PARAMETREE: An Algorithmic-Parametric Tool for Evaluating the Contribution of the Trees on Rainwater Management

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Abstract. This paper explores the application of an algorithmic-parametric tool that uses urban forestry as a design strategy to reduce the occurrence of flooding. The study was carried out following three main stages: (1) a literature review on the capacity of rainwater retention in tree species with dense canopies; (2) the creation of an algorithmic-parametric tool using C# scripting in Grasshopper to calculate the influence of the trees in reducing the runoff coefficient; and (3) a simulation using Rhinoceros and Grasshopper to verify the performance of such tool. The results show a new method of calculation to estimate the runoff formation in urbanized areas as well as it confirms the contribution of the trees in mitigating flooding.

Keywords: Parametric analysis, Biophilic urbanism, Urban planning, Runoff, Urban forestry

1. Introduction

As a result of an aggressive urbanization towards the natural landscape**,** cities have expressed a series of disruptions in their morphology, like the high percentage of soil impermeability, the heat island effect and the poor distribution of green mass, increasing environmental risks within the context of the livability of urban spaces (Ferrão, 2017). Many theories and strategies have been developed and applied to urban planning to restore the city and nature interface and to mitigate the aforementioned problems. In that role of strategies, the one selected to ground the present research is the urban biophilia: a compilation of design actions that aims to reconcile the built and the natural ecosystems through an incorporation of dynamics that once were set apart in the natural domain, drawn, in this case, to reintegrate city and nature (Beatley, 2011).

The biophilic theory covers a wide field of dynamics related to nature complexity. In this study, the scope was focused on the specific dynamics of urban flooding, which is the major cause behind material losses in urban settlements (EM-DAT, 2020). It considers some research findings that highlights the sponge effect observed in green infrastructures. These infrastructures retain a percentage of rainwater in their canopies, reducing the amount that reaches the soil and, consequently, decreasing runoff (Fogeiro, 2019). For this study, researchers considered the green mass of trees as an efficient strategy to reduce urban runoff, which can be also improved with the addition of other green structures to the urban fabric. The concept follows the evidence that urban livability depends on the number of public spaces with a green design.

According to Silva & Santos (2018), a single tree can intercept up to 49% of the rainwater in the area comprised by its canopy. This promising result have motivated this research to take a closer look onto the potential of urban forestry in reducing floods. Seeking this aim, an algorithmic-parametric tool was developed using the Grasshopper application to evaluate the contribution of the trees in the mentioned process by automatizing the calculations needed to estimate runoff formation through a series of simulations. The generic site used to apply the simulations is located in the southeast region of Brazil, where the researchers had access to local bioclimatic information.

The use of an algorithmic-parametric tool in this process is justified by the possibility that these tools can offer in decomposing a complex design problem into a group of simple steps by defining parameters that relates a digital model to a specific context observed on site. Thereby this methodology is drawn to help in the search for solutions to urban problems through the simulation of how such solutions interfere into the urban context (Lima, Costa, & Rosa, 2020).

1.1. Urban Forestry and Sponge Effect

Fazio (2010) states that a tree, before reaching saturation, can store in its canopy more than 300 liters of rainwater in a rain event with the intensity of 25 to 50 millimeters. Extrapolating this data over a lapse of time of one year, it is said that urban trees can help to reduce runoff formation by 2 to 7 percent. However, as Cappiella, Schueler, & Wright (2005) indicate, this capacity of interception can change depending on the structure of the canopy ramification, the density of leaves distribution, the texture of leaves and bark, and the intensity of rainfall.

Also, Alves (2015) explains that it is important to consider the intensity of rainfall due to the impact on the speed of saturation of the canopies: the more intense is the rain, the faster the canopies will saturate and less rainwater they will intercept. Therefore, since the focus is to work on solutions to mitigate flooding, this study has adopted the assumption that the highest rainfall events are the most indicative context to cause that problem. Even though the trees may retain less rainwater in a high intensity rain event, Fazio (2010) points out that when the urban fabric combines those with other vegetations and permeable areas, the runoff can be reduced in 65 percent.

In a situation of extreme rain conditions, the best type of tree for achieving a good capacity of rainwater retention is the one with a dense canopy structure. Some authors in Brazil have already mapped the performance of some species with that characteristic. A compilation is presented in Table 1, organized in two different columns: one for low intensity rainfall (i_m < 25 mm/h) and another for high intensity rainfall (25 < i_m < 79.2 mm/h).

Table 1. Rainwater retention by tree species and intensity of the rain.

Author	Specie	Retention (i_m < 25mm)	Retention (25 < i_m < 79.2 mm)
Silva & Santos (2018)	*Alchornea triplinervea*	49.13%	-
	Peltophorum dubium	32.17%	-
	Tabebuia heptaphylla	34.48%	-
Alves (2015)	*Mangifera indica*	29.85%	12.63%
	Pachira aquatica	33.58%	12.12%
	Caesalpinia peltophoroides	20.15%	7.45%
	Licania tomentosa	26.12%	9.59%
Silva et al. (2009)	*Tipuana tipu*	60%	-

Sources: Silva & Santos (2018), Alves (2015) and Silva et al. (2009).

The species presented in Table 1 are commonly used in urban forestry in Brazil, especially in the southeast region. Nonetheless, it is important to clarify that there are still an incipient number of studies developed on this field in Brazil, which sets some limitations to fully understand the performance of other species. In addition, not all studies were able to analyze this performance in a high intensity rainfall. Despite these constraints, this literature review has shown that the trees can indeed contribute to reduce runoff even during a high intensity rainfall. Also, it has demonstrated that there are differences according to the characteristics of each tree species, which reveals the need for mapping the performance of each with the aim of improving the quality of urban forestry.

1.2. Runoff Calculation Procedures

Pruski, Brandão, & Silva (2014) consider that there are three mathematic variables that interfere in runoff formation (Q_{max}): the average runoff coefficient of the materials that cover the soil (C), the maximum intensity of rainfall (i_m) and the area of the basin (A). These three variables compose the rational equation, a calculation method for estimating runoff formation that is commonly applied in the field of urban drainage, as it follows.

$$Q_{max} = \frac{C.\, i_m.\, A}{360} \tag{1}$$

The variable (C) is an average between the runoff coefficient for every material that covers the soil in the selected basin (C_n), the area that each of them occupies (A_n) and the area of the basin (A). The equation is described below.

$$C = \frac{C_1.\, A_1 + C_2.\, A_2 + \cdots + C_n.\, A_n}{A} \tag{2}$$

Similarly, the component for the maximum intensity of rainfall (i_m) is also calculated with an equation associated with climatic variables, in which the variable (i_m) results from a ratio between the return period of a rainfall (T), the time of concentration of the basin (t) and the variables for adjustment of the data collected by the rain station (K, a, b, c).

$$i_m = \frac{K.\, T^a}{(t + b)^c} \tag{3}$$

As demonstrated by the equations, the rational method for runoff calculation does not consider directly the influence of the trees onto the hydrological dynamics. They are implicit under the variable (C) of the runoff coefficient, which could lead to miscalculations as the trees intercept part of the rainwater, reducing the amount that falls onto the ground and so lessening the interaction in between rainwater and whatever material that is underneath the canopy. That said, this study conducts an adaptation in this calculation method to make clear the influence of the trees in this process and hereby quantifying their contribution to runoff decreasing.

2. Methodology

The methodological approach applied to this study is divided into four different phases. The first phase comprises an estimative of the values collected for the capacity of rainwater retention in the tree canopies during a high intensity rainfall because some of the species identified in the literature review miss this information. This estimative is made by a ratio between the capacities of rainwater retention in a high intensity rainfall and in a low intensity rainfall for the species that present these two parameters, in a search for a constant value that should be multiplied by the retention percentage in a low intensity rainfall. This will result in the projected value for a high intensity rainfall.

The second phase is dedicated to a literature review on books and scientific papers that relate to this field of investigation with the focus on collecting information about the runoff coefficient of the most common materials applied in urban areas. This is relevant for the correct functioning of the equation proposed in this study once it is created from the rational method that used the runoff coefficient as one of the variables to estimate the runoff flow in a given situation.

The third phase contemplates the adaptation of the rational method for estimating runoff considering the influence of rainfall interception by the trees, which is done by adding two variables: one for the area of the canopies and another for its rainfall retention capacity. The idea of using the area of the canopies is justified by the overall pattern of calculation observed in the rational method, which makes an analysis through a two-dimensional overview. Afterwards, an algorithmic-parametric tool is constructed in Grasshopper. As mentioned before, this tool is intended to help to understand how a design will impact on the hydrological dynamics in an urban context. By creating this tool in Grasshopper, it is possible to analyze designs available on the interface with Rhinoceros. That said, the tool is made by using C# programming to generate components with parts of the equation that, when together, will calculate the final result for runoff flow based on the data collected from a model in Rhinoceros.

At last, the fourth phase comprises the application of the tool onto three different contexts to analyze the runoff flow in both low and high intensity rainfalls: (1) a context with no tree and a high percentage of impermeable areas, (2) a context with trees and a high percentage of impermeable areas and, finally, (3) a context with the same set of trees but with permeable materials covering the ground, like porous concrete. Then, the results attained with this digital tool are compared to the ones from the application of a conventional analogical method to verify possible inaccuracies.

3. Results

3.1. Rainfall Interception by Tree Species

The Table 2 presents the results from a ratio in between the capacities of rainwater retention in a low and in a high intensity rainfall. As observed in the results obtained for the species *Pachira aquatica*, *Caesalpinia peltophoroides* and *Licania tomentosa*, the value 0.36 seems to be an ideal constant to describe the impact of canopy saturation on rainwater retention.

Table 2. Results for the ratio in between the capacities of rainwater retention in a low and in a high intensity rainfall.

Specie	Retention [r1] (i_m < 25mm/h)	Retention [r2] (25 < i_m < 79.2 mm/h)	r2/r1
Mangifera indica	29.85%	12.63%	0.423
Pachira aquatica	33.58%	12.12%	0.361
Caesalpinia peltophoroides	20.15%	7.45%	0.369
Licania tomentosa	26.12%	9.59%	0.367

This constant, then, is multiplied by the capacity of rainwater retention in a low intensity rainfall to estimate a projected retention value for a high intensity rainfall context. The results are organized in Table 3.

Table 3. Estimative for the capacity of rainwater retention by tree species.

Specie	Retention [r1] (i_m < 25mm/h)	Constant	Projected Retention [r2] (25 < i_m < 79.2 mm/h)
Alchornea triplinervea	49.13%	0.36	17.69%
Peltophorum dubium	32.17%	0.36	11.58%
Tabebuia heptaphylla	34.48%	0.36	12.41%
Tipuana tipu	60%	0.36	21.60%

3.2. Runoff Coefficient by Materials and Ground Features

The values for the runoff coefficients by material and ground features presented in Table 4 were collected through a literature review. The focus was on materials and features commonly observed in urban areas as well as on some examples of permeable materials. According to the results, the closer the coefficient value to 1, the less permeable is the material.

Table 4. Runoff Coefficient by Materials and Ground Features.

Author	Material / Feature	Runoff Coefficient (C)
Goldenfum & Tucci (1996)	Asphalt	0.830
	Grass	0.150
	Built Elements	0.850
	Concrete	0.880
	Exposed Soil	0.600
Araújo, Tucci, & Goldenfum (2000)	Interlocked Brick Flooring	0.780
	Paving Stone	0.600
	Porous Concrete	0.005
	Interlocked Brick Flooring with Grass	0.030

Sources: Goldenfum & Tucci (1996) and Araújo, Tucci, & Goldenfum (2000).

3.3. Proposed Equation and Algorithmic-Parametric Tool Formulation

The equation proposed in this paper was created over the rational method's equation (Equation 1) by adding a factor related to the area covered by the trees and their respective capacity of retention. This new equation is described below.

$$Q_{max} = \frac{C.\, i_m.\, [(A - A_t) + A_t.\, (1 - r)]}{360} \quad (4)$$

As demonstrated in the equation, the area covered by the trees (A_t) are subtracted from the total area of the basin (A) as the dynamics of that parcel of the soil are different from the rest of the basin because of the interference of the trees while intercepting part of the rainwater. Thus, the runoff formation on the ground under the canopies are calculated separately, considering the capacity of rainwater interception (r). Before transforming this new equation into an algorithmic-parametric tool, the equation was reorganized into smaller segments, being divided into four parts as described in Figure 1.

$$Q_{max} = \frac{C \cdot i_m \cdot [(A - A_t) + A_t \cdot (1 - r)]}{360}$$

runoff calculation   material aspects   climatic aspects   urban forestry aspects

Figure 1. Subdivision of the proposed equation.

Then, each part was translated into a Grasshopper component using C# programming in a way that the calculation process could run automatically inside the software's interface. The tool is already equipped with the information related to the nine materials specified in this research and to the eight species of trees documented. Its final composition is presented in Figure 2.

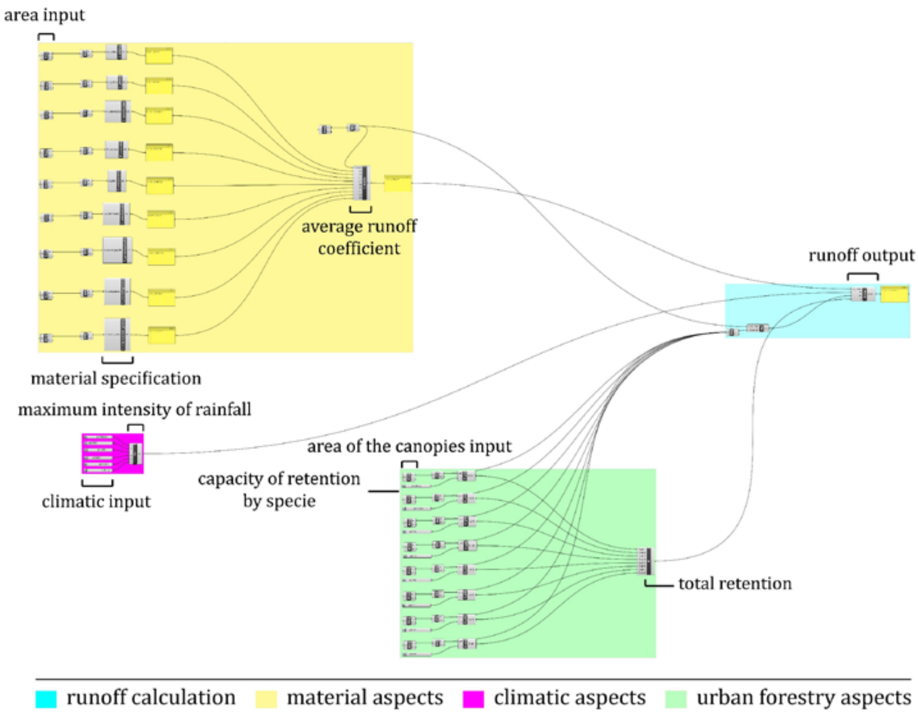

Figure 2. The algorithmic-parametric tool in Grasshopper.

3.4. Testing the Tool

The tool was applied to measure the runoff formation in three different contexts designed in Rhinoceros for both low and high intensity rainfalls, totaling six different situations. Figure 3 shows the plans of all the three models produced in Rhinoceros to represent each context.

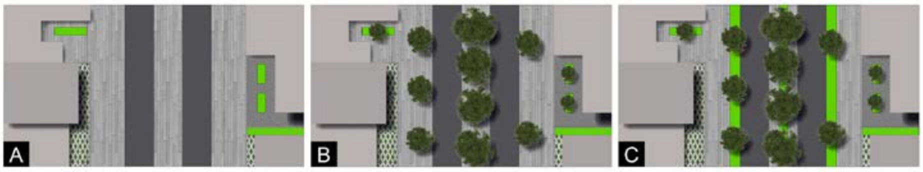

Figure 3. Different urban contexts modelled for the testing process: (A) a highly impermeable area with no trees, (B) a highly impermeable area with trees and (C) a highly permeable area, including permeable paving, with trees.

After modelling the generic urban contexts in Rhinoceros, the algorithmic-parametric tool in Grasshopper was applied to collect the data related to the area of materials and of the canopies, so the runoff calculation process could be automatically unleashed. Also, the climatic inputs were provided based on a survey made by Senna (2009), that gathered a range of climatic variables from rain stations all over the state of Espírito Santo, in Brazil. For these series of simulations, the rain station selected is located in the city of Vitória. A screenshot of this process is shown in Figure 4.

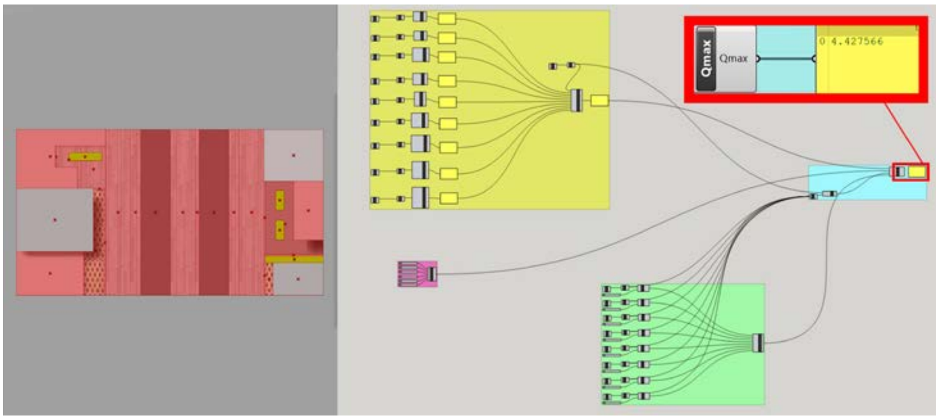

Figure 4. Screenshot of the application of the algorithmic-parametric tool to the runoff calculation process based on the data collected from an urban model in Rhinoceros.

The main features of each context, such as the areas of materials, the areas covered by different tree species, as well as the runoff formed in each of them, are detailed in Table 5.

Table 5. Contexts Description and Runoff Formation for a Rainfall Intensity of 12 mm/h (Low Intensity) and 80 mm/h (High Intensity).

	Materials / Features / Trees	Area (ha)	Total Area (ha)	Runoff (Q_{max}) (i_m = 12 mm/h)	Runoff (Q_{max}) (i_m = 80 mm/h)
A	Asphalt	4.75	24.52	0.66	4.43
	Concrete	8.58			
	Grass	0.47			
	Interlocked Brick Flooring	1.05			
	Interlocked Brick Flooring with Grass	0.87			
	Built Elements	8.80			
B	Asphalt	4.75	24.52	0.56	3.94
	Concrete	6.88			
	Grass	2.18			
	Interlocked Brick Flooring	1.05			
	Interlocked Brick Flooring with Grass	0.87			
	Built Elements	8.80			
	Pachira aquatica	1.99			
	Tipuana tipu	2.66			
C	Asphalt	4.75	24.52	0.38	2.69
	Porous Concrete	6.23			
	Grass	2.82			
	Interlocked Brick Flooring	1.05			
	Interlocked Brick Flooring with Grass	0.87			
	Built Elements	8.80			
	Pachira aquatica	1.99			
	Tipuana tipu	2.66			

3.5. Comparing the Tool to a Conventional Method

To analyze the quality of the result obtained after applying the tool to the urban contexts presented, another calculation method was used to stablish a comparison in between a digital tool and a conventional analogical method. The method selected to this stage is the pixel map (Juan et al., 2017), in which, usually, an aerial image of the area serves as a base to the investigation. On top of the aerial image, a pixel grid is drawn and the type of material or land feature that occupies the largest area in each pixel is selected and mapped. After that, the number of pixels is counted for each material or land feature and multiplied by the area of the pixel. This will result in the area of each component identified in the image. The pixel dimensions should be adjusted in order to better meet the visibility requirements for material identification. Although, it is important to clarify that the smaller the pixel, the better is the resolution of the mapping process, so the results tend to be more precise.

As the generic sites used in this research were modelled digitally, instead of using an aerial image to create the pixel map, the grid was traced directly on the model, on Rhinoceros. The model selected to this process is the one tagged with (C) in Figure 3, which has a good distribution of trees and permeable areas. To express the interference of the pixel size in the accuracy of the final results, two dimensions of pixels were used: a grid with pixels with the dimensions of 1 x 1 meter and another grid with 3 x 3 meters pixels. The result of this mapping is shown in Figure 5.

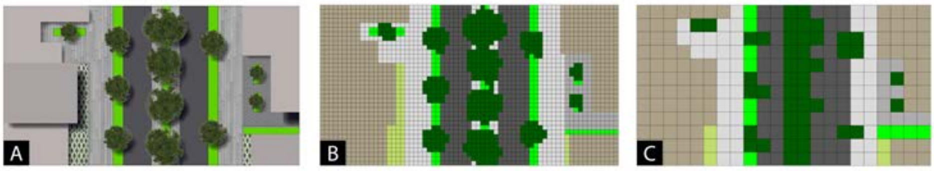

Figure 5. Results of the pixel mapping procedure: (A) top view of the three-dimensional site model, (B) pixel map with 1 x 1 meter pixels and (C) pixel map with 3 x 3 meters pixels.

It is possible to observe that the strategy of the pixel map generates some distortions to the area of each component of the image. As stated before, if the pixel dimensions increase, the appearance gets more distorted, so as the area of each component. In the pixel map with 3 x 3 meters pixels, some features have totally disappeared, like a grass verge on one side of the street. Despite these distortions, another difficulty found in this process is the identification of the materials that cover the ground under the trees, once the canopies compromise the visibility of such details, leading to rougher approximations in the areas, especially in the case of a vaster site with a lower quality aerial image.

The area of each component and the runoff were calculated. The results attained from both the pixel map and the digital tool are displayed in Table 6.

Table 6. Comparison between the results from different methods.

	Materials / Features / Trees	**Area (ha)**	**Total Area (ha)**	**Runoff (Q_{max}) (i_m = 12 mm/h)**	**Runoff (Q_{max}) (i_m = 80 mm/h)**
A (Digital Method)	Asphalt	4.75	24.52	0.38	2.69
	Porous Concrete	6.23			
	Grass	2.82			
	Interlocked Brick Flooring	1.05			
	Interlocked Brick Flooring with Grass	0.87			
	Built Elements	8.80			
	Pachira aquatica	1.99			
	Tipuana tipu	2.66			
B (1 x 1 Pixel Map)	Asphalt	5.04	24.12	0.39	2.70
	Porous Concrete	6.15			
	Grass	2.62			
	Interlocked Brick Flooring	1.08			
	Interlocked Brick Flooring with Grass	0.71			
	Built Elements	8.52			
	Pachira aquatica	1.74			
	Tipuana tipu	2.29			
C (3 x 3 Pixel Map)	Asphalt	5.40	23.76	0.38	2.68
	Porous Concrete	7.11			
	Grass	1.44			
	Interlocked Brick Flooring	1.08			
	Interlocked Brick Flooring with Grass	0.45			
	Built Elements	8.28			
	Pachira aquatica	1.62			
	Tipuana tipu	2.52			

As displayed in Table 6, the area of each component identified in the site selected to this study have changed according to the size of the pixel applied to the map. These differences have led to modifications on the final results for the runoff, both for a low and a high intensity rainfall. In the 1 x 1 meter pixel map, the results for the runoff are higher than the ones obtained from the digital tool, because the distortions enlarged the area of asphalt, which is an impermeable material. On the other hand, in the 3 x 3 meters pixel map, the results are closer to the ones found with the application of the tool, because the distortions, for instance, increased the area of porous concrete as well, which is a quite permeable material, compensating, proportionally, the differences in the area of other components.

Considering that the site used for this demonstration is relatively small, when applying these two different methods in the area of an entire river basin, for example, these divergences on the final results tend to be more expressive, impacting on the effectiveness of a design proposal regarding urban flooding. This attests that the algorithmic-parametric tool presented in this paper is adequate to improve the preciseness and the quality of the data collected from the site.

4. Discussion

After the simulations, the algorithmic-parametric tool has demonstrated a high effectiveness in collecting data from the models designed in Rhinoceros and in calculating the runoff formation according to the equation proposed in this study. All the information presented in the theoretical approach was confirmed in the test: in the context of a high intensity rainfall, the trees, while covering just 18.96% of the total area, have reduced 11.06% of the runoff and, in association with permeable materials, the runoff has dropped dramatically in 39.28%, which certifies that urban forestry is, indeed, a promising strategy for improving the quality and the resiliency of urban areas.

In terms of contributions to the field of study, this tool allows a faster evaluation of how our designs could impact the environment and how they could be improved to better fit into the hydrological dynamics, because of the automatization of the calculation procedures. In addition, it provides a new calculation method in which the trees are considered as part of the hydrological dynamics. Also, it avoids certain approximations on the data collected in the site, which could happen while using another methodology, like the pixel map, to gather information on the area of materials, as the tool works with the exact area of the model, providing more realistic results at the end of the process.

The tool can, as well, serve as an instrument to foresee the impacts of urban policies updates onto the environmental processes that take part in the city, especially the policies that control the proportion between land occupancy and the minimum required for permeable areas. Moreover, this tool also provides with means to understand and quantify the amount of tree covering that is necessary to help to rebalance the built environment, which, in the context of Brazilian forests, could result in the regeneration of parts of the Atlantic Forest within the urban fabric, once it was the intense occupation of Brazil's coastal zone that led to almost the eradication of this biome.

However, the limitation lies on the still incipient studies on how different tree species of Brazilian flora intercept rainwater. That narrows the diversity of solutions for urban forestry proposals that could be created and assessed with this tool. This opens up a new demand for scientific investigation, that could be carried out with shared efforts from the fields such as botanical science and environmental engineering, for example. Another possible approach regarding that matter is to propose an estimation of rainwater interception based on the architecture of the tree. In this process, species with similar leaf size and texture, canopy structure and bark roughness could retain approximately the same amount of rainwater, which could somehow compensate the incipient work of mapping the performance of different tree species of Brazilian flora.

To match the complexity of urban and natural environments, further adaptations could be implemented to the tool, so it would be able to address a wider range of combinations of green infrastructure elements, like bushes and other plants. Also, other variables that relate to the topographic aspects of a river basin could be added to this mechanism, helping to restore its natural stream in case of degraded urban rivers that, likewise the excess of soil impermeabilization and the lack of green mass, affect the hydrological dynamics in the built environment.

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