

Setting up design storms to determine the volume of retention tanks

Paramétrage de pluies de projet pour le dimensionnement des ouvrages de rétention

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ABSTRACT

This study aims at developing a new design tool of storm water storage structures based on the use of the concept of design storms and IDF (Intensity-Duration-Frequency) curves. For that purpose, we have collected rainfall data from the Urban Community of Lyon in France, measured over 16 years on the station GERLAND. From these data and through an experimental design, we conducted a frequency analysis of storage volumes based on the definition and implementation of a frequential model (the Gumbel model) and thus defined storage volumes associated with return periods. For each experiment, with respect to the Montana coefficients and the return periods, we then investigated, using simple triangle design storms, the durations of rainfall for which estimated storage volumes were slightly above the storage volumes obtained with the Gumbel method taken as reference. Following this study, we elaborated a mathematical model linking the duration of the design storm with the runoff coefficient, the release rate and the return period. The results of storage volumes obtained show that the new tool leads to an adequate design of the storage structures.

RÉSUMÉ

Cette étude vise la mise au point d'un nouvel outil de dimensionnement des ouvrages de stockage des eaux pluviales basé sur l'utilisation du concept de pluie de projet et des courbes IDF (Intensité-Durée-Fréquence). A cet effet, nous disposons de données pluviométriques de la Communauté Urbaine de Lyon, mesurées sur 16 années sur la station de GERLAND. A partir de ces données et par le biais d'un plan d'expérience, nous avons conduit une analyse fréquentielle des volumes de stockage reposant sur la définition et la mise en œuvre d'un modèle fréquentiel à savoir le modèle de Gumbel et ainsi défini des volumes de stockage associés à des périodes de retour. Pour chaque expérience, en fonction des coefficients de Montana et des périodes de retour associées, nous avons ensuite recherché, par le biais de pluies de projet simple triangle, les durées de pluies pour lesquelles les volumes de stockage estimés étaient juste supérieurs aux volumes de stockage obtenus avec la méthode de Gumbel prise comme méthode de référence. A l'issue de cette étude, nous avons réalisé un modèle mathématique reliant la durée de pluie de projet au coefficient de ruissellement, au débit de fuite et à la période de retour. Les résultats des volumes de stockage obtenus montrent que le nouvel outil permet de dimensionner de façon adéquate les ouvrages de stockage.

KEYWORDS

Retention tank, design storm, experimental design, storage volume

1 INTRODUCTION

It was noticed that most natural hydrological disasters in our countries are consequences of lacks in management of hydrographical systems, or even of errors in the conception and in the maintenance of rainwater sewer networks [Tassin B & al, 2004]. However, these drainage works were conceived, in France, from the design methods recommended by the "Technical Guidelines of 1977" [MINISTERES, 1977]. That's the reason why, for the past twenty years, the question of whether or not to renew the design methods of sewerage and drainage systems, and thus renew the Technical Guidelines of 1977 has been put [CERTU, 2003]. This question is all the more legitimate that, between 1949 and 2003, the approach of integration of sewage system in urban planning and environment changed as well from a legal point of view as from a technical one (see French Water Act of 03/01/92, the European Directive of May 21, 1991 on urban waste water treatment, French Decentralization Act of 1982). Moreover, the growth of scientific and technical knowledge has enabled the development of methods that focus on taking local conditions into account. Because of this constant development of knowledge, [CERTU, 2003] in his document "The city and its sewage system" (in French "La Ville et son assainissement") reminds that it is justified to use other models if they prove to be better adapted to the local context than the models generally in use.

1.1 Definition of problem

Nowadays, no design methods proposed in the Technical Guidelines of 1977 seems particularly satisfactory for storage structures of storm water. Indeed, in their study analyzing the "dimensioning" properties of storms using a stochastic rainfall model [Gaume E & al, 2000] showed that the two design methods proposed in the Technical Guidelines of 1977 (rainfall method and volumes method) are not fully efficient. They often appear to lead to oversized or undersized structures. The stochastic method is also recommended by [Chocat B & al, 1997] and [STU, 1983]. However it is somewhat cumbersome in its implementation and often unrealistic while most design offices do not have the urban hydrological models to perform continuous simulations using extensive rainfall data and may lack of the expertise requested for statistical analysis.

1.2 Objective, Methodology and data used

Given the foregoing, we opted to elaborate a new design tool of rainwater storage structures accounting for their functional, economical and environmental characteristics (Reduction of storm peaks, reduction of sewer systems size and cost, site enhancement, etc...). We plan to use the concept of design storm that uses the IDF curves to determine storage structures volumes, applied to the triangle design storm. In order to establish a mathematical relationship between the duration of design storm and characteristics of the storage structure and watershed, an experimental design is elaborated. This design includes 36 cases of watersheds subjected to 16 years of rainfall recorded in Lyon Gerland. We then performed a statistical analysis of volumes and define storage volumes associated with return periods for each experiment. According to the coefficients of Montana and the return periods, we then determined for each case, using simple triangle design storms, the durations of rainfall for which estimated storage volumes were immediately above the storage volumes obtained with the statistical analysis taken as reference method. Following that, we performed a mathematical model linking the duration of the design storm with the runoff coefficient, the leak flow rate and the return period. The rainfall data used in our study are the time series of rain in the urban community of Lyon-France "station Gerland". These data are original recordings of 1567 hyetographs for a total duration of 16 years.

2 CONSTRUCTION OF IDF CURVES

The IDF curves are a widely used tool to dimension structures and also to make local or regional estimates of extreme precipitation, [H Madsen et al, 1998], [Roux, 1996], [Xia Z, 2005]. To build the IDF curves we have to identify, for each event of the time series, the average maximum intensity that is to say the maximum corresponding to the different cumulated durations that we selected (6, 12, 18, 24, 30, 60, 120, 240, 360, 480) min. . We retain the P highest values, with P between N and 2N with N the number of years of observation (here 16 years)

We selected a sample size of $P = 30$ values of average maximum intensity, and then we assigned to each of these values an empirical frequency of non-exceedance (according to Hazen). We then use the Gumbel distribution to conduct our frequency analysis. In urban hydrology, [Engeland K et al, 2005] [M Lang, 2000], [Margoum M, 1994], this law is frequently used to model extreme events, especially for rainfall. On the other hand, [Musy, 2003] showed that fitted results are often satisfactory

if the Gumbel distribution and the empirical distribution of Hazen are combined.

The relevance of the choice of a value of $P = 30$ for the implementation of the Gumbel distribution has been verified by performing a calibration with the following values of P ($P = 30, P = 25, P = 20, P = 15, P = 10$). A fit, using a measure of the variability of the estimated values, is necessary to minimise the error made upon of the parameters of the statistical law. This can be done by calculating the coefficient of variation (CV) or the asymmetry coefficient of Pearson, [Roux, 1996], [Kakmier LJ, 1982], [Baillargeon, 2003].

The coefficient of variation of the sample is given by equation (1):
$$C_v = \frac{\sigma(x)}{\mu(x)} \tag{1}$$

Where: $\mu(x)$ Is the mean of the sample; $\sigma(x)$: The standard deviation of the sample.

The method of moments is used to perform the adjustment. This method allows equating sampling moments and theoretical moments of the Gumbel law using equations (2) (3) (4) (5):

$$f(x) = e^{-e^{\frac{-(x-a)}{b}}} \tag{2}$$

$$x = s[-\ln(-\ln f(x))] + x_0 \tag{3}$$

$$s = 0,780.\sigma(x) \tag{4}$$

$$x_0 = \mu(x) - 0,577.s \tag{5}$$

The calculated values of the coefficient C_v show that the variability of each type of population (observed and theoretical) is lower for a sample size of $P = 30$. We then selected this sample for a relevant use of the Gumbel distribution.

Once our data are fitted with a Gumbel law, we can construct the corresponding IDF curves (figure 1) using the Montana equation (6).

$$i(t) = at^b \tag{6}$$

where a et b are the Montana coefficients, i is the rainfall intensity and t is the time.

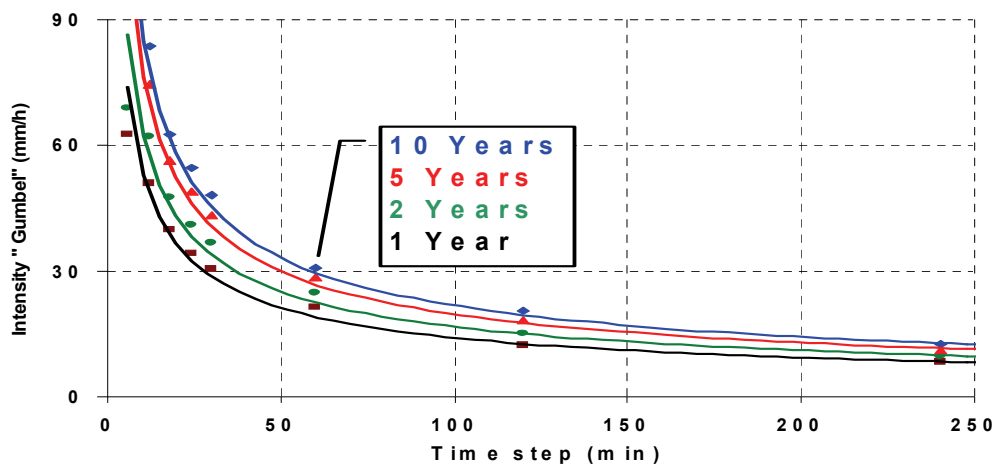


Figure 1: IDF Curves of the Gerland station

The coefficients of Montana of Gerland “ a ” and “ b ” issued from the IDF curves are presented in the table 1.

Return period	1year	2 years	5 years	10 years
a	3,535	4,117	5,2355	5,8793
b	-0,5876	-0,5845	-0,6008	-0,604

Table 1: The coefficients of Montana "a" and "b" of Gerland station

3 EXPERIMENTAL DESIGN

Experimental design is commonly used in the study of complex phenomena which need to be clarified in order to better understand their functioning and to optimise their performances. The approach is experimental: the information on the observed phenomenon is obtained from experiments (or computations simulating experiments). First, we have to list the parameters liable to influence the determination of retention tank volume. These parameters are the physical characteristics of the watershed (the area S , the runoff coefficient C , the slope I , the elongation coefficient M), the admissible release rate Q_{ad} , and the return period T . These parameters are also called explanatory variables and their values are associated with "description" levels. Secondly, we have to choose an experimental design matrix adapted to our case. We choose the matrix of the orthogonal experimental design of type $L_{16}4^5$ (table 2) which is build with 5 explanatory variables (here S, C, M, I, Q_{ad}) divided in 4 levels (0, 1, 2, 3). The explanatory variable T is not in the test matrix because the return period T is a "block factor", it represents an experimental condition that will vary during testing. So we have to repeat the experimental design for every return period that we want to test (here 1, 2, 5, and 10 years).

<i>explanatory variables</i>	S	C	M	Q_{ad}	I
Realization	Levels				
1	0	0	0	0	0
2	0	1	1	1	1
3	0	2	2	2	2
4	0	3	3	3	3
5	1	0	1	2	3
6	1	1	0	3	3
7	1	2	3	0	1
8	1	3	2	1	0
9	2	0	2	3	1
10	2	1	3	2	0
11	2	2	0	1	3
12	2	3	1	0	2
13	3	0	3	1	2
14	3	1	2	0	3
15	3	2	1	3	0
16	3	3	0	2	1

Table 2: Orthogonal matrix type $L_{16}4^5$ "experimental design"

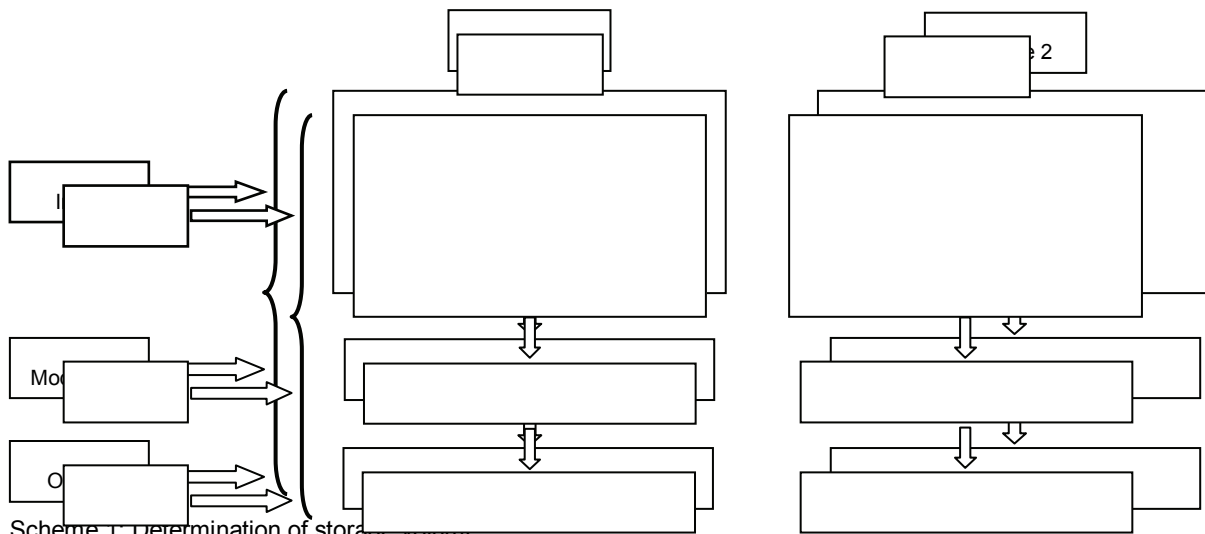
We will have finally to model $((16 \cdot 2) + 4) = 36$ watersheds because we initially chose 8 catchments areas of 0.01, 0.1, 1, 10, 50, 100, 500 and 1000 ha, involving the combination of two experimental designs $L_{16}4^5$ and therefore $(16 \cdot 2) = (32)$ experiments, to which we have added a other area of 250ha to reduce the amplitude between the watersheds of 100 ha and 500 ha, resulting in 4 additional experiments. Table 3 shows watersheds characteristics used for the 8 catchments area.

<i>Catchment's Area (ha)</i>	$(0.01), (50)$	$(0.1), (100)$	$(1), (500)$	$(10), (1000)$
Variables	Discretisation			
C (%)	30	50	70	90
M	1	2	3	4
Qad (l/s/ha)	1	2	3	4
slope (% or ‰)	1‰	5‰	1%	2%

Table 3: Discretisation of watersheds characteristics and storage structures

Our goal is on one hand to determine the storage volumes of the structure according to the return periods and on the other hand to determine the design storm duration required to evaluate correctly

the storage structure volume. The process can be schematized as follows:



Scheme 1: Determination of storage volume.

Scheme 2: Determination of design storm duration to evaluate exactly the storage structure volume.

4 STORAGE VOLUMES CALCULATION USING THE GUMBEL METHOD

The rainfall-runoff transformation is modelled with a linear reservoir model. This modelling is applied on each of our 36 watersheds using as input the recorded rainfall hyetographs. Then, we estimate storage volumes associated with return periods from the Gumbel law associated with the empirical distribution of Hazen. In summary, we are conducting a frequency analysis of storage volumes obtained with the time series.

The linear reservoir model is based on two kinds of functions:

- A production function is expressed by equation (7): $H_R = C_R(H_P - P_i)$ (7)

where H_R is the height of runoff water (mm), H_P the height of precipitation (mm), P_i the initial losses (mm) (that we consider here equal to zero) and C_R the runoff coefficient.

- A transfer function which it is expressed by two equations (8), (10):

The storage equation: $V_s(t) = K.Q_s(t)$ (8)

where $V_s(t)$ is the stored volume in the watershed (m^3), $Q_s(t)$ the outflow rate (m^3/s) and K the storage coefficient of the model (min).

K is estimated in equation (9) by M.Desbordes expression involving descriptive parameters of the watershed [Chocat et al, 1997]:

$$K = 0.245 \times S^{-0.0076} \times C_R^{-0.512} \times P^{-0.401} \times L^{0.608} \quad (9)$$

where C_R is the runoff coefficient of watershed, S the Area of watershed (ha), P the mean slope of watershed (m/m), L the longest water travel in watershed (m).

And the continuity equation or equation of volume conservation:

$$\frac{dV_s(t)}{dt} = Q_e(t) - Q_s(t) \quad (10) \quad \text{with} \quad Q_e(t) = C_R . S . i(t) \quad (11)$$

where $Q_e(t)$ is the inflow of the watershed (m^3/s) and i is the rainfall intensity (mm/h).

The frequency of non-exceedance is constructed from the empirical formula of Hazen Eqs (12) (13):

$$F_d = 1 - F ; F = \left(\frac{r - 0.5}{p} \right) \quad (12) \quad T = \frac{N}{F \times P} = \frac{N}{r - 0,5} \quad (13)$$

where F is the frequency, F_d the non exceedance frequency, r the rank, P the sample size (30), T the return period and N the observation period (16 years).

We then calculate the storage volumes from Gumbel for different return periods (1yr, 2yrs, 5yrs and 10yrs) from the equation (14):

$$V_{Gumbel} = s \times \left(-\text{Ln} \left(-\text{Ln} \left(1 - \frac{16}{30 \times T} \right) \right) \right) + x_0 \quad (14)$$

where T is the Return period (years) and s, x_0 are the Gumbel parameters.

Figure 2 presents a plot of storage volumes of reservoir model versus $[\text{Ln}(-\text{Ln}(Fd))]$, and the distribution of volumes obtained from Gumbel for watershed number 21 which has the following characteristics:

$$S = 100ha; C = 30\%; M = 2; Q_{ad} = 3; P = 2\%; K = 24,2975min$$

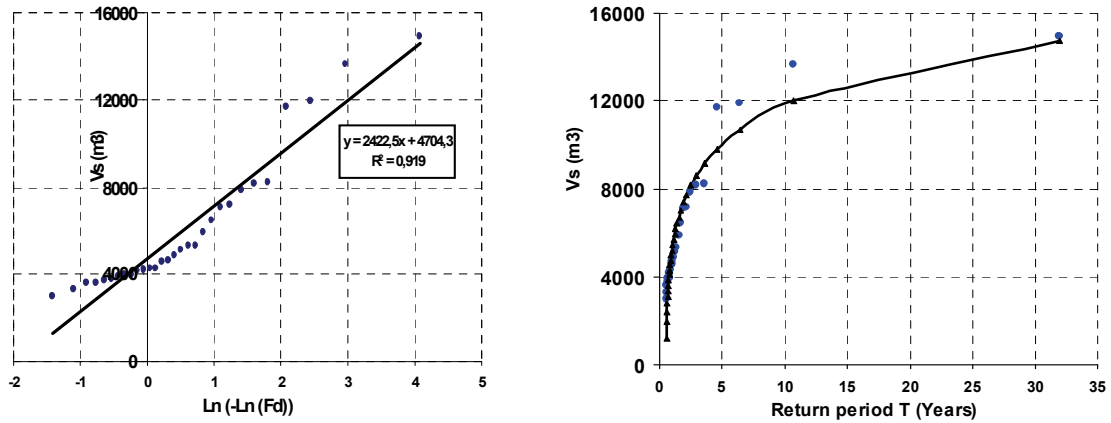


Figure 2: Storage volumes of reservoir model, and Distribution volumes of Gumbel watershed N 21

The table 4 shows Gumbel storage volumes obtained for watershed 21 for different return periods (1, 2, 5 and 10 years).

return periods (years)	1	2	5	10
Gumbel Volumes (m3)	5325,00	7546,7	10046,26	11829,78

Table 4: Gumbel storage volumes (m3)

5 A NEW METHOD USING A DESIGN STORM

5.1 Choice of Design Storm type

We try to define the appropriate design storm in terms of duration, maximum intensity and height, which would be adapted to our problem. The construction of triangle-type design storms requires a statistical analysis of their characteristic features, in order to associate a risk to a given storm. For that purpose, we rely on the IDF curves and the associated Montana coefficients. It remains then to define the duration of the storms. Since the objective is to determine storage volumes of 36 watersheds from these design storms used as input to our linear reservoir model, our principle is to find durations of design storms for which the derived storage volumes are just above the volumes calculated with Gumbel and then establishing a mathematical relationship between these durations and the various hydrological parameters.

5.2 The mathematical model of total duration of design storm D

We use the multiple regression model which allows to establish a relationship between the storm duration D and the group of explanatory variables (S, C, M, I, Q_{ad} , T). The model can be written as (15):

$$D = \beta_0 + \beta_1 S + \beta_2 C + \beta_3 I + \beta_4 M + \beta_5 Q_{ad} + \beta_6 T \quad (15)$$

β_i being the explanatory variables coefficient, S the area of watershed (ha), C the runoff coefficient (%), I the mean slope (m/m), M the elongation coefficient, Q_{ad} the admissible release rate (l/s/ha) and T the return period (yrs).

The general expression of the mathematical model includes 7 parameters (or coefficients) which

define 7 equations in the following way:

$$\begin{aligned}
 n\beta_0 + \beta_1 \sum S_i + \beta_2 \sum C_i + \beta_3 \sum I_i + \beta_4 \sum M_i + \beta_5 \sum Q_{adi} + \beta_6 \sum T_i &= \sum D_i \\
 \beta_0 \sum S_i + \beta_1 \sum S_i^2 + \beta_2 \sum S_i C_i + \beta_3 \sum S_i I_i + \beta_4 \sum S_i M_i + \beta_5 \sum S_i Q_{adi} + \beta_6 \sum S_i T_i &= \sum S_i D_i \\
 \beta_0 \sum C_i + \beta_1 \sum C_i S_i + \beta_2 \sum C_i^2 + \beta_3 \sum C_i I_i + \beta_4 \sum C_i M_i + \beta_5 \sum C_i Q_{adi} + \beta_6 \sum C_i T_i &= \sum C_i D_i \\
 \beta_0 \sum I_i + \beta_1 \sum I_i S_i + \beta_2 \sum I_i C_i + \beta_3 \sum I_i^2 + \beta_4 \sum I_i M_i + \beta_5 \sum I_i Q_{adi} + \beta_6 \sum I_i T_i &= \sum I_i D_i \\
 \beta_0 \sum M_i + \beta_1 \sum M_i S_i + \beta_2 \sum M_i C_i + \beta_3 \sum M_i I_i + \beta_4 \sum M_i^2 + \beta_5 \sum M_i Q_{adi} + \beta_6 \sum M_i T_i &= \sum M_i D_i \\
 \beta_0 \sum Q_{adi} + \beta_1 \sum Q_{adi} S_i + \beta_2 \sum Q_{adi} C_i + \beta_3 \sum Q_{adi} I_i + \beta_4 \sum Q_{adi} M_i + \beta_5 \sum Q_{adi}^2 + \beta_6 \sum Q_{adi} T_i &= \sum Q_{adi} D_i \\
 \beta_0 \sum T_i + \beta_1 \sum T_i S_i + \beta_2 \sum T_i C_i + \beta_3 \sum T_i I_i + \beta_4 \sum T_i M_i + \beta_5 \sum T_i Q_{adi} + \beta_6 \sum T_i^2 &= \sum T_i D_i
 \end{aligned}$$

This leads therefore to a 7 unknown matrix problem.

5.2.1 Estimated model coefficients

From the 36 watersheds identified above and the 4 return periods, we establish a model that links the duration of triangle design storms with explanatory variables, by the least squares method. Finally, we obtain the following equation (16):

$$D = 239,7424 + 0,0077S + 1,6305C - 75,1143I - 0,0002M - 38,4702Q_{ad} + 27,3980T \quad (16)$$

The linear regression of rainfall durations shows a good fit between simulated and calculated durations with a correlation coefficient $R^2 = 0,8384$ and a slope $y = 0,986x$

5.2.2 Analysis of the model variance and determination of the best sub-model

The results of the numerical tests are then analysed in order to adjust the regression model obtained previously to rank the explanatory variables according to their influence on the rainfall duration. The statistical tools used to determine the best sub-model are the Fisher-Snedecor test (test of equal variances) and the Student's t-test (test of marginal contribution). We try here to explain whether the variations in rainfall durations are caused by changes in explanatory variables (variation explained by regression) or by unpredictable fluctuations due to the dispersion of the rainfall durations (residual variation). For each of these variations we calculate the regression mean squares MS_R and residual mean squares MS_{RES} and we deduce the residual variance s^2 , the Standard deviation of residues s , the F Fisher-Snedecor parameter and the coefficient of determination R^2 . The results show that 86% of the variability of the duration of rainfall is explained by the explanatory variables. We then calculate the F (Fischer-Snedecor) parameter with probability to be exceeded of 5%, a commonly used value [G Baillargeon, 2003], [D Benoist et al, 1994]. We now aim at defining the quality of regression, that is to say, to conclude whether or not it is significant as a whole. This has been done using the Fisher-Snedecor test also called significance test.

The Fisher-Snedecor test can be expressed as: under the hypothesis $H_0: \beta_j = 0$ we conclude that the explanatory variables have no influence on the rainfall duration, and under the hypothesis H_1 : At least one β_j is different of (0) and β_j has an effect on the rainfall duration. We reject H_0 if $F > F_{0,05;k;n-k-1}$ where (k) is the number of variables and (n) the number of trials. From the tabulated Fisher-Snedecor law it comes $F_{0,05;6;137} = 2.17$. We have $F = MS_R / MS_{RES} = 139,28$ then $F > 2.17$; and therefore we reject H_0 and retain H_1 . Considering this result, we conclude that the contribution of all explanatory variables to explain the fluctuations of the storm durations is significant at 5%. However, when we state that the regression is significant as a whole, this does not necessarily mean that all variables in the regression equation have a significant contribution. We must therefore determine whether the marginal contribution of each explanatory variable is significant. For this we use the Student's t-test to determine the relevance of each explanatory variable. The following hypotheses are formulated: ($H_0: \beta_j = 0$) ; $j = 1, 2, \dots, k$; ($H_1: \beta_j \neq 0$).

We reject H_0 if $t > t_{0,05/2;n-k-1}$ or if $t < -t_{0,05/2;n-k-1}$, or $t > t_{0,025;137}$ or $t < -t_{0,025;137}$

The results of analysis the Student's t-test are summarized in the table 5:

explanatory variables	(Student's t-test)	Decision criterion: reject H_0 if $t > 2,258$ or $t < -2,258$	Results
S	0,6318	$t < 2,258$	non significant
C	9,3921	$t > 2,258$	significant
I	- 0,1375	$t < -2,258$	non significant
M	- 0,2007	$t > -2,258$	non significant
Q	- 11,0797	$t < -2,258$	significant
T	24,7022	$t > 2,258$	significant

Table 5: Student's t-test results

The marginal contribution test reveals that the explanatory variables S, I and M are not significant. To optimize the sub-model we eliminate the explanatory variables S, I, M because they do not have a significant contribution in explaining fluctuations in rainfall duration. Finally, we obtain then equation with only three explanatory variables (17):

$$D = f(C, Q_{ad}, T), \quad D = 239,5362 + 1,6369C - 38,4774Q_{ad} + 27,3980T \quad (17)$$

5.2.3. Comparison of results of the Gumbel method versus the new method

To compare results between the new method and the Gumbel method, we calculate the storage volumes with the two methods for the 36 watersheds and for the four return periods (1, 2, 5, and 10 years), then we calculate the relative differences in volumes between the two methods (figure 3). These differences are estimated as a percentage % using the equation (18):

$$deviation = 100 * (V_N - V_G) / V_G \quad (18)$$

with V_N the storage volume (m3) determined by the new method and V_G the storage volume (m3) determined by the method of Gumbel

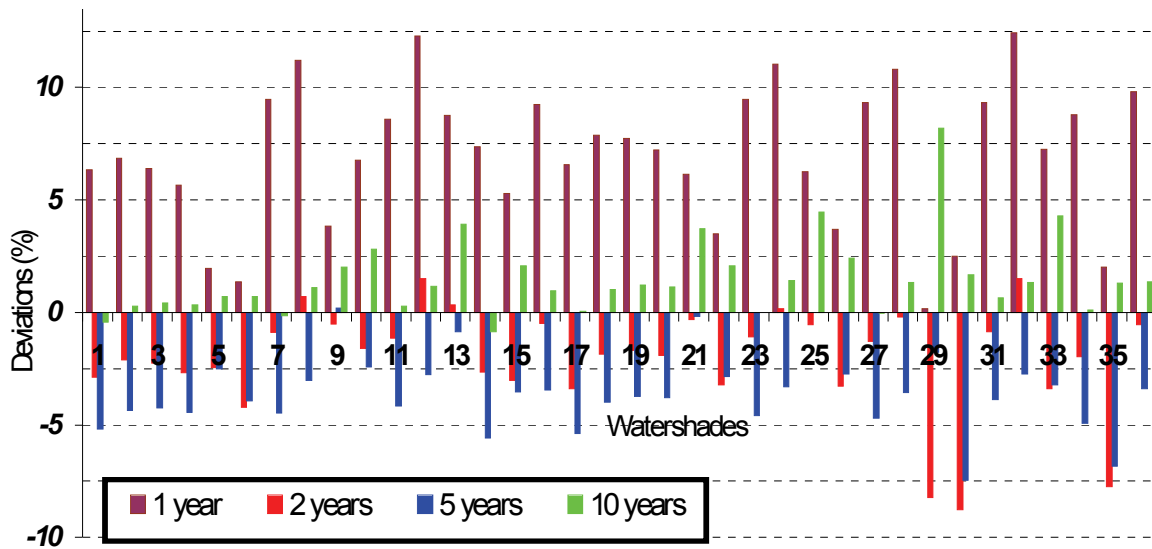


Figure 3: Deviations (%) of all storage volumes between the new method and the Gumbel method for each return period.

Given the small deviatons (compared to the high relative differences in storage volumes between Gumbel method and the two methods of “Technical Guidelines of 1977”, Rainfall method and Volumes method (figure 4)) obtained between the two methods in both directions (oversizing or undersizing), we can conclude that this new method is suitable to size storage structures whatever the return period considered.

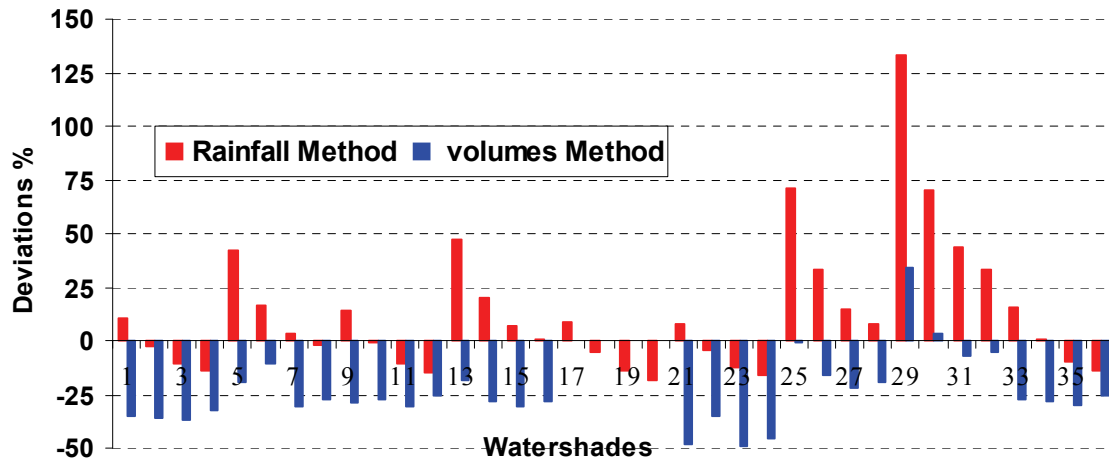


Figure 4: Deviations (%) volumes between the Rainfall method, Volumes method and the Gumbel method

The degree of association (correlation coefficient R) between storage volumes obtained with Gumbel, and storage volumes obtained with the new method, is very high ($R^2 > 0,999$) for each return period (1, 2, 5 and 10 years) (figure 5).

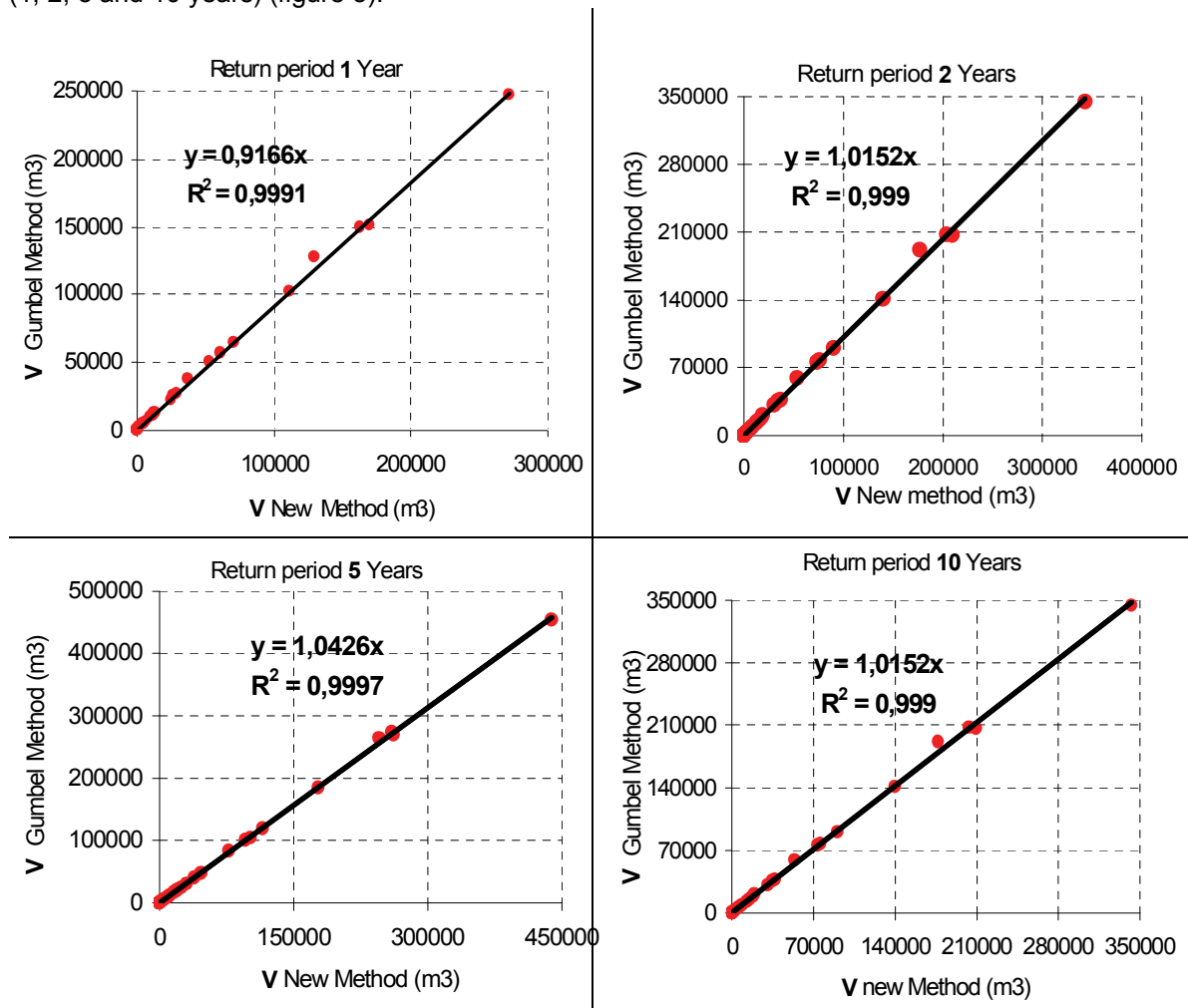


Figure 5: Correlation of storage volumes given by the new method and the Gumbel method

6 CONCLUSION

The use of the concept of Design Storm for storage structures design has already been undertaken by other authors, such as [Xia, 2005] who has shown that the use of series of double triangle Design

Storms was inappropriate for dimensioning retention tanks. We therefore tried to find another way to use Design Storms to solve this problem. The new design tool we propose provides some answers to the difficulties encountered by professionals in urban hydrology (local authorities and design offices...) trying to apply the principles of the Guide "The city and its sewage system" [CERTU, 2003] leading to give up the "Technical Guidelines of 1977" [MINISTERES, 1977]. The design tool that we developed has also the particularity to be accessible and robust. Its major limitation, similar to the "Technical Guidelines of 1977" methods, is to consider only constant release rates and runoff coefficients. Indeed, it appears more like a pre-sizing tool and has to be completed later by a simulation model taking into account, amongst others, varying release rate, geometry of the watersheds, filling materials... in order to verify the initial design.

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