THEORETICAL ANALYSIS OF URBAN RUNOFF POLLUTOGRAPHS. IDENTIFICATION OF CHARACTERIZATION VARIABLES AND IMPACT

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ABSTRACT

This research presents a novel methodology to determine runoff water retention volumes that allow the design of storage tanks for storm sewer overflows. It is based on the use of the Stormwater Management Model (SWMM) to generate hydrographs and runoff pollutographs of a fictional urban basin. Three pollutants (TS, BOD_5 and TN) are simulated for a given set of rains and the values taken by a proposed set of characterization variables for the pollutographs obtained are analyzed. Correlation and determination coefficients that exist between the different variables are analyzed while also performing a multivariate characterization using PCA and cluster analysis. In the case study presented, using IDF curves of the studied city, a probability of occurrence (Tr) is assigned to the values taken by the proposed characterization variables. To assess the impact and identify the most unfavorable pollutographs within the set of selected rains, impact evaluation variables (IEV's) are established, based on the proposed characterization variables and by simulating the discharge to a receiving water body (river with initial concentration and constant flow). Finally, a storm sewer overflow is simulated, deriving a maximum flow for purification, and dimensioning retention tanks for different fractions of the total volume of runoff to control the maximum values of a specific IEV impact evaluation variable. Taking a design return period of 10 years, the results obtained in the study case were 146.50 m^3/ha imp for a 100% retention of the total runoff volume and 117.20 m^3/ha imp for an 80% retention.

KEYWORDS: urban runoff, pollutographs, variables and impact, storm sewer overflow, storm tanks

ABBREVIATIONS

ADD	Antecedent Dry Days (days)
BOD_5	Biochemical Oxygen Demand at 5 days (mg/L)
C	Runoff coefficient of the rational method or Concentration (mg/L)
CA	Cluster Analysis
Cd	Concentration (mg/L) of runoff water discharge
Cfp	Concentration (mg/L) at which Fp occurs
Ci	Concentration (mg/L) at the time i
Clast	Last concentration (mg/L)
Cm	Average concentration (mg/L)
Cp	Peak concentration (mg/L)
C(t)	Variation of concentration C as a function of time t giving rise to the pollutograph
Cr	Concentration (mg/L) in the river at the point of mixing
Cr_{Fm}	Concentration (mg/L) in the river at the point of mixing due Fm and Qmean discharge
Cr_{Fp}	Concentration (mg/L) in the river at the point of mixing due Fp and Qfp discharge
Cro	Initial concentration (mg/L) in the river
D	Rain duration (min)
DD	Accumulation of dust and dirt (kg) during ADD time
DD_7	Accumulation of dust and dirt (kg) after 7 days.
Dif.P90 Vstorage	Absolute value of the difference between Vstorage and P90 (m^3/ha imp)
EMC	Event Mean Concentration/Weighted average concentration (mg/L)
F	Frequency associated to the return period of a rain of an intensity "I" and a duration "D" or Mass flow rate (kg/min)
Fd	Mass flow rate (mg/s) of runoff water
F_i	Mass flow rate (kg/min) at the time i
Fm	Average mass flow rate (kg/min)
Fp	Peak mass flow rate (kg/min)
Fro	Initial mass flow (mg/s) in the river
I	Rain intensity (mm/h)
I-D	Intensity, duration
IDF	Intensity, duration, frequency
IEV	Impact Evaluation Variable
iev	Value of the IEV impact evaluation variable
$\overbrace{iev}^{I,D}$	Value of the IEV impact evaluation variable for an intensity "I" and a duration "D" of the rainfalls matrix
K_j	Weight coefficient ("weight" or importance) of each characterization variable chosen
MaxDD	Maximum accumulation (kg) of dust and dirt in the urban basin
Mt	Pollutant Load of Runoff (kg)
$(maxVAR)_j$	Maximum value of the selected characterization variable, of the entire rainfalls matrix chosen
n	Manning roughness coefficient
P	Precipitation (mm)

P90	Percentile 90
PC1	First principal component
PC2	Second principal component
PC3	Third principal component
PCA	Principal Component Analysis
P(t)	Variation of precipitation P as a function of time t
Q	Flow (L/s)
Qd	Discharge flow (L/s) of runoff water
Qdw	Average dry weather flow (L/s/ha)
Qfp	Flow (L/s) at which Fp occurs
Q_i	Volume flow rate (L/s) at the time i
Qmax	Maximum flow (L/s)
Qmean	Average flow (L/s)
Q_{ro}	Initial flow (L/s) of the river
Q(t)	Variation of the flow Q as a function of the time t that gives rise to the hydrograph
Q_{WWTP}	Runoff water flow (L/s) that is admitted to treatment in the WWTP
R	Coefficient of correlation
R^2	Coefficient of determination
RVF	Retained Volume Fraction (%) of Vstso
T	Number of characterization variables chosen to find the variable IEV
Tclast	Time (min) at which Clast occurs
Tcp	Time (min) at which Cp occurs
Tfp	Time (min) at which Fp occurs
TN	Total nitrogen (mg/L)
TP	Total phosphorus (mg/L)
Tqmax	Time (min) at which Qmax occurs
Tr	Return period (years)
Tr_{ssd}	Return period (years) of storm sewer design
TS	Total Solids (mg/L)
TSS	Total Suspended Solids (mg/L)
Tt	Runoff duration (min)
VAR_j	Any variable of characterization of the pollutographs
$\overbrace{VAR_j}^{I,D}$	Is the value of the characterization variable "j" for an intensity "I" and a duration "D" of the rainfalls matrix
Vloss	Loss volume (m^3)
Vrain	Rain volume (m^3)
Vstorage	Storage tank volume (m^3/ha imp) of the storm sewer overflow
Vstso	Storm sewer overflow (m^3/ha imp)
Vt	Total runoff volume (m^3)
WWTP	Wastewater Treatment Plant

THEORETICAL ANALYSIS OF URBAN RUNOFF POLLUTOGRAPHS. IDENTIFICATION OF CHARACTERIZATION VARIABLES AND IMPACT

1. INTRODUCTION

The problem of urban runoff pollution has been studied extensively during the last two decades even more when global climate change has in many cases caused an increase in the possible impacts that runoff can cause.

Anthropogenic activities alter the natural conditions of the basins. The level of urbanization fundamentally affects the existence of natural vegetation and the degree of waterproofing of surfaces. This modifies surface flows under rain events causing alterations of hydrographs, higher peak values and flow rates, increased concentrations of discharges to receiving water bodies and elevation of mobilized pollutant masses. Furthermore, the alteration of the hydrological regime and the presence of pollutants end up affecting the organisms of the aquatic environments and alter the character of the ecosystems (Andrés-Doménech, Hernández-Crespo, Martín, & Andrés-Valeri, 2018; Del Río-Cambeses, 2011; Perales-Momparler et al., 2017; Reoyo-Prats et al., 2017; Suárez et al., 2008; Wang, Sun, & Sweetapple, 2017).

There are many studies on the characterization of urban runoff throughout the world. However, the presence of pollutants and their concentrations are very heterogeneous due to the multiple factors that can influence the formation of urban runoff and its own composition. This therefore makes its quantification and fundamentally its estimate as to its quality difficult. At the field level, carrying out runoff sampling campaigns demand a large effort in infrastructure (materials, equipment, laboratory, etc.) and human resources and usually involve significant time and costs (Freni, Mannina, & Viviani, 2009a; Sun & Bertrand-Krajewski, 2012). Besides, it is necessary to characterize not only one point of the discharge of the analyzed basin but multiple points to obtain representative values. Thus, as a complement and / or alternative to field measuring campaigns, mathematical modeling is used.

The runoff is due to a complex hydrological and hydraulic phenomenon whose estimation and representation, is studied and modeled satisfactorily resulting in a graphical representation in the form of hydrograph (variation in time of flow rates or laminar runoff) (Dotto et al., 2011). However, estimating the concentrations of the different pollutants that accompany these flows is a more intricate problem. Runoff water quality and its variation as a function of time can be estimated with different models; for example, with washoff equations applied to the pollutants that have previously accumulated (accumulation curves) in the dry weather days (Andrés-Doménech et al., 2018; Freni, Mannina, & Viviani, 2009b). Pollutant mass flow rates variation during storms in sewer systems is described by two curves: hydrograph Q(t) and pollutograph C(t) for each contaminant considered, where Q is the flow rate (L/s) and C is the concentration (mg/L). For a basin, these two curves vary from one rain event to another, depending on several parameters: the hyetograph that provides the variation of the precipitation P(t), the prior dry weather period and the rain, the condition of the sewerage system, the amount of pollutant deposited, the accumulated mass of pollutants over the basin, the characteristics of the basin and the sewer system, etc. (Bertrand-Krajewski, Chebbo, & Saget, 1998).

Scientific computing allows a large number of scenarios to be evaluated and analysed in a faster, cheaper and more secure way than with the traditional methods of prototyping and experimentation (Denning, 2000). The widespread use of the SWMM program around the world by scientists and researchers for the simulation of runoff in urban watersheds makes it an ideal tool to obtain the hydrographs and pollutographs discussed above, to characterize quantitatively and qualitatively the pollution events that produce the rains. The SWMM allows the simulation of flows and polluting loads of urban runoff, as well as their transport through the drainage network (Temprano, Arango, Cagiao, Suárez, & Tejero, 2007).

The purpose of this research is to present a new methodology based on scientific computing that allows to compare pollutographs of different I-D rains and select the most unfavourable regardless of the chosen pollutants. In this context, the choice of simulated pollutants and the validation process of the mathematical model (SWMM) with real data are not limiting factors.

The present investigation analyzes, for a specific urban basin, the form and behavior of the hydrographs and pollutographs obtained from the simulation with the SWMM, by identifying their characterization variables. Combination of these characterization variables allow additional definition of impact evaluation variables to find the most unfavorable pollution events taking into account several possible scenarios: a direct discharge to the receiving water body and, a storm sewer overflow accompanied by storage in retention tanks.

2. MATERIALS AND METHODS

2.1. Case study and initial data

A representative urban basin of cities like Santander (Spain) has been chosen for the study of pollutographs. It involves a surface of 1 hectare, defined by a cell of 100 m by 100 m. An impermeability of 60% and a slope of 0.5% were assumed. The U.S. EPA SWMM 5.1.013 program was used to obtain hydrographs and pollutographs. With this model, the Manning roughness coefficient “n” for impermeable areas was adjusted so that the maximum flow of the hydrograph (in the absence of evaporation, infiltration and storage in depression) coincides approximately with that obtained by the rational method (assuming that the percentage of impermeability is approximately equal to the runoff coefficient C). A value of n equal to 0.00479 was obtained. For the permeable zone a value of 0.4 was used (Temprano et al. (2007)). To estimate the storage in depressions in the impermeable area, the detailed formula in Huber & Dickinson (1992) was applied, obtaining a value of 1.080889 mm (0.042554 in) for a slope of 0.5%. For the permeable zone a value of 6.35 mm (0.25 in) was assumed (Huber & Dickinson (1992)). To calculate the infiltration, the Horton model was used for a clay soil that is predominant in Santander with a maximum rate of 36 mm/h (1.4713 in/h), a minimum rate of 3.84 mm/h (0.1512 in/h) and with a decay constant equal to 0.00116 s^{-1} (Monte & Marco (1992)).

The simulation month was August and the evaporation was simulated by choosing an arbitrary value of 3.75 mm/day = 0.148 in/day (a 25% increase over the SWMM default value) although it has little influence on discrete events. Its influence is greater in continuous simulation (Huber & Dickinson, 1992).

2.2. Accumulation curves and pollutant washoff

An accumulation curve of DD (dust and dirt) of the exponential type and dependent on the length of curbs in the basin was chosen:

$$MaxDD = Max.Buildup \cdot Curb\ length \quad (1)$$

$$DD = MaxDD \cdot (1 - e^{-Rate\ Constant \cdot ADD}) \quad (2)$$

MaxDD: maximum accumulation (kg) of dust and dirt in the urban basin

ADD: Antecedent Dry Days (days)

DD: Accumulation of dust and dirt (kg) during ADD time

It was assumed a residential-commercial type basin (Huber & Dickinson, 1992), with the following parameter values: Max.Buildup = 197.65 kg/km (13.257 lb/100 ft). Rate Constant = 1 day^{-1} and Curb length = 0.7267 km of curb (23.83467 ft/100 ft).

Summarizing:

$$DD = 143.626 \cdot (1 - e^{-ADD}) \quad (3)$$

Since the assumed accumulation curve shows an asymptote at 10 days, a value of ADD = 7 days (> 90% accumulation) was taken for all simulations, resulting in a value of 143.495 kg for DD_7.

The following pollutants were simulated as a fraction of DD (Huber & Dickinson (1992)): BOD_5 = 5.03/1000*DD, TS = 1000/1000*DD, TN = 0.48/1000*DD.

For the pollutant washoff, an exponential function was used in the SWMM program with Coefficient = 2 and Exponent = 0.84. These values were obtained when testing the model and adjusting the % removel of DD approximately to those cited by Lazaro (1990). For this, it was assumed as a hypothesis that the runoff duration approximated the rain duration (valid the smaller the modeled watershed) and that the runoff intensity was similar to the intensity of the rainfall affected by the C coefficient of the rational method. Once these assumptions were accepted and in the absence of evaporation, infiltration and storage in depressions, the rainfall intensities and durations thus estimated were used, to obtain through the model (SWMM) the removal percentages suggested by adjusting the values of the exponential washoff function.

No snow presence was simulated in the basin or its fusion. Nor was rainwater pollution simulated, nor was dirt removal by street sweeping considered. Erosion was not simulated (in urban watersheds the percentage of land susceptible to being eroded is low and will be even lower as the degree of urbanization increases). The storm term was not used in this study since the analyzed rains lack phenomena associated with them such as: ice, hail, electricity, snow or strong winds.

2.3. Rainfalls matrix

In this study the precipitation was introduced through a rectangular design hyetograph that corresponds to an intensity I and a duration D. For the calibration of the washoff function, a set of rains I-D was used. A range of values was selected in which the combination [high intensities-short durations] and [low intensities-long durations] causes a % elimination of DD equal to or greater than 90%. In this study the ranges were Rain intensities from 0 to 300 mm/h and Rain durations from 0 to 300 min. Once the respective ranges were selected, they were discretized to constitute a matrix where the elements thereof are rains of different intensity and duration. In this investigation the following matrix was selected:

As rows, at the following intensities (mm/h): 0, 1, 3, 5, 7, 10, 20, 40, 60, 80, 100, 120, 140, and 300. As columns, at the following durations (min): 0, 2, 4, 6, 8, 10, 15, 20, 25, 30, 35, 50, 80, 120, 180, 240, and 300. The discretization of the range of intensities has a lower weight than the discretization of the range of durations, since the percentage of elimination of DD, grows exponentially with duration.

An adequate selection of rains (design events) that will constitute the rainfalls matrix, will collect practically all the options that can constitute a temporal pattern of rainfalls succession as mentioned in Andrés-Doménech (2010) discussed by Clar, Barfield, & O'Connor (2004).

2.4. Simulation and obtainment of hydrographs and pollutographs

With the fixed intensity-durations matrix, applying the SWMM 5.1 model (Tools/Console mode, Yang & Chui (2018)) each of the rains was simulated by reading an external data file that contained the commented hyetographs, thus obtaining the necessary data to continue with the analysis. 360 min was always used as simulation time and 1 min as time step in it. The routing model was the kinematic wave, obtaining the same results as with the dynamic wave. Since the simulated hypothesis is very simple, it was enough to use the kinematic wave. With each simulated rain, a report per object was obtained in the form of a table for each simulation step time with the results of the runoff flow and the respective concentrations of the pollutants. As an effective duration of each event, the runoff duration was taken until such time as the runoff flow becomes zero, cutting the values of the hydrograph and the pollutographs with that duration. At this point it is convenient to define what is understood by hydrograph and pollutographs. Hydrograph: It is the variation of the flow in the time that the runoff lasts ($[L^3/T]$ - T). Pollutographs: on the one hand, a) the variation of the concentration of a pollutant over the runoff duration ($[M/L^3]$ - T) and on the other, b) the variation of the mass flow of a pollutant at runoff duration (M/T - T). To differentiate the two pollutographs, the mass flow will be referred from this point as mass flow rate. The SWMM does not report mass flow values, so the values obtained in the SWMM were taken to a spreadsheet to better calculate and represent the hydrographs and pollutographs commented.

$$Fi = Qi \cdot Ci \tag{4}$$

Fi: Mass Flow Rate at the time i

Qi: Runoff at the time i

Ci: Concentration at the time i

2.5. Identification of hydrograph and pollutographs characterization variables

For each simulated rain, the characterization variables detailed, in Figure 1, were identified: I, D, P, Vrain, Vloss, Vt, Qfp, Qmax, Qmean, Cp, Cfp, Clast, Cm, EMC, Mt, fp, Fm, Tcp, Tfp, Tqmax, Tclast, Tt (consult list of abbreviations).

Where:

$$EMC = \frac{Mt}{Vt} = \frac{\int_0^{Tt} C(t) \cdot Q(t)\, dt}{\int_0^{Tt} Q(t)\, dt} \tag{5}$$

and, plus:

$$Qmean = \frac{Vt}{Tt} \tag{6}$$

$$Fm = \frac{Mt}{Tt} = EMC \cdot Qmean \tag{7}$$

$$Fp = Cfp \cdot Qfp \tag{8}$$

2.6. Examples of characteristic graphs of hydrographs and pollutographs

To calculate all the characterization variables described, the hydrograph and pollutographs data obtained from the simulation with the SWMM were exported to a spreadsheet as an auxiliary tool.

From the rainfalls matrix, one rain is taken as an example with I = 140 mm/h, D = 4 min to present characterization graphs of the contamination event (see Figure 2).

Some additional examples of the pollutographs obtained within the selected rainfalls matrix can be seen in Figure 3 where their ordinate axes have been normalized (see Figure 2) to the maximum value of each pollutograph.

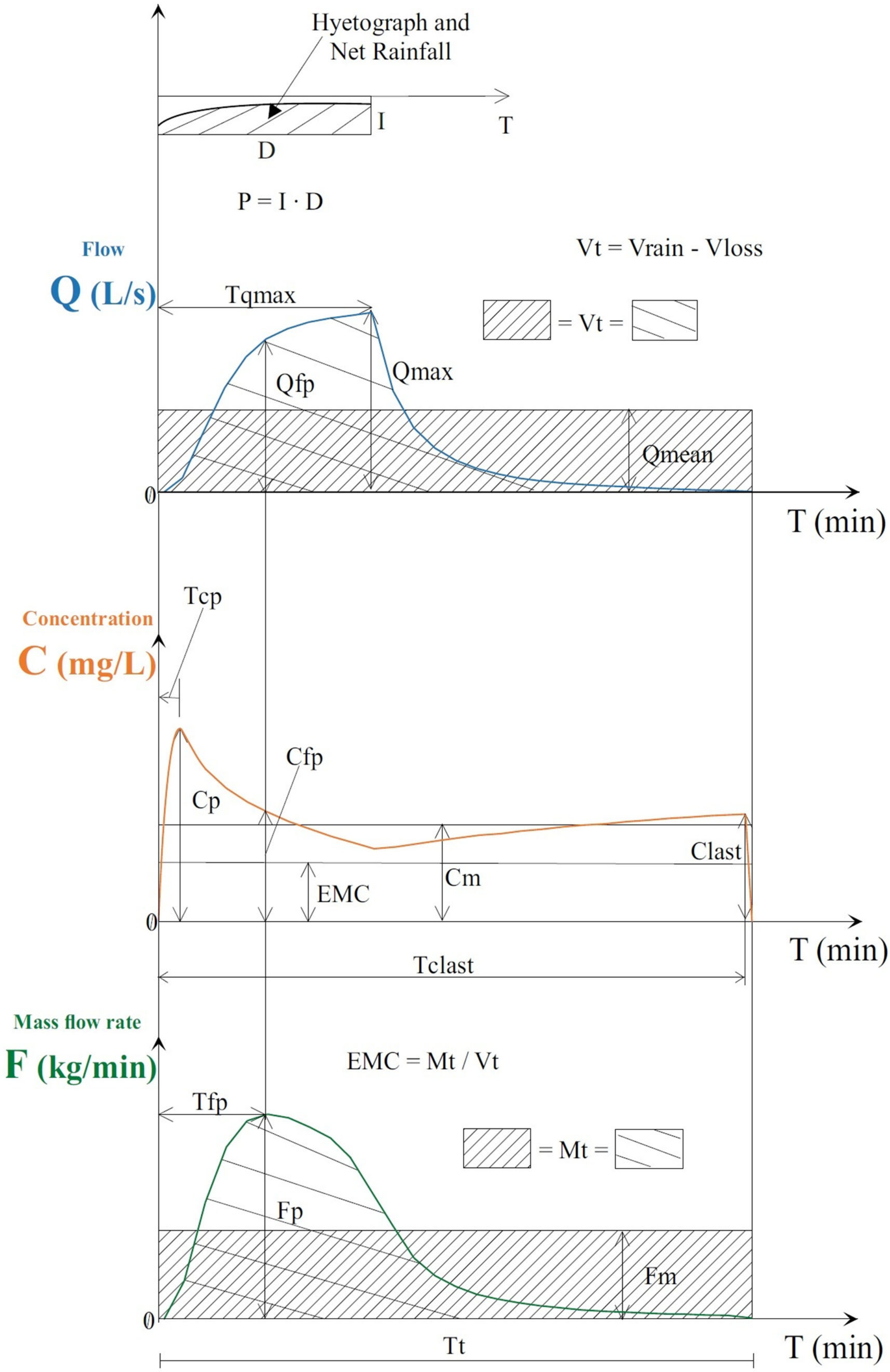

Figure 1. Hydrograph and pollutographs characterization variables

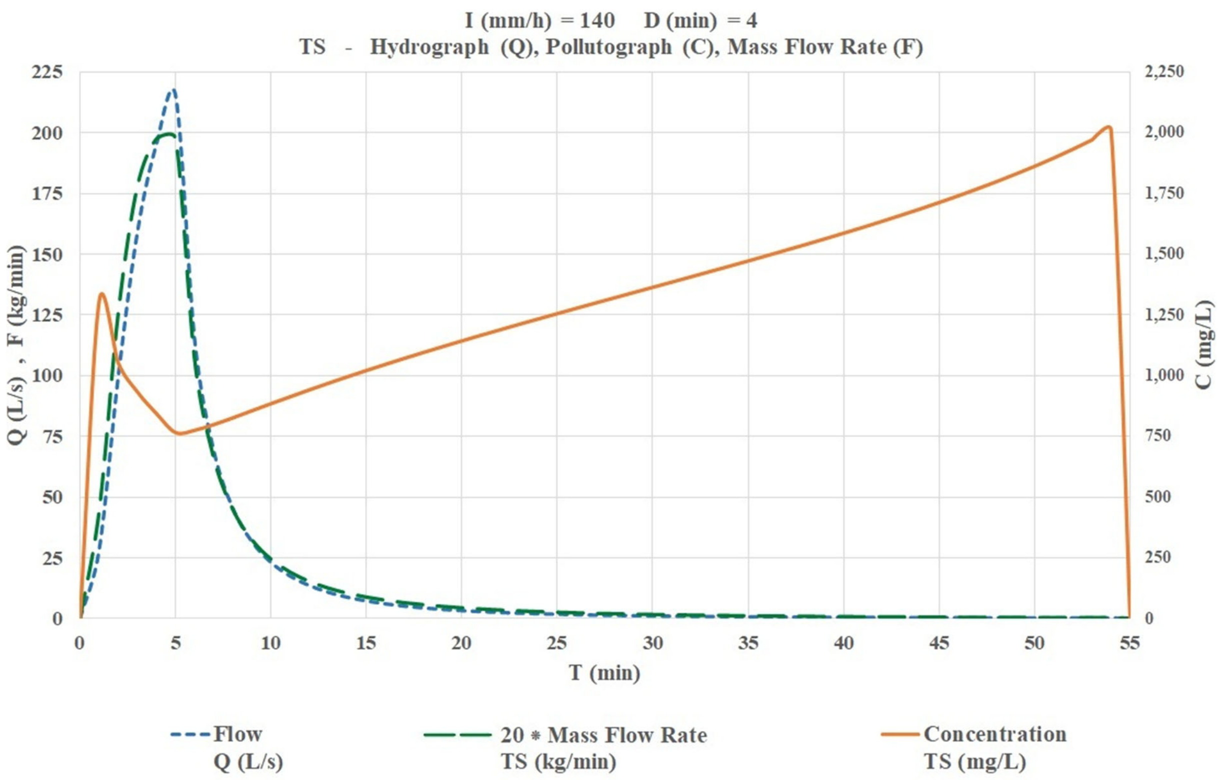

Figure 2. Hydrograph and pollutographs (TS pollutant) obtained for the rain I = 140 mm/h, D = 4 min

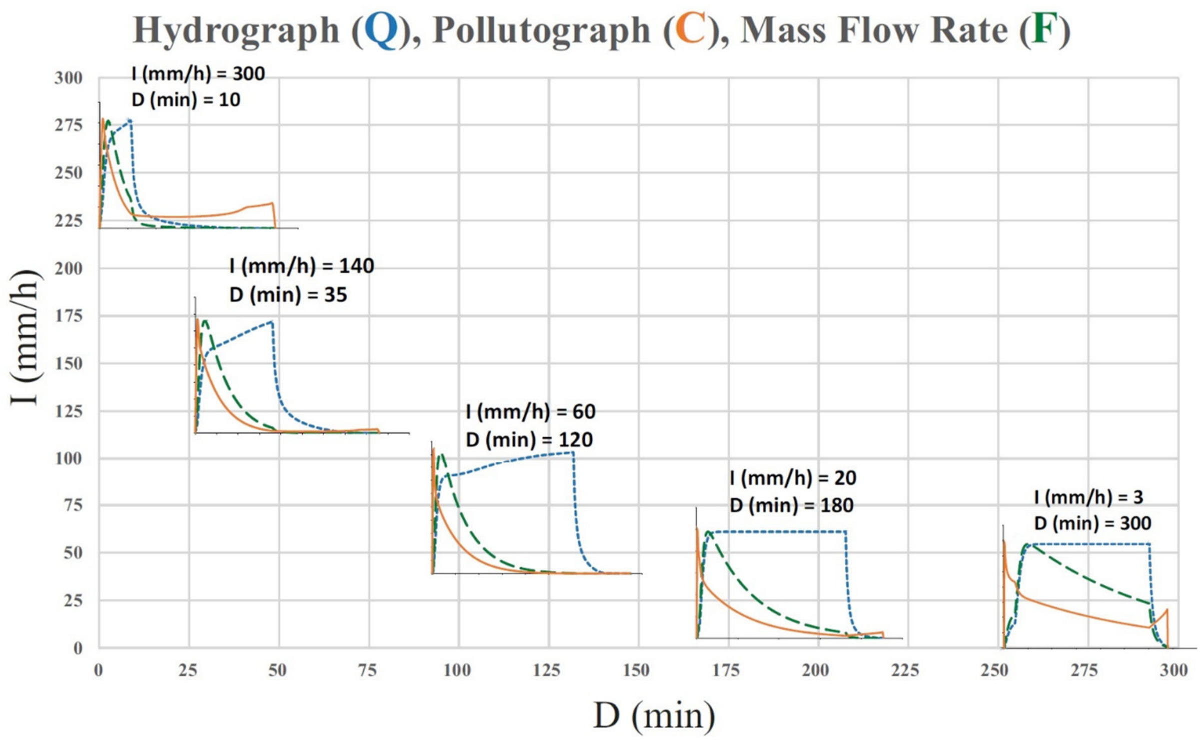

Figure 3. Examples of pollutographs within the selected rainfalls matrix

3. RESULTS AND DISCUSSION

3.1. Resulting values of the variables for each simulated pollutant

Performed the simulations with SWMM 5.1, values of the characterization variables of the pollutographs were obtained for the three simulated contaminants (BOD_5, TS, TN) observing the following behavior:

Independent variables of the type of pollutant: I, D, P, Qmean, Qmax, Qfp, Vrain, Vt, Vloss, Tqmax, Tt. The behavior of these variables is independent of the type of pollutant.

Equal values of the variables for each type of pollutant: Tcp, Tclast, Tfp. These variables have equal values for the three pollutants simulated.

Values of the variables that can be expressed as a fraction of TS: Cp, Clast, Cm, EMC, Cfp, Fp, Fm, Mt. If the values of these variables are known for TS, they can be found for BOD_5 = 5.03/1000 of TS, and TN = 0.48/1000 of TS or any other pollutant.

In this article, the choice of contaminants is not critical. Others could have been chosen, such as TSS, TP, etc. as fractions of DD. Temprano et al. (2007) cite for example TSS = 200/1000 of DD.

3.2. Characterization variables values for each I-D of the selected rainfalls matrix and its contour plots

Table S1 of supplementary data shows all the values that are obtained from the simulations of the selected rains. Also been detailed for each variable, the values of: mean, maximum, minimum, standard deviation, coefficient of variation (%) and P90.

Taking Qmean and EMC as the only two examples (out of 20 possible), the values obtained from the variables for the selected rainfalls matrix and their corresponding contour plots can be represented as follows: Qmean (Table 1 and Figure 4) and EMC (Table 2 and Figure 5).

Table 1. Qmean (L/s) values in the rainfalls matrix

I (mm/h)	D (min)															
	2	4	6	8	10	15	20	25	30	35	50	80	120	180	240	300
300	26.60	45.54	65.25	85.18	104.87	151.46	190.79	222.23	251.91	277.98	346.00	442.50	520.95	589.41	630.40	657.70
140	11.38	19.36	26.97	34.42	41.77	59.63	76.49	92.11	106.41	119.44	151.93	196.14	231.57	261.90	279.77	291.56
120	9.65	16.30	22.71	28.87	34.87	49.33	62.99	75.73	87.49	98.28	125.46	162.89	193.08	218.98	234.24	244.31
100	7.72	13.27	18.56	23.56	28.34	39.64	50.22	60.10	69.29	77.79	99.49	129.94	154.80	176.20	188.83	197.16
80	5.90	10.43	14.74	18.76	22.53	31.15	38.96	46.17	52.85	59.07	75.14	98.28	117.54	134.24	144.10	150.60
60	4.03	7.51	10.62	13.65	16.47	22.79	28.24	33.06	37.42	41.40	51.67	66.89	80.17	92.03	99.12	103.80
40	2.18	4.48	6.61	8.68	10.60	14.90	18.58	21.77	24.57	27.03	32.94	40.68	46.76	52.23	55.76	58.24
20	0.61	1.54	2.62	3.67	4.62	6.88	8.81	10.47	11.92	13.20	16.25	20.20	23.27	25.85	27.36	28.35
10	0.31	0.49	0.68	1.14	1.61	2.78	3.77	4.66	5.43	6.11	7.72	9.79	11.39	12.72	13.50	14.01
7	0.21	0.34	0.46	0.57	0.78	1.54	2.25	2.92	3.49	3.99	5.12	6.63	7.79	8.76	9.32	9.68
5	0.14	0.24	0.32	0.40	0.47	0.75	1.25	1.71	2.13	2.51	3.40	4.54	5.41	6.13	6.54	6.81
3	0.07	0.13	0.19	0.23	0.27	0.37	0.45	0.58	0.81	1.05	1.64	2.41	3.00	3.47	3.74	3.92
1	0.00	0.00	0.01	0.04	0.06	0.09	0.12	0.14	0.16	0.17	0.21	0.26	0.52	0.77	0.91	1.00

Minimum: 0.00 Mean: 58.65 Standard deviation: 106.14

Maximum: 657.70 P90: 179.99 Coefficient of variation (%): 180.96

Table 2. EMC (mg/L) values in the rainfalls matrix

I (mm/h)	D (min)															
	2	4	6	8	10	15	20	25	30	35	50	80	120	180	240	300
300	774.97	609.33	492.99	404.48	336.81	228.38	168.78	132.78	109.13	92.53	63.43	38.90	25.65	16.98	12.69	10.13
140	1,054.98	884.92	777.17	694.55	625.85	490.92	392.45	320.28	267.04	227.16	154.11	92.40	60.06	39.37	29.28	23.31
120	1,116.62	941.41	833.87	752.79	685.82	553.42	453.38	376.70	317.82	272.33	186.06	111.25	72.04	47.09	34.98	27.82
100	1,193.33	1,009.60	900.84	821.01	755.93	627.64	528.57	449.44	385.92	334.84	232.71	139.38	89.85	58.52	43.39	34.47
80	1,293.46	1,096.20	983.60	903.68	840.21	717.18	621.75	543.39	477.87	422.81	304.34	185.14	119.00	77.15	57.05	45.26
60	1,437.02	1,215.15	1,094.72	1,012.06	948.23	828.83	738.63	664.34	600.90	545.83	417.84	268.10	174.16	112.52	82.94	65.66
40	1,683.79	1,404.60	1,264.27	1,173.26	1,106.07	986.25	898.60	827.15	766.09	712.67	584.79	418.86	294.79	198.59	147.88	117.35
20	2,218.77	1,844.46	1,624.20	1,495.28	1,408.49	1,270.82	1,181.95	1,113.72	1,056.60	1,006.54	882.42	701.49	539.33	389.27	299.31	241.30
10	2,565.15	2,335.69	2,186.00	1,981.91	1,830.29	1,613.95	1,497.90	1,420.48	1,361.77	1,313.42	1,199.46	1,031.94	866.00	686.38	559.56	467.15
7	2,755.12	2,515.39	2,370.68	2,272.98	2,151.97	1,857.44	1,699.01	1,602.02	1,534.25	1,481.93	1,367.80	1,209.41	1,051.65	872.14	736.59	631.60
5	2,935.45	2,682.19	2,534.89	2,434.86	2,360.01	2,171.56	1,948.95	1,812.27	1,723.32	1,659.22	1,533.88	1,379.83	1,231.92	1,059.80	923.63	812.93
3	3,211.69	2,973.75	2,807.70	2,702.66	2,617.40	2,481.78	2,399.43	2,298.04	2,143.93	2,024.29	1,826.76	1,651.66	1,513.38	1,358.19	1,231.50	1,123.28
1	0.00	0.00	3,410.12	3,314.50	3,236.55	3,083.94	2,982.42	2,911.21	2,861.75	2,825.53	2,749.61	2,667.86	2,290.32	2,080.55	1,967.47	1,879.98

Minimum: 0.00 Mean: 1,075.26 Standard deviation: 887.92

Maximum: 3,410.12 P90: 2,491.86 Coefficient of variation (%): 82.58

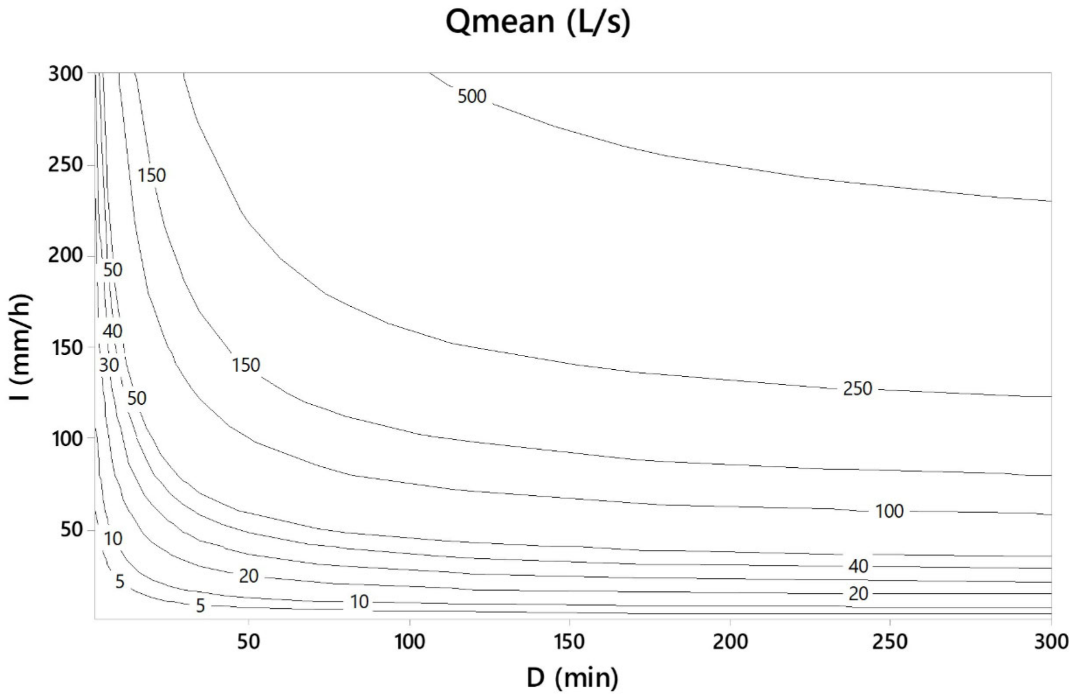

Figure 4. Contour plot of Qmean (L/s)

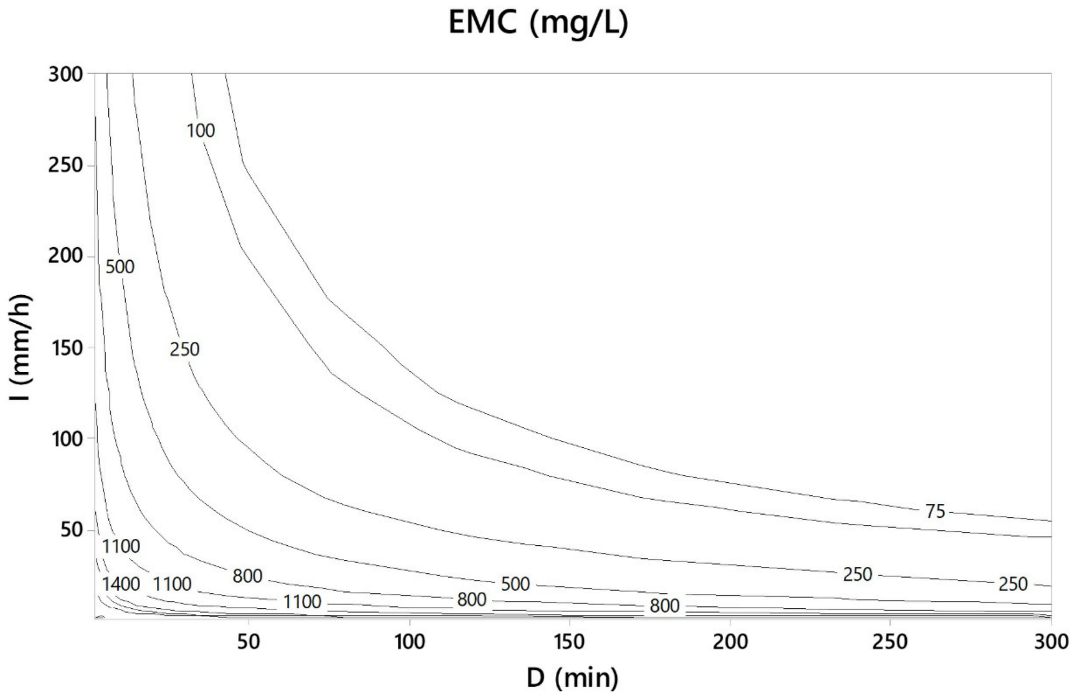

Figure 5. Contour plot of EMC (mg/L) for TS pollutant

In the same way, the rest of the characterization variables of the pollutographs can be observed in Table S1 and Figure S1 of supplementary data.

Probability of occurrence of the values of the characterization variables

Each event of contamination can be associated with the frequency of the rain that originated it. This can be done with IDF curves; specifically, taking the city of Santander as an example (Temprano & Tejero, 2002):

$$I = 130 \cdot Tr^{0.42} \cdot D^{-0.52} \quad (9)$$

$$Tr = \left(\frac{I}{130 \cdot D^{-0.52}}\right)^{\frac{1}{0.42}} \quad (10)$$

Where:

I: Rain Intensity (mm/h)

Tr: Return period (years)

D: Rain Duration (min)

In an I-D graph it is clearly known that Tr for a given "I" of rain, increases from left to right (from a smaller "D" to a larger one). Also, for a given "D" of rainfall, the Tr is increased from the bottom up (from a smaller "I" to a higher).

The variable Tr can be represented by superimposing its lines on any graph of the characterization variables of the pollutographs; thus, for any point within the rainfalls matrix, the precise value of the characterization variable and its associated “probability” of occurrence (Tr) can be known (see Figure 6).

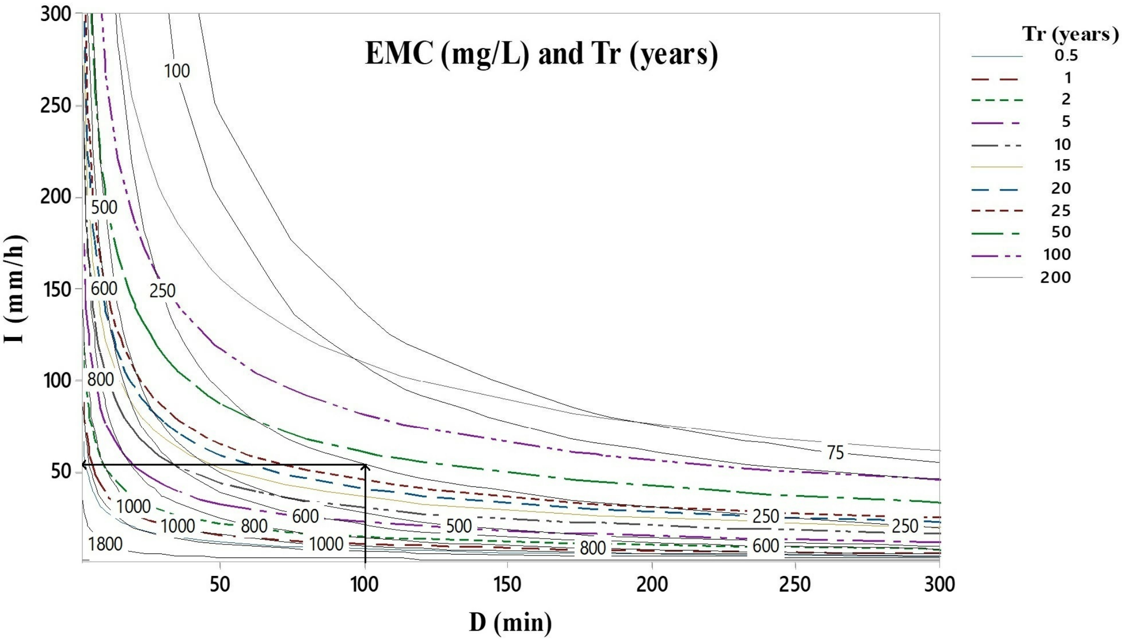

Figure 6. Contour plot of EMC (mg/L) and Tr (years) for TS pollutant

As an example, it can be observed that for an I = 55 mm/h, D = 100 min, an EMC = 250 mg/L is obtained with an approximate probability of occurrence Tr = 38 years.

The Figure 6 can also be represented maybe better in a Table 3 where the EMC values are accompanied by their corresponding Tr in format $\frac{EMC}{Tr}$.

So that, any of the remaining variables of characterization of the pollutographs could also be represented in the same way allowing to analyze their values and their probability of IDF occurrence.

3.3. Correlation coefficients and coefficients of determination of the characterization variables

Added Tr (years) as an additional variable to consider, Table S2 of supplementary data shows the correlation coefficients "R" and coefficients of determination "R^2" existing among all the characterization variables for the TS pollutant.

Better coefficients of determination for each characterization variable

The Table 4 shows the five best R^2 for each TS pollutant characterization variable.

3.4. Principal component analysis (PCA) and cluster analysis (CA)

Principal component analysis (PCA) and cluster analysis (CA) are among the most common multivariate statistical methods used in environmental studies. The PCA can be used to reveal relationships in complex and large data sets by reducing the dimensionality of the data. The data set is transformed into a new set of variables, main components, which represent the majority of the variation in the original data. The first main component explains the greatest possible variance of the data, and each subsequent component explains the largest possible amount of the remaining variance. The results of a PCA are generally reported as scores and loadings (Björklund, 2011).

When performing the PCA (Figure 7) it can be observed that the first component corresponding to the highest eigenvalue of 12.24 accounted for more than 53.20% of the total variance. The second component corresponding to the second eigenvalue equal to 4.99 explained more than 21.70%, and the third component corresponding to the third eigenvalue (equal to 2.74) explained more than 11.90% giving an accumulated value of approximately 86.80%.

Table 3. EMC (mg/L) and Tr (years) values in the rainfalls matrix for TS pollutant

I (mm/h)	D (min)															
	2	4	6	8	10	15	20	25	30	35	50	80	120	180	240	300
300	774.97 17.27	609.33 40.75	492.99 67.32	404.48 96.12	336.81 126.71	228.38 209.33	168.78 298.89	132.78 394.00	109.13 493.77	92.53 597.60	63.43 929.39	38.90 1.663.09	25.65 2.747.47	16.98 4.538.91	12.69 6.480.93	10.13 8.543.21
140	1,054.98 2.81	884.92 6.64	777.17 10.97	694.55 15.66	625.85 20.64	490.92 34.10	392.45 48.69	320.28 64.18	267.04 80.44	227.16 97.35	154.11 151.40	92.40 270.92	60.06 447.56	39.37 739.39	29.28 1.055.74	23.31 1.391.69
120	1,116.62 1.95	941.41 4.60	833.87 7.60	752.79 10.85	685.82 14.30	553.42 23.62	453.38 33.73	376.70 44.46	317.82 55.72	272.33 67.44	186.06 104.89	111.25 187.69	72.04 310.07	47.09 512.24	34.98 731.41	27.82 964.15
100	1,193.33 1.26	1,009.60 2.98	900.84 4.92	821.01 7.03	755.93 9.26	627.64 15.30	528.57 21.85	449.44 28.81	385.92 36.10	334.84 43.69	232.71 67.95	139.38 121.59	89.85 200.88	58.52 331.86	43.39 473.84	34.47 624.62
80	1,293.46 0.742	1,096.20 1.75	983.60 2.89	903.68 4.13	840.21 5.45	717.18 9.00	621.75 12.85	543.39 16.93	477.87 21.22	422.81 25.68	304.34 39.94	185.14 71.48	119.00 118.08	77.15 195.08	57.05 278.55	45.26 367.18
60	1,437.02 0.374	1,215.15 0.883	1,094.72 1.46	1,012.06 2.08	948.23 2.75	828.83 4.54	738.63 6.48	664.34 8.54	600.90 10.70	545.83 12.95	417.84 20.14	268.10 36.03	174.16 59.53	112.52 98.34	82.94 140.42	65.66 185.10
40	1,683.79 0.143	1,404.60 0.336	1,264.27 0.555	1,173.26 0.793	1,106.07 1.05	986.25 1.73	898.60 2.47	827.15 3.25	766.09 4.07	712.67 4.93	584.79 7.67	418.86 13.72	294.79 22.67	198.59 37.45	147.88 53.48	117.35 70.49
20	2,218.77 0.027	1,844.46 0.065	1,624.20 0.107	1,495.28 0.152	1,408.49 0.201	1,270.82 0.332	1,181.95 0.473	1,113.72 0.624	1,056.60 0.782	1,006.54 0.947	882.42 1.47	701.49 2.63	539.33 4.35	389.27 7.19	299.31 10.27	241.30 13.53
10	2,565.15 0.0053	2,335.69 0.012	2,186.00 0.020	1,981.91 0.029	1,830.29 0.039	1,613.95 0.064	1,497.90 0.091	1,420.48 0.120	1,361.77 0.150	1,313.42 0.182	1,199.46 0.283	1,031.94 0.506	866.00 0.836	686.38 1.38	559.56 1.97	467.15 2.60
7	2,755.12 0.0022	2,515.39 0.0053	2,370.68 0.0088	2,272.98 0.013	2,151.97 0.016	1,857.44 0.027	1,699.01 0.039	1,602.02 0.051	1,534.25 0.064	1,481.93 0.078	1,367.80 0.121	1,209.41 0.216	1,051.65 0.357	872.14 0.590	736.59 0.843	631.60 1.11
5	2,935.45 0.0010	2,682.19 0.0024	2,534.89 0.0039	2,434.86 0.0056	2,360.01 0.0074	2,171.56 0.012	1,948.95 0.017	1,812.27 0.023	1,723.32 0.029	1,659.22 0.035	1,533.88 0.054	1,379.83 0.097	1,231.92 0.160	1,059.80 0.265	923.63 0.378	812.93 0.499
3	3,211.69 0.0003	2,973.75 0.0007	2,807.70 0.0012	2,702.66 0.0017	2,617.40 0.0022	2,481.78 0.0036	2,399.43 0.0052	2,298.04 0.0068	2,143.93 0.0085	2,024.29 0.010	1,826.76 0.016	1,651.66 0.029	1,513.38 0.048	1,358.19 0.079	1,231.50 0.112	1,123.28 0.148
1	0.00 0.0000	0.00 0.0001	3,410.12 0.0001	3,314.50 0.0001	3,236.55 0.0002	3,083.94 0.0003	2,982.42 0.0004	2,911.21 0.0005	2,861.75 0.0006	2,825.53 0.0008	2,749.61 0.0012	2,667.86 0.0021	2,290.32 0.0035	2,080.55 0.0057	1,967.47 0.0082	1,879.98 0.011

Table 4. Best coefficients of determination R2 of the characterization variables of the pollutographs for the TS pollutant

I (mm/h)	Qfp (L/s) ; 0.994	Fp (kg/min) ; 0.982	Qmax (L/s) ; 0.945	Cp (mg/L) ; 0.606	Qmean (L/s) ; 0.535
D (min)	Tclast (min) ; 0.983	Tt (min) ; 0.983	Tqmax (min) ; 0.741	Vloss (m^3) ; 0.531	P (mm) ; 0.303
P (mm)	Vrain (m^3) ; 1.000	Vt (m^3) ; 0.995	Qmean (L/s) ; 0.834	Tr (years) ; 0.800	Vloss (m^3) ; 0.643
Qmean (L/s)	Vt (m^3) ; 0.836	P (mm) ; 0.834	Vrain (m^3) ; 0.834	Qmax (L/s) ; 0.719	Tr (years) ; 0.686
Qmax (L/s)	Qfp (L/s) ; 0.951	I (mm/h) ; 0.945	Fp (kg/min) ; 0.922	Qmean (L/s) ; 0.719	Cp (mg/L) ; 0.522
Qfp (L/s)	I (mm/h) ; 0.994	Fp (kg/min) ; 0.988	Qmax (L/s) ; 0.951	Cp (mg/L) ; 0.608	Qmean (L/s) ; 0.545
Vrain (m^3)	P (mm) ; 1.000	Vt (m^3) ; 0.995	Qmean n (L/s) ; 0.834	Tr (years) ; 0.800	Vloss (m^3) ; 0.643
Vt (m^3)	P (mm) ; 0.995	Vrain (m^3) ; 0.995	Tr (years) ; 0.847	Qmean (L/s) ; 0.836	Vloss (m^3) ; 0.571
Vloss (m^3)	Tqmax (min) ; 0.782	P (mm) ; 0.643	Vrain (m^3) ; 0.643	Tclast (min) ; 0.577	Tt (min) ; 0.576
Cp (mg/L)	Cfp (mg/L) ; 0.718	Fp (kg/min) ; 0.682	EMC (mg/L) ; 0.637	Qfp (L/s) ; 0.608	I (mm/h) ; 0.606
Clast (mg/L)	Cm (mg/L) ; 0.949	Mt (kg) ; 0.936	EMC (mg/L) ; 0.865	Cfp (mg/L) ; 0.568	Cp (mg/L) ; 0.503
Cm (mg/L)	Clast (mg/L) ; 0.949	Mt (kg) ; 0.883	EMC (mg/L) ; 0.846	Cfp (mg/L) ; 0.578	Cp (mg/L) ; 0.564
EMC (mg/L)	Cfp (mg/L) ; 0.868	Clast (mg/L) ; 0.865	Cm (mg/L) ; 0.846	Mt (kg) ; 0.805	Cp (mg/L) ; 0.637
Cfp (mg/L)	EMC (mg/L) ; 0.868	Cp (mg/L) ; 0.718	Cm (mg/L) ; 0.578	Clast (mg/L) ; 0.568	Tcp (min) ; 0.496
Fp (kg/min)	Qfp (L/s) ; 0.988	I (mm/h) ; 0.982	Qmax (L/s) ; 0.922	Cp (mg/L) ; 0.682	Fm (kg/min) ; 0.557
Fm (kg/min)	Fp (kg/min) ; 0.557	Cp (mg/L) ; 0.536	Qfp (L/s) ; 0.500	Cfp (mg/L) ; 0.483	I (mm/h) ; 0.474
Mt (kg)	Clast (mg/L) ; 0.936	Cm (mg/L) ; 0.883	EMC (mg/L) ; 0.805	Vloss (m^3) ; 0.518	Cfp (mg/L) ; 0.487
Tqmax (min)	Vloss (m^3) ; 0.782	Tclast (min) ; 0.745	Tt (min) ; 0.745	D (min) ; 0.741	P (mm) ; 0.521
Tcp (min)	Cfp (mg/L) ; 0.496	Tfp (min) ; 0.398	EMC (mg/L) ; 0.373	Cp (mg/L) ; 0.263	Clast (mg/L) ; 0.186
Tclast (min)	Tt (min) ; 1.000	D (min) ; 0.983	Tqmax (min) ; 0.745	Vloss (m^3) ; 0.577	Mt (kg) ; 0.357
Tfp (min)	Tcp (min) ; 0.398	Cp (mg/L) ; 0.326	Fp (kg/min) ; 0.175	I (mm/h) ; 0.154	Fm (kg/min) ; 0.148
Tt (min)	Tclast (min) ; 1.000	D (min) ; 0.983	Tqmax (min) ; 0.745	Vloss (m^3) ; 0.576	Mt (kg) ; 0.357
Tr (years)	Vt (m^3) ; 0.847	P (mm) ; 0.800	Vrain (m^3) ; 0.800	Qmean (L/s) ; 0.686	Qmax (L/s) ; 0.344

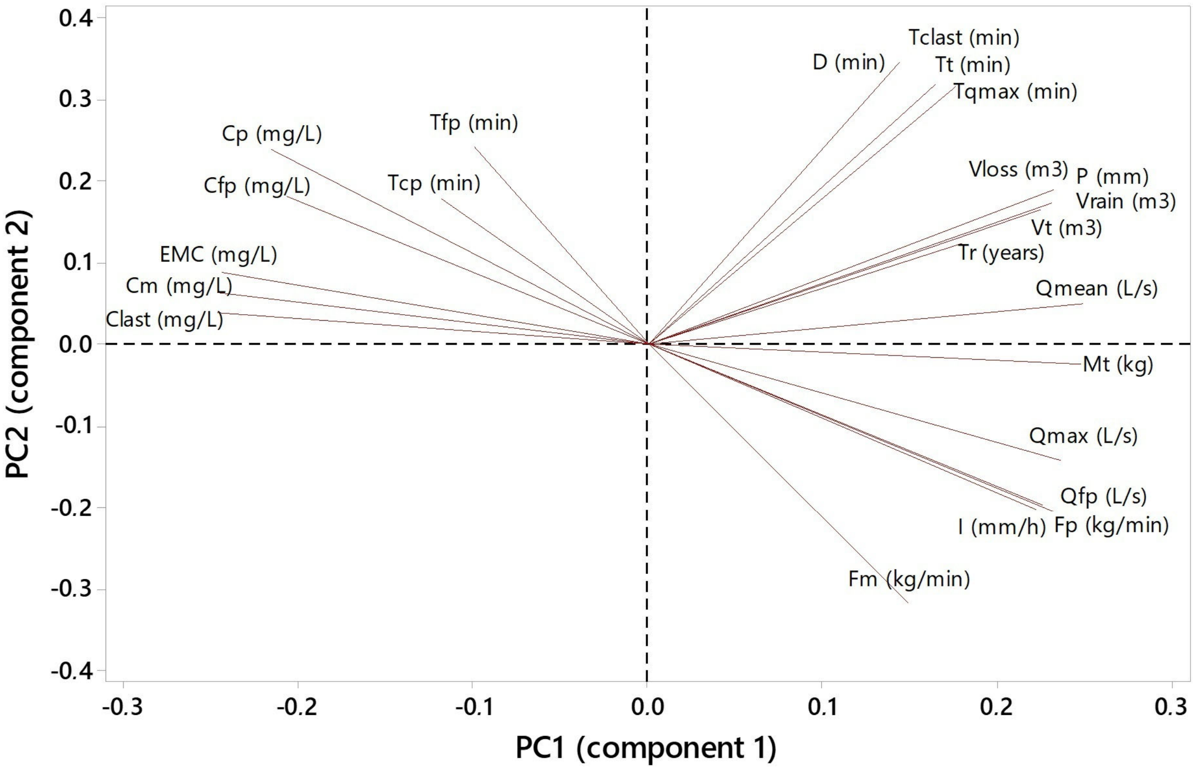

Figure 7. Principal component analysis (PCA) of characterization variables of the pollutographs for the TS pollutant

The graph shows two clearly differentiated groups [PC1 (+'s) and PC1 (-'s)] whose correlation coefficient between each variable in one group with another variable in the other group is negative. Group 1 (from lowest to highest PC2): Clast, Cm, EMC, Cfp, Cp, Tcp, Tfp. Group 2 (from lowest to highest PC2): Fm, I, Fp, Qfp, Qmax, Mt, Qmean, Tr, Vt, Vrain, P, Vloss, Tqmax, Tt, Tclast, D.

Tclast and Tt have the same values of PC1, PC2 and PC3 as do P and Vrain.

Within the groups, subgroups could also be identified, for Group 1 there would be subgroup (a): Clast, Cm, EMC subgroup (b): Cfp, Cp and subgroup (c): Tcp, Tfp. For Group 2 there would be subgroup (d): Fm; subgroup (e): I, Fp, Qfp, Qmax, Mt; subgroup (f): Qmean, Tr, Vt, Vrain, P, Vloss and subgroup (g): Tqmax, Tt, Tclast, D.

These groups and subgroups can also be deduced when conducting a cluster analysis (Figure 8). In cluster analysis, objects are grouped according to their characteristics. Groups of objects must show high homogeneity within the group and high heterogeneity between groups. Similarity between groups is measured by Euclidean distance, often illustrated in a dendrogram; smaller distances indicate greater similarity and vice versa (Björklund, 2011).

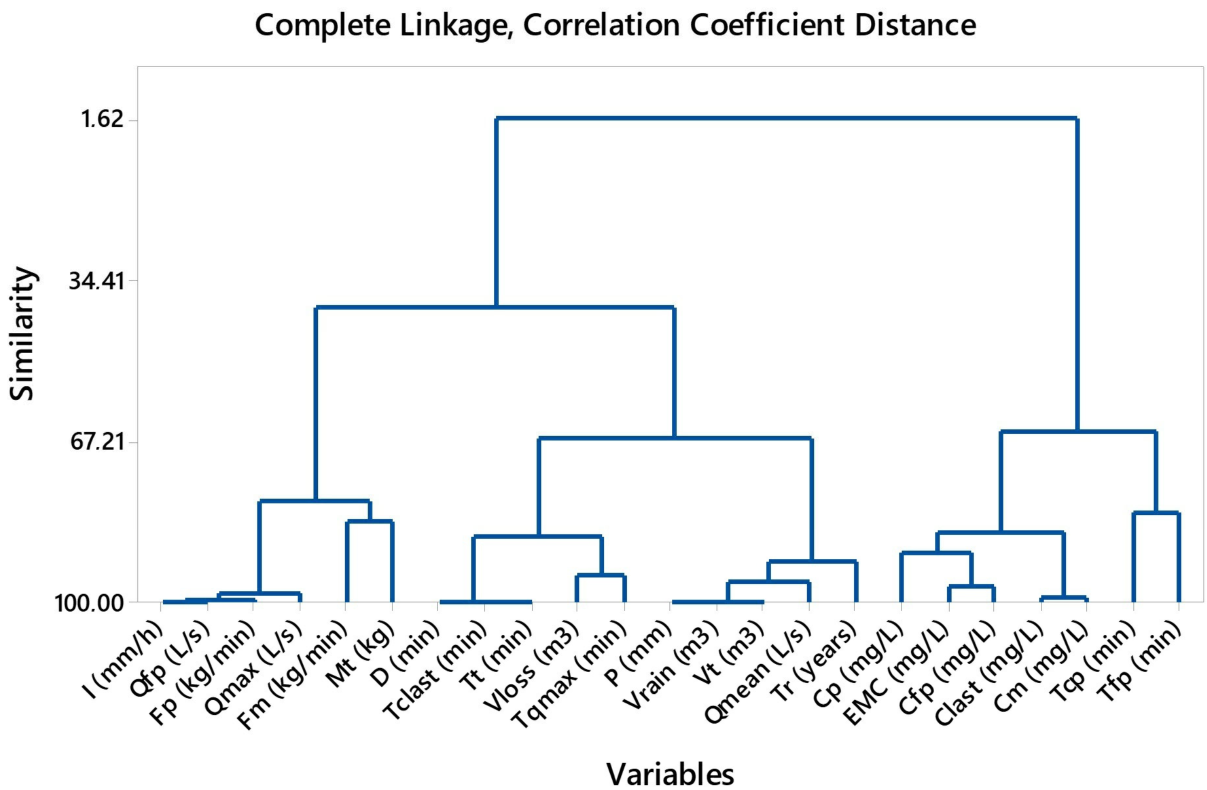

Figure 8. Cluster analysis (CA)/Dendrogram of characterization variables of the pollutographs for the TS pollutant

3.5 Impact and more unfavorable pollutographs identification

Defining a more unfavorable event depends on the objective of application. Thus, it may be different if the discharge of runoff to a receiving water body is considered and, in turn, different if this is a river, estuary, sea, etc. or your direct entry to a WWTP; or if the goal is to design a control and overflow treatment system.

From a qualitative point of view, the most unfavorable pollutograph will be the one that contributes the most pollution. It is necessary to define what is understood as greater contamination since this can be concentration, instantaneous mass flow or spilled mass. In turn, these variables, given their variation in the pollutograph, will have to be characterized (mean values, peak values, etc.). In addition, there will be other conditions that make a certain contamination (the variable) more or less unfavorable. Among these "unfavorable" conditions, it is worth highlighting the time of action of the variable, mass discharged, associated water volume and probability of occurrence of the event.

Generally, the most unfavorable sense of these conditions is: greater mass, less volume, greater time and greater probability.

When analyzing this effect and trying to represent it by means of the variables that characterize the hydrograph and the pollutographs, the following scenarios are identified (Table 5):

For concentrations or discharged masses, a greater volume or a greater flow associated with them, causes a greater dilution and therefore less unfavorable contamination events.

Table 5. Most unfavourable situations to evaluate pollution events

↑ Greater values ↓ Lower values	Effect
↑: Cp, Clast, Cm, EMC, Cfp, Fp, Fm, Mt	Greater pollution
↓: P, Qmean, Qmax, Qfp, Vrain, $(Vloss)^{-1}$, Vt	Less volume of water discharge
↑: Tqmax, Tcp, Tclast, Tfp, Tt	Longer event duration
↓: Tr (IDF Curves)	Greater probability

To evaluate the most unfavorable pollutographs, a resulting variable called IEV (Impact Evaluation Variable) was calculated using the following formulas:

$$(maxVAR)_j = max\begin{pmatrix} \overbrace{VAR_j}^{I1,D1} & \overbrace{VAR_j}^{I1,D2} & \overbrace{VAR_j}^{I1,D3} & \dots & \overbrace{VAR_j}^{I1,Dn} \\ \overbrace{VAR_j}^{I2,D1} & \overbrace{VAR_j}^{I2,D2} & \overbrace{VAR_j}^{I2,D3} & \dots & \overbrace{VAR_j}^{I2,Dn} \\ \overbrace{VAR_j}^{I3,D1} & \overbrace{VAR_j}^{I3,D2} & \overbrace{VAR_j}^{I3,D3} & \dots & \overbrace{VAR_j}^{I3,Dn} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ \overbrace{VAR_j}^{Im,D1} & \overbrace{VAR_j}^{Im,D2} & \overbrace{VAR_j}^{Im,D3} & \dots & \overbrace{VAR_j}^{Im,Dn} \end{pmatrix} \quad (11)$$

Where:

VAR_j: Any variable of characterization of the pollutographs

I1, I2, I3, … , Im: are the rainfall intensities chosen from the selected matrix

D1, D2, D3, … , Dn: are the rain durations chosen from the selected matrix

$\overbrace{VAR_j}^{I,D}$: Is the value of the characterization variable "j" for an intensity "I" and a duration "D" of the rainfalls matrix

$(maxVAR)_j$: Maximum value of the selected characterization variable, of the entire rainfalls matrix chosen

When higher values (↑ Greater values) of a specific characterization variable were searched, the following expression was used:

$$K_j \cdot \frac{\overbrace{VAR_j}^{I,D}}{(\mathrm{maxVAR})_j} \quad (12)$$

And when lower values were searched (↓ Lower values), was used:

$$K_j \cdot \left(1 - \frac{\overbrace{VAR_j}^{I,D}}{(\text{maxVAR})_j}\right) \tag{13}$$

So that; the value of the impact evaluation variable "iev" of a set "T" of characterization variables for a rainfall of intensity "I" and a duration "D" of the rainfalls matrix was:

$$\overbrace{iev}^{I,D} = \sum_{j=1}^{T}\left[K_j \cdot \frac{\overbrace{VAR_j}^{I,D}}{(\text{maxVAR})_j} \quad or \quad K_j \cdot \left(1 - \frac{\overbrace{VAR_j}^{I,D}}{(\text{maxVAR})_j}\right)\right] \tag{14}$$

Being:

iev: Value of the IEV impact evaluation variable

$\overbrace{iev}^{I,D}$: Value of the IEV impact evaluation variable for an intensity "I" and a duration "D" of the rainfalls matrix

T: Number of characterization variables chosen to find the variable IEV

K_j: Weight coefficient ("weight" or importance) of each characterization variable chosen

As it was desired that the impact assessment variable had a 10 point scale impact evaluation, it had to be fulfilled that:

$$\sum_{j=1}^{T} K_j = 10 \tag{15}$$

Therefore, the impact assessment variable could be expressed as follows:

$$IEV = \begin{pmatrix} \overbrace{iev}^{I1,D1} & \overbrace{iev}^{I1,D2} & \overbrace{iev}^{I1,D3} & \dots & \overbrace{iev}^{I1,Dn} \\ \overbrace{iev}^{I2,D1} & \overbrace{iev}^{I2,D2} & \overbrace{iev}^{I2,D3} & \dots & \overbrace{iev}^{I2,Dn} \\ \overbrace{iev}^{I3,D1} & \overbrace{iev}^{I3,D2} & \overbrace{iev}^{I3,D3} & \dots & \overbrace{iev}^{I3,Dn} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ \overbrace{iev}^{Im,D1} & \overbrace{iev}^{Im,D2} & \overbrace{iev}^{Im,D3} & \dots & \overbrace{iev}^{Im,Dn} \end{pmatrix} \tag{16}$$

3.5.1 Impact evaluation variables (IEV's)

Determining the unfavourability of a pollutograph when looking for a greater mass discharge, smaller volume and longer time would result, for example, in finding IEV variables such as (Table 6):

Table 6. IEV's examples

IEV	FORMULA
↑Mt↓P	$\uparrow Mt \downarrow P = K_1 \cdot \frac{Mt}{\max(Mt)} + K_2 \cdot \left(1 - \frac{P}{\max(P)}\right)$ $K_1 = K_2 = 5$
↑Mt↑Tt	$\uparrow Mt \uparrow Tt = K_1 \cdot \frac{Mt}{\max(Mt)} + K_2 \cdot \frac{Tt}{\max(Tt)}$ $K_1 = K_2 = 5$
↑Mt↓Vt	$\uparrow Mt \downarrow Vt = K_1 \cdot \frac{Mt}{\max(Mt)} + K_2 \cdot \left(1 - \frac{Vt}{\max(Vt)}\right)$ $K_1 = K_2 = 5$
↑EMC↑Tt	$\uparrow EMC \uparrow Tt = K_1 \cdot \frac{EMC}{\max(EMC)} + K_2 \cdot \frac{Tt}{\max(Tt)}$ $K_1 = K_2 = 5$
↑Mt↓Vt↑Tt	$\uparrow Mt \downarrow Vt \uparrow Tt = K_1 \cdot \frac{Mt}{\max(Mt)} + K_2 \cdot \left(1 - \frac{Vt}{\max(Vt)}\right) + K_3 \cdot \frac{Tt}{\max(Tt)}$ $K_1 = K_2 = K_3 = 3.33$

The graphic representation of these IEV's can be seen in Figure S2 of Supplementary data.

In these examples of IEV's, the variable Tr has not been taken into account in a premeditated manner so that it can be applied as a final criterion to analyze the unfavorability of the pollutograph and thus be able to apply the proposed methodology to other geographical areas with their corresponding IDF curves.

IEV's variables that have been discarded since they contribute little to the determination of the unfavorability of pollutographs due to the duplicity of effects they incorporate (see equations in point 2.5) or because of their little or obvious information they provide, they have been: ↑Fm↑EMC; ↑Fm↑Mt; ↑Fm↑Tt; ↑Fp↑ Cp; ↑Fp↓ Qmean.

In general terms, from the conceptual point of view, the IEV variable that allows to better categorize the most unfavorable pollutographs is ↑Mt↓Vt↑Tt.

3.5.2 Discharge analysis to a receiving water body

Taking as a final destination of the urban runoff a receiving water body such as a river and assuming complete and instantaneous mixing in the whole section of the river in which the discharge occurs, the following equation could be applied:

$$Cr = \frac{Cro \cdot Qro + Cd \cdot Qd}{Qro + Qd} = \frac{Fro + Fd}{Qro + Qd} \tag{17}$$

Where:

Cr: Concentration (mg/L) in the river at the point of mixing

Cro: Initial concentration (mg/L) in the river

Qro: Initial flow (L/s) of the river

Fro: Initial mass flow (mg/s) in the river

Cd: Concentration (mg/L) of runoff water discharge

Qd: Discharge flow (L/s) of runoff water

Fd: Mass flow rate (mg/s) of runoff water

a) Discharge in average conditions:

Using the Fm and Qmean characterization variables as discharge variables and using the above equation, a new IEV variable can be found:

$$Cr_{Fm} = \frac{Fro + Fm}{Qro + Qmean} = \frac{Cro\ \cdot Qro + \ EMC\ \cdot Qmean}{Qro + Qmean} \tag{18}$$

Cr_{Fm}: Concentration (mg/L) in the river at the point of mixing due Fm and Qmean discharge

b) Discharge under peak conditions:

Using the Fp and Qfp characterization variables as discharge variables:

$$Cr_{Fp} = \frac{Fro + Fp}{Qro + Qfp} = \frac{Cro\ \cdot Qro + \ Cfp\ \cdot Qfp}{Qro + Qfp} \tag{19}$$

Cr_{Fp}: Concentration (mg/L) in the river at the point of mixing due Fp and Qfp discharge

In order to observe the effect that each of the chosen rainfalls matrix pollutographs exerts on the river as a direct discharge, the following values have been assumed keeping them constant:

Cro = 10 mg/L for TS pollutant

Qro = 10 L/s

Thus, the new variables IEV: Cr_{Fm} and Cr_{Fp} can be calculated for each pollutograph of the chosen rainfalls matrix and represented in a table with their corresponding values: mean, maximum, minimum, standard deviation, coefficient of variation (%) and P90 (see Table S1) and in graph form (see Figure S2).

To determine the unfavorability of the pollutographs from the point of view of discharge to the river, the following additional IEV variables can be found (Table 7).

As a most unfavorable condition, Cr_{Fp} is considered to have an incidence time associated with the receiving water body of twice the Tfp time.

The graphical representation of these IEV's can be seen in Figure S2 and their ten highest values with their corresponding associated I-D-Tr are presented in Table 8 and Table 9:

Table 7. IEV's examples to analyse urban runoff discharges to the river

IEV	FORMULA
$\uparrow Cr_{Fm} \uparrow Tt$	$\uparrow Cr_{Fm} \uparrow Tt = K_1 \cdot \frac{Cr_{Fm}}{\max(Cr_{Fm})} + K_2 \cdot \frac{Tt}{\max(Tt)}$ $K_1 = K_2 = 5$
$\uparrow Cr_{Fp} \uparrow 2$ Tfp	$\uparrow Cr_{Fp} \uparrow 2 \cdot T_{Fp} = K_1 \cdot \frac{Cr_{Fp}}{\max(Cr_{Fp})} + K_2 \cdot \frac{2 \cdot T_{Fp}}{\max(2 \cdot T_{Fp})}$ $K_1 = K_2 = 5$

Table 8. Ten highest values of $\uparrow Cr_{Fm} \uparrow Tt$ with its corresponding unfavourable rains I-D-Tr (Santander) for the TS pollutant

I (mm/h)	D (min)	Tr (years)	$\uparrow Cr_{Fm} \uparrow Tt$
5	300	0.50	7.60
7	300	1.11	7.46
3	300	0.15	7.46
10	300	2.60	7.15
5	240	0.38	7.06
7	240	0.84	7.00
3	240	0.11	6.78
10	240	1.97	6.72
7	180	0.59	6.60
5	180	0.27	6.54

Table 9. Ten highest values of $\uparrow Cr_{Fp} \uparrow 2 \cdot Tfp$ with its corresponding unfavourable rains I-D-Tr (Santander) for the TS pollutant

I (mm/h)	D (min)	Tr (years)	$\uparrow Cr_{Fp} \uparrow 2 \cdot Tfp$
1	180	0.006	6.27
1	240	0.008	6.27
1	300	0.011	6.27
1	120	0.003	6.03
60	2	0.374	5.12
40	4	0.336	5.11
80	2	0.742	5.08
20	10	0.201	5.04
20	8	0.152	5.00
40	6	0.555	4.99

Other IEV's variables such as ↑Fm↓ Qmean and ↑ Fp↓ Qfp are discarded since their contribution to the determination of the unfavorability of pollutographs in the river discharge due to duplication of effects they incorporate (see equations in point 2.5) is not clear.

3.5.3 Overflow analysis and retention tanks sizing

The unfavorability of the pollutographs can also be investigated from the point of view of the necessary volume of storage of the surface runoff that each pollutograph demands when simulating the overflow of a stormwater sewer system where part of the runoff has been sent to a Wastewater Treatment Plant (WWTP).

a) Dry weather flow:

   For the urban basin of 1 ha, a water supply demand of 250 L/hab/day is assumed (Ayuntamiento de Santander, 2007; Hermoso, García-Ruiz, & Osorio, 2018) and with a population density of 100 hab/ha (Temprano et al., 2007) which results in an average dry weather flow of Qdw = 25 m^3/day/ha = 0.289 L/s/ha.

b) Diverted flow to WWTP:

   Several researchers mention different values for the allowable flow to be derived to WWTP based on a maximum dilution. E.g. Suárez-López et al. (2012) in the analysis of the behavior of a detention-spillway tank based on the maximum flow sent to the WWTP, mentioned 3 Qdw; 6 Qdw; 9 Qdw; De Martino, De Paola, Fontana, Marini, & Ranucci (2011) mention values of 3 to 7 Qdw; Anta et al. (2007) cite investigations with 2.5 Qdw; 5 Qdw; 7 Qdw; 9.9 Qdw. In the present investigation, a value of 9 Qdw = 2.604 L/s is assumed for the 1 ha urban basin.

   Since an exclusively pluvial network is simulated, the flow of 2.604 L/s = Q_{WWTP} will correspond to the flow of runoff water that is admitted to treatment in the WWTP (see Figure 9).

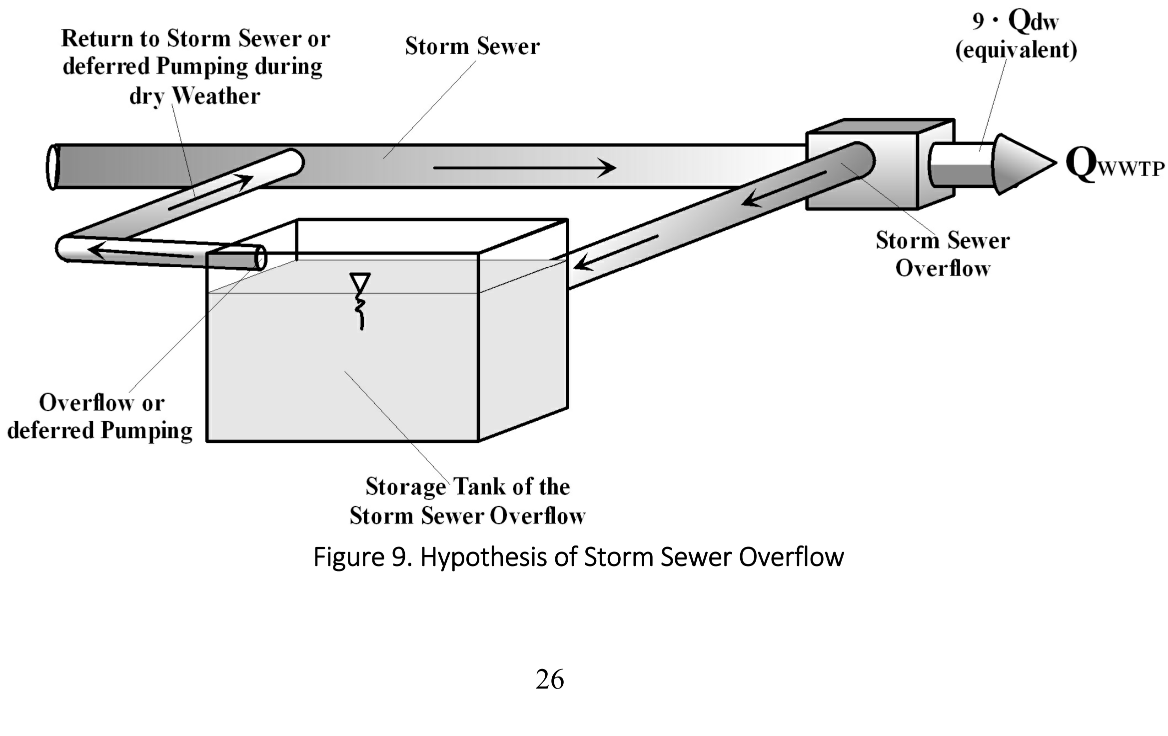

Figure 9. Hypothesis of Storm Sewer Overflow

c) Overflow and retention tank:

In each pollutograph of the chosen rainfalls matrix the runoff water overflow will occur between times 0 and Tt in which it is fulfilled that:

$$Q(t) > Q_{WWTP} \quad (20)$$

And the 100% of the overflow volume during times 0 and Tt will be:

$$Vstso = \int_{0}^{Tt} (Q(t) - Q_{WWTP})\, dt \quad (21)$$

Vstso: Storm Sewer Overflow (m^3/ha imp)

Vstso is expressed as ha imp (impervious hectare) since Q(t) corresponds to the runoff flow of the simulated urban basin (1 ha).

Using the characterization variables Qmax and Qmean of the hydrographs, the overflow volume for each I-D position of the rainfalls matrix could be calculated:

$$Vstso = (Qmax - Q_{WWTP}) \cdot Tt \quad (22)$$

$$Vstso = (Qmean - Q_{WWTP}) \cdot Tt \quad (23)$$

The Qmean option is chosen as the approximate method since with Qmax the resulting volumes would be excessive (higher than real values). However, it should be noted that there would be I-D's in the rainfalls matrix that still fulfilling:

$$Qmean < Q_{WWTP} \quad (24)$$

and would have small runoff water overflows since:

$$Qmax > Q_{WWTP} \quad (25)$$

Not taking this situation into account, the expression is chosen:

$$Vstso = (Qmean - Q_{WWTP}) \cdot Tt \quad (26)$$

to estimate the storm sewer overflow volume for a given I-D.

On the other hand, if defined:

$$Vstorage = RVF \cdot Vstso \quad (27)$$

RVF: Retained Volume Fraction (%) of Vstso

Vstorage: storage tank volume (m^3/ha imp) of the storm sewer overflow

Vstso and Vstorage, by definition, will always have an EMC concentration associated.

Calculating for the entire Vstorage rainfalls matrix, eliminating those I-D rains where: Qmean ≤ Q_{WWTP}; and eliminating those I-D rains that exceed a Tr_{ssd} (Return period of storm sewer design) (e.g. 10 years) a series of rains could be had with an associated Vstorage. An example of this is the

Vstso and Vstorage matrices for a specific case of RVF and Tr_{ssd} and where the P90 value is the 90th percentile of the rainfall series data mentioned above.

If in Table 10 the value of Vstorage that is closest to P90 is searched for each intensity, the data series could be further limited. In addition, if each value is assigned its corresponding ↑Mt↓Vt↑Tt and its Tr (Santander), the following design values (Table 11) could be obtained.

In Table 11, we look for the values that:

a) Have the highest value of ↑Mt↓Vt↑Tt.

b) More approximate the value of P90 = 108.93 (Table 10); that is, minimizing Dif.P90 Vstorage.

$$Dif.P90Vstorage = |Vstorage - P90| \quad (28)$$

Dif.P90 Vstorage: Absolute value of the difference between Vstorage and P90 (m^3/ha imp)

c) Have the lowest associated Tr.

In summary, find the values of Vstorage that meet: ↑↑Mt↓Vt↑Tt; ↓Dif.P90 Vstorage and ↓Tr. The order of application of this search "filter" is important; that is, look for values of the variable IEV ↑Mt↓Vt↑Tt with greater impact, then look for storage volume values that are closest to the P90 of its series and finally, look for the lowest associated Tr values.

So, for the condition RVF = 80% and Tr_{ssd} (Santander) = 10 years, the solution would be Vstorage = 117.20 m^3/ha imp, Dif.P90 Vstorage = 8.27 m^3/ha imp, ↑Mt↓Vt↑Tt = 9.43 and a Tr = 1.11 years for a more unfavourable pollutograph produced by a precipitation I = 7 mm/h and D = 300 min within the selected rainfalls matrix.

Repeating the same methodology for several values of Tr_{ssd} and RVF, the Table 12 is obtained.

Table 10. Vstorage (m^3/ha imp) for TS pollutant with RVF = 80% and Tr (Santander) = 10 years

I (mm/h)	D (min)															
	2	4	6	8	10	15	20	25	30	35	50	80	120	180	240	300
300																
140	22.75	45.03														
120	17.93	36.81	55.97													
100	13.01	28.67	44.43	60.35	76.59											
80	8.22	20.67	33.21	45.75	58.33	90.42										
60	3.49	12.71	21.93	31.27	40.60	63.93	87.35	111.11								
40		4.76	10.77	16.90	23.03	38.36	53.68	69.01	84.33	99.66	145.63					
20			0.03	2.82	5.62	12.94	20.26	27.58	34.89	42.21	64.17	108.08	166.63	254.45		
10						0.51	3.70	7.01	10.33	13.64	23.59	43.48	70.00	109.79	149.57	189.36
7								1.03	3.14	5.26	11.48	24.16	41.08	66.45	91.83	117.20
5											3.57	11.46	21.97	37.73	53.50	69.27
3													3.00	9.16	15.32	21.48
1																

Minimum: 0.03 Mean: 46.65 Standard deviation: 48.06

Maximum: 254.45 P90: 108.93 Coefficient of variation (%): 103.03

Table 11. For each Intensity: values of Vstorage (m^3/ha imp) closer to P90 with its corresponding ↑Mt↓Vt↑Tt (10 point scale) and Tr (years) for TS pollutant. [RVF = 80% and Trssd (Santander) = 10 years]

I (mm/h)		D (min) 4	6	10	15	25	35	80	180	300
140	Vstorage: ↑Mt↓Vt↑Tt: Tr:	45.03 5.17 6.64								
120			55.97 5.38 7.60							
100				76.59 5.73 9.26						
80					90.42 5.96 9.00					
60						111.11 6.32 8.54				
40							99.66 6.36 4.93			
20								108.08 7.01 2.63		
10									109.79 8.14 1.38	
7										117.20 9.43 1.11
5										69.27 9.13 0.499
3										21.48 8.56 0.148

Table 12. Values of Vstorage with its corresponding unfavourable rains I-D-Tr (Santander) for the TS pollutant (For different RVF's and Trssd's)

Tr_{ssd} (years)	RVF (%)	I (mm/h)	D (min)	↑Mt↓Vt↑Tt	P90 (m^3/ha imp)	Vstorage (m^3/ha imp)	Dif.P90 Vstorage (m^3/ha imp)	Tr (years)
5	30	5	300	9.13	35.90	25.97	9.93	0.50
5	50	5	300	9.13	59.84	43.29	16.55	0.50
5	80	5	300	9.13	95.74	69.27	26.48	0.50
5	100	5	300	9.13	119.68	86.58	33.10	0.50
10	30	7	300	9.43	40.85	43.95	3.10	1.11
10	50	7	300	9.43	68.08	73.25	5.17	1.11
10	80	7	300	9.43	108.93	117.20	8.27	1.11
10	100	7	300	9.43	136.17	146.50	10.33	1.11
15	30	7	300	9.43	53.07	43.95	9.12	1.11
15	50	7	300	9.43	88.45	73.25	15.20	1.11
15	80	7	300	9.43	141.52	117.20	24.32	1.11
15	100	7	300	9.43	176.90	146.50	30.40	1.11
20	30	7	300	9.43	54.91	43.95	10.96	1.11
20	50	7	300	9.43	91.51	73.25	18.26	1.11
20	80	7	300	9.43	146.42	117.20	29.22	1.11
20	100	7	300	9.43	183.02	146.50	36.52	1.11
25	30	7	300	9.43	61.05	43.95	17.10	1.11
25	50	7	300	9.43	101.74	73.25	28.49	1.11
25	80	7	300	9.43	162.79	117.20	45.59	1.11
25	100	7	300	9.43	203.49	146.50	56.98	1.11

The estimated storage volumes (Table 12) can be summarized as follows:

a) RVF = 30%

With Tr_{ssd} = 5 years, it was obtained 25.97 m^3/ha imp.

With Tr_{ssd} ≥ 10 years, it was obtained 43.95 m^3/ha imp.

b) RVF = 50%

With Tr_{ssd} = 5 years, it was obtained 43.29 m^3/ha imp.

With Tr_{ssd} ≥ 10 years, it was obtained 73.25 m^3/ha imp.

c) RVF = 80%

With Tr_{ssd} = 5 years, it was obtained 69.27 m^3/ha imp.

With Tr_{ssd} ≥ 10 years, it was obtained 117.20 m^3/ha imp.

d) RVF = 100%

With Tr_{ssd} = 5 years, it was obtained 86.58 m^3/ha imp.

With Tr_{ssd} ≥ 10 years, it was obtained 146.50 m^3/ha imp.

From this summary it can be concluded that the design values of storm tanks, for the case studied and with RVF values between 30% and 100%, would be between 44 and 147 m^3/ha imp. Without limiting RVF values, similar results have been obtained by other researchers; e.g. Andrés-Doménech (2010) cites in his research several methods concerning the volumetric sizing of storm tanks. For example, mention a technical report of the Environment Agency, UK on "Constructed Wetlands and Links with Sustainable Drainage Systems" (2003) where it is recommended to retain 100 to 150 m^3/ha imp [10 to 15 mm of net rain (runoff)]. It also cites Italian criteria with values of 100 to 150 m^3/ha imp to significantly reduce the frequency and volumes of spills and pollutants masses. In Spain, Andrés-Doménech (2010), quote to Temprano, Suárez, & Tejero, (1998) and Temprano & Tejero (2002) with tanks volumes values of the order of 120 m^3/ha imp. He also cites researches from the Valencia City Council and the Department of Hydraulic and Environmental Engineering of the UPV that result in volumes of storm tanks between 65 and 80 m^3/ha imp. It also quotes the state company ACUAMED with projects with ratios of 100 m^3/ha imp for the metropolitan area of the city of Valencia.

If in the methodology described in point 3.5.3.c we take into account the rainfalls (I-D's) in the rainfalls matrix that meet the Qmean < Q_{WWTP} condition but have small runoff water overflows because Qmax > Q_{WWTP}, they would be obtained P90 values (Table 10) slightly lower. However, the values in Table 11 would be the same (rains with small overflows are below the solutions in this table) and therefore the storage volumes and I-D positions of the most unfavorable rains described in the Table 12 would not change.

The estimated volumes (Table 12) correspond in all cases to low intensity rains "I" and long duration "D":

a) I (mm/h) = 5; D (min) = 300; P (mm) = 25; Tr (years) = 0.50 for Santander; Mt (kg) = 113.95; Mt/DD_7 (%) = 79.41.

b) I (mm/h) = 7; D (min) = 300; P (mm) = 35; Tr (years) = 1.11 for Santander; Mt (kg) = 126.57; Mt/DD_7 (%) = 88.21.

If different ADD values are analyzed, values greater than 7 give, as a replica, the same rains resulting from Vstorage since the values of Mt are practically the same, the same as their % of elimination. For smaller values of ADD the values of Mt change and therefore the % of elimination.

Even though, Andrés-Doménech (2010) mentions that researchers such as Clar et al. (2004), question studying design events to size storage tanks since they obviate the time of separation of ADD events. In this investigation it is verified that, from the point of view of the contamination of unfavourable events, more important than the value of the antecedent dry days ADD assumed, is its position with respect to the maximum possible value of accumulation MaxDD in the studied area. To apply the methodology described in this document to any other urban basin, the ADD assumed must be very close to the asymptote of the DD accumulation curve chosen. To make this methodology more general and take into account different values of ADD, a correction should be made to the calculation of the IEV variable: ↑Mt↓Vt↑Tt. Since both Vt and Tt are independent variables of ADD, the correction would focus on the variable ↑Mt. So that:

$$\uparrow Mt \ \downarrow Vt \uparrow Tt = K_1 \cdot \frac{\boldsymbol{Mt}}{\mathbf{MaxDD}} + K_2 \cdot \left(1 - \frac{Vt}{\max(Vt)}\right) + K_3 \cdot \frac{Tt}{\max(Tt)} \quad (29)$$

Keeping

$$K_1 = K_2 = K_3 = 3.33 \quad (30)$$

and considering positions in the rainfalls matrix (I-D rains, Vstorage) in which for example $\frac{Mt}{\mathrm{MaxDD}} < 0.5$. ADD's that would cause unfavourable low pollution situations with associated runoff would not be taken into account unlike those that would produce ADD's with DD accumulation values close to the asymptote of the assumed accumulation curve.

The methodology used in this research could be summarized as follows in Figure 10:

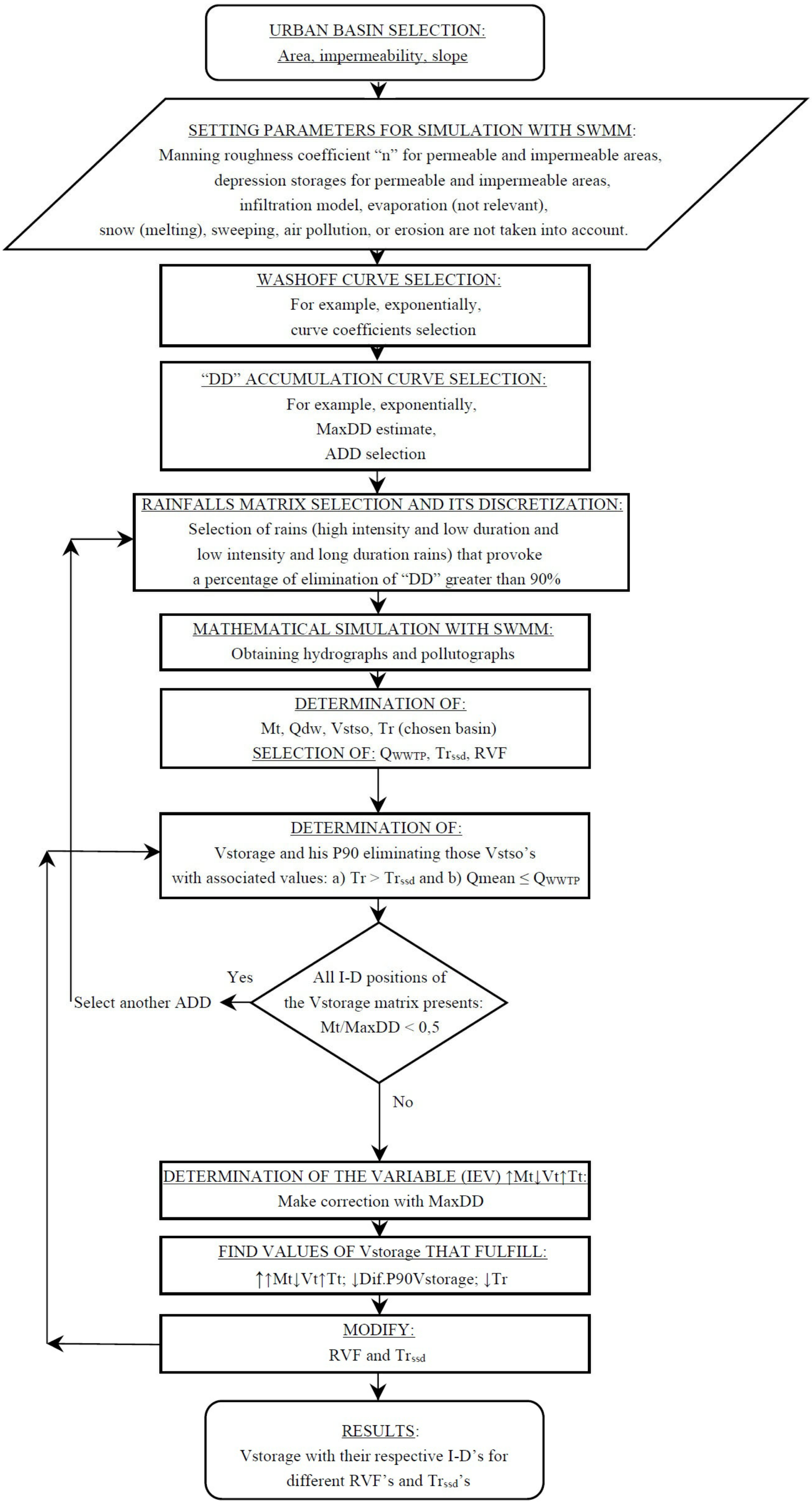

Figure 10. Flow chart of the proposed methodology

The scope of the analysis of this research is limited by the ideal basin used and by the values of the simulation parameters adopted when representing a specific reality. However, both the proposed methodology and the results can be generalized, by applying them to other realities.

4. CONCLUSIONS

In the rainfalls matrix there is an area where the pollutographs have Clast values greater than Cp; this occurs approximately for “I” rainfall intensities greater than 150 mm/h and “D” durations smaller than 8 min and for intensities smaller than 150 mm/h and “D” durations lower than 20 min (see contour plot of (Clast - Cp) > 0, Figure S1). In this area Clast may have values of 2,692.3 mg/L of TS being higher with Cp in 1,194.8 mg/L (rainfall of I = 100 mm/h, D = 2 min). When observing the pollutograph of this rain, it was possible to verify that this Clast value was accompanied by a runoff flow of 0.074 L/s. Thus, there may be pollutographs that, in their final part, have very long "tails" with very high concentration values accompanied by very small flow rates thus distorting the representativeness, for example, of the variable Cm. Something that does not happen with the EMC variable.

When observing the most representative correlations between the variables (Table S2) it was found that the intensity of the rain “I” correlated quite well with the variables Qfp, Fp, Qmax with values R ≥ 0.972. The EMC variable was correlated with Cfp with an R = 0.932 and with Mt with an R = -0.897 and the rain duration "D" was correlated with Tqmax with a value R = 0.861. The variable IEV ↑Mt↓Vt↑Tt was correlated with Mt with an R = 0.927 and with EMC with an R = -0.808. The Cr_{Fm} variable had low correlations with the characterization variables of the pollutographs, R ≤ 0.210. Cr_{Fp} was correlated with Cfp with an R = -0.786 and with EMC with an R = -0.744. The variables IEV ↑Cr_{Fm}↑Tt and ↑Cr_{Fp}↑2·Tfp had low correlations with the characterization variables of the pollutographs; R ≤ -0.510 and R ≤ -0.573 respectively.

The IEV variable that best allowed to find the most unfavorable pollutographs was ↑Mt↓Vt↑Tt. When observing the graph of this IEV (Figure S2) it was possible to verify that the unfavorability of the pollutographs grows from a shorter rain duration "D" to a greater one. Also, taking into account the isolines of the IEV variable and its associated Tr in the rainfalls matrix, it can be concluded that the unfavorability of the pollutographs grows from higher rainfall intensity "I" to a lower one. Thus, the most unfavorable pollutographs are presented for low intensity rains "I" and long duration "D".

In the analysis of discharge to a receiving medium when analyzing the IEV (↑Cr_{Fm}↑Tt, Figure S2 and Table 8) a behavior similar to the previous IEV commented in the previous paragraph could be verified; the tendency of greater unfavorability is the same in the rainfalls matrix. That is to say, the most unfavorable situations are also presented for low intensity rains "I" and long duration "D".

The variable IEV (↑Cr_{Fp}↑2·Tfp, Figure S2 and Table 9) presents its most unfavorable values for low intensity rains “I”; nevertheless, its unfavorability is independent of the duration of the rain "D" once the Tfp time is reached in each of the analyzed pollutographs. If Tfp resembles the concentration time of the basin; from the hydrological point of view, it could be affirmed that in the runoff (after the concentration time of the analyzed urban basin has elapsed), the unfavorable events associated with it in peak conditions, are independent of the "D" duration of the rainfalls.

This research presents a novel methodology to determine runoff water retention volumes that allow the design of storage tanks for storm sewer overflows. It is applicable to any urban basin. However, the return period Tr of the study area should be used, thus specifying the assignment of the probability of occurrence of the most unfavorable events of pollution caused by urban runoff in the study basin.

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DECLARATION OF INTEREST STATEMENT

The authors report there are no competing interests to declare

DATA AVAILABILITY

Supplementary data to this article:

- Table S1: values of the characterization variables
- Table S2: correlation and determination coefficients
- Figure S1: contour plots of the characterization variables
- Figure S2: contour plots of IEV's variables

are available online at http://dx.doi.org/10.17632/9br5hkzn94.1

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