Journal of Hydrology 541 (2016) 1340–1347

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Sizing a rainwater harvesting cistern by minimizing costs

Norman Pelak [a,*], Amilcare Porporato [a,b]

[a] Duke University, Department of Civil and Environmental Engineering, Room 121 Hudson Hall, Box 90287, Durham, NC 27708, USA
[b] Duke University, Nicholas School of the Environment, Environment Hall, 9 Circuit Drive, Box 90328, Durham, NC 27708, USA

ARTICLE INFO

Article history:
Received 26 April 2016
Received in revised form 11 August 2016
Accepted 20 August 2016
Available online 23 August 2016
This manuscript was handled by A. Bardossy, Editor-in-Chief, with the assistance of Purna Chandra Nayak, Associate Editor

Keywords:
Rainwater harvesting
Optimal size
Cost minimization
Sustainable water use

ABSTRACT

Rainwater harvesting (RWH) has the potential to reduce water-related costs by providing an alternate source of water, in addition to relieving pressure on public water sources and reducing stormwater runoff. Existing methods for determining the optimal size of the cistern component of a RWH system have various drawbacks, such as specificity to a particular region, dependence on numerical optimization, and/or failure to consider the costs of the system. In this paper a formulation is developed for the optimal cistern volume which incorporates the fixed and distributed costs of a RWH system while also taking into account the random nature of the depth and timing of rainfall, with a focus on RWH to supply domestic, nonpotable uses. With rainfall inputs modeled as a marked Poisson process, and by comparing the costs associated with building a cistern with the costs of externally supplied water, an expression for the optimal cistern volume is found which minimizes the water-related costs. The volume is a function of the roof area, water use rate, climate parameters, and costs of the cistern and of the external water source. This analytically tractable expression makes clear the dependence of the optimal volume on the input parameters. An analysis of the rainfall partitioning also characterizes the efficiency of a particular RWH system configuration and its potential for runoff reduction. The results are compared to the RWH system at the Duke Smart Home in Durham, NC, USA to show how the method could be used in practice.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

In a period of rapidly rising populations and climate uncertainty, rainwater harvesting (RWH) is seen as an increasingly attractive option to reduce the pressure on diminishing water supplies in many regions of the world (Pandey et al., 2003). Its potential for runoff reduction also has benefits even in areas where water is relatively abundant (Steffen et al., 2013; Sample and Liu, 2014; Walsh et al., 2014; Wang and Zimmerman, 2015). When used as an alternative water supply, captured rainwater may be used in nonpotable applications such as agriculture, car washing, and toilet flushing. Less commonly due to the cost of treatment, it may be used as a potable water source. In this paper we focus on designing RWH systems for domestic, nonpotable uses with a relatively constant demand, thereby avoiding complications such as the dependence of agricultural demand on soil moisture levels and the additional cost and complexity of incorporating a water treatment system.

The volume of the storage tank or cistern is perhaps the most important aspect in the design of a RWH system, but the methods to determine this volume have various drawbacks. Basic methods which could be applied by anyone exist (Ball, 2001; Krishna et al., 2005; Jones and Hunt, 2008) and may be as simple as sizing the cistern based on a fraction of the total average annual rainfall, but this approach ignores much of the information that could be obtained to better inform the design. Numerous methods of a more technical nature have been employed to study this question, focusing to a large degree on design criteria related to reliability, which is generally defined as the percentage of time that the RWH system was able to meet the desired demand (e.g., Basinger et al., 2010). Reliability is naturally of concern in the design of any RWH system, and is likely to be the dominant one in situations where it is the primary or the only water source. However, other water sources (such as municipal supplies or water trucks) may be available, each with an associated cost. Considering these sources in the design process allows for a more complete picture of the utility and benefits of the system. Economic considerations must also be examined, as the appeal of RWH will be limited if it is not cost-effective. Government regulations encouraging or mandating such

---

* Corresponding author.
E-mail address: nfp5@duke.edu (N. Pelak).

http://dx.doi.org/10.1016/j.jhydrol.2016.08.036
0022-1694/© 2016 Elsevier B.V. All rights reserved.

Nomenclature[1]

A	roof area (m^2)	R	rainfall rate (m/d)
c	normalized storage volume (–)	RWH	rainwater harvesting (–)
D_c	cistern demand index (–)	r	water unit cost ($\$/m^3$)
G	total cost ($)	SH	smart home (–)
G_d	distributed costs ($)	T	lifetime of cistern (d)
G_f	fixed costs ($)	V	cistern volume (m^3)
h	constant water demand rate ($m^3\,d^{-1}$)	α	mean rainfall event depth (mm)
H	water demand rate (from cistern) ($m^3\,d^{-1}$)	ϕ	runoff coefficient (–)
H_m	water demand rate (from municipal source) ($m^3\,d^{-1}$)	γ	dimensionless cistern volume (–)
p_0	probability that $c = 0$ (–)	λ	mean rainfall event frequency (d^{-1})
Q	overflow rate (m^3/d)	Θ	heaviside step function (–)
q	storage capacity unit cost ($\$/m^3$)		

systems also provide a political dimension which could increase their attractiveness.

Many previous studies (e.g. Lee et al., 2000; Ghisi et al., 2007; Cowden et al., 2008; Basinger et al., 2010; Jones and Hunt, 2010; Khastagir and Jayasuriya, 2010; Steffen et al., 2013; Fernandes et al., 2015) utilized numerical approaches to study optimal cistern design. Some, including Lee et al. (2000), Ghisi et al. (2007), Khastagir and Jayasuriya (2010), and Steffen et al. (2013), developed regression equations which are simple to use, but dependent on numerical data and thus highly specific to certain areas. These investigations also often had applications to particular regions or cities (Lee et al., 2000; Ghisi et al., 2007; Guo and Baetz, 2007; Cowden et al., 2008; Abdulla and Al-Shareef, 2009; Basinger et al., 2010; Jones and Hunt, 2010; Khastagir and Jayasuriya, 2010; Palla et al., 2012; Assayed et al., 2013; Mehrabadi et al., 2013; Steffen et al., 2013; Hanson and Vogel, 2014; Wang and Zimmerman, 2015; Rostad et al., 2016) and typically used available local rainfall records to optimize their designs. The drawbacks of relying too heavily on specific rainfall observations are that rainfall records are insufficient to capture the true variability, and moreover the results may not hold in other regions. Climate change is likely to increase the variability in rainfall patterns and amounts in the future (Easterling et al., 2000; Feng et al., 2013), adding further uncertainty and necessitating methods which can account for such changes, such as synthetic analytical representations of rainfall.

Here we develop an analytical expression for the optimal cistern size of a RWH system based on economic considerations. We use a parametric description of rainfall, in which rainfall occurs as a marked Poisson process (e.g., Rodríguez-Iturbe and Porporato, 2004). This simple representation of rainfall is parsimonious, mathematically tractable, and may be easily adapted to future climate scenarios with different rainfall patterns by adjusting the climate parameters. In areas where rainfall cannot be modeled exponentially, seasonal variation in rainfall could be incorporated by employing a time-dependent Poisson process, a route which will be explored in future contributions. A similar approach, which also took into account the length of individual storm events, was used by Guo and Baetz (2007) to derive an analytic expression for optimal cistern size. However, as with most of the studies discussed previously, it focused on optimizing the cistern volume to obtain a desired reliability. Here we provide an expression that optimizes the cistern volume by minimizing the total cost, and make an application of the results to the Duke Smart Home in Durham, NC.

Minimizing total cost to find the optimal cistern storage volume has been used by several other authors. Okoye et al. (2015) used linear programming methods to minimize an objective cost function. Other studies used nonlinear programming methods to explore the tradeoffs between maximizing rainwater capture and reducing or delaying runoff (Sample and Liu, 2014), to design water networks for RWH in residential developments (Bocanegra-Martínez et al., 2014) and for water capture-reuse systems in a housing complex (García-Montoya et al., 2015). These latter two studies had the dual goals of minimizing freshwater consumption and total cost. Walsh et al. (2014) examined the interesting case of a RWH system which was operated with the primary goal of runoff reduction. Liaw and Tsai (2004) developed curves by which an optimal cistern size could be selected which met a given reliability level and also minimized a cost function. Campisano and Modica (2012) used historical rainfall data to simulate the water balance in the cistern, developed empirical equations to describe the water savings efficiency in terms of dimensionless parameters, and combined these with a cost function which was then minimized. In contrast, our analysis is not dependent on historical rainfall data or simulations and is backed by mathematical models which have been widely applied to hydrological problems (see Section 2).

We also note that DeBusk et al. (2013) examined four existing RWH systems in North Carolina and found that they were not cost-effective over their expected lifetimes, but it is not clear that these systems were operated or sized in such a way as to minimize the owner's water-related costs. Our goal here is to assess the conditions of optimal cistern size as a function of rainfall regime as well as fixed and distributed costs under ideal operating conditions to provide a benchmark for further study and analysis of the impact of pricing policies and sustainability incentives on water consumption.

In the following sections, we will first describe the water balance in the cistern and formulate the problem in mathematical terms. Then, general solutions to related problems obtained by other researchers will be shown, along with the partitioning of the water balance. Finally, we will develop a cost function for the cistern over its lifetime and find an exact expression for the cistern volume which minimizes the total cost.

2. Stochastic water balance in cisterns

The mass balance of water in a cistern which is filled by means of rooftop rainwater harvesting is as follows

$$V\frac{dc}{dt} = \phi A R(t;\alpha,\lambda) - H(c) - Q(c), \tag{1}$$

where V [m^3] is the cistern volume, c is the normalized cistern storage volume ranging from zero to one, ϕ is a runoff coefficient, A [m^2] is the area of the roof capable of collecting water, R [m/d] is the

---

[1] A guide to the symbols and abbreviations used in this paper.

Download English Version:

https://daneshyari.com/en/article/6409485

Download Persian Version:

https://daneshyari.com/article/6409485

Daneshyari.com