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Life cycle and hydrologic modeling of rainwater harvesting in urban neighborhoods: Implications of urban form and water demand patterns in the US and Spain

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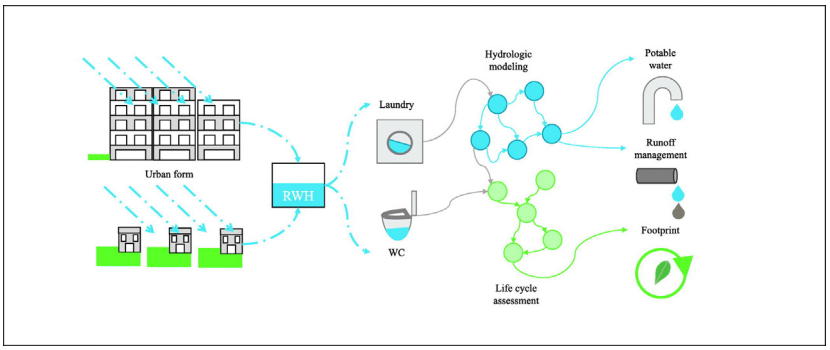
HIGHLIGHTS

- We combined hydrologic modeling and life cycle assessment for rainwater management.
- Two neighborhoods were compared based on urban form and water demand.
- Rainwater harvesting reduced stormwater runoff and offered environmental benefits.
- Higher urban density and water demand increase the benefits of rainwater harvesting.

GRAPHICAL ABSTRACT



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ABSTRACT

Water management plays a major role in any city, but applying alternative strategies might be more or less feasible depending on the urban form and water demand. This paper aims to compare the environmental performance of implementing rainwater harvesting (RWH) systems in American and European cities. To do so, two neighborhoods with a water-stressed Mediterranean climate were selected in contrasting cities, i.e., Calafell (Catalonia, Spain) and Ukiah (California, US). Calafell is a high-density, tourist city, whereas Ukiah is a typical sprawled area. We studied the life cycle impacts of RWH in urban contexts by using runoff modeling before (i.e. business as usual) and after the implementation of this system. In general, cisterns were able to supply >75% of the rainwater demand for laundry and toilet flushing. The exception were multi-story buildings with roofs smaller than 200 m^2, where the catchment area was insufficient to meet demand. The implementation of

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RWH was environmentally beneficial with respect to the business-as-usual scenario, especially because of reduced runoff treatment needs. Along with soil features, roof area and water demand were major parameters that affected this reduction. RWH systems are more attractive in Calafell, which had 60% lower impacts than in Ukiah. Therefore, high-density areas can potentially benefit more from RWH than sprawled cities.

1. Introduction

Reliably providing potable water and maintaining drainage standards to adequate levels for urban land use are important goals of water management in any city. Yet, these goals are being challenged by urbanization and climate change. More than 50% of the global population lives in urban areas (United Nations, 2015), and extreme drought and precipitation events resulting from climate change put additional pressure on the urban water system. As a result, cities are aiming to become more resilient and are applying circular economy strategies to the built environment and production systems, among others (Ellen MacArthur Foundation, 2017). In the case of water, rainwater harvesting (RWH) is a potential circular solution that fosters regenerative and closed-loop systems that could alleviate the pressure on both water and stormwater infrastructure. Solving these threats to our conventional infrastructure has led to an exponential increase in RWH studies (Campisano et al., 2017; Leong et al., 2017; Pacheco and Campos, 2017; Vieira et al., 2014).

Several key points on RWH systems can be drawn from prior assessments. RWH may reduce the environmental impacts of water supply systems (Ghisi et al., 2009; Proença et al., 2011), while simultaneously reducing runoff (Sample and Liu, 2014; Tavakol-Davani et al., 2015). The hydrologic and environmental performance of RWH systems depends on the balance between water demand and available rainwater, which are location-sensitive parameters affected by the building type, water use, and climate.

Harvested rainwater has been used to meet various water demands, including car and parking lot cleaning (Ghisi and de Oliveira, 2007; Villarreal and Dixon, 2005) and lawn or agricultural irrigation (Liang and van Dijk, 2011; Yuan et al., 2003), but the most commonly studied end uses are toilet flushing (Anand and Apul, 2011; Bronchi et al., 1999; Devkota et al., 2015, 2013; Furumai, 2008) and laundry (Angrill et al., 2016; Vargas-Parra et al., 2013). On average, these two end uses constitute 27% (Mayer et al., 1999; Vickers, 2001) and 10–20% (Mudgal et al., 2009; OECD, 2002) of indoor potable water use, respectively. However, indoor water demand has recently decreased due to the implementation of new technologies with increased water-use efficiency (Deoreo and Mayer, 2012).

The actual water consumption can vary based on the number of occupants, seasons, building features, habits, and efficiency of water devices. Chang et al. (2013) estimated that these parameters could affect water use by up to 87% per household in old, high-density residential neighborhoods in the US. In urban landscapes, the social dimension (e.g., water use patterns) and urban configuration play critical roles in water consumption (Fragkou et al., 2016), resulting in further variations to the economic and environmental performance of RWH systems. For example, the effects of varying demand patterns during tourist seasons have not been studied, which may be a significant component to demand patterns as, in some cities, populations can double due to tourism. Depending on policies, social perception, and the type of building (single vs. multi-family buildings, and service buildings), the water use and the efficiency of RWH systems may also vary (Domènech and Saurí, 2011; Morales-Pinzón et al., 2012b). Recent studies suggested that RWH implemented in high occupancy buildings may have lower environmental impacts than in buildings with a greater amount of area per occupant (Vargas-Parra et al., 2014). Similarly, when these buildings are connected to combined sewers, the savings in energy and greenhouse gas emissions of RWH may be larger as compared to the ones connected to separate sewers (Devkota et al., 2015). Yet, the optimal scale for implementing RWH may be groups of houses or apartment buildings (Morales-Pinzón et al., 2012a), suggesting a need for neighborhood or larger scale analyses that account for the hydrologic and environmental effects of RWH based on urban form and demand patterns.

In this study, we posed two different questions: (i) is runoff a determining factor in defining the environmental feasibility of RWH at a neighborhood scale? (ii) if so, are there differences when urban form, water demand, and sanitation design vary? We hypothesized that RWH might reduce the urban runoff and management in wastewater treatment plants (WWTP) once it is collected by combined sewers. This might translate into environmental impact reductions from the use of RWH systems. Additionally, the life cycle environmental impacts of RWH systems might be lower in areas where the water demand is high, such as high-density neighborhoods. To test these hypotheses, we present a preliminary assessment that compares two urban neighborhoods that are similar in terms of rainwater availability. However, they vary with respect to building types and water use patterns due to differences in urban form, urban infrastructure, and population density. Our specific objectives were to: (i) characterize two neighborhoods with different demand patterns and urban infrastructure, such as high-density residential areas (i.e., European coastal urban model) and sprawled distinctive building use (i.e., American urban model); (ii) design RWH systems and compare the demand met in each case; (iii) determine the effects of RWH on urban runoff, and (iv) determine how the life cycle environmental impacts of RWH systems and drainage infrastructure altered in each neighborhood.

2. Materials and methods

The novelty of this approach is the combination of a set of methods, as depicted in Fig. 1. We first selected two sites and characterized their urban form (Section 2.1). The RWH systems were sized (Section 2.2) for each study site using a 15-year time series of daily rainfall data to capture changes in seasonality. Based on the supply and demand patterns, we estimated runoff volumes pre- and post-RWH implementation (Section 2.3). Lastly, we used the life cycle assessment (LCA) methodology to estimate the environmental impacts for each study site in a business-as-usual (BAU) scenario (no RWH) and after implementing RWH.

2.1. Site selection and description

To identify potential drivers towards the use of RWH, we selected two different cities. Because we sought to understand the potential effects of urban planning and water demand, the independent variable that drove site selection was the level of natural resources; in the present study, rainfall. Based on this first limitation, the candidate cities were required to have distinct building types, urban form, and water demand. As a result, Calafell (Catalonia, Spain) and Ukiah (California, US) were identified as they both represent the Mediterranean climate according to the Köppen Climate classification (Kottek et al., 2006) and have similar rainfall patterns. Ukiah and Calafell experience approximately 529 and 597 mm of annual rainfall, respectively. These precipitation depths reflect an average of the previous 15 years of data retrieved from Menne et al. (2012).

Ukiah and Calafell were also selected based on their distinct building patterns and urban form. In Ukiah, the urban landscape follows the