ASSESSING THE POTENTIAL OF RAIN GARDENS IN FLOOD MITIGATION: AN EPA/SWMM-5 HYDROLOGICAL SIMULATION STUDY IN THE CÓRREGO DO NADO BASIN, BELO HORIZONTE, BRAZIL.

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ABSTRACT

Floods in urban areas are one of the most common and striking disasters. Among strategies to mitigate flood, the potential role of rain gardens still lack understanding in spatial dynamic models. This study aimed to investigate the runoff attenuation potential of the rain gardens that were implemented in 2022 and 2023 in the Córrego Nado Watershed, municipality of Belo Horizonte, Brazil. The SWMM-5 software from the Environmental Protection Agency of the United States (EPA) was used. The rain gardens have demonstrated potential, on a smaller scale, to reduce runoff. The analysis indicates that the characteristics of each sub-basin influences the performance of the rain gardens, with sub-basin 4140210 showing greater final storage than sub-basin 4140207, despite having a similar number of rain gardens.

Key-Words – Urban Floods. SWMM-5. Hydrological Simulation. Rain Gardens.

1. INTRODUCTION

Floods are complex physical phenomena that impact both rural and urban areas, intertwining human activities with hydrological phenomena [1]. In addition, Land Use and Land Cover dynamics is closely connected to flood events [2]. Particularly in urban settings, floods are influenced by changes of natural hydrological systems due to urbanization, notably through increased soil impermeability [3]. Consequently, assessing flood risk and hazard in urban areas needs close attention on the part of public policies governing urban planning, as well as patterns of housing and urban infrastructure. Hence, there is a significant potential for reevaluating land use in urban areas, which could involve restoring natural floodplains and landscapes to mitigate the impacts of floods. Such measures aid in flood risk reduction and also contribute to the resilience and sustainability of urban environments.

As an alternative approach, we can mention the implantation of green infrastructures associated with LID (Low Impact Development), which uses the nature-based solutions logic to integrate the urban landscape with the natural conditions that have been modified [4]. These practices are based on the maintenance of natural landscapes and permeable areas through the use of permeable pavements, infiltration gardens for household or condominium, green roofs, rain gardens, etc. [5].

Belo Horizonte's municipal city hall through its Urban Policy Secretariat (*Secretaria Municipal de Política Urbana - SMPU*), the Capital Development Superintendence (*Superintendência de desenvolvimento da capital*), and the Municipal Informatics and Information Company of Belo Horizonte (Prodabel) are implementing 60 rain gardens in Córrego do Nado Basin with the objective of minimizing the effects of floods. The project has a partnership with ICLEI - Local Governments for Sustainability and has begun in 2022.

Therefore, the objective of this research is to assess the potential of rain gardens as urban elements to reduce surface runoff and consequently mitigate flooding in the Córrego do Nado Basin in Belo Horizonte through a LID-based simulation.

2. MATERIALS AND METHODS

2.1. Study Area

The study area for this research is the sub-basins 4140207 and 4140210 in the Córrego do Nado basin (Figure 1) in Belo Horizonte city. This basin was chosen due to its pioneering implementation of Rain Gardens by the City Council. Córrego do Nado basin covers an area of 12.39 km², representing 3.8% of Belo Horizonte territory.

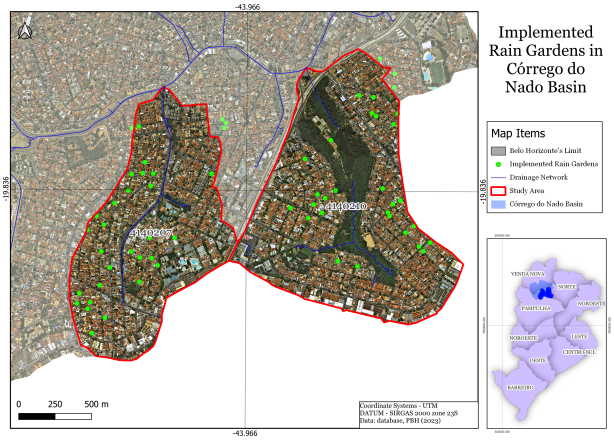


Figure 1: Study Area.

2.2. Data Used

The input data required for the model were the digital terrain model (DTM), an optical remote sensing image and the precipitation data. The DTM was accomplished through

point clouds made available by Belo Horizonte's City Hall (2023) in its cartographic and geographic information catalog. The DTM has 5m spatial resolution. The image is an orthophoto also available in the City Council catalog, with a 0.20m spatial resolution image. The precipitation data was calculated by the IDF (Intensity, Duration and Frequency) curve regionalized by [6].

2.3. The Hydrological Model

The Storm Water Management Model - SWMM is a dynamic rainfall-runoff hydrological model from the U.S. Environmental Protection Agency (US EPA). It brings the possibility of simulating both hydrological and hydraulic processes. The model is represented by physical objects, the precipitation and evaporation data which is driven by the hyetograph; one or more hyetograph can generate the rainfall data in the sub-basins. The sub-basins includes all the information of land use and land cover, terrain, soil, and permeabilization distribution. The connections and the nodes include the information on water level elevation in the conduits and the storing elements, considered when using an unsteady flow propagation model.

2.4. Channel Network Extraction

When using the DTM, the first step to parameterize the model, was to extract the hydrological parameters. The first step to derive information from the DTM, was to make it hydrological consistent, ensuring the flow connectivity. This was made by filling the sinks through the tool "remove pits" from TerraHidro [7]. The second step was the use of the flow tracing algorithm of SAGA GIS, using the Kinematic Routing Algorithm [8], responsible for producing a flow accumulation output grid. Then, using the values of maximul accumulation for each sub-basins as initial thresholds, the channel network and the flow directions were extracted. The channel network was used to calculate the mean flow width (W) and the flow directions were used in association with the slope map to draw the conduits in the sub-basins discretization.

2.5. Precipitation Entry Parameters Calculation

SWMM model accommodates various types of precipitation data, each of which serving different purposes. In this research, the intensity of precipitation approach was chosen, due to its capacity to represent extreme rainfall events crucial in flood analysis. The choice of the precipitation input is of special importance, due to the rapid conversion of rain to runoff, and hence the changes in a hyetograph can create similar variation in the runoff [9]. It is typically depicted through an Intensity, Duration, and Frequency (IDF) curve.

For the Belo Horizonte metropolitan area, the IDF relations were regionalized by [10], based on the historical precipitation of this area and the typical hyetographs of the continuous time series, lately presented by [6]. The estimation of the project values [10] are given in figure 2.

The losses from evaporation were not considered due to their effectless nature in single events within urban basins.

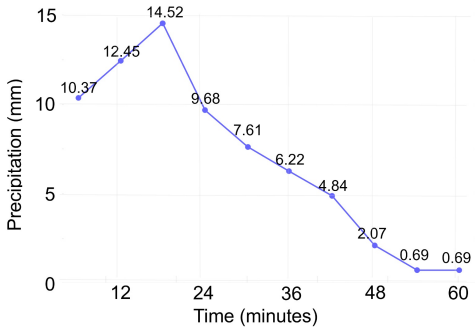


Figure 2: Hyetograph for the Projected Precipitation.

2.6. Sub-Basins Discretization and Parameterization

The sub-basins were discretized according to the pre-definitions established by Belo Horizonte. The next step was to delimitate the area (A) and the mean flow width (W) of the sub-basins. For W, we initially calculated the maximum overland flow, using the drainage network extracted from the DTM. Then, The maximum overland flow which is the path of surface flow and the maximum flow width before it is absorbed or piped is divided by the area. It was calculated by measuring the water courses in QGIS. Although this method could provide W, it was necessary to improve the sensibility test for this parameter, ensuring the lowest continuity error. The last parameter for the sub-basins is the slope (S), which was extracted using QGIS. The parameters associated with LULC include the Curve Number (CN) values and the percentage of impermeable area (Ai), as well as Manning's roughness coefficients for permeable - N-Perm and impermeable areas - N-Imperm [11]. The CN values were determined through studies conducted as part of the Master Drainage Plan. Finally, to calculate the Manning's roughness coefficients for both impermeable and permeable areas, the optical remote sensing classification of land cover was utilized, employing the values provided by [11]. The parameters are given in table 1.

Table 1: Entry Parameters for Sub-basins

Sub-Basin	4140207	4140210
Area/ha	126.3	168.4
Mean Flow Width	138.07	2646.06
Slope(%)	5.62	5.67
CN	83.66	88.01
Ia(%)	65.8	63.9
N-perm	0.16245	0.171755
N-imperm	0,007896	0,007668

2.7. Junctions and Conduits Parameters

The junctions and conduits in SWMM are represented by the nodes and links. The parameters needed for the junctions are: elevation, maximum water depth, its initial depth, and the ponded area when flooded. For the conduits, the length, the

Manning´s roughness coefficients, the shape of the conduit, and other parameters related to the water transport are needed. The parameters were dimensioned and adapted according to the atlas instructions for the elaboration of drainage projects of the Drainage Master Plan [12].

2.8. Runoff Simulation

The simulations were carried out in a Rainfall/Runoff dynamic model for a singular rainfall event with a duration of 1 hour. The infiltration model used was the curve number method (CN) from the Natural Resource Conservation Service of the United States (NRCS - USA). For the flow routing propagation, both kinematic wave routing and steady flow methods were tested.

Sensitivity tests in hydrological models are important because they can help to understand the role of some parameters in a global perspective. This in turn may help to assess the stability of the model with respect to a certain parameter. The sensitivity tests were conducted with a "one-at a time" method, using a univariate test. The most sensitive parameters in the model included the Mean Flow Width, impervious area, the Manning's roughness coefficient for pervious surfaces (N-Perm), and the storage capacity.

2.9. LID-control Simulation

The rain gardens were simulated in SWMM-5 using the function "LID-Control". The parameters for the Rain Garden are related to three main structures: i) Surface, which includes Berm Height Values, Vegetation Volume Fraction, Surface Roughness, and Surface Slope; ii) Soil, which is composed by Thickness, Porosity, Field Capacity, Wilting Point, Conductivity, Conductivity Slope, and Suction Head; and iii) Storage, which owns parameters such as Thickness, Void Ratio, Seepage Rate, and Clogging Factor. Most of the values were used testing default values, but the surface parameters and the thickness parameter were adapted from [11]. The LID controls are represented by a combination of vertical layers with properties defined per unit area, which allows LID controls with different areas being implemented easily in the sub-basins. The performance simulation of LID controls can be conducted by analyzing their influence on runoff and infiltration. In the Rain Garden performance report, there are various components of the water balance produced by the LID, including inflow to the surface, infiltration, evaporation, surface runoff, flow removed by the storage, and water stored in all the steps of the simulated event.

In addition, the simulation of LID controls in SWMM requires input parameters related to the relationship between the rain gardens and the sub-basin, taking into account the specific characteristics of the sub-basin. For this purpose, it was necessary to enter the area values of each LID unit, which were obtained from the database of the Belo Horizonte's municipal city council, where the gardens have areas of 16.3 m² and 10.15 m². Additionally, the other necessary parameters were the percentage of the sub-basin area occupied by the rain garden, the percentage of the rain garden soil that was primarily saturated, which was defined as the wilting point (0% saturated) for all gardens. Lastly, the impervious and pervious areas treated by the rain garden were considered, along with the percentage of impervious area treated by the rain gardens. This was calculated by multiplying the total area of the sub-basin by the percentage of impervious area to obtain the total impervious area. Then, the area of the sub-basin was multiplied by the percentage occupied by the rain gardens to determine the area of the gardens.

3. RESULTS

3.1. Comparison between the Simulation With and Without the Rain Gardens

The simulation had an initial surface runoff continuity error of -5.95%, and after the calibation and sensitivity test, the error dropped to 0.67%. The flow routing error continuity was 0% because the simulation parameter considered was the steady flow.

The graph in Figure 3 shows the comparison between the runoff in the scenario with the rain gardens, and the one without it.

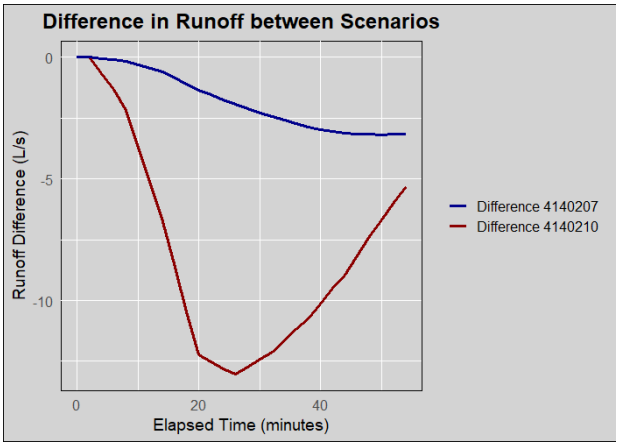


Figure 3: Runoff Comparison for the scenarios.

It can be observed that the scenario with rain gardens partially resulted in a reduction of surface runoff. However, there is a noticeable difference in runoff between the two analyzed sub-basins, which can be explained by their morphometric characteristics, percentage of impermeable areas and land use and cover. Sub-basin 4140210 has a greater mean flow width, and its streets are more sloped, allowing more water flow to reach the rain gardens, consequently resulting in greater storage within them. Furthermore, the gardens of 4140210 proved to be more effective, indicating that the selection of its locations may have contributed to this difference. Despite the reduction in runoff in both sub-basins, it appears that such LID controls probably had a more local impact than a major effect at the sub-basin scale [4].

However, the figure 4 shows the metrics of the perfomance of each of the rain gardens. Most of them, had similar results of final storage and inflow. There is a slight variation between the final storage and inflow values among the rain gardens,

with no significant differences observed among them. For comparison between the two sub-basin, it is possible to see that the rain gardens in sub-basin 4140210 have higher values of final storage and inflow.

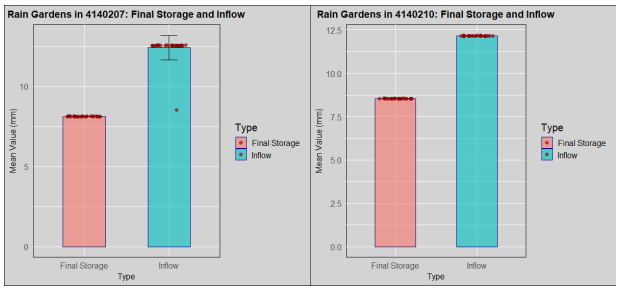


Figure 4: Perfomance of the Rain Gardens.

4. DISCUSSION AND CONCLUSIONS

Córrego do Nado has several areas mapped as risk areas of floods, this mapping was made by Belo Horizonte's hydrological study and identified the flood spots distributed along the drainage basin of the watershed. This study identified a greater runoff coefficient in sub-basins 4140207 and 4140210, which follows the selection of areas for implantation of the rain gardens and also the mapping of risk areas and the sub-basins that has the lowest drainage index [13]. Both this and Belo Horizonte's study can be evaluated by the constant and recurring floods that happens in the sub-catchments notably in Vilarinho Avenue located in the outlow.

The implementation of rain gardens, in a general way, shows that the LID strategies had an effective role in decreasing the runoff in Sub-basin 4140210, but in principle did not show expressive results in sub-basin 4140207.

The model has some limitations that require attention and should be addressed in further developments of this study. They mainly relate to the hydraulic parameters, which need careful attention to be accurate and represent the observed reality. In this work, all the hydraulic parameters were adapted and tested. In view of the the hydraulic parameters imprecision, the flow routing model adopted was the steady flow, with lower continuity errors. The kinematic wave flow should be also evaluated to check the contribution of nodes and links to the sub-basin flood. The model uses an extreme rainfall scenario defined with only one project rain. In order to evaluate and validate the model, it should be further simulated based on real rain scenarios. We finally ought to mention that the extreme rainfall employed in this work was adapted from an outdated study, since we intended to cope with an extreme rain in compliance with the current climate change context.

5. ACKNOWLEDGMENTS

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