SUDS TREATMENT TRAIN MODELING USING SWMM

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ABSTRACT

Sustainable drainage systems (SuDS) promote sustainable cities and communities by reducing problems related to urban stormwater management. A SuDS treatment train (SuTT) sequentially combines several SuDS typologies reducing stormwater quantity while improving runoff water quality. In this study, the Storm Water Management Model (SWMM) is used to model a SuTT located in Bogotá (Colombia). The model considers the hydrological, hydraulic and water quality performance of the experimental setup. The SuTT consists of a vegetated swale and an extended dry detention basin. Geographic information systems (GIS), remote sensing (RS) products, and experimental data from the SuTT are used to configure the SWMM model. Simulation results indicate that the input parameters derived from the GIS and RS products processing produced a good set of input parameters for the hydrologic model. SWMM is able to represent the SuTT inflow hydrograph nicely. However, the SuTT outflow hydrographs still need further fine-tuning or calibration in the hydraulics parameters. SWMM can reproduce the attenuation effect of the SuTT when hydraulic elements (i.e. links and nodes) are used to represent the SUDS typologies. The configured SWMM model, without any calibration process, is capable of representing the hydrologic model and to some extent the hydraulic model of the experimental SuTT. On the other hand, the water quality model needs further assessment on the washoff and buildup equations coefficients to adjust coefficient values that may represent the conditions of the land uses at the study area.

Keywords: SWMM, SuDS treatment train, hydrologic, hydraulic and water quality modeling.

1 INTRODUCTION

The urbanization process has increased the amount of impermeable surfaces in urban areas and has decreased the infiltration capacity of the soil. Consequently, higher surface runoff volume is produced increasing the flooding issues on urban areas where the hydraulic sewerage system capacity can be exceeded (Tabach et al., 2008). Sustainable drainage systems (SuDS) are currently used to face stormwater issues related to the runoff quantity and quality that drains to rivers and other receiving water bodies or the sewerage system (León, 2015). However, the design process of this structures is challenging given the land cover complexity of urban areas. The design and planning process of SuDS in urban areas may be improved by using geographic information systems (GIS) and remote sensing (RS) products to obtain input parameters for integrated mathematical models that represent the dynamics of these nature-based solutions.

During the last decades, GIS processing and remote sensing products have been extensively used to extract lands surface or drainage area characteristics, commonly used as input parameters for hydrologic models (Gangodagamage and Agrarwal, 2001). Typically, sub-catchment area, slope, and subcatchment geometric description are derived from a digital elevation model (DEM), while imperviousness is obtained from a land cover map (Gaurav et al., 2015). There are several studies that show how hydrologic models are developed to assess SuDS structures by deriving parameters such as directly connected impervious area, subcatchment width and slope from GIS and RS processing (Vojtek and Vojteková, 2016; Shen and Zhang, 2015; Mancipe *et al.*, 2014).

The Stormwater Management Model (SWMM) is used in this research to simulate the runoff quantity and quality of an urban area draining to a SuDS treatment train (SuTT). SWMM is widely used for planning, analysis, and design of urban drainage systems and SuDS (EPA, 2017). SWMM has capabilities to simulate hydrologic, hydraulic, and water quality processes in SuDS. However, most of the studies developed in SWMM heavily focus on either hydraulic modeling (Kang et al, 2015) or hydrologic/water quality modeling of SUDS (Maharjan et al., 2017). Few studies analyze the combined hydrological, hydraulic and water quality performance of SuDS typologies or SuTT in SWMM (Cambez et al., 2008). In this study, the SWMM model is implemented using GIS and RS products to simulate a SuTT of an experimental setup located in Bogotá, Colombia.

2 MATERIALS AND METHODS

2.1 Description of the experimental SuTT and its study area

Bogotá is the capital of Colombia with a tropical weather (no seasons) and highly influenced by El Niño-Southern Oscillation (ENSO) phenomenon. The average monthly temperature fluctuates between 6 and 19 °C. Total annual rainfall in Bogotá ranges between 535 mm and 1368 mm, and average monthly rainfall varies from 16.4 mm to 209 mm. Bogotá has 200 water bodies such as rivers, streams and channels.

In 2013, the metropolitan water utility of Bogotá (EAB) and the local environmental authority (SDA) recognized the importance of using SuDS to improve water quality that drains to the urban water bodies and to prevent flooding issues in the city. A SuTT was constructed in 2017 on a strategic area at the San Cristobal Sur Metropolitan Park (Jiménez et al, 2019) steaming from a research collaboration between the EAB, the SDA, and the Universidad de los Andes (Universidad de los Andes, 2015).

The constructed SuTT consists of a vegetated swale with a drainage area of 1.48 Ha, surface width of 2.80 m and length of 70 m and a dry extended detention basin with a drainage area of 1.56 Ha, mean surface width of 16.33 m and length of 49 m. The vegetated swale pretends to partially decrease runoff volumes and convey the runoff to the dry extended detention basin where the runoff volume is temporarily detained/retained. The water quality of the runoff is improved throughout the two SuDS typologies. For the SuTT there is available hydraulic design characteristics, topography and soil characteristics (i.e. Infiltration capacity, soil types, land uses). Rainfall, flow and water quality observed data is obtained from three monitoring campaigns between May 2007 to May 2018 carried out by the Universidad de los Andes and EAB (Giraldo et al, 2019).

2.1.1 Rainfall data

During the three monitoring campaigns, 14 events were registered and monitored. The rainfall data was measured by pluviometers located within the park. Table 1 shows a summary of the five storms events selected for this study (Ramirez, 2018). These storm events are selected because they registered consistent flow and water quality data for comparing purposes with the SWMM model results. Each event is configured in SWMM as a time series with 1-minute time interval.

	Table 1. Rainfall data for the SWMM model							
Event	Date (M/D/Y)	Initial time	Ending time	Total precipitation (mm)	Duration (min)	Antecedent dry period (hours)		
1	11/09/2017	14:50	15:40	4.7	60	19.33		
2	11/23/2017	14:31	14:53	2.0	16	70.45		
3	12/01/2017	13:20	14:10	4.8	50	19.20		
4	04/10/2018	13:44	15:38	4.4	115	7.97		
5	04/13/2018	13:29	14:00	1.6	32	20.62		

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2.1.2 Observed flow and water quality data

Observed flows and water quality data were measured in two control points at the inlet and outlet of the SuTT (see Figure 1). The observed flows are measured by an electronic device and verified by volumetric measurements during each storm event. The observed hydrographs at the SuTT inlet point present high peaks at the beginning of the storm event that decreases over time. In contrast, at the SuTT outlet the hydrograph has an attenuated peak flow as expected (Ramirez, 2018).



Figure 1. SuTT of the San Cristobal Sur Park

A flow weighted composite sample is obtained from each event at a constant time interval to determine the event mean concentration (EMC) for total suspended solids (TSS), total solids (TS), metals, BOD₅, COD, Total Organic Carbon (TOC), Total Coliforms and E. Coli. The composite sample was storage on individual bottles and taken for analysis to the EAB laboratory (Ramirez, 2018). For the SWMM model, only total suspended solids (TSS) are considered at the inlet and outlet of the SuTT. Eq. 1 is used to calculate the simulated EMC.

$$EMC = \frac{\sum_{i=1}^{n} V_i^{*C_i}}{\sum_{i=1}^{n} V_i}$$
[1]

where,

 V_i is the discharge amount corresponding to each time interval of the hydrograph, C_i is the pollutant concentration for each time interval and n is the total time-interval volumes. Table 2 shows the summary of observed water quality data for the five storm events selected.

Table 2. TSS EMC measured at the SuTT							
	Date (M/D/Y) Inlet (mg/L) Outlet (mg/						
Storm event							
1	11/09/2017	320	267				
2	11/23/2017	593	192				
3	12/01/2017	786	163				
4	04/10/2018	368	155				
5	04/13/2018	117	74				

2.2 Model configuration

2.2.1 Hydrological model

The required input parameters for the hydrologic model in SWMM are obtained from a DEM and an orthophotography of the study area using GIS processing. The DEM is reconditioned using streets and the drainage system in order obtain the urban drainage areas and their characteristics (e.g. Area –A-, width –W-, slope –S-) through a conventional drainage area delineation process. The orthophotograph is classified with a maximum likelihood method in ArcGIS to obtain the percentage of impervious area for each subcatchment. Parameters such as manning values for impervious and previous areas, surface depression storage, surface roughness, and infiltration data are taken from bibliography references and experimental results from previous studies of the Universidad de los Andes (Universidad de los Andes, 2017).

2.2.2. Hydraulic model

A low impact development (LID) module is available on SWMM to represent SuDS typologies. However, SWMM hydraulic elements (storage units, conduits, junctions, etc.) are used instead of the LID control module elements to include water quality expressions associated to pollutant removal at each SUDS typology.

The hydraulic model is configured in SWMM based on the geometric attributes (i.e. pipes, drainage points, etc.) registered in the design memories of the SuTT implemented. The vegetative swale is represented as a trapezoidal open conduit with 0.45 m maximum depth and 70 m long. Roughness is assumed as 0.045 and a 4.97 mm/h seepage (Universidad de los Andes, 2017). The pre-treatment chamber and the detention dry pond are both represented as storage units with known depth-area curves. An initial depth is setup for the detention dry pond to simulate the permanent water level retained by the water quality control volume.

2.2.3. Water quality model

In this study only the TSS are simulated in SWMM for simplicity of the assessment. The water quality model includes two sections: a hydrological pollutant model (i.e. initial TSS rain concentration, TSS buildup, and TSS washoff) and a hydraulic pollutant model (i.e. TSS removal). A concentration of 9 mg/l of TSS is set as the rain concentration based on reported data from Universidad de los Andes, (2017). Eq. [2] shows the exponential buildup used for TSS buildup process.

$$B = C_1 (1 - e^{-C_2 * t})$$
[2]

where,

B is the pollutant buildup mass per unit of subcatchment area (kg/ha); *C1* is the maximum buildup possible (kg/ha); *C2* is the buildup rate constant (1/days); and *t* is the time (days) (Cambez et al., 2008). Event mean concentration model is used to model TSS washoff. SWMM requires a land use definition for each

subcatchment. Two different land uses are defined for the study area: high-density residential areas and low-density residential areas. Table 3 indicates the buildup and washoff properties defined in SWMM (EPA, 2009).

Table 3. Buildup and washoff properties							
Properties	High-density residential areas	Low-density residential areas					
Build-up							
Max. Buildup	0.16	0.19					
Rate constant	0.5	0.5					
Normalizer	Curb length	Curb length					
Washoff							
EMC	160	200					

Although, there are several expressions used to simulate pollutant removal in SuDS, for this research the TSS removal is simulated by an equation taken from Crites et al, (2010) and configured on the storage unit treatment editor of the extended dry detention basin (see Eq. 3).

$$C = \frac{TSS}{(1+0.001*HRT)}$$
[3]

where,

C is the outlet concentration; TSS is the initial concentration of the TSS pollutant, and HRT is the hydraulic residence time.

2.3 Model efficiency indexes

The simulations results are compared with the observed data at the inlet/outlet control points to assess the model performance. The Nash-Sutcliffe (NS), relative volume error (RVE) and relative mean square error (RMSE) index are used in this study.

2.3.1 Nash Sutcliffe (NS)

This index evaluates if the shape of the observed hydrograph is similar to the simulated one (Moriasi, 2007). The NS is defined by Eq.4.

$$NS = 1 - \left[\frac{\sum_{i=1}^{n} (Q_i \text{ observed } -Q_i \text{ simulated})^2}{\sum_{i=1}^{n} (Q_i \text{ observed } -\bar{Q}_i \text{ simulated})^2}\right]$$
[4]

where,

n is the number of time-interval flows and Q is the flow value for each time-interval. When the NS value is near to 1, the observed hydrograph similar to the simulated hydrograph.

2.3.2 Relative volume error (RVE)

This index evaluates the volume errors between the observed and simulated hydrograph. When the RVE is near to 0, the observed volume is similar to the simulated volume (Adams and Pagano, 2016). The RVE is defined as Eq.5.

$$RVE (\%) = \left[\frac{\sum_{i=1}^{n} [V_{observed}(i) - V_{simulated}(i)]}{\sum_{i=1}^{n} V_{observed}(i)}\right] * 100$$
[5]

where,

n is the number time-interval flows and *V* is the volume for each time-interval.

2.3.3 Root mean squared error (RMSE)

This index indicates the absolute fit of the simulated data and how close are the observed data. It measured how far off an observed value is from the simulated value. The RMSE is calculated with Eq. 6 (Crespo and Tenelanda, 2014).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (Q_{i \ observed} - Q_{i \ simulated})^{2}}{n}}$$
[6]

where,

n is the number time-interval flows and *Q* is the flow value for each time-interval.

3 RESULTS AND DISCUSSIONS

3.1 SWMM model configuration

Figure 2 depicts the drainage areas obtained from the GIS processing of the reconditioned DEM and the orthophotograph. The reconditioning process of the DEM was found as a critical step to obtain the necessary level of discretization for the study area. If the DEM is not reconditioned with streets and the drainage system, the drainage area delineation process tends to generate only one drainage area, imposing additional work to stablish the actual area draining to the SuTT. Further field verification allowed identify four subcatchments as the areas that actually drain to the SuTT (see outlined red polygons in Figure 2). The total drainage area for the SuTT is 0.8 Ha lower that the drainage area used on the SuTT design (e.g. the vegetated swale with a drainage area of 1.48 Ha and the dry extended detention basin with a drainage area of 1.56 Ha). Table 4 summarizes these subcatchments characteristics. Total drainage area

Table 4.Subcatchment characteristics.							
Subcatchment	Area (ha)	Width (m)	%Slope	%Impervious			
2	0.399	25.87	2.04	24.90			
3	0.086	194.15	4.49	4.97			
6	0.237	58.52	2.46	23.00			
7	0.078	26.39	5.30	27.00			
Area total	0.8						



Figure 2. Resulting subcatchments from the DEM drainage area delineation process

3.2 SWMM hydrologic and hydraulic model results

Table 5 shows the efficiency indexes calculated for each storm event at the inlet/outlet control points. Although, there is not a calibration and validation process, the model tends to represent nicely the SuTT inflow hydrographs. Four out of five storm events obtained a good representation of the peak-flow and shape at the SuTT inlet hydrographs with high NS and low RMSE indexes. This means that the GIS and RS products processing produce a good set of input parameters for the hydrologic model. However, SWMM fails to represent the volume and peak-flow for most of the SuTT outlet hydrographs with the model configuration used. This means that further tuning or calibration of hydraulics parameters may be needed in the model.

On the other hand, the RVE index shows that the model tends to underestimate the runoff volume for most of the storm events with percentages lower than 20%, acceptable according to Adams and Pagano (2016). Overall, the configured SWMM model, without any calibration process, is capable of representing the hydrologic model and to some extent the hydraulic model of the experimental SuTT.

Table 5. Model efficien	cy indexes for each event
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Event	Control point	NS	RVE	RMSE
1	Inlet	0,84	-15,01	1,17
	Outlet	0,11	-15,62	0,13
2	Inlet	0,70	-44,19	0,67
	Outlet	0,08	-35,64	0,13
3	Inlet	0,36	-26,54	1,18
	Outlet	0,45	2,59	0,11
4	Inlet	-1,00	24,67	0,60
	Outlet	-1,68	-21,49	0,36

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Event	Control point	NS	RVE	RMSE
5	Inlet	0,53	-1,26	0,35
	Outlet	-876,43	411,83	0,13

Figure 3 shows the observed and simulated hydrographs for the studied storm events. It can be observed how remarkable the model simulates the inflow and outflow hydrographs, despite the mathematical differences shown by the efficiency indexes. The configured model nicely simulates the attenuation effect produced by the SuTT. Using hydraulic elements to represent the SUDS typologies within SWMM allowed the model to reproduce the attenuation effect observed from the experimental SuTT.





3.3 SWMM water quality model performance

Given that the observed TSS pollutograph is not available, the EMC for each storm event was calculated using Eq.1. Table 6 summarizes the simulated and observed EMC results. Even though, considerably differences can be observed between the simulated and the observed EMC, is important to notice that the observed EMC values are higher than the typical EMC for residential land uses (i.e 101 mg/L) (EPA, 2005). An

exception to this trend can be observed for small storm events (i.e. storm event 5). A surcharging node in the sewer network may be contributing wastewater to the inlet of the SuTT for big storm events. However further field monitoring is being carried out to confirm this presumption which may allow to improve the EMC values used for the simulations.

Table 6. TSS EMC for each event								
Storm Event	Date (M/D/Y)	Total precipitation (mm)	Duration (min)	Observed- Inlet (mg/L)	Simulated -Inlet (mg/L)	Observed- Outlet (mg/L)	Simulated -Outlet (mg/L)	
1	11/09/2017	4.7	60	320	23.42	267	2.84	
2	11/23/2017	2	16	593	8.63	192	0.41	
3	12/01/2017	4.8	50	786	23.73	163	2.07	
4	04/10/2018	4.4	115	368	8.87	155	0.52	
5	04/13/2018	1.6	32	117	10.78	74	0.02	





Figure 4 presents the simulated pollutographs at the inlet/outlet control points. The pollutographs from the events 2 and 4 (see Figure 4b and 4d) represent storm events where apparently there is no TSS contribution to the SuTT from the subcatchments and only comes from the rain concentration. From Table 6 and Figure 4 can be observed that EMC values for the inlet control point seem to low and quite close to the TSS rain concentration. Therefore, further assessment on the washoff and buildup equations is needed to adjust coefficient values that may represent the conditions of the land uses. The treatment equation used on this research was not the appropriated for the detention dry pond, a detailed analysis using different TSS removal equations is currently ongoing.

4 CONCLUSIONS

Simulation results demonstrate that SWMM is able to represent the hydrologic and hydraulic performance of the experimental SuTT when hydraulics elements are used to represent SUDS typologies. However, a calibration/validation process is recommended to improve the representation of the outlet control point at the SuTT.

The GIS and RS products processing produce a good set of input parameters for the hydrologic model whereas the DEM reconditioning step using streets and the drainage system certainly improved the hydrological model discretization for an urban area.

Water quality simulations in SWMM requires further analysis and possibly field measurements to obtain a good EMC estimation. An online monitoring is suggested for the experimental SuTT to evaluate the simulated and observed pollutographs.

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