UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Tecnura
https://revistas.udistrital.edu.co/ojs/index.php/Tecnura/issue/view/1108
DOI: https://doi.org/10.14483/22487638.17575

ESTUDIO DE CASO

Urban Drainage Water Quality Modeling on the SWMM Software, Northeastern Sector, Santa Inés District, Tunja

Modelación de calidad de agua del drenaje urbano en el software SWMM, sector nororiental, Santa Inés, Tunja

Melquisedec Cortés-Zambrano[1], Mónica Yineth Lara-Pérez[2], Iván Darío Acosta-Sabogal[3]

Fecha de Recepción: 09 de febrero de 2021 **Fecha de Aceptación**: 07 de febrero de 2022

Cómo citar: Cortés-Zambrano., M. Lara-Pérez., M.Y. y Acosta-Sabogal., I.D. (2022) Urban Drainage Water Quality Modeling on the SWMM Software, Northeastern Sector, Santa Inés District, Tunja. *Tecnura*, **26**(72), 167-184. https://doi.org/10.14483/22487638.17575

Abstract

Objective: This research aimed to design a drainage quality hydrodynamic model of the northeastern sector of Tunja (Santa Inés neighborhood), Boyacá, Colombia, which was validated and calibrated by means of the mean square error method, where a comparison between the values observed in the field and the simulation results in the model was determined in order to observe and analyze the effect of precipitation on pollutants before entering the treatment plant.
Methodology: For this study, rainfall and water flow equipment were installed in the district. A validated and calibrated urban drainage model was created on the SWMM 5.1 software, which allowed a temporal hydrodynamic modeling of the system. In addition, samples were taken to determine the quality of the water arriving at the treatment plant and evaluate the transportation of pollutants, as well as the possibility of hydrogen sulfide generation in the study area.
Results: The results obtained with the model show that all pollutants generate drag in their concentrations. An excess of these values is observed within the total flow, which demonstrates the relevance of accumulation, washing, and transport processes, in light of the pollutant remnants causing the flow to decrease before the pollutant load.
Conclusions: Our sampling indicates that it is necessary to analyze the coliforms present in wastewater discharges, as well as the sulfate, nitrite, and nitrate values in the case of a specific discharge. The entity in charge of discharge control must be then informed.
Financing: Universidad Santo Tomas - Tunja

Keywords: sewerage, water quality, modeling, SWMM

---

[1] PhD in Materials Engineering and Science, Master's degree in Civil Engineering with an emphasis on Water Resources and Hydroinformatics, Civil engineer. Professor at the Department of Civil Engineering, Universidad Santo Tomás. Tunja, Colombia.
Email: melquisedec.cortes@usantoto.edu.co

[2] Master's degree in Civil Engineering with an emphasis on Hydro-Environment Engineering, civil engineer. Professor at the Department of Civil Engineering, Universidad Santo Tomás. Villavicencio, Colombia.
Email: monicalara@usantotomas.edu.co

[3] Specialist in Water Resources, Civil engineer. Professor at the Department od Civil Engineering, Universidad Santo Tomás. Villavicencio, Colombia.
Email: ivan.acosta@usantotomas.edu.co

Resumen

Objetivo: Esta investigación pretendió diseñar un modelo hidrodinámico de calidad de drenaje urbano del sector nororiental de Tunja (barrio Santa Inés), Boyacá, Colombia, calibrado y validado por el método del error cuadrático medio, donde se determinó una comparación entre los valores observados en campo y los resultados de la simulación en el modelo en aras de observar y analizar el efecto de la precipitación sobre los contaminantes antes de ingresar a la planta de tratamiento.
Metodología: Para el presente estudio se instalaron equipos de precipitación y flujo de agua en el distrito. Se creó un modelo de drenaje urbano validado y calibrado en el programa SWMM 5.1, que permitió obtener la modelización hidrodinámica temporal del sistema. Adicionalmente se tomaron muestras de agua en la red para conocer la calidad de agua que llega a la planta de tratamiento y evaluar el transporte de los contaminantes y la posible generación de sulfuro de hidrógeno en la red de estudio.
Resultados: Los resultados obtenidos con el modelo muestran que todos los contaminantes generan arrastre de sus concentraciones. Se observa un exceso de estos valores frente al caudal máximo, lo cual demuestra la relevancia de los procesos de acumulación, lavado y transporte, en vista de que el remanente de contaminantes es lo que ocasiona que el caudal disminuya primero que la carga contaminante. Adicional a esto se presenta un análisis en los tramos de concreto en la red para así determinar la posible generación de sulfuro de hidrogeno, como se presenta en la Tabla 7 de este documento.
Conclusiones: Nuestro muestreo indica que es necesario analizar los coliformes presentes en los vertimientos de aguas residuales, así como los valores de sulfatos, nitritos y nitratos en el caso un vertimiento puntual. Posteriormente se debe informar a la entidad encargada de control de vertimientos.
Financiamiento: Universidad Santo Tomas, Tunja, Boyacá, Colombia.

Palabras clave: alcantarillado, calidad del agua, modelado, SWMM

Table of Contents

INTRODUCTION

Nowadays, the city of Tunja is experiencing a phenomenon of occupation or alteration of the natural channels of rainwater or runoff that lead these flows to the receiving bodies, thus causing an impact on the drainage since the hydrology of the natural basins is not respected, which affects their drainage capacity. In addition, there is considerable and accelerated urban development in the city's northeastern sector, which has caused concern due to this and the continuous substitution of drainage surfaces that allow infiltration by hard and impermeable areas, causing overflows and floods that affect the citizens (Amaya-Tequia, 2019).

In a city whose aqueduct and sewerage networks are growing, it is necessary to know the operating behavior of the system. Knowing the hydraulic operation of the networks in real time is a vital tool to identify areas of conflict, vulnerabilities, and risks. Thus, it is also possible to propose prevention measures, dictate alternative solutions, optimize the functioning of the urban drainage system, prevent damage and problems in the structures, prioritize resources, meet contractual targets, and improve the citizens' quality of life (Gerencia de Planeación y Construcciones, 2017).

The over-dimensioning of the elements of a unitary urban sewerage system, even though it allows the transport of flows collected from rainfall runoff, provides a significant potential for sedimentation of wastewater solids during dry periods. This is because runoff speeds are, in many cases, inadequate to keep them in suspension. As a result, during periods without rainfall, the ducts act as reservoirs for said sediments, thus affecting water quality (Seco & Gómez-Valentín, 2011). Earlier, there was a tendency to not consider water quality aspects in the design and operation of drainage systems. This trend remains in the development of most projects (Rodríguez, 2005).

The management of pollution associated with urban runoff is a difficult problem to solve, especially considering the stochastic nature of rainfall and the hydrological regimes of some rivers (Obermann *et al.*, 2009). The natural channels of some regions have flows whose seasonal differences are significant, which makes them more sensitive to discharges from unit systems at times when the water flow provided by the spillways may be of the same order or greater than the flow rate. The assessment of urban rainwater quality is of great importance for the current approach to integrated urban drainage management. The characteristics of wastewater can be determined in different ways depending on the specific purpose. A sampling software for water characterization and quality control involves careful analysis of the samples type, the number of samples, and the parameters to be studied (Romero-Rojas, 2004).

It is important to know where and how the flows are incorporated into the network in order to be able to analyze their hydraulic behavior. For this reason, together with the Veolia Aguas de Tunja S.A. E.S.P. company, a measurement and modeling of the contaminants present in the water was carried regarding BOD (biological oxygen demand), COD (chemical oxygen demand), lead, TSS (total suspended solids), and nitrogen, with the purpose of improving rainfall drainage to avoid economic, environmental, and public health consequences as a result of climate change and its impact on the design flow of urban drainage systems (Veolia Tunja, 2017).

In addition to the above, an analysis of the possible generation of sulfides is also carried out, since one of the main causes for the deterioration of drainage systems is microbiological corrosion. An example of this is *Thiobacillus Thiooxidans*, which is also known as *Acidthiobacillus thiooxidans*, a sulfur-oxidizing organism that has been reported in sewerage systems in several countries including Mexico, the United States, Japan, Belgium, and China. The restoration costs of the concrete elements affected by microbiological corrosion represent a great investment in some countries and cities such as Germany, where it accounts for 40 % of the US$100 billion invested in wastewater infrastructure; Belgium, where it accounts for 10 % of the total expenditure; and Los Angeles, USA, where approximately US$400 million are invested. It is also estimated that the United States spends around US$25 billion annually on the maintenance of sewerage systems (Cortés & Vera, 2019). The corrosion of concrete structures is very common in the world; it is a silent phenomenon that must be addressed because of the large amount of money that is lost in performing maintenance works (Cortés & Vera, 2019).

METHODOLOGY

1. Area characterization and sampling

Topological base drainage network of the Santa Inés district (Amaya-Tequia, 2019)

Once the activities involving inspection, network cadastre, verification of the connectivity of the system, and identification of initial wells were performed, the delimitation of the Santa Inés district, as indicated in Figure 1, was carried out.

The points where the wastewater sampling was conducted are also indicated in Figure 1. These points were chosen given their location, as they are at the beginning, the middle (where a significant part of the system's water is collected), and at the end of the network.

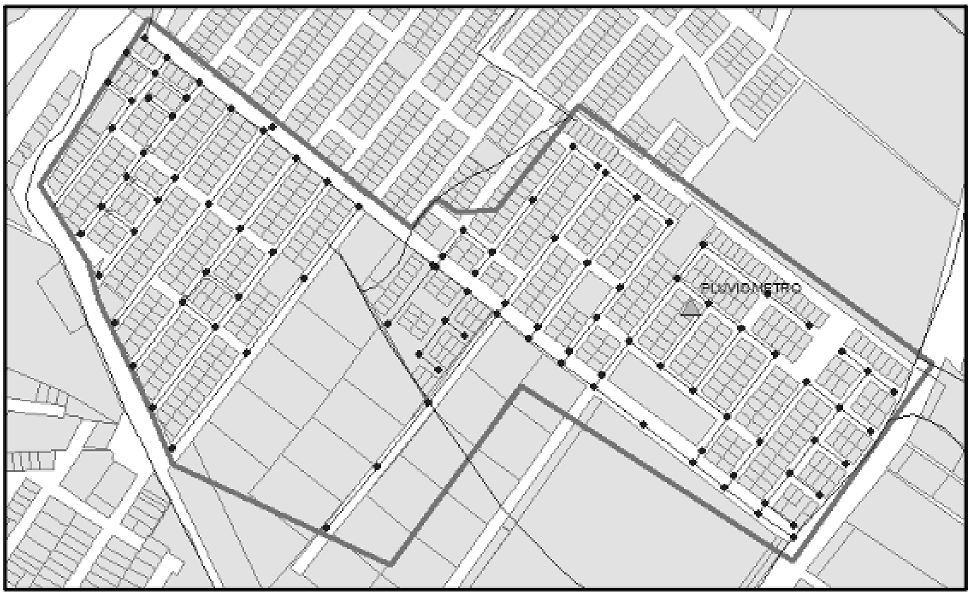


Figure 1. Urban basin of the Santa Inés drainage network

Source: Authors.

EPA modeling - SWMM (Gironás *et al.*, 2009)

SWMM's rainwater management model is a dynamic rain runoff simulation model that calculates quantity and quality mainly in urban areas. It operates in a collection of sub-catchment areas that receive precipitation and generate runoff and polluting loads. Routing transports the runoff through a pipe system, tracking its quality within each sub-uptake and the quality of the water in each pipe during a simulation period composed of multiple time steps.

This software shows how to simulate the accumulation and washing of pollutants in an urban basin. The influence of different land uses on pollutant accumulation is considered, and the average concentrations of events such as exponential functions are used to represent the washing process. The quality of surface runoff is an extremely important but very complex problem in the study of wet climate flows and their environmental impact. SWMM provides a flexible set of mathematical functions that can be calibrated to estimate the accumulation of pollutants on the Earth's surface during dry weather periods, as well as their release from runoff during storm events.

Hydrogen sulfide (U.S. Environmental Protection Agency, 1974)

Hydraulic characterization

Hydraulic characterization of sewage is necessary to determine the correlation between existing and predicted sulfur concentrations. It requires measuring the speed, flow depth, and slope of the sewer, by means of hydraulic relations. The flow rate and depth are obtained at the time of sampling of sulfides.

Speed can be measured through several methods (*e.g.*, flotation speed). The slope of the culvert can be measured on the ground or taken in the form of constructed plans. The actual hydraulic roughness coefficient (n) can be calculated using the Manning Equation (1):

$$n = \frac{1,486\ R^{2/3} S^{1/2}}{V} \tag{1}$$

where:
V: average speed ft/s
S: slope
A: hydraulic radio (ft)
N: roughness coefficient

Wastewater characterization

Parameters such as biochemical oxygen demand, pH, temperature, dissolved oxygen, and sulfate need to be controlled; their concentrations can be measured by individual or composite laboratory tests.

The daily mean sulfide concentration and pH values can be calculated by applying a correction factor (which is derived from the diurnal sulfide variation graph) to the sulfide concentrations measured in one day. Since speed is one of the determining factors in the generation of sulfides, it is feasible that all three conditions of possible sulfide generation exist in a pipe at some point within a period of 24 h. Therefore, for definition purposes, the three categories that define the sulfide generation characteristics of a pipeline are based on the average speed for the maximum flow period of 6 h.

Predictive equations

The quantitative Pomeroy and Parkhurst method for the prediction of sulfides has proven its effectiveness in studies conducted in California, Louisiana, and Texas. It was developed and is applicable only for partially filled trunk sewage culverts when conditions are favorable for sulfide accumulation. Since misleading results may be obtained under other conditions, indicators are evaluated to determine whether there is a possibility of sulfide generation before using this method.

Sulfur generation indicators

The recommended method of analysis is to evaluate the formula Z and A/B curves. If any of the indicators shows that conditions are favorable for the generation of sulfides, the Pomeroy and

Parkhurst method is used to determine if there is a real problem. If both indicators show no potential for sulfide generation, no further analysis is required.

Z formula

The first equation to express the necessary conditions for sulfide generation in gravity nets was developed in 1946. This formula did not deal with sulfide levels, but merely with whether a build-up of sulfide could occur. In 1950, Davy presented a more complete formula that related the Reynolds number, the BOD5 effectiveness, the flow cross-sectional area, and the surface width. This work was later modified by Pomeroy to develop what is known as the Z formula:

$$Z = \frac{eBOD}{S^{0,50}Q^{0,33}} \times \frac{P}{b} \tag{2}$$

Where:
Z: defined function
S: slope
$eBOD$: effective BOD5, (mg/L)
P: wet perimeter (ft)
Q: flow rate (ft^3/s)
b: width (ft)

Table 1. Interpretation of Z values

Z value	Sulfur condition
Z < 5.000	Sulphur is rarely produced
5.000 ≤ Z ≤ 10.000	Secondary condition for sulfide accumulation
Z > 10.000	Sulfur accumulation is common

Source: (U.S. Environmental Protection Agency, 1974)

RESULTS

1. Characterization

The sewerage system of the neighborhood is of combined nature since the pipe system collects and transports both waste and rainwater. The pipes are built from concrete (96 %) and PVC (4 %). The outflow well provides the right conditions for the installation of a flow meter, with a depth to level of

1,58 m. The main collector is built from concrete pipe with a diameter of 30 inches. A simultaneous monitoring of rainfall and flow during 4 months was carried out, and the representativeness of these events was executed by cross-referencing the data recorded in the measuring equipment, verifying the magnitude and time of occurrence between hydrograms and hietograms (Amaya-Tequia, 2019). Within the monitoring period (year 2018), six representative rainfall events were captured, the model of this research was implemented on July 16 th because sampling was conducted on that day, with the results shown in Table 2 and obtaining a maximum flow of 161,13 l/s.

Table 2. Rainfall events, precipitated volume, and associated return period

Event	Total rain (mm)	Rainfall volume (m^3)	Duration (min)	Intensity (mm/h)	Return period
July 16th	3,75	598,50	35	6,43	< 2 years

Source: Authors.

Sampling was carried out for 24 h in dry and rainy periods at the established points of the network. During the sampling, *in situ* parameters such as pH, temperature, and percentage of dissolved oxygen were measured, and the corresponding samples were taken to the laboratory in order to analyze the other parameters. Tables 3, 4, and 5 present the results at each of the sampling points in the study area.

Table 3. Results for point 3955

Parameter	Method	Units	Dry period	Rainy period
BOD-5	SM5210 B	mg O_2/L	315,6	96
COD	SM 5220 B	mg O_2/L	522,16	481
Chlorides	SM 4500-CL-D	mg Cl_-/L	60,69	52,0
pH	SM 4500-H-B		6,94	7,96
TSS	SM 2540-D	mg/L	132,5	86,0
Sulfates	SM 4500-SO4-E	mg S_{O4-}/L	61,90	68,9
Sulfides	SM 4500 S2-F	mg S_-/L	<4	350

Source: Authors.

Table 4. Results for point 3910

Parameter	Method	Units	Dry period	Rainy period
BOD-5	SM5210 B	mg O_2/L	372,15	267
COD	SM 5220 B	mg O_2/L	541,86	481
Chlorides	SM 4500-CL-D	mg Cl_-/L	53,55	37
pH	SM 4500-H-B		6,89	8,10
TSS	SM 2540-D	mg/L	115	85
Sulfates	SM 4500-SO4-E	mg S_{O4-}/L	44,90	63,7
Sulfides	SM 4500 S2-F	mg S_-/L	<4	294

Source: Authors.

Table 5. Results for point 4091

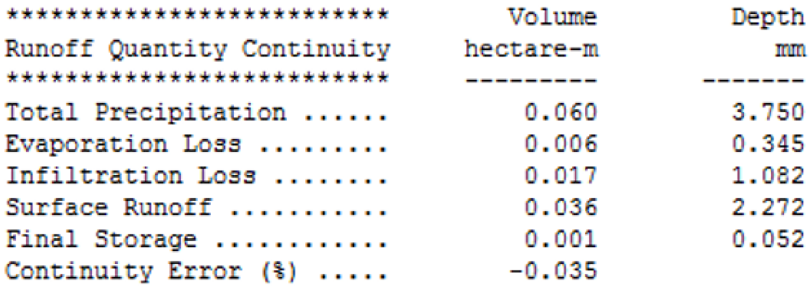
Parameter	Method	Units	Dry period	Rainy period
BOD-5	SM5210 B	mg O_2/L	365,165	321
COD	SM 5220 B	mg O_2/L	522,16	518
Chlorides	SM 4500-CL-D	mg Cl_-/L	60,69	41
pH	SM 4500-H-B		7,04	7,04
TSS	SM 2540-D	mg/L	117,5	30
Sulphates	SM 4500-SO4-E	mg S_{O4-}/L	74,05	86,9
Sulphides	SM 4500 S2-F	mg S_-/L	<4	385

Source: Authors.

2. SWMM model

To this date, there are several studies on modeling sewerage systems. It has been deduced that the spatial simplification scale influences the results of the SWMM simulation (Marcor & Pedraza, 2012). The total concentration time of the urban watershed of the study area was estimated via the Carter method at 21,60 minutes, considering the weighted average slope of sub-basins and the main length of the flow (Amaya-Tequia, 2019).

In 2012, a study was conducted with the purpose of determining specific quality patterns of the behavior of the sewerage system of a sector in Catalonia, where the unitary network was calibrated and validated with data of rainfall episodes. For ease of access, the SWMM software and the variables adopted in the simulation were tailored when performing the calibration and validation of the proposed model (Seco & Gómez-Valentín, 2011). This model treats each basin as a non-linear reservoir obtained by the continuity and the Manning equation for each sub-basin (Hogue *et al.*, 1988). Figure 2 presents the continuity of the simulated runoff in the model.

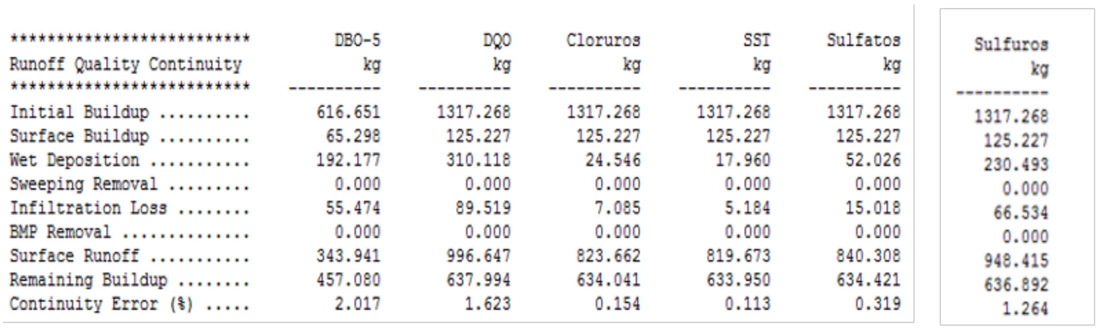


```
**************************        Volume         Depth
Runoff Quantity Continuity     hectare-m            mm
**************************     ---------       -------
Total Precipitation ......         0.060         3.750
Evaporation Loss .........         0.006         0.345
Infiltration Loss ........         0.017         1.082
Surface Runoff ...........         0.036         2.272
Final Storage ............         0.001         0.052
Continuity Error (%) .....        -0.035
```

Figure 2. Runoff continuity

Source: Authors.

Figure 3 shows the runoff quality in the continuity balance throughout the study area. Input loads are expressed as Ïnitial Buildup"prior to the start of the simulation, "Surface Buildup"during the dry period, and "Wet Deposition"pollutants in the rain. The output loads include Ïnfiltration Loss", generated by direct rain; "Surface Runoff", the pollutant load which includes a portion of accumulation; and the continuity report, indicated by Remaining Buildup".



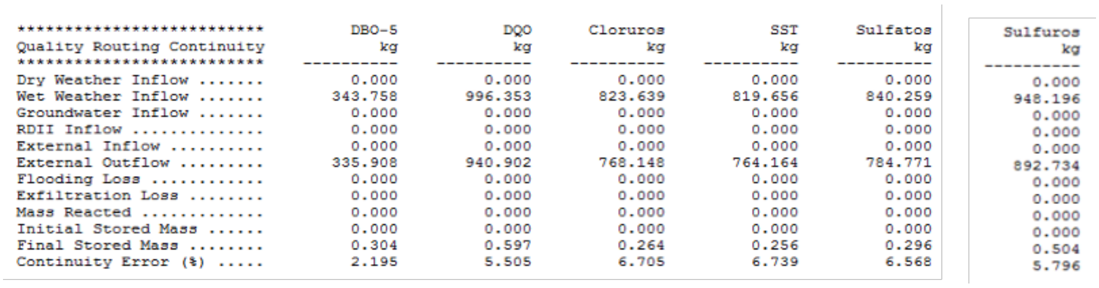
```
**************************        DBO-5          DQO     Cloruros          SST     Sulfatos
Runoff Quality Continuity            kg           kg           kg           kg           kg
**************************   ----------   ----------   ----------   ----------   ----------
Initial Buildup ..........      616.651     1317.268     1317.268     1317.268     1317.268
Surface Buildup ..........       65.298      125.227      125.227      125.227      125.227
Wet Deposition ...........      192.177      310.118       24.546       17.960       52.026
Sweeping Removal .........        0.000        0.000        0.000        0.000        0.000
Infiltration Loss ........       55.474       89.519        7.085        5.184       15.018
BMP Removal ..............        0.000        0.000        0.000        0.000        0.000
Surface Runoff ...........      343.941      996.647      823.662      819.673      840.308
Remaining Buildup ........      457.080      637.994      634.041      633.950      634.421
Continuity Error (%) .....        2.017        1.623        0.154        0.113        0.319
```

```
  Sulfuros
        kg
----------
  1317.268
   125.227
   230.493
     0.000
    66.534
     0.000
   948.415
   636.892
     1.264
```

Figure 3. Runoff quality in the study area

Source: Authors.

Figure 4 shows the quality routing. Only runoff loads through the transport system are shown. Dry weather is not shown; it is only supplied by the user through external inputs. Therefore, the three variables represented are "Wet Weather Inflow", .^{Ex}ternal Outflow", and "Final Stored Mass". The entry for wet weather is the same.

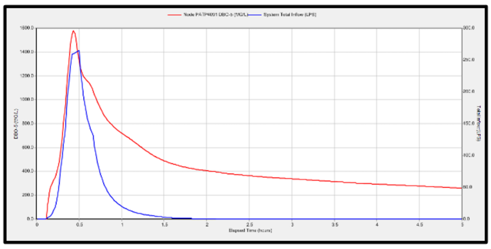


```
**************************        DBO-5          DQO     Cloruros          SST     Sulfatos      Sulfuros
Quality Routing Continuity           kg           kg           kg           kg           kg            kg
**************************   ----------   ----------   ----------   ----------   ----------    ----------
Dry Weather Inflow .......        0.000        0.000        0.000        0.000        0.000         0.000
Wet Weather Inflow .......      343.758      996.353      823.639      819.656      840.259       948.196
Groundwater Inflow .......        0.000        0.000        0.000        0.000        0.000         0.000
RDII Inflow ..............        0.000        0.000        0.000        0.000        0.000         0.000
External Inflow ..........        0.000        0.000        0.000        0.000        0.000         0.000
External Outflow .........      335.908      940.902      768.148      764.164      784.771       892.734
Flooding Loss ............        0.000        0.000        0.000        0.000        0.000         0.000
Exfiltration Loss ........        0.000        0.000        0.000        0.000        0.000         0.000
Mass Reacted .............        0.000        0.000        0.000        0.000        0.000         0.000
Initial Stored Mass ......        0.000        0.000        0.000        0.000        0.000         0.000
Final Stored Mass ........        0.304        0.597        0.264        0.256        0.296         0.504
Continuity Error (%) .....        2.195        5.505        6.705        6.739        6.568         5.796
```

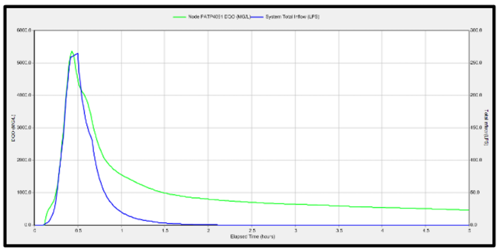
Figure 4. Routing quality

Source: Authors.

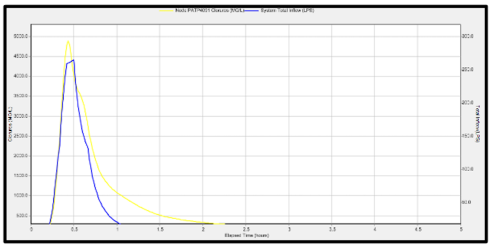
Figure 5 compares the results of the measured flow with respect to the different pollutants established in the model at the point at the outlet of the basin. For all pollutants, the concentrations exceeded the maximum flow, thus demonstrating the initial analysis in which the importance of the accumulation, washing, and transport processes was mentioned, given that it is the remains of the pollutants generated that affect the flow.



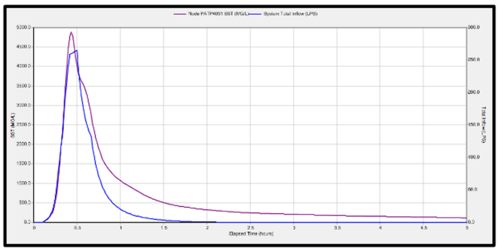
BOD$_5$ – TOTAL FLOW



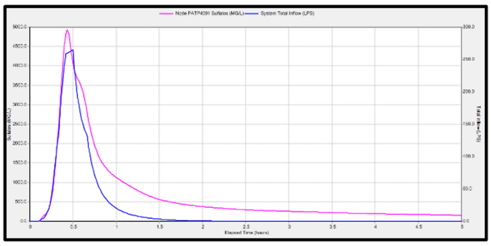
COD – TOTAL FLOW



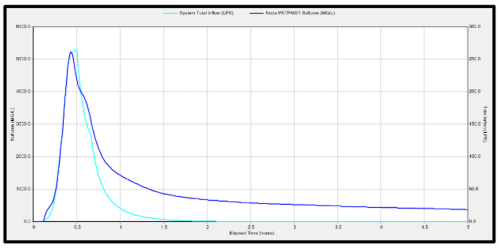
CHLORIDE– TOTAL FLOW



TSS – TOTAL FLOW



SULFATE – TOTAL FLOW



SULFUR – TOTAL FLOW

Figure 5. Behavior of pollutants and total flow during a rainfall event

Source: Authors.

Figure 6 shows the behavior of all the pollutants studied in a rainy period. It is evident that BOD5 has a lower concentration than the others and COD is the one with the highest concentration.

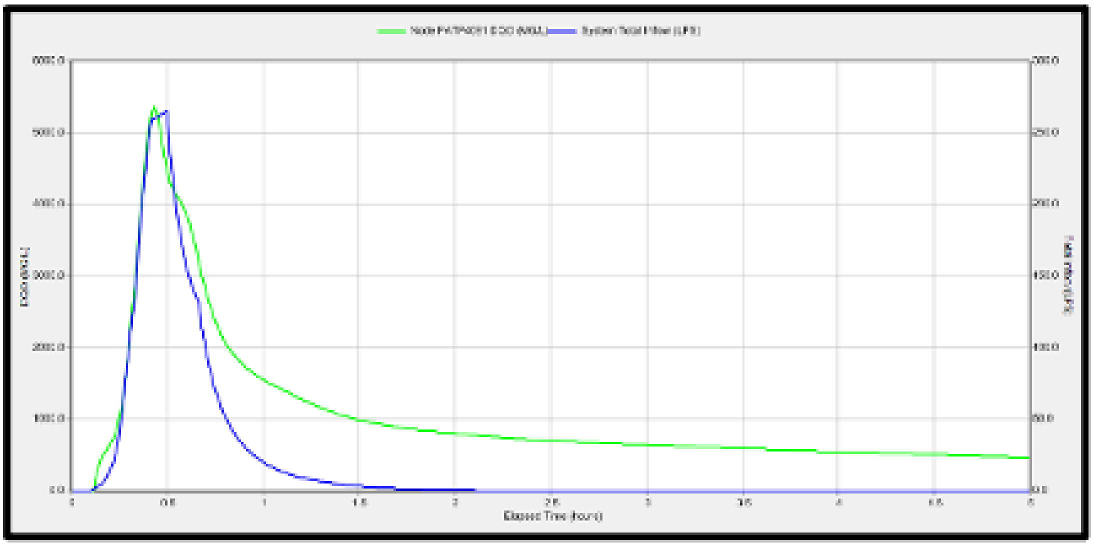


Figure 6. Comparison of pollutants evaluated in a rainfall event

Source: Authors.

2. Hydrogen sulfide prediction

Table 6 shows the results of all sections of the study area. Green indicates that sulfide is rarely produced; yellow indicates a probability that it will occur; and red shows hydrogen sulfide accumulation.

Table 6. Hydrogen sulfide production probability

Tranche	eBOD5 (mg/l)	S	Flow rate (ft3/s))	P (ft)	b (ft)	Z
PATLAL4741	2,73	0,0028	0,0074	0,85	0,772	286,948
PATLAL4742	785,70	0,0072	0,3517	1,15	1,008	14.961,449
PATLAL4743	699,03	0,0047	0,3510	1,74	1,274	19.732,557
PATLAL4744	61,98	0,0054	0,3687	2,19	1,306	1.959,816
PATLAL4745	452,33	0,0013	0,1928	1,22	1,050	25.010,071
PATLAL4746	377,38	0,0026	0,0773	1,08	0,962	19.325,388
PATLAL4747	0,00	0,0070	0,0000	0,33	0,320	0,000
PATLAL4748	0,00	0,0060	0,0000	0,00	0,035	0,000
PATLAL4749	484,43	0,0004	0,1056	1,18	1,030	55.131,607
PATLAL4750	641,96	0,0029	0,2525	0,15	1,179	2.428,179
PATLAL4751	80,70	0,0136	0,3524	1,74	1,274	1.334,034
PATLAL4752	717,51	0,0018	3,0452	3,21	2,394	15.509,457

Table 6. Hydrogen sulfide production probability

Tranche	eBOD5 (mg/l)	S	Flow rate (ft3/s))	P (ft)	b (ft)	Z
PATLAL4754	853,94	0,0012	2,7259	3,16	2,379	23.519,386
PATLAL4757	0,00	0,0050	0,0000	0,37	0,366	0,000
PATLAL4758	0,00	0,0083	0,0064	1,04	0,937	0,000
PATLAL4759	32,86	0,0029	0,0675	1,55	1,214	1.898,148
PATLAL4760	48,38	0,0046	0,2892	2,27	1,296	1.878,098
PATLAL4761	921,83	0,0017	3,9376	3,41	2,443	20.049,830
PATLAL4762	887,79	0,0006	4,0877	3,31	2,421	30.969,852
PATLAL4763	913,54	0,0000	4,3991	3,16	2,379	0,000
PATLAL4764	5,54	0,0035	0,0650	1,77	1,280	320,329
PATLAL4765	874,58	0,0032	4,5093	3,36	2,432	13.064,168
PATLAL4766	48,20	0,0021	0,2140	2,86	2,176	2.319,844
PATLAL4768	590,94	0,0042	0,1900	1,41	1,203	18.467,157
PATLAL4769	0,00	0,0039	0,0000	0,65	0,623	0,000
PATLAL4771	862,19	0,0009	4,6746	3,67	2,481	25.334,140
PATLAL4772	60,10	0,0028	0,3945	2,33	1,286	2.816,970
PATLAL4773	463,27	0,0020	0,2214	1,25	1,069	19.934,308
PATLAL4774	0,00	0,0009	0,0000	0,61	0,573	0,000
PATLAL4775	974,49	0,0066	0,2472	1,15	0,967	22.679,642
PATLAL4776	0,00	0,0053	0,0000	0,66	0,623	0,000
PATLAL4777	0,00	0,0205	0,0000	0,00	0,035	0,000
PATLAL4778	0,00	0,0025	0,0000	0,00	0,030	0,000
PATLAL4779	828,45	0,0031	0,2338	1,15	0,967	28.491,066
PATLAL4780	402,73	0,0029	0,2137	1,15	1,008	14.134,925
PATLAL4781	40,38	0,0034	0,3803	2,01	1,311	1.452,415
PATLAL4782	873,11	0,0018	4,9479	3,67	2,481	17.733,161
PATLAL4783	863,97	0,0006	5,2470	3,62	2,476	29.716,490
PATLAL4784	0,00	0,0037	0,0000	0,78	1,134	0,000
PATLAL4785	36,42	0,0037	0,3489	1,90	1,303	1.236,264
PATLAL4787	870,89	0,0027	5,5373	3,62	2,476	13.859,458
PATLAL4788	879,92	0,0015	5,7527	3,62	2,476	18.495,793
PATLAL4789	875,06	0,0018	5,7255	3,52	2,461	16.470,123
PATLAL4790	27,54	0,0073	0,2080	2,15	1,142	1.018,695
PATLAL4791	307,30	0,0012	0,2211	1,18	0,926	18.608,470
PATLAL4792	1.030,76	0,0020	0,2483	1,87	1,146	59.200,972

Table 6. Hydrogen sulfide production probability

Tranche	eBOD5 (mg/l)	S	Flow rate (ft3/s))	P (ft)	b (ft)	Z
PATLAL4794	1.267,01	0,0040	0,2444	1,33	1,053	40.473,978
PATLAL4795	0,00	0,0035	0,0000	0,70	0,657	0,000
PATLAL4796	31,83	0,0053	0,2352	1,69	1,143	1.037,811
PATLAL4797	0,00	0,0029	0,0000	0,74	0,689	0,000
PATLAL4798	0,00	0,0037	0,0000	0,00	0,035	0,000
PATLAL4799	0,00	0,0025	0,0000	0,00	0,035	0,000
PATLAL4800	0,00	0,0057	0,0000	0,00	0,035	0,000
PATLAL4801	0,00	0,0047	0,0000	0,00	0,031	0,000
PATLAL4802	0,00	0,0035	0,0000	0,00	0,035	0,000
PATLAL4803	0,00	0,0018	0,0000	0,00	0,035	0,000
PATLAL4804	0,00	0,0019	0,0000	0,70	0,657	0,000
PATLAL4805	641,97	0,0044	0,2066	1,12	0,951	19.181,969
PATLAL4806	836,67	0,0027	0,3704	1,55	1,120	31.057,307
PATLAL4807	0,00	0,0053	0,0000	0,40	0,392	0,000
PATLAL4809	22,86	0,0040	0,0346	1,16	0,917	1.379,208
PATLAL4810	57,18	0,0086	0,3931	2,04	1,125	1.518,157
PATLAL4811	925,85	0,0042	6,1080	3,26	2,408	10.606,031
PATLAL4994	70,92	0,0108	0,2617	2,01	1,311	1.627,460
PATLAL4995	501,12	0,0020	0,1208	1,31	1,105	27.077,951
PATLAL4996	105,79	0,0100	0,2850	1,98	1,310	2.424,133
PATLAL4997	654,80	0,0014	0,1649	1,49	1,191	39.640,400
PATLAL4998	1.025,13	0,0035	0,1896	1,12	0,986	33.712,539
PATLAL4999	0,00	0,0046	0,0000	0,00	0,035	0,000
PATLAL5000	0,00	0,0034	0,0000	0,00	0,035	0,000
PATLAL5001	0,00	0,0032	0,0000	0,75	0,712	0,000
PATLAL7594	40,84	0,0007	0,0046	0,66	0,623	9.346,264
PATLAL7595	0,00	0,0022	0,0000	0,46	0,450	0,000
PATLAL7596	540,94	0,0062	0,0791	0,81	0,746	17.278,768
PATLAL7597	0,00	0,0047	0,0000	0,61	0,586	0,000
PATLAL7598	1.077,87	0,0062	0,1190	0,85	0,772	30.387,260
PATLAL7599	364,71	0,0010	0,1151	1,18	1,030	27.500,090
PATLAL7600	1.070,14	0,0038	0,3535	1,34	1,121	29.416,646
PATLAL7601	434,09	0,0101	0,3496	1,28	1,087	7.212,652
PATLAL7604	0,00	0,0054	0,0000	0,81	0,746	0,000

Table 6. Hydrogen sulfide production probability

Tranche	eBOD5 (mg/l)	S	Flow rate (ft3/s))	P (ft)	b (ft)	Z
PATLAL7606	0,00	0,0044	0,0000	0,57	0,545	0,000
PATLAL7607	1.038,02	0,0018	0,0646	0,85	0,772	66.811,409
PATLAL7608	245,85	0,0024	0,0600	0,91	0,820	14.086,141
PATLAL7609	709,01	0,0051	0,2211	1,01	0,882	18.706,940
PATLAL7610	1.001,47	0,0145	0,3563	1,18	1,030	13.436,455
PATLAL7612	680,12	0,0024	0,4248	1,84	1,677	20.397,905
PATLAL7613	671,07	0,0039	0,7674	2,12	1,873	13.211,050
PATLAL7615	908,96	0,0014	1,3003	2,37	2,031	26.256,416
PATLAL7616	572,65	0,0016	1,4592	2,61	2,159	15.333,006
PATLAL7619	872,21	0,0028	2,5246	2,89	2,285	15.472,388
PATLAL7620	0,00	0,0038	0,0000	0,52	0,501	0,000
PATLAL7621	311,75	0,0014	0,0650	0,95	0,842	23.382,543
PATLAL7622	854,89	0,0026	0,2260	1,18	1,030	31.519,325
PATLAL7623	353,90	0,0019	0,2468	1,34	1,121	15.548,603
PATLAL7624	851,85	0,0040	0,7999	1,55	1,214	18.593,306
PATLAL7625	263,12	0,0081	0,8013	1,82	1,291	4.449,585
PATLAL7626	71,53	0,0042	0,0321	0,81	0,746	3.718,041
PATLAL7627	84,73	0,0033	0,0300	0,89	0,821	5.086,538
PATLAL7628	384,87	0,0016	0,1010	1,08	0,962	23.324,631
PATLAL7629	0,00	0,0073	0,0000	0,23	0,227	0,000
PATLAL7630	0,00	0,0067	0,0000	0,65	0,623	0,000
PATLAL7631	0,00	0,0087	0,0000	0,40	0,392	0,000
PATLAL7632	5,24	0,0020	0,0028	0,78	0,719	877,806
PATLAL7633	318,60	0,0018	0,1596	1,23	1,007	16.701,222
PATLAL7634	277,06	0,0015	0,3348	1,43	1,088	13.416,357
PATLAL7635	922,40	0,0006	0,2458	1,22	1,050	70.174,637
PATLAL7636	158,64	0,0140	0,2437	1,15	1,008	2.435,488
PATLAL9265	229,37	0,0039	0,0406	0,75	0,712	11.200,975
PATP4812	0,00	0,0080	0,0000	0,00	0,076	0,000

Source: Authors.

Oxygen influence on sulphur generation (Roca-Hernández, 2012)

In a sewer system that circulates by gravity, water is aerated. This process can be slow in large collectors due to the gentle slope and flow depth. The rate increases in smaller pipes, and this does not happen in pressure systems, so the oxygen is consumed in a shorter time, thus yielding a higher concentration of sulfides. Oxygen is consumed by microorganisms present in the body of water (in the biofilm of the pipes), and the rate of consumption and oxygen can vary depending on the distance that the wastewater has to travel due to the diffusion in the biologically active film of the pipe wall.

The structure of the biofilm is formed by several layers, with an aerobic and an anaerobic zone. If the former prevails, the conditions will be given for sulfate reduction to occur. The relationship between these zones is delimited by the concentration of organic matter. If the oxygen concentration in the current is close to zero, then not all the sulfide can be oxidized and passed into the current.

CONCLUSIONS

The behavior of the physicochemical and microbiological characteristics measured along the sewerage network at the three established points evidences that there is spatial uniformity in the analyzed parameters and that there is little variability in their behavior when the first wash occurs at each point. All this, considering the results indicated in Tables 3, 4, and 5.

The design of the hydrodynamic model of urban drainage quality of the northeastern sector of Tunja, Santa Inés neighborhood, was performed, calibrated, and validated via the SWMM 5.1 software based on data obtained in the field.

The implementation of the model allowed concluding that the sewerage of the city of Tunja, despite being combined, and considering the current dumping regulations in Colombia, namely Resolution 0631 of 2015 (Ministerio de Ambiente y Desarrollo Sostenible, 2015) which indicates the maximum allowable values for any type of dumping, requires prior treatment to avoid contamination in the dry period. As indicated by the rule, the maximum allowed value for suspended solids is 90 mg/L. This limit was exceeded in all three points. During the rainy period, although the value was not exceeded at the two points near the exit, it was very close to the limit: 85 and 86 mg/L, respectively.

It is recommended that treatment alternatives be considered in the activated sludge process, based on the relationship between BOD and COD, since waste can be degraded through a biological process (Ramos-Velandia, 2017).

Given that the Z formula has generally been successful in predicting the occurrence of sulfide problems in gravity sewers, for our network, specifically with 96 % of the pipelines, approximately 48 % show no likelihood of sulfur generation. For pipelines that are likely to generate hydrogen sulfide, it is recommended to ensure proper aeration in order to avoid gas accumulation.

FUNDING

This work was funded by Universidad Santo Tomás (Tunja, Boyacá, Colombia).

REFERENCES

[Amaya-Tequia, 2019] Amaya-Tequia, E. (2019). *Modelización hidráulica de drenaje urbano. Aplicación sector nororiental distrito Santa Inés Tunja-Boyacá* [Undergraduate theis, Unversidad Santo Tomás]. `http://hdl.handle.net/11634/22086` ↑Ver página 168, 169, 170, 174, 175

[Cortés & Vera, 2019] Cortés, M., & Vera, E. (2019a). Durability considerations for mitigating corrosion caused by biogenic sulfuric acid in sewerage system. *Journal of Physics: Conference Series*, 1386, 012088. `http://dx.doi.org/10.1088/1742-6596/1386/1/012088` ↑Ver página 170

[Cortés & Vera, 2019] Cortés, M., & Vera, E. (2019b). Methodology for simulating the process of microbiologically induced degradation of concrete by chemical exposure of speccimens under controlled laboratory conditions. *Journal of Physics: Conference Series, 1386*, 012089. `https://doi.org/10.1088/1742-6596/1386/1/012089` ↑Ver página 170

[Cortés-Zambrano *et al.*, 2020] Cortés-Zambrano, M., Amaya-Tequia, E., & Gamba-Fernández, D. (2020). Implementation of the hydraulic modelling of urban drainage in the northeast sector, Tunja, Boyacá. *Revista Facultad de Ingeniería Universidad de Antioquia, 101*, 74-83. `https://doi.org/10.17533/udea.redin.20200798` ↑Ver página

[Gironás *et al.*, 2009] Gironás, J., Roesner, L. A., & Davis, J. (2009). *Storm Water Management Model Applications Manual.* United States Environmental Protection Agency. `http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EA7H.txt` ↑Ver página 168, 171

[Hogue *et al.*, 1988] Hogue, T. S., Gupta, H., & Sorooshian, S. (1988). *A 'user-friendly' approach to parameter estimation in hydrologic models. Journal of Hydrology, 320*(1-2), 202-217. `https://doi.org/10.1016/j.jhydrol.2005.07.009` ↑Ver página 176

[Pérez-Carmona, 2013] Pérez-Carmona, R. (2013). *Diseño y construccion de alcantarillados sanitario, pluvial y drenaje en carreteras*. Ecoe Ediciones. ↑Ver página

[Rodríguez, 2005] Rodríguez, J. (2005). *Desarrollo y aplicación de un modelo de calidad del agua del interceptor Fucha - Tunjuelos - Canoas* [Master's thesis, Universidad de los Andes]. `https://repositorio.uniandes.edu.co/bitstream/handle/1992/8998/u270910.pdf?sequence=1` ↑Ver página 169

[Romero-Rojas, 2004] Romero-Rojas, J. A. (2004). *Tratamiento de aguas residuales*. Escuela Colombiana de Ingeniería Julio Garavito. ↑Ver página 170

[Seco & Gómez-Valentín, 2011] Seco, R., & Gómez-Valentín, M. (2011). *Aplicación del modelo SWMM 5.0 para la estimación del arrastre de depósitos de sedimentos y contaminantes asociados en sistemas de* *alcantarillado unitario* [Conference presentation]. IWA Spain National Young Water Professionals Conference, Madrid, Spain. http://hdl.handle.net/2117/18111 ↑Ver página 169, 176

[Temprano & Tejero, 2002] Temprano, J., & Tejero, I. (2002). Detention storage volume for combined sewer overflow into a river. *Environmental Technology, 23*(6), 663-675. https://doi.org/10.1080/09593332308618381 ↑Ver página

[Roca-Hernández, 2012] Roca-Hernández, R. (2012). *Estudio de la eliminacion y de la prevencion de la generacion de sulfuros en redes de saneamiento* [Master's thesis, Universidad Politecnica de Cartagena]. https://www.upct.es/hidrom/publicaciones/Tesis_pfc/redes_de_saneamiento%20.pdf ↑Ver página 169, 181

[Obermann *et al.*, 2009] Obermann, M., Rosenwinkel, K., & Tournoud, M. (2009). Investigation of first flushes in a medium-sized mediterranean catchment. *Journal of Hydrology, 373*(3), 405-415. http://dx.doi.org/10.1016/j.jhydrol.2009.04.038 ↑Ver página 169

[Marcor & Pedraza, 2012] Marcor, J., & Pedraza, R. (2012). Efectos de la discretización en la simulación de la escorrentía urbana. *Ingeniería del Agua, 13*(1), 35-46. https://doi.org/10.4995/ia.2006.2882 ↑Ver página 175

[Ministerio de Ambiente y Desarrollo Sostenible, 2015] Ministerio de Ambiente y Desarrollo Sostenible (2015). *Resolución número 0631. Por la cual se establecen los parámetros y los valores límites máximos permisibles en los vertimientos puntuales a cuerpos de aguas superficiales y a los sistemas de alcantarillado público y se dictan otras disposiciones.* https://www.rds.org.co/es/recursos/resolucion-631-de-2015-parametros-vertimientos#:~:text=Por%20la%20cual%20se%20establecen,y%20se%20dictan%20otras%20disposiciones. ↑Ver página 182

[Ramos-Velandia, 2017] Ramos-Velandia, C. C. (2017). *Evaluacion de un sistema de tratamiento de lodos activados para la remocion de carga organica en las aguas residuales domesticas generadas en el colegio San Viator* [Undergraduate thesis, Universidad de América]. https://hdl.handle.net/20.500.11839/6578 ↑Ver página 182

[U.S. Environmental Protection Agency, 1974] U.S. Environmental Protection Agency. (1974). *Process Design Manual for Sulfide Control in Sanitary Sewerage Systems*. United States of America: EPA. ↑Ver página 168, 171, 173