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# Life cycle based evaluation of harvested rainwater use in toilets and for irrigation

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A B S T R A C T

Harvested rainwater is an alternative water source for buildings, especially for non-potable uses such as irrigation and toilet flushing. While rainwater harvesting is perceived as a sustainable design approach, there is limited information on the environmental and economic performance of this technology. To address this literature gap, life cycle assessment and life cycle costing tools were applied for a dormitory that could potentially use harvested rainwater to flush toilets or to irrigate the lawn. Five scenarios were modeled including a new versus renovated building and irrigation versus toilet flushing water end use. The rainwater cisterns for all the scenarios were sized using the Yield After Spillage approach and long term daily precipitation of Toledo. Energy and greenhouse gas emissions were calculated using Economic Input Output Life Cycle Assessment (for construction phase and energy use by pump) and GaBi (for water and wastewater treatment) databases. The life cycle environmental impacts and costs were estimated and compared to the business as usual scenario, where the water supply demands are met by municipally supplied potable water in a combined or separate sanitary sewer network. It was discovered that energy and greenhouse gas emission payback periods can be achieved for almost every scenario. Yet cost payback periods of implementing harvested rainwater were found to be longer than the life time of the building except for two scenarios: using rainwater for irrigation in a renovation project and using rainwater for toilet flushing in a new construction project. These two scenarios had the lowest cost, energy and greenhouse gas emission impacts among all scenarios modeled. Reducing occupancy to match toilet flushing demand increased the per person impact. However, in general, the per person impacts were much lower than a person's impact from driving or electricity use. While separate sewers divert the stormwater runoff to the water bodies and thereby prevent the environmental problems resulting from combined sewer overflows, a rainwater harvesting system connected to separate sewers was found to reduce the energy and greenhouse gas emissions less than so if the rainwater harvesting system were connected to combined sewers.

## 1. Introduction

Municipalities supply cities with a single quality of water for potable as well as non-potable purposes. Harvested rainwater is an alternative water source for buildings, especially for non-potable uses such as irrigation and toilet flushing. Rainwater harvesting is perceived as a sustainable design approach because it is expected to improve the resiliency and the efficiency of the infrastructure by decentralizing the water source, matching water quality to its intended use (and thereby not over-treating the water), and by reducing the volume of water pumped long distances (Apul, 2010). In the United States, indoor and outdoor residential water use averages 0.382 $m^3$ (382 L) per day per person and 19% and 25% of this amount are used for toilet flushing and lawn irrigation, respectively (Vickers, 2001). Therefore, major reductions in municipal potable water demand are possible by using harvested rainwater as the water source for irrigation and toilet flushing.

Rainwater harvesting is also helpful for urban stormwater management. Rainwater is considered a nuisance for urban areas and our infrastructure is designed to convey storm water offsite typically to surface water but in some cases to a wastewater treatment plant. Approximately 800 cities in the U.S have combined sewer systems in which both the sewage from buildings and rainwater runoff from impervious areas are directed towards the

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wastewater treatment systems (USEPA, 2004). The City of Toledo, Ohio has experienced several issues with its combined sewer system. Even with the Environmental Protection Agency's Clean Water Act, which required the city to more than double their sewage treatment capacity, over 40,00,000 cubic meters (4 billion liters) of raw sewage are discharged into area waterways each year due to the combined sewer system throughout the city (USEPA, 2004; Gomberg, 2007). Nationwide, combined sewer and sanitary sewer annual overflows are estimated to reach 3.2 and 0.0378 billion cubic meters, respectively (USEPA, 2004). Rainwater is one of the most easily and freely available sources of water that can be used for non-potable purposes. Use of this resource for non-potable purposes can not only reduce the demand for potable water but also can also reduce the influent flows to the wastewater treatment plants, help mitigate sewer overflows and ultimately reduce the stress on the water and wastewater infrastructure.

Rainwater harvesting is not a new technology, but it has been receiving much attention recently due to rising interest in sustainable urban design. There is a rapidly growing body of literature on how rainwater harvesting can improve water resource management at the building, community or city scales (Furumai, 2008; Schwecke et al., 2007; Ghisi et al., 2006; Zhang et al., 2009; Villarreal and Dixon, 2005). The cost of implementing rainwater harvesting systems has also been studied by several authors (Zhang et al., 2009; Chiu et al., 2009; Rahman et al., 2010; Anand and Apul, 2010; Tam et al., 2010; Yuan et al., 2003; Liaw and Tsai, 2004; Ghisi and Mengotti de Oliveira, 2007; Ghisi et al., 2009; Liang and Van Dijk, 2011; Farreny et al., 2011; Morales-Pinzón et al., 2012; Walsh et al., 2014; Ghisi et al., 2014). Similarly, many authors studied the energy and greenhouse gas implications of rainwater harvesting systems (Anand and Apul, 2010; Racoviceanu and Karney, 2010; Crettaz et al., 1999; Angrill et al., 2012; Gardner and Vieritz, 2010; Proenca et al., 2011; Morales-Pinzón et al., 2012; Vargas-Parra et al., 2013; Ghimire et al., 2014; Vieira et al., 2014). Yet, there still remain some knowledge gaps especially in modeling and using environmental criteria to assess rainwater harvesting systems (Angrill et al., 2012). Previous studies have either been ambiguous or lacked information on the comparative benefits of using harvested rainwater for: i) lawn irrigation versus flushing toilets, ii) new construction versus renovation projects, and iii) in a combined versus separate sewer setting. Most of the previous studies on life cycle assessment and life cycle costing of rainwater harvesting system focused on residential (Rahman et al., 2010; Ghisi and Mengotti de Oliveira, 2007; Zhang et al., 2009; Tam et al., 2010; Rahman et al., 2010; Morales-Pinzón et al., 2012; Walsh et al., 2014; Proenca et al., 2011; Ghimire et al., 2014), educational (Anand and Apul, 2010; Ghisi et al., 2014; Bronchi et al., 1999), office buildings (Devkota et al., 2013; Zimmerman, 2014; Ward et al., 2012) or gas stations (Ghisi et al., 2009), while no prior work focused modeling a dormitory building using a life cycle perspective. The water demand to flush the toilets is higher in a dormitory (5 flushes per person per day) than in an office type building (4 flushes per person per day) (Vickers, 2001). Due to their typical tall and narrow building designs, it is possible that there may not be sufficient harvested rainwater to flush the toilets in dormitories, which creates an interesting problem with respect to how the environmental impacts may be distributed in such a case. Finally, previous studies presented results from the perspective of the building, presenting results for the entire building. However, with the onset of growing population and growing interest to understand an individual's impact on the environment, we argue in this paper that effects should also be measured on a per person basis to inform society and engineering design. The goal of this study was to address these knowledge gaps by analyzing the economic and environmental implications of five different rainwater harvesting scenarios designed for toilet flushing and/or irrigation in an existing University of Toledo dormitory building.

## 2. Methods

### 2.1. Building description

All simulations were done for University of Toledo's Crossings building. In North America, it has become imperative for most universities to make progress towards sustainability. On this path, it is common to direct sustainability efforts to residence halls with a goal of exemplifying sustainable living for students. The Crossings building was selected in this study because it is representative of other higher education dormitories. It is a five story building with a total living area of 20,465 m$^2$, roof area of 4093 m$^2$, and lawn area of 11,660 m$^2$. It has 24 suites on each floor. Each suite includes a furnished living room and a private bathroom. The structure houses in-hall dining, laundry and a recreation room for the students. It has 649 students in 6-person suites with 3 double bedrooms in each suite. There are also 3 apartments for staff and 20 single residence assistants' rooms.

### 2.2. Scenarios

Five scenarios were developed to investigate the best way to utilize rainwater harvesting at the Crossings building (Fig. 1). Currently, the potable municipal water is the only source of water used in Crossings. The amount of potable water use in sinks, showers, and laundering were assumed to be the same among scenarios. Effects of using rainwater in toilet flushing and irrigation were modeled. The scenarios varied with respect to water source, end use, building type and occupancy load.

- *Scenario 0: Business As Usual (business as usual)* – Current, existing system in Crossings building. City supplied potable water is used for both flushing toilets and irrigation.
- *Scenario 1: Rainwater Irrigation-renovated (RI-ren)* – Crossings was modeled as being *renovated* to collect roof runoff for its use in *irrigation*. In this scenario, since the volume of water required to irrigate at the site was larger than the volume available from rainwater collection, both rainwater and potable water were required to irrigate.
- *Scenario 2: Rainwater Toilet Flushing-renovated* – Crossings was modeled as being *renovated* to collect roof runoff for its use in *toilet flushing*. In this scenario, rainwater was supplemented

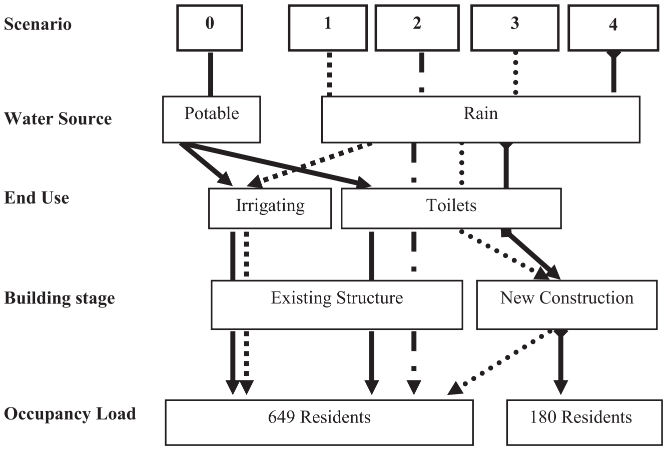

**Fig. 1.** Rainwater harvesting scenarios.