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Introducing demand to supply ratio as a new metric for understanding life cycle greenhouse gas (GHG) emissions from rainwater harvesting systems

Jay P. Devkota [a], Steven J. Burian [b], Hassan Tavakol-Davani [b], Defne S. Apul [a,*]

[a] 2801 W. Bancroft, Department of Civil Engineering, University of Toledo, Toledo, OH 43606, USA
[b] 110 S. Central Campus Dr, Department of Civil & Environmental Engineering, University of Utah, Salt Lake City, UT 84112, USA

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A B S T R A C T

Rainwater harvesting (RWH) is a decentralized approach to meet non-potable water supply needs and stormwater management goals. Life cycle environmental impacts of RWH systems have been reported in previous studies, but the effects of different building configurations and the type of sewer connections have not been fully studied. In this study, we aim to go beyond case studies by developing an approach that shows how RWH life cycle assessment (LCA) results change for different building roof areas, occupancies, and sewer connections. We propose and analyze the ratio of building occupancy to roof area which can be expressed as demand to supply (D/S) ratio to estimate life cycle greenhouse gas (GHG) emissions of implementing RWH system when the harvested rainwater is used to flush the toilets. Result showed that for all the building roof area to occupancy configurations considered in this study, RWH systems had lower GHG emissions except in some separate sewer scenarios. Size of the cistern, water savings as well as life cycle GHG emissions varied as a function of D/S ratio. It was found that changing roof area and occupancy have different effects on cistern size, water savings and life cycle GHG emissions measured with respect to D/S ratio. Water savings and cistern size increased until D/S equaled 1 and remained constant for higher value when roof area was constant. The duo were constant until D/S ratio of 1 and decreased for higher D/S value. Though minimum life cycle GHG emissions were noticed for spacious building, the maximum savings in emissions were noted at D/S ratio equal to or more than 1 when the building footprint was kept constant when the building was connected to a combined sewer network. For occupancy constant case, maximum savings were reported at D/S equal to 1. Similarly when the building was connected to a separate sewer network, minimum emissions as well as maximum savings were reported at lowest possible D/S value when the building footprint was constant and at D/S less than or equal to 1 when the occupancy was kept constant. A recommendation framework was provided based on the results obtained to help designers and practitioners design the RWH system to minimize GHG emissions.

1. Introduction

Rainwater harvesting (RWH) is gaining more attention in the United States (US) and globally to address limited water resources and water leakages, stormwater management needs, and financial challenges faced by existing water supply systems (Jones and Hunt, 2010; CEC, 2005; Mehta, 2009; USEPA, 2002). Common uses of harvested rainwater are toilet flushing (Bronchi et al., 1999; Fewkes, 1998; Furumai, 2008; Ghimire et al., 2014; Devkota et al., 2013; Angrill et al., 2012; Tavakol-Davani et al., 2015), irrigation (Li and Gong, 2002; Stout et al., 2015), laundry washing (Bronchi et al., 1999; Angrill et al., 2012), car and parking lot cleaning (Ghisi et al., 2009; Villarreal and Dixon, 2005), and water cooling (Furumai, 2008). Use of harvested rainwater in toilet flushing is especially promising because it constitutes a large fraction (27%) of indoor non-potable water use (Mayer and William, 1999; Vickers,

Abbreviations: BAU, business as usual; RWH, rainwater harvesting; D/S, demand to supply ratio; CSO, combined sewer overflow; LCC, life cycle costing; LCA, life cycle assessment; GHG, greenhouse gas.

* Corresponding author. Tel.: +1 419 530 8132.
E-mail address: defne.apul@utoledo.edu (D.S. Apul).

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2001) that does not require significant water treatment (Krishna, 2005; Herrmann and Schimda, 2000; Coombes et al., 2002). Rainwater harvesting has stormwater management benefits as well (Walsh et al., 2014). For example, Steffen et al. (2013) reported the potential for a reasonable implementation of rainwater harvesting to reduce up to 20% of stormwater runoff in most regions of the US. In communities served by combined sewer systems, this reduction of stormwater runoff can reduce combined sewers overflows (CSO) and ultimately reduce the estimated 3.2 billion cubic meters (USEPA, 2004) of diluted sewage released to receiving waters of the US each year by CSOs.

There is a fast growing literature on environmental life cycle assessment (LCA) of RWH systems, with many studies focusing on using harvested rainwater for toilet flushing. From these studies, we have some understanding of how RWH system impacts vary for different conditions. For example, RWH scenarios with high efficiency toilets have lower GHG emissions than those with standard toilets (Anand and Apul, 2010; Crettaz et al., 1999; Racoviceanu and Karney, 2010). The cost and environmental impacts of potable water can play an important role in whether the RWH system will be economically and environmentally attractive (Devkota et al., 2013). The environmental impacts of non-potable use of rainwater for toilet flushing can be lower than that of using municipal water if rainwater cistern is placed on the rooftop thereby avoiding pumping (Ghimire et al., 2014). Implementing RWH system in newly constructed buildings results in lower environmental impact than in renovated buildings (Angrill et al., 2012; Devkota et al., 2015). Using rainwater for irrigation results in lower environmental impact than using it for toilet flushing (Devkota et al., 2015). Environmental impacts from RWH systems also vary with population densities with compact densities resulting in lower impact than diffuse densities (Angrill et al., 2012).

One issue with prior RWH LCA studies is that they often studied specific buildings. From prior studies it is not possible to discern if the results can be generalized to other cases. In this study, we aimed to go beyond case studies by developing an approach that shows how RWH LCA results change for different system configurations. We proposed and demonstrated that different system configurations can be represented by the balance between water demand and water supply in a building which can be mathematically represented as the ratio of annual water demand to rainwater supply (D/S). The water demand parameter captures the outdoor (e.g. irrigation) and indoor (e.g. toilet flushing) water uses in a building. The rainwater supply parameter captures the effects of the roof area, annual precipitation, and tank size. The interplay between demand and supply of water is also important from a green infrastructure (GI) perspective. While there are many examples of GI (e.g. bioswales, porous pavements, rain gardens, green roofs), RWH is the only GI that affects both the stormwater and the water supply infrastructure directly. Demand and supply estimations are essential for sizing the rainwater tank (Devkota et al., 2013; Anand and Apul, 2010; Ghisi and Ferreira, 2007; Aladenola and Adeboye, 2010; Palla et al., 2011) and have only been used for that purpose in the RWH literature. Our study is the first to propose the use of D/S as a key parameter for understanding the life cycle GHG emissions from implementing RWH systems.

2. Methodology

2.1. Goal and scope

The goal of this LCA study was to demonstrate the effects of D/S on the environmental life cycle GHG emissions of RWH systems. For our analysis we chose toilet flushing as the end use for harvested rainwater because it constitutes a large fraction (37%) of water use in office buildings (Saving Water in Office Building, EPA, 2012). The RWH system was assumed to be implemented at a typical medium size office building in Toledo, OH. Office buildings constitute only 15% of the building stock (US Census, 2000) and 5.1% of the LEED certified buildings (National Green Building Adoption Index, 2014) in the United States. However, the growth of LEED certification in office buildings is very high and it is now almost the norm rather than the exception to construct or manage sustainable office buildings (National Green Building Adoption Index, 2014). In addition, adoption of a new technology by the society can be more easily facilitated if it is first introduced at the workplace rather than at individual homes. Starting out with a typical medium size office building, the system configurations were varied by changing the occupancy and roof area and calculating the corresponding D/S.

Each building configuration was modeled twice; first assuming the building is connected to a combined sewer, and second assuming the building is connected to a separate sewer. Sewer connection type is important because RWH systems pose an interesting situation with respect to combined sewers. Due to intense precipitation events during wet weather, a combined sewer system can exceed its capacity and overflow. In general, combined sewer systems are considered less environmentally friendly than separate sewers because during a combined sewer overflow (CSO), raw sewage is discharged into water bodies causing water pollution. Collecting the stormwater on site using an RWH system reduces the volume of CSOs (Steffen et al., 2013) and also avoids the treatment of this runoff at the wastewater treatment plant thereby reducing the GHG emissions (Devkota et al., 2015). For an RWH system, the GHG reduction from not treating the stormwater would be in addition to the GHG reduction from not using potable water. In contrast, when a building is connected to a separate sewer network, there is no need for stormwater treatment since stormwater goes directly to water bodies. Hence, in a separate sewer system, the emission reductions by implementing RWH systems are only from reduction in tap water consumption. Therefore, when RWH system is implemented in a combined sewer network the GHG emission savings are higher than when it is implemented in a separate sewer network (Devkota et al., 2015).

To avoid burden shifting, a comprehensive LCA should include all life cycle phases and all relevant impact categories. Yet installation stage has large data and modeling uncertainties and is also not considered to be critical for the LCA of RWH systems (Peuportier, 2001; Blengini and Di Carlo, 2010). Therefore, only raw material extraction, manufacturing, transportation, operation, and disposal phases were modeled in this study. Similarly, instead of modeling a range of environmental impacts, only GHG emissions were modeled to illustrate the efficacy of the proposed D/S ratio as a key system parameter in RWH LCA modeling. We selected global warming impact over other impact categories because GHG emission data are typically easier to access and relate closely to energy usage (and often to other environmental impacts) thereby providing a key metric for business decisions (GHG Protocol).

Previous RWH LCA studies used different functional units to evaluate environmental impacts of using harvested rainwater. For example, Ghimire et al. (2014) used one cubic meter of water (for non-potable domestic and agricultural irrigation). Angrill et al. (2012) used one cubic meter of rainwater per person per year (for laundry). Morales-Pinzón et al. (2012) used one cubic meter of rainwater for laundry for 50 years. Bronchi et al. (1999) used water volume normalized to kg of clothes washed (50 l of water to wash 2.75 kg of clothes). Crettaz et al. (1999) used water needed for toilet flushing per person per day.

Starting out with the idea that RWH systems cannot always meet the full water needs of a building, it would be expected that additional municipal water will be required in many cases. In such

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