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Computational modelling of urban drainage network using LID alternatives in a sub-basin in Maringá city, Paraná, Brazil

Modelagem computacional da rede de drenagem urbana usando alternativas LID em uma sub-bacia na cidade de Maringá, Paraná, Brasil

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Abstract

Urbanization development can lead to inundations so urban floods become more frequent. In the city of Maringá, Paraná, this type of event is often observed in some specific dense urban locations, resulted by intense rainfall. In this context, the objective of this paper is to perform a computational modelling in the urban drainage network, most specifically in the sub-basin defined by the intersection of avenues Guaiapo and Palmares, in the city of Maringá, Paraná, considering the current situation and with the application of *Low Impact Development* (LID) compensatory techniques. In this regard, the computational program *SewerGEMS*® was used to develop the scenarios simulations. The results shown that the actual network is undersized (Scenario 01), and it is proposed the adoption of LID compensatory measures (Scenarios 02, 03 and 04). The computational modelling in the elaboration of the scenarios was effective and it may support the municipal urban management with the implementation of an adequate and efficient system of stormwater management.

Keywords: Urban floods; Urban drainage compensatory techniques; Urban water management.

Resumo

Com o avanço da urbanização, tornam-se frequentes os problemas de alagamentos, inundações e enchentes urbanas. Na cidade de Maringá, Paraná, constatam-se alagamentos frequentes, decorrentes de chuvas intensas, em pontos específicos densamente urbanizadas. Neste contexto, o objetivo desse trabalho é elaborar cenários de um trecho da rede de drenagem urbana, mais especificamente no ponto de cruzamento entre as avenidas Guaiapó e dos Palmares, localizado na cidade de Maringá, Paraná: com a situação atual e utilizando técnicas compensatórias de *Low Impact Development* (LID). Para isso, foi utilizado o programa computacional *SewerGEMS*® a fim de realizar as simulações dos cenários propostos. Os resultados mostraram que a rede atual no trecho considerado está subdimensionada (Cenário 1) e uma das soluções propostas é a adoção de técnicas compensatórias LID para construção dos Cenários 2, 3 e 4. Conclui-se que a modelagem computacional para a elaboração de cenários mostrou-se efetiva e pode ser uma grande aliada para fornecer subsídios para a gestão municipal urbana, auxiliando na implementação de um manejo de águas urbanas adequado e eficiente.

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Palavras-Chave: Alagamentos urbanos; Técnicas compensatórias em drenagem urbana; Gestão de águas urbanas.

1 Introduction

Urbanization results in the presence of impermeable areas in the cities, leading to the decrease in infiltration, interception and storage of stormwater in the ground, and also the increase of surface runoff, affecting the local hydrological cycle. Hence, flooding problems become frequent in urban areas, downgrading the water quality by the presence of pollutants in these spaces brought by the land use change and amount of water runoff in urban centers (BAEK *et al.*, 2015; PALANISAMY; CHUI, 2015; PALLA; GNECCO, 2015; XU *et al.*, 2018). The urban drainage model, based on the hygienist concept and commonly used in urban drainage projects in Brazil, is projected to collect and quickly carry rainwater to the pipelines. However, this management model makes all runoff water to be drained rapidly, with high volume and high speed. Furthermore, this amount of water may be amplified by climatic change, with a bigger frequency and intensity of rainfall, making the sustainable management even more difficult (ZHOU, 2014; WANG; WANG, 2018; JOHSON; GEISENDORF, 2019).

The city of Maringá is an example for this type of scenario, due to its fast urbanization, with a heavy land use change starting in the decade of 1970, leading to 95.6% of population concentrated in urban areas of the city in 2010 and a continuous expansion of constructions in natural areas (VALLE *et al.*, 2016). In addition, the city presents frequent floods caused by intense rainfall since the end of the decade of 1990; however, recently less intense rains have provoked significative flooding points, related to the increase in impermeable areas. (GARCIA *et al.*, 2015). Besides this, the micro drainage urban network is dimensioned by the municipal administration, with an adopted return period equal to three years, lower than the recommended in the literature, leading to undersized parameters, since the area is composed mainly by commercial and public buildings, where, according to *Fundação Centro Tecnológico de Hidráulica* (FCTH, 1999), the recommended return period is five years. Thus, the urban micro drainage system may be undersized, implying in more frequent floods due to intense rains (GONÇALVES *et al.*, 2015; SOUZA; ZAMUNER, 2016).

In the context of the increasing urbanization and consequently soil sealing, adverse effects occur in urban areas, such as increase in volume and speed of surface runoff, reduction in water infiltration and in groundwater recharge (HOANG; FENNER, 2016; TEDOLDI *et al.*, 2016; LÄHDE *et al.*, 2019). The stormwater management should be considered in a more sustainable way, as in the application of compensatory techniques, with hydraulic and hydrologic benefits, since the implementation of structural measures attenuates the peak flow, whether by the detention in the origin of the flow or by the storage within the basin. To that end, existing environmental measures may be applied to reach a sustainable development in urban centers, as raingardens, detention basins, trenches and seepage ditches (MGUNI; HERSLUND; JENSEN, 2016; FOOMANI; MALEKMOHAMMADI, 2019; JOHSON; GEISENDORF, 2019).

Given this scenario, besides the sustainable urban drainage system, different practices are being proposed in the literature, with the goal of reducing the urbanization environmental impact in water balance. As examples: Sustainable Drainage Systems (SUDS), Water Sensitive Urban Design (WSUD), Best Management Practices (BMPs) e Low Impact Development (LID) (RIZZO et al., 2018).

The LID techniques objectivate the adaptation or mitigation of hydrological impacts adverse effects due to the quick urbanization and climatic change in watersheds, and consequently prevent the pollution and enhance urban ecosystem (BAEK *et al.*, 2015; ECKART; MCPHEE; BOLISETTI, 2018). LID practices offer an innovative approach to manage surface runoff without relying on conventional techniques. There is some integration with the conventional system, though, objectivating the emulation of environmental and hydrological functions of a basin (WANG *et al.*, 2018; YANG; CHUI, 2018).

In order to reduce the effects of urbanization, the LID is a technique to increase the infiltration area for rainfall, reducing the surface runoff, peak flow volumes and urban floods (PALLA; GNECCO, 2015). To achieve this, a variety of measures may be applied, as detention ponds for rainfall water, permeable concrete systems, bioretention cells, rainwater captation and green roofs (PALANISAMY; CHUI, 2015).

Nonetheless, for an hydrological basin with multiple sub-basins there is a complexity in establishing the LID controls for each one of these sub-catchments. For instance, the locations and combinations of LID may be ample due to the numerous resources available to reduce water runoff in the cities. Therefore, the simulation and optimization tools are applied to assist the implementation of LID controls (ECKART; MCPHEE; BOLISETTI, 2018).

Computational modelling is one of the most effective tools for design and optimization of the urban drainage network system, aiming the determination of the adequate LID technique for the study area, as each of the techniques has its own hydrological response and characteristic in handling the water. There is a wide variety of methods that include the LID simulation and its integration in urban basins, being the most applied model in researches the Stormwater Management Model (SWMM), which presents coherent results with reality. The optimization tools are useful to conveniently assess and compare the LID scenarios in a water basin, since a greater precision may be achieved even in less complex methods (BAEK *et al.*, 2015; ECKART; MACHPEE; BOLISETTI, 2017; ZANANDREA; SILVEIRA, 2019).

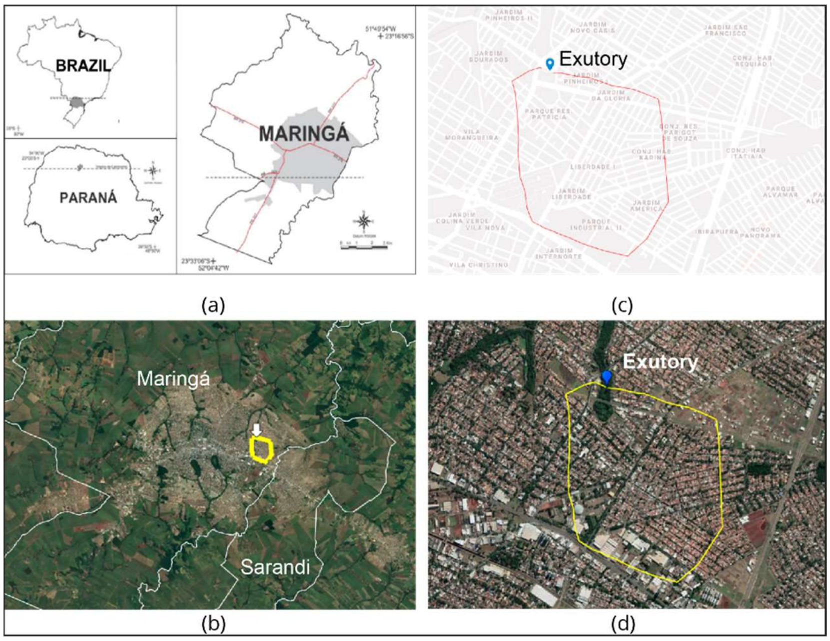
Within this context, the proposal of this study is to perform the computational modeling of an urban drainage network, more specifically for area of the intersection between Guaiapo and Palmares avenues, located in Maringá, Paraná. The modelling takes in consideration the current situation and compensatory techniques of Low Impact Development (LID).

2 Materials and Methods

2.1 Study Area

The study was carried out in the municipality of Maringá, situated in the north portion of Paraná state, as illustrated in Figure 01 (a). In the first phase of the study, it was selected a region of frequent floods in the city, as shown in Figure 01 (b), according to the Civil Defense, the Fire Department and other institutions, using as parameters the frequency of occurrence of these floods and the extension of the damages to the public patrimony and to population. The established area was the sub-basin defined closely to the intersection between Guaiapo and Palmares avenues, with an area of 2.28 km² and a perimeter of 5.73 km, represented in Figure 01 (c) in red color. Figure 01 (d) presents the aerial visualization of the same area, demonstrating the predominance of a watertight area, with a heavy presence of buildings and paved streets. The blue ring of Figures 1 (c) and (d) represents the water confluence point (exutory) of the sub-basin.

Figure 1 – Location of the city of Maringá, Paraná (a); delineation of the sub-basin inside the municipality (b); sub-basin boundaries (c); aerial visualization (d)



(a) (c)

(b) (d)

Source: (a) Adapted from Terassi and Souza (2015). (c) Adapted from GMaps (2020). (b,d) Adapted from GEarth (2020).

2.2 Initial configuration for simulation

The sub-basin was established based on level curves and the topography of the area, considering the mapped network pipeline for the city. It was applied the academic version of the software *SewerGEMS®* for analysis and simulation of urban drainage network, following the guidelines of the software handbook, BENTLEY (2018). Firstly, the level curves were inserted with the respective topographic altitudes, represented by the gray color, and it was traced the delimitation of the study area, in red color, relating it to the actual situation of the area, in pink, as observed in Figure 02.

Figure 2 – Background Layers – level curves and sub-basin delimitation

2.3 Configuration for Scenario 01 Simulation – Actual situation of the network

The next step included the configuration of the simulation data. The method of calculation in the software SewerGEMS® was the rational method (GVF-Rational – StormCAD), recommended for small basins of approximately 2 km² (DAEE, 2005), which was ideal for this study, as the contribution area equals to 1.00 km², with a minimum time of concentration of five minutes. The material of the network was adopted as concrete, in accordance with Municipality Supplementary Law n. 766. With respect to the pluviometric parameters, it was applied the heavy rainfall equations using the software *Plúvio 2.1*. For the city of Maringá, the following equation is valid

$$i = \frac{1341{,}717\ x\ {T_R}^{0{,}175}}{(t + 15{,}461)^{0{,}838}} \tag{1}$$

Where i is the intensity of rainfall (mm/h), T_R is the return period (years), t is the duration of rainfall (minutes) and the local parameters calculated are: $a = 0.175$, $b = 15.461$, $c = 0.838$.

The return period was adopted as three years, and the duration of rainfall equal to five minutes, as recommended by Maringá Management Secretariat, leading to an equivalent rainfall intensity of 129.60 mm/h. The value adopted for the runoff coefficient was 0.90, in accordance with the following references: Wilken (1978); Sao Paulo municipal government, that recommends a value between 0.70 and 0.95 for paved central areas; ASCE (1969), with a recommendation from 0.70 to 0.90 in central commercial areas. For the simulation it was considered as inputs the minimum and maximum limits for flow speed and coverage, following the recommendations of Tucci (2004), the slope and water level in the pipes, following the guidelines of NBR 9649 (ABNT, 1986), with the respective values presented in Table 01.

With all the necessary parameters configured, it was plotted the existent pipelines of the urban drainage network of the city, taken from the digital cartography of the municipality. However, it wasn't possible to calibrate the model with all the existent network in the digital file, and the location of manholes, slopes, rugosity and depth were adopted for this present work. For the manhole locations, the Google Earth® visualization was taken into consideration to confirm the existence of the ones listed in the digital file, excluding the ones that were not executed, and including the ones that were not in the original project. The depth for the pipes were not presented in the file, and it was adopted the minimum 1.30 m and greater depth when necessary. The same is valid for the slopes, adopted as a slope accompanying the level of the ground. The capacity of the manhole is 75% of y/D, according to NBR 9649 (ABNT, 1986), however for this study it was adopted a value of 95% in order to reach a bigger capacity in the pipeline. Lastly, for the delimitation of contribution areas, the *software* applied the Thiessen polygon method.

Table 1 – Maximum and minimum limits for parameters

Restriction patterns		Values
Speed (m/s)	Minimum	0.00010
	Maximum	5.00000
Coverage (m)	Minimum	0.60
	Maximum	4.00
Slope (m/m)	Minimum	0.00010
	Maximum	1.00000
Water line depth (%)	Percentage	95.0

2.4 Configuration for Scenarios 02, 03 and 04 Simulation - *Low Impact Development* techniques

For the configuration for these scenarios, there was a change in the calculation methodology, selecting the Explicit (SWMM Solvers) method, as it considers the outflow from LID to the contribution area of the simulation. Besides this, it was necessary the addition of the infiltration parameter in LID, calculated from the Green-Ampt model. The precipitation data was maintained according to the described for Scenario 01. Before the scenarios simulations, it was necessary configurate the parameters of the compensatory techniques of Low Impact Development. For these scenarios, the adopted techniques were the porous paving and the raingardens, as the most viable alternatives for the study area. Moreover, the LID simulation parameters for each of the techniques were defined, following references of previous studies in this regard. The applied parameters in porous paving were based in the papers of Zhang and Guo (2014) and Zanandrea and Silveira (2018), and are presented in Table 02. The parameters for the raingardens were based in the work of Bai et al. (2019) and also in discussions in the SWMM fórum, and are also listed in Table 02.

Table 2 – Configuration parameters for porous pavement and raingardens

Parameters	Porous pavement configuration	Raingarden configuration
General Name		

Low Impact Development Control Type	Porous Pavement	Rain Garden
Surface		
Surface Storage Depth (mm)	3.00	100.00
Vegetative Cover Fraction	0.00	0.10
Surface Manning's	0.05	0.013
Surface Slope (m/m)	0.01	0.01
Soil		
Soil Thickness (mm)	25.00	1000.00
Soil Porosity	0.46	0.33
Field Capacity	0.20	0.25
Soil Conductivity (mm/h)	25.00	10.00
Conductivity Slope	10.00	1.00
Wilting Point	0.10	0.15
Suction Head (mm)	3.50	5.00
Storage		
Height (mm)	350.00	-
Storage Void Ratio (Voids/Solids)	0.60	-
Storage Conductivity (mm/h)	7.00	400.00
Storage Clogging Factor	180.00	-
Underground drainage		
Drain Coefficient (mm^{1-n}/h)	1.00	-
Drain Exponent	0.50	-
Drain Offset Height (mm)	200.00	-
Pavement		
Pavement Thickness (mm)	100.00	-
Pavement Void Ratio (Voids/Solids)	0.20	-
Impervious Surface Fraction	0.00	-
Permeability (mm/h)	540.00	-
Pavement Clogging Factor	180.00	-

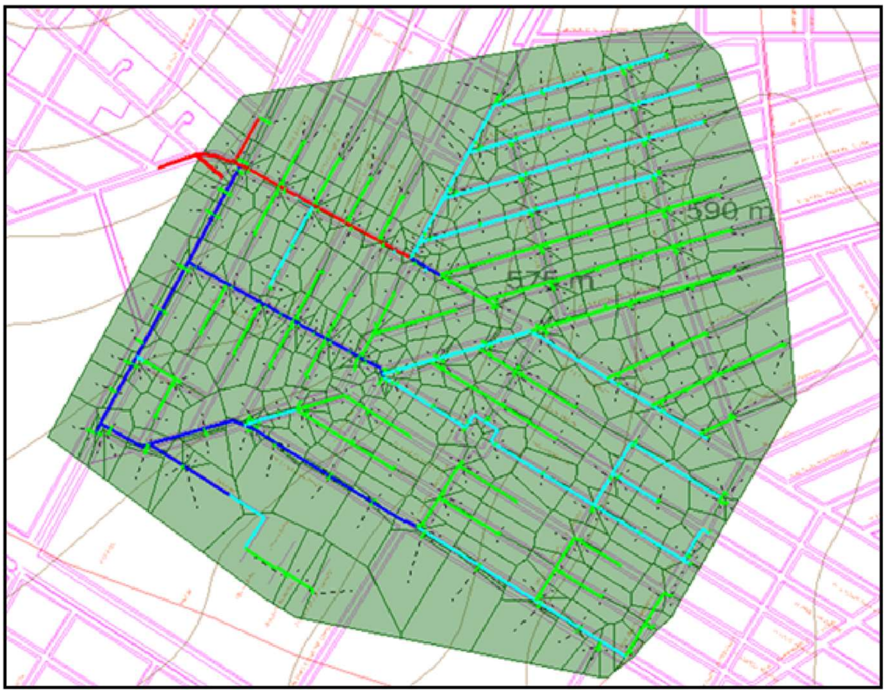
After setting the LID simulation parameters, the urban drainage network was outlined by the software and connected with the catchment area, where it is expected to have a modification in the performance due to the compensatory techniques. Lastly, the low impact measure applied in the simulation was assigned to this catchment area.

3 Results and Discussion

3.1 Scenario 01 – Diagnosis of the current situation

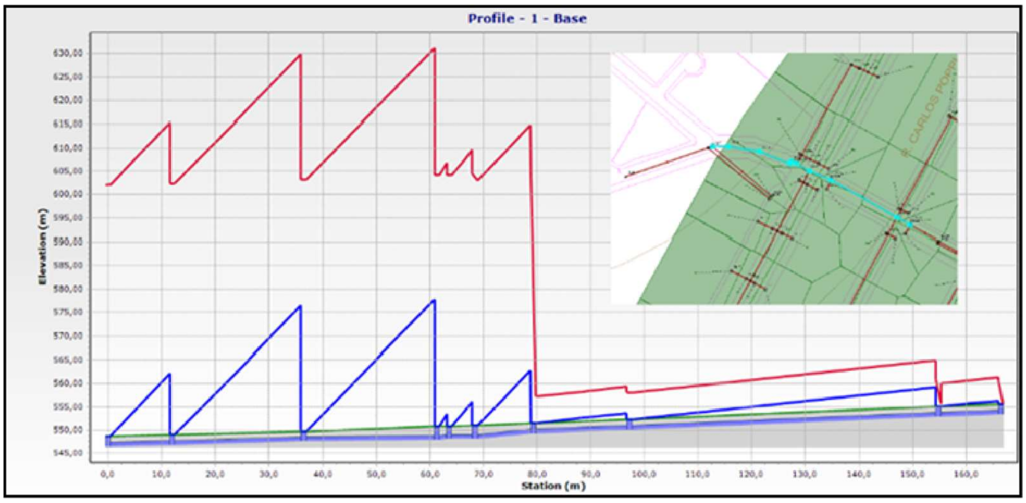
Figure 03 illustrates the pipeline diameters of the current network, with each color representing a different size of the drains. According to the illustration, the green color represents pipes with equivalent diameter of 400 mm; the light blue color the equivalent diameter of 600 mm; the dark blue color the diameter of 800 mm; and the red color the diameter of 1000 mm.

Figure 3 – Representation of equivalente diameters in current urban drainage system



From the simulation it could be noticed that the network is undersized and does not have the capacity to properly drain the area, as illustrated in Figure 04. The figure presents the cross section for a section of the network, with the blue line representing the hydraulic line, the red line representing the energy line and the green line representing the topography.

Figure 4 – Cross section of the selected segment (in light blue) of the urban drainage network



It must be emphasized that one of the reasons for the results in the first scenario is the use of project data, from adopted values by the municipality, with a return period of three years, a time of concentration of five minutes and an equivalent rainfall of 129.60 mm/h. However this value can be reduced by the application of other calculation parameters. The literature recommends the adoption of return periods between two and ten years for urban micro drainage, varying according to land use – residential, commercial or public service uses. For instance, in case of the existence of commerce in the sub-basin, the recommendation is to adopt the return period of five years (FCTH, 1999). Knowing that, with a return period of five years and the equivalent time of concentration equals to ten minutes, the intensity of rainfall is 118.00 mm/h, according to equation (1), so this result is smaller than the chosen for the computational modelling.

Besides this, the project value adopted by Maringá Municipality for the runoff coefficient is equal to 0.67. However, when observing the studied sub-basin it is possible to notice that it is a mainly built-up area, with a high proportion of sealed area. Hence, the adopted value by the municipality is not coherent with the current situation, in a lower scale when compared with the observed in loco. Thus, due to this incoherence in the parameters, a runoff coefficient of 0.9 was adopted.

To address this situation, in order to minimize the occurrence of floods, the application of LID measures is recommended, and three scenarios are proposed in the following sections of this paper. The selection of the solutions for the problematic have considered only low impact development techniques, without the physical interferences in the pipelines.

3.2 Scenario 02 – LID Simulation with Porous Paving Technique

The first proposal is the utilization of porous paving in the parking lot of the International Exhibition Center Francisco Feio Ribeiro, as illustrated in Figure 05, with the LID simulation area patterned in gray and covering an equivalent area of 85,355.10 m².

Figure 5 – Application of porous paving in the parking loto f the International Exhibition Center Francisco Feio Ribeiro

The outputs derived by the simulation of this scenario, in numerical terms, is presented in Table 03, for a simulation time of 24 hours in the studied sub-basin.

Table 3 – Scenario 02 simulation results

Analysis	**Volume (m³)**
LID Initial Storage	210.00
Total Precipitation	22920.00
Infiltration Loss	2510.00
Runoff	19250.00

Final Storage	1530.00
Consistency Error (%)	-0.688

3.3 Scenario 03 – LID Simulation with Raingarden Technique

The second scenario performs the proposal of the utilization of raingardens in the pitch of the Municipal School Rosa Palmas Planas, as illustrated in Figure 06, with an equivalent area as 9,397.90 m².

Figure 6 – Application of raingarden in the pitch of the Municipal School Rosa Palmas Planas

In Table 04 are listed the results obtained in the simulation the scenario 03, with the same simulation time as for scenario 02.

Table 4 – Scenario 3 simulation results

Analysis	**Volume (m^3)**
LID Initial Storage	1410.00
Total Precipitation	21520.00
Infiltration Loss	890.00

Runoff	19480.00
Final Storage	2730.00
Consistency Error (%)	-0.702

3.4 Scenario 04 – LID Simulation with both Porous Paving ans Raingarden Techniques

For the fourth scenario, the two previously mentioned techniques were applied, in order to perform a combined LID alternative with the porous paving in the parking lot of the exhibition center and also the raingarden in the pitch of the school. The purpose was to evaluate the integrated performance of these two measures in the observed rainwater runoff over the selected urban area. Figure 07 illustrates the areas for both techniques combined with the drainage network, resulting in an area equal to the summation for scenarios 02 and 03, totaling 94,753.00 m².

Figure 7 – Integrated LID techniques in urban drainage network: porous paving and raingarden

Table 05 exhibits the results for the combined simulation of the two compensatory techniques in the drainage network.

Table 5 – Scenario 04 simulation results

Analysis	**Volume (m^3)**
LID Initial Storage	1620.00
Total Precipitation	22920.00
Infiltration Loss	2510.00
Runoff	19070.00
Final Storage	3130.00
Consistency Error (%)	-0.645

By the obtained results in presented in Tables 03, 04 and 05, it is clear that the LID techniques influence in the diminution of the surface runoff, as a fraction infiltrates the soil, contributing to the decrease of the amount of water reaching the manhole and consequently the drainage pipelines. This way, the proposed measures have the potential to reduce the volume of floods in the study area. However, due to the large area of the sub-basin, the implementation of the proposed porous pavement and raingarden are not sufficient in absorbing the whole amount of water from the frequent floods observed.

In face of these results, it is encouraged the adoption not only of these mentioned measures but also of other compensatory techniques, in a combined LID implementation. Nonetheless, the physical and financial resources must be taken into consideration for these possible solutions.

4 Conclusion

With the results obtained by this research, it can be concluded that the urban drainage network for the studied intersection is undersized and it is necessary the increase in the diameters of the pipeline, aiming the drainage of all runoff occurring in the basin. However, a solution of resizing is not viable due to the high cost not only of a new pipeline, but also of labor, social charges, excavation, installation, among other costs.

Therefore, a possible solution is the utilization of compensatory techniques of Low Impact Development in the urban drainage network. The results indicated that the usage of these techniques is effective in the reduction of surface runoff volume, and consequently reduces the volume of water reaching the pipeline. Although positive results in the reduction of concentrated volume in the sub-basin, the simulation has demonstrated that still a great volume of runoff would persist. That is because of the large contribution area of the sub-basin in the studied manholes. Thus further studies are necessary regarding another alternatives of LID techniques, and this way observe the advantages and limitations for each one of the measures and reach the best scenario for this problematic.

It is suggested for future researches the modelling of simulations with the application of a new set of compensatory techniques, and compare them to the ones applied in this study. Besides this, other suggestion is the investigation of costs and budget estimations for the financial viability of the LID applications. It should be emphasized that the economic feasibility of the proposed solutions was not in the scope of this paper. Although, the authors believe that there are conditions for the implementation of the mentioned techniques, and recommend the evaluation by the municipal public power.

Finally, it is possible to conclude that the proposed objectives for this present paper were reached, resulting in the elaboration of the current scenario in the urban drainage network for the selected study area with the application of LID techniques, obtaining results that may give new information and orientation to the urban municipal government.

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