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Optimization of a storm drainage network using the storm water management model software in different scenarios

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Abstract. The research developed was based on the design and optimization of a storm drainage network, with the objective of finding solutions to possible flooding events. For this purpose, three study areas of different topographic conditions were defined in the city of San José de Cúcuta, Colombia, with an extension of 16.82 ha (high slope zone), 12.85 ha (medium slope zone) and 12. 10 ha (low slope zone); subsequently, a storm drainage network was designed for each of the study areas based on the current specifications of Colombian standards; the storm drainage network was modeled using the storm water management model software of the Environmental Protection Agency of the United States of America, a cost-benefit comparison was developed for the two alternatives. At the conclusion of the investigation, it was found that by elaborating the cost structure for the different conditions from both the initial and optimized designs, a savings of 17.8% was obtained in the high slope, 22.4% in the medium slope and 24.6% in the low slope, mainly in activities such as excavation and pipe diameters.

1. Introduction

The development of any community is related to the proper provision of the most basic public services, such as energy, water and sanitation. Within the cleaning service, it is important to have an appropriate disposal of wastewater and rainwater, in order to mitigate problems of health and public risk, due to the constant interaction of man with the environment. The objective of the rainwater drainage system is to achieve a rapid evacuation of the rainwater runoff from the public roads during a rainfall event, thus avoiding the affectation of both vehicular and pedestrian traffic, and at the same time reducing the risk of flooding in a given sector. However, despite the fact that the design considers the weather, geological, geotechnical and topographical conditions, it is common to observe flooded areas and collapse in the system during rainy seasons.

Based on the above and seeking to mitigate these problems as much as possible, modeling and analysis software has been developed that is valuable in the design or review stage of the sewerage system. For this reason, in order to satisfy the requirements of Colombian standards, such as resolution 0330 of June 2017 [1] and the basic water and sanitation regulations, in those cases where a hydraulic analysis is required under the condition of non-permanent flow, it is necessary to implement hydrological models that allow the design hydrographs to be obtained, in order to determine the behavior of the entire system and the faults that occur in the different sections and components of the sewage network [2]. Taking into account that these give an approximation of what would be the most critical cases in different time cycles for a given precipitation, the proposed research used the storm water management model (SWMM) software from the Environmental Protection Agency (EPA) of the United

States of America, which "is a free rainwater management model that simulates the movement of precipitation from the soil surface through the channel network" [3].

Research such as the Xinglong Jinan Area Runoff Simulation Study based on low-impact development, in which an urban stormwater model was built using SWMM software, which could simulate the runoff process of different development modes in different return periods obtained good and reasonable simulation results [4]. In addition, the research on the simulation and optimization of an urban sewerage system had the objective of determining the different hydraulic parameters that produce a minimum cost for a project like this, allowing to guarantee that no overflows or overloads will occur in the sewerage system [5]. Contributing to this type of studies, the present investigation developed the design and optimization of the pluvial sewage network, modeling with the EPA SWMM software and cost analysis of the same to establish the most appropriate alternative to be applied in the defined study areas and in search of solutions to possible flooding events.

2. Materials and methods

Below, the methodology and equations used in the development of this research are presented in order to determine failures in the system and the elements that compose it.

2.1. Definition of the study areas

Three zones of the city of San José de Cúcuta, Colombia, were selected, these had different topographic conditions such as the zone of high slope (14%), located in the Gaitán neighborhood, the zone of medium slope (4.70%), located in the Loma Bolívar neighborhood and the zone of low slope (1.90%) located in the García Herreros neighborhood, which fulfilled the requirement of having an area equal to or greater than 10 hectares, obtained randomly from the area under study, in order to achieve reliable results.

The determination of the contour lines was developed in the three study zones through the use of tools such as Google Earth® and CivilCAD, which allowed determining the necessary elevations to establish the flow of water in the streets and later to carry out the design in the different topographic conditions. In addition, the tributary areas for each street were fixed and with this information the possible expansions that drain to each study area were found, as it happened in the investigation [6] in which pavement curves were obtained from the planialtimetric survey carried out in the sectors that drain towards the flood, representing important information to carry out the analysis of the superficial hydrodynamics of the road and of the drainage structures.

The EPA SWMM software requires additional information for each sub-basin such as the average slope and width, the previous base topography was used using Equation (1) and Equation (2) obtained from [2].

$$\text{Pending} = \frac{\text{Upper and lower elevation}}{\text{Length}} * 100, \tag{1}$$

$$\text{Average width} = \frac{\text{Tax area}}{\text{Length}}. \tag{2}$$

2.2. Design of rainwater drainage system with the rational method

In order to design the storm drainage network, the first thing that was done was to determine the Return period, based on the methodology proposed in article 135 of resolution 0330 of June 2017 [1], the return period is obtained according to the drainage characteristics of the study zone and because more than one discharge occurs in the same zone, of which one has a tributary area between 2 ha - 10 ha and the other with tributary areas greater than 10 ha, it was decided to take a return period of 10 years, because in the EPA SWMM program it must manage a single return period.

Afterwards, In order to determine the location of the collectors, a previous analysis of the water sheet in the streets was carried out, and those that exceeded 7 cm were taken as flood criteria; subsequently, it was calculated, taking into account the following equations taken from the regulations on water and basic sanitation (RAS) [2] and the Book "Hidrología Aplicada" [7], as presented below.

2.2.1. Time of entry. This is the time it takes for the runoff to reach the collector's sump. The United States of America FAA Equation (3) was used to calculate the entry time, obtained from [2]. It is important to note that the minimum time of entry in initial wells is 5 minutes.

$$T_e = \frac{0.707*(1.1 - C) * L^{1/2}}{S^{1/3}}, \quad (3)$$

where Te is the entry time (min); C is the separation coefficient (non-dimensional); L is the maximum length of surface runoff flow (m); S is the average slope between the furthest point and the point of entry to the network (m/m).

2.2.2. Time of concentration. It is understood as the sum of the time of entry and the time of travel in the collector. For this case, it is equal to the entry time because there is no collector. The minimum time of concentration (T_c) in initial wells is 10 minutes and maximum 20 minutes.

2.2.3. Intensity design. It is the average rate of rainfall in millimeters per hour for a drainage area. The intensity is selected from the duration of the design rainfall (D) and the return period, see Equation (4) obtained from [2].

$$I = \frac{P^t_{Tr}}{D}, \quad (4)$$

where I is the intensity of design rain (mm/h); P^t_{Tr} is the design precipitation (mm); D is the design duration (h)

2.2.4. Design flow rate. It is the flow of surface runoff defined according to the rational method, applicable to drainage areas smaller than 80 ha, see Equation (5) obtained from [2].

$$Q=2.78 * C * I * A, \quad (5)$$

where Q is the design flow rate (L/s); C is the runoff coefficient (dimensionless); I, is the design rainfall intensity (mm/h); A is the basin area (Ha); 2.78 is the conversion factor. Moreover, tie-line power was developed to verify that the conditions of minimum depth to key are met, the calculation of the energy, key and tray levels must be performed, ensuring that no backwaters are generated for subcritical regime. This section was developed taking into account the provisions of [8]. The equations of the Empresas Públicas de Medellín (EPM), Colombia, design standard [9] were used to determine the falls in the wells, since minor falls are obtained and it is not necessary to handle special joint structures, compared to the equations established in the technical regulations of the potable water and basic sanitation sector about the EPM's sewer system design standards.

Finally, modeling was executed in the environmental protection agency's storm water management model software. As a first step, initial data were defined for each of the elements that make up the model in order to facilitate data entry, taking into account the EPA SWMM user manual [10]. Later, using the drawing tools, each of the elements that make up the project were elaborated until the final model was obtained. Finally, the simulation of each of the study areas (high, medium and low slope) was carried out. The modeling in EPA SWMM was carried out in a similar way to the one developed in [11], in which the topology of the network was taken into account, involving elements such as wells, diameters, lengths of sections, slopes, flows, among others.

3. Results

The results obtained from the research are presented below, in three sections: the optimization of the storm drainage network, the modeling with the software and the cost analysis made both to the initial design and to the optimized one.

3.1. Optimization of the storm drainage network

The optimization of the sewerage was carried out from the hydrogram generated in the final section of each simulation model. First, the peak flow was taken, and it was reduced to a percentage which should guarantee that the time between these two does not exceed 20 minutes. For the 3 study zones, a reduction percentage of 30% was established, taking into account that the overload time for discharge 1 was 11 minutes for the high slope (Figure 1), 12 minutes for the medium slope (Figure 2) and 13 minutes for the low slope (Figure 3), as shown below, fulfilling in all cases with the required time.

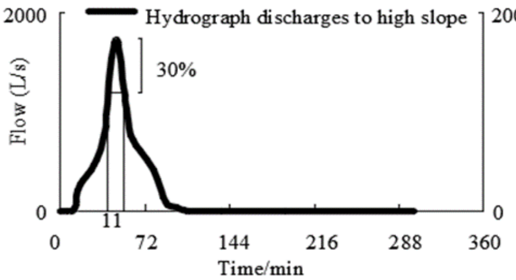

Figure 1. Unit hydrograph discharges 1 high slope.

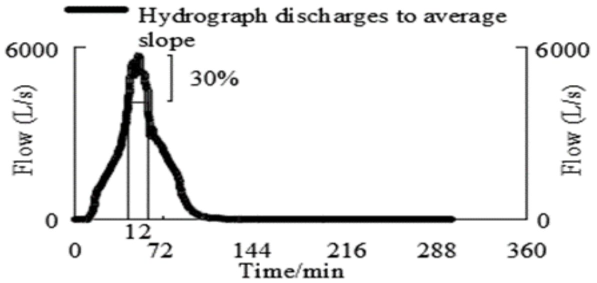

Figure 2. Unit hydrograph discharges 1 average slope.

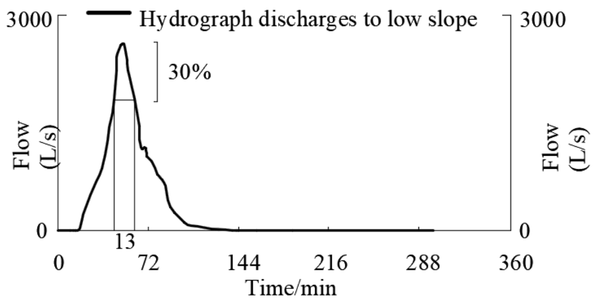

Figure 3. Low-slope discharge 1-unit hydrograph.

3.2. Modeling with software

Once the reduction percentages for each section in the different scenarios were defined, the collectors were again sized with the objective of reducing their diameter to make the system work at its maximum capacity. Subsequently, the design is modeled again in gradually varied flow by EPA SWMM in order to examine the water level for the peak flow, giving profiles that correspond to the most representative sections of each area, see Figure 4, Figure 5, and Figure 6, as it was done in the study [12], which developed the iteration of the possible height of the water sheet, identifying the contours that achieve flooding.

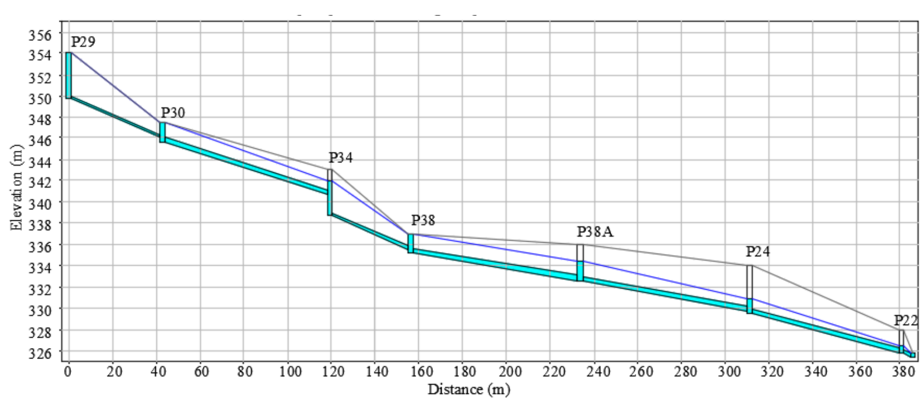

Figure 4. Water sheet level at 48 minutes of precipitation started - high slope.

The patterns obtained show that in Figure 4, well P29 is working at maximum capacity for 13.2 minutes, and well P38 for 19.2 minutes. Furthermore, Figure 5 shows that for the section P2-Channel, wells P2 and P1 are working at maximum capacity for 7.2 and 7.8 minutes respectively. Finally, Figure 6 shows that for the section P6-Channel 1, well P6 works at maximum capacity for 8.40 minutes. Based on the above, it can be indicated that the water sheets do not reach the maximum height of the well, which in turn determines that there are pipes working at maximum capacity, which does not mean that there is a risk of flooding in the surrounding streets.

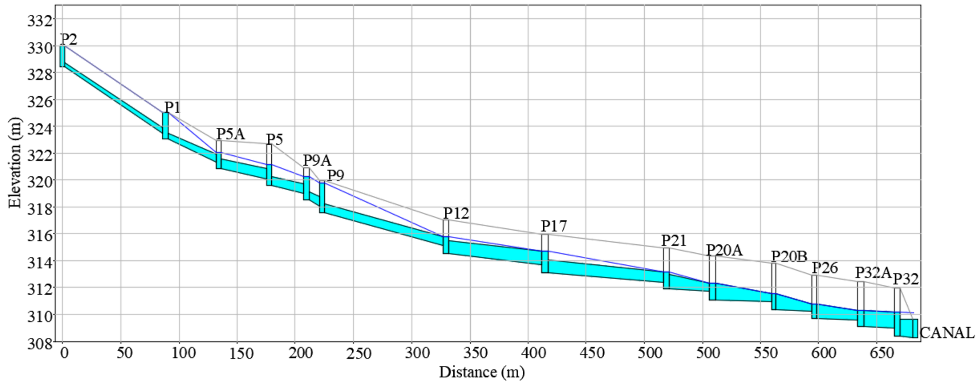

Figure 5. Water sheet level at 48 minutes after precipitation started - average slope.

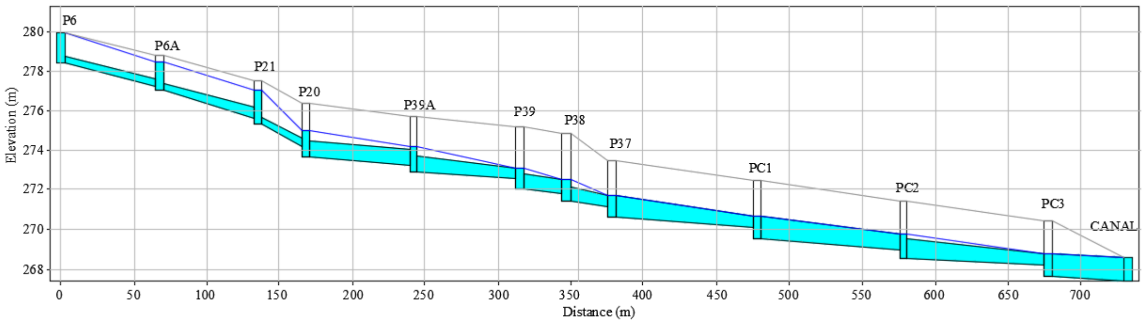

Figure 6. Water sheet level 54 minutes after precipitation started - low slope.

3.3. Cost analysis

The budget was made both for the traditional design and for the optimized one in the 3 study areas. Tables 1, Table 2, and Table 3 show the difference in costs for each zone. For the high slope, the optimization represents a saving of $ 96876058, which corresponds to 17.8%. On the other hand, for the medium slope zone, the budget has a reduction of $ 350140666, equivalent to 22.4% and in the low slope zone the reduction was $ 604325382, equivalent to 24.6%. Analyzing the results of the costs obtained, it is observed that the optimized design is the most appropriate to apply in the 3 defined study areas.

Table 1. Cost variation - high slope.

Activity	Design	Optimized	Difference
PVC pipe	$ 386232359	$ 324317218	$ 61915141
Fill in	$ 79784829	$ 62612244	$ 17172584
Inspection wells	$ 42433565	$ 33252656	$ 9180909
Earth moving	$ 34230175	$ 25622751	$ 8607424
Total	$ 542680927	$ 445804869	$ 96876058

Table 2. Cost variation - average slope.

Activity	Design	Optimized	Difference
PVC pipe	$ 1403103857	$ 1067614708	$ 335489149
Fill in	$ 83929060	$ 74370149	$ 9558911
Earth moving	$ 35648964	$ 31256737	$ 4392228
Inspection wells	$ 37251502	$ 36551124	$ 700378
Total	$ 1559933383	$ 1209792717	$ 350140666

Table 3. Cost variation - low slope.

Activity	Design	Optimized	Difference
PVC Pipe	$ 2331240048	$ 1738399269	$ 592840779
Earth moving	$ 63282878	$ 57456381	$ 5826496
Inspection wells	$ 57617853	$ 52200695	$ 5417158
Fill in	$ 3072602	$ 2831653	$ 240949
Total	$ 2455213380	$ 1850887998	$ 604325382

4. Conclusions

The EPA SWMM modeling of each of the designs was done observing the behavior of the system in unsteady flow, even though the design met the requirements established by Colombian standards, collectors were found to be working partially full, which meant that the dimensions could be adjusted to improve their efficiency.

Once the hydrographs obtained from the design were analyzed, it was estimated that there was a 30% reduction in the peak flow rate at the general level of the sewerage system, which was reflected in a considerable reduction in diameters and therefore an increase in the ratio and/or the collectors. When analyzing the optimized system in the software, it was found that there were wells that reached the limit of their capacity, but this did not imply a risk of flooding since their duration was analyzed and these were less than 20 minutes as initially established. With the initial and optimized designs, the cost structure for the different conditions was elaborated giving a saving of 17.8% in the high slope, 22% in the medium slope and 24.6% in the low slope, mainly in activities such as excavation and pipe diameters.

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