Flooding Risk Assessment of the Sewerage Risk Management Unit 251 of Zone 2 of Bogota, Colombia

2022 Congreso Internacional de Innovación y Tendencias en Ingeniería (CONIITI) | 978-1-6654-6525-0/22/$31.00 ©2022 IEEE | DOI: 10.1109/CONIITI57704.2022.9953665

Carlos Morales
MS Civil Engineering, Universidad Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, Colombia
carlos.morales-v@mail.escuelaing.edu.co

Yuly Sánchez
Professor of Center for Environment Studies, Universidad Escuela Colombiana Julio Garavito
Bogota, Colombia
yuly.sanchez@escuelaing.edu.co

Mehrab Mehrvar
Professor, Department of Chemical Engineering
Toronto Metropolitan University
Toronto, Canada
mmehrvar@ryerson.ca

Edgar Quiñones
Professor and Director of PhD Program, Universidad de Cartagena,
Cartagena, Colombia
equinonesb@unicartagena.edu.co

German Santos
Professor and Director of MS Civil Engineering, Universidad Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, Colombia
german.santos@escuelaing.edu.co

German Acero
Professor, Department of Civil Engineering MS Program, Universidad Escuela Colombiana de Ingeniería Julio Garavito
Bogotá, Colombia
german.acero@escuelaing.edu.co

Resumen— *La lluvia en Colombia es la principal causa de inundaciones. En 2008, más de un millón de colombianos vieron afectadas sus viviendas por las dificultades para drenar el agua de lluvia a través de los sistemas de alcantarillado existentes, provocando inundaciones en la zona urbana. La Zona 2 de la Empresa de Acueductos y Alcantarillados de Bogotá y la Unidad de Gestión de Alcantarillado 251 están ubicadas en el centro oriente de la ciudad. Luego de la evaluación y diagnóstico del sistema de alcantarillado pluvial y sus redes existentes, esta región fue identificada como una zona de alta vulnerabilidad por riesgos de inundaciones. Se debe analizar y determinar el riesgo por inundaciones que sufre la población durante la temporada de lluvias.*

Palabras clave—Riesgo de Inundaciones, Alcantarillado Pluvial, Vulnerabilidad, Unidad de Gestión de Alcantarillado.

Abstract— *The rain in Colombia is the main cause of flooding. In 2008, more than one million Colombians had their homes affected by rainwater draining difficulties through the existent sewerage systems, causing floods in the urban area. Zone 2 of Aqueduct and Sewerage Company of Bogota and Sewerage Management Unit 251 are located in the center east of the city. After the evaluation and diagnosis of the storm sewer system and its existing networks, this region was identified as an area of high vulnerability due to flooding risks. The risk must be analyzed and determined due to floods suffered by the population during the rainy season.*

Keywords—Flood Risk, Pluvial Sewerage, Vulnerability, Sewer Management Unit.

I. Introduction

Currently, Bogota has several points of flooding risks, and the Aqueduct and Sewerage Company of Bogota (in Spanish EAAB-ESP) has identified the most frequent problems that occur within the hydraulic networks in these localities. The most common hydraulic and structural issues found were obstructions, loss of network capacity, breaks, and cross-connections with rainwater. Rain is the most important threatening factor leading to flooding which affects economic assets and housing. Furthermore, it makes it difficult to drain rainwater and wastewater through sewage systems.

One of the areas inspected by the EAAB-ESP for having high vulnerability due to flooding risks is Zone 2. In order to obtain a diagnosis and a flood risk assessment of the Sewer Management Unit 251 of Zone 2 of the EAAB-ESP, a two-stage methodology was implemented as follows:

Stage 1: The verification of the existing information of hydrological and hydraulic diagnostic criteria of the storm sewer networks of the UGA 251, and defining the hydraulic diagnostic criteria of the storm sewer networks of the UGA 251.

Stage 2: The verification of the hydraulic diagnosis of the storm sewer networks of the UGA 251, carried out in Stage 1, diagnosing and assessing afterward flooding risks.

II. Study Location

The storm sewer network of the Risk Management Unit 251 of Zone 2 of the EAAB-ESP, has an area of 100.17 ha and is a part of the Salitre Basin and also of the Rio Nuevo sub-basin, serving the following neighborhoods: Las Ferias, Metropolis, Bellavista Occidental, and Jose Joaquin Vargas. To delimit drain areas, the shape information of the storm sewer networks of the UGA 251 of Zone 2 of EAAB-ESP was used. A total of 79 drain areas were defined for the same number of sinks, which drain an area of 14.87 ha (Fig. 1). The simplified storm sewer network has a length of 2.17 km, distributed in 0.049 km of brick (2.27% of the network), 2.02 km of concrete (93.41% of the network), and 0.094 km of unknown material (4.33% of the network).

Fig 1. Simplified Distribution areas of UGA 251. (*Source: ArcMap 10.2.2)*

III. HYDROLOGICAL ANALYSIS

The delimitation of the drainage areas was distributed in 79 areas and the same number of sinks, which drain an area of 14.87 hectares. The diagnostic flow rates were established on the application of the rain-runoff model developed by the Soil Conservation Service (SCS), which is based on the effective precipitation of the rain design.

The Soil Conservation Service (SCS) developed a method for calculating the storm's initial abstractions, including interception, surface arrest, and infiltration quantified by a parameter known as the runoff curve number [2]. For the determination of the percentage of impermeable area, a Raster classification was carried out, using ArcGIS software, with an attached satellite picture of the city of Bogota of 2016, obtained through Web Map Service of the Special Administrative Unit of Digital Cadastral (in Spanish IDECA).

The Curve Number (CN) is a measure of the potential runoff production of the soil. This parameter was calculated in a weighted manner according to the areas of each use. A CN of 80 was adopted for permeable surfaces, whereas for impermeable surfaces, a CN of 98 was adopted, which corresponds to parking lots, roofs, and paved areas; in both cases, a soil hydrological group D was considered, which corresponds to soils that have low infiltration rates [2]. The concentration-time is the time it takes for a drop of storm runoff to travel from the hydraulically furthest point of the basin to the point of analysis and it is defined as the time of entry (See equation 1).

$$t_c(min) = t_e + t_t \qquad (1)$$

Where: tc: Time of concentration, te: Time of entrance, tt: Time of transit

The lagging time corresponds to 60% of the concentration-time (See equation 2).

$$t_{lagging}(min) = 0.6\, t_{concentration} \qquad (2)$$

Where: tl: Time of lagging, tc: Time of concentration

The entry time was estimated using Equation (3), with the velocity obtained from the Soil Conservation Service Manual [3]:

$$t = \frac{1}{60}\sum \frac{L}{V} \qquad (3)$$

Where: t = travel time (mins), L= length of the flow path (m), V= average velocity of water flow.

To get the velocity value, there are two methods depending on the area, as the Equations (4) and (5) show:

$$\text{Paved Areas:} \quad V = 6.1960\, S^{0.5} \qquad (4)$$

$$\text{Unpaved Areas:} \quad V = 4.9178\, S^{0.5} \qquad (5)$$

Where: V (m/s): velocity, S (mm/mm): Basin Average Slope

The transit time was estimated using Equation (3) from the velocity in the pipes, considering a water depth of 80% of the maximum depth for closed pipes, and provided it has the maximum capacity.

The Intensity-Duration-Frequency (IDF) curve was determined in the centroid of each of the neighborhoods. Using the IDF curves, it is possible to estimate the intensity of storms of different durations and for different return periods.

The IDF curves are described by the following expression:

$$Intensity = C_1(Duration(minutes) + X_O)^{C_2} \qquad (7)$$

Where: I(mm/h): Intensity, C1: Runoff coefficient 1, D (h): Duration, X0 (mm): Length, C2: Runoff coefficient 2.

In Equation (7), the duration corresponds to 360 minutes, which is the typical duration of the storm recommended in the NS-085 of the EAAB-ESP [2].

With the intensity value extracted from the IDF curves for the 5-year return period, the total rainfall volume to be distributed is calculated as:

$$P(mm) = I\left(\frac{mm}{h}\right) \times\ D\ (6\ hours) \qquad (8)$$

Where: P (mm/h): precipitation, I(mm/h): Intensity, D (h): Duration

The distribution of the total rainfall volume was made from the temporal distribution shown in Figure 2, which is suggested in the sewer design standard (NS-085) of the EAAB-ESP [2].

By applying the rain-runoff model developed by the Soil Conservation Service (SCS), the maximum design flow rates were estimated in accordance to the related information and the hydrological model that was employed with the HEC-HMS software, as required by current regulations. The design flow rate obtained was 5.1 m^3/s.

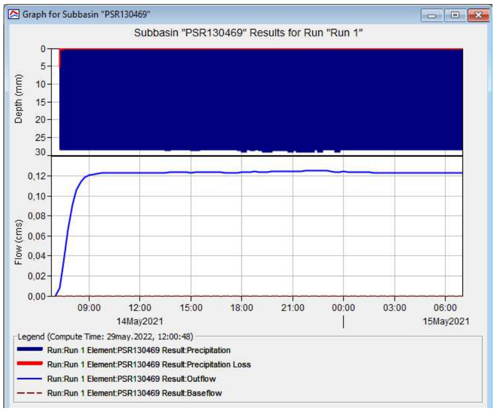

Fig. 2. Unit hydrograph of the sump PSR130469. (*Source: Hec HMS 4.6)*

IV. SIMPLIFIED RAINWATER SEWER SYSTEM

The simplified UGA 251 storm sewer network has 2.17 km of materials such as concrete, brick, and a small percentage of unknown material, as shown in Table 2 and Figure 3.

TABLE 1.SIMPLIFIED RAINWATER SEWER SYSTEM PIPE MATERIAL DISTRIBUTION OF UGA 251 SIMPLIFIED

Material	Length (m)	Length (km)	%
Unknown	93.72	0.094	4.33%
Brick	49.16	0.049	2.27%
Concrete	2023,91	2.024	93.41%
Total	2166,79	2.17	100.00%

The manholes of the simplified rainwater network have 52 sewer structures, including manholes and inspection chambers, of which 82.69% have the good physical condition and whose material is brick in its entirety.

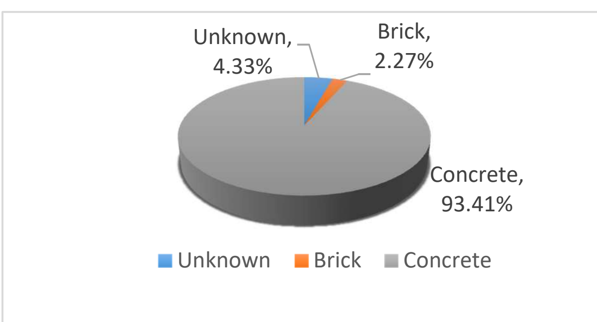

Fig. 3. Simplified Distribution of UGA 251 Pipe Materials. (*Source: Microsoft Excel 2019)*

TABLE 2.PHYSICAL STATUS OF THE MANHOLES OF THE RAINWATER NETWORK OF THE SIMPLIFIED UGA 251

Physical State	Quantity	%
Good	43	82.7%
Unknown	9	17.3%
Total	52	100.0%

V. HYDRAULIC ANALYSIS

To perform the hydraulic analysis of the network, the SewerGEMS V8i software from Bentley was used. SewerGEMS software allows to simulate the flow of a non-permanent regime and gradually varying flow conditions. The procedure consisted of first carrying out an analysis of the current operating situation of the network, taking into account the demand found in the hydrological analysis. The evaluation of the sewer network is aimed at identifying its elements that present deficiency or risk for the proper operation of the system. The hydraulic diagnosis was carried out using the real internal diameter of the pipe. Following the provision of the NS-085 Standard of the EAAB-ESP, the hydraulic parameters to evaluate are as the following [2]:

Minimum velocities: For storm sewer systems, the minimum required velocity shall guarantee a shear stress value greater than or equal to 3 N/m^2 for the design flow rate and greater than or equal to 1.5 N/m^2 for the 10% of the pipe's full capacity.

Maximum velocities: In sewer networks, maximum velocity is a function of the sensitivity to abrasion of the material that sewer network is made of. The maximum permissible values for different materials are as follows:

TABLE 3.MAXIMUM PERMISSIBLE VELOCITY IN CLOSED CONDUCTS OF THE RAINWATER SEWER SYSTEM

Material[a]	Maximum permissible velocity (m/s)
Closed ducts	
Cast in place concrete (box culvert)	5.0
Precast concrete (pipes)	6.0
PVC - PEAD	9.0
Fiberglass GRP	4.0

a. NSR 085 of EAAB-ESP

Pipe Section Dimensioning: As a design requirement and also to allow adequate aeration of rainwater, it is necessary to establish the maximum flow depth in each of the pipes. The maximum depth to diameter ratio (y/D), should be calculated with the maximum design flow.

TABLE 4.MAXIMUM (Y/D) PIPE RATIO FOR RAINWATER SEWAGE SYSTEM

Real internal diameter (mm)[a]	Maximum y/D (%)
Less than 50	70
Between 500 and 1000	80
Greater than 1000	85

a. NSR 085 of EAAB-ESP

The values shown above that relate the flow depth, with the pipe diameter, can be used for new systems, rehabilitations, and optimization of the existing systems. For box culverts, the level of the water cannot exceed 90% of the internal height.

Minimum diameters: In the rainwater system, especially in the first sections, the circular sections are the most common for collectors. The minimum nominal diameter allowed in this rainwater collection and evacuation network is 300 mm.

VI. Hydraulic Analysis Results

Shear Stress (Minimum Velocity): In this scenario, it was found that 70.59% of the modeled collectors met the appropriate shear value. Fig. 4. shows the sections with shear deficiencies identified with red legend and values lower than 3 N/m^2.

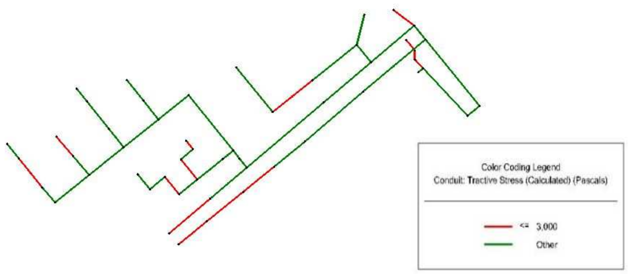

Fig. 4. Shear Stress Current Rainwater Scenario of Simplified UGA 251. (*Source: SewerGEMS V8i)*

Shear Stress for the 10% of filling capacity (Minimum Velocity): In this scenario, it was found that 70.59% of the modeled collectors met the appropriate shear value. Fig. 5. shows the sections with shear deficiencies identified with the red legend and values lower than 1.5 N/m^2.

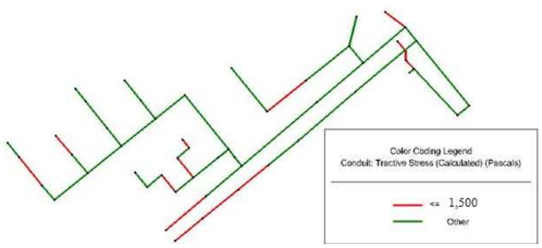

Fig. 5. Shear Stress for the 10% of the filling capacity of The Simplified UGA 251. (*Source: SewerGEMS V8i*)

Maximum (HW/D) Pipe ratio for rainwater sewage systems: In this scenario, it was found that 92.16% of the modeled collectors met the maximum filling ratio. Fig.6. shows the sections that exceed the filling ratios, identified in the legend table as zero. These sections have values greater than 70% for collectors of nominal diameter less than 500 mm, 80% for collectors of nominal diameter between 500 mm, and 1000 mm, and greater than 85% for collectors of nominal diameter higher than 1000 mm.

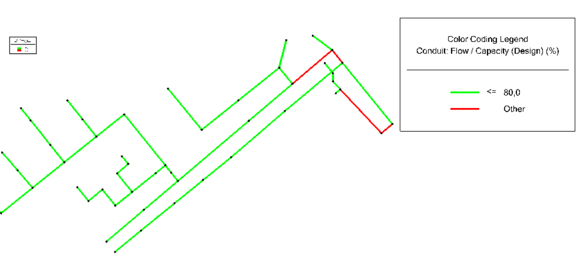

Fig. 6. Maximum (y/D) Filling Pipe Ratio for Current Rainwater Sewage Systems Scenario. (*Source: SewerGEMS V8i*)

VII. Methodology For Diagnosing -Simplified UGA 251 Flooding Risk

The risk can be manifested by the degree of damage caused by a natural phenomenon [7]. The risk manifested through the floodings and the overflows of the rainwater in the storm sewer network.

Risk management is assumed as a social process, in accordance to the provisions of the framework law about the disaster management of the country [8], which in turn has 3 statements: knowledge of risk, risk reduction, and disaster management.

Regarding the sectoral perspective of the provision of the public home services and to achieve a comprehensive approach, it is essential to take into account the evaluation of two risk approaches:

- Risk in the process of providing public home services.
- Risk generated by the effect of the provision of public home services in the city.

The risk is associated clearly with the features of danger, intensity of threat and vulnerability using the risk arithmetic method:

$$R = P \times I \times V \times E \quad (9)$$

Where: R= risk, degree of damage caused, P= Probability of occurrence of danger, I= Intensity of threat, V= Vulnerability of problem, E= Elements associated with vulnerability.

VIII. Probability Of Occurrence Of Danger From Hydraulic Analysis Results

Probability of occurrence of danger from Shear Stress (Minimum Velocity):

As shown in Fig. 7., of the local storm sewer network, 15 of 51 networks do not comply with the value of the shear stress parameter, i.e., less than 3 N/m^2.

The probability of occurrence of danger (P) from Shear Stress (Minimum Velocity) is $\frac{15}{51}$ = 0.2941, which means, 29.41%.

Fig. 7. Shear Stress (Minimum Velocity) Results. (*Source: ArcMap 10.2.2)*

Probability of occurrence of danger from Shear Stress for 10% of the full filling capacity (Minimum Velocity)

As shown in Figure 8, for shear stress of the local storm sewer network, 15 of 51 network sections do not comply with the value of the shear stress for 10% of full filling capacity, i.e., less than 1.5 N/m^2.

The probability of occurrence of danger (P) from Shear Stress for 10% of full filling capacity (Minimum Velocity) is $\frac{15}{51}=$ 0.2941, which means, 29.41 %.

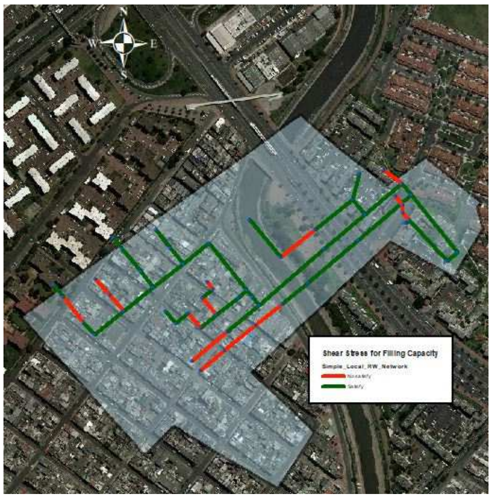

Fig. 8. Shear Stress for 10% of full filing capacity Results. (*Source: ArcMap 10.2.2)*

Probability of occurrence of danger from Maximum (HW/D) Pipe ratio for rainwater sewage systems

As shown in Fig. 9., from the local storm sewer network, 4 of 51 network sections do not comply with the filling ratio parameters.

For collectors of 500 mm of nominal diameter, a filling ratio parameter of 70% is obtained. For collectors of nominal diameter between 500 mm and 1000 mm, the filling ratio parameter is greater than 85%, and for collectors of nominal diameter greater than 1000 mm, the filling ratio parameter is greater than 90%.

Fig. 9. Maximum (HW/D) Pipe Ratio Results. (*Source: ArcMap 10.2.2)*

IX. Hazard Intensity For The Rainwater Sewage System Network For Simplified UGA 251

The hazard intensity (I) of danger depends on several factors. The main one is the water height.

The water height level shall be considered, as the only determining parameter to define the hazard intensity. Each flooding is assigned an intensity ratio related to the depth of flooding [8].

TABLE 5. INTENSITY CLASSIFICATION BASED ON WATER HEIGHT LEVEL

Water Height Level [a]	Score	Measure
5 cm <	1	Low Intensity
5 cm< h < 30 cm	5	Medium Intensity
> 30 cm	10	High Intensity

a. Granger, 2009

The hazard intensity that was employed for the risk diagnosis of the storm sewer network of the UGA 251 located in Zone 2 was the same as the one used for the hydrological analysis. For return time of 25 years and a duration of 60 minutes, showed a hazard intensity of 52.66 mm.

According to Table 6. (Intensity Classification based on Water Height Level), the intensity found at 5.26 cm was classified as Medium Intensity with the score of 5.

X. Vulnerability Of The Rainwater Sewage System Network For the Simplified UGA 251

Vulnerability is defined as the predisposition of different components and structures such as: aqueduct, sewerage, and cleanliness around the hazards that damage them, in addition to their ability to overcome the impact of an alarming event.

As always there will be, the susceptibility or predisposition to damage due to the operation of the network system. For this particular case of the storm sewer network, a vulnerability factor was determined with a value of **1**, regardless of whether the risk elements affect living beings and material goods.

XI. Risk Elements (The Quantitative Characterization Associated With The Vulnerability)

The risk elements are those systems or units, which are highly affected by floods in local or national areas of high economical value, environment, housing, workplaces, schools, and universities, among others. The identification and quantification of risk are particularly difficult, due to the various types of impact: functional, economic, and environmental, among others [12].

TABLE 6. RISK ELEMENTS ASSOCIATED WITH A VULNERABILITY SCORE

Risk Elements [a]	Vulnerability Score
Hospitals	13
Public buildings	13
Commercial areas	12
Industrial areas	12
Residential areas	10

Risk Elements [a]	Vulnerability Score
Highways	5
Primary roads	5
Secondary roads	4
Workshops	3
Cellars	3
Parking spaces	2
Pedestrian zones	1
Parks	1

a. Granger,2009

Among the risk elements associated with vulnerability, public buildings was chosen with the score of 13.

XII. Diagnosis Of Floodings Risks Of The Rainwater Sewer Network Of Simplified UGA 251

To be able to diagnose the flooding risks, the previously found factors must be taken into accounts such as the probability of occurrence of danger (P), the hazard intensity (I), the vulnerability of the problem (V), and the elements associated with the vulnerability (E) [10], the risks are classified in the Table 8 and Equation (9).

TABLE 7. CLASSIFICATION OF FLOOD RISKS

Risk Classification (%)	Level Classification [a]
0 %- 20 %	very low risk
20.1 %- 40 %	low risk
40.1 %- 60 %	medium risk
60.1 %- 80 %	high risk
80.1 %- 100 %	very high risk

a. Grange, 2009

The following Table 9 shows the risk classification results, from the parameters previously mentioned.

TABLE 9.PARAMETERS OF EVALUATION

Risk	Shear Stress	Shear Stress for 10% of filling capacity	Maximum (y/D) Pipe Ratio for rainwater systems
Probability of occurrence of danger (P)	0.29	0.29	0.08
The intensity of threat (I)	5	5	5
Vulnerability (V)	1	1	1
Elements of vulnerability (E)	13	13	13
Percentage of Risk (%)	19.12	19.12	5.1
Measure Risk (Criterion)	Very Low Risk	Very Low Risk	Very Low Risk

XIII. Conclusions and Recommendations

From the flooding risk assessment, the following results were obtained: for the shear stress, the risk percentage is 19.12% and its classification is very low risk, for the shear stress for 10% of full filling capacity: the risk is 19.12% and its classification is very low risk. Finally for the maximum filling ratio (HW/D): the risk is 5.1% and its classification is very low risk.

The sections that failed the hydraulic evaluation in more than 3 parameters out of 5, must be reconditioned. The 15 of 51 pipe sections were affected by to shear stress and shear stress for 10% of full filling capacity with a relatively small length of 0.511 km of the network and less than the 25% of the selected rainwater network. Furthermore, 4 pipe sections exceeded 80% of the maximum filling ratio (HW/D), with a length of 0.185 km of the network and 8.56% of the total simplified rainwater network.

A total of 19 pipe sections, i.e., 37.25% of the affected network shall be reconditioned to solve the 3 hydraulic evaluation parameters in accordance to the design and operation criteria indicated in the NS-085 of the EAAB-ESP. Finally, the pipe sections that presented the problems shall be verified using the closed-circuit television (CCTV) for sedimentation levels and employ punctual maintenance to improve the drainage system.

Acknowledgments

We are very grateful to the Aqueduct and Sewerage Company of Bogota (EAAB-ESP) for the support and Scholarship Emerging Leaders in the Americas Program (ELAP).

References

[1] Bogota (Colombia), “Instituto de Gestión del Riesgo y Cambio Climático” (2019) IDIGER Available online: https://www.idiger.gov.co/rinundacion (Accessed on March 3th of 2021)
[2] Bogota (Colombia), “Empresa de Acueducto y Alcantarillado de Bogotá” (2010). Technical Standard of service. Technical aspects for inspection of sewer networks and structures (NS-058). Available online: https://acueducto.com.co (Accessed on March 3th of 2021)
[3] Bogota (Colombia), “Empresa de Acueducto y Alcantarillado de Bogotá (2006). Plan Maestro de Acueducto y Alcantarillado. Bogotá: EAB-ESP. Available online: https://acueducto.com.co (Accessed on September 13th of 2021)
[4] Bogota (Colombia). “Empresa de Acueducto y Alcantarillado de Bogotá “ (2006). Plan Maestro de Acueducto y Alcantarillado. Bogotá: EAB-ESP. Available online: https://acueducto.com.co (Accessed on September 13th of 2021)
[5] Bogota. Alcaldía Mayor de Bogotá (2018). “Decreto 837 de 2018”. Available online: https://www.idiger.gov.co/ (Accessed on May 18th of 2021)
[6] Blaikie P, Cannon T., Davis I., Wisner B. (2014). “Natural Hazards, People´s Vulnerability, and Disasters”, New York, Routledge, Second Edition. Available online: http://www.scirp.org/ (Accessed on January 24th of 2021)
[7] Caradot N., Cherqui N., (2010). “L’évaluation du risque de débordement des systèmes de gestion des eaux urbaines. Contributions méthodologiques de deux cas d’études (Lyon et Mulhouse)”. Available online : https://www.researchgate.net/ (Accessed on September 13th of 2021)
[8] Cherqui, F., Chapgier J., Caradot N., Granger D. (2011). “Urban flood risk assessment using sewer flooding databases”. France: IWA Publishing. Water Science & Technology. Available online: https://www.researchgate.net// (Accessed on May 19th of 2021).
[9] ArcGIS Desktop, ArcMap 10.2.2.
[10] The Hydrologic Modeling System (HEC- HMS).
[11] Bentley Open Flows SewerGEMS.