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FEATURE ARTICLE

Life cycle assessment of low impact development technologies combined with conventional centralized water systems for the City of Atlanta, Georgia

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HIGHLIGHTS

- Hybrid system of LID technologies and conventional system was examined.
- Bioretention areas, rainwater harvesting, and xeriscaping were considered.
- Technology feasibility was simulated for land use and population density.
- Synergistic effects of technologies were quantified in defined zones.
- Uncertainty test was conducted with pedigree matrix and Monte Carlo analysis.

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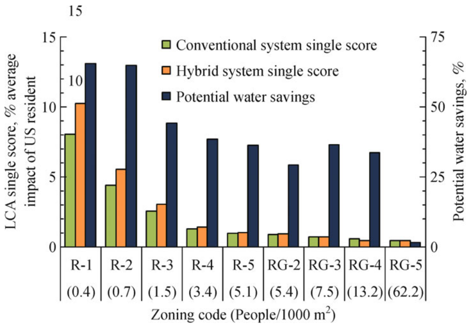
GRAPHIC ABSTRACT



ABSTRACT

Low-impact development (LID) technologies, such as bioretention areas, rooftop rainwater harvesting, and xeriscaping can control stormwater runoff, supply non-potable water, and landscape open space. This study examines a hybrid system (HS) that combines LID technologies with a centralized water system to lessen the burden on a conventional system (CS). CS is defined as the stormwater collection and water supply infrastructure, and the conventional landscaping choices in the City of Atlanta. The study scope is limited to five single-family residential zones (SFZs), classified R-1 through R-5, and four multi-family residential zones (MFZs), classified RG-2 through RG-5. Population density increases from 0.4 (R-1) to 62.2 (RG-5) persons per 1,000 m^2. We performed a life cycle assessment (LCA) comparison of CS and HS using TRACI 2.1 to simulate impacts on the ecosystem, human health, and natural resources. We quantified the impact of freshwater consumption using the freshwater ecosystem impact (FEI) indicator. Test results indicate that HS has a higher LCA single score than CS in zones with a low population density; however, the difference becomes negligible as population density increases. Incorporating LID in SFZs and MFZs can reduce potable water use by an average of 50% and 25%, respectively; however, water savings are negligible in zones with high population density (i.e., RG-5) due to the diminished surface area per capita available for LID technologies. The results demonstrate that LID technologies effectively reduce outdoor water demand and therefore would be a good choice to decrease the water consumption impact in the City of Atlanta.

1 Introduction

Large-scale centralized water systems provide the essential services of water supply, wastewater treatment, and stormwater runoff control. Most centralized water supply systems withdraw 100% of their water from the environment and treat it to potable quality regardless of the intended water use. Four percent of total electricity consumed in the United States (US) is used for transporting and treating water and wastewater [1]. Transportation of water from surface reservoirs to residential areas accounts for ~80% of consumed electricity for water supply systems

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[1]. As population expands, such water supply systems cannot be sustained with limited water resources and that makes it impossible to reduce carbon emissions if fossil fuel-based energy is used [2,3]. In the US, ~40 million people in 772 cities rely on combined sewer systems (CSS) [4] that transport domestic wastewater and stormwater runoff in a single pipeline network connected into wastewater treatment plants. Energy and chemicals are consumed to treat domestic wastewater as well as stormwater runoff. Furthermore, CSS is vulnerable to overflow and flooding during intensive rain events, which, in turn, can contaminate surface waters and increase erosion. Apprehension over flooding and surface water contamination is growing as the impervious surface area expands with increased urbanization, and as more extreme rain events are observed due to climate change.

Low-impact development (LID) technologies, such as rain gardens, green roofs, and rainwater harvesting, are decentralized alternatives that control stormwater runoff and supply water on site. Many studies describe how LID technologies control the rate and volume of stormwater runoff, and prevent degradation of surface water quality and aquatic habitats [5–10]. Additionally, implementing LID technologies creates green spaces, which reduce heat stress mortality, and increase property value and recreational opportunities [11,12]. Rainwater harvesting technology converts stormwater runoff into a water resource, which can be used for groundwater recharge and non-potable purposes such as irrigation, toilet flushing, and laundry [13–17].

Farreny et al. (2011) analyzed the cost-benefit of four rooftop rainwater harvesting strategies in new or retrofit construction for: (1) residential neighborhoods of single-family homes, and (2) multi-story buildings [18]. The study concluded that the residential neighborhoods of single-family homes benefit more than multi-story buildings, regardless of whether they were new or retrofit construction. This conclusion is strongly influenced by the small rainwater volume per dwelling for an area with a high population density and our study also examines this in detail.

Few studies that conduct life cycle assessments (LCA) for LID technologies consider land use, population density, and centralized water systems. Angrill et al. (2012) conducted LCAs to determine the best scenario of rooftop rainwater harvesting for the tank location within two different residential types: detached single-family houses and 5-story apartment buildings [19]. The comparison was conducted for the functional unit of 1 m^3 rainwater use. Distributing the storage tanks over the roof of each apartment building resulted in the best environmental performance in their study. However, if the rainwater use per dwelling of an area is compared, the single-family house community could result in better environmental performance than the apartment building community of high population density. Thus, our study simulates areal rainwater use for different residential types and population density.

Spatari et al. (2011) compared the life cycle energy consumption and greenhouse gas emissions of green infrastructure (GI), permeable pavement and street trees, to a conventional street design. GI results in slow payback times as it reduces stormwater runoff and energy demand for a CSS but consumes more embodied energy as compared to conventional street construction [20]. De Sousa et al. (2012) compared carbon emissions of three strategies, GI, detention tanks connected to wastewater treatment plants, and detention tanks and on-site treatment facility, to control a same volume of combined sewer overflow [21]. Permeable pavement, rain gardens, and subgrade cistern were considered as the GI not connected to CSS. GI decreases at least 78% of the carbon emissions compared to the other two strategies due to low energy and chemicals consumption for operation and maintenance. It can be concluded from the two studies that GI lessens burden on CSS, but controlling stormwater separately with domestic wastewater has more influence on reducing energy use and greenhouse gas emissions. As most stormwater runoff is controlled using separate storm sewer (SSS) in the City of Atlanta (CoA), the effects of LID technologies on SSS were conducted in this study.

Wang et al. (2013) compared green alternatives (bioretention basin, green roof, and permeable pavement) with the existing CSS, SSS, and integrated alternatives that combine one green alternative with the SSS [22]. This study concludes that the construction phase of a bioretention basin results in the least climate change and economic costs for removing water pollutants, while SSS consumes the least energy for removing pollutants [22]. It was also concluded that the impact of SSS differs depending on the water quality of stormwater runoff. Although we do not consider the effect that land use has on the generated stormwater quality, our study simulates stormwater runoff volume in different residential communities for the comparison of LID technologies and SSS.

We evaluate the effects of LID technologies together within a conventional system (CS) for a variety of residential communities in the CoA that vary by land use and population density. LID technologies considered in this study include bioretention areas, rainwater harvesting, and xeriscaping. Stormwater runoff is detained and filtered using bioretention areas. Rainwater harvested from rooftops is used for irrigation and/or toilet flushing. The outdoor water demand for lawns is reduced by xeriscaping, which is to landscape with native or low water plants. Even when these LID technologies are implemented, a centralized water system is required to supply potable water and discharge stormwater runoff whether or not it's filtered by bioretention areas. Therefore, we propose hybrid system (HS) in which the LID technologies are combined with the stormwater collection and water supply infrastructure of the city's centralized water system. We defined CS as the water supply and stormwater collection infrastructure of the CoA's centralized water system with conventional landscaping, lawns. Feasibility on the use of LID technologies was simulated for nine residential communities with different land use and population density. Finally, we compared the LCA single scores of CS and HS for nine residential zones and evaluated the LID technologies' effects on CS for each zone.

2 Methods

2.1 Functional units and LCA scope

Bioretention areas were compared with the CoA's stormwater collection system for 1-m^3 stormwater runoff generated in 2010. Most stormwater runoff is collected through separate pipelines within the city [23]. The design life of bioretention areas was assumed as 30-years [22,24]. Rainwater harvesting was compared with the CoA's water supply system for 1-m^3 water distributed to the point-of-use (i.e., irrigation and toilet flushing), assuming a 50-year design life [25]. Xeriscaping was compared to lawns, a conventional landscaping choice in the CoA's residential zones, for 1-m^2 of open space. A 10-year design life was assumed for both options [26]. The construction and maintenance phases were scoped for the LID technologies. Only the operation phase was evaluated for the CS components. The decommissioning phase was excluded in this study as its impact is minor and uncertain due to the development of new recycling processes [24,25].

2.2 Residential zones and water flows

The zoning code of the CoA regulates five single-family house zones (SFZs), classified as R-1 through R-5, and six multi-family apartment zones (MFZs), classified as RG-1 through RG-6. By investigating geographical information systems (GIS) files showing the CoA's zones [27], we verified that five SFZs, R-1 through R-5, and four MFZs, RG-2 through RG-5, exist in the city, and selected one median-sized example for each zoning class. Impervious land surface area, rooftop shape and area, landscaped open space, building height, and the number of households were determined using a satellite map, an area calculator, and real-estate information available online. The number of residents was estimated using the number of households and the household sizes: (1) 3.25 persons for a single-family house, and (2) 1.56 persons for a multi-family apartment unit. The household sizes were estimated from the numbers of single and multi-family households, the average household size, and the ratio of single person households for the CoA [28]. The top-view maps of the nine residential zones and land use data are presented in Fig. S1 and Table S1 of the Supplementary Material (SM).

Stormwater runoff volume was quantified using the Soil Conservation Service method and the CoA's 2010 daily precipitation data [29]. Runoff volumes (in.) are correlated with rainfall intensities (in.) according to curve numbers (CNs), a quantified characteristic of the land cover [30]. This method is appropriate for 24-h rainfall intensities (in. day^{-1}). The CNs of the nine residential zones were determined according to the impervious land surface area and the soil moisture condition associated with seasons (i. e., dormant or growing season) and 5-day total antecedent rainfall intensity [30–32].

We used a per capita indoor water demand estimated for single-family households, 299 L·day^{-1}, in both residential types [33]. The frequency of toilet use and shower time are not dependent on residential type, even though multi-family households can use less water than single-family households due to low-income level or built-in low-flow appliances [34–36]. Outdoor water use was calculated by multiplying the size of landscaped open space (i.e., lawns) by an annual irrigation factor, 165 L·m^{-2}·yr^{-1}. The irrigation factor corresponds to a conventional landscaping type used in residential communities of the Atlanta metro area in the humid southern zone of US [37]. Variations of irrigation factor by turf grass species were not incorporated in this study.

2.3 Materials, processes, and direct emissions of LID technologies and conventional system components

2.3.1 Centralized water system

The input data of materials, processes, and direct emissions related to the CoA's water supply and stormwater collection were taken from our previous LCA study for the CoA's centralized water system [23].

2.3.2 Bioretention areas

Design parameters and effects of LID technologies are briefly illustrated in Table 1. Bioretention areas reduce stormwater runoff, delay its peak flow rate, and remove water pollutants in areas less than either ~20,000 m^2 (5 acres) or a single residential lot [38]. We designed the total size of bioretention areas for each zone to contain stormwater runoff for 85.3 mm·day^{-1}, which is the rainfall intensity with a 1-year return period in the Atlanta metro area [30]. Materials (e.g., gravel, PVC pipe, and mulch) and processes (e.g., excavation and mulching) that are required for installing and maintaining bioretention areas were determined according to the design criteria that are shown in Fig. 1 [38].

The drain layer placed under the filter layer drains the filtered stormwater runoff, which then flows into the SSS through two longitudinal PVC pipes and one lateral pipe, each placed every 7.62 m (25 ft). A liner is installed underneath the drain layer to prevent groundwater contamination. Because we designed the total bioretention

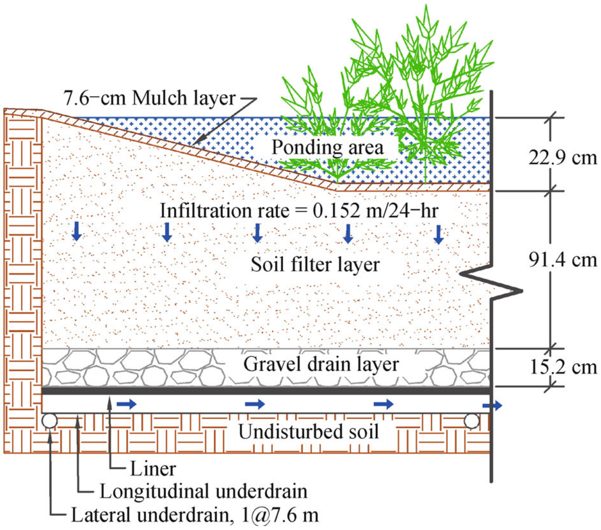

Fig. 1 Bioretention area design parameters, not to scale

area within a zone, and each was designed according to the land use of a residential community, the pipeline length was determined for the smallest dimension (i.e., ~5 m x ~10 m) of each bioretention area, as regulated by the USEPA [42].

Landscape for the ponding area is composed of native vegetation and a 7.62cm (3 in.) mulch layer that is replaced biennially as it is biodegraded or lost to the environment [30]. A 100-km truck-transportation distance was assumed between local stores and residential zones. The impact of native plants on the environment was assumed to be negligible because neither herbicides, pesticides, nor fertilizer are used for growing plants within the ponding area. The direct emissions of water pollutants into the environment were calculated according to the removal efficiency of the bioretention areas (Table 1), and the water pollutant concentrations estimated for the city's stormwater runoff [23]. The removal efficiency of heavy metals was assumed equivalent to that of suspended solids, 80%, since heavy metals in stormwater runoff are mostly adsorbed by the soil [39].

2.3.3 Rainwater harvesting

Rainwater harvested from rooftops was simulated using the CoA's 2010 daily precipitation data, rainwater loss, and harvesting efficiency. Rainwater loss in rooftop wetting, evaporation, and first flush is 1.02 L/m^2 for each rain event [43,44]. The above-ground storage tank, made from high density polyethylene (HDPE), was sized to collect 80% of annual precipitation and supply a constant amount of rainwater every day and reserve a 15-day rainwater supply for a dry season. The maximum consecutive days having their total precipitation less than a day's rainwater use was 15 days in 2010. Harvesting greater than 80% would require a dramatically larger and impractical tank. The value of the first day's rainwater volume in the tank was also used as the last day's volume because the rainwater harvesting continues for several years even though the simulation was conducted for a year, 2010. The maximum volume of commercialized storage tanks is less than or equal to 10,000 gallons, therefore, multiple tanks were used for each zone to accommodate storage needs.

The length of PVC half-rounded gutter was determined according to each rooftop shape as illustrated in Fig. S1. PVC downspout pipelines were designed to connect from the rooftop to each rainwater tank. Therefore, the downspout pipeline length was matched to the height of houses or apartment buildings, where the height of one story was assumed as 3.3 m. However, in the case of the 31 story high-rise apartment building in RG-5 the downspout pipeline was designed to convey rainwater only one story, from its decorative roof to storage tanks on its flat rooftop (Fig. S1). All the rainwater is used for toilet flushing of top floor residents. Distribution pipelines conveying rainwater for toilet flushing were designed to connect storage tanks to the center of the top floor [25]. Distribution pipelines in R-1 and R-3 zones are not required since all the harvested rainwater was used for outdoor irrigation.

Pumps and pumping energy were designed according to the rainwater volume needs for irrigation and toilet use, horizontal and vertical distribution distances, and an operating pressure with 60% energy efficiency. Debris, dirt, and bird excretions in rainwater are removed through a downspout strainer and first flush diverter. The rainwater supplied for toilet flushing is treated using sediment filter and UV disinfection.

2.3.4 Lawn and xeriscaping

Lawn, a conventional landscaping choice, was compared to xeriscaping, which uses native or low water-intensive plants. The materials and processes to maintain lawns were determined from literature [26]. Reductions in water consumption, fertilizer, herbicide, and pesticide use are shown in Table 1. Mulch applied to the soil surface is replaced every 2 years [40,41]. The planting process for xeriscaping was considered as the construction phase; however the phase was not scoped for lawns already used in residential zones. The lifespans of materials designed for each technology were obtained from the life expectancy chart of International Association of Certified Home Inspectors [45]. The material use was calculated according to the lifespan of each LID technology.

2.4 LCI, LCIA, and FEI

SimaPro 8.0 was used to conduct the LCAs since it

Table 1 Design criteria and effects of LID technologies

bioretention areas	
design life [22,24]	30 years
design criteria	1-year return period rainfall intensity
pollutant removal efficiency [38]	
total suspended solids	80%
total phosphorus	60%
total nitrogen	60%
heavy metals [39]	80%
rainwater harvesting	
design life [25]	50 years
design criteria	80% of annual precipitation
rainwater use	outdoor irrigation and toilet flushing
xeriscaping	
design life [26]	10 years
design criteria	landscaped open space
maintenance reduction [40,41] (compared to lawns)	
water consumption	50%
fertilizer use	61%
herbicide use	22%
pesticide use	22%

provides diverse inventory databases and impact assessment methodologies. Air, water, soil emissions, and resource use were inventoried using ecoinvent v. 3.0, US LCI, and US input-output databases. In cases where US data did not exist for certain materials or processes, international data within the databases were used after modifying influential impact sources, such as electricity or fuel use with US data. The material, process, and direct emission inputs for each technology are presented in Tables S2-S5. The emissions and resource use of a by-product is determined from the dataset of its related product on weight basis [46]. All the emissions and resource use were characterized and normalized into ten impact categories using TRACI 2.1 (v. 1.02) [47], an LCIA methodology developed for North America. Characterized impacts are normalized to the US per capita annual emissions (2008) in the TRACI. A single score was calculated manually by weighting the normalized impacts. A set of weighting factors applicable to the TRACI are 2%, 29%, 4%, 3%, 6%, 8%, 5%, 9%, 8%, and 10% for ozone depletion, global warming, smog formation, acidification, eutrophication, carcinogenic effects, non-carcinogenic effects, respiratory effects, ecotoxicity, and fossil fuel depletion, respectively [48].

The impact of freshwater consumption is not considered in the TRACI. Therefore, we used the freshwater ecosystem impact (FEI) indicator to evaluate the impact of freshwater consumption on the regional water ecosystem. FEI is the product of the freshwater volume consumed in a process and the water resource stress, which is defined as the ratio of water withdrawal to water availability (WTA) [49,50]; however, due to similarities in measurement, we used the water supply stress index (WaSSI) instead of the WTA [23]. Accordingly, the FEI can vary with respect to the river basin's water stress. The WaSSI of the middle Chattahoochee River basin, where the CoA located, is 0.248 [51]. WTA or WaSSI values greater than 0.2 or 0.4 refer to a moderate or severe stress level, respectively [51,52]. Since the FEI refers to the reduction of freshwater volume within an ecosystem it is expressed as "m^3 ecosystem equivalent."

2.5 Uncertainty and sensitivity analysis

Material, process, or infrastructure uses and direct emissions can be uncertain because of measurement errors or data deficiency. Data uncertainty can be quantified using the standard deviation, which depends on the input type (e.g., infrastructure or electricity) and six data qualities [53]. The standard deviation according to the input type is basic uncertainty, which is compiled in the ecoinvent database from published work. The six data qualities are reliability (i.e. data verification), completeness (i.e., representativeness), temporal correlation, geographic correlation, further technological correlation, and sample size. These qualities modify the basic uncertainty using the pedigree matrix approach [54]. Impact values were calculated 5,000 times using the standard deviations of all the inputs according to Monte Carlo method [53]. The procedure for quantifying and testing data uncertainty is provided in SimaPro 8.0. Furthermore, we examined the sensitivity of impact according to a change of each input (e.g.,±10%).

2.6 Community-level comparison

We simulated the feasibility of LID technologies for nine residential zones. Stormwater runoff volumes, bioretention area, water demand, rainwater use, and landscape choice (i.e. lawn or xeriscape) were decided for each zone and normalized to 1,000 m^2. By inputting the environmental impacts for each LID technology and CS components into the water flows and landscaped areas, we quantified the environmental impacts of CS and HS for each zone.

3 Results and discussion

3.1 Life cycle inventory (LCI)

Input data (i.e., material use and direct emissions) related to bioretention areas, rainwater harvesting, xeriscaping, and lawns are presented in the supplementary material in Tables S2-S5, along with detailed information about how they were computed. In the case of rainwater harvesting, the inputs used for harvesting 1 m^3 rainwater vary by zone. The inputs designed for each zone are presented in Table S4.

3.2 LCA comparison of LID technologies to CS components

3.2.1 Environmental impacts of LID technologies and CS components

The environmental impacts of CS components and LID technologies are shown in Table 2 per functional unit. All impact values are compared to the average annual impacts of a US resident in 2008. The comparison of LID technologies with CS components are illustrated in Fig. S2 with normalized impacts. The contributions of input data toward each impact of LID technologies and lawns are presented in Tables S6–S8.

3.2.2 Bioretention areas

The bioretention areas' greatest impact categories are eutrophication (0.007%), carcinogenic effects (0.03%), non-carcinogenic effects (0.005%), and ecotoxicity (0.02%) (See Table 2 and Fig. S2). Water pollutants, mulch, and PVC pipes are major impact sources and contribute at least 78% toward each impact as shown in Table S6. Water pollutants contribute 78%, 21%, and 48% toward the eutrophication (1.41E-03 kg N eq), the non-carcinogenic effects (5.16E-08 CTUh), and the ecotoxicity (1.70 CTUe), respectively, and are presented in Table S11. PVC pipe contributes 70%, 37%, and 28% toward the carcinogenic effects (1.54E-08 CTUh), non-carcinogenic effects, and ecotoxicity categories, respectively. Mulch contributes 28% and 17% toward the non-carcinogenic effects and ecotoxicity categories, respectively.

The CoA's stormwater collection system's largest impact categories are eutrophication (0.02%), non-carcinogenic effects (0.005%), and ecotoxicity (0.03%) (See Table 2 and Fig. S2). Water pollutants in the stormwater runoff are the main contributors toward the impact of this system because the operation phase involves collecting stormwater runoff and discharging it directly into the water environment. By utilizing bioretention area, the eutrophication (3.42E-03 kg N eq), non-carcinogenic effects (5.34E-08 CTUh), and ecotoxicity (3.71 CTUe) impacts for 1 m^3 of stormwater runoff can be reduced by 59%, 3%, and 54%, respectively. However, as a result of weighting normalized impacts, the single score of bioretention area (5.01E-03%) is greater compared to the stormwater collection system (3.90E-03%) (See Table 3) mainly due to the carcinogenic effects caused by utilizing bioretention areas.

Table 2 Life cycle environmental impacts of conventional system components and LID technologies compared to the average impacts of US residents per year (2008) *

impact		conventional system			LID technology		
		stormwater collection, 1 m^3	water supply, 1 m^3	lawn, 1 m^2	bioretention areas, 1 m^3	rainwater harvesting, 1 m^3	xeriscaping, 1 m^2
ozone depletion	kg CFC-11 eq (%)	0 (0)	1.55E-8 (0)	2.89E-8 (0)	3.14E-9 (0)	2.09E-8 (0)	2.02E-8 (0)
global warming	kg CO_2 eq (%)	0 (0)	5.73E-1 (0.0024)	3.41E-1 (0.0014)	3.78E-1 (0.0016)	4.03E-1 (0.0017)	5.67E-1 (0.0023)
smog formation	kg O_3 eq (%)	0 (0)	3.75E-2 (0.0027)	1.52E-2 (0.0011)	4.84E-2 (0.0035)	2.09E-2 (0.0015)	9.18E-2 (0.0066)
acidification	kg SO_2 eq (%)	0 (0)	5.15E-3 (0.0057)	3.19E-3 (0.0035)	2.36E-3 (0.0026)	2.31E-3 (0.0025)	4.94E-3 (0.0054)
eutrophication	kg N eq (%)	3.42E-3 (0.0160)	3.27E-4 (0.0015)	2.04E-4 (0.0009)	1.41E-3 (0.0065)	1.75E-4 (0.0008)	2.45E-4 (0.0011)
carcinogenic effects	CTUh (%)	2.93E-12 (0)	1.53E-8 (0.0301)	6.20E-9 (0.0122)	1.54E-8 (0.0302)	8.31E-9 (0.0163)	6.11E-9 (0.0120)
non-carcinogenic effects	CTUh (%)	5.34E-8 (0.0051)	2.68E-8 (0.0026)	1.69E-7 (0.0160)	5.16E-8 (0.0048)	2.97E-8 (0.0028)	5.62E-8 (0.0054)
respiratory effects	kg $PM_{2.5}$ eq (%)	0 (0)	2.89E-4 (0.0012)	2.09E-4 (0.0009)	1.22E-4 (0.0005)	1.38E-4 (0.0006)	1.74E-4 (0.0007)
ecotoxicity	CTUe (%)	3.71 (0.0336)	2.78E-1 (0.0025)	5.85E-1 (0.0053)	1.70 (0.0153)	5.20E-1 (0.0047)	1.09 (0.0099)
fossil fuel depletion	MJ surplus (%)	0 (0)	5.53E-4 (0)	3.14E-4 (0)	1.20E-2 (0.0001)	4.86E-2 (0.0003)	8.67E-5 (0)
single score	%	0.0039	0.0039	0.0029	0.0050	0.0026	0.0033

Note: * Percent (%) values indicate the amount each impact contributes to the average impact of a US resident in the 2008

3.2.3 Rainwater harvesting

The largest impact categories for rainwater harvesting are acidification (0.003%), carcinogenic effects (0.02%), non-carcinogenic effects (0.003%), and ecotoxicity (0.005%) (See Table 2 and Fig. S2). The HDPE storage tank contributes 46%, 55%, and 54% toward the acidification (2.31E-03 kg SO_2 eq), carcinogenic effects (8.31E-09 CTUh), and ecotoxicity (5.20E-01 CTUe) impacts, respectively (see Table S7). PVC gutter and pipeline contribute 35% to the carcinogenic effect and 25% to the ecotoxicity impacts. Pumping equipment is linked with 46% of the non-carcinogenic effects (2.97E-08 CTUh) and pumping energy (0.138 kWh) contributes 41% to acidification.

The CoA's water supply system's greatest impacts are acidification (0.006%) and carcinogenic effects (0.03%) (See Table 2 and Fig. S2). The major sources of those impacts are electricity consumption and chemical use (See Table S7). The electricity (0.615 kWh) that is consumed for supplying 1 m^3 potable water to the point-of-use contributes 82% to the acidification impact (5.15E-03 kg SO_2 eq). Aluminum sulfate, a typical coagulant for water treatment, accounts for 73% of the carcinogenic effects (1.53E-08 CTUh). Using harvested rainwater decreases the acidification and the carcinogenic effects by 55% and 46%, respectively. Accordingly, the single score of rainwater harvesting (0.0026%) is 34% less than the water supply system's (0.0039%) even though rainwater harvesting has 14% and 88% greater impacts on the non-carcinogenic effects and ecotoxicity categories, respectively.

3.2.4 Xeriscaping

Xeriscaping has greatest impact on the smog (0.007%), acidification (0.005%), carcinogenic effects (0.01%), non-carcinogenic effects (0.006%), and ecotoxicity (0.01%) categories (See Table 2 and Fig. S2). All of impact values of xeriscaping and lawns are presented in Table S8 with contributions of the inputs to each impact. Mulch contributes toward 76% of the smog formation (9.18E-02 kg O_3 eq), 61% of the acidification (4.94E-03 kg SO_2 eq), 50% of the carcinogenic effects (6.11E-09 CTUh), 58% of the non-carcinogenic effects (5.62E-08 CTUh), and 59% of the ecotoxicity (1.09 CTUe) categories. Potable water use for irrigation contributes 21% toward the carcinogenic-effects. Transportation is linked with 24% of the non-carcinogenic effects and 24% of the ecotoxicity impact.

The major impacts of lawns are the carcinogenic effects (0.01%) and non-carcinogenic effects (0.02%) (See Table 3 and Fig. S2). Mowing contributes toward 51% of the carcinogenic effects (6.20E-09 CTUh) and 90% of the non-carcinogenic effects (1.69E-07 CTUh) (See Table S8). Potable water use for irrigation accounts for 41% of the carcinogenic effects. Both landscaping options cause a similar level of carcinogenic effects, but xeriscaping has 67% less non-carcinogenic effects than lawns due to mulch use and lack of mowing. However, the single score of xeriscaping (0.0033%) is greater compared to lawns (0.0029) because mulch transportation results in higher smog formation, acidification, and ecotoxicity impacts for xeriscaping than lawns. Nevertheless, xeriscaping reduces 50% of the water consumption for outdoor irrigation than lawns. The water consumption impact is not incorporated in the single scores estimated from the TRACI method.

3.3 Uncertainty test and sensitivity analysis

Standard deviations, referring to the data uncertainty, are presented in Table S9. Figure 2 shows the distribution of LCA single score values within a 95% confidence interval for each CS and LID technology. The *top of the line* is the 95th percentile, the *bottom line* is the 5th percentile, the *upper box line* is the 75th percentile, the *lower box line* is the 25th percentile, and the *midline* indicates the median score. A comparison of performance between the LID technologies and their respective conventional system components was simulated for individual impact categories with a 95% confidence interval (See Table S10). As a result of testing the data uncertainty, bioretention areas have less impact on eutrophication and ecotoxicity compared to the stormwater collection system, but have greater impact on the carcinogenic effects. The probability of having less impact on non-carcinogenic effects is merely 51%. The probabilities that rainwater harvesting has less impact than water supply system are 100%, 70%, 48%, and 31% for the acidification, carcinogenic effects, non-carcinogenic effects, and ecotoxicity categories, respectively. It is certain that xeriscaping has less impact on non-carcinogenic effects and greater impact on smog formation, acidification, carcinogenic effects, and ecotoxicity categories compared to lawns.

It is possible to predict how the impacts would change according to ±10% change of material, process, infrastructure uses (Tables S6 through S8) or direct emissions (Table S11). For example, bioretention areas typically have a 30-year design life and PVC pipe has a 60-year life span, and, therefore, reusing PVC pipes for another bioretention area would reduce its impacts by 50%. Accordingly, the contributions of PVC pipes toward the carcinogenic effects, non-carcinogenic effects, and ecotoxicity categories of the bioretention areas (See Table S6), decrease by 35%, 19%, and 14%, respectively.

3.4 Community level comparison

3.4.1 Water flows and landscaped area

Water flows and landscaped area were compared between nine residential zones per 1,000 m^2 land area in Table S12.

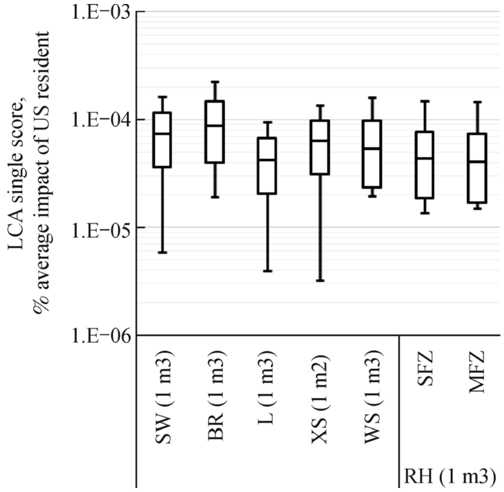

Fig. 2 Distribution of LCA score values for stormwater (SW), bioretention (BR), lawns (L), xeriscaping (XS), water supply (WS), and rainwater harvesting (RH) systems in Single Family Zones (SFZ) and Multi-family Zones (MFZ)

As population density increases from 0.4 persons (R-1) to 62.2 persons (RG-5), water use (including outdoor irrigation) ranges from 164 $m^3 \cdot yr^{-1}$ (134 $m^3 \cdot yr^{-1}$) in R-1 to 4,683 $m^3 \cdot yr^{-1}$ (45.6 $m^3 \cdot yr^{-1}$) in RG-5. The impervious land surface area, such as rooftop and parking space, also increases from 18% (R-1) up to 85% (RG-4) and, conversely, the landscaped area decreases 85% (R-1) down to 15% (RG-4). Even though the high-rise apartment building zone (RG-5) has the highest population density, its lawn area is greater than the two-story apartment building zones (RG-3 and RG-4). Annual stormwater runoff volume is ~173 $m^3 \cdot yr^{-1}$ in SFZs for 2010 daily precipitation, and it increases up to 474 $m^3 \cdot yr^{-1}$ in RG-3 and RG-4. The land occupancies of bioretention areas and xeriscaping, and the potable water replaced with rainwater are also presented in Table S12.

3.4.2 Synergistic effects of LID technologies

By comparing both CS and HS at a community level for each of the nine residential zones, the influence of land use and population density becomes prevalent. Figure 3(a) below shows the performance of the rainwater harvesting

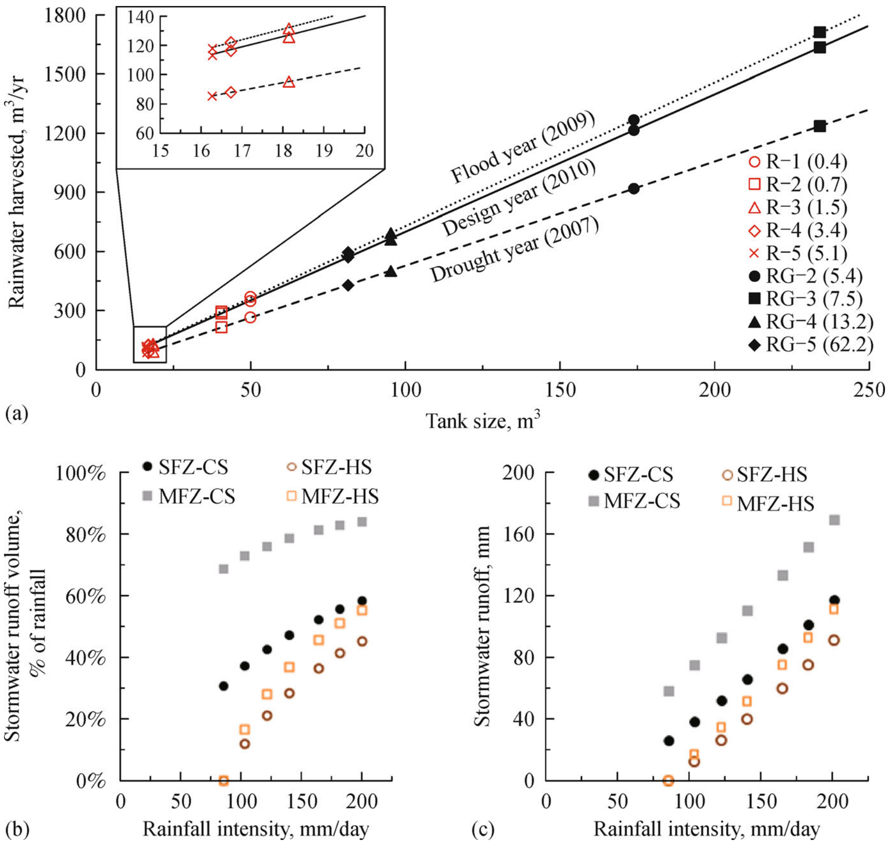

Fig. 3 Community level performance of rainwater harvesting tanks and bioretention areas: (a) rainwater harvested by zone (people/1000 m^2); (b) average stormwater runoff volume generation as a percentage of rainfall in single family zones (SFZ) and multifamily zones (MFZ) for a conventional system (CS) and a hybrid system (HS), and; (c) average stormwater runoff generated in SFZs and MFZs for CS and HS

system during selected flood (2009), drought (2007), and design (2010) years. The cumulative rainfall for each of these years is shown in Fig. S3. During the chosen drought year, the designed system is able to harvest 75% of harvested volume in 2010; however, during the flood year (2009), only a 4% increase in rainwater harvesting from 2010 is achieved. Calculated values of rainwater harvesting, including the optimum tank size and harvesting potential for each year are shown in Table S13.

The average performance of bioretention areas within SFZs and MFZs for various rainfall intensities is shown in Fig. 3(b) and (c). The performance of bioretention areas for each zone is shown in Table S14. SFZs and MFZs have an average impervious surface of 21% and 71%, respectively. Therefore, the impact that bioretention areas have on reducing the amount of stormwater generated is much more evident within MFZs, where approximately half of the stormwater runoff can be reduced for a 100-year rainfall event (201 mm) in the CoA.

The synergistic effects between the selected LID technologies within each zone are shown in Table 3. Bioretention areas designed without considering rainwater harvesting occupy 8% (SFZs) and 17% (MFZs) of a zone size. When both are used, the land occupancy decreases to 7% (SFZs) and 14% (MFZs) because rainwater storage tanks are able to collect at least 40% of their storage capacity for the 1-year return period rainfall intensity in the Atlanta metro area. Due to the synergistic effects, the bioretention areas could be built for the designed rainfall intensity in the zones (RG-3 and RG-4) that have open space smaller than that of bioretention areas designed without rainwater harvesting. Xeriscaping does not influence the land occupancy of bioretention areas.

The land occupancy of xeriscaping alone is 79% for SFZs and 29% for MFZs (See Table 5) replacing the lawn area completely. However, xeriscaped area decreases to 71% for SFZs and 15% for MFZs when applied together with bioretention areas because bioretention areas and xeriscaped area replace the lawn area together. The effect can be weakened using rainwater harvesting together because it decreases the size of bioretention areas. However, the land occupancy of xeriscaping is still reduced compared to solely using the technology.

When rainwater harvesting is designed without xeriscaping, the rainwater utilization rates are 25% and 22% for SFZs and MFZs, respectively. However, the rates increase to 34% and 23%, respectively, when both rainwater harvesting and xeriscaping are jointly implemented. This is because stored rainwater, which results from decreased water demand, can be redirected toward toilet flushing. However, bioretention areas hardly influence the rainwater utilization rate because all the residential zones have too large of either a landscaped open space, or a water demand, to reduce rainwater use.

The amount of water savings is inversely related to the population density, as shown in Fig. 4. Due to the large open spaces of low density zones, irrigation of lawns constitutes a majority of the water demand. Thus, implementing LID technologies severely reduces water demand. In a high density zone (i.e., RG-5), indoor water use accounts for 99% of the water demand; however, the amount of space available for LID implementation to meet the water demand is very limited. The reader should note, however, that due to the in decrease in irrigated space (i.e., lawns), the water demand per person significantly decreases within the CS from 448 m^3/yr (R-1) to 110 m^3/yr (RG-5). After LID implementation (i.e., HS), the average per capita water demand in SFZs and MFZs is reduced to 109 m^3/yr and 86 m^3/yr, respectively; however, per capita water demand in RG-5 remains largely

Table 3 Synergistic effects between bioretention areas, rainwater harvesting, and xeriscaping

zone	land occupancy of bioretention areas		land occupancy of xeriscaping		rainwater utilization rate[a)]	
	bioretention areas only	bioretention areas + rainwater harvesting (+ xeriscaping)[b)]	xeriscaping only	xeriscaping + bioretention areas + rainwater harvesting	rainwater harvesting only	rainwater harvesting + xeriscaping (+ bioretention areas)[b)]
single-family house zone (SFZ)						
R-1	8%	7%	82%	74%	24%	41%
R-2	8%	8%	74%	66%	30%	46%
R-3	7%	7%	86%	79%	19%	26%
R-4	8%	7%	77%	70%	25%	29%
R-5	8%	7%	75%	67%	26%	29%
multi-family apartment building zone (MFZ)						
RG-2	12%	9%	58%	49%	21%	23%
RG-3	19%	16%	17%	1%	33%	34%
RG-4	20%	15%	15%	1%	32%	33%
RG-5	17%	16%	26%	10%	1%	1%

Notes: [a)] Rainwater utilization rate refers to the rainwater use compared to water demand; [b)] An LID technology in parentheses do not influence the synergistic effects of the other two technologies unaffected. Accordingly, the remaining water demand in HS reflects the remaining indoor water use. Incorporating other water reuse strategies not discussed in this study, such as graywater reclamation, may help meet this demand.

3.4.3 Environmental impact comparison

Figure 4 shows the LCA single score values for both CS and HS in each zone within the CoA. In both CS and HS, as population density increases the single score value decreases. The carcinogenic impact is the largest contributor to the single score. In CS the carcinogenic impact is generated from both the water supply system and lawns. Accordingly, as population density increases, both the per capita water supply volume and the lawn area decrease. In HS the stormwater pollutants and xeriscaping are the largest contributors to the carcinogenic impact for lower density (R-1~RG-3) areas. As population density increases and the per capita landscaped area decreases, the water supply system becomes the largest contributor toward the carcinogenic impacts.

Non-carcinogenic effects and ecotoxicity are the second largest contributors toward the single score values of CS and HS. The three major impacts of CS and HS are presented in Fig. 5.

HS reduces the non-carcinogenic effects and ecotoxicity impacts in SFZs, as a result of the decreased water demand of lawns. The use of xeriscaping and bioretention areas in SFZs results in a higher carcinogenic impact in HS than in CS, largely due to the PVC pipe used in construction. HS

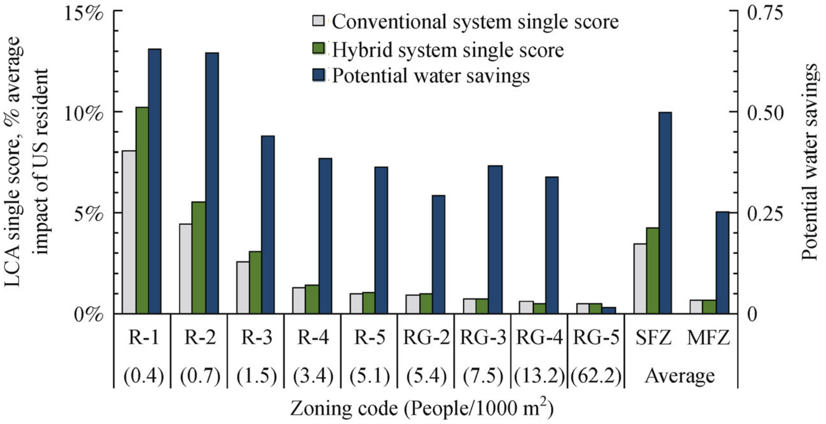

Fig. 4 LCA single score and potential water savings for CS and HS in nine residential zones within the CoA

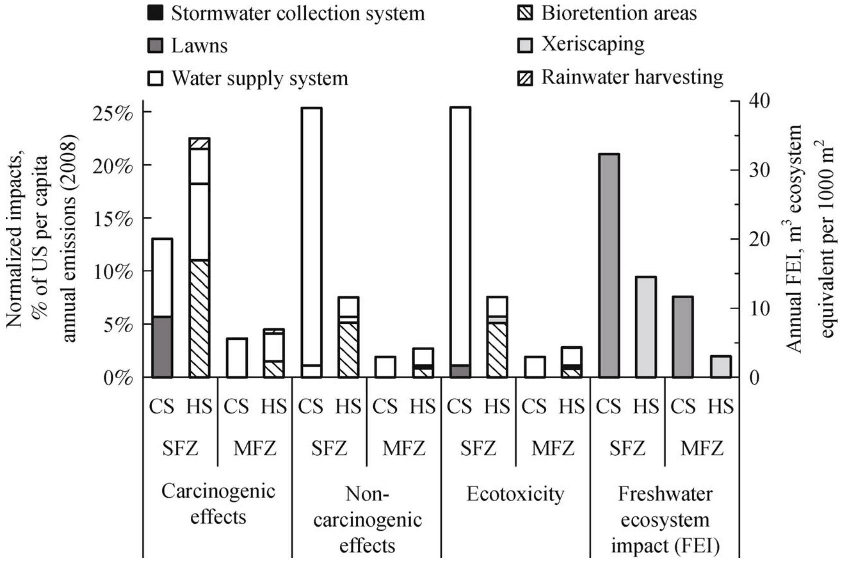

Fig. 5 Impact comparison of conventional system (CS) to hybrid system (HS) for single-family house zones (SFZs) and multi-family apartment building zones (MAZs)

only has a slightly larger impact within MFZs for all three categories.

3.4.4 Freshwater ecosystem impact

Water consumption for the manufacture of individual technologies was ignored because the water consumption for outdoor irrigation (i.e., evaporative loss) is much larger. The FEI comparison of CS and HS is presented in Fig. 5 for two residential types, and in Table S15 for the nine zones. The FEIs of CS are 33.4 and 11.8 m^3 for SFZs and MFZs, respectively. The FEIs of HS are 14.6 and 3.1 m^3 for SFZs and MFZs, respectively. Accordingly, utilizing HS reduces the impact by 55% and 74% compared to CS in SFZs and MFZs, respectively.

4 Conclusions

The results in this study suggest that a HS can satisfy a large portion of the water demand, especially in low density zones. Despite resulting in higher LCA single scores, incorporating LID technologies at a community level can satisfy a majority of the outdoor water demand; however, in high population-dense zones, the water savings become negligible. During the selected drought year, the rainwater harvesting tanks were able to accumulate 75% of the design year's volume, while only increasing harvests by 4% during a flood year. Despite being the largest contributor toward carcinogenic, non-carcinogenic, and ecotoxicity impacts in SFZs, bioretention areas effectively reduce stormwater runoff by ~50% for a 100-year rainfall event. PVC pipes used in bioretention areas mainly cause the impact, as evaluated in the LCA of bioretention areas. Xeriscaping also contributes to increasing the impact in SFZs. Strictly speaking; mulch use is the impact source and is relatively high in SFZs, which have a large open space size.

This study was conducted not only to compare the life cycle environmental impacts of individual technologies or systems, but also to evaluate how multiple LID technologies, with diverse functions, could improve the environmental impacts of an overall conventional system as a function of land use and population. By testing more precipitation data sets, study results can be refined and confirmed. Nevertheless, the framework provided by this study can be used to simulate more alternatives and advanced to determine the best combinations of alternatives for each zone, providing municipalities with a strong toolset for community planning and design.

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