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Assessment of rainwater harvesting system through continuous simulation with sub-daily data

Avaliação de sistema de captação de água de chuva através de simulação contínua com dados subdiários

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ABSTRACT

A rainwater harvesting system, designed for non-potable water uses, can be helpful for runoff generation control. To evaluate this, sub-daily time steps for monitoring and continuous simulations are important tools. Therefore, this paper shows a performance assessment of a rainwater harvesting system for both roof runoff control (maximum flow rate and drained volume) and to meet water demand, from data obtained in a monitoring apparatus and also from continuous simulation using 1-minute time steps data. The model SWMM was calibrated and validated for both a roof and a monitoring apparatus during the monitored period 2018-2019. Thereafter, continuous simulations were accomplished using rainfall, evaporation, and demand time series. For this stage, data satisfied nearly seven years (2014-2020) containing one-minute time step values. Results have shown the control is influenced by the combined action of the first-flush diverter and rainfall regime and was shown to be greater at maximum flow rate than volume.

Keywords: Rainwater harvesting; Continuous simulation; Runoff control; Roof runoff modeling.

RESUMO

O sistema de aproveitamento de águas da chuva, concebido para usos da água não-potáveis, pode ser útil no controle da geração de escoamentos superficiais. Para avaliar isto, intervalos de tempo sub-diários no monitoramento e simulações contínuas são ferramentas importantes. Portanto, este artigo mostra a avaliação do desempenho do sistema de aproveitamento de águas da chuva, tanto para controle do escoamento superficial de um telhado (vazão máxima e volume) como para atender a demanda de água, a partir de dados obtidos em um aparato de monitoramento e também de simulação contínua utilizando dados discretizados com passo de tempo de 1minuto. O modelo SWMM foi calibrado e validado para um telhado e para o aparato de monitoramento, no período monitorado de 2018 a 2019. Posteriormente, foram realizadas simulações contínuas utilizando séries temporais de precipitação, evaporação e de demanda, de quase sete anos (2014-2020). Os resultados mostraram que o controle é influenciado pela ação combinada do dispositivo de descarte das primeiras águas e do regime pluviométrico, tendo sido maior na vazão máxima do que no volume.

Palavras-chave: Aproveitamento de água do telhado; Simulação contínua; Controle do escoamento; Modelagem do escoamento em telhado.

INTRODUCTION

The pursuit of sustainable urban development has resulted in new conceptions for traditional drainage systems (França et al., 2022) coming about new approaches that acknowledge stormwater as a multifunctional resource, increasing possibilities of using it as a strategy for reducing the negatives outcomes of catchments urbanization (Abdelkebir et al., 2021). Along this path, it has been found that implementing alternatives to restore water quality and near-natural flow regime results in broad benefits to the environment and urban landscape (Delleur, 2003; Fletcher et al., 2013; Ramírez-Agudelo et al., 2021). This is aligned with the Sustainable Development Goals (SDG), which address the need to ensure universal availability and management of water and sanitation, with an emphasis on efficient water use and encouraging reuse (Organização das Nações Unidas, 2015).

In this approach, the conection among urban water infrastructures has to be taken into account, being be possible through decentralisation, greening, circular economy, and digitalisation (International Water Association, 2021). Rainwater Harvesting System (RWHS) can play this role because is a descentralized water supply system that decreases operation and maintenance costs of the built infrastructure and can reduce roof runoff (Akther et al., 2018; Liu et al., 2021; Rodrigues et al., 2021; Araujo et al., 2021).

In RWHS, the stored volume can meet a portion of the consumption corresponding to non-potable water, thus reducing the volumes abstracted from traditional supply sources (Abu-Zreig et al., 2019; Custódio & Ghisi, 2019) and contributing to reducing the magnitude and frequency of peak flows (Campisano et al., 2017), chiefly in association with other systems such as green roofs (Cristiano et al., 2023). Araujo et al. (2021) showed the effect of RWHS deployment at Curve Number (CN), making possible the emergence of conditions close to natural land runoff (preurbanization).

Although the runoff decrease is an outcome of RWHS (Akter et al., 2020; Deitch & Feirer, 2019; Freni & Liuzzo, 2019; Tamagnone et al., 2020; Teston et al., 2018), there are compatibilization difficulties because the rain barrel water stored volume has to be available to meet demand. Conversely, for runoff generation control, it is necessary making available enough volume to detain the next rainfall (Dornelles, 2012; Hentges, 2013; Jensen et al., 2010; Palla et al., 2017; Petrucci et al., 2012). To study suitably this interaction between so different purposes, high temporal resolutions are required at monitoring and simulation, owing to fast hydrological response. Araujo et al. (2021) and Cristiano et al. (2023) have used daily scale to do it, but their results go beyond the lot scale, being feasibles to understand the effects on catchment. Perius et al. (2021) recommend a daily scale when the aim is sizing reservoirs for water demand meeting, and Campisano & Modica (2015) recommend sub-daily time steps to accomplish runoff analysis. All of them have used continuous simulation and some authors notice it as a natural evolution in rainfall-runoff simulations in urban áreas (Grimaldi et al., 2021).

Therefore, this paper aims to add to advancing the understanding of RWHS performance for both roof runoff control (maximum flow rate and drained volume) and meeting water demand, from data obtained in a monitoring apparatus and also from continuous simulation using sub-daily time steps, allowing analysis of several events from different durations and magnitudes of precipitation and flow rate.

MATERIAL AND METHODS

The flowchart in Figure 1 shows the study phases. The SWMM model was calibrated and continuous simulations were accomplished using rainfall and demand time series. Data satisfied nearly seven years (2014-2020) containing one-minute time step values.

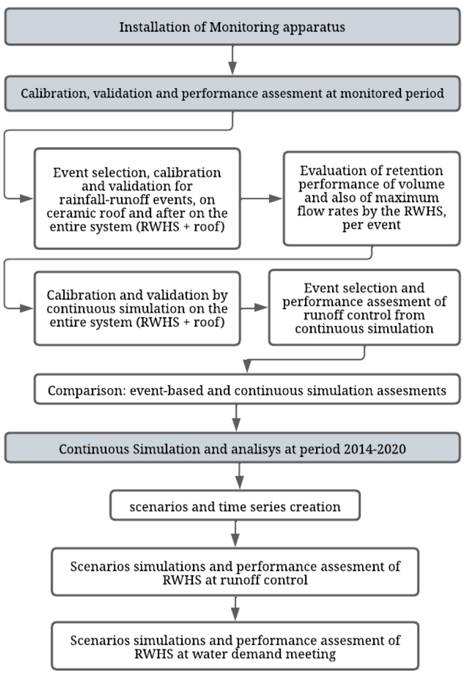

Figure 1. Flowchart with study phases.

Monitoring apparatus (RWHS)

The RWHS was assembled in the first semester of 2018. Before that, Cunha & Neves (2017) determined the specific volume of 93L/m^2 through the simulation method recommended, at time, by NBR 15.527/2007 (Associação Brasileira de Normas Técnicas, 2007) and supressed from current norm (Associação Brasileira de Normas Técnicas, 2019), performing daily water balance that has met demand at 89% of the simulation period, with data from a station 10.3km from the study site. This rain gauge was only used for sizing because the one used in this study was set up in april 2014.

As per Figure 2, the RWHS received runoff from a roof portion of 3.43m^2, composed of (a) a gutter 1m long; (b) a triangular spillway, with a level sensor; (c) a first-flush diverter 80cm long, with nominal diameter of 75mm and orifice at the bottom. Besides, It has an approximate volume of 3.5L, equivalent to 1mm of rainfall; (d) a reservoir (rain barrel) that stores up to 200L approximately, equivalent to 58mm of rainfall; (e) overflow in the reservoir and (f) faucet.

Input and output flow rates were identified and quantified from data with different intervals and lengths of time series, as presented in Table 1.

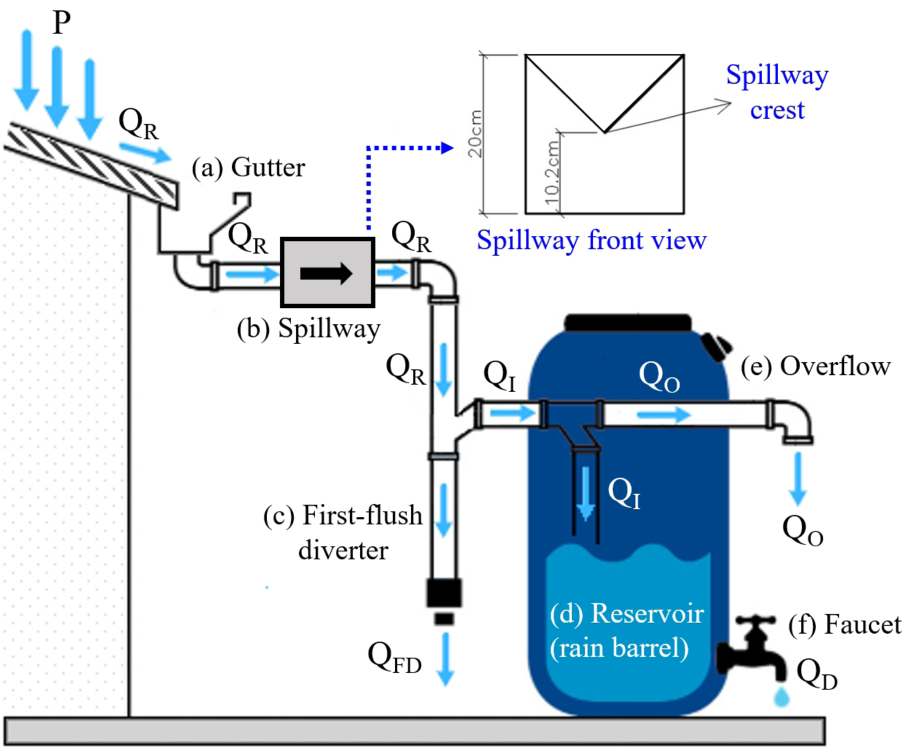

Figure 2. Sketch of RWHS and monitored variables. P is precipitation, Q_R is roof flow rate that goes through spillway and reaches the vertical conduit, Q_{FD} is the flow rate through the first-flush diverter, Q_I is the input flow rate into the rain barrel, Q_D is the flow rate demand in use and Q_O is overflow flow rate.

Table 1. Inputs and outputs of RWHS.

Data		Period	Time step	Method of measurement/obtainment
Rainfall		2014-2020	1min	Tipping-bucket rain gauge
Flow rates		06/2018-01/2020 (with flaws)	1min	Calibrated triangular spillway and water level sensors
The water level in the reservoir (rain barrel)		06/2018-02/2019	1min	water level sensors in the reservoir
Evaporation		1922-1978	Monthly daily average	Weather climate Station Maceió (Tabuleiro)
Water demand	Daily consumption	17/12/2017-31/12/2017	Daily	Water meter readings (Neves, 2019)
	Weekly consumption	04/01/2021-23/02/2021	Weekly	Water meter readings
	Monthly consumption	2017-2020	Monthly	Consumption time series
	System uses	26/07/2018-05/05/2019	Per use	Neves (2019)

Fonte: Santos (2021).

Calibration, validation, and performance assessment at monitored period

The analysis of the RWHS behavior has occurred with the monitored period 2018-2019 data and events were selected in two moments: observing minimum intervals between rainfall of 1h and afterward matching them with spillway hydraulic head data.

Then, calibration of rainfall-runoff events was performed on the ceramic roof and also in RWHS, by the trial and error method. In the ceramic roof, the SCS model was adopted as runoff separation algorithm (CN parameter) and the SWMM nonlinear reservoir for flow routine with parameters Area (A), Width (W), Slope (S), Manning's roughness coefficient at impervious surfaces (nimp) and permeable surfaces (nperm), Depression Storage at impervious surfaces (PAimp) and permeable surfaces (PAperm), Imperviousness (AI) and Impervious Areas Without Depression Storage (AS/A).

Calibration and validation were evaluated by the Nash-Sutcliffe efficiency coefficient (Nash & Sutcliffe, 1970) (Equation 1) and by relative percent differences between observed and simulated values of volumes and peak flow rates (|RPD|volume e |RPD|Qmax) (Equations 2 e 3). NSE values above 0.5 are acceptable (Johannessen et al., 2019; Rosa et al., 2015), and |RPD| values less than 25% are also deemed acceptable.

$$NSE = 1-\frac{\sum_{i=1}^{Nt}\left(Q_{obs_i}-Q_{c_i}\right)^2}{\sum_{i=1}^{Nt}\left(Q_{obs_i}-Q_{o,m}\right)^2} \tag{1}$$

where: $Qobs_i$ is the observed flow rate at end of time step i (m^3/s), Q_{ci} is the calculed flow rate at end of time step i (m^3/s), $Q_{O,m}$ is the average of observed flow rates (m^3/s) and N_t is the number of time steps at analised event.

$$\left|RPD_Q\right| = \frac{Q_{obs}-Q_{sim}}{Q_{obs}} \cdot 100 \tag{2}$$

$$\left|RPD_Q\right| = \frac{Q_{obs}-Q_{sim}}{Q_{obs}} \cdot 100 \tag{3}$$

where: V_{obs} is the observed volume (m^3), V_{sim} is the simulated volume (m^3), Q_{obs} is the maximum observed flow rate (m^3/s) e Q_{sim} is the maximum simulated flow rate (m^3/s).

In the entire system (roof + RWHS), the calibrated parameter was the diameter of the orifice at the bottom first-flush diverter, owing to the paucity of daily maintenance. Hence, sometimes the orifice was partially blocked by sediments carried from the roof. NSE was used to evaluate the quality of calibration with the depths, observed and simulated by SWMM, in the reservoir.

The evaluation of retention performance of volume and also of maximum flow rates by the RWHS, per event, was done using retention efficiency indicators calculated by, Equations 4 and 5. The input were hydrographs determined from spillway data, while the output resulting from these hydrographs propagation at RWHS, similar to Palla et al. (2017) and Tamagnone et al. (2020). The input hydrographs simulated scenario no RWHS, while output hydrographs simulated the existence of RWHS.

$$ER_{Q}= \frac{Q_I-Q_O}{Q_I} \cdot 100 \tag{4}$$

$$ER_{Q}= \frac{Q_I-Q_O}{Q_I} \cdot 100 \tag{5}$$

where: V_I is input volume (m^3), V_O is output volume (m^3), Q_I are maximum input flow rates (m^3/s) and Q_O are maximum output flow rates (m^3/s).

Calibration and validation of the SWMM model by continuous simulation at RWHS have occurred using initial parameter values from event-based calibration, and also using demand, precipitation, and evaporation data. Demand was added in simulation as a negative inflow (term used in SWMM) to the reservoir, that is, a time series of flow rates with 1min time step for the monitored period. The parameter "soil's drying time" was calibrated. It is the number of days required for a saturated soil to completely drain and its significance in calibration is only observed when evaporation is considered.

The periods used were July-October 2018 (calibration) and November/2018-March/2019 (validation). Over again, the NSE coefficient was used, and the root mean square error (RMSE) (Equation 6), was also used by Jamali et al. (2020).

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(V_{obs_i} - V_{c_i}\right)^2\right]^{\frac{1}{2}} \tag{6}$$

where: $Vobs_i$ is the observed volume rate at end of time step i (cm), Vc_i is the simulated volume rate at end of time step i (cm) e N_t is the number of time steps at analised event.

The performance of RWHS at the control of roof runoff generation from the continuous simulation was evaluated picking 48 events, classified through total rainfall and maximum intensity so that the frequency distribution was uniform. The behavior of RWHS during the period of July/2018-march/2019 was evaluated from the use of Equations 4 and 5.

Simulations have occurred from time series of precipitation and evaporation, keeping in mind distinct initial conditions as such main reservoir water level, and analyzing the precipitation and monitored demand influence. To compare event-based analysis and continuous simulations analysis, all the indicators already mentioned were used. All that was essential to accomplish the next phase.

Continuous simulation and analysis in the period 2014-2020

That phase has taken place with nearly seven years time series considering six demand scenarios for non-potable uses garden irrigation, vehicle washing and terrace washing i.e. no uses that require hydraulic installations or pumping systems. The flow rates demand time series were generated, based on monitored volumes and the average flow rates of house used in the study area (Ferreira, 2017).

First of all, a reference scenario (CR) was created, in which frequencies of uses were defined by residents' behavior from monitoring carried out by Neves (2019). Several studies have also been used: Thackray et al. (1978) estimated that garden irrigation corresponds to 2.1 to 3.9% of daily consumption, Qasim (1994) pointed out a value of 3%, Macintyre (1982) estimated consumption of 1.5L.m^{-2} and Perius et al. (2021) have used 190L.use^{-1}.

The estimation of the terrace washing considered an average consumption of 1,5L.m^{-2} for a 48m^2 terrace area (Melo & Azevedo Netto, 1988) and Perius et al. (2021) have used 280L.use^{-1} for cleaning external areas. As for vehicle washing, Qasim (1994) estimated this use equal to 1% of daily consumption in a residence, a volume of 209L.use^{-1} with monthly Frequency, and Perius et al. (2021) have used 220L.use^{-1}. The rational Water Use Program of SABESP (Companhia de Saneamento Básico do Estado de São Paulo, 2007) recommends the use of buckets for vehicle washing, resulting in a volume of 40L.use^{-1}.

The consumption parameters for creating the reference scenario (RC) were: garden irrigation with an area of 11m^2, a volume of 22L and daily frequency, vehicle washing with a volume of 29L and weekly Frequency, and terrace washing with an area of 48 m^2, the volume of 72L and fortnightly frequency. Moreover, the following was deemed annual cleaning of the reservoir, as recommended by NBR 15.527/2019 (Associação Brasileira de Normas Técnicas, 2019). There hasn't been garden irrigation when daily precipitation was above 7mm, according to the observed behavior of residents and rain gauge data.

The simulated scenarios were: 50%×RC (50% decrease in RC demand), 80%×RC (20% decrease in RC demand), 120%×RC (20% increase in RC demand), 150%×RC (50% increase in RC demand), and 200%×RC (100% increase in RC demand).

After simulations of the scenarios, the performance evaluation of RWHS in runoff control was done with indicators ER_V and ER_{Qmax} (Equations 4 and 5). As to meeting demand, the RWHS was evaluated from two dimensionless indicators defined by Dixon et al. (1999), and adopted by Palla et al. (2017) and Sampaio & Alves (2017): water saving efficiency (E) (Equation 7) and rainwater overflow ratio (O) (Equation 8).

$$E = \frac{\sum_{t=1}^{N} Y_t}{\sum_{t=1}^{N} D_t} \tag{7}$$

$$O = \frac{\sum_{t=1}^{N} O_t}{\sum_{t=1}^{N} Q_t} \tag{8}$$

where: Y_t (m^3) represents the rainwater supply (yield) at each time step t, D_t (m^3) is the rainwater demand at each time step, O_t (m^3) represents the rainwater exceeding the system capacity at each time step t, Q_t (m^3) is the system inflow in the reservoir at each time step and N is the total number of simulation time steps.

The indicator full reliability (FR) (Sampaio & Alves, 2017), has been also used, as per Equation 9.

$$FR = \frac{N_{atend}}{N_{dr}} \times 100 \tag{9}$$

where N_{atend} is the total number of simulation time steps in which demand was met and N_{dr} is the total number of simulation time steps in which there has been required demand. Based on results of continuous simulation, we had the reservoir volume conditions and the required demand, allowing us to calculate the ratio between met demand and required demand within a 1-minute interval.

The rainfall influence on RWHS performance has been also ascertained both at runoff detention and meeting of demand.

RESULTS AND DISCUSSIONS

Analysis of the monitored period

Event selection, calibration, and validation for rainfall-runoff events, on the ceramic roof and after on the entire system (RWHS + roof)

Nine events have been picked out for calibration and eight for validation, on the ceramic roof, during the period 2018-2020, according to Table 2. Parameter values are in Table 3. AS/A, W, and AI were the most sensitive parameters. nimp and PAimp were slightly sensitive and nperm, PAperm, and CN did not show sensitivity.

The SWMM model application manual (Gironás et al., 2009) suggests using 25% for AS/A. However, calibration has been made owing to sensitivity in both magnitudes of flow rates and the position of peak flow rates. As to nimp, the manual recommends the use of nimp = 0.014 for ceramics and nimp = 0.015 for ceramic bricks. Meantime, higher values have been found, with an average of 0.03 and a coefficient of variation of 59%, reaching the value of 0.06 at event 15.

For validation, averages of calibrated parameters have been used. Table 4 shows results, in which the best are highlighted in gray.

At calibration, NSE values were equal to or greater than 0.50 for most events, and $|RPD_Q| < 25\%$ was observed at all events. $|RPD_V|$ have shown an average of above 50%, enclosing values above 100%. At validation, These indicators have presented worse values for averages than calibration, albeit better results have been seen for maximum flow rates. The best events were 5-9.

Broadly speaking, the best events were those with higher flow rates. Low flow rate values are coupled with higher uncertainties quantified through prediction intervals on the regression equation of spillway which is a functional relationship between flow rate and hydraulic head on its crest (Santos, 2021; Almeida Júnior, 2018; Neves, 2019). The model has presented limitations in the representation of hydrographs when these have had several flow rate peaks.

As for calibration and validation on the entire system (RWHS + roof), the diameter of the orifice at the bottom first-flush diverter was added as a parameter. The average of calibrated values equal to 1.0mm was adopted in the model.

As for the assessment of RWHS performance at volume retention and maximum flow rates retention, Table 5 shows results, including the runoff pathway. At event 1 (06/29/2018) and event 5 (09/09/2018), runoff volume has gone directly and just about totally to the first-flush diverter, resulting in great volume reductions. The average attenuation of the maximum flow rate was much higher than that of volume, 82%, and 34%, respectively.

Table 2. Selected events for calibration (C) e validation (V) at the roof and monitored period, where P is total Precipitation, D is duration, C_i initial condition in the reservoir, V_S is estimated volume from spillway and L_S is estimated runoff depth of the from the spillway.

Event	Date	P (mm)	D (min)	C_i (%)	V_S (L)	L_S (mm)	Phase
1	29/06/2018	9.60	132.00	63	7.59	2.21	V
2	02/07/2018	45.20	188.00	99	63.42	18.49	V
3	30/07/2018	7.00	17.00	72	5.06	1.48	V
4	31/07/2018	10.80	10.80	85	10.72	3.13	V
5	09/09/2018	5.80	83.00	40	6.74	1.97	V
6	08/11/2018	7.20	67.00	39	23.83	6.95	V
7	08/11/2018	6.60	29.00	48	23.23	6.77	C
8	27/11/2018	7.40	72.00	67	22.18	6.47	V
9	10/12/2018	5.00	9.00	69	15.43	4.50	C
10	15/12/2018	6.00	14.00	75	17.84	5.20	V
11	18/10/2019	6.60	13.00	52	4.72	1.38	C
12	21/11/2019	4.00	58.00	19	4.73	1.38	C
13	15/12/2019	3.20	9.00	29	6.81	1.99	C
14	19/12/2019	8.00	28.00	100	18.60	5.42	C
15	31/12/2019	7.40	33.00	91	6.10	1.78	C
16	20/01/2020	3.60	13.00	88	6.06	1.77	C
17	23/01/2020	3.80	28.00	97	4.50	1.31	C

Table 3. Calibrated parameters at the roof from select events at monitored period.

Event Parameter	7	9	11	13	14	15	16	Average
W (m)	1.00	1.00	0.75	0.80	0.80	0.70	0.70	0.82
AI (%)	100.00	70.00	60.00	70.00	80.00	50.00	65.00	70.71
AS/A (%)	100.00	100.00	10.00	20.00	25.00	0.00	0.00	36.43
PAimp (mm)	1.00	3.00	2.60	1.27	1.27	3.00	1.50	1.94
nimp	0.010	0.010	0.050	0.040	0.020	0.040	0.015	0.026

Table 4. Calibration and validation results of SWMM at the roof and monitored period. CV is the coefficient of variation.

Calibration			
Event	**NSE**	**│RPD_V│(%)**	**│RPD_Q│(%)**
7	0.8	2.0	3.5
15	0.8	21.7	3.8
11	0.5	108.8	4.1
12	-0.3	123.3	11.3
13	0.7	24	19.9
14	0.95	11.2	5
15	0.7	49.3	5.4
16	0.8	25.1	14.5
17	0.1	181.9	1.6
Mean	0.56	60.8	7.7
CV (%)	71%	103%	80%
Validation			
Event	**NSE**	**│RPD_V│(%)**	**│RPD_Q│(%)**
1	-6.91	200.88	73.11
2	-0.74	127.32	3.02
3	-3.39	182.45	90.98
4	-2.92	112.28	84.41
5	0.40	52.23	14.56
6	0.50	32.91	37.42
8	0.82	21.81	31.16
10	0.22	34.01	41.81
Mean	-1.50	95.49	47.06
CV (%)	-1.80	0.74	0.69

Calibration and validation for the entire system (RWHS + roof) and performance assessment of runoff control: continuous simulations

The time series were divided into two parts: calibration (07/08/2018-10/31/2018) and validation (11/01/2018-03/10/2019). In the calibration stage, the parameter "soil's drying time" was calibrated and validated using evaporation data. Its value was 15 days. For calibration, the NSE value was 0.94 and the RMSE value was 13.6L. For validation, the NSE value was 0.95 and of RMSE value was 10.7L.

As to the performance assessment of runoff control, Figure 3 presents results for indicators ER_V and ER_Q at the assessment of runoff retention for 48 events obtained after the simulation of the entire monitoring period. Volume reduction was much lower than maximum flow rate reduction, namely ER_V values were much lower than ER_{Qmax} values, and there has been more variability at ER_V values than ER_{Qmax} values, with medians of 34% and 98%, respectively.

Figures 4 and 5 show an increase in ER_V with increasing total rainfall. The same happens observing maximum intensity, especially with total rainfall values greater than or equal to 6 mm and maximum intensity values greater than or equal to $36 mm{\cdot}h^{-1}$.

Comparison between event-based and continuous simulation assessments

A comparison between event-based analysis and continuous simulation analysis of the ER_V and ER_Q values for the monitoring period is in Figure 6. The event-based analysis used 10 events measured by the spillway and the continuous simulation analysis used the 48 selected events. The median volume decrease at event-based (33%) is very close to continuous simulation (34%). The same has happened median maximum flow rate (88% and 98%).

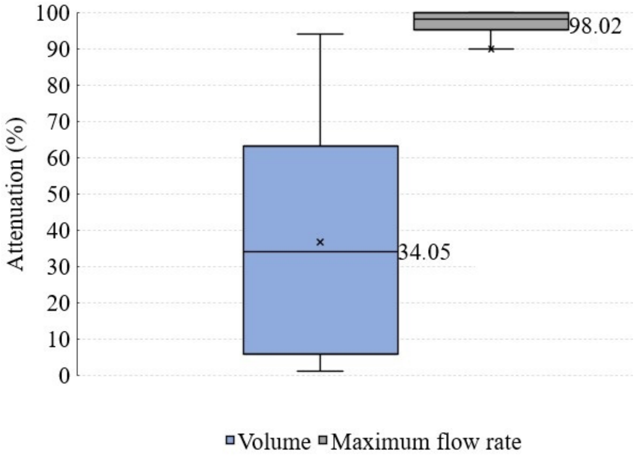

Figure 3. Volume and maximum flow rate attenuations owing to RWHS, for selected events at the continuous simulation at monitored period.

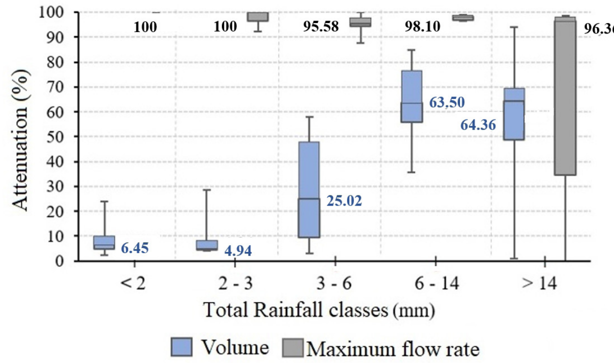

Figure 4. Influence of total precipitation classes at attenuations of volume and maximum flow rate owing to RWHS, for selected events at the continuous simulation at monitored period.

Table 5. Performance of RWHS for events at monitored period: P is total precipitation, I_{mean} is average intensity, I_{max} maximum intensity, IC is an initial condition in the reservoir, F_d is a pathway with flow going straight to first-flush diverter, F_o is a pathway with flow going to the reservoir after has overflowed first-flush diverter, ER_V is volume retention efficiency and ER_Q is maximum flow rate retention efficiency.

Event	Date	P (mm)	I_{mean} ($mm{\cdot}h^{-1}$)	I_{max} ($mm{\cdot}h^{-1}$)	IC (%)	Runoff pathway	ER_V (%)	ER_Q (%)
1	29/06/2018	9.60	4.36	24	63%	F_d	2%	83%
2	02/07/2018	45.20	14.43	48	99%	F_o	4%	3%
3	30/07/2018	7.00	24.71	60	72%	F_o	7%	88%
4	31/07/2018	10.80	8.88	48	85%	F_o	24%	84%
7	09/09/2018	5.80	4.19	60	39%	F_o	4%	84%
8	08/11/2018	7.20	6.45	36	39%	F_o	42%	88%
9	08/11/2018	6.60	8.43	72	48%	F_o	65%	96%
10	27/11/2018	7.40	6.17	60	68%	F_o	58%	96%
11	10/12/2018	5.00	33.33	72	69%	F_o	66%	96%
12	15/12/2018	6.00	25.71	120	74%	F_o	68%	98%
			Mean				34%	82%
			Standard deviation				29%	28%
			Coefficient of variation				84%	35%

Fonte: Santos (2021).

Analysis for the simulated period 2014-2020

Demand scenarios and performance assessment of RWHS for runoff control

As for the water demand, from data of residence consumption and monitoring, it has been estimated a water consumption of around 450L.day^{-1}. Of these, about 5-27% could be replaced by rainwater, considering the uses of vehicle washing (6%), terrace washing (16%), and garden irrigation (5%).

It should be stressed that the required water demand (estimated from monitoring of residence uses) is not necessarily the met water demand. This one is the portion of the required demand that RWHS was able to meet. Thus, despite scenarios have simulated changes in required water demand from 5,340L at 50%×RC until 21,360L at 50%×RC, the met demand at six scenarios remained at nearly 2,200L.year^{-1}, corresponding to 1.3% of total annual water consumption at residence. Owing to this limitation, values of ER_V and ER_Q have had very similar results in all scenarios, although has occurred greater variability at ER_V than at ER_Q, as is shown in Figure 7.

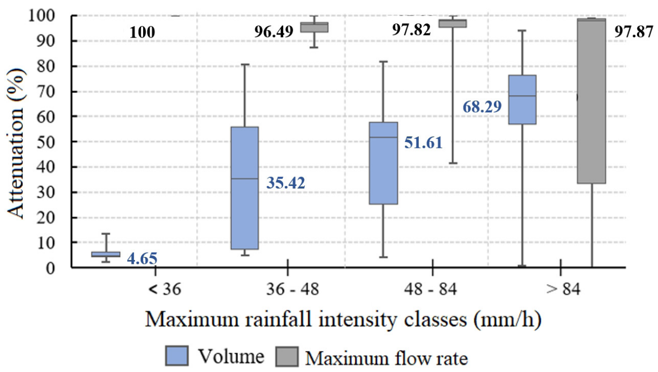

Figure 5. Influence of maximum rainfall intensity classes at the attenuations of volume and maximum flow rate owing to RWHS, for selected events after continuous simulation at monitored period.

As to total precipitation influence and also maximum intensity influence, they were very similar: ER_V value grows when total precipitation and maximum intensity value increase in an almost linear pattern. ER_Q presents high values regardless of rainfall characteristics (Figures 8 and 9).

To evaluate the influence of rainfall characteristics, the frequency distribution was performed on the following classes of total rainfall: < 3mm, 3-5mm, 5-10mm, 10-20mm, and> 20mm. As for rainfall intensity, the classes were as follows: < 30mm.h^{-1}, 30-40mm.h^{-1}, 40-60mm.h^{-1}, 60-80mm.h^{-1}, > 80mm.h^{-1}.

In 2016 there have been the highest Frequency (38.5%) of total rainfall less than 3mm, and also the highest frequency (36.5%) of maximum rainfall intensities less than 30mm.h^{-1}. In this same year, the median ER_V presented the lowest value (30.7%), according to Figure 10. There was no highlight year for maximum values of total rainfall or rainfall intensity, i.e. frequency distribution was nearly uniform.

Figure 11 shows how the first-flush diverter affects the retention of volume and maximum flow rate. When maximum rainfall intensity is less than 30mm.h^{-1}, more than 90% of the inflow volume is drained through the first-flush diverter. Virtually, there is no attenuation of volume and maximum flow rate. In six years, nearly 25% of events had more than 90% of their volume going straight to the first-flush diverter.

Performance assessment of RWHS at water demand meeting

Indicators E, O, and FR are shown in Figures 12 and 13. There is a decrease at E with increasing demand requirement, reaching a maximum value of 0.38 for the 50%×RC scenario and FR of 37%.

Local rainfall characteristics influence indicators. In the year containing both more low precipitation events and low maximum intensity events (2016), E reached its lowest value (0.12), while in the year with the most intense events (2020), there was the highest value of E (0.29), as shown at Figure 14.

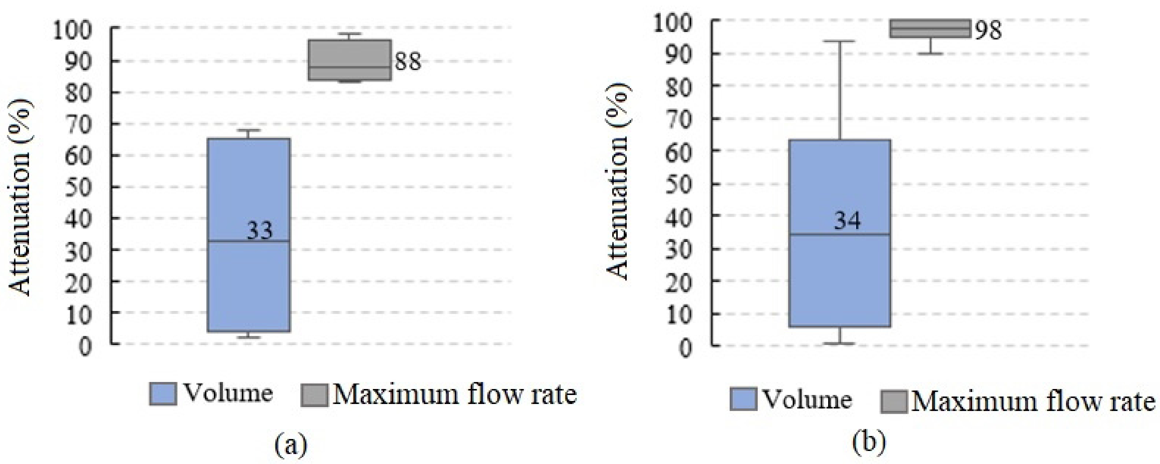

Figure 6. Comparative analysis of volume and maximum flow rate attenuations owing to RWHS, for selected events at monitored period: (a) 10 estimated events from spillway; (b) 48 selected events from continuous simulation.

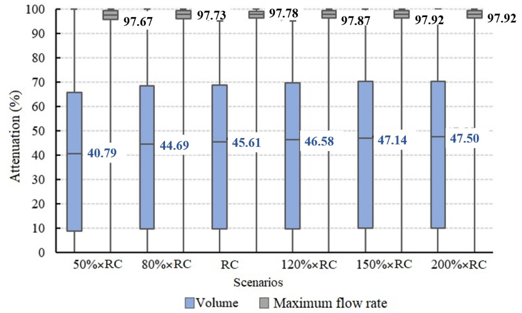

Figure 7. Volume and maximum flow rate attenuations, at all demand scenarios, owing to RWHS, after continuous simulation at period 2014-2020. RC is Reference Scenario.

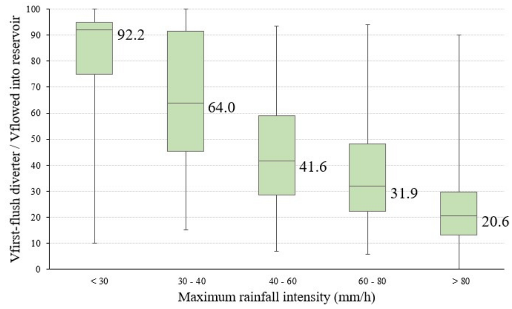

Figure 11. Classes of maximum rainfall intensity x ratio of two volumes (the one has flowed into first-flush diverter and the one has flowed into reservoir), after continuous simulation for reference scenario at period 2014-2020.

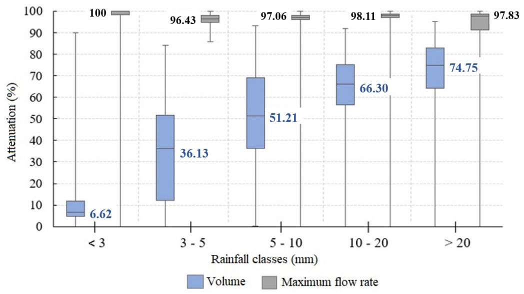

Figure 8. Total precipitation influence at volume and maximum flow rate attenuations, at reference scenario, owing to RWHS after continuous simulation at period 2014-2020.

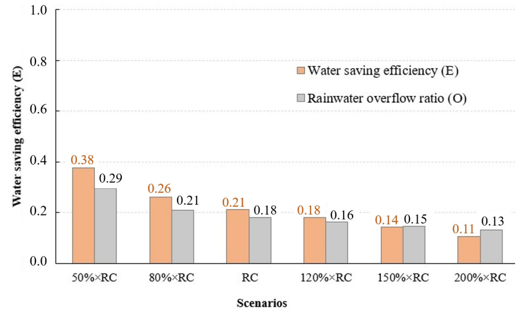

Figure 12. Water saving efficiency (E) and rainwater overflow ratio (O) after continuous simulation in the period 2014-2020 at all scenarios. RC is Reference Scenario.

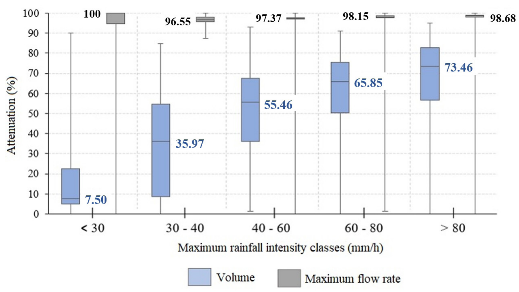

Figure 9. Maximum rainfall intensity influence at volume and maximum flow rate attenuations, at reference scenario, owing to RWHS after continuous simulation at period 2014-2020.

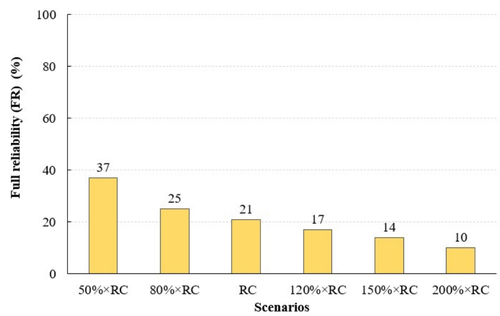

Figure 13. Full reliability (FR) after continuous simulation in the period 2014-2020 at all scenarios. RC is Reference Scenario.

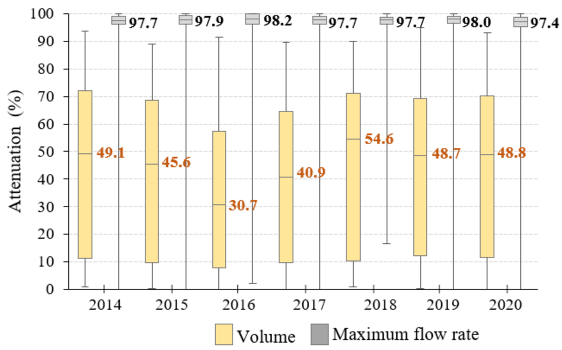

Figure 10. Volume and maximum flow rate attenuations, per year, from the continuous simulation of the period 2014-2020.

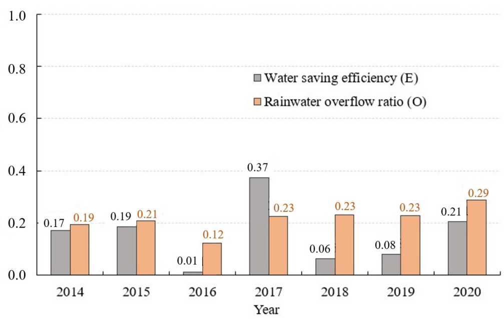

Figure 14. Water saving efficiency (E) and rainwater overflow ratio (O), per year, after continuous simulation of the period 2014-2020.

CONCLUSIONS

This study provided an important opportunity to advance the understanding of RWHS impact on roof runoff control (maximum flow rate and drained volume) and demand meeting for non-potable purposes, using continuous simulation through the SWMM model from sub-daily data of rainfall, roof flow rate, and monitoring experimental apparatus. Time series with 1min time steps were used in the period 2014-2020.

Results have shown difficulties at demand meeting, but an important role in roof runoff control. The control is influenced by the combined action of the first-flush diverter and rainfall regime and was shown to be greater at maximum flow rate than volume.

Results of this work open up possibilities for studies involving small-scale modeling with SWMM, monitoring of first-flush diverter, monitoring of roof flow rate, more detailed description of residential consumption, and the more realistic effect of rainwater harvesting systems deployment on a watershed scale, given that a discretization time step compatible with such a small order of magnitude was used.

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