Journal of Environmental Management 180 (2016) 82–93

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Uncertainty analysis of daily potable water demand on the performance evaluation of rainwater harvesting systems in residential buildings

Arthur Santos Silva*, Enedir Ghisi

Federal University of Santa Catarina, Department of Civil Engineering, Laboratory of Energy Efficiency in Buildings, Florianópolis, SC 88040-900, Brazil

ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form
6 May 2016
Accepted 11 May 2016

Keywords:
Rainwater harvesting
Performance evaluation
Water demand
Sensitivity analysis
Uncertainty analysis

ABSTRACT

The objective of this paper is to perform a sensitivity analysis of design variables and an uncertainty analysis of daily potable water demand to evaluate the performance of rainwater harvesting systems in residential buildings. Eight cities in Brazil with different rainfall patterns were analysed. A numeric experiment was performed by means of computer simulation of rainwater harvesting. A sensitivity analysis was performed using variance-based indices for identifying the most important design parameters for rainwater harvesting systems when assessing the potential for potable water savings and underground tank capacity sizing. The uncertainty analysis was performed for different scenarios of potable water demand with stochastic variations in a normal distribution with different coefficients of variation throughout the simulated period. The results have shown that different design variables, such as potable water demand, number of occupants, rainwater demand, and roof area are important for obtaining the ideal underground tank capacity and estimating the potential for potable water savings. The stochastic variations on the potable water demand caused amplitudes of up to 4.8% on the potential for potable water savings and 9.4% on the ideal underground tank capacity. Average amplitudes were quite low for all cities. However, some combinations of parameters resulted in large amplitude of uncertainty and difference from uniform distribution for tank capacities and potential for potable water savings. Stochastic potable water demand generated low uncertainties in the performance evaluation of rainwater harvesting systems; therefore, uniform distribution could be used in computer simulation.

1. Introduction

As water is a key resource for human living and development, its management should be improved properly through the years. A report by the United Nations World Water Assessment Programme has shown that the sustainable use of water drives consequences far beyond social, economic and environmental dimensions, as it influences human health, availability of food and energy, industrial development and urbanization growth (WWAP, 2015).

Economy and population growth worldwide, urbanization, migration and industrialization as well as the growth of production and consumption lead to more freshwater withdrawal and environmental pollution. In general, the major priority for many countries is to assure the institutions capacity to manage water resources by integrating it to socio-economic development and reduction of poverty.

The Water National Agency (ANA, 2013) states that Brazil has a high freshwater availability compared to other countries. The agency analysed data over the period 1961–2007 and verified that the average annual rainfall in Brazil is 1761 mm, and it ranges from 500 mm in the northeast region to over 3000 mm in the Amazon region.

The surface water availability in Brazil is 91,000 m^3 in the whole country, considering 95% of permanence water flow. This availability was calculated by the Water National Agency (ANA, 2013) by taking the twelve most representative watersheds to calculate the indicator of incremental water flow for drought period (that means the 95% of occurrence of permanence flow). The natural long-term water flow of the watersheds was not used as an indicator due to the interference of drought periods and seasonal behaviour.

Although there is high water availability, it is expected that the

* Corresponding author.
E-mail addresses: arthurssilva07@gmail.com (A.S. Silva), enedir.ghisi@ufsc.br (E. Ghisi).

http://dx.doi.org/10.1016/j.jenvman.2016.05.028
0301-4797/

water demand in Brazil will increase from 570 m^3/s in 2015 to 630 m^3/s in 2025 (ANA, 2010).

According to the Water National Agency (ANA, 2010) the major problems of water supply in Brazil are due to the limited productive capacity of the existing surface or underground systems. For the whole country, 45% of the cities have satisfactory water availability to guarantee urban water supply, while 46% require expansion and improvement of existing systems, and 9% require investments in new water sources (both underground and surface).

The use of rainwater as a water source is an alternative to mitigate freshwater availability. Rainwater harvesting can reduce freshwater direct withdrawal and reduce efforts for providing infrastructure and maintenance of existing and new water supply systems. It can be used for non-potable end-uses without the need of great amount of chemical or biological treatment (Fewkes, 2000). As a matter of fact, rainwater harvesting is important to reduce the dependence on centralized water supply, as well as reducing maintenance, operation and infrastructure costs of public water supply (Gurung and Sharma, 2014; Silva et al., 2015).

There are many numerical and simulation methods for determining rainwater system performance, such as sizing tank capacity, calculating spillage and efficiency, determining the potential for potable water savings and other performance indicators.

A Brazilian standard (NBR 15527) addresses some methods for sizing rainwater tank capacity. From the literature, simulation methods are good tools for evaluating rainwater system performance as they consider stochastic variations in rainwater availability and consumption through predefined time steps (ABNT, 2007). The problem of simplified or "practical" sizing methods is that they consider average values for some important variables, but not the heterogeneity of each location and operation of each building.

Fewkes (2000) studied spatial and temporal variations in rainfall and how they can be incorporated in behavioural models that simulate rainwater harvesting systems. Two well-known models were used, i.e., "yield after spillage" (YAS) and "yield before spillage" (YBS) (Jenkins et al. (1978) apud Fewkes (2000)). The authors concluded that the simplified monthly model could be used as an alternative for modelling the performance of rainwater collectors. Ghisi et al. (2012) have also analysed temporal variations of short- and long-term rainfall data for evaluating rainwater system performance. The difference from longer periods to short periods was never greater than 5% on the potential for potable water savings indicator, which confirms that short-term time series can be used as they provide reliable results. Campisano and Modica (2014) showed that the timestep (daily and sub-daily data) influences the performance of rainwater harvesting systems, especially in small tank sizes and high water demand.

Rupp et al. (2011) performed a comparative analysis of different methods presented in the Brazilian standard NBR 15527 (ABNT, 2007) for sizing rainwater storage tanks. A computer programme called *Netuno* was also used. *Netuno* estimates the potential for potable water savings for different tank capacities based on daily rainfall. All of the normative methods showed to be inadequate for sizing rainwater tanks compared to *Netuno*. Also, Cordova and Ghisi (2011) compared *Netuno* with the YAS and YBS models and concluded that the three methods show results that are statistically equivalent.

There are other studies that have assessed rainwater harvesting system performance. Appan (2000) studied rainwater harvesting from rooftop of high-rise buildings in Singapore by using a simulation model and hourly water demand for supplying non-potable water. Zhang et al. (2009) analysed rainwater harvesting in high-rise buildings in Australia and concluded that bringing together rainwater usage and efficient water fixtures (by reducing water demand) could contribute to reduce potable water consumption and improve water distribution efficiency in a long-term period. Imteaz et al. (2011) analysed an existing rainwater harvesting system on Swinburne University Hawthorn campus, in Australia, by improving the tank capacities. Sample and Liu (2014) analysed near-optimum solutions considering runoff capture reliability and water supply, considering different input variables and locations. Some studies have also analysed the benefits of rainwater harvesting to reduce urban rainwater runoff, such as Burns et al. (2014) and Petrucci et al. (2012).

By analysing different combinations of roof area, rainwater demand and potable water demand for rainwater harvesting in Brazil, Ghisi (2009) concluded that the sizing and evaluation of rainwater system should be performed for each specific situation, as input variables for simulation approaches influence all performance indicators. System sizing methods based on local or general recommendation could lead to low efficiency and high-cost systems.

Different aspects for sizing rainwater tanks or calculating performance indicators were found in the literature. However, parameters related to potable water demand variability (which is a key factor for all possible analyses) were not properly addressed in previous studies.

Thus, the objective of this paper is to perform a sensitivity analysis of common design variables of a rainwater harvesting system, and an uncertainty analysis of daily potable water demand for system performance assessment in residential buildings.

2. Method

Method was divided in five phases: (1) definition of the simulation model and general demonstration of the experiment; (2) definition of rainfall data and the independent variables of the experiment; (3) detailing potable water demand parameters; (4) definition of the dependent variables; and (5) statistical treatment of the results.

2.1. Simulation model and experiment

The *Netuno* computer programme was used to perform the simulations. *Netuno* (Ghisi et al., 2014a,b) was validated by Rocha (2009) and has been used with success in other researches (Ghisi, 2009; Ghisi et al., 2012, 2014a,b; Ghisi and Schondermark, 2013).

The aim of the *Netuno* programme is to estimate the potential for potable water savings for different tank capacities for rainwater storage. For the calculation procedures, *Netuno* uses input data such as daily rainfall, potable water demand *per capita*, rainwater demand (as a percentage of potable water demand), number of occupants, roof area, tank capacity, initial rainfall to be discarded and runoff coefficient.

The algorithm begins calculating the captured water volume $Q_{(t)}$ according to Eq. (1) for each day t. The next step is to determine the water volume consumed in day t using Eq. (2), and also to calculate the total available rainwater volume in the tank at the end of each day using Eq. (3). From the values obtained using Eqs. (1) and (3), for each time step t that represents the number of days in the rainfall time series, the potential for potable water savings is estimated using Eq. (4).

$$Q_{(t)} = P_{(t)} \times A \times c_p \quad (1)$$

$$C_{p(t)} = min\left\{ \begin{array}{l} d_p \times D_{(t)} \times n \\ S_{(t-1)} + Q_{(t)} \end{array} \right. \quad (2)$$