are at risk for paying their water bills, and this number is expected to grow to 35.6 percent in the near future based on projected water rates (Mack and Wrase 2017). Thus, the conventional urban water system is broadly recognized as unsustainable and under stress from demographic, socio-economic, and climate changes (Daigger 2009).

As a response to the significant challenges of the current urban water management, there has been growing attention to alternative water sources and water-conserving technologies. Previous studies reported that water-conserving technologies that use locally available water sources, such as rainwater and gray water, reduce residential water and energy consumption (Malinowski et al. 2015; Steffen et al. 2013; Younos 2011; Zadeh et al. 2013; Zhang et al. 2010), as well as increase environmental benefits, including reduced stormwater runoff and pollutant loads (Malinowski et al. 2015). Water-conserving technologies, such as rainwater and gray-water systems, provide cities with the means to augment the current supply capacity without extending the existing water supply network and infrastructure (Domènech and Saurí 2010; Lucas et al. 2010). Further, on-site water-conserving technologies allow up to a 40 percent reduction in residential potable water demand (Steffen et al. 2013; Zadeh et al. 2013) that can result in a substantial reduction in household's water-bill burden (Gurung et al. 2016).

Financial benefits and costs are key decision criteria for the adoption of on-site water-conserving technologies (Tam et al. 2010), and there is a wide variety of studies that investigate the financial feasibility of water-conserving technologies (Farreny et al. 2011; Friedler and Hadari 2006; Liang and van Dijk 2010; Roebuck and Ashley 2007; Tam et al. 2010; Yu et al. 2015; Zadeh et al. 2013; Zhang et al. 2010). Most of these are conducted for a single unit or a residential complex (Farreny et al. 2011), thereby offering little policy insight for city- or neighborhood-wide applications of technologies. On the other hand, studies conducted for a city or neighborhood suggest little beyond how built-environment characteristics affect water-saving potential or the cost-efficiency of water-conserving technologies. More critically, previous studies employ a static approach that assumes fixed built-environment characteristics and water fixture conditions over the period of analysis. This approach neglects housing stock dynamics and a growing proportion of residential units equipped with high-efficiency fixtures. Consequently, this approach is likely to overestimate benefits of water-conserving technologies.

In this study, we present a comparative analysis of water-saving potential and financial feasibility of policy implementation strategies requiring on-site rainwater or gray-water systems in residential units in three neighborhoods in the city Atlanta, Georgia. The three neighborhoods are distinguished by income level and each represents a high-, medium-, or low-income neighborhood. We developed a dynamic model that incorporates changes in housing stock and fixture-efficiency conditions to evaluate on-site water-conserving technologies of rainwater and gray-water systems at the neighborhood scale. Taking into account the difference in household profiles and built-environment characteristics of the three neighborhoods, we examine how these characteristics affect the effectiveness and efficiency of water-conserving technologies. We also extend our cost-benefit analysis to explain how on-site water technologies may reduce the high water-bill burden that exists in low-income neighborhoods in Atlanta.

Descriptions of Three Neighborhoods in Atlanta

The city of Atlanta is located within a fast-growing metropolitan area of the Southeastern United States (Figure 1). The population of the metropolitan area of Atlanta grew by 11.3 percent since 2010 and is now at 5,884,736. The city of Atlanta population grew by 15.7 percent during the same period and now is 486,290. Another 2.5 million in population is projected to be added to the metro area by 2040 (Atlanta Regional Commission 2018). Meeting the growing demand for water from the influx of new population and businesses is a major challenge for the city.

The primary source of water for the metro area and core city is the Chattahoochee river. This river is part of the Apalachicola-Chattahoochee-Flint river basin which three states, Georgia, Alabama, and Florida, rely upon and have been in litigation over water use for nearly three decades. Atlanta is under significant pressure to reduce its water use. Further, aged water infrastructure has led to major loss of water from the system. The city is still using its original water supply pipelines, installed between 1893 and 1924, with water mains last renewed in the 1950s. It is has recently undertaken a major upgrade and greening of its water system to extend its current three-day water reserve level to more than 30 days (Saunders 2016).

The three neighborhoods analyzed for our Atlanta study were carefully selected to maximize variations in land-use and socio-economic characteristics with each having a transit station. To confirm the boundary of each neighborhood, we took the following systematic steps; 1) designated the transit station as the neighborhood center, 2) drew a radius boundary that was a half-mile from the center, and then 3) defined a set of Census Block Groups that intersect with each buffer as a neighborhood. We selected the neighborhoods of Lindbergh, King Memorial, and Bankhead, which represent the high-, the medium-, and the low-income neighborhood, respectively (Figure 1).

In Table 1, the authors present data on key characteristics of each neighborhood. Lindbergh is an affluent neighborhood located northeast of downtown Atlanta. It has a mixed land-use pattern with dense commercial and multifamily buildings around the transit center surrounded by large single-family parcels.

King Memorial is also a mixed-use and dense urban neighborhood east of downtown. The residential parcels for single-family homes are relatively small and there are also many small-size multifamily units for one- or two-person households. Bankhead is a distressed neighborhood with a large number of abandoned homes and vacant parcels. The housing stock of this neighborhood is relatively old compared to other two neighborhoods and contains low-rise and small-scale multifamily buildings as well as single family homes.

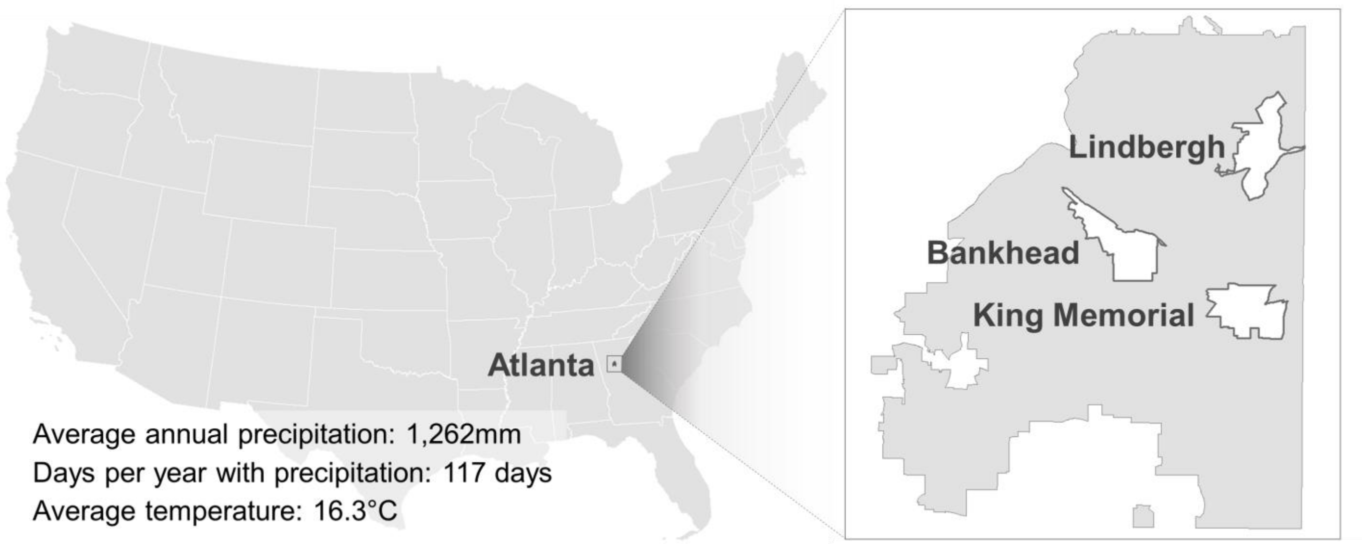

Figure 1. Location and Climate Statistics of Atlanta and Selected Neighborhoods

Table 1. Socio-economic and Land-use Profiles of Selected Neighborhoods

	Lindberg	King Memorial	Bankhead
Socio-economic profiles			
% white	81.89	70.97	12.76
Unemployment rate	4.07	7.86	28.96
% Poverty	6.12	12.80	34.59
Median income ($)	95,480	65,420	26,000
% of home ownership	76.92	66.80	48.82
Land-use profiles			
Site areas (km^2)	5.92	5.16	8.26
Land use characteristics			
Single-family	36.84%	21.94%	11.47%
Multifamily	15.61%	17.13%	5.00%
Average parcel footprint (m^2/unit)			
Single-family	1,189	544	788

Multifamily	161	136	203
# of multifamily units per parcel	34.33	13.49	13.95
Population per unit			
Single-family	2.15	1.80	2.35
Multifamily	1.96	1.64	2.14
Vacancy rate	12.93%	16.88%	37.03%
Units by built years			
Constructed after 2012	5.87%	6.32%	7.71%
Constructed 1991-2011	52.08%	42.28%	36.34%
Constructed before 1990	42.05%	51.40%	55.95%
Number of Units			
Single-family	1,833	2,080	1,202
Multifamily	5,733	6,491	2,036
Total population	13,206	11,953	4,527

Source: American Community Survey 5-year Estimates (2011-2015), Fulton County Tax Parcel GIS data (2017), and Fulton County Building Structure GIS data (2016)

Methodology

Neighborhood Water Demand Model

The modeling framework is presented in Figure 2. The model begins with a neighborhood's housing stock and examines the dynamics of its continuous changes through a process of old residential units being replaced by new ones. Tracking housing dynamics is imperative to this study because it provides basic data for the water demand projection, such as the number of residential units by type, and enables estimates of Low-Efficiency Fixture (LEF) and High-Efficiency Fixture (HEF) stocks in a neighborhood. Combining these estimates with other parameters that represent household water-use patterns and local climate, we evaluate indoor and outdoor water consumption by water-use purposes and types of residential unit. Based on this information, we project future neighborhood water demand, non-potable water consumption, and the amount of gray water produced. This process is required to evaluate water-saving potential of on-site water-conserving technologies.

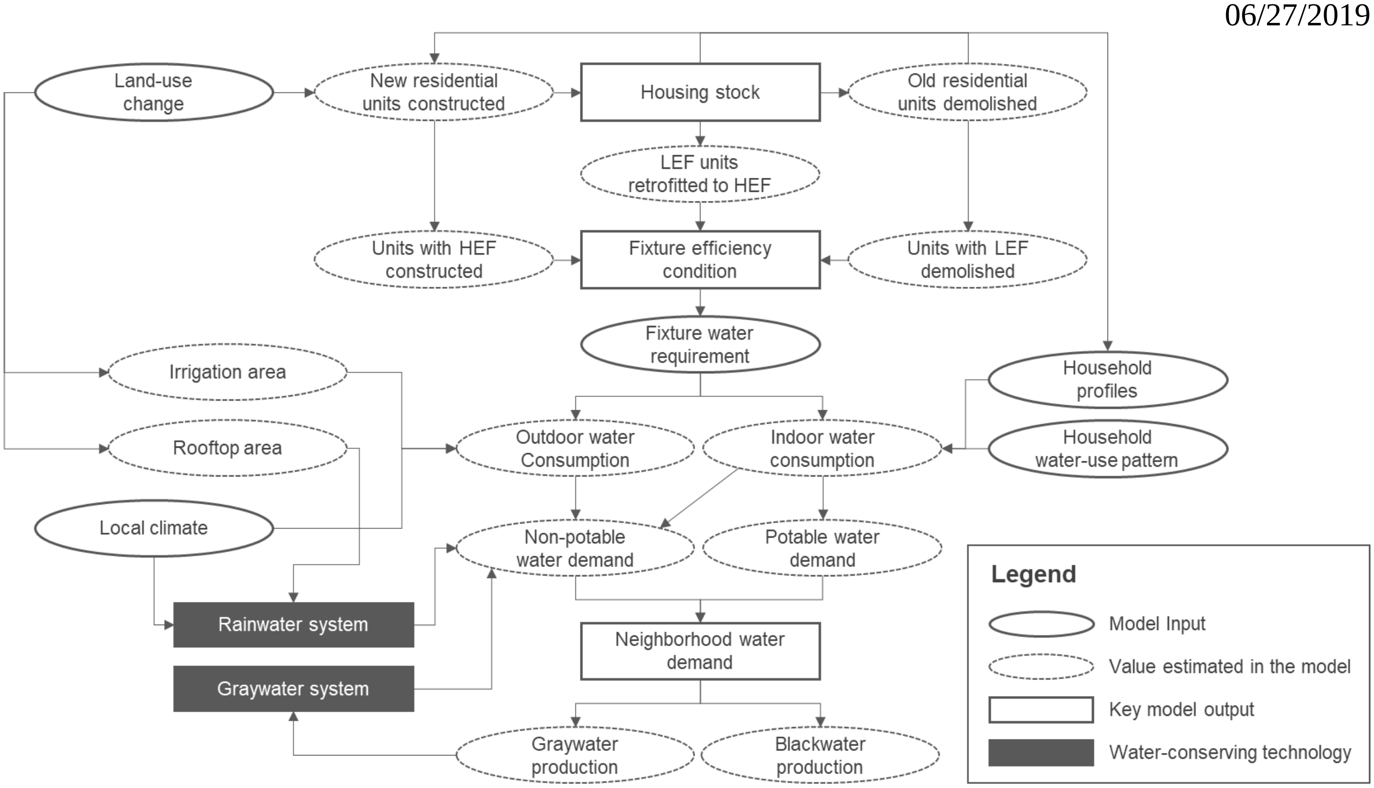

Figure 2. Modeling Framework for Neighborhood Water Demand Projection

Housing Stock Dynamics

The housing stock dynamic is often characterized by the new construction rate, renovation and transformation rate, and the demolition rate (Aksözen et al. 2017). However, in the absence of robust parameters for three neighborhood areas, we developed a simplified housing dynamic model from the demolition rate. For simplification, we adopted two assumptions. First, we assume that demolished housing stock will be immediately replaced by new housing stock (100% construction rate). Second, we consider a housing unit that has undergone a major renovation as a newly developed unit, thereby eliminating the use of a renovation rate in our analysis. This is because a housing unit that has either been demolished or undergone a major renovation is assumed to be equipped with high-efficiency fixtures.

Demolition activity is a function of the age profile of existing housing stock and expected building lifetime. We obtained age profiles within the three neighborhoods from American Community Survey 5-year Estimates (2011-2015). Lifetime distributions are often approximated in previous studies due to limited data availability. This study adopts a normal distribution function to represent the lifetime distribution of a building following Bergsdal et al. (2007) and Sartori et al. (2008). A normal distribution function requires defining two parameters: the mean (μ) and the standard deviation (σ). Previous studies take values that range from 75 to 125 as the expected lifetime of a building, and use 0.25μ as the standard deviation of the expected lifetime (Bergsdal et al. 2007; Sartori et al. 2008). The expected period for a major renovation of a building is commonly assumed in a range from 30 to 50 years (Sartori et al. 2008). Based on these estimates, we take 50 and 12.5 as the mean and standard deviation of the normal distribution function. The survival rate of a building at time t is represented as the following equation (Equation (1)) with the normal probability density function f(x).

$$S(t) = 1 - \int_0^t f(x \mid \mu = 50\,, \sigma = 12.5) \quad (1)$$

The number of residential units by built years is calculated using the above survival function with additional assumptions on land-use change and the vacancy rate. To compare the effectiveness and the efficiency of water-conserving technologies under status-quo growth scenarios in the three case-study neighborhoods, we assume that the current land-use patterns are fixed throughout the period of study. In other words, the total number of single-family and multifamily residential parcels will remain unchanged in the three neighborhoods. The vacancy rate is assumed to gradually decline, reaching 4.3 percent by 2068, the rate that is considered as the equilibrium or natural vacancy rate of Atlanta (Gabriel and Nothaft 2001).

Fixture Efficiency

Our model estimates the composition of LEF and HEF within neighborhoods based on the housing stock profiles and the assumption of the natural replacement rate (NRR) of a water fixture. In estimating the fixture efficiency, we pay special attention to two years, 1991 and 2012, when Georgia’s Plumbing Code first adopted, and subsequently reinforced the prohibition of LEF. We calculated the composition of LEF and HEF for toilets, bathroom faucets, showerheads, kitchen faucets, washing machines and dishwashers applying NRRs associated with the expected lifespan of each water fixture. For example, the annual NRR of 4 percent is applied to toilets with an expected lifespan of 25 years, while that of 12 percent is applied to showerheads (CUWCC 2005).

Water Demand Projection

Using neighborhood household profiles and fixture conditions, the model estimates current and future household water demands by water-use purposes. Indoor water demand is calculated based on assumptions of household water-use behaviors from Oldford and Filion (2012) and DeOreo et al. (2016), as well as fixture water flow rates. For the water requirement of LEF, we employed estimates from Koomey et al. (1995), while, for HEF, we referenced Georgia's Plumbing Code that specifies the maximum flow rate of high efficiency plumbing fixtures (Georgia Department of Community Affairs 2012). According to our estimates of fixture water flow rates, unit water consumption is expected to decrease by 9 – 63 percent for HEF. The equation for estimating the household indoor water demand (IWD) is presented as Equation (2). All parameters used to estimate water demand is presented in Appendix 1.

$$\mathrm{IWD} = PH \times (T_F \times T_U + BF_F \times BF_U + S_F \times S_U) + (KF_F \times KF_U + W_F \times W_U + D_F \times D_U) \quad (2)$$

where, PH is the number of persons per household, T, BF, S, KF, W, and D represent toilet, bathroom faucet, showerhead, kitchen faucet, washing machine and dishwasher. Subscripts F and U indicate fixture types (LEF or HEF) and household water-use patterns. In the absence of reliable benchmarking parameters, we assume that water use from a kitchen faucet, washing machine, and dishwasher is fixed per household. We acknowledge this is a limitation of our study considering previous findings of correlation between household size and appliance use frequency (Abdallah and Rosenberg 2012; DeOreo et al. 2016).

We estimated outdoor water demand using the size of irrigation areas in the three neighborhoods and water requirements for a unit irrigation area. To estimate the average size of irrigation areas, we use aerial images from the National Agriculture Imagery Program (NAIP) and identify vegetated areas within residential parcels. The images from NAIP have a spatial resolution of one meter and include four spectral bands (red, green, blue, and near infrared). Using these images, we calculate the Normalized Difference Vegetation Index (NDVI) that combines red and near-infrared (NIR) wavelengths to identify sunlight reflected by plants (Baret and Guyot 1991). Typically, the higher NDVI value indicates a denser concentration of vegetation within a pixel (Cheng et al. 2008; Gandhi et al. 2015). This study applies the thresholds that consider the NDVI values between 0.15 – 0.30 as less densely vegetated areas and the values larger than 0.3 as densely vegetated areas. A detailed description of NDVI thresholds are presented in Appendix 2. The NDVI values are calculated using standard equations (Rouse et al. 1974). Then, we calculate the total irrigation areas by the NDVI threshold, residential unit types, and neighborhoods.

The unit water requirement for irrigation area is associated with local climatic conditions and the concentration of vegetation within irrigation areas. The equation used for the calculation of irrigation water requirement per square meter is presented as Equation (3) (Alliance for Water Efficiency 2016).

$$\text{Outdoor water demand}\left(\frac{Liter}{m^2}\right) = \frac{1}{IE} \times (ET_0 \times K_L - P \times R_\varepsilon) \times 25.385 \qquad (3)$$

where, IE is typical irrigation efficiency, ET_0 is Atlanta's 5-year average of reference evapotranspiration (40.2 inches per year), K_L is a landscape coefficient that represents the percent of reference evapotranspiration needed by plant (0.6 for less densely vegetated area and 0.65 for densely vegetated areas), P is Atlanta's 5-year average of annual rainfall measured in inches (49.71 inches), and, R_ε is effective rainfall of the U.S. Southeastern area (47%), which represents the percent of annual rainfall contributing to plant water requirement.

Evaluation of On-site Water Conserving Technologies

Types of Technology

We examined on-site rainwater harvesting systems that supply non-potable water for outdoor water use, and rainwater and gray-water systems that supply non-potable water for both outdoor and indoor water uses. Following the general perception of recycled water, the purposes for non-potable water use are limited to garden irrigation for outdoor uses, and toilet flushing and washing machines for indoor uses (Farreny et al. 2011; Roebuck et al. 2012). In general, these types of water use comprise approximately 41 percent of households' indoor water consumption (DeOreo et al. 2016), and we expected to account for over the half of households' water consumption including outdoor water uses.

A rainwater system typically consists of a collection network, rainwater tank, and other attachments, such as filters, pumps, and controlling devices. Rainwater is a relatively high-quality water source that can be used for indoor potable water with an additional disinfection process (Cook et al. 2013). Atlanta's potable rainwater ordinance enacted in 2011 also requires chlorination, UV, ozone, or iodine treatment for indoor uses of rainwater, and it only allows rainwater collected from roof surface (Atlanta Georgia 2011). In this study, we only take rainwater collected from rooftop surfaces into account, even for outdoor-use only rainwater systems given the lower quality of rainwater collected from other surfaces (Göbel et al. 2007). The difference between rainwater systems for outdoor uses, and for both indoor and outdoor uses, is the presence of purification components and distribution network for indoor water uses.

A gray-water system consists of multiple components involved with filtration, sedimentation, disinfection, and storage, while the technological complexity of a system may differ depending on the required quality of reclaimed water. Gray water can be collected directly from domestic wastewater with dual pipe networks that separate less contaminated wastewater generated from hand-washing sinks, showers, bathtubs, and washing machines from blackwater (Yu et al. 2015). Thus, gray-water technology is less affected by local climatic conditions (Rozos et al. 2009), and the scalable adoption in a dense urban environment is more applicable than the rainwater technology (Bertrand 2008). On the other hand, because its water quality is inferior to rainwater, there are concerns over health risks (Dixon et al. 1999). State governments, including Georgia, have established regulations on gray-water reuse, which makes illegal the adoption of low-tech gray-water systems that do not have disinfection treatment. For this reason, we only consider high-tech commercially-available gray-water systems that satisfy Georgia's minimum quality guidelines for gray-water recycling (State of Georgia 2009).

Policy Implementation Strategies

This study evaluates three policy implementation strategies that aim to disseminate on-site water-conserving technologies for residential units (Table 2). The first implementation strategy is designed to enforce a new plumbing code that requires all newly constructed residential units to be equipped with on-site water technologies. We expect minimum policy resistance from this strategy because costs required for the strategy are hidden in housing prices or rents, and, further, owners and renters will eventually benefit from reduced water bills. The second strategy is the most progressive one that requires on-site water-conserving technologies to all new and existing residential units. In this case, all existing residential units are required to undergo major retrofitting to install water-conserving technologies, e.g., installation of water tank, pump, purifier, and water pipes. Although substantial policy resistance is expected, this strategy is suitable for a neighborhood that aims to reduce water demand the in a short-term. Lastly, the third strategy is also aimed at both for newly constructed and existing residential units, but it assumes an incremental diffusion of technologies for existing residential units. This paper assumes the annual adoption target as 2.5 percent of residential stock built before the enforcement of the new plumbing code, which means it will take 40 years to retrofit all residential stock.

Table 2. Descriptions of three policy implementation strategies

	Implementation Strategy 1 (Minimum intervention)	Implementation Strategy 2 (Maximum water-saving)	Implementation Strategy 3 (Incremental diffusion)
Newly developed units	Built with on-site water-conserving technologies		
Existing units	No adoption of water technologies	Equip with on-site water-conserving technologies in first year	2.5% of existing units will be equipped with technologies annually

Water Saving Potential

The water-saving potential of on-site residential water-conserving technologies is defined as the minimum value between the amount of non-potable water produced from technology and the amount of non-potable water demand by a household. The non-potable water demand is defined as household's water consumption that can be replaced by non-potable water. In other words, it is the sum of a household's water consumed for garden irrigation, toilet flushing, and washing machines. The amounts of non-potable water produced from a rainwater and a gray-water system are calculated using the Equation (4) and Equation (5).

$$\text{Rainwater production } (Liter) = RA \times P \times CE \times 25.385 \quad (4)$$

where, RA is squared meters of rooftop area, P is Atlanta's 5-year average of annual rainfall measured in inches, and, CE is collection efficiency, assumed to be 0.7 followed by observations from Liaw and Chiang (2014).

$$\text{Gray water production } = (WW_{BF} + WW_S + WW_W) \times TE \quad (5)$$

where, WW is the amount of wastewater generated in a household, and subscripts BF, S, and W represents bath faucets, showerheads, and washing machines. TE is treatment efficiency of a gray-water system, assumed to be 0.85 in this study.

Cost-benefit Analysis

We conducted cost-benefit analyses both for the individual adoption of technology over its life span (20 years), and for 50-year outcomes of neighborhood-wide adoptions of technology according to the three implementation strategies. The cost-benefit analysis is the most common method to assess economic feasibility of an environmental program that involves comparing the flow of expected costs and benefit from the program over a designated period (Atkinson and Mourato 2006). Among various decision rules of cost-benefit analysis (Christian Amos et al. 2016), we present Net Present Values (NPV), Benefit-Cost ratio (BC ratio), and payback period in this study.

The NPV is the sum of current value of future cash flows from a project. Thus, the NPV larger than zero indicates that benefits resulted from a project exceed its costs, which offers an economic rationale for the project. To calculate the current value, the assumption of a discount rate is required. We used a zero percent discount rate because we lacked data to support an expectation that the water price, as well as costs required for acquisition, installation, and operation would not increase at a similar rate of inflation over our extended period of investigation.

The BC ratio is the sum of discounted benefits divided by the sum of discounted costs, and a ratio greater than one indicates the benefits of a project exceed its costs. We use the BC ratio is to facilitate the comparison of analysis results by implementation strategies and neighborhoods at different scales (Boardman et al. 2017). The payback period is the time expected for a project to earn net revenue equal to net cost of a project. In this study, the payback period reflects the time required to offset capital costs when a household adopt water-conserving technologies.

We also estimate benefits of on-site water-conserving technologies by measuring reduced water bills for households. We calculate reduced water bills based on combined water rates of Atlanta, which is the sum of water and sewer rates. Depending on monthly household water consumption, the price of one CCF of water will fall within the range of $12.32 – $21.85, according to Atlanta's tiered water rate structure (City of Atlanta 2017).

For the evaluation of costs associated with technologies, we estimate the total cost of a system includes expenses for acquisition, installation, maintenances, and operation of systems. To estimate the acquisition cost, we first estimated required storage sizes or daily treatment capacities by unit types and neighborhoods. We calculate the storage capacity of a rainwater system according to the Water Balance Method that takes yearly distribution of rainwater supply and demand into account (Texas Water Development Board 2005). The required treatment capacity of a gray-water system is assessed based on results of our simulation model. Then, we reference actual market prices of commercially available rainwater and gray-water systems from websites of U.S. distributors and product catalogs (Aqua2Use 2018; INTEWA United States 2018; RainHarvest Systems LLC 2018). We specifically identified product lines that offer size and treatment capacity options, and selected a product best fitted to each residential unit in our neighborhoods.

Installation costs include material and labor expenses for placement of systems, as well as establishing collection and distribution systems. We only considered above-the-ground installation which is less expensive than under-the-ground installation. We also assumed that residential units are already equipped with basic rooftop fixtures, such as gutter and downspouts, and irrigation systems. The expected installation workload is highest for installing gray-water systems which require collection, indoor distribution, and outdoor distribution networks. The workload is lowest for installing rainwater systems for irrigation that only require an outdoor distribution network. To evaluate costs associated with material and labor, we primarily followed the methodology employed in Yu (2015) after the adjustment of local-specific parameters, such as the number of bathrooms.

Lastly, maintenance and operation costs of systems are estimated based on product information provided in catalogs and user manuals. In general, most systems recommend replacing filter cartridges within 1-5 years and UV lamps annually. The maintenance costs associated with these activities are estimated based on actual market prices of replacement components. We also considered electricity uses for the operation of systems. According to product specifications, a system with purification devices requires less than 2kWh, while one without requires 1kWh per one kiloliter treatment. Although a larger system is likely to be more efficient, because of lacking appropriate data, we applied these values for all systems to calculate annual electricity uses. Finally, the annual electricity cost is calculated by multiplying annual electricity uses by Atlanta's average electricity cost ($0.121/kWh) (Bureau of Labor Statistics 2018).

Water Affordability

The most widely applied method of measuring water affordability is to calculate the average per household costs of water and wastewater bills relative to the median household income and compare this percentage with a set of affordability standards. This study adopted the water affordability standard suggested by the U.S. Environmental Protection Agency (EPA) that considers annual household water bills greater than 4.5 percent of median household income to be unaffordable and a high burden (National Drinking Water Advisory Council 2003). Note that this affordability metric has some flaws. First, it does not take income stratification of a neighborhood into account and, thus, is likely to obscure water affordability problems of the lower income groups. Second, this measurement is insensitive to the costs of living that vary across cities and determine household disposable income (Teodoro 2018).

Results and Discussions

Future Household Water Consumption and Neighborhood Water Demand

Our model estimates that the average monthly water consumption in the three neighborhoods ranges from 12.22 (King Memorial) to 16.10 (Lindbergh) cubic meters for a single-family unit, and 9.89 (King Memorial) to 11.78 (Bankhead) cubic meters for a multifamily unit in 2018 (Figure 3). A single-family unit in Lindbergh is expected to consume the largest amount of water primarily because of outdoor water consumption. For a multifamily unit, Bankhead has the largest average amount of water use due to aged water fixtures, more persons per unit, and more irrigation water consumption. The authors validate our estimates using the actual water meter data of Atlanta (2013-2015), which was provided by city's Department of Watershed Management. Actual water meter readings in the three neighborhoods ranges from 12.71 (King Memorial) to 15.85 (Lindbergh) cubic meters for a single-family unit, and 10.36 (King Memorial) to 13.23 (Lindbergh) cubic meters for a multifamily unit. The percent errors of estimated water demand fall in a range of -18.26 – 10.79 percent, which gives confidence to our estimates.

Retrofitting of conventional water fixtures into water-conserving fixtures in accordance with Georgia's Plumbing Code (Georgia Department of Community Affairs 2012) would reduce the average amount of water consumed by existing residential units. Between 2018-2068, water consumption of an existing single-family residential unit is projected to decrease between 16.1 – 17.2% percent and an existing multifamily unit would decrease by 15.9 –17.2 percent (Figure 4). The reduction in water consumption from fixture retrofitting tends to be larger in single-family units than multifamily units since single-family units have higher water-conserving potential due to using water indoors and outdoors. The projected percent reduction in average water consumption between 2018-2068 will vary among three neighborhoods, as a result of differences in their age distribution of existing housing stock and household water-use patterns associated with their built environment.

Based on per household water consumption and changes in the number of residential units between 2018-2068, projected water demand is expected to increase in Bankhead, 25.1 percent, while that of other two neighborhoods decrease by 8.3 percent (Lindbergh) and 4.3 percent (King Memorial). Neighborhood water demand decreases slightly in Bankhead between 2018 and 2026 until the water demand from new infill residential exceeds the amount reduced by fixture retrofitting. In 2068, our model predicts that 73,466, 71,260, and 32,940 cubic meters of water will be required monthly for Lindbergh, King Memorial, and Bankhead, respectively.

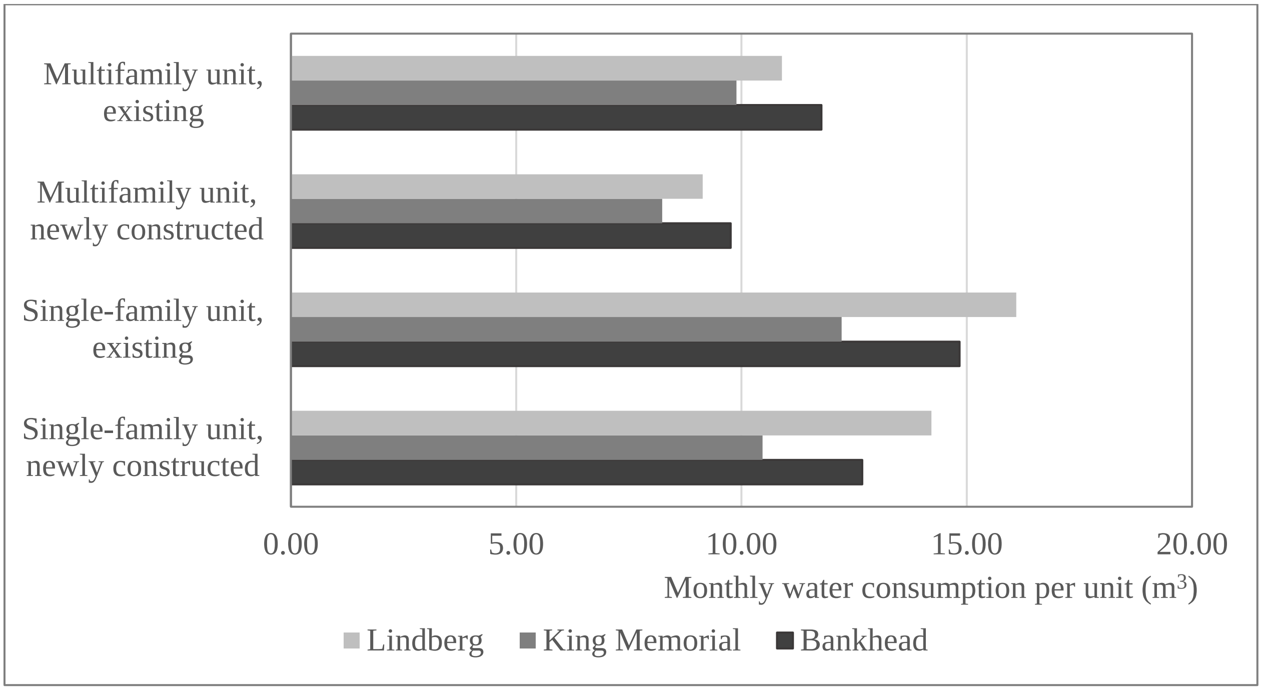

Figure 3. Household water consumption of three neighborhoods in 2018

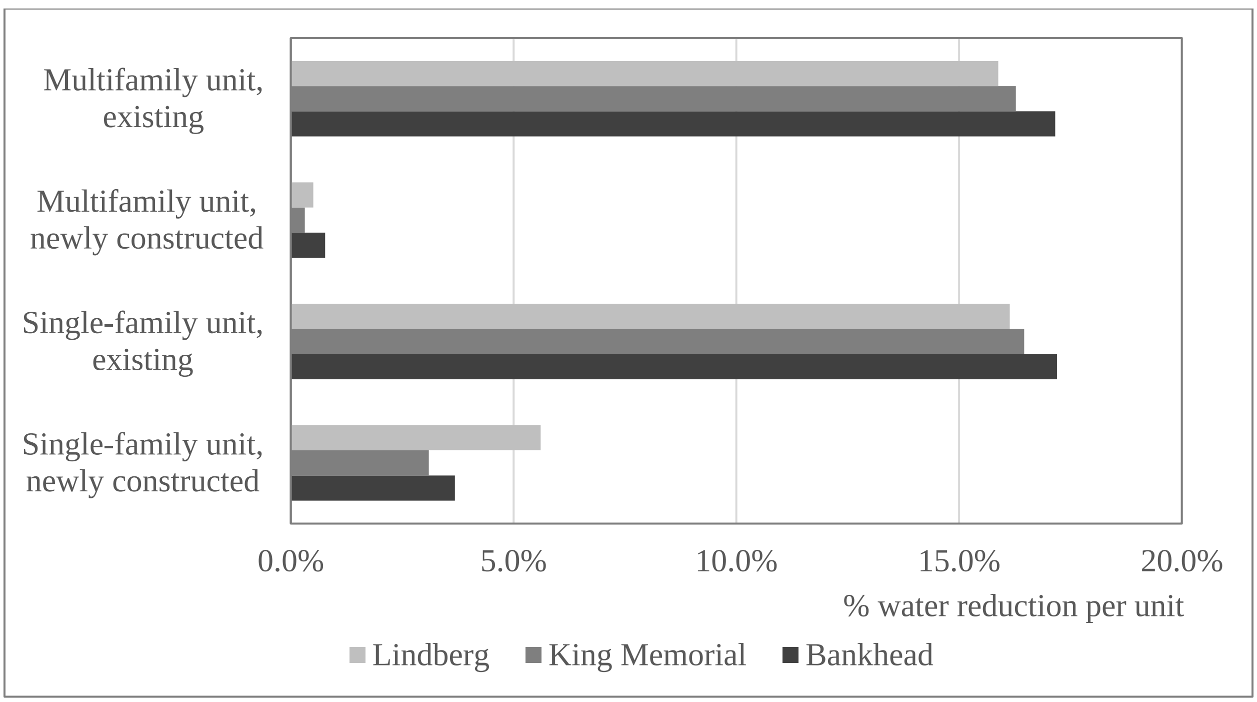

Figure 4. The percent of water consumption reduced in three neighborhoods between 2018-2068

Water Saving Potential of On-site Technologies

The effectiveness of an on-site system is defined as the maximum amount of reduced potable water consumption resulting from the system's production and household consumption capacity of non-potable water. In general, a rainwater system for a single-family unit can produce enough non-potable water for a household. However, most multifamily buildings require a gray-water system to meet the non-potable water demand as per unit rainwater collection area would be too small to support the households' demand as can be seen in the case of Lindbergh (Figure 5). King Memorial represents an exception as its multi-family rainwater system is expected to produce enough non-potable water because of unique built-environment characteristics of small-scale development with a large building-to-land ratio, and a small household size per unit.

The amount of reduced potable water consumption will vary across types of technology, residential unit, and neighborhood (Table 3). In general, a rainwater system for both indoor and outdoor use has the highest water-saving potential for a single-family unit, and a greywater system is the most effective for a multifamily unit. The type of residential unit that has the highest water-saving potential is the existing single-family unit. This unit type is expected to reduce potable water consumption by 13.7 to 25.5 percent with a landscape rainwater system, and 29.1 to 34.0 percent with a greywater system. A single-family unit in Lindbergh and a multifamily unit in Bankhead which has the higher average household water consumption, both have the highest water-saving potential with landscape rainwater and gray-water technologies. However, the indoor rainwater system for a multifamily unit is the most effective technology for King Memorial due to this neighborhood's unique built-environment characteristics.

In Figure 6, projections of reduced residential water demand of Lindbergh for three implementation strategies are presented. The percent reduction in potable water demand with water-conserving technologies decrease over time as the growing number of housing units is equipped with HEF. All implementation strategies will reach to the similar level of potable-water saving in 2068, while the time required to achieve the maximum water-saving potential varies. The most effective water-saving strategy, Implementation

Strategy 2, which requires all newly developed and existing residential units to equip with water-conserving technologies is expected to reduce neighborhood's water demand by 34.0 to 37.2 percent in 2068 with on-site greywater systems. In Strategy 1, which requires only newly developed residential units to equip with technologies, the total amount of reduced potable water with on-site greywater systems are 49.8 to 60.1 percent levels compared to that of Strategy 2. The total amount of reduced water demand in Strategy 3, which aims at incrementally adopting on-site technologies for existing residential units, is 71.6 to 78.1 percent levels of that from Strategy 2.

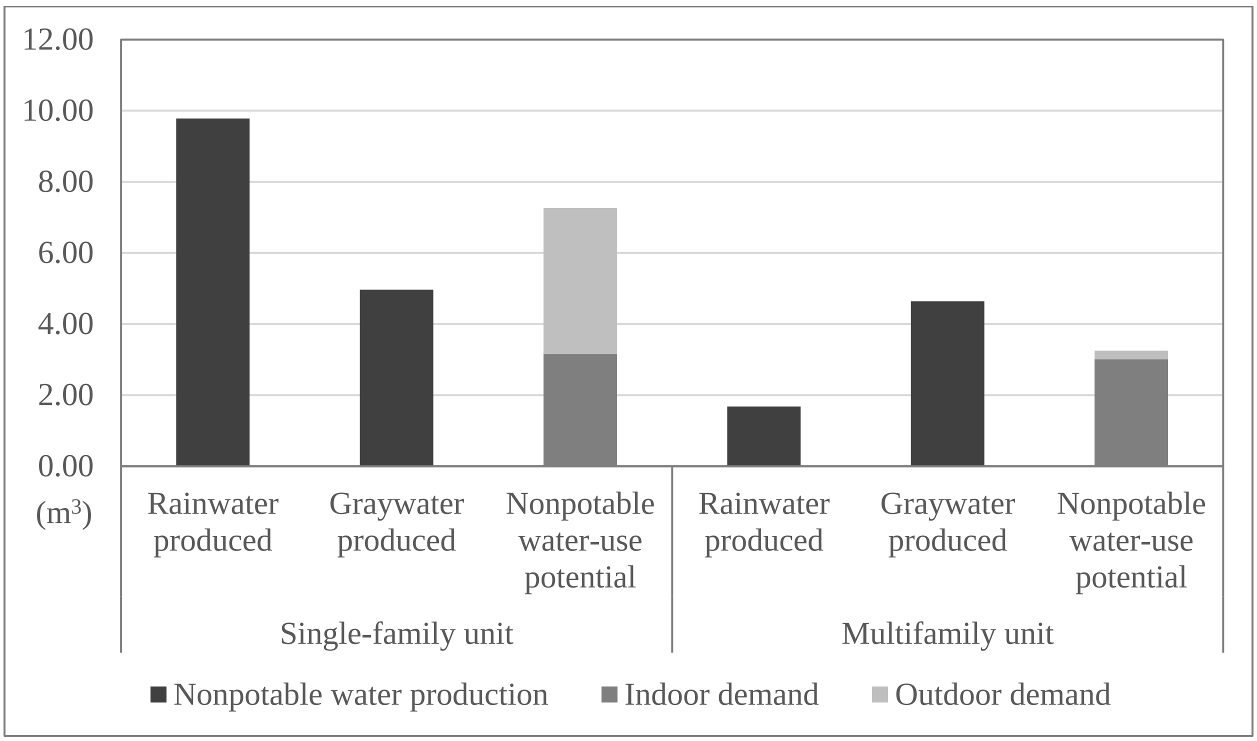

Figure 5. Non-potable water production and consumption potential per household – Lindbergh, 2018

Table 3. Reduced potable water consumption (cubic meters) per residential unit in 2018

Neighborhoods	Single-family, new	Single-family, existing	Multifamily, new	Multifamily, existing
Rainwater (landscape) system				
Lindbergh	4.109	4.109	0.238	0.238
King Memorial	1.672	1.672	0.134	0.134
Bankhead	2.408	2.408	0.388	0.388
Rainwater (landscape and indoor) system				
Lindbergh	6.560	7.263	1.681	1.681
King Memorial	3.949	4.633	2.238	2.238
Bankhead	4.959	5.827	1.636	1.636
Gray-water system				
Lindbergh	3.999	4.690	2.592	3.249
King Memorial	3.538	4.154	2.330	2.970
Bankhead	4.263	5.012	2.833	3.641

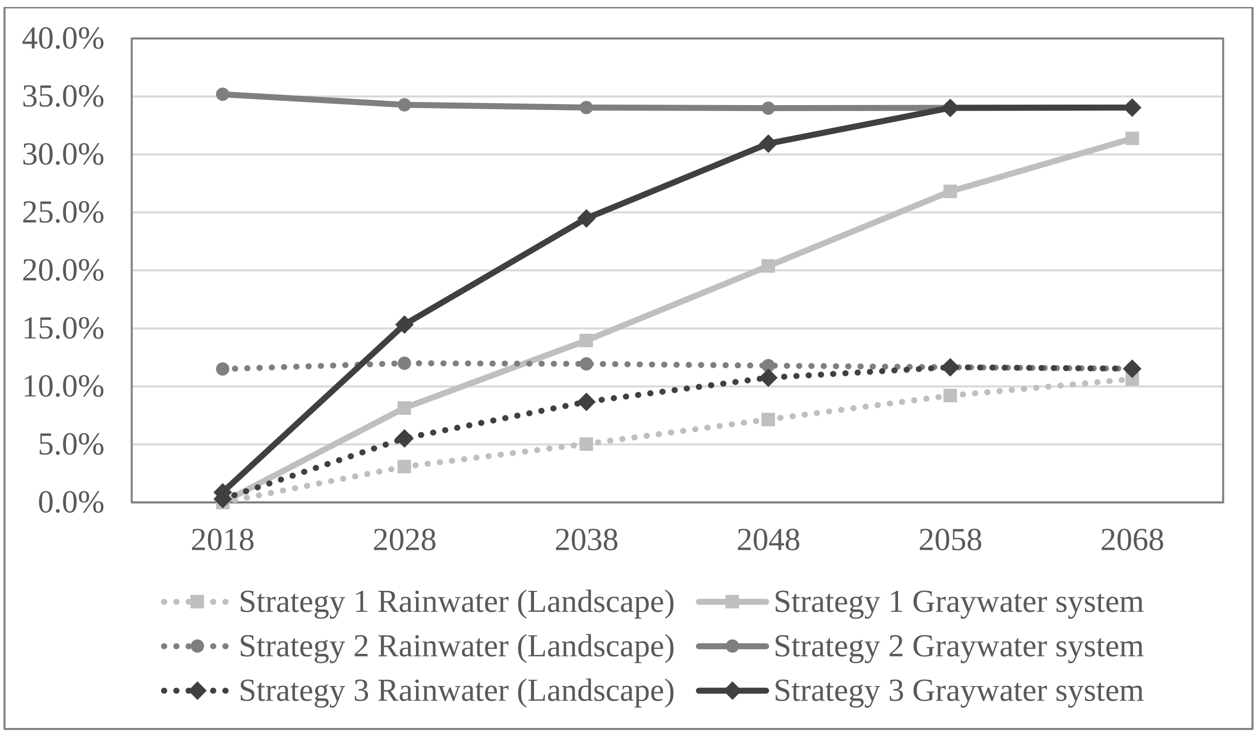

Figure 6. Reduced water consumption: three Lindbergh implementation strategies

Estimated Costs Associated with On-site Technologies

The cost of on-site water conserving technologies depends on multiple factors that vary across types of residential unit and land-use characteristics. The material cost related to the purchase of an on-site system (e.g., a rainwater tank and a greywater system) and its accessories (e.g., filter, pump, and controller) is determined by the required treatment capacity. The price of a commercially available above ground rainwater system with a capacity for a single-family unit ranges from $1,200 (2,650-liter cistern) to $1,580 (6,435-liter cistern), and a greywater system for a single-family unit costs approximately $6,000 (200 liters per day). The equipment cost per capacity tends to decrease rapidly as the capacity of an individual system increases. Thus, the cost of equipping a multifamily unit is significantly lower than that of a single-family unit. The equipment costs for multifamily units also varies depending on characteristics of a multifamily building and are estimated to be $733 for a new multifamily unit in King Memorial and $1,259 for an existing multifamily unit in Bankhead (Figure 7).

Installation costs for a water-conserving system depends on the type of technology adopted. Parameters used for estimating installation costs are presented in Appendix 3. The installation cost of a rainwater system for landscape water-use only is much smaller than a rainwater system for both indoor and landscape water use which requires fixture retrofitting for non-potable water transfer. The installation of a greywater system costs more because it requires additional pipes to collect greywater from bathroom sinks, showers, tubs, and washing machines. The cost for installing distribution and collection pipes are much higher for existing residential units due to the higher labor costs required for retrofitting. The estimated cost of installing a greywater system in a new multifamily unit is $993 – $1,002, compared to $3,429 – $3,474 in an existing multifamily unit.

Lastly, the annual operation cost associated with system maintenance and electricity use range from $27.8 to $116.3 per single-family unit and from $4.6 to $24.5 per multifamily unit. Again, a rainwater system for landscape water use has the smallest operation cost mainly because the city’s water quality guideline for rainwater systems are not applied to irrigation-purpose rainwater systems. In general, the operation costs for greywater systems are highest because of their many components, including prefiltration devices, air blowers, and UV disinfection devices, require regular maintenance.

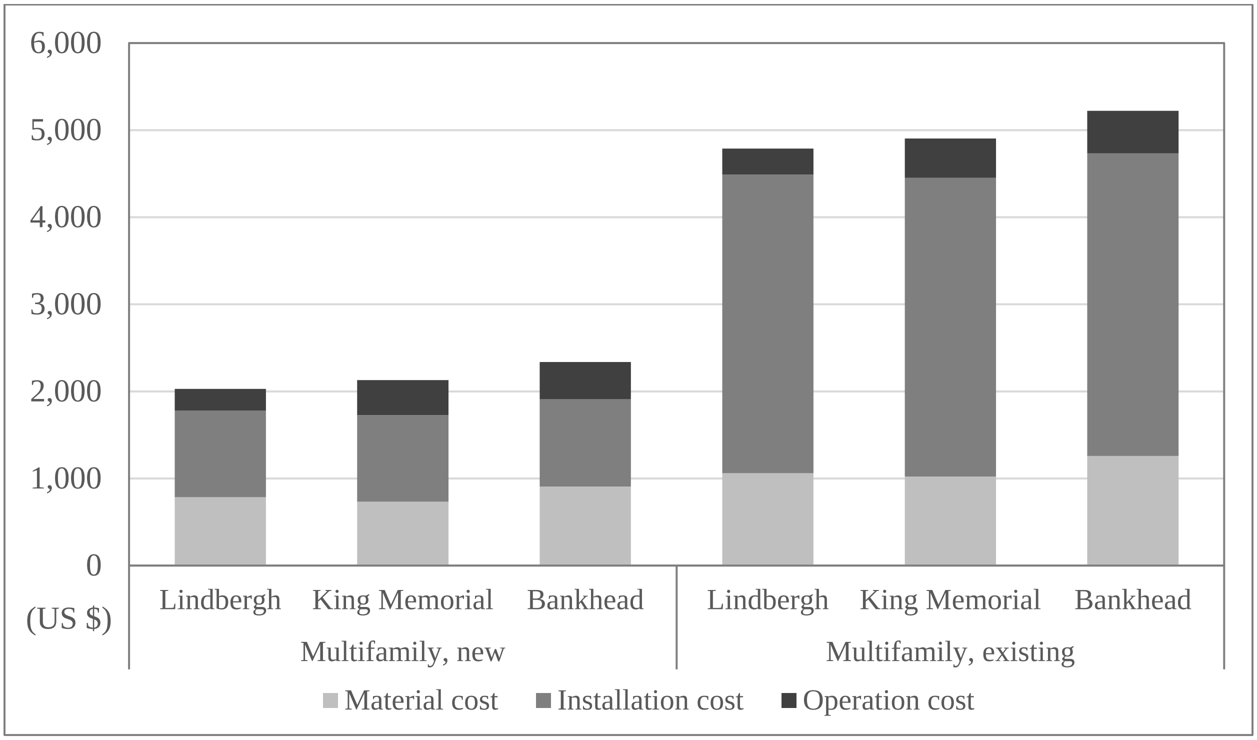

Figure 7. Estimated capital cost and 20-year operation cost of a greywater system

Cost-Benefits Analysis of Individual On-site Technologies

The results of *our cost-benefit analyses of average-type residential unit of each neighborhood are presented in Table 4*. Compared to previous case studies, the authors found the economic feasibility of water-conserving technologies of our case area to be relatively high. This is mainly because Atlanta has one of the highest water rates among major cities in the U.S. (Walton 2015). Indeed, the tiered water rates of Atlanta that have a range of \$4.35 – \$7.72 per one cubic meter is higher than that for all cities in previous studies (Appendix 4), including Barcelona (Spain, US\$1.32/m^3), Beijing (China, US\$ 0.56/m^3), Melbourne (Australia, US\$2.06-3.90/m^3), Sydney (Australia, US\$1.10/m^3), and Yorkshire (U.K., US\$3.27/m^3) (Farreny et al. 2011; Gato-Trinidad and Gan 2014; Liang and van Dijk 2010; Mitchell and Rahman 2006; Roebuck et al. 2012).

The cost-benefit analysis results show that on-site rainwater systems are economically feasible for single-family and multifamily units, except those in the King Memorial neighborhood. Rainwater systems for single-family units in King Memorial are not economically feasible because of insufficient non-potable water demand due to smaller household sizes and smaller irrigation areas. In the three neighborhoods, on-site rainwater systems supply enough non-potable water for single-family residential water use mainly because of sufficient rainfalls (48.79 inches per year) and small monthly rainfall fluctuation in Atlanta.

Similar to the results of previous studies, the NPV of greywater systems applied to single-family units are negative in all neighborhoods (Brown 2007; Memon et al. 2005; Yu et al. 2015). However, greywater systems applied to a multifamily unit in all the three neighborhoods have positive NPVs, and relatively short payback periods (12-14 years) compared to the 16-22 payback years reported in previous studies (Imteaz and Shanableh 2012; Liang and van Dijk 2010). The shorter payback period in our analyses is likely attributable to gray-water systems are greater sensitivity to economies of scale and cost-effective when applied to a large-scale and densely developed multifamily complex.

Our cost-benefit analysis results show that on-site water-conserving technologies are cost-effective, even when applied to a neighborhood's average residential unit. However, the prolonged payback periods may be the reason for the slow diffusion of on-site water-conserving technologies, since consumers are reluctant to invest in energy-saving equipment with extended payback periods (Cunningham and Joseph 1978). As the authors noted earlier, Atlanta imposes a flat sewer charge for indoor rainwater systems. This charge would increase the annual cost of indoor rainwater systems by $88.63 (King Memorial) to $208.74 (Lindbergh) lowering the economic feasibility of indoor rainwater systems. After considering the flat sewer charge, BC ratio for a single-family indoor rainwater system in Lindbergh slightly exceeds one (NPV: $233, BC ratio: 1.024).

Table 4. BC ratios of water-conserving technologies (zero interest rate applied)

Types of resident units	Rainwater (landscape)	Rainwater (Indoor and landscape)	Gray water (Indoor and landscape)
Single-family, New			
Lindbergh			
NPV ($)	3,919	4,408	-2,799
BC ratio	2.238	1.771	0.721
Payback period (years)	7	8	n.a.
King Memorial			
NPV ($)	-700	-354	-5,362
BC ratio	0.759	0.934	0.464
Payback period (years)	n.a.	n.a.	n.a.
Bankhead			
NPV ($)	1,298	-1,971	-3,290
BC ratio	1.433	1.359	0.673
Payback period (years)	12	12	n.a.
Multifamily, New			
Lindbergh			
NPV ($)	132	565	1,128
BC ratio	1.900	1.371	1.544
Payback period (years)	8	13	12
King Memorial			
NPV ($)	-131	895	708
BC ratio	0.545	1.475	1.326
Payback period (years)	n.a.	12	14
Bankhead			
NPV ($)	107	400	1,107
BC ratio	1.309	1.245	1.465
Payback period (years)	13	15	12

Evaluation of Three Implementation Strategies

Table 5 shows the neighborhood-scale cost-benefit analysis results of on-site water-conserving technologies by the three different implementation strategies. Land-use profiles and household characteristics of each neighborhood employed as parameters for the neighborhood-scale analysis are presented in Table 1. The implementation strategy that regulates equipping new residential units with on-site water-conserving technologies (Strategy 1) shows the highest economic feasibility, while the water-saving potential of such strategy is relatively low (Figure 6). The maximum water-saving approach, Strategy 2, which forces all residential unit a neighborhood to install water-conserving technologies by a designated date (2018) is a less preferable in terms of cost-effectiveness. However, in Lindbergh, Strategy 2 produces a slightly higher BC ratio than that of Strategy 3, which calls for incremental retrofitting of existing residential units. This is mainly because the benefits of on-site technologies decrease over time as the increasing number of housing units is equipped with HEF.

The NPVs and BC ratios presented in Table 5 are calculated based on the technologies that have the highest NPV by each neighborhood and residential type. The most cost-effective technologies differ by neighborhood and implementation strategy. This implies that it will be difficult to establish a city-wide policy that mandates on-site water-conserving systems. It also shows the need for a policy that is flexible enough to incorporate large differences in household and land-use characteristics across neighborhoods within the city. In addition, any policy aiming at the diffusion of on-site water-conserving technologies should be carefully designed considering the synergy between technologies and implementation strategies.

Note that the BC ratios for the neighborhood-wide application of water-conserving technologies are lower than those of individual applications presented in Table 4. This can be understood as the cost of inflexibility resulting from obligating the adoption of technologies without considering the planned or remaining lifetime of residential buildings. For instance, according to Strategy 2, each residential unit that becomes obsolete before the lifetime of on-site water conserving technologies (20 years) still installs the technologies. If we incorporate administrative costs for auditing the installation and the operation of on-site water-conserving systems, the BC ratios for the neighborhood-wide application will even be lower. Thus, policy decisions on water-conserving technologies should be made in consideration of such inefficiency and implementation costs.

This study conducts cost-benefit analysis from a customer perspective and assumes that water and sewer rates reflect capital, operation, and maintenance costs of a city's water service. However, water rates may not accurately reflect potential benefits of water-conserving technologies, such as deferrals of future infrastructure augmentation and reduction in pumping energy (Gurung et al. 2016; Lucas et al. 2010; Malinowski et al. 2015). They also do not account for negative environmental consequences associated with centralized urban water infrastructures, such as stream depletion and habitat destruction (Gleick 1998; Werbeloff and Brown 2011). Thus, policy decisions on water-conserving technologies should be made with technical, environmental, and societal concerns, rather than solely on financial assessments.

It is important to note that our study is conducted based on residential units having average characteristics of neighborhoods and tests implementation strategies that target every residential unit. In reality, there is a wide variation in the characteristics of households and residential units. To accommodate household variability, future modeling should be refined with a detailed housing unit profile in a neighborhood. For example, researchers may want to explore the use of recently developed real-estate databases that offers an application programming interface (API), such as Zillow and Trulia. Resulted model may facilitate cities' development of regulations applied to residential units that meet specific conditions, such as sizes and types of residential unit. The implementation of more refined regulation may further enhance cost-efficiency of the city-wide application of on-site water-conserving technologies.

Table 5. Estimated costs and benefits for 50 years of operation of three implementation strategies

	Selection of the best technology*				
	Single-family units	Multi-family units	**NPV (US$)**	**BC ratio**	**Cost per unit water saving (US$/m^3)**
Implementation Strategy 1					
Lindbergh	RW (indoor)	Gray water	15,481,495	1.559	3.121
King Memorial	RW (indoor)	RW (indoor)	6,987,450	1.225	3.522
Bankhead	RW (indoor)	Gray water	6,178,029	1.461	3.325
Implementation Strategy 2					
Lindbergh	RW (indoor)	Gray water	14,424,748	1.198	4.127
King Memorial	RW (landscape)	RW (indoor)	-2,988,296	0.945	4.751
Bankhead	RW (indoor)	Gray water	4,299,003	1.147	4.348
Implementation Strategy 3					
Lindbergh	RW (indoor)	Gray water	10,379,063	1.195	4.167
King Memorial	RW (indoor)	RW (indoor)	849,838	1.017	4.382
Bankhead	RW (indoor)	Gray water	4,320,333	1.198	4.160

* Choice of the best technology has been made based on the maximum NPV.

Social Implications of On-site Water Conserving Technologies

On-site water-conserving technologies have substantial social implications as these technologies contribute to the improvement of water access across social groups. Indeed, the enhancement of water affordability can be achieved not only by reducing water rates but also by equipping low-income households with water-efficient fixtures and technologies. Low-income households may benefit more from on-site water-conserving technologies given that they tend to live in older homes with less efficient fixtures and appliances (Cluett et al. 2016). Furthermore, plumbing codes that require residential units to use water-efficient fixtures and technologies can be an effective solution to the split incentive problem; that is, situations where landlords and tenants respond differently to incentive, which can hinder the adoption of energy-efficient technologies (Bird and Hernandez 2012).

In Table 6, we present the effects on-site technologies have on water affordability. According to the US EPA criterion, Bankhead low-income neighborhood, where the average single-family unit spends 4.27 percentage of its annual income for water, has a substantial water affordability problem. On-site water-conserving technologies could have a considerable effect on water affordability in this neighborhood by reducing households' annual water bills by $230 for a single-family unit with a rainwater irrigation system, and $279 for a multifamily unit with a gray-water system. These results suggest that on-site technologies can be used as a policy instrument for low-income households to correct unequal access to safe water (Leigh and Lee 2019).

Table 6. Effects of on-site water conserving technologies on water affordability

	Lindbergh	King Memorial	Bankhead
Annual median household income	$95,480	$65,420	$26,000
Estimated annual water bill (2018)			
Single-family, existing	$1212	$901	$1111
Multifamily, existing	$794	$713	$865
% of water bill to annual income			
Single-family, new existing	1.27%	1.38%	4.27%
Multifamily, existing	0.83%	1.09%	3.33%
Estimated annual water bill after adopting the best technologies of Strategy 1			
Single-family, existing	$820	$741	$881
Multifamily, existing	$565	$529	$586
% of water bill to annual income after adopting the best technologies of Strategy 1			
Single-family, existing	0.86%	1.13%	3.39%
Multifamily, existing	0.59%	0.81%	2.25%

Conclusions

In this paper, the authors presented an integrative modeling framework that incorporates housing dynamics, water fixture retrofitting, and water demand to investigate the effectiveness and the efficiency of on-site water-conserving technologies. The approach taken in this study can be especially useful when designing city- or neighborhood-wide policies on water-conserving technologies, which require long-term considerations of dynamics in land use, population, water fixtures, and water-use patterns.

Our research established that the costs and benefits of the neighborhood-wide application of on-site water-conserving systems are different from the sum of costs and benefits of individual systems. Although we found positive NPVs from implementing water-conserving technologies at the neighborhood scale, the value is lower than that from the cost-benefit analysis of a single on-site system. This was due to inefficiencies that that are the result of applying uniform regulations to different neighborhood types. Consequently, our research points to the need to design implementation strategies that require residential units adopting of on-site technologies targeted to specific conditions.

Our comparative neighborhood analysis showed that effectiveness and cost-efficiency of on-site water-conserving technologies can vary significantly across sub-areas within a city. This implies that effective water-conserving technology programs can be developed by focusing on a homogeneous neighborhood boundary. The choice of technology and implementation strategies should take into account local conditions, such as land-use characteristics and household structures. It is also necessary to consider socio-economic conditions of neighborhoods and to adopt technologies that can help relieve energy burdens and achieve equitable access to water for low-income neighborhoods.

In conclusion, our research demonstrates that the city-wide application of on-site water-conserving technologies is economically viable and can be a useful local policy tool to address environmental, economic, and social concerns associated with the delivery of urban water service. Further studies are needed to compare on-site water-conserving technologies and clustered-scale technologies. Finally, to bridge the current knowledge gaps and overcome institutional inertia that impede the diffusion of decentralized water technologies (Brown et al. 2006), there is need for a decision-making framework for specific implementation strategies.

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