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Research papers

Relevance of hydrological variables in water-saving efficiency of domestic rainwater tanks: Multivariate statistical analysis

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ABSTRACT

This research investigated the relevance of four hydrological variables in the performance of a domestic rainwater harvesting (DRWH) system. The hydrological variables investigated are average annual rainfall (P), precipitation concentration degree (PCD), antecedent dry weather period (ADWP), and ratio of dry days to rainy days (n_D/n_R). Principal component analyses are used to group the water-saving efficiency into a select set of variables, and the relevance of the hydrological variables in a water-saving efficiency system was studied using canonical correlation analysis. The P associated with PCD, ADWP, or n_D/n_R attained a better correlation with water-saving efficiency than single P. We conclude that empirical models that represent a large combinations of roof-surface areas, rainwater-tank sizes, water demands, and rainfall regimes should also consider a variable for precipitation temporal variability, and treat it as an independent variable.

1. Introduction

Population growth in cities has a significant impact on the quantitative and qualitative availability of fresh water resources, requiring new approaches to water management in urban areas (Palla et al., 2011). In some regions of the world, authorities are adopting alternatives to meet the growing demand for fresh water, including the use of rainwater, water reuse, and desalination.

The use of alternative water sources is very important for managing water resources, and the use of rainwater is one measure that has been adopted for water conservation, not only for domestic use but also for industrial use (Khastagir and Jayasuriya, 2010; Palla et al., 2012). Rainwater has been used to supplement other water supplies in several parts of the world where the conventional water supply system does not satisfactorily meet the needs of the population (Liaw and Tsai, 2004). In Australia, government officials offer incentives and subsidies to promote the installation of rainwater utilization systems (Imteaz et al., 2012; Rahman et al., 2012). In Brazil, public funding supported the installation of more than 580,000 rainwater tanks in rural areas throughout the country.

Currently, the performance of domestic rainwater harvesting (DRWH) systems is evaluated by reservoir water balance using long-term rainfall time series (Ghisi et al., 2006; Ghisi et al., 2007; Imteaz et al., 2012; Rahman et al., 2012; Mehrabadi et al., 2013). These studies provide DRWH performance indices for different rainwater tank sizes, roof-surface areas, and levels of demand. However, these results are applied only in specific locations that provided rainwater tank outcomes related to specific rainfall time series. Other research has sought an empirical relationship between the DRWH performance indices and some of the following variables: rainwater tank size, roof area, demand, and a hydrological variable (Eroksuz and Rahman, 2010; Rahman et al., 2012; Hajani and Rahman, 2014b). The empirical models can also use dimensionless index-like independent variables (Fewkes, 1999; Khastagir and Jayasuriya, 2010; Liaw and Chiang, 2014a). However, the equation that represents the relationship between the DRWH performance indices and the independent variables only can be applied in the region that provides the long-term time series data used for analysis.

In empirical models, the main hydrological variable used is the average annual rainfall (P), without incorporating variable representing the temporal variability of precipitation for a specific region. This modeling method cannot therefore be extrapolated across regions with variations in rainfall depending on the time of year; for example, localities may have the same annual rainfall

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but different temporal variability, thereby producing different rainwater tank efficiency.

According to Imteaz et al. (2012), many studies have used average annual rainfall data to model a DRWH system; however, in areas of high inter-annual rainfall variability, analysis that considers long-term mean annual rainfall may not be useful. Imteaz et al. (2013) evaluated the results of DRWH reliability in different areas of Melbourne, Australia, and concluded that it is necessary to change the traditional design practice of considering a single annual rainfall value for rainwater-tank sizing, and the results of these studies should vary if applied in places with different rainfall intensities and patterns.

Palla et al. (2012) evaluated DRWH reliability in the different climates of Europe and studied the effect of meteorological parameters such as antecedent dry weather period (ADWP), depth, and intensity and duration of rainfall on the performance of DRWH systems. They concluded that ADWP was the most significant parameter correlated with DRWH performance indices.

The present study investigated the relevance of four hydrological variables in the performance of DRWH systems with the intent to evaluate each hydrological variable in terms of being able to be used in empirical models. The hydrological variables investigated are average annual rainfall (P), precipitation concentration degree (PCD), antecedent dry weather period (ADWP), and ratio of dry days to rainy days (n_D/n_R). With the exception of P, all other variables represent the temporal variability of precipitation. The results of this research: (1) give support for the inclusion of hydrological variables that represent the temporal variability of precipitation in empirical models; (2) present a methodology for analyzing the relevance of different variables in water-saving efficiency of a DRWH system (methodology not unpublished, but not previously applied in DRWH system analyses); and (3) introduce the variable PCD, which has never been used before in DRWH system analyses.

2. Material and methods

2.1. The behavior model

The present study was performed in 50 locations in the state of Rio Grande do Norte, Brazil (Fig. 1), all of them with 48-year data series of daily rainfall, covering the same period from 1963 to 2010. All rainfall series data were provided by Agricultural Research Corporation of Rio Grande do Norte State (Empresa de Pesquisa Agropecuária do Rio Grande do Norte, EMPARN).

The system behavior analysis was performed with the water balance simulation model using daily simulations. Yield before spillage (YBS) and yield after spillage (YAS) models were developed by Jenkins et al. (1978) and indicate different rules for reservoir operations to carry out simulations. In the YBS model, after-rainfall water has been added, demand is met, and spillage is computed in the model. In the YAS model, demand is met after rainfall water has been added to the reservoir and spillage has occurred.

Mitchell (2007) investigated the impact of the computational time step, the computational operation rule (YAS and YBS), the initial volume of the reservoir, and the length of the simulation period on the accuracy of the model. In the results of this study, the YAS model was more accurate than the YBS model, regardless of the computational time step adopted, and YAS model provided more conservative efficiency values. However, the fact that the YAS model provides a conservative estimate of system performance was pointed out by another researcher (Fewkes, 1999) as a critique of the model. Liaw and Tsai (2004) recommended the YBS model, especially when there is a combination of a small reservoir and large demand, because in these situations the water-saving efficiency can be zero, preventing evaluation of the system.

In this study, the simulations were conducted with the YAS model. The YAS model is based on the following equations (Eqs. (1) and (2)):

$$Y_t = \min\begin{cases} D_t \\ V_{t-1} + I_t \end{cases}, \tag{1}$$

$$V_t = \min\begin{cases} V_{t-1} + I_t - Y_t \\ C - Y_t \end{cases}. \tag{2}$$

where Y_t is the volume that supplied the demand in the final time interval t; V_{t-1} is the stored volume in the final time t – 1; V_t is the stored volume in the final time interval t (current time); I_t is the water drained from the roof to the reservoir in the time interval t; D_t is the total demand for water in the time interval t; and C is the rainwater tank capacity.

The reservoir behavior was analyzed for water-saving efficiency, according to Fewkes (1999), in Eq. (3):

$$E = \frac{\sum_{t=1}^{T} Y_t}{\sum_{t=1}^{T} D_t} \times 100. \tag{3}$$

where E is the system's water-saving efficiency to meet the demand (%); Y_t is the volume that supplied the demand in any time interval t; D_t is the total water demand in the time interval t (daily demand); and T is the total time (in days) of the series. The water-saving efficiency is interpreted as a measure of the system's quantitative performance over the long-term simulation period (Palla et al., 2012).

To simulate the performance of a DRWH system, a daily water balance simulation model was built in Visual Basic language for Excel (Microsoft; Redmond, Washington, USA). For each locality, a 48-year data series of daily rainfall was used. This sort of approach with long-term rainfall data produces average water-saving efficiency. For the current research, this approach is sufficient, as we are investigating the relevance of a set of hydrological variables in water-saving efficiency; the use of average outcomes is adequate. It should be noted, however, that if the purpose of the research is to indicate the degree of water-saving efficiency for the system-user, it should be clarified that the results presented are the average efficiency, and because of inter-annual rainfall variabilities, is not certain to save the same amount of water every year. Another alternative is to present the efficiency of rainwater tanks under different climate conditions (i.e. dry, average, wet years), as was done in Imteaz et al. (2012), Imteaz et al. (2013) and Hajani and Rahman (2014a).

2.2. Scenarios

Simulations of DRWH systems were created for combinations of hydrological conditions and system characteristics as follows: 50 rainfall regimes (with annual rainfall ranging from 477 to 1699 mm), four rainwater demand amounts (50, 100, 150, and 200 L day^{-1}), five rainwater-tank sizes (1, 5, 10, 15, and 20 m^3), and four roof-surface areas (50, 100, 150, and 200 m^2). Diverse combinations of demand, rainwater-tank size, and roof-surface area generated 80 simulations for each of the 50 locations.

These scenarios were evaluated by a dimensionless index, pi (Eq. (4)) defined using the variables: annual rainwater demand (D), rainwater-tank capacity (C) and roof-surface area (A).

$$\pi = \frac{A \cdot C}{D^{5/3}} \tag{4}$$

The π results of 80 combinations of D, C, and A were divided into four groups of equal size (20 elements), classified according to the schema presented in Table 1.