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Use of SWMM Model to Simulate the Effect of Compensatory Techniques in the Brazilian Semi-Arid Region

Aplicação do Modelo SWMM para Simular os Efeitos de Técnicas Compensatórias no Semiárido Brasileiro

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ABSTRACT

Urbanization has as one of its most expressive effects the impermeabilization of the soil, what significantly increases the surface runoff and alters the natural hydrological cycle. This paper proposes the application of compensatory techniques of urban drainage in the urban watershed of the Alto da Universidade allotment, located in the Universidade neighborhood of Vitória da Conquista, in Bahia state, Brazil. Such techniques consist of devices that can reduce surface runoff in the post-urbanization scenario, promoting a more sustainable balance between the urban environment and the natural hydrological cycle. In addition, such devices can increase the infiltration of rainwater into the soil, improving water quality and promoting the recharge of underground water tables. To simulate the efficiency of the compensatory techniques, the Storm Water Management Model (SWMM) software was used. The devices used in the simulation were the infiltration trench and the rain garden, which proved to be efficient for the case study. A significant reduction in peak flow was observed, falling from 10.55 $m^3 \cdot s^{-1}$ to 0.61 $m^3 \cdot s^{-1}$, what would contribute to a significant decrease of possible damages caused downstream of the system, in addition to increasing recharge rates of the water table.

Keywords: SWMM. Compensatory Techniques. Urban Drainage.

RESUMO

Um dos efeitos mais expressivos da urbanização é a impermeabilização do solo, o que aumenta de forma significativa o escoamento superficial e altera o ciclo hidrológico natural. Este trabalho propõe a aplicação de técnicas compensatórias de drenagem urbana na bacia urbana do loteamento Alto da Universidade, localizado no bairro Universidade, do município baiano de Vitória da Conquista. Tais técnicas consistem em elementos que reduzem o escoamento superficial no cenário pós-urbanização, promovendo um equilíbrio mais sustentável entre o meio urbano e o ciclo hidrológico natural. Além disso, tais elementos podem aumentar a taxa de infiltração da água da chuva no solo, melhorando a qualidade da água e promovendo a recarga dos lençóis freáticos. Para simular a eficiência das técnicas compensatórias, utilizou-se o software SWMM (*Storm Water Management Model*). Os elementos usados na simulação foram a trincheira de infiltração e o jardim de chuva, que se provaram eficientes neste estudo de caso. Uma redução significativa no pico do volume do escoamento superficial foi observada, caindo de 10,55 m^3 para 0,61 $m^3 \cdot s^{-1}$, o que contribuiria para uma significante diminuição dos possíveis danos causados à jusante do sistema, além de aumentar de forma considerável a recarga do lençol freático.

Palavras-chave: SWMM. Técnicas Compensatórias. Drenagem Urbana.

1. INTRODUCTION

The growth of urban areas has many impacts such as the increase of impervious surfaces, soil compaction, and tree and vegetation removal (EPA, 2007). These occurrences change the dynamics of the natural hydrologic cycle, decreasing the amount of stormwater that would infiltrate and, consequently, increasing the volume of the surface runoff (TUCCI, 2005). To minimize possible consequences, such as floods, it is very important that cities possess adequate systems capable of properly managing such increased volume of surface runoff generated during storms.

According to Tucci (2014), urban drainage involves different approaches that aim to minimize the risks of the occurrence of floods. Structural measures of urban drainage can be classified, traditionally, in two groups: microdrainage and macrodrainage. The first group refers to solutions such as gutters, storm drains and underground pipelines, which collect stormwater from batches of land and small areas. Macrodrainage elements, on the other hand, receive rainwater from larger areas, and include water channels, rivers, lakes etc.

Garrido Neto et al. (2019) discuss that due to growing environmental awareness, more sustainable techniques began to be implemented in urban drainage systems. To describe such a more sustainable approach, many terms have been used: low impact development, sustainable urban drainage systems, compensatory techniques, water sensitive urban design, alternative techniques etc. (FLETCHER et al., 2014).

Compensatory techniques, the term that was adopted in this paper to describe sustainable drainage measures, aim to diminish the runoff peak flow generated by storms as an attempt to reduce the occurrence of floods. At the same time, there is an increase in the recharge of water tables, an essential source of water for many populations.

Such methodology includes techniques and practices that can reserve rainwater and increase infiltration rates. Rain gardens, green roofs, rainwater harvesting and infiltration trenches are some examples of elements that fit this classification and that can be used in combination with the traditional urban drainage structures.

The Alto da Universidade is an allotment located in Brazil’s semi-arid region. Its project was approved by the responsible authorities in the 80s and did include an urban drainage system, which was not obligatory at that time. By the time this work was completed, the allotment still had not been effectively executed. During storms, the natural topography of the location directs the surface runoff to a small lake, located inside a nearby state university.

However, the construction of the structures of the allotment will increase drastically the surface runoff, what can provoke problems especially in downstream areas.

In this work, a suggestion with the application of compensatory techniques of urban drainage in the Alto da Universidade allotment was simulated using the SWMM model. The main goal was to assess the effectiveness of such measures in reducing the future runoff peak flow generated by storms, considering the situation when the area is fully urbanized.

2. MATERIALS AND METHODS

The Alto da Universidade allotment is in the Universidade neighborhood, in the municipality of Vitória da Conquista, state of Bahia, Brazil. The climate of the area is semi-arid, and this municipality has annually a precipitation of around 800 mm (BERNARDES et al., 2018). According to Cardoso and Nobrega (2024), the soil in this area is classified as red-yellow latosol, which is characterized as being a profound and porous type of mineral soil.

Figure 1 presents the planned allotment, with the configuration of the streets and the subdivision of the land, as well as the contour lines and the location of the highest and lowest topographic points. Using the AutoDesk Civil 3D software, the following characteristics of the allotment were obtained: total area of 50.95 hectares, highest altitude of 959.48 m and lowest altitude of 915.03 m, thalweg of 1.52 km.

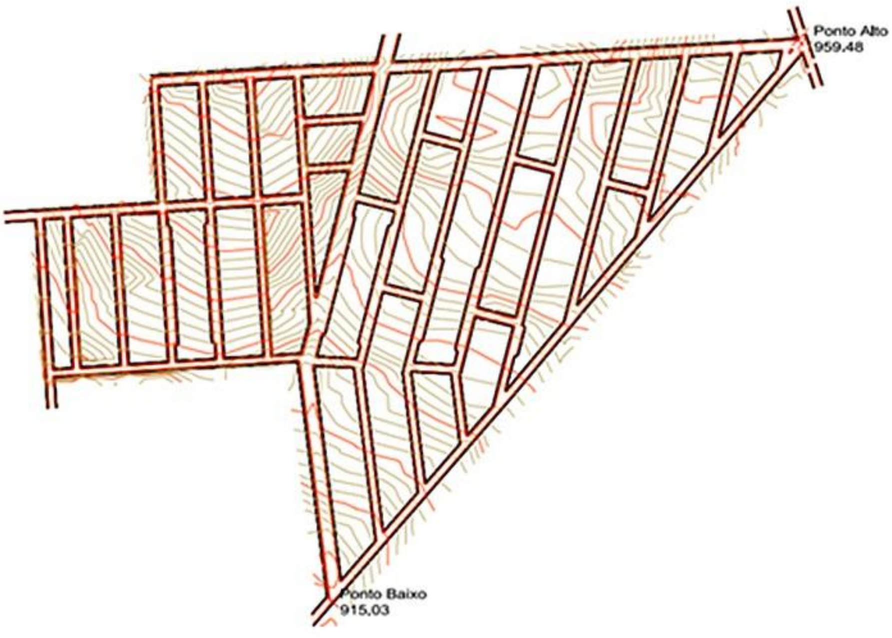

Figure 1. Alto da Universidade Allotment Configuration

The rational method (Equation 1) was used to estimate the surface runoff in the allotment. According to Tucci (2005), this method, which converts rainfall intensity into surface runoff, can be applied to watersheds with area of 2 km² or less. The Alto da Universidade allotment has 0.51 km², fitting such condition.

$$Q = \frac{CiA}{360} \quad (1)$$

Where:

Q = surface runoff ($m^3 \cdot s^{-1}$),

C = runoff coefficient (dimensionless),

i = rainfall intensity ($mm \cdot h^{-1}$), and

A = watershed area (ha).

The rainfall intensity can be calculated using intensity-duration-frequency equations, as represented by Equation 2. According to Souza et al. (2015), such equations relate intense storms of certain location with their return period and duration.

$$i = \frac{(K \; x \; Tr^{a})}{(t+b)^{c}} \quad (2)$$

Where:

i = rainfall intensity ($mm \cdot h^{-1}$),

Tr = return period (years),

t = duration of the rainfall (min), and

k, a, b and c = dimensionless parameters.

The return period is the inverse of the probability of exceedance of a specific value of the variable which is being considered (VOLPI et al., 2015). For example, if the probability of exceeding a specific rainfall intensity every year is 4%, the return period is 25 years. For microdrainage structures, the handbook of urban drainage of Curitiba (PARANÁ, 2022) recommends adopting a return period between 2 and 10 years. Taking this into account, it was chosen, for this work, a value of 10 years for such parameter.

The dimensionless parameters shown in Equation 2 were obtained using the hydrogical software Plúvio 2.1, which presents values of dimensionless parameters to be used in this equation for various locations of Brazil. The values for the studied area are 2862.118, 0.205; 34.443 and 0.958, for k, a, b and c, respectively.

In the rational method, the duration of the rainfall is considered as being equal to the time of concentration of the watershed, which is the time spent by a single drop of rain to dislocate from the most distant spot in the watershed until its outlet (CHOW, MAIDMENT and MAYS, 1988). Tucci et al. (2014) recommends, for small watersheds, the use of the Kirpich Formula to determine the time of concentration, shown in equation 03.

$$tc = 57 \cdot \left(\frac{L^3}{\Delta h}\right)^{0,385} \quad (3)$$

Where:

tc = time of concentration (min),

L = thalweg length (km), and

Δ h = difference between the altitude of the furthest point in the watershed and its outlet (m).

The time of concentration found using Equation 3 was 21.45 minutes. Applying the mentioned values in Equation 02, a rainfall intensity of 97.21 mm·h^{-1} was found.

The runoff coefficient is the relation between the surface runoff and the rainfall that originated it, according to DNIT (2005). In the literature, it is possible to find values of runoff coefficient for different types of surfaces. In this work, values used are the ones indicated by DNIT (2005) for the different conditions of the soil of the allotment.

According to the regulation of the municipality in which the allotment is located, at least 30% of the area of each batch of land needs to be reserved for permeable spaces (VITÓRIA DA CONQUISTA, 2018). Taking this into account, for this study, in the post-urbanization scenario, 70% of each batch of land was considered as being occupied by impermeable constructions, with a runoff coefficient of 0.9, and 30% was considered as being occupied by permeable areas with a runoff coefficient of 0.2. This way, the runoff coefficient for each batch of land was considered as being 0.72, which is the weighted average of the values mentioned previously. In addition, the value for this parameter was adopted as being 0.9 for the pavements and sidewalks, and 0.2 for the gardens and other common permeable areas.

As mentioned before, in the present, the allotment is still in its natural condition. Considering that the present surface of the area is grass and the slope is less than 7%, the runoff coefficient for the present situation (pre-urbanization condition) was adopted as being 0.2.

The allotment was divided into 68 subcatchments, as shown in Figure 2. Considering all the parameters discussed previously and using the rational method, the peak flow of the surface runoff in the pre-urbanization condition was determined as being 2.75 m³·s^{-1}. In the post-urbanization scenario, this value will be 10.30 m³·s^{-1}, considering all the assumptions made for the calculation, as presented. This represents an increase in the peak flow of 3.74 times, what shows how urbanization will impact the natural hydrological cycle of the location.

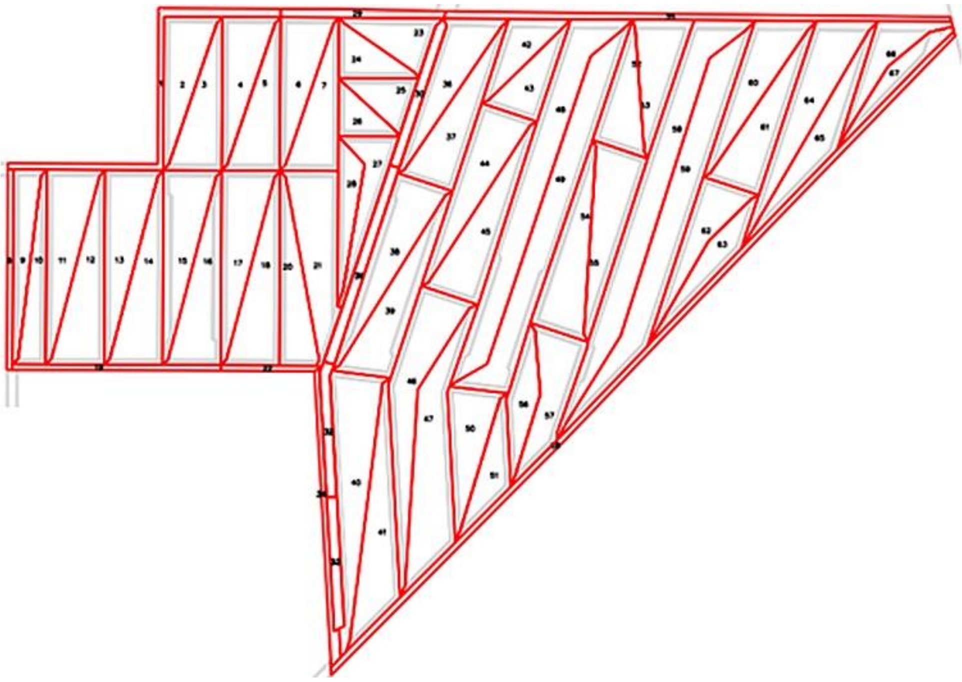

Figure 2. Subcatchments

The drainage system defined for this work includes structures traditionally used in urban drainage (gutters, stormwater drains and pipes) and compensatory techniques. Due to the allotment topography, one of its streets (street “F”) would direct the rainwater away from the outlet of the watershed. To solve this problem, a system of underground high-density polyethylene (HDPE) pipes were simulated in this area, altogether with stormwater drains. Following the recommendation of DNIT (2004), the diameter of the underground HDPE pipes was defined as being 600 mm. The pipe covering defined was between 0.80 to 6.00 m in the driveways.

Compensatory techniques aim to reduce the impact caused by urbanization on the natural hydrological cycle. In other words, such techniques seek to decrease surface runoff generated by storms, as well as increase the infiltration rates. In this work, two different devices that fit this classification were chosen to be applied in the simulation: rain gardens and infiltration trenches.

According to Bernardes et al. (2018), the water table in the municipali-ty of Vitória da Conquista is, in medium, at 25 meters of depth. The infiltration trenches used in the simulation have 1 meter of width and 1 meter of depth, with a corrugated HDPE pipe in its bottom, following the recommendations of DNIT (2016). These devices were simulated alongside the streets, surrounding the areas where the houses will be constructed. On the other hand, the rain gardens are 2.70 meters of width and 1 meter of depth. These devices were placed in specific locations, fitting the design of the allotment as planned (Figure 1).

1.4 Simulation Using EPA SWMM Model

The EPA Stormwater Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used to simulate runoff quantity and quality. This model is widely used throughout the world for studies related to urban drainage.

As defined previously, the duration of the rainfall was considered to be 21.45 minutes and the rainfall intensity adopted was 97.21 $mm \cdot h^{-1}$, considering a return period of 10 years. These data were linked to a rain gauge in the software, in which the time interval was defined as 1 minute.

The determination of the parameters for the rain gardens and the infiltration trenches was based on specialized literature and can be seen in Tables 1 and 2. The seepage rate used was found in the work by Amaral et al. (2018) and considers that the soil of the watershed is already saturated due to previous rainfalls. Void ratio value was found in the work of Rossman (2010), as well as the flow coefficient, the porosity, field capacity, witting point, conductivity, conductivity slope and suction head.

Table 1. Adopted parameters for the infiltration trenches.

Item	Unity	Adopted Value
Surface		
Berm Height	mm	1000
Vegetation Volume	m³	0.2
Storage		
Thickness	mm	1000
Void Ratio (Voids/Solids)	-	0.75
Seepage Rate	$mm \cdot h^{-1}$	44.00
Clogging Factor	-	0.5
Drain		
Flow coefficient	$mm \cdot h^{-1}$	2
Flow Exponent	-	0.5
Offset	mm	5

Table 2. Adopted parameters for the rain gardens.

Item	Unity	Adopted Value
Surface		
Berm Height	mm	2700.00
Vegetation Volume	m³	0.20
Surface Roughness	-	0.025
Surface Slope	%	0.50
Soil		

Thickness	mm	500.00
Porosity	-	0.43
Field Capacity (Volume fraction)	-	0.32
Wilting Point (Volume Fraction)	-	0.22
Conductivity	$mm \cdot h^{-1}$	5.08
Conductivity Slope	%	50.00
Suction Head	Mm	240.00
	Storage	
Thickness	Mm	500.00
Void Ratio (Voids/Solids)	-	0.75
Seepage Rate	$mm \cdot h^{-1}$	44.00
Clogging Factor	-	0.50
	Drain	
Flow coefficient	$mm \cdot h^{-1}$	0.00
Flow Exponent	-	0.00
Offset	mm	0.00

3. RESULTS AND DISCUSSION

As expected, the compensatory techniques used in the simulation notably reduced the peak flow in the outlet of the allotment. The modeling suggests that the peak flow would be diminished from 10.55 $m^3 \cdot s^{-1}$ to 0.61 $m^3 \cdot s^{-1}$, representing a 94.21% decrease. The modeled scenario considered extensive use of compensatory techniques, what can explain such significant decrease. Xie et al. (2017) also used SWMM to analyze the possible impact of the use of com-pensatory techniques in an urban area. These authors modeled scenarios with different rainfall return periods and obtained a reduction rate of peak flow ranging from 100% to 15.9%, what shows that the results can greatly vary depending on the conditions of the modeled scenario. The chosen types of compensatory techniques used also interfere in the peak flow reduction. In another use of SWMM, Arjenaki et al. (2020) modeled the performance of permeable pavement, rain barrels and green roof in an urban location. On average, results varied between 21% and 46% of peak flow reductions, and the green roof was the method with the best results.

The peak flow reduction is an important consequence of the implementation of compensatory techniques. By diminishing the runoff and peak flow, sediment transport is also reduced, what can help to preserve receiving water bodies, what, in this case, is the lake located in the downstream area. In addition, floods in downstream areas are also attenuated, representing a remarkable benefit for the people who live in those areas.

Another important benefit from this result is the increase in the groundwater recharge rates, as well as the decrease in groundwater salinity (CHAHAR, GRAILLOT, GAUR, 2012). Underground water plays an essential part for a great number of people, but such reserves, due to overexploitation, have been decreasing continuously. It is essential, then, to look for mechanisms to re-charge the underground reservoirs, to avoid problems for the populations that need these reserves to survive.

In addition, the modeling shows that all the water from the rainfall infiltrates and flows out of the watershed after approximately 20 hours. This feature is important to avoid the proliferation of vectors like Aedes aegypti, which needs stagnant water to reproduce.

The modeled system was able to reserve more than 100 m^3 of rainwater. As time passes, the reserved amount diminishes, since infiltration is occurring. Rain gardens and infiltration trenches increase the infiltration rates and, when the soil becomes saturated, work as temporary reservoirs along the watershed, which allows the water to slowly infiltrate in the soil through time. Chahar, Graillot and Gaur (2012) explain that, specifically in the case of the infiltration trenches, the captured volume of run-off is temporarily stored in the voids of the gravel and, subsequently, infiltrates into the soil adjacent to the trench.

Figures 4 and 5 show information about the water flowing through the pipes, which are present in the infiltration trenches and in the traditional part of the drainage system. The water level inside of the pipes was inferior to 75% and the highest speeds are between 3.50 to 5.25 $mm \cdot s^{-1}$, which are below the maximum speed recommended by NOVACAP (2017) for HDPE pipes. These results show that the pipes would not present any problems during the storm event, since these values are inside the recommended range found in literature.

Figure 3. Maximum level of water inside the pipeline.

Figure 4. Maximum speed in the pipeline.

Since this work studies a planned area, observation data, usually used to calibrate the model parameters, as explained by Yang et al. (2023), are not available. This also applies to data to validate the model. Although this brings more uncertainty to the results, as reported by Lisenbee and collaborators in a paper published in 2022 (LISENBEE, HATHAWAY and WINSTON, 2022), often urban drainage models remain uncalibrated when analyzing planning scenarios. In their work, this group of researchers modeled bioretention and found that SWMM results were acceptable even when making uncalibrated simulations. In any case, it is recommended that, before effectively implementing the pro-jected area, experiments and data be collected to perform the model calibra-tion and validation.

It is important to emphasize that, in order to maintain a satisfactory efficiency of the compensatory techniques, regular maintenance is mandatory. Macedo et al. (2017) highlighted that compensatory techniques can present problems due to lack of maintenance and inspection. Thus, the results ob-tained when using compensatory techniques in terms of peak flow reduction and increase of infiltration rates can rapidly negatively change throughout the years if proper maintenance and inspections are not executed.

4. CONCLUSIONS

In this work, compensatory techniques were integrated in a proposition of stormwater management system for an allotment located in Brazil’s semi-arid region. Using the EPA SWMM, the system was modelled, and its effectiveness was analyzed.

The allotment was subdivided into 68 subcatchments. A return period of 10 years was adopted for the project, and the respective rainfall intensity was calculated. Using Kirpich Formula, time of concentration was determined and, altogether with the respective runoff coefficient of each subcatchemnt, the runoff was calculated.

The peak flow in the outlet of the allotment was reduced from 10.55 $m^3 \cdot s^{-1}$ to 0.61 $m^3 \cdot s^{-1}$, what shows that the rain gardens and infiltration trenches would maximize infiltration and minimize runoff. Such effects are important to increase water table recharge rates, at the same time it diminishes the downstream flow. In addition, the HDPE pipeline employed showed, in the simulation, adequate functioning in terms of interior level of water and water speed.

This work shows the importance of integrating compensatory tech-niques into urban drainage designs. Even in normal conditions, floodings are a usual event in many cities around the world. Extreme climatic events have maximized this scenario, and it is crucial to adopt more and more sustainable measures to adapt to this new condition. EPA SWMM model is a relevant tool for planning and analyzing stormwater management systems, both the more traditional ones and the ones that make use of compensatory techniques.

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