Bioretention sizing criteria for synthetic storms by hydrologic and hydraulic simulation mixing flood routing with Green-Ampt model

Critères de dimensionnement de la biorétention des tempêtes synthétiques par simulation hydrologique et hydraulique combinant le tracé des crues avec le modèle Green-Ampt

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RÉSUMÉ

L'absence de simulations hydrauliques pour dimensionner les biorétentions LID complique l'évaluation réelle de l'efficacité et de la résilience de la pratique. En outre, les critères ne font pas l'objet d'un consensus mondial, et bon nombre d'entre eux ont été élaborés pour des conditions uniques, par exemple des objectifs différents, le climat et l'occupation des sols. Par conséquent, ce travail vise à associer des méthodes synthétiques telles que l'hyétographe adapté à Chicago, l'hydrogramme, le routage des crues et le modèle Green-Ampt du Soile Conservation Service afin de concevoir une méthode hydrologique et hydraulique permettant de simuler des systèmes de biorétention afin d'évaluer les indicateurs d'efficacité. Les résultats ont montré que le système conçu est capable d'atténuer quelque peu une tempête de 2 heures sur 5 ans dans la ville de São Carlos, São Paulo - Brésil. En outre, le système a diminué de près de 50% le débit de pointe et a également augmenté de 100% le temps de pointe du débit sortant. Cependant, la relation entre la zone de biorétention et le bassin hydrographique était proche de 6%, ce qui pourrait indiquer un système surdimensionné pour une tempête de 5 ans. Cette biorétention dimensionnée sera construite et calibrée afin d'obtenir de meilleurs paramètres. Une fois cela fait, des simulations avec des tempêtes de 5, 10 et 15 ans pourraient être évaluées pour évaluer la sécurité de l'eau en efficacité du système.

ABSTRACT

Absence of hydraulic simulations to size bioretentions LIDs compromises the efficiency and resilience assessment of the practice. Furthermore, there is no consensus in the criteria of sizing, and many of those was developed for different objectives, climates and land uses. Therefore, this work aims to join the synthetic methods of Chicago, adapted hyetograph, Soil Conservation Service unit hydrograph, flood routing and Green-Ampt model i tosimulate efficiencies of bioretention. Applying the method in a 94m² roof catchment, the results showed that the system is capable to mitigate a 2-hour-10-year storm in the city of São Carlos, São Paulo – Brazil, with slackness. Furthermore, the system decreased almost 80% of the peak flow and increased 33,33% the outflow peak time. However, the relationship between the bioretention area and the catchment was close to 6%, which could indicate an oversized system for a 10-year storm. This sized bioretention will be build and calibrated to estimate more realistic parameters. Simulations with 15, 20 and 25 years storms can be used to evaluate system's efficiency once the system is built.

KEYWORDS

Bioretention sizing, Chicago hyetograph, Flood routing, Green-Ampt, Unit Hydrograph

1 INTRODUCTION

A common problem in unplanned cities is to the growth in imperviousness. River rectification has been usually done diminishing concentration times and improving the drainage capacity. This risk-transfer solution does not solve the problem. An alternative solution is to use compensatory techniques (CTs) to reestabilish the previous natural condition. For instance, detention ponds can be placed downstream to diminish peak flow. Usually, once detention ponds are considered for big catchment areas, more complexity is added due to needed geologic, structural, environmental hydrologic and hydraulic projects, which could make it a punctual and expensive solution. (MIGUEZ, 2016).

Other kinds of compensatory techniques are described in the literature, as Low Impact Development (LID) used in several countries like in the United States, Canada and New Zeeland, according to Fletcher et al, (2015). Those incorporate infiltration retention and detention techniques such as infiltrations ponds, rain gardens, green roofs, detention and infiltration swales and other types of infiltration/detention structural measures. These techniques aim to diminish the impact of increasing peak flow generated by the post urbanization and to improve the quality of storm water. These approaches improve runoff quality and quantity and can be used in non-consumptive purposes.

Regarding bioretention cells, there is no clear manual for methods, criteria or regimentations for sizing and projects in Brazil. On the other hand, countries as Australia, United States and United Kingdom, have sizing manuals for LID practices including rain gardens or bioretention cells since the 90's. (PRINCE GEORGE'S COUNTY DEPARTMENT OF ENVIRONMENTAL RESOURCE, 2002; VIRGINIA DEPARTMENT OF CONSERVATION AND RECREATION, 1999).

However, apply worldwide developed criteria, which its majority has been made for different climate conditions, land use occupation patterns and different weight in objectives could not be the best approach. For example, in Brazil, maybe is more important a peak flow reduction than in other countries with more developed cities designed to have more resilience to flood mitigation.

Therefore, this work aims to develop a sizing method for bioretentions considering rain patterns of sub-tropical climate. This method has been used to design a bioretention in a lot-scale for actual experimental objectives. From monitoring, modelling and calibration, it will be possible to evaluate the sensitivity of key-parameters to objectives, such as the outflow peak and time.

2 HYDROLOGIC AND HYDRAULIC BIORETENTION SIZING CRITERIA

It is necessary develop a hydrologic and a hydraulic model to evaluate the performance of a bioretention cell. Metrics such as the quantity of water that passes through the filter media and the spill, the maximum outflow peak and time could be indicators of efficiency. Usually, bioretention cells are used for relative small catchment areas, e.g roofs catchments. So, rational method as a rain-flow model is feasible for hydrologic method. On the other hand, temporal variation of precipitation could be evaluated with an adapted Chicago hyetograph (main intensity in the half of the rainfall, which can be applied for sub-tropical climate) method combined with Soil Conservation Service method and unit hydrograph to assess the possible bioretention efficiency.

Before the start of the hydraulic model, its necessary calculate infiltration rates and volumes in every time-step which is data entry for hydraulic simulation. The model used to estimate infiltration rate was the Green-Ampt, a physically based model. (GREEN and AMPT, 1911).

For hydraulic simulation, a modified flood routing was used, based on Akan (1993). The difference is the necessity to develop an auxiliary table relating the storage and the outflow for each height of saturation zone. Figure 1 shows a schematic flowchart to develop the hydrologic and hydraulic models.

$$P = f(TR, IDF, t) \quad (1)$$

$$Q_{in} = f(CN, P, A) \quad (2)$$

$$T_x = \min\left[\ C_i = f(\theta_s, \theta_i, K_{sat}, \omega, P)\ ;\ \frac{\Delta P_i + \Delta h_{p,i}}{\Delta t}\right] \quad (3)$$

$$Q_{out} = f(Q_{in}, T_x, h, h_s, \phi_h) \quad (4)$$

Where C_i is the infiltration capacity, ΔP_i is the rainfall variation in a time step i, Δh_i is the ponding depth variation.

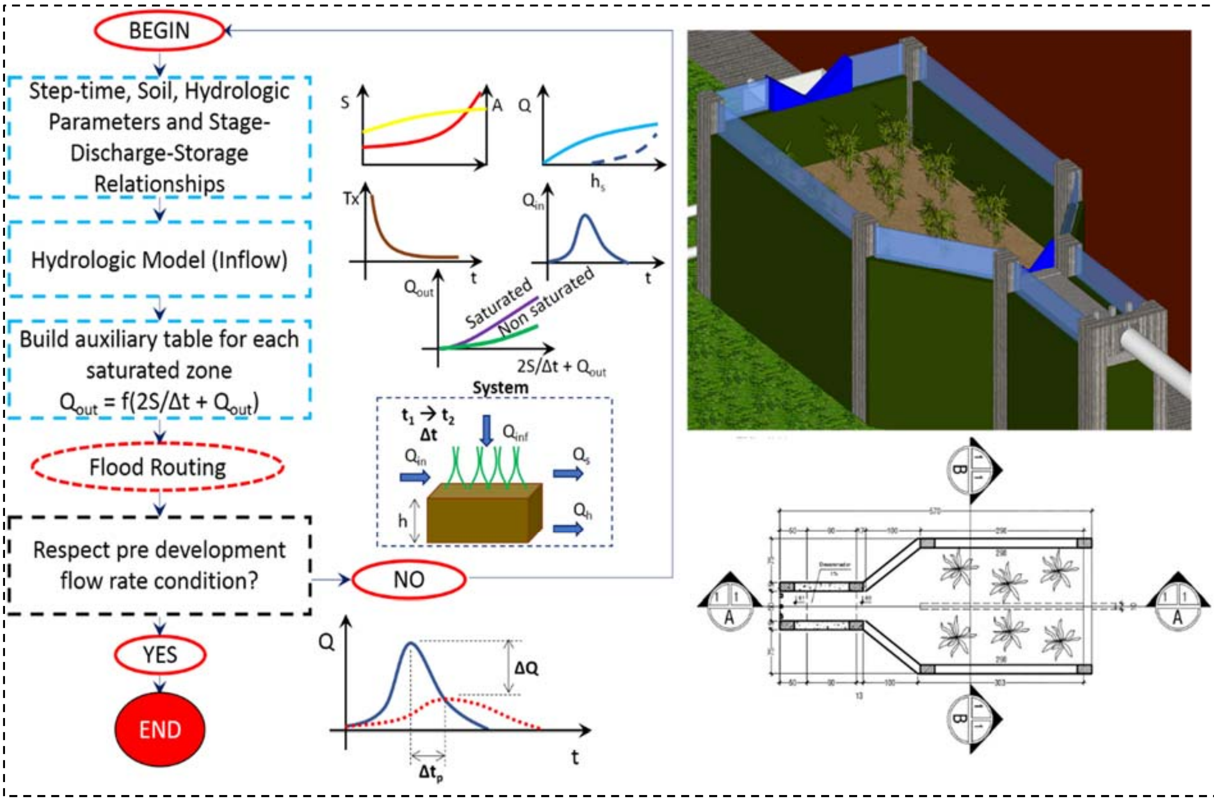

Figure 1 – Flowchart of bioretention simulation model for a design storm. S is the real storage in a control volume in red, A is the surface area in yellow, h is the height considering the referential in the technique bottom, h_s is the spill elevation, cyan continuous line is the hole outflow, blue dashed line is spill outflow, T_x is infiltration rate per time in brown continuous line, Qi_n is the inflow modelled through a hydrologic synthetic model, Δt is the step-time assumed for the simulation, Q_{out} is the sum of spill and hole outflow in the time t, Q_h and Q_s is the outflow of hole and spill respectively, ΔQ is the decrease of peak flow and Δt_p is the increase of peak time.

3 CASE STUDY

In order to size a bioretention cell to catch a roof with 94m², CN = 98, C = 0.95, were used in the designed model to size a 6m² bioretention cell, receiving stormwater. The outflow hydrographs were compared to pre-development maximum flow rate. A 1-meter height bioretention was set and composed by 0,4m of gravel and 0,6m of sand with an average saturated conductivity of 24cm/h. A 0,6m ponding depth located in the top of sand layer was defined to retain more water during intense storm events. The matric pressure was estimated as 4.9 cm of water. We considered 0,47 for the saturated soil moisture and 0.06 for the initial soil moisture. The spill elevation is defined in the top of ponding depth and is considered as a triangular spill. The perforated pipe in the technique's bottom presented 32mm of diameter. Considering the technique initially 50% saturated it is possible do the simulation for a 2 hour 10-year storm using Chicago adapted hyetograph. The SCS-CN hydrograph was used as an input to PULS method modified with Green-Ampt.

3.1 SIMULATION

Figure 2 shows the simulation results. It shows that the system was filling up in the first 80 minutes due to the initial 50% saturated conception. The maximum inflow did not match with maximum outflow and seems proportional with the volume in the control volume. It implied in more hydraulic head in the perforated pipe, which caused a peak flow nearby 100min. Table 1 shows the sizing indicators of the bioretention efficiency.

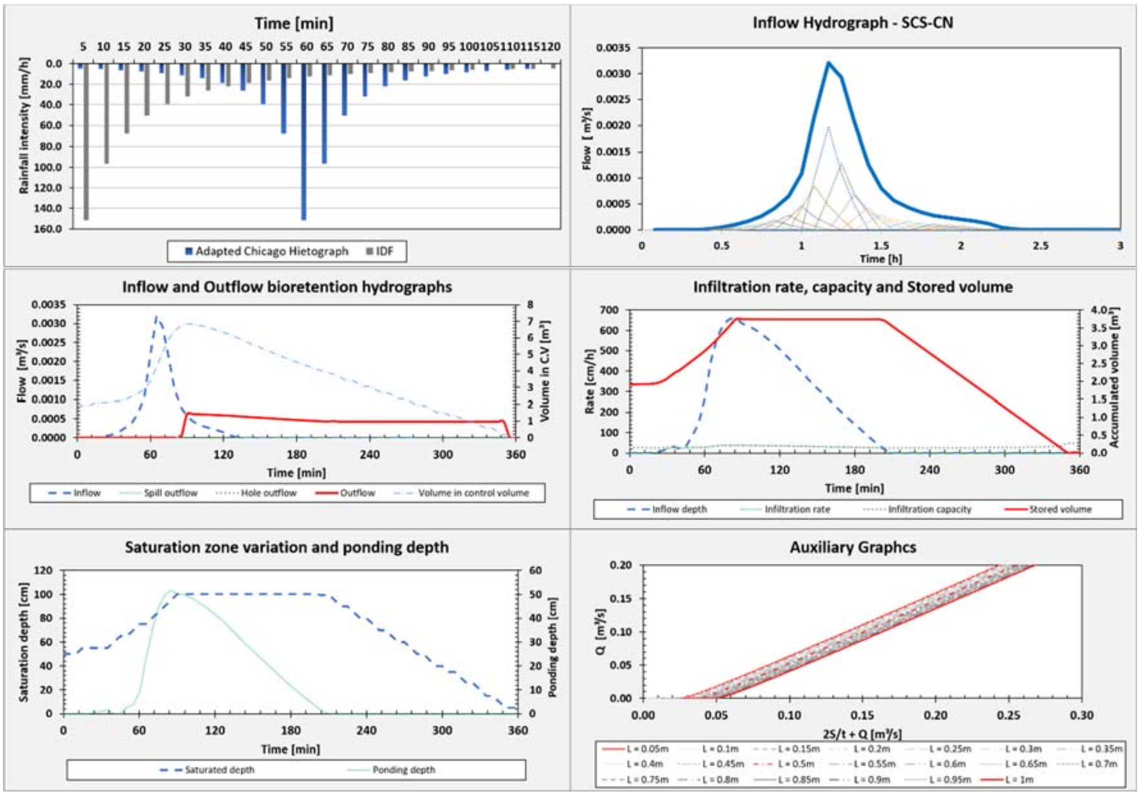

Figure 2 – Chicago adapted hyetograph, SCS unit hydrograph and simulation graphics for designed bioretention.

Bioretention system sizing efficiency indicators							
Q_p	0,6L/s	V_{inf}/V_{LID}	0,97	V_0	1.91m³	$\Delta Q/I_{max}$	81,3%
t_p	60min	V_h	7.7m³	T_b	350min	V_{inf}	5,8m³

Table 1 – Bioretention efficiency indicators. Q_p is the maximum outflow, t_p is the outflow peak time, V_{inf}/V_{LID} indicates the quantity of volume witch infiltrates in comparison with the LID volume, V_h and V_s is the total volume which passed through the hole. V_0 is the initial system volume, T_b is the base time flow, $\Delta Q/I_{max}$ indicates the percentage of diminished outflow. The time of the outflow is 15min later than the hyetograph.

4 CONCLUSIONS

The proposed method needs to be calibrated with real data to evaluate its capacity to predict outflow. The accuracy of outflow is important to verify its reduction and the technique's capacity to reestablish pre-urbanization flow. The results showed that a smaller bioretention could be designed for this case, however the ponding depth was almost in the limit (60cm). We recommend simulate a 2 hour-15,20,25 year-storm and assess the outflow hydrographs for further research. The comparison with the pre-urbanization hydrograph of extreme events are important to evaluate the impacts and resilience of a lot scale LID.

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