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Outflow adjustment coefficient for the design of storage facilities using the rain envelope method applied to Brazilian state capitals

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ABSTRACT

Detention devices are often used as alternative measures for stormwater control. The Envelope Curve Method is widely used in Brazil to estimate detention device volumes. This method estimates the storage volume based on inlet and outlet balance, where the inlet is obtained by the Rational Method and the outlet by orifice bottom discharge. Usually, the outlet flow is adopted as a constant and equivalent to the maximum allowed, and this procedure can cause reservoir undersizing. This paper evaluates detention control measures' hydraulic behavior for the Envelope Curve Method and proposes the inclusion of an outflow adjustment coefficient (C_{out}), seeking to compensate for the adoption of constant outlet flow simplification. Values for this coefficient were estimated for several Brazilian state capitals, ranging from 0.62 up to 0.65. The undersizing hypothesis due to the adoption of constant outlet flow was confirmed, as the simulations showed the need for an increase between 8.4% to 16.8% in the device size. This undersizing may be compensated for by applying the outflow adjustment coefficient (C_{out}).

Keywords: adjustment coefficient, detention facilities, envelope curve, hydrologic design outflow adjustment coefficient.

Coeficiente de ajuste para o dimensionamento de reservatórios pelo método da curva envelope aplicado a capitais estaduais brasileiras

RESUMO

Reservatório de detenção são usualmente empregados para realizar o controle de escoamento pluviais. Um dos métodos de dimensionamento de dispositivos de reservação, muito utilizado no Brasil, é o método da curva envelope. Este método estima o volume necessário de armazenamento por meio do balanço dos volumes de entrada e saída, sendo a entrada com base no Método Racional e a saída por orifício de descarga de fundo. Neste método é adotada uma vazão constante de saída igual à máxima permitida, o que pode causar subdimensionamentos. Este artigo teve como objetivo avaliar o comportamento hidráulico de medidas de controle de detenção dimensionadas pelo Método da Curva Envelope, e propor uma alteração nesta metodologia, com a criação de um coeficiente de ajuste da vazão de saída (C_{out}), visando compensar a simplificação de utilizar a vazão efluente constante. Valores para esse coeficiente foram estimados para diversas capitais brasileiras, variando de 0.62 a 0.65. A hipótese de subdimensionamento devido à adoção de uma vazão constante foi confirmada, pois as simulações mostraram a necessicidade de um aumento entre 8.8% a 16.8% no tamanho do dispositivo de controle. Uma compensação para esse problema pode ser obtida aplicando o coeficiente de redução da vazão de saída (C_{out}).

Palavras-chave: coeficiente de ajuste, curva envelope, dimensionamento hidrológico, dispositivos de detenção.

1. INTRODUCTION

The urbanization process modifies the physical characteristics of the watershed, increasing impervious surfaces and changing the hydrologic cycle. These changes cause an increase in stormwater runoff volume and peak flow and decrease flow time (Chen *et al.*, 2015; Guan *et al.*, 2016; Zhou, 2014).

Their impacts on the hydrologic cycle result in an increase in the frequency of water-related disasters such as floods and, as a consequence, there are stormwater control measures (SCMs) that seek to compensate for the effects of urban occupation. Among the SCMs adopted, storage measures stand out, which restrict the inlet hydrograph, providing temporary storage of the runoff. Several municipalities in Brazil, such as Porto Alegre, Brasília, and São José do Rio Preto, have adopted these measures for new construction in order to control hydrological impacts, with the requirement that reservoir construction include an outflow restriction of flow to the public drainage system (Brasília, 2018; Porto Alegre, 2014; São José do Rio Preto, 2008)

There are several methods for design or preliminary design of detention facilities, among them the rain envelope method, which is often used in Brazil.

Butler *et al.* (2018) presents the envelope method as a preliminary sizing of reservoirs, and Azzout *et al.* (1994) presents it as a simplified sizing method. Baptista *et al.* (2011) and Miguez *et al.* (2015) call the methodology the rainfall method of envelope curves, and present it as a simplified form of structure design. Some examples of use from the rain envelope method can be seen in Lucas *et al.* (2013), in the design of a filter-swale-trench system; Angelini Sobrinha *et al.* (2012), in the design of an infiltration well; and in Cadore *et al.* (2016), for bioretention areas. In addition, Silveira and Goldenfum (2007) presented a generalized methodology for preliminary sizing of SCMs using the envelope curve method.

The envelope curve method is characterized as being simple and straightforward, with several simplifications, among which we highlight the adoption of the outflow rate as a constant equal to the rate of outflow when the storage facility is full and the outlet is under maximum head, which may cause under-dimensioning in the structures. These simplifications are the core of criticism of adopting the sizing results of this method needing further sizing checks. On the other hand, there is no approach to redress the undersizing effect on the results by envelope curve use.

This article evaluates the hydraulic behavior of stormwater control detention measures designed by the rain envelope method, proposes a change in this methodology with the creation of an outflow adjustment coefficient (C_{out}) in order to correct the underestimation caused by using the outflow rate as a constant value.

2. MATERIAL AND METHODS

2.1. Rain envelope method or rainfall method

The rain envelope method or rainfall method, presented by Urbonas and Stahre (1993), is a simple method for determination of detention volume based on mass balance in a detention facility. It uses curves of cumulative runoff volume and cumulative volume of outflow at different durations of rainfalls, where the largest difference between the two curves expresses the storage volume. The method does not consider the time of concentration of the basin and uses the rational method to estimate the flow contribution to the detention facility, being indicated to areas smaller than around 80 ha (ASCE, 2017).

The first step in this method is to calculate the cumulative runoff volume for a range of storm durations. This is done by incrementally increasing the storm duration and, for each duration, the volume is calculated from Equation 1, using the runoff coefficient (C), the ration between the runoff and the respective precipitation, and the average rainfall intensity determined by an intensity-duration-frequency (IDF) curve.

$$V_{in} = \frac{C.I.A.t}{3600 \cdot 1000} \quad (1)$$

Where Vin = cumulative runoff volume (m³); C = runoff coefficient (varies from 0 to 1); I = average rainfall intensity (mm.h^{-1}); A = tributary area (m²); t = duration (s).

The volume of the outflow curve varies according to design characteristics. For detention facilities with nozzles or orifices as outlets, the outflow can be determined, considering free discharge at atmospheric pressure, using Equation 2. The volume of outflow is commonly estimated by Equation 3, using the simplification that the structure empties at a constant rate equal to the maximum possible outlet outflow (considering the device full and outlet under maximum head). As already shown by Urbonas and Stahre (1993), with the exception of special flow regulators the outflow is not constant and varies with the depth of water as the structure fills and empties.

$$Q_{out} = C_d.A_o.\sqrt{2.g.h} \quad (2)$$

$$V_{out} = Q_{out}.t \quad (3)$$

Where: Cd = discharge coefficient ; Ao = area of the opening (m²); g = gravitational acceleration (m.s^{-2}); h = effective head seen by the orifice (m); $Vout$ = cumulative outflow volume (m³); $Qout$ = maximum outflow rate (m³.s^{-1}); t = duration (s).

To provide the controlled release of flows when the detention facility's water exceeds its storage volume, commonly spillways are used. The discharge flow of the spillway can be determined by Equation 4.

$$Q_s = C_s.L.h^{\frac{3}{2}} \quad (4)$$

Where: Qs = spillway flow (m³.s^{-1}); Cs = spillway discharge coefficient; L = spillway width (m); h = head over the spillway crest (m).

The storage volume obtained by the method is the largest difference between the two curves obtained by Equations 1 and 3, defined by Equation 5 and illustrated in Figure 1.

$$Vr = max\,(V_{in} - V_{out}) \quad (5)$$

Where: Vr = storage volume (m³).

The simplification of using, during all rainfall periods, the outflow rate equal to the maximum possible outlet flow causes a cumulative outflow volume curve with values greater than what they are supposed to be, resulting in lower volumes of reservation, reducing the safety of the project.

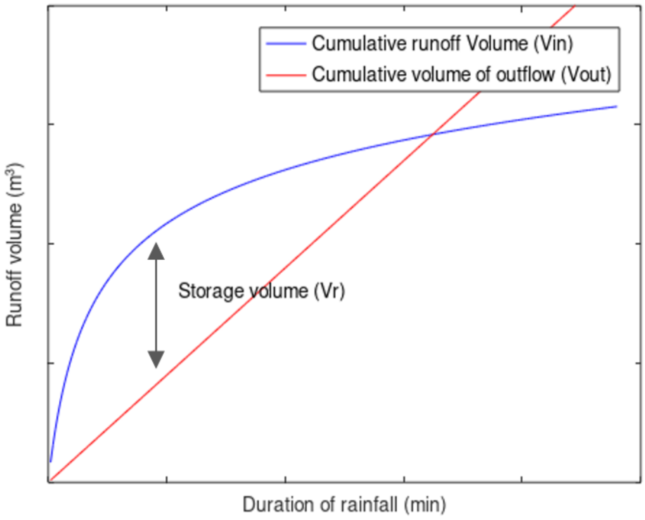

Figure 1. Storage volume using the rain envelope method.

2.2. Curve envelope method verification

In order to identify the impact of the simplification of the reservoirs designed by the envelope method, the hydraulic behavior of the structure storage volume obtained by the envelope curve method was simulated using one of the most traditional models to simulate reservoir routing; it was developed by Puls (Nascimento and Baptista, 2009).

The IDF curve used to obtain the rainfall used for the envelope curve and Puls method was the recommended IDF curve for the 8th District of Porto Alegre (Bemfica *et al.*, 2000) with a return period of 10 years (Equation 6).

$$I = \frac{1297.9\, T_R{}^{0.171}}{(rd+11.6)^{0.85}} \tag{6}$$

Where I = average rainfall intensity (mm.h^{-1}); T_R = return period (years); rd = rain duration (min).

For the envelope curve method, the characteristics of the tributary site were: tributary area (A) of 1000 m² and runoff coefficient (C) of 0.9. The outlet was considered as an orifice with diameter of 25 mm, and the input for the outflow rate was considered a constant obtained by Equation 3, with a maximum depth of water of 1 m and a discharge coefficient of 0.94, according to experimental values found for this outlet diameter and water depth (Drummond, 2014). From this information, with Equation 5, the storage volume was obtained.

These characteristics were chosen for Q_{out} to be smaller than the Porto Alegre outflow restriction flow to the public drainage system (20.8 l.s^{-1}.ha^{-1} or 2.08 l.s^{-1} for this tributary area) (Porto Alegre, 2014).

For the Puls method, the same IDF curve was used, with a time distribution obtained by the alternating blocks hyetograph method (Chow *et al.*, 1988), centralized peak and rain discretization of 1 minute in order to obtain a hyetograph.

The inflow hydrograph of the reservoir was determined from the hyetograph multiplied by the same values of runoff coefficient and tributary area for each time interval of the hyetograph, thus obtaining the inflow hydrograph. The outflow rate was defined by Equation 3, with the same characteristics of outlet for envelope curve, but considering the outflow rate variable in time, function of water depth. In case of exceeding storage volume during the simulation, a spillway was designed to remove excess water, with the discharge flow obtained by Equation

4, with C_s of 1.77.

2.3. Reservoir hydraulic behavior with traditional envelope curve method storage volume

For the rain and tributary characteristics described in the method verification, the envelope curve is shown in Figure 2. The constant outflow rate of the method (Q_{lim}) resulted in 2.04 $l.s^{-1}$ and the storage volume was 40.2 m³, occurring with a rainfall duration of 102 minutes.

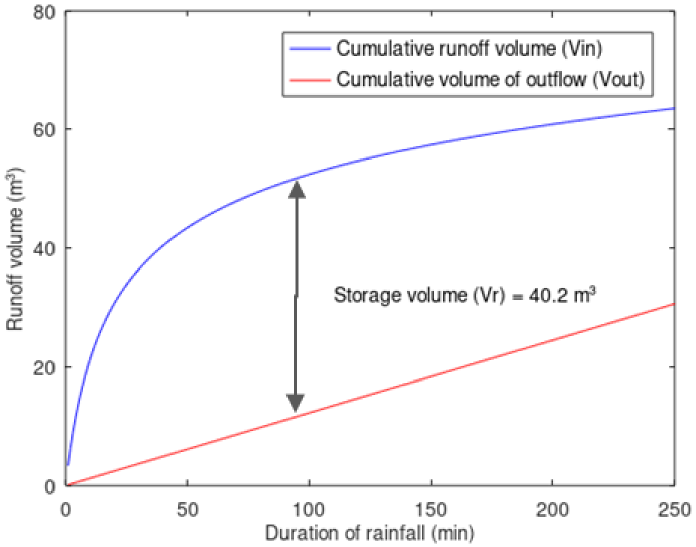

Figure 2. Envelope curve method for Porto Alegre with: C = 0.9; Q_{lim} = 2.04 $l.s^{-1}$; A = 1.000 m².

Figure 3 presents the reservoir outflow hydrographs for the Puls method, with simulations for rainfall durations from 10 to 120 minutes for Porto Alegre by the alternating blocks method. The storage volume of the reservoirs used in all simulations were the ones found using the envelope method, 40.2 m³. The results show that the design volume was not adequate to withstand the runoff volumes of rainfall durations above 60 minutes; therefore, the 102 minutes of rainfall duration, duration from the envelope method, also had water depth above 1 m, causing the spillway to remove the excess water and the outflow rate to peak above 2.04 $l.s^{-1}$.

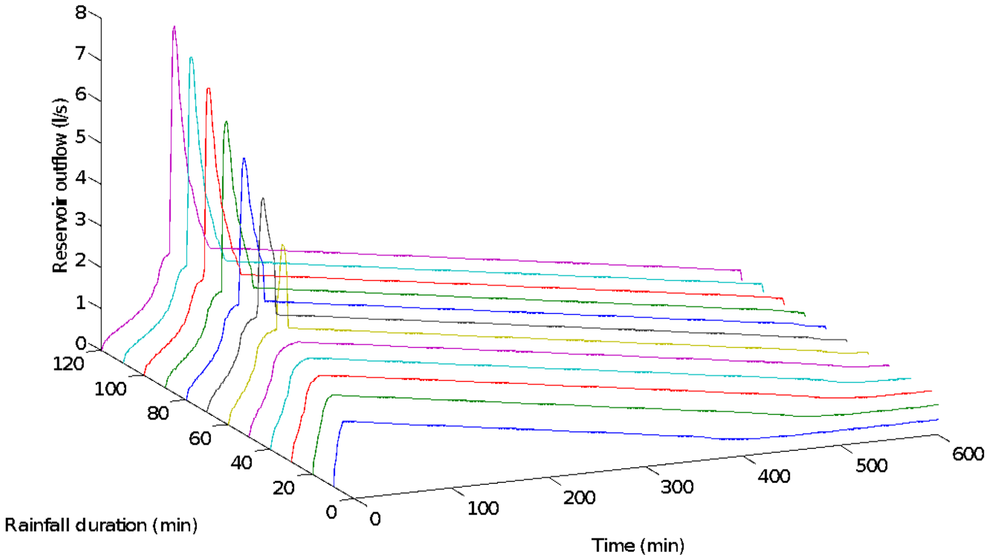

Figure 3. Verification reservoir outflow hydrographs by Puls simulation for the traditional envelope curve sizing method.

The difference between the outflow estimated by the verification method (Puls) and the constant outflow for the envelope method is shown in Figure 4.a, simulation of rainfall duration of 102 minutes for Porto Alegre, where the green area of the figure represents the outflow volume difference between the methods.

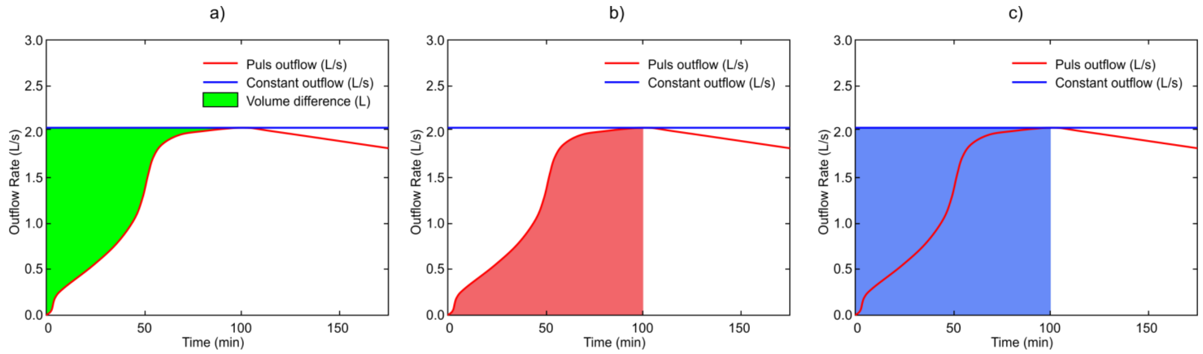

Figure 4. Outflow comparisons of Envelope and Puls methods: a) volume difference between Puls and Envelope outflows; b) outflow volumes by Puls simulation; c) outflow volumes by Envelope.

2.4. Proposed methodology to compensate for the constant outflow simplification

An outflow adjustment coefficient (C_{out}) was created in order to compensate for the simplification of constant outflow, adopting the ratio between the accumulated volume obtained by the Puls methodology (an area under the red line in Figure 4.b up to reach the blue line for constant outflow) and the constant outflow (a rectangular area in Figure 4.c under blue line until to intercept the red line). The coefficient was obtained using the same rainfall duration as found for the storage volume in the envelope curve, called "critical duration time" (Tcrit), and gradually increasing the storage volume until the minimum detention volume that would not cause the water depths above the maximum, i.e., spillway unused (Equation 7).

$$C_{out} = \frac{V_{Puls}}{V_{out}} \tag{7}$$

Where C_{out} = outflow adjustment coefficient; V_{Puls} = cumulative outflow volume by Puls method (m^3).

From the C_{out}, the incremental volume, denominated as V_i, is determined by Equation 8. The incremental volume is then added to the storage volume determined by the envelope curve method, resulting in the adjusted storage volume (Equation 9).

$$V_i = (1 - C_{out})Q_{lim}.t \tag{8}$$

$$V_{RA} = max(V_{in} - V_{out}) + V_i \tag{9}$$

Where V_i = incremental volume (m^3); V_{RA} = adjusted storage volume (m^3).

2.5. Sensitivity of C_{out} to input parameters

The sensitivity of C_{out} was evaluated by simulating different runoff coefficients and sizes of orifices as outlets, modifying the inflow and outflow of the methods. The same methodology of the previous verification was used. The sensitivity of C_{out} as a function of the Runoff coefficient C and Q_{lim}, constant outflow as a function of orifice diameter (D), for a return period of 10 years is shown in Table 1.

Table 1. C_{out} sensitivity for period return of 10 years.

Q_{lim} (D)	Runoff Coefficient (C)		
	0.2	0.6	1.0
1.31 l/s (20 mm)	0.66	0.64	0.63
8.18 l/s (50 mm)	0.82	0.69	0.68

The value of C coefficient varied from 0.2 to 1.0, and the maximum flow capacity from 1.31 $l.s^{-1}$ to 8.18 $l.s^{-1}$, respectively, for commercial diameters of orifices of 20 mm and 50 mm.

The results showed that the value of the C_{out} increases when the value of the C reduces, and that C_{out} is also higher when the diameter of the orifice is higher. Therefore, the combination of higher C and smaller diameter results in a smaller coefficient, which is the less favorable scenario, since the smaller the C_{out} the greater the incremental volume V_i.

In order to observe the impact of a higher period return on the coefficient, the process was repeated for a period return of 50 years. The coefficients found are shown in Table 2 and were similar to those with a period return of 10 years.

Table 2. C_{out} sensitivity for return period of 50 years.

Q_{lim} (Diameter)	Runoff Coefficient (C)		
	0.2	0.6	1.0
1.31 l/s (20 mm)	0.66	0.63	0.62
8.18 l/s (50 mm)	0.77	0.68	0.66

3. RESULTS

3.1. C_{out} applied to Brazilian state capitals

According to the results of Tables 1 and 2, the least favorable condition for the coefficient Cout, the smallest value, occurs with a higher C and smaller orifice diameter. Cout values were determined for several Brazilian state capitals, using Equation 7 with the same methodology previously described. The adopted conditions were the same as used in the curve envelope method verification: coefficient C equal to 0.9; outlet considered as an orifice as 25 mm of diameter; discharge coefficient of 0.94; maximum water depth of 1 m; tributary area of 1000 m². The rain parameters for each state capital are presented in Table 3, following the format of Equation 10. Figure 5 shows the studied cities locations in Brazil.

$$I = \frac{a.{T_R}^b}{(rd+c)^d} \tag{10}$$

Where: a, b, c e d are adjusted parameters for each city.

Table 4 presents the values of the C_{out} for period returns of 10 and 50 years, showing the dispersion between them for the different regions of Brazil. The C_{out} values presented in the table were the coefficients obtained for the rainfall duration equal to the critical time T_{crit}.

Even though there is a great variability in the pluviometric characteristics of the Brazilian state capitals presented, there is only a small variation in the values of C_{out}. Table 5 presents the storage volume (Vr) needed for each city for a return period of 10 years using the envelope curve method and the adjusted storage volume (V_{RA}) when considering the coefficient C_{out}.

The results showed a C_{out} coefficient ranging from 0.62 to 0.65 and an increase in storage volume considering the proposed methodology from 8.4% to 16.8%.

Table 3. IDF curves parameters for several Brazilians state capitals.

City	Parameters			
	a	b	c	d
Aracaju[1]	834.2	0.179	15	0.726
Belém[1]	1085.5	0.156	12	0.758
Belo Horizonte[2]	1447.9	0.100	20	0.840
Brasília[3]	1574.7	0.207	8	0.884
Cuiabá[4]	1016.5	0.133	7.5	0.739
Curitiba[5]	5726.6	0.159	41	1.041
Florianópolis[1]	1754.2	0.187	36	0.823
Fortaleza[7]	2345.3	0.173	28.3	0.904
Goiânia[8]	920.5	0.142	12	0.760
Manaus[1]	1136.5	0.158	10	0.764
Porto Alegre[9]	1297.9	0.171	11.6	0.850
Porto Velho[1]	1181.4	0.159	11	0.757
Rio Branco[1]	1419.3	0.162	18	0.795
Rio de Janeiro[10]	1239.0	0.150	20	0.740
São Luiz[1]	1519.4	0.161	28	0.777
São Paulo[11]	3462.6	0.172	22	1.025
Teresina[1]	1248.9	0.177	10	0.769

[1]Fragoso Jr. (2004); [2]Zahed Filho and Marcellini (1995); [3]Distrito Federal (2009); [4]Castro *et al.* (2011); [5]Fendrich (2003); [7]Silva *et al.* (2013); [8]Oliveira *et al.* (2003); [9]Bemfica *et al.* (2000); [10]Bertoni and Tucci (1993); [11]Wilken (1978).

Figure 5. Spatial location of the cities used in the study.

The results are similar to those found by Guo (1999), 0.64 to 0.75 for an outflow reduction coefficient and he also concludes that not using the adjustment factor can result in approximately 20% underestimation of detention volume.

Table 4. Values of the C_{out} for period returns of 10 and 50 years and several Brazilian Capitals.

City	T_R- 10 years	T_R - 50 years
	C_{out}	C_{out}
Aracaju	0.65	0.65
Belém	0.64	0.64
Belo Horizonte	0.65	0.64
Brasília	0.62	0.62
Cuiabá	0.64	0.64
Curitiba	0.64	0.63
Florianópolis	0.65	0.64
Fortaleza	0.64	0.63
Goiânia	0.65	0.64
Manaus	0.64	0.64
Porto Alegre	0.64	0.63
Porto Velho	0.64	0.64
Rio Branco	0.64	0.64
Rio de Janeiro	0.65	0.65
São Luiz	0.65	0.64
São Paulo	0.64	0.63
Teresina	0.64	0.63

Table 5. Storage Volume (Vr) and Adjusted storage volume (V_{RA}).

City	Vr (m^3)	V_{RA}(m^3)	%
Aracaju	52.0	60.8	16.8%
Belém	56.0	64.1	14.6%
Belo Horizonte	37.0	42.0	13.7%
Brasília	48.4	52.7	8.8%
Cuiabá	56.0	64.2	14.6%
Curitiba	60.3	66.1	9.5%
Florianópolis	65.8	75.3	14.4%
Fortaleza	54.1	60.4	11.7%
Goiânia	41.8	48.0	14.9%
Manaus	58.0	66.1	13.9%
Porto Alegre	40.2	44.7	11.2%
Porto Velho	64.4	73.5	14.1%
Rio Branco	61.1	69.4	13.6%
Rio de Janeiro	73.6	85.3	15.8%
São Luiz	73.5	84.5	15.0%
São Paulo	44.1	47.8	8.4%
Teresina	67.7	76.6	13.1%

4. DISCUSSION AND CONCLUSIONS

This paper evaluated the performance of storage facilities designed by the envelope curve method and showed undersizing in the storage volume when considering a simplification of the outflow rate as a constant value equal to the maximum discharge capacity of the outlet. The hydraulic verification results showed that the reservoirs were insufficient to store the inflow volumes. Thus, an outflow adjustment coefficient C_{out} was proposed in order to compensate for the considered simplification.

The application of the proposed methodology was applied to several Brazilian state capitals and indicated there is little variation in the value of C_{out}, ranging from 0.62 to 0.65, even though there is great variability in the pluviometric characteristics of these cities. The results also showed that, for the studied cities, the adjusted methodology caused an increase in the storage volume from 8.4% to 16.8%.

Finally, the parameters adopted (lot area; runoff coefficient; return period; orifice diameter; IDF of 17 Brazilian States Capital) for the simulations were the most frequent values for the urban lots, so this criteria can indeed be representative for several areas and even for the whole country after analysis of results for Cout, as it varies only within a narrow range.

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