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Optimal sizing of storage tanks in domestic rainwater harvesting systems: A linear programming approach

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ABSTRACT

This paper proposes an optimization model to determine the optimal tank size of a single residential housing unit for rainwater harvesting and storage. Taking into account the site specific data such as the rainfall profile, the roof area of the building, the water consumption per capita and the number of residents, an integrated optimization model based on linear programming is proposed to decide on the size of rainwater storage tank to build such that the net present value of the total tank construction costs and freshwater purchase costs is minimized. The proposed model was tested on a case study from Northern Cyprus, the results of which emphasized the feasibility of rainwater harvesting as a sustainable supplement to the depleting aquifers in the region. The study also offers managerial insights on the impact of various parameters such as the number of residents, roof area, discount rate, water consumption per capita, unit cost of building the rainwater tank, and rainfall characteristics on the optimal tank size and on the net financial benefit gained from rainwater harvesting through detailed sensitivity analysis.

1. Introduction

The quest to curb the menace of water scarcity has motivated considerable research interest in a wide range of applications aimed at providing a sustainable solution to ensure water security in both rural and urban areas. Desalination, greywater harvesting, rainwater harvesting (RWH), and virtual water are some of these notable applications with proven documented research results (Bani-Melhem et al., 2015; Jiang et al., 2015; Morales-Pinzón et al., 2015; Scarborough et al., 2015). Among these alternatives, RWH systems have stood out and their application has gained wider acceptance (Aladenola and Adeboye, 2010; Morales-Pinzón et al., 2015; Silva et al., 2015; Unami et al., 2015) because these systems are not only sustainable means of supplementing available water resources to overcome the chronic water scarcity but also proactive ways of mitigating the menace of urban flood (Sample and Liu, 2014).

The domestic use of freshwater accounts for approximately 10% of the total global freshwater consumption (Bocanegra-Martínez et al., 2014). RWH has been widely applied for the domestic use under different climatic conditions (Domènech and Saurí, 2011; Hadadin et al., 2010; Silva et al., 2015; Ward et al., 2012). The low-quality domestic use of rainwater includes but not limited to toilet flushing, laundry, car washing, and irrigation (Villarreal and Dixon, 2005), whereas the high-quality domestic use of harvested rainwater includes potable uses after some treatment. Although the technology of RWH has been recommended for areas with annual rainfall above 1000 mm (Aladenola and Adeboye, 2010), considerable research studies have been performed for the areas characterized with low precipitation (Abdulla and Al-Shareef, 2009; Domènech and Saurí, 2011; Hadadin et al., 2012).

Various models ranging from behavioral (Liaw and Tsai, 2005; Palla et al., 2011) to probabilistic (Basinger et al., 2010; Kim et al., 2012; Su et al., 2009) have been used in the literature for the rainwater harvesting practice. The assessment of suitability of some models for domestic application was performed by Ward et al. (2010). Campisano and Modica (2012) mentioned that the feasibility of RWH systems depends entirely on the characteristic of the rainwater storage tank, water demand pattern of households, rooftop effective area of the building, and rainfall profile of the site. Similarly, Santos and Taveira-Pinto (2013) concluded that variation in rainfall profile has the most significant effect on the optimal tank size when they applied different criteria in the sizing of rainwater storage tanks. The mentioned characteristics not only affect the water saving efficiency but also the economy of the designed

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Nomenclature

Acronyms

CV	coefficient of variation
IBR	increasing block rate
LP	linear programming
NFB	net financial benefit
RWH	rainwater harvesting
TDC	total discounted cost
TL	Turkish lira

Indices

j	price levels
t	periods of the year

Parameters

a	cost incurred per unit volume of rainwater tank built
A_{col}	area of the rooftop collector
b_{tj}	cost per volume of purchasing water from the utility network in period t at the price level j
c_f	dimensionless runoff coefficient
$Cost_{PFN}$	total discounted cost of satisfying demand completely by purchasing water from the utility network
CP_t	cost of purchasing water from the utility network in period t
d_t	domestic household water demand in period t
f_{ini}	fixed cost of installing the rainwater tank
i	discount rate
J	number of price levels
k	price level with the greatest unit price to be incurred for a purchased volume of freshwater
n	number of residents
N_t	number of days in period t
rd_t	measured rainfall depth in period t
r_t	amount of rainwater that can be harvested and stored in period t
s_{max}	maximum size for the volume of rainwater tank that can be built
τ	length of the planning horizon
V^*	purchased volume of freshwater
V_j	maximum cumulative volume of freshwater that can be purchased at the jth price level
W_d	volume of water usage per day per capita

Variables

I_t	inventory level of the rainwater tank at the end of period t
P_{tj}	amount of water purchased from the utility network at the jth price level in period t
R_t	amount of rainfall stored by the rainwater tank in period t
T_{cap}	volume of the rainwater tank to build
U_t	amount of water used from the rainwater tank to satisfy demand in period t
Z	objective function value

storage tank. Often times, the economic potential of RWH exists due to avoiding freshwater purchase but the overall feasibility of integrating a rainwater storage unit may still be infeasible due to initial capital cost of installation (Kim et al., 2014). For this reason, most governments are providing rebates in the form of exemption from stormwater taxes or offset in the initial capital cost of installation to encourage the deployment of the RWH systems (Domènech and Saurí, 2011; Imteaz et al., 2012; Rahman et al., 2012). Domènech and Saurí (2011) mentioned that subsidies up to 1200 € are granted to a household installing a RWH system in Barcelona, Spain. Similarly, the Victoria Government and Sydney Water Corporation offer up to Aus $500 and Aus $1400, respectively, as rebates to properties that have rainwater tanks installed in Australia (Imteaz et al., 2012; Rahman et al., 2012).

Coombes and Barry (2008) compared the relative efficiencies of runoff into dams with rooftop RWH using duration curves developed for supplying water to the cities of Brisbane, Melbourne, Perth, and Sydney. They concluded that RWH is more resilient to the impacts of climate change. Ghisi (2010) considered the parameters affecting the sizing of rainwater tanks for domestic use and recommended that regional assessment of rainwater tank sizing be carried out by taking into account local rainfall data, roof areas, number of residents, potable water demand, and rainwater demand. Tam et al. (2010) compared the cost of procurement, installation and operation of rainwater tanks to the benefits of the use of a rainwater tank in an empirical study to aid residential decision-making. Domènech and Saurí (2011) assessed the social experience, freshwater savings, and economic costs associated with the use of RWH in single and multi-family buildings in Spain. Imteaz et al. (2011) presented a daily water balance model for domestic rainwater usage so as to provide decision support for the performance analysis of rainwater tanks in commercial buildings with large roof area. The authors claimed that optimal tank size was obtained by studying the effect of varying parameters of tank size and roof areas on cumulative overflow loss and cumulative water saved. Khastagir and Jayasuriya (2010) used multivariate regression between domestic rainwater tank capacities and roof catchment area to develop a dimensionless curve for assessing water supply effectiveness. They considered the developed dimensionless curve as a step toward developing a web-based interactive tool for optimum tank selection. Similarly, Campisano and Modica (2012) developed a regression model which enables the evaluation of water saving and overflow discharge from domestic RWH systems. They evaluated the optimal tank size by applying a minimum cost approach on the developed regression model and concluded that the economic attractiveness of large tanks decreases as rainwater availability decreases. Morales-Pinzón et al. (2015) proposed a predictive model for estimating the financial and environmental feasibility of RWH for different housing configurations in Spain. Imteaz et al. (2012) assessed the rainwater harvesting potential for southwest Nigeria using a daily water balance model. They found that the analysis using monthly rainfall data tends to overestimate the required rainwater tank size and recommended the use of daily data. Lü et al. (2013) presented a multi-criteria optimization approach for rainwater utilization, which was evaluated using a case study in Shanghai, China. They concluded that the rainwater utilization could enhance the sustainability of cities with the involvement of stakeholders' preferences. Al-Ansari et al. (2013) proposed a combination of linear programming model together with a watershed modeling system to maximize the irrigation area, which could be supplied from a selected reservoir. Huang et al. (2013) proposed a stochastic optimization approach for the integrated urban water resource planning with the aim of optimizing water flows in cities facing significant water shortage. Sample and Liu (2014) proposed a nonlinear metaheuristic search algorithm for the identification of near-optimal least cost solutions for the dual purpose of water supply and runoff capture across a wide range of land uses and locations in Virginia, USA. They concluded that the net benefits are very sensitive to water and wastewater charges. Gurung and Sharma (2014) presented the economies of scale on communal rainwater tank system design. Bocanegra-Martínez et al. (2014) proposed a nonlinear mixed integer programming model to harvest, store, and distribute rainwater for multiple residential