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Dimensioning Urban Drainage Systems in Housing Subdivisions in the Amazon Using Different Hydrological Models

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Abstract

Hydrological studies for sizing urban drainage systems in the Amazon have often been neglected and little investigated for rainwater projects. This research evaluated alternative hydrological models used in sizing urban drainage network projects in subdivisions with subsidized houses in the Amazonian region in Brazil. Statistical tests of these models were performed for both original and alternative scenarios. The methodological steps we conducted as follows: 1) evaluate the dimensioning of infrastructure project networks, considering two case studies contemplated by the Calha Norte Program (CNP) in the state of Amapá; 2) test the statistical significance of the dimensioning of network diameters ($\alpha < 0.05$), considering a) benchmark project (MD or M1) approved by the Ministry of Defense; b) determination of concentration time (C_t) and rainfall intensity-duration-frequency (IDF) relationships, as well as estimating diameters using alternative models. The results indicated a significant influence on the diameters of the projected rainfall networks ($p < 0.05$), suggesting that alternative models predicted more unfavorable flow peaks than the original model. We conclude that the benchmarking model underestimated the diameter of the project compared to alternative models, which means the optimized C_t parameter significantly impacts dimensioning estimates in rainwater projects in these Amazonian municipalities. This suggests that underestimated parameters in MD may cause inefficiency in the stormwater system projects in future similar scenarios.

Keywords

Hydrological Studies, Concentration Time, Calha Norte Program, Amapá

1. Introduction

Urban drainage is essential for basic sanitation, planning, and the orderly development of cities (Sabóia et al., 2017; Zhang et al., 2022; Sousa et al., 2023). Its importance is reflected in flood prevention and control measures (Adugna et al., 2019; Sousa et al., 2021), maintaining public health by reducing waterborne diseases (Christofidis et al., 2019; Resplandes et al., 2021), and reducing property damage and the risks of human losses (Adugna et al., 2019; Christofidis et al., 2019). It is also reflected in efforts to reduce erosion and the pollution of rivers and groundwater (Hou et al., 2021; Sousa et al., 2023), ensuring the well-being and quality of life of the population along with the conservation of ecosystems (Faria et al., 2022).

The recently enacted Legal Framework for Sanitation in Brazil (Law No. 14.026/2020) defines urban drainage as the set of "infrastructure and operational facilities, transportation, detention or retention to mitigate flooding, treatment and final disposal of drained rainwater, including the cleaning and preventive inspection of networks" (Brasil, 2020).

Refining the design and dimensioning of drainage infrastructure projects is advantageous for implementing this urban equipment. In addition, it is important to highlight the local specificities of each region, mainly related to hydrological studies (Rocha et al., 2022) and planimetric mappings (Rosa et al., 2018).

The northern and northeastern regions of Brazil, especially the Amazonian states, suffer from the absence of local drainage projects and the insufficiency of these services to serve the population (SNIS, 2021). The state of Amapá, particularly its smaller municipalities, lacks basic scientific studies that specifically address this type of analysis, focused on structuring and implementing urban drainage systems (de Abreu et al., 2020; Back & Candorin, 2020).

Small municipalities in the Amazon face many kinds of infrastructure shortages. In this regard, the Calha Norte Program was created in 1985 by the Federal Government to serve as a tool to encourage socioeconomic development in this region. This program aims to implement basic drainage infrastructure in remote Amazonian municipalities, as well as assist populations and improve the standard of living (Brasil, 2019), as is the case of Pracuúba and Calçoene in Amapá, Brazil.

This research aims to optimize the dimensioning precision of drainage infrastructure in subdivisions of small Amazonian municipalities by adjusting and/or replacing more general parameters and statistically testing its objective application from more effective input data related to projected rainfall.

For this purpose, the original project (MD or M1) for the construction of urban drainage systems, approved and subsidized by the Calha Norte Program, was analyzed for the housing subdivisions in Calçoene and Pracuúba. The goal is to develop scientific bases and more solid subsidies for similar future projects and to produce potential new models for estimating hydrological parameters, with which statistical comparisons can be made between the original project scenario (MD) and the alternative ones. This analysis also aims to improve the accuracy of the formulations, especially in obtaining the projected rainfall.

The rationale for the study in these two subdivisions is the absence of reliable, long-term rainfall intensity-duration-frequency (IDF) data. In addition, there is a growing demand for new projects associated with the housing deficit for low-income populations in the region. In this context, we believe that we can contribute to the improvement of the quality of life and social well-being of these small, remote Amazonian municipalities, where infrastructure is generally precarious and inefficient (Brasil, 2019; Rangel et al., 2021; Programa Calha Norte, 2022).

2. Material and Methods

2.1. Study Area

The present study was conducted by dimensioning an analysis of urban drainage network projects in two subdivisions in Calçoene and Pracuúba (**Figure 1**). Calçoene has 10,612 inhabitants and an urbanized area of 3.36 km², while Pracuúba has 3803 inhabitants and an urbanized area of 1.49 km² (IBGE, 2022).

Both municipalities are partially drained by the Araguari River basin (**Figure 1**). This is the largest and most important basin in Amapá (Bárbara et al., 2005)

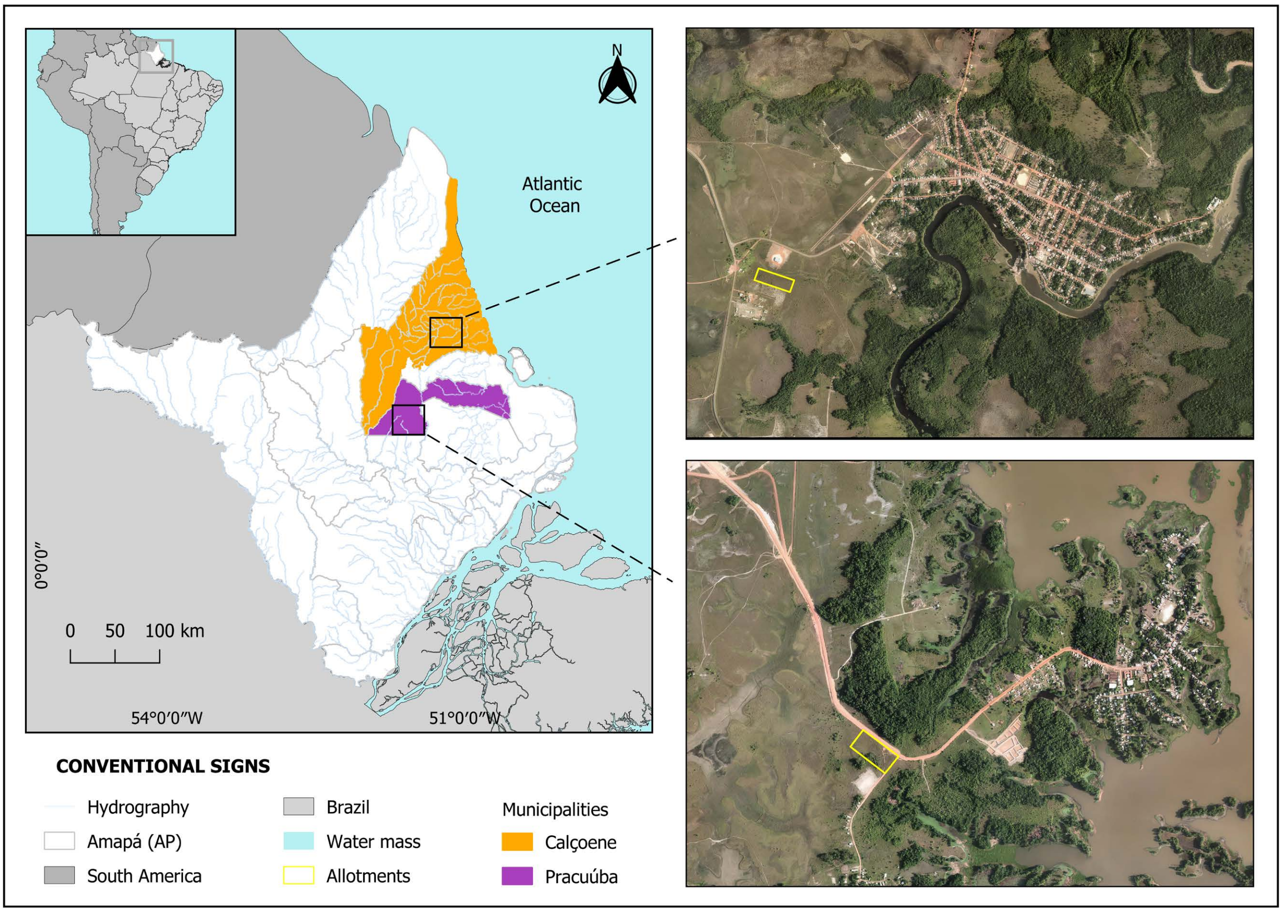

Figure 1. Location of the municipalities of Calçoene (upper right image) and Pracuúba (lower right image). Caption: The square in yellow refers to the subdivision's location in relation to each municipality's urban area (Authors, 2023).

and is more than 300 km long from its source in the Tumucumaque Mountains National Park to its mouth on the right bank of the Amazon River (Marques et al., 2022). These Amazonian ecosystems and the local population have been impacted by anthropogenic and hydroclimatic processes, of which mining, agriculture, extensive buffalo farming, operation of hydroelectric power plants, and sea level rise stand out. These environmental impacts, combined with climate change, significantly alter some of the hydrological processes and the basin morphology (Cunha, 2013; Santos et al., 2018; Araújo et al., 2020; Silva Júnior et al., 2021; Marques et al., 2022).

Calçoene and Pracuúba have historically endured a lack of drainage and urban planning infrastructure (IBGE, 2022). Thus, two subdivisions with subsidized houses were planned to collaborate with the region's socioeconomic development and implementation of basic infrastructure, enabling assistance to their populations and improving the standard of living (**Figure 1**) (Brasil, 2019).

The Calçoene subdivision (**Figure 1**, upper right image), located at 2˚29'25.2"N and 50˚58'13.4"W, was initially built to accommodate 61 - 62 residential units for families of up to 5 people in an area of 27533.64 m^2. The Pracuúba subdivision (**Figure 1**, lower right image) is located at 1˚44'21.9"N and 50˚48'03.8"W, with the same number of residential units as Calçoene, but over a slightly larger area (29377.36 m^2). Both are the result of agreements to implement the Calha Norte Program under numbers 895,552/2019 and 905,609/2020 for Calçoene and 895,553/2019 and 915,672/2021 for Pracuúba (Programa Calha Norte, 2021a; Programa Calha Norte, 2021b).

2.2. Preliminary Analysis Material

Through the site plans (**Figure S1**), it was possible to allow the region to receive rainwater infrastructure intervention in relation to the urban agglomeration and initially visualize the interaction of the future drainage system with the environment (Programa Calha Norte, 2021a; Programa Calha Norte, 2021b). Then, using the planimetric survey plans (**Figure S2**), the natural path of rainfall-runoff was identified through visual interpretation. This is a guiding factor in the development of the network layout, since runoff will converge at the same point downstream, the outlet, where it will be discharged (de Souza & Zamuner, 2016; Programa Calha Norte, 2021a; Programa Calha Norte, 2021b).

The project graphics (see examples in **Figure S3**), containing the subdivision drainage plans, allowed the verification of distances, areas and identification of the entire project layout, longitudinal profiles, rainwater collection, and conduction devices, as well as construction details (Programa Calha Norte, 2021a; Programa Calha Norte, 2021b).

2.3. Dimensioning Review

2.3.1. Rational Method

The original project (M1) was designed through the rational method, using the "Multiplus Pro-Sanitation version 17" software. This method is the most widely used in micro drainage projects in Brazil (Bidone & Tucci, 1995) and requires the definition of standard rainfall for the analysis of the river basin and its network of conduits for the transport of rainwater via the use of the intense rainfall equation (IDF) (Mendes & Andrade, 2021).

The rational method, commonly applied to small basins, recommends that the duration of rainfall can be defined as equivalent to the concentration time (C_t), that is, the time it takes the entire basin to contribute to the flow of the study in question (Tomaz, 2011). It is also based on the assumptions that rainfall intensity, flow velocity, catchment area, and impermeability are uniform (Wang & Wang, 2018), which introduces limitations to the method. However, it leads to satisfactory results when applied to small basins (Miguez et al., 2016).

Although subject to small variations as a function of unit conversion, the flow calculation adopted can be demonstrated by the following equation:

$$Q = \frac{C * I * A}{3.6} \tag{1}$$

where:

Q—peak flow (m^3/s)

C—dimensionless coefficient of surface runoff

I—rainfall intensity (mm/h)

A—catchment area (Km^2)

All culverts in the projects received the coefficient "C" of 0.8 as input. This value can be considered conservative in this case because, according to Wilken (1978), values between 0.70 - 0.95 are indicated for densely built regions in cities with paved streets and sidewalks. In addition, the catchment areas were inserted through polygonal lines provided in a specific plan of the original project (**Figure S3**, item B).

2.3.2. Intense Rainfall Equation

Intense rainfall equations, known as IDF ratios, synthesize the maximum intensity of rainfall associated with a predetermined return time and duration (Basso et al., 2019), where rarer rains tend to present rainfall of greater intensity (Wang & Wang, 2018). Knowing these ratios is very important for sizing hydraulic structures to manage and convey rainwater, especially culverts, catchments, and detention basins (Basso et al., 2016).

To define the rainfall intensity to be used in the dimensioning of the original project, Equation (2) was used according to the coefficients obtained through a study presented in 2013 to the Brazilian Society of Agrometeorology (**Table 1**)

Table 1. Constant coefficients for the intense rainfall equation used in the original project (ANA, 2011; Queiroz Júnior et al., 2013).

Municipality	Rainfall station used	Historical series (years)	K	a	b	c
Calçoene	Calçoene	31	1547.4608	0.0930	9.7907	0.7243
Pracuúba	Tartarugalzinho	11	1027.0365	0.1136	9.7920	0.7243

(Queiroz Júnior et al., 2013). The intense rainfall equation can be shown according to the following variables:

$$I = \frac{K * (Rp)^a}{(t+b)^c} \quad (2)$$

where:

I—Rainfall intensity (mm/h)

Rp—return period (years)

t—rain duration time (min)

K, *a*, *b*, *c*—constant coefficients

2.3.3. Original Model Parameters

The input parameters used in the original dimensioning model are return time, minimum velocity, maximum velocity, rainfall duration, and projected rainfall intensity.

The return time, also called the recurrence time, comprises an average interval associated with the time it takes for a critical rainfall event to be equaled or exceeded. Moreover, it is determined considering safety conditions, functionality, and economic feasibility (Lira et al., 2019). The projects analyzed used a value of 10 years, common to microdrainage projects. In Brazil, values between 2 and 10 years are used (Tomaz, 2011; Miguez et al., 2016).

Minimum and maximum velocities are relevant premises to avoid sediment deposition inside the culvert structures, which is not transported by the low velocity and the appearance of erosion and damage to the structures caused by high velocity (Tomaz, 2011). In the original projects, velocities of 0.6 m/s and 5.0 m/s, respectively, were defined.

The rainfall duration was set at 10 minutes, as is commonly applied in drainage projects (Tomaz, 2011). The tabulated C_t input (**Table 2**) can be inserted according to Miguez et al. (2016). However, this is recommended in the case of urbanized areas upstream of the first stretch.

It is possible to observe isolation of the subdivisions in relation to the urban core of the municipal centers (**Figure 1**), which can cause uncertainty and generate inconsistencies in the dimensioning calculations since the projected rainfall depends directly on this data. In this case, a detailed time calculation is recommended (Tomaz, 2011; Miguez et al., 2016). The projected rainfall intensity adopted in Calçoene was 220.59 mm/h, and in Pracuúba was 153.51 mm/h.

Table 2. Concentration time for urbanized areas (adapted from (Miguez et al., 2016)).

Typology of the upstream area	Gully slope	
	<3%	>3
Dense construction areas	10 min	7 min
Residential areas	12 min	10 min
Parks, gardens, fields	15 min	12 min

The characterization of the implementation of the subdivisions in relation to the respective urban centers was verified and confirmed (**Figure 1**) in a new collection of remote sensing images updated with the "Amapá Continuous Digital Cartographic Base Project", authored by the Government of the State of Amapá and the Brazilian Army (Amapá, 2023).

2.4. Proposition of New Models

Through the Kirpich model (Equation (3)) presented in the form of the California Cuverts Practice Calculus (Miguez et al., 2016), we established an alternative C_t. The value was then applied in the form of duration in the IDF equations used to characterize new models for estimating diameters (D1, D2, D3, and D4), one of them being the IDF relationship with original parameters.

$$C_t = 57 \cdot \left(\frac{L^3}{H}\right)^{0.385} \tag{3}$$

Where:

C_t—concentration time (min)

L—length of the main thalweg of the basin (Km)

H—unevenness between the highest point of the basin and the outlet (m)

The operation of digital remote sensing models, using QGIS version 3.28.2, made it possible to define the values of the length and slope variables applicable to Kirpich's method. The most relevant watershed upstream of the subdivision and the initial flow collection devices of each subnetwork of Calçoene and Pracuúba were used as a benchmark (**Figure 2**).

To make the analyses more robust, and due to the lack of diversity of hydrological studies to characterize intense rainfall equations in Amapá (Back & Candorin, 2020), more scenarios were created using new coefficients applied to the intense rainfall equation, according to Back & Candorin (2020). The geographical adaptation of using rainfall stations closer to the stations considered in the original project was also performed (**Table 3**).

Using the coefficients and according to Queiroz Júnior et al. (2013) and Back & Candorin (2020), three additional dimensioning process models were created with a focus on the diameter found for each stretch of the networks, considering different input parameters in the scenarios (**Table 4** and **Table 5**). The objective was to evaluate the changes in diameter, flow, C_t, and rainfall intensity to carry

Table 3. Coefficients applicable to the intense rainfall equation in Amapá (Adapted from (Back & Candorin, 2020)).

Subdivision location	Rainfall station used	Geographic coordinate system	Historical series (years)	K	A	b	c
Calçoene	8,250,002 (Calçoene)	2˚30'00.0"N 50˚57'00.0"W	1976-2018	1158.5000	0.244	9.19	0.706
Pracuúba	8,151,000 (Tartarugalzinho)	1˚34'48.0"N 50˚54'00.0"W	1985-2017	998.1000	0.164	9.19	0.706

K, a, b, c—constant coefficients.

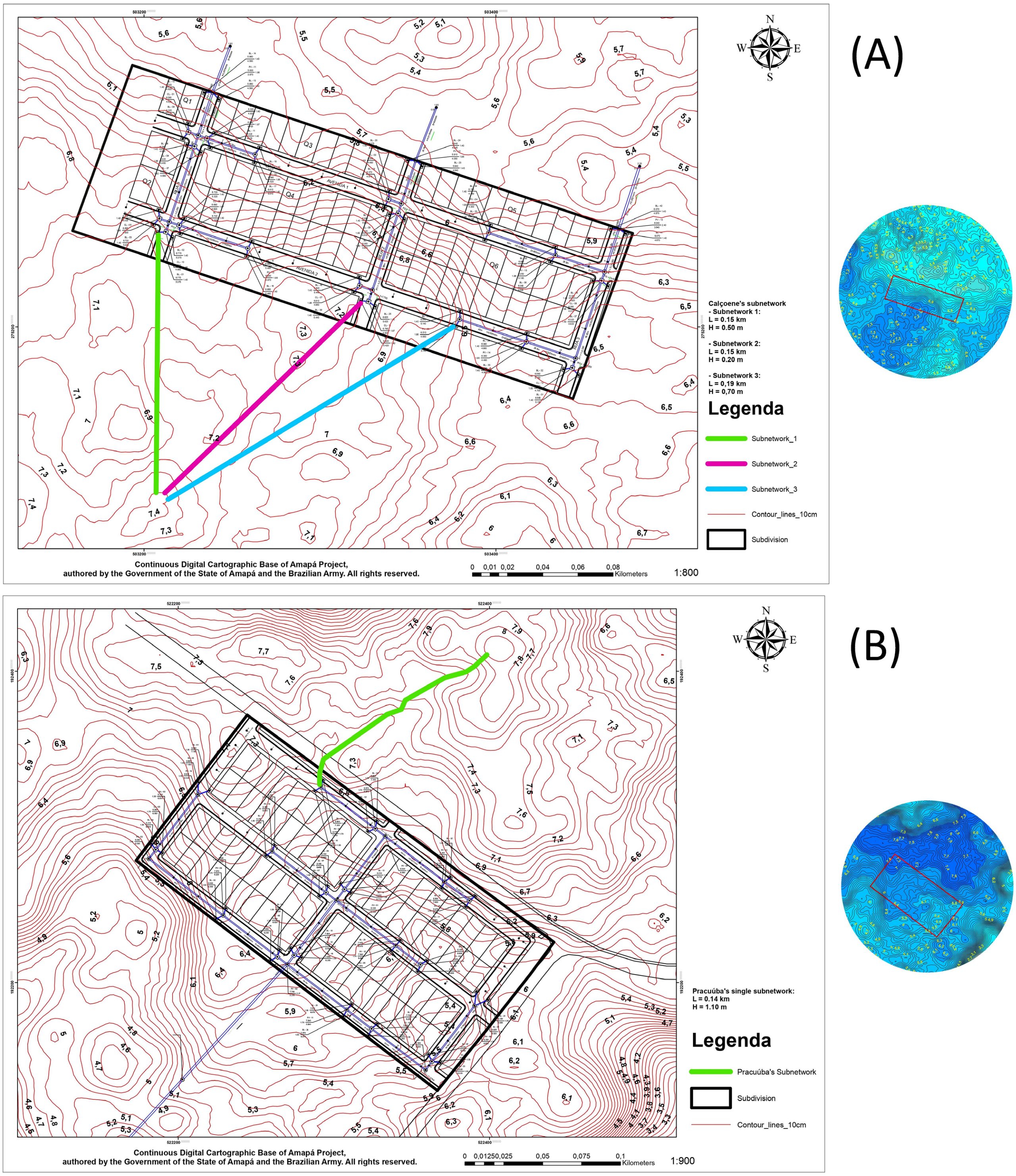

Figure 2. (A) On the left is the location of the subnetworks in relation to the most important watershed in the municipality of Calçoene. On the right is an example of the unevenness (H) of the terrain. (B) On the left is the location of the subnetworks in relation to the most important watershed in the municipality of Pracuúba. On the right is an example of the unevenness (H) of the terrain (Authors, 2023).

out a comparative study and verify the possible significance of the variations in results in each subnetwork of Pracuúba and Calçoene.

Table 4. Different ways of finding hydrological parameters applicable to the rational method for defining new projected rainfall (Authors, 2023).

Model	IDF curve coefficients	Concentration time (projected rainfall duration)
M1 (Original)	Queiroz Júnior et al. (2013)	Tabulated = 10 min
M2	Queiroz Júnior et al. (2013)	Kirpich Model
M3	Back & Candorin (2020)	Tabulated = 10 min
M4	Back & Candorin (2020)	Kirpich Model

Table 5. Variables applied to the equations to determine the rainfall intensity of each model. Caption: in bold, the results of rainfall intensity (I) (Authors, 2023).

Project	Model	*K*	*a*	*b*	*c*	Rp (years)	L (km)	H (m)	T (min)	I (mm/h)
Sub-network Calçoene I	M1 (Original)	1547.4608	0.0930	9.7907	0.706	10	-	-	10.00	220.59
	M2	1547.4608	0.0930	9.7907	0.724		0.1500	0.50	8.32	235.23
	M3	1158.5000	0.2440	9.1900	0.706		-	-	10.00	252.37
	M4	1158.5000	0.2440	9.1900	0.706		0.1500	0.50	8.32	269.24
Sub-network Calçoene II	M1 (Original)	1547.4608	0.0930	9.7907	0.706	10	-	-	10.00	220.59
	M2	1547.4608	0.0930	9.7907	0.724		0.1500	0.20	11.84	206.84
	M3	1158.5000	0.2440	9.1900	0.706		-	-	10.00	252.37
	M4	1158.5000	0.2440	9.1900	0.706		0.1500	0.20	11.84	236.58
Sub-network Calçoene III	M1 (Original)	1547.4608	0.0930	9.7907	0.706	10	-	-	10.00	220.59
	M2	1547.4608	0.0930	9.7907	0.724		0.1900	0.70	9.60	223.88
	M3	1158.5000	0.2440	9.1900	0.706		-	-	10.00	252.37
	M4	1158.5000	0.2440	9.1900	0.706		0.1900	0.70	9.60	256.16
Pracuúba Single Network	M1 (Original)	1027.0365	0.1136	9.7920	0.724	10	-	-	10.00	153.51
	M2	1027.0365	0.1136	9.7920	0.724		0.1434	1.10	5.83	182.21
	M3	998.1000	0.1640	9.1900	0.706		-	-	10.00	180.85
	M4	998.1000	0.1640	9.1900	0.706		0.1434	1.10	5.83	215.00

For the scenarios proposed using Kirpich's method to define the C_b, the flow coefficient was not fully preserved in relation to the original scenario. This was due to the forest areas upstream of the subdivisions having a greater impact on soil permeability, so a coefficient of 0.2 was adopted. In the other areas, the coefficient of 0.8 was maintained.

The catchment areas affecting each subnetwork's initial collection devices were also modified. In general, they were expanded to include the area between the watershed and the start of the subdivision's rainwater collection.

The pipe utilization rate, that is, the maximum filling of the pipes, was also adapted to the set of parameters indicated by Tucci (2004) in models where the use of the circular culvert stretch is full (100%). It is worth noting that the original model used a 95% rate. However, no references were found in the literature for this specific value, which was, standardized at 100% or 90% by Azevedo Netto & Araújo (1998), 100% by Wilken (1978), 85% by Methods and Durrans (2003) and 82% by DAEE/CETESB (1980). The minimum and maximum velocities were maintained at 0.6 m/s and 5.0 m/s, respectively, in all scenarios (Tucci, 2004). Return times were maintained at 10 years in all scenarios.

Tabulation of New Results

After processing the dimensioning, complete hydraulic calculation tables were generated in Microsoft Excel 365 for each model, named M1, M2, M3, and M4. From these results, a summary was then extracted for each stretch of the project, with a description of the devices linked to the stretch, their length and diameter as ballast for evaluating the capacity of the real system and comparing outputs.

2.5. Statistical Analyses

As a complement to the estimated diameters resulting from different inputs and hydrological models, a series of statistical tests were developed to test the impact of these independent variables on the estimates of the project diameters (D1, D2, D3, and D4).

The following were performed: descriptive statistical analyses, tests of assumptions of normality (Shapiro-Wilk), homoscedasticity of variances and residual variation, paired Wilcoxon test for nonparametric comparisons in pairs or double entries, and tests of multiple regression analyses. To this end, R 4.0.3 (Crawley, 2007; R Development Core Team 2020) was used.

The dependent variable was the diameter (D), and the independent variables were the catchment area (A), flow coefficient (C), rainfall intensity (I), and concentration time (C_t). It is important to note that the "municipality" factor was used to test whether there is any effect of "locality" on the variations of inputs in the calculated diameters (D).

In this regard, the research questions are summarized as follows: 1) Did the estimated diameters (D) show significant differences in the drainage network when the models (original and new proposed ones) were tested? 2) Are the responses of the different models sensitive to oversimplification errors of drainage and rainwater project parameters, estimated at M1, when considering different approaches in relatively geographically close Amazonian municipalities (Calçoene and Pracuúba)?

In summary, the statistical significance of the network diameter dimensioning outputs (D) ($\alpha < 0.05$) was tested, considering the following assumptions: 1) study of the effective benchmark project approved by the Ministry of Defense (MD) and 2) analysis of alternative hydrological-hydraulic scenarios modeled. As a practical effect, the multi-comparative analysis of the results served to test whether there would actually be a need for optimization (or not) in the dimensioning of the original project (M1 or MD), with potential impacts on the technical and economic sizing, when proposing new models.

3. Results and Discussion

3.1. Model Diameters

Based on the complete processing of the dimensioning of each model for each subnetwork analyzed (**Table S1**), the following diameters were found, broken down according to the project stretch, which represents the route between two system devices. "CU" represents culvert, "CB" means connection box, "MH" indicates maintenance hole, and "ES" symbolizes the energy sink positioned at the end of the network in the outlet.

The initial stretches of the catchment network, starting with the acronym "CU," were hidden (**Table 6** and **Table 7**), as there was no change in diameters, and all (by project premise and convention) are at least 400 mm, a value that persisted in all models and all networks analyzed. The project assumptions also predicted a minimum diameter of 600 mm for the main culverts, represented by the connections between MH-CB, MH-MH, and MH-ES.

In Calçoene Subnetworks I and II (**Table S2** and **Table S3**), the diameter outputs were identical in all four scenarios. However, in Subnetwork III, there were changes in the results for concrete pipes, mainly in the final stretches of the network, compared to the original model (M1) (**Table 6**). Although quantitatively, there are many more unchanged stretches when considering the importance of the stretch given by its length in meters; in model M2, there were changes in 11.41% of the total length of the network, especially the reduction in the diameter of the MH-13-ES stretch from 1000 mm to 800 mm.

In the M3 model, we found a 9.02% change in the length of the network, highlighted by an increase in the diameter of the MH-15-MH-5 stretch from 600 mm to 800 mm. The results of the M4 model indicate a 20.44% change in the network's total length, with an increase in the MH-15-MH-5 stretch from 600 mm to 800 mm and a reduction in diameter in the MH-13-ES stretch from 1000 mm to 800 mm.

Table 6. Summary of diameters for Calçoene Subnetwork III. Caption: In bold, the diameters that changed compared to the original model (Authors, 2023).

Stretch	Length [m]	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)
MH-4-MH-15	40.00	600	600	600	600
MH-9-MH-14	40.00	600	600	600	600
CB-12-MH-6	5.76	600	600	600	600
MH-15-MH-5	29.50	600	600	**800**	**800**
MH-14-MH-6	29.50	600	600	600	600
MH-6-CB-8	46.52	600	600	600	600
CB-8-MH-5	5.28	600	600	600	600
MH-5-MH-13	25.90	800	800	800	800
MH-13-ES	37.31	1.000	**800**	1.000	**800**

Table 7. Summary of diameters in the Pracuúba network. Caption: In bold, the diameters that changed compared to the original model (Authors, 2023).

Stretch	Length [m]	D1 (mm)	D2 (mm)	D3 (mm)	D4 (mm)
MH-6-CB-4	44.98	600	600	600	600
MH-14-CB-5	44.46	600	600	600	600
CB-2-MH-12	20.00	600	600	600	600
MH-10-CB-7	43.67	600	600	600	600
CB-1-MH-13	20.00	600	600	600	600
MH-8-CB-6	43.85	600	600	600	600
CB-4-MH-5	6.82	600	600	600	600
MH-5-CB-3	43.60	600	600	600	600
CB-5-MH-3	7.34	600	600	600	600
MH-3-MH-4	60.00	600	600	600	600
MH-12-MH-1	48.20	600	600	600	600
CB-7-MH-1	8.13	600	600	600	600
MH-13-MH-9	48.20	600	600	600	800
CB-6-MH-9	7.95	600	600	600	600
CB-3-MH-11	20.00	600	600	600	60
MH-4-CB-8	43.89	600	600	600	600
MH-9-CB-13	42.94	600	**800**	600	**800**
MH-11-MH-2	48.20	600	600	**800**	600
CB-8-MH-2	7.91	600	600	600	600
CB-13-MH-1	8.86	600	800	600	**800**
MH-1-CB-12	44.44	800	800	800	800
CB-12-MH-2	7.35	800	800	800	**1.000**
MH-2-MH-7	100.00	1.000	**1.200**	**1.200**	**1.200**
MH-7-MH-15	100.00	1.000	**1.200**	**1.200**	**1.200**
MH-15-ES	79.64	1.000	**1.200**	**1.200**	**1.200**

Despite flow differentiations in all models, Calçoene Subnetworks I and II data were insufficient to determine differences in diameter dimensioning results. These are the smallest networks analyzed, with lengths ranging from 180 m to 294 m, which suggests that the size of the systems was not enough to increase variations in the culverts.

In these cases, the minimum diameters of the project premise were able to hide any variations in a large part of the route, as observed in the complete subnetwork dimensioning spreadsheets (Table S1).

The M2 models used Kirpich's method to obtain the C_t and, consequently, rainfall duration (Table 4). The reduction in diameter in the last stretch of M2 of Calçoene Subnetwork III is justified by the changes in the catchment area, flow coefficient, and C_t, which are the main variables for obtaining peak flow (Wang & Wang, 2018; Alamri et al., 2023).

In Calçoene, the rate of original rainfall duration and that obtained through Kirpich's method were very similar: 10 minutes and 9.6 minutes, respectively, which did not occur in Pracuúba. However, using the IDF ratios of Back & Candorin (2020) impacted and considerably increased the rainfall intensity in the M3 and M4 models.

For Calçoene Subnetwork III, Kirpich's method and the Back & Candorin (2020) IDF ratios behaved inversely in terms of their influence on diameters. Compared to the original model (M1), changing the way the C_t was obtained generated the smallest set of diameters (M2) and changing the equation for defining standard rainfall (M3) generated the largest set of diameters. The simultaneous replacement of the C_t calculation method and the intense rainfall equation (M4) generated an intermediate set of diameter values with a reduction in one stretch and an increase in another.

For Pracuúba (**Table 7**), all the alternative models, M2, M3, and M4, showed increased diameters from 1000 m to 1200 mm in the MH-2-MH-7, MH-7-MH-15, and MH-15-ES stretches. Added to these changes, in the M2 model, there was an increase from 600 mm to 800 mm in the MH-9-CB-13 stretch, totaling an increase of 28.38% in the total length of the subdivision drainage network.

In the M3 model, there was a change from 600 mm to 800 mm in the MH-11-MH-2 stretch, which, together with changes in the final stretches, represented 28.84% of the change in diameters concerning the total length of the system. In the M4 model, in addition to the changes in the last three stretches of the system, there were also increases from 800 mm to 1000 mm in the CB-12-MH-2 stretch and 600 mm to 800 mm in the MH-9-CB-13 and CB-13-MH-1 stretches, totaling 29.81% of the total length of the rainwater culvert network.

In Pracuúba, all diameters increased. This occurred due to the change in how the C_t was obtained and the variation in the IDF ratios used. That is, both behaved similarly, enhancing rainfall intensity. **Table 5** evidences this information, given that M2 generated 182.21 mm/h of rainfall and M3 generated 180.85 mm/h of rainfall intensity.

The slope found upstream of the subdivision, resulting from the characteristics of the relief at the site, was a preponderant factor since at a length (L) similar to Calçoene, the unevenness (H) generated a much shorter C_t. This corroborates with Back (2014), Leal & Tonello (2016), and Souza et al. (2018), who stated that the physiographic characteristics of a basin are of great importance in determining C_t.

In the M4 model, when Kirpich's method and the IDF ratios of Back & Candorin (2020) were combined, the greatest impact of changing diameters was generated. Compared to the alternative models, the original project (M1) was undersized by at least 28.38% of its length. Adugna et al. (2019) in a water capacity assessment in Addis Ababa, Ethiopia, attested to a flash flood scenario in a system where more than 72% of drainage channels were oversized due to obstructions from pollution. This underscores the attention needed for recurring maintenance and cleaning of the system, especially in systems with partial undersizing scenarios (de Souza & Zamuner, 2016; Daltoé et al., 2016; da Silva et al., 2020).

An undersized system does not have the same technical efficiency and support capacity and can cause socio-environmental and even economic impacts (Alamri et al., 2023), such as increased risks of flooding, property damage, and material and human losses (Sabóia et al., 2017; Christofidis et al., 2019; Sousa et al., 2021; Hou et al., 2021). Therefore, it is important to ensure the appropriate dimensioning, considering the specificities of each region. This premise is fundamental in the Amazon, as this region still has low population contingents and potential areas to be rapidly densified and urbanized.

3.2. Statistical Tests

Based on analysis of the hydrological and hydraulic dimensioning variables of the rainwater conduits for Calçoene and Pracuúba (Amapá/Brazil), Wilcoxon tests (bi-caudal) and multiple linear regressions were performed.

The Wilcoxon nonparametric test showed in the paired comparisons of the "D" medians that the comparative responses between the D1 networks do not differ significantly from the D: D1 - D2 network → (V = 3.2, p-value = 0.1294, not significant).

The remaining paired comparisons resulted in the following parameters D: D1 - D3 → (V = 0.0, p-value = 0.0369, Significant); D2 - D3 → (V = 3.2, p-value = 0.1294, not significant); D1 - D4 → (V = 5.0, p-value = 0.0234, Significant); D2 - D4 → (V = 0.0, p-value = 0.1489, not significant); D3 - D4 → (V = 7.0, p-value = 0. 484, not significant).

Figure 3 shows the discrete variations of diameters "D" calculated for each network in the respective municipality (CAL1, CAL2, CAL3, and PRA), considering four models (D1, D2, D3, and D4) in the dimensioning of the rainwater network.

The Wilcoxon tests compared the Calçoene × Pracuúba outputs with significant results for D1 - D3 ($p < 0.05$) and D1 - D4 ($p < 0.05$). The differences between the M1 model and the M3 and M4 models are due to the IDF relationships, with the original model based on the coefficients of Queiroz Júnior et al. (2013) and the M3 and M4 models based on the studies by Back & Candorin (2020).

These results indicate a significant influence from adopting coefficients with different values for the same location, showing that the lack of studies of intense rainfall for Amapá can generate significant variations in rainfall (Back & Candorin, 2020). However, the dimensioning results for Calçoene when related to Pracuúba distorted the impact of the intrinsic characteristics of each subdivision, which generated a loss of expressiveness in some analyzes due to relief characteristics, slope, and area of the basin, which reduced flow peaks in Calçoene and

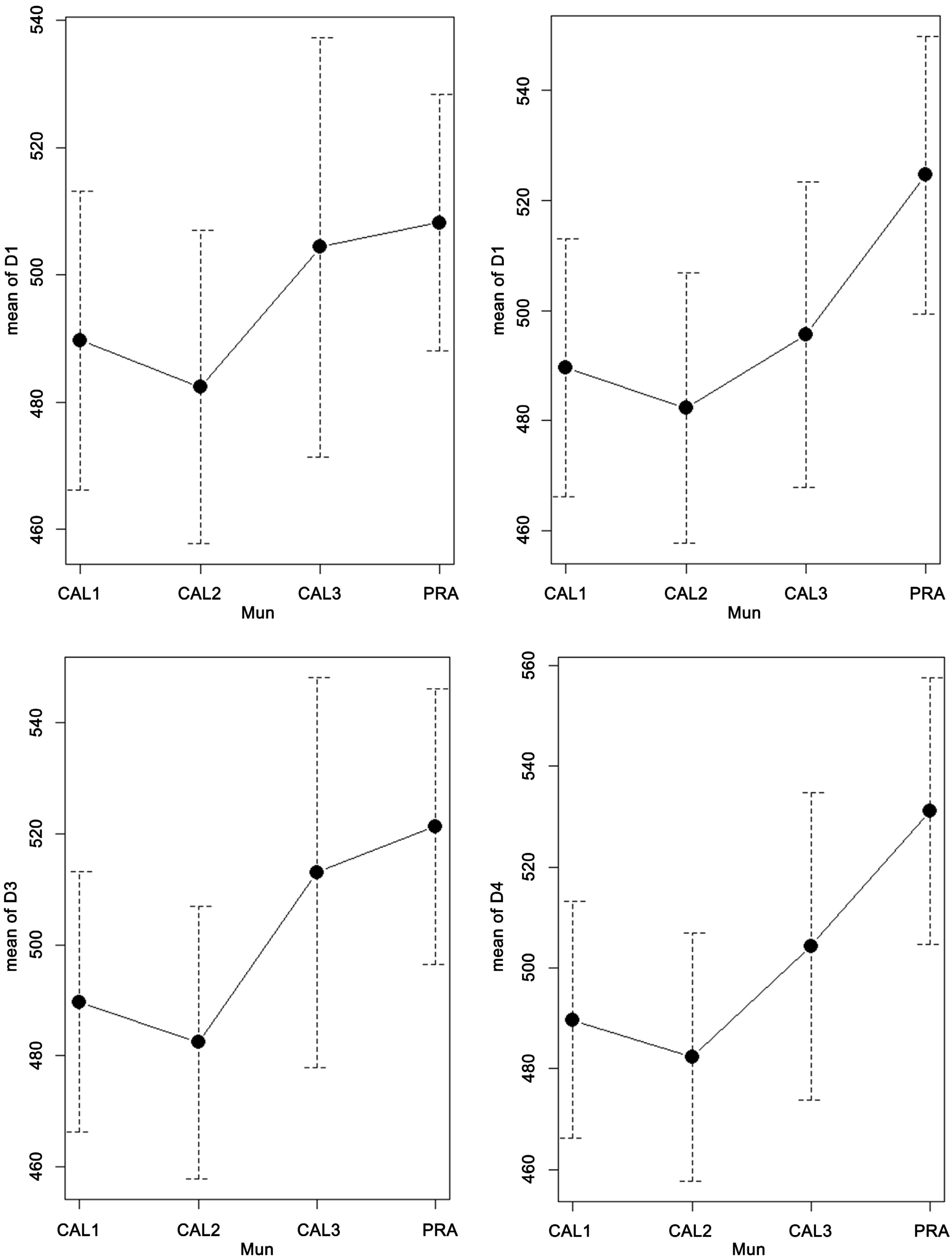

Figure 3. Estimated average diameters (mean, in mm, D1, D2, D3, D4) for the municipalities (Mun) of Calçoene and Pracuúba resulting from the application of the four different dimensioning models (CAL1, CAL2, CAL3, PRA) (Authors, 2023).

increased in Pracuúba. Put on the same plane, these relationships lessen the impact of scenarios that involve the analysis of replacing the method for estimating concentration times, which is highly dependent on the physiographic characteristics of the basin (Leal & Tonello, 2016; Souza et al., 2018).

In each of the subnetworks, the multiple regressions showed the significant explainability of the diameters (D1, D2, D3, D4) as a function of the independent parameters considered in this research: catchment area (A), flow coefficient (C), rainfall intensity (I), and concentration time (C_t) ($p < 0.05$). Therefore, all diameters (D1, D2, D3, D4) showed the expected significant dependence ($p < 0.0001$). For example, on the one hand, D1 was explained by three basic dimensioning variables (A, I, C_t), and its explainability resulting from the analysis was 71.97% R_{aj}^2. On the other hand, D2 was explained by only two variables (A, C_t), with R_{aj}^2 explainability equal to 74.91%. Similar to D1, D3 was explained by three variables (A, I, C_t), showing the best explainability, with R_{aj}^2 equal to 78.82%. Like D2, D4 was explained by only two variables (A, C_t), and its explainability was R_{aj}^2 equal to 75.63%.

The variables A and C_t had a significant influence on all the dimensioning models. This behavior highlights the relevance and sensitivity of these variables in the design and dimensioning of rainwater networks in the Amazon. In addition, the results suggest the need to pay attention to them more accurately; only in this way would it be possible to adequately estimate peak flows and safely dimension urban drainage networks in the region (Rocha et al., 2022; Alamri et al., 2023).

4. Conclusion

The evaluation of the design of drainage networks in Calçoene and Pracuúba showed significant differences ($p < 0.05$) concerning the responses of the models for D1 - D3 and D1 - D4. The Pracuúba subdivision indicated the most significant scenarios of undersizing. In addition, the significant influence of the relevant independent parameters (Ac, C_t, I) in relation to the estimated diameter of the network (D) was confirmed. These results are due to the use of different models or input parameters of the proposed scenarios ($p < 0.05$).

The scarcity of rainfall series data (IDF) generates unreliable input data in the Amazon. This fact can significantly impact dimensioning estimates in rainwater projects in new subdivisions built in areas with little urbanization. This was observed in the D1, D2, D3 and D4 estimates. Therefore, without consistent data available, conceptual projects use references not based on local data or similar physiographic characteristics, suggesting that the parameter estimates may also reflect the susceptibility of these networks to inefficiency in more frequent scenarios.

These findings suggest that the alternative models (M2, M3, and M4) predicted more unfavorable peak outlets than the original model (MD or M1). This confirms that the reference model adopted in the original project was not very efficient. That is, the original system was undersized in some analyses, pointing to the need to size the networks using more robust, accurate, and optimized predictive models.

As difficulties encountered during this research, we can mention the absence of data on intense rainfall for cities in Amapá in rainwater project standards, in particular, NBR 10844/1989, which despite its focus on the design of building projects, is the only one that has a chapter dedicated to providing data on intense rainfall. Limitations of information were also found regarding the precise geographic positioning of the rainfall stations adopted in the study to acquire the IDF coefficients from Queiroz Júnior et al. (2013). This information would help to analyze the positioning of the stations in relation to the study areas.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Supplementary Material

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