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Performance of rainwater harvesting systems under scenarios of non-potable water demand and roof area typologies using a stochastic approach

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A B S T R A C T

Urban water systems throughout the world are under recurring and increasing water scarcity, given demand growth, aging infrastructure, variability and uncertainty imposed by climate change. Rainwater harvesting systems (RWHS) represent a promising alternative to increase flexibility and robustness of water supply systems. Given the importance of the tank size in establishing a reliable RWHS, we propose an implicit stochastic approach to assess performance and aid designers. The main objective of this study is to simulate common non-potable water demand and roof area typologies and verify how the demand and roof area affect the efficiency of the RWHS. To highlight the usefulness of the model to aid in the definition of tank sizes, we have also performed an economic assessment. Results are specific to the study region's climate and might vary under different climate. However, we have chosen a rather unfavourable climate, with poor rainfall distribution along the year. Under such conditions, results are likely closer to lower bound benefits. This indicates potential water savings benefits of a RWHS even for unfavourable scenarios. The RWHS indicated to be more efficient at meeting demands with smaller Demand-Roof Area ratios. Furthermore, it was possible to determine the efficiency of the RWHS under various scenarios, identifying the minimum and maximum likely benefits. Several scenarios were compared directly allowing for the establishment of a general maximum tank size per unit roof area in a given region of interest, beyond which no significant benefits are likely. The economic assessment indicates positive net present values for investing in RWHS, especially for large rooftop areas and small Demand-Roof Area ratios. Under such conditions, investing in a RWHS has very low risk and will most likely have short payback times.

1. Introduction

Providing water supply to urban demands meets increasingly complex challenges given water scarcity, growth of competing demands, aging infrastructure, variability and uncertainty under climate change. The water management focus on integrated demand and supply solutions requires systemwide approaches. Therefore, the need to manage demand for potable water is gaining attention rather than focusing in large water supply engineering projects that would distress the system to an even greater extent.

Rainwater Harvesting Systems (RWHS) can augment water supply to meet urban and rural needs, adding to flexibility and robustness to water systems. By exploring other alternatives such as RWHS, urban water systems can have its supply portfolio diversified, while some of the demand is met and more costly expansion infrastructure is postponed, with added economical and financial benefits. RWHS can also fulfil part of the non-potable water demand, preventing the use of potable water for less

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qualified demanding uses such as car washing, lawn irrigation, toilet flushing, and cooling for air conditioning (Gikas and Tsihrintzis, 2012). RWHS require minimal installation and design effort and are a promising alternative to reduce potable water use (Nolde, 2007), as these potentially reduce the wastewater load, and in some cases, diminish the impact of floods by increasing system's detention capacity. Furthermore, water obtained with RWHS is a low cost alternative during dry periods, when potable water cost is higher or water supply systems face severe shortages.

Widespread use of RWHS in urban areas is still limited, due to economic reasons including long payback time periods, especially for smaller domestic systems. Santos and Taveira-Pinto (2013) found payback times greater the 200 years for the typology of a dwelling. Devkota et al. (2015) found payback times longer than 75 years for some scenarios simulated in a university accommodation building. Payback times depend on several variables, which are related to local factors, such as the rainfall pattern, installation and maintenance costs of the RWHS and costs of water, energy and workmanship. In addition, as a common pool resource, water is often priced below its value, which includes opportunity cost from alternative uses and environmental value (Loucks and Beek, 2005). However, densely populated urban areas throughout the world are already facing severe water scarcity issues, and the application of economic water management instruments (i.e. water tariffs) could turn the table towards feasibility of alternatives like RWHS when water becomes more costly.

There are several factors affecting RWHS's efficiency, such as roof top area, non-potable demand, the rainfall patterns and the storage tank design. Here efficiency refers to how well the RWHS is productive of desired effects. Rooftop area and water demand are given, thus tank storage capacity is a decision variable. The storage tank capacity should be selected in part as a function of the rainfall pattern of the region of interest (uncertainty). Considering the installation costs of the system are mostly driven by the tank size (Chilton et al., 2000), its efficiency in meeting the demand and offsetting water costs is a key element when designing RWHS. Thus, decisions about the tank size are critical.

Various tank design methods are employed in order to determine tank size and efficiency under various pre-established tank sizes. Many of the approaches used are deterministic, based on a daily simulation model of tank use using rainfall data available as an input. Rahman et al. (2012) simulated benefits of three different tank sizes using this approach for several locations in Australia; Zhang et al. (2009) used similar approach to optimize the tank size searching for the highest reliability and performed an economic analysis for four cities in Australia; Ward et al., 2010 used a deterministic mass balance simulation to compare results with simpler designing methods for a housing complex and an office building. Although less frequently, probabilistic approaches also have been used, for example, Youn et al. (2012) developed a method to set probabilistic relationships between storage capacities and deficit rates accounting for climate change for a typology of a four-story building. Another alternative to account for uncertainty are stochastic models: Leung and Fok (1982) performed a stochastic assessment to verify the minimally sufficient system capacity of a RWHS in Hawaii; Basinger et al. (2010) proposed a model to assess RWHS reliability based on a nonparametric stochastic rainfall generator and tested it for a multifamily residential building for different non-potable water uses.

In fact, deterministic approaches are ubiquitous and often are performed along with economic assessments. Moreira Neto et al. (2012) performed an economic analysis of implementation of RWHS in an Airport in Brazil and simulated the tank use daily with a deterministic approach considering pre-defined tank sizes with a 20-year-long rainfall data. Santos and Taveira-Pinto (2013) compared detailed and simple methods by simulating the performance of the tank for a dwelling and public building located in different regions of Portugal. Relatively short rainfall data records were used to estimate savings in water purchasing, 10 and 5 years respectively. Okoye et al. (2015) developed an optimization linear model to determine the optimal tank storage and the net financial benefit, using a deterministic approach for simulating rainfall harvesting for domestic use. A conclusion of this study is that the optimal tank size increases along with roof area and decreases with the unit costs associated with building the tank. Those studies consider a full economic analysis but do not account for the variability and uncertainty related to rainfall events that would have a major effect on water savings. The use of probabilistic or stochastic approaches along with optimization cost models would improve the reliability of such models. Karim et al. (2015) also uses a deterministic model to simulate the reliability of RWHS and performs a sensitivity analysis with variation in demand and roof area for the typology of buildings. The variability of rainfall considered by their approach was to determine dry, wet and average years from a 20-year daily rainfall data. The study region in Karim et al. (2015) has a hot, wet and humid tropical climate, with a distinct monsoonal season and high variability in precipitation. They could determine a tank size beyond which there would be no added benefit, however limited by a 20-year horizon of rainfall variability.

Su et al. (2009) suggests a probabilistic approach to design RWHS using the city of Taipei as target area and simulating RWHS efficiency for its main typology, buildings. This research takes into account the uncertainties by fitting the system response in a 50 year-long simulation period into probability functions. Nevertheless, this method requires long rainfall datasets such as 50 years. Frequently, records as long as this are not available, requiring different approaches. Morales-Pinzón et al. (2012) present a modelling tool to assist the evaluation of RWHS integrating structural elements (sizing of storage tanks), cost estimation and quantitative environmental analysis with a systems dynamics approach. However, the users are considered homogeneous with respect to roof area and the effect of rainfall variability was investigated considering only three scenarios (pessimistic, average and optimistic). In this paper we investigate different user typologies and explore a more complete range of probabilities given rainfall variability (probabilities of exceedance of given results from 5% to 99%), which provides a better understanding of uncertainty and risk when investing in RWHS.

Analysis of several typologies for a given location is rarely available, and the importance of the simple relationship of roof area and demand for the feasibility of application of RWHS and its efficiency was not yet broadly assessed. This paper presents a methodology that contributes to improve the design of the tank size and addresses some of the limitations of existing literature. Our study contributes to the field by (a) exploring the potential benefits and uncertainty of a RWHS under different building characteristics (i.e. demand and rooftop area) and (b) identifying the upper bound of the tank size for each building characteristic, deficit rate (percentage of the demand not met) and economic benefit probabilities. Moreover, we integrate well-known and proven methods (Markov-based synthetic rainfall generator with a gamma theoretical probability distribution function; a tank use simulation and a Monte Carlo approach) in a single and simple model to explore the uncertainty of the rainfall.

The results and methodology proposed in this paper are useful for estimating potential water savings and economic benefits of a RWHS and providing a comparison platform to test the performance of the tank considering different demand-roof area ratios under stochastic conditions, therefore, this allows for a broad