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On the Relationship between the Urbanization and the Hydrological Response of a Catchment

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Abstract The features of the hydrological response of a catchment to a rainy event depend on the morphology of the catchment and also on the importance of the event. The urbanization, translated by impermeabilisation of which the consequences are the growth of the streamed volumes and the decrease of the superficial flow times, increases the risk of flooding by runoff.

In this work, we have studied the effect of the urbanization on the hydrological response of a catchment located in the south part of the city of Annaba (Algeria). To simulate the transformation rainfall-flow, the non-distributed model of linear reservoir has been chosen. The obtained results show that in case of the urbanization, the lag time of the considered catchment is a lot shorter and also the peak flow increases considerably.

Keywords flooding, hydrological response, linear reservoir models

1. Introduction

The importance of the flooding by runoff is bound to the morphology of the catchment and to the climatic conditions. The human activity, as the urbanization, constitutes one of the factors aggravating the risk of flooding [1]. The first consequence of the urbanization is the impermeabilisation of soils that causes a reduction of the infiltration in these last, and contributes to an increase of the streamed volumes. Under the effect of the impermeabilisation, some catchments saw their lag time divided by an active factor of five to fifteen [2]. In the developing countries, as Algeria, the growth of the industry involved a real urban demographic explosion. The emergency to build often limited the reflection on the consequences of the urbanization on the water cycle in urban environment. At the present time, these consequences become obvious, and with them their succession of nuisances of all orders: permanent dysfunctions of the urban sewer systems and frequent floodings [3]. To be able to act better on the risk of floodings and to manage it, the most efficient mean is the previous simulation of the effect of the urbanization on the hydrological response of the catchment to urbanize during his urban planning process. The dynamic methods, used in urban hydrology, permit to simulate the water cycle since rain until the flow in the outlet of the catchment, that is to say, to get a representation of the hydrograph. The dynamic modelling includes several steps, in particular: modelling of the rain whose model represents the fundamental entry to the runoff models, modelling of the rainfall-flow transformation and modelling of the flowing in the networks (drainage network and sewer systems) [4].

Changes in land use have made it necessary to take into account rapidly-evolving morphology of urban catchments and of natural catchments. In natural settings, the notion of linking the hydrological response of a catchment to its geomorphology has given rise to a complete body of studies over the last two decades. The Geomorphologic Instantaneous Unit Hydrograph (GIUH) was first introduced using probabilistic concepts [5], [6]. The proposed theory assumes that both the structure of the river drainage network and the travel time of water particles adhere to probabilistic distributions. Also, linear reservoir models were, and are still, very frequently used for simulating rainfall-runoff processes and, more precisely, for determining the unit hydrograph of catchment area [7-10].

In urban settings, the areas drained by a sewer system were defined and estimated by property blocks connected to the sewer inlets. The most widely used models: SWMM [11] or MOUSE [12] combines a hydrological stage which simulates the hydrograph from small urban catchments with the propagation of these hydrographs in the main pipe network. The modelling of the rainfall-flow transformation is less detailed and often calls synthetic hydrographs, such as the widely used linear reservoirs [13], [14]. The studies on the hydrological response of an urban catchment to a shower have been made on the identification of unit hydrograph from urban databanks and from the semi-distributed linear non linear model of rainfall-runoff transformation [15-16].

This paper is constituted of the following manner: in the next section, we propose a pluviometrical mathematical model development methodology, and let's present the description of the modelling of transformation rainfall-runoff by the "urban" catchment and by "rural" catchment. The results of application of the models are the subject of the third section. Finally, we give some conclusions in the fourth section.

2. Methodology

2.1 Modelling of the runoff

The runoff can be defined as the hydrological response of a catchment to a shower, and represented by the evolution in the time of the flow on a given time interval (runoff hydrograph) during this shower. This response corresponds to an interaction between the morphological features, the nature of the soil and the occupation of the soils of the catchment. To value the runoff hydrograph of the catchments, we had resort to a conceptual storage model (reservoir model). The latter considers the catchment like a complex system of reservoirs achieving a transfer of flux. The more used reservoir model in urban hydrology is the linear reservoir model, which represents the transformation of a rainfall excess hydrograph in hydrograph in the outlet [4].

The linear reservoir model combines the equation of continuity

$$\frac{dVs}{dt} = Qe(t) - Qs(t), \qquad (1)$$

with a storage equation linearly joining the stocked volume to the retiring flow:

$$Vs(t) = KQs(t), \qquad (2)$$

where K is the parameter of the model, homogeneous to a time and named lag time (s); $Qe(t)$ represents the entering flow or the flow of rainfall excess (m^3/s); $Qs(t)$ is the flow at the exit (m3/s); $Vs(t)$ gives the instantaneous stocked volume in the catchment (m^3).

For a stationary linear system, which is not spatially distributed, the linear reservoir model expresses itself directly from the equations (1) and (2) in only one differential equation:

$$K\frac{dQs}{dt} = Qe(t) - Qs(t). \qquad (3)$$

The instantaneous unit hydrograph of this system is given by the following relation [13]:

$$U(t) = \frac{1}{K} e^{-t/K}. \qquad (4)$$

The parameter K will be determined by the relation (5), proposed by M. Desbordes [4]:\ $K = 5.07\ A^{0.18}\ (1 + IMP)^{-1.9}\ I^{-0.36}\ L^{0.15}\ Hp^{-0.07}\ Dp^{0.21}$, (5)

where A : surface of the catchment (hectares);

Dp : duration of the period of "critical rain" of the basin (min.);

Hp : rainfall depth during this length (mm);

I : slope of the longest course (%);

IMP: imperviousness coefficient (%);

L : length of the longest water travel (m).

For the little urbanized or "rural" catchment, we opted for the model of two linear reservoirs in series with the same parameter K. The instantaneous unit hydrograph, corresponding to this type of model, answers to:

$$U(t) = \frac{1}{K}\left(\frac{t}{K}\right)e^{-t/K}, \tag{6}$$

where $K = c\,L\left(\frac{A}{I}\right)^{0.5}$, $0.6 \le c \le 1.8$.

The runoff models, developed above, treat the transformation of the only rainfall excess in flow. Sometimes these models are called as “transfer function”. But their implementation requires a previous modelling of the losses which achieves the transformation of the “gross” rainfall into the rainfall excess. This last is called “production function”. To this subject, one will note that the rainfall excess doesn't cover any observable physical reality, it represents the gross rainfall fraction, before this last arrives to soil, and that will server only to the food of the runoff in the outlet of the considered receiving surface.

2.2 Modelling of the rain

2.2.1 Design storm model

The fundamental entry of the urban runoff models is the design storm or the synthetic hyetograph. The design storm is a fictional rain event. Currently, in the most countries, the used design storms are characterized by neighbouring shape hyetographs. These last are constituted of a period of relatively long rain of sustained intensity, inside which comes to fit a shorter episode, characterized by a very strong intensity which return period is associated to the design storm. The met shapes are variable: triangular, fitting of rectangles (design storm of Chicago type), of trapezes etc. The design storm model that we chose is a simplification of Desbordes’s model: design storm of double symmetrical triangle form or Chocat-Thibault’s model [4]. The interest of this model, it is that the features of the design storm (total rain duration, duration of the intense period, precipitate depths), can be obtained from the features of the catchment and from the local curves IDF (intensity-duration-frequency). For the curves in question, we propose the methodology of construction.

2.2.2 Methodology of construction of the IDF curves

The obtaining of the IDF curves requires the transformation of the raw values of the precipitations in a set of annual maximal values on different durations (τ = 5, 10,... min), then the adapted adjustment to the data of the obtained set [17]. It has been determined that the shapes of frequency curves of the depths of the maximal precipitations for the different durations $H\tau=H\tau\ (F)$ and of the maximal daily precipitations $Hj\ (F)$ for the same period of observation are identical [18]. Following this definition, we propose to present the report of the values $\varphi(\tau)=H\tau(F)/Hj(F)$ corresponding to a given frequency (F), under the following exponential shape:

$$\varphi\ (t, T) = a_o\ (T) * t^{\,n\,(T)}, \tag{7}$$

where a_o and n are the adjustment parameters; T is the return period $(T=1/(1-F))$ in years; t is the duration.

In this case, the report $\varphi\ (t, T)/t = i_o\ (t, T)$ will present a reduction curve:

$$i_o(t,T) = \frac{a_o(T)}{t^{b(T)}} \tag{8}$$

with $i_o(t, T)$ as the mean maximal relative intensity ($\frac{mm}{mm * \min}$).

The mathematical expression of the families of IDF curves deduced from the product of the equation (8) and the daily precipitations $Hj\ (T)$. It is of the following type:

$$i(t,T) = \frac{a(T)}{t^{b(T)}} \tag{9}$$

where $i\ (t, T)$ is the mean maximal intensity on the duration t for a return period T;

$a\ (T) = a_o\ (T) * Hj\ (T)$.

The proposed methodology permits to express the rain intensity variation in function of daily precipitations for different return periods in a meteorological station. It happens often that the measure network is composed of the stations, which do not have possessed the pluviographs. Thus, this methodology can be applied to the regionalization of the IDF curves, in other words, to the elaboration of the curve of the regional relative maximal intensity (Eq. (9)).

2.3. Modelling of the runoff losses

The losses and the runoff are enough difficult phenomena to dissociate. They occur at the same time and are often dependent. To calculate the hydrograph in the outlet of the catchment, it is of use to make use of two models:

- the first model, production model or model of the losses, transforms the gross rainfall into rainfall excess, that participates effectively in the runoff;
- the second model, model of transfer, transforms the rainfall excess in hydrograph in the outlet of the catchment.

For an urbanized catchment of which the imperviousness coefficient is superior to 20 %, when one uses the linear reservoir model as transfer model, what is of our case, the runoff losses are represented by the imperviousness coefficient IMP. It implies that the initial losses are negligible, and that one doesn't take in account, at resulting hydrograph level, the effect of the permeable surfaces. On the weakly urbanized surfaces, the losses and runoff phenomena result from a set of transformations bound to the features of the soil and to the climatic conditions. For a “rural” catchment, these notions are replaced by the one of the mean blade (variable in the time, which one can decompose in initial losses and continuous losses). The continuous losses that are provoked by the phenomenon of infiltration concern only the permeable surfaces and are more important than the initial losses (storage in the depressions, evaporation). To describe the losses due to the infiltration of the “rural” catchment, we chose the most current model, the Horton model [19]:

$$f(t) = f_c + (f_o - f_c)e^{-kt}, \qquad (10)$$

where *f (t)* is the limit velocity of potential infiltration at time *t* (mm/h) ; *fc* is the limit velocity of infiltration (mm/h) ; *fo* is the initial velocity of infiltration at time *0* (mm / h) ; *k* is the factor depending of the soil-vegetation complex.

For the “rural” catchment, the transformation of the gross rainfall hyetograph in the rainfall excess hyetograph is defined as follows:

$$i_n(t) = i_b(t) - f(t) \qquad (11)$$

with $i_n(t)$ as the rainfall excess hyetograph and $i_b(t)$ as the design storm hyetograph.

3. Results and Discussion

The zone of study is located in the southern part of the town of Annaba, itself located at the North-East of Algeria at the edge of the sea Mediterranean. This zone is included in the plan of development and urbanism of the area of Annaba, like zone to urbanize (Figure 1).

The climate is Mediterranean, which is characterized by abundant storms of short duration during the period going from october to april. The annual average temperature is of 15°C.

Figure 2 present the delimitation from a DEM (digital elevation model) of the catchment area to analyze. The catchment area covers a surface of 278 ha. The altitudes vary from 20 to 120 m above sea level. In the current state, this catchment area is urbanized to 12.8 %, the remainder is a grassy ground. It is drained by a thalweg of which the length is of 1800 m and the mean slope is equal to 6 %. The particularity of this catchment is to be crossed by a road, which is perpendicular to the thalweg. This road has an evacuation work of the storm water issuing from the considered catchment area. Hydraulic capacity of the work is equal to 8.8 m ^{3}/s, and it is located at the level of the catchment area outlet. One would like to note that the downstream part of the catchment area was subject of small floods at the time of important storm.

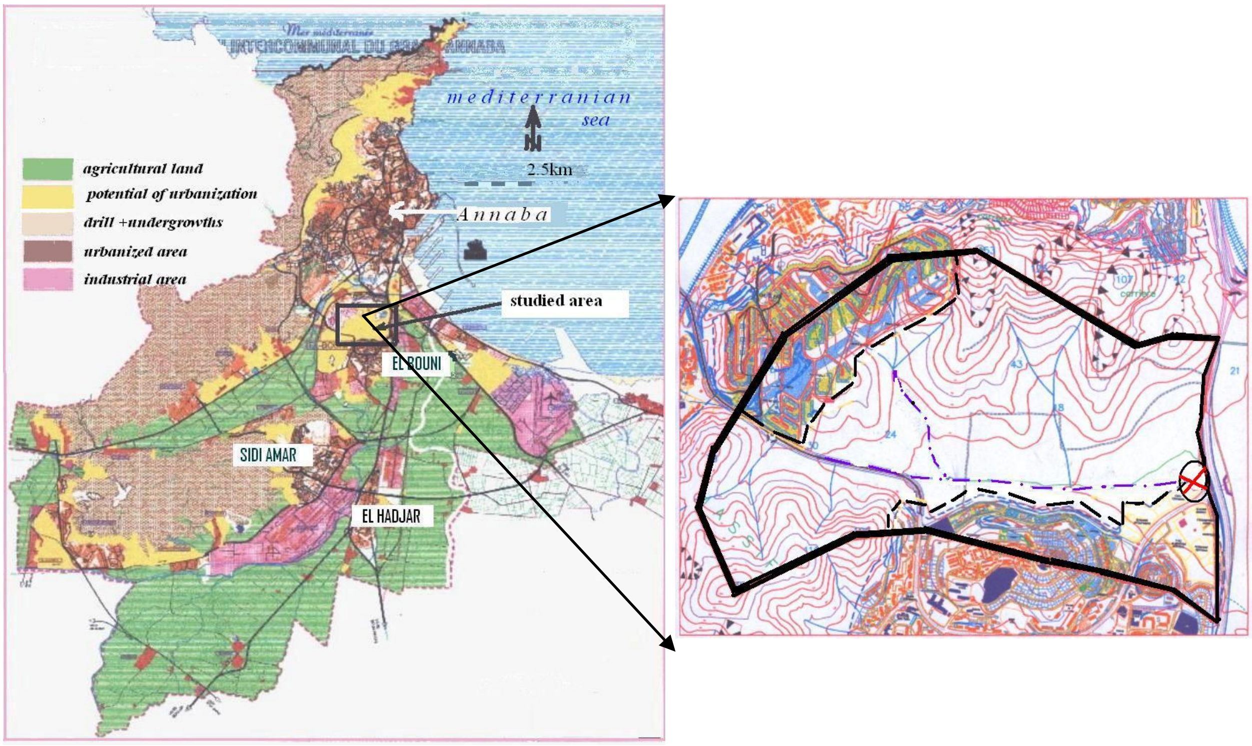

Figure 1: Localization and representation from the DEM of the studied area. On right subfigure, the relief of area is represented by means of the level curves and the continuous bold line delimits studied catchment area. Urbanized areas are delimited by the broken lines. The outlet of the catchment area is marked by a cross.

To construct the hyetograph of the design storm, we conducted the establishment of the IDF curves from the sets data given by the climatic station situated at 2 km of the survey zone for a period of observation of 17 years. The nine sets of data to analyze was constituted of the annual maximal values of the precipitations corresponding to the different durations (15, 30 min, 1, 2, 3, 6, 12, 24 hrs) and of the daily precipitations. The results of statistical analysis of samples are carried in table 1.

Table 1: statistical characteristic by sample

Statistical characteristics	**Durations τ (min)**								**Daily rainfall depths (mm)**
	15	**30**	**60**	**120**	**180**	**360**	**720**	**1440**	
Mean $\hat{\mu}$ (mm)	12.2	17.0	20.3	22.9	25.6	30.4	40.0	51.1	56.6
Standard deviation $\hat{\sigma}$ (mm)	4.53	6.45	7.56	8.58	9.32	18.3	21.7	27.8	28.1
Coefficient of variation C_V	0.37	0.38	0.37	0.37	0.38	0.56	0.54	0.54	0.5

Since the small size of data series, a probabilistic approach was used to estimate the quantiles of annual maxima of various return periods. This approach realizes the adjustment of a statistical law to these last. Several authors already used this method [20-22]. The statistical law, most frequently to model the extreme event, proves to be that of Gumbel (GEV1). Several statistical studies, undertaken on the estimation of extreme precipitations of short duration in the various climatic areas, notice the prevalence of the Gumbel distribution [14, 23].

Thus, our choice was related to the statistical law Gumbel.

The Gumbel distribution function *F(x)* is given:

$$F(x) = \exp\left\{\exp\left[-\frac{1}{c}(x-\zeta)\right]\right\}, \qquad (12)$$

$$F(x) = \exp[-\exp(-u)]$$

with ζ the location, c the scale and u the Gumbel reduced variate, $u = -\ln(-\ln(F))$.

The quantile function, the inverse of equation (12) is given by:

$$x(F) = \varsigma + c\ln[-\ln F(x)] = \varsigma + cu\,. \qquad (13)$$

To estimate the parameters of the Gumbel distribution, we have used the method of moments [9]. The idea of the latter is to equal the sample moments $\hat{\mu} = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, $\hat{\sigma}^2 = s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$ and the theoretical ones of the chosen law. The two first theoretical moments of the Gumbel distribution are expressed from the location and scale parameters in the following manner:

$$\mu = \varsigma + b\gamma$$
$$\sigma^2 = \frac{\pi^2}{6}c^2\,, \qquad (14)$$

with $\gamma = 0.5772$ (Euler constant), and μ , σ^2 are the mean and variance, respectively.

Therefore, we obtain the following formulas for the estimation of the parameters:

$$\hat{c} = \frac{\sqrt{6}}{\pi}\hat{\sigma}$$
$$\hat{\varsigma} = \hat{\mu} - \hat{b}\gamma \qquad (15)$$

The application of the values of the statistical characteristics in equation (15) permitted us to estimate parameters of the Gumbel distribution for each set of data.

To test the conformity of the considered law to the annual maxima, which form the samples, we have applied the Pearson chi-square test. The latter shows that the law of Gumbel can be adopted at the 5% signification level. For indicative purpose, the figure 2 presents the results of Gumbel adjustment of rainfall depths.

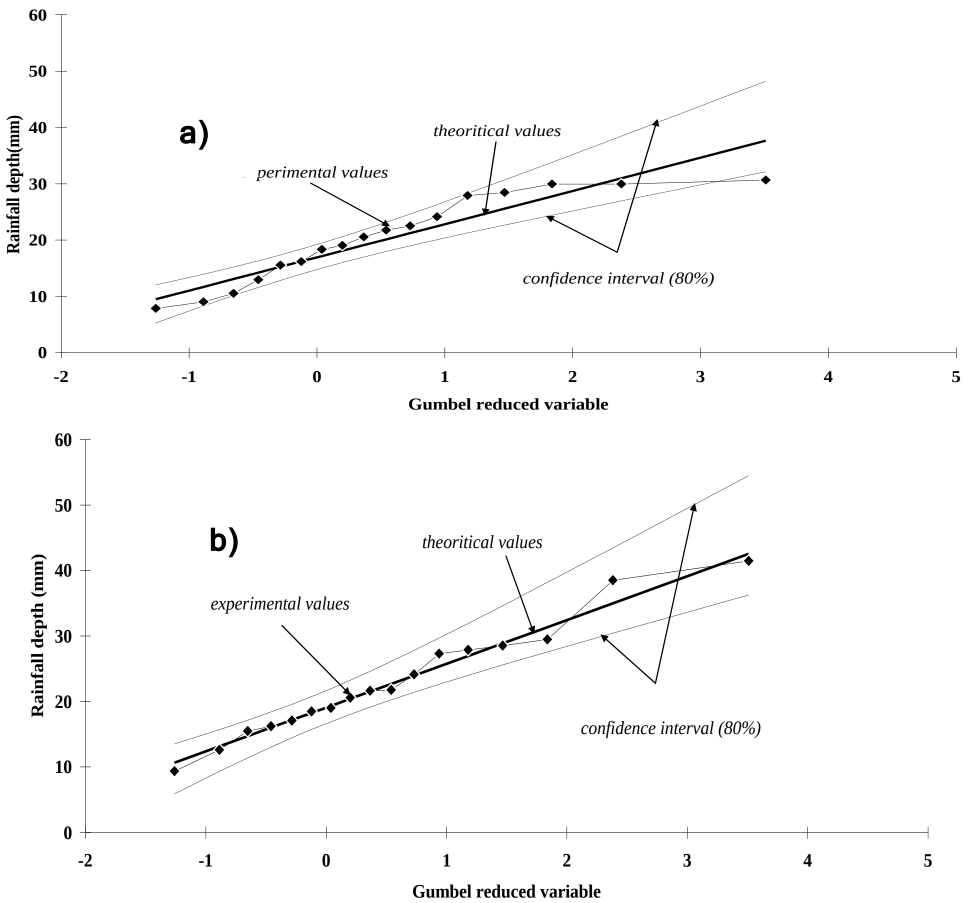

Figure 2: Adjustment of rainfall depths for durations of 60 min (a) and 120 min (b) with Gumbel law

The following stage of suggested methodology consisted in defining the parameters of the mathematical model of IDF curves. For that purpose, we initially calculated the reports of the estimated quantiles $\varphi(\tau,T)=H\tau(T)/Hj(T)$ for the specified return periods T=10, 20, 50 and 100 years. Then, these new sets of data were adjusted with the exponential curves of equation 7. The adjustment parameters $a_o(T)$ and $n(T)$ are obtained by means of the method of least squares. Finally, the parameters *a(T)* and *b(T)* of the mathematical model are determined according to the equation 9. The values of adjustment parameters $a_o(T)$ and $n(T)$ and of the parameters *a(T), b(T)* are consigned in Table 2. Figure 4 presents IDE curves for the return periods of 10, 20, 50 and 100 years.

Table 2: Values of the parameters of adjustment, empirical model and the root mean square errors (RMSE) for the return periods of 10, 20, 50 and 100 years.

Return periods	Parameters				RMSE
	a_o	n	a	b	(%)
10 years	4.85	0.33	452.36	0.67	6.5
20 years	4.58	0.34	493.66	0.66	7.33
50 years	4.29	0.35	555.24	0.65	8
100 years	4.16	0.36	601.83	0.64	8.79

To evaluate the reliability of the proposed of establishment of IDF curves, we calculate for each return period the root mean square error (RMSE)

$$RMSE(\%) = 100\sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(\frac{i_k^T - i_k^E}{i_k^T}\right)^2} \qquad (16)$$

Where i_k^T is the intensity of rain obtained by the frequency analysis; i_k^E is the intensity of rain obtained by the empirical equation 9 and *N* is the number of duration.

Calculations of the root mean square errors (RMSE) relative for different return periods showed that their values are about 6.5 to 8.7 %, which is low. On the other hand, the relative deviations (ε) for the various durations (ε (τ, *T*)) exceed, sometimes, the 10%. The relative maximum deviation (εmax = 14 %) was observed for the duration τ = 180 min (*T*=100 years).

By looking at table 2, one notes that the relative error (RMSE) increases slightly in the increasing order of sizes of the return period. That is due to the high relative deviation for some duration, and is explained, partly, by the effect of the weak size of samples on the estimating of the Gumbel parameters.

In same table 2, we see that the value of the parameter *b* is differed little from a return period to the other. Thus, IDF curves present the quasi parallel lines in double logarithmic scale (Figure 3).

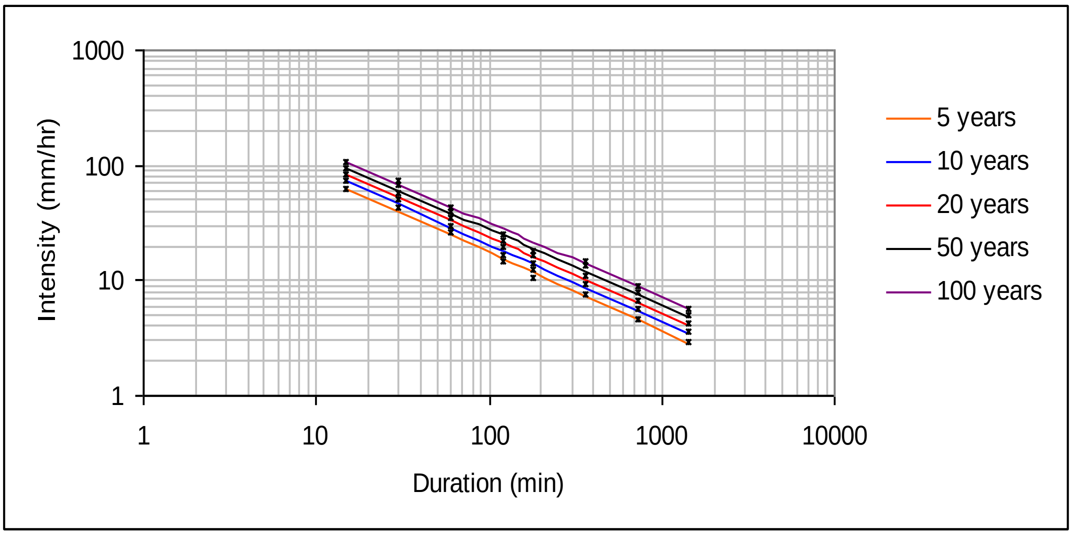

Figure 3: Rainfall IDF (intensity-duration-frequency) curves for the return periods of 5, 10, 20, 50 and 100 years. The stars (*) represent the empirical quantiles of the intensity

To construct the design storm and to define the parameters of the intense period, we used the IDF curve corresponding to the return period equal to fifty years. The hyetograph of the design storm is represented in the figure 4. This hyetograph is defined like entry of the runoff model of the “urban” catchment of which the degree of impermiabilisation is expressed by the imperviousness coefficient *IMP*=60%. The value of the latter has been chosen as equal to this of the adjacent urban catchment.

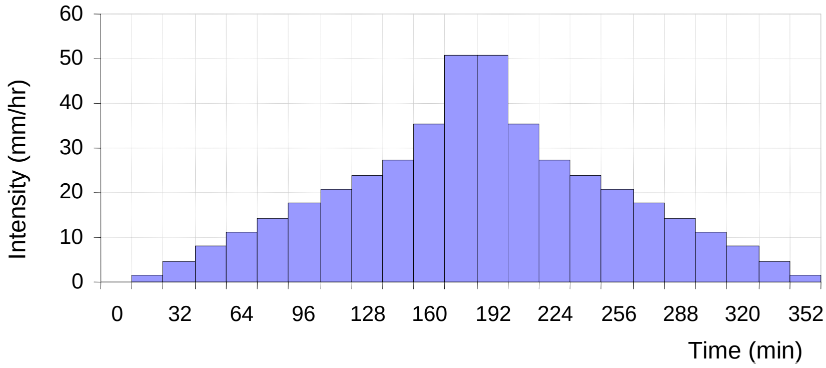

Figure 4: Design storm (double symmetrical triangle)

The application of the equations (10) and (11) permitted us to construct the hyetograph of the rainfall excess, that is the entry in the runoff model of the “rural” catchment (Figure 5).

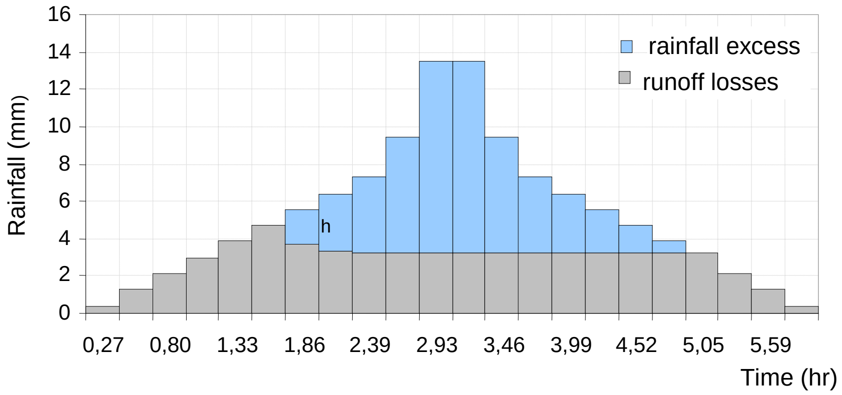

Figure 5: Hyetograph of rainfall excess

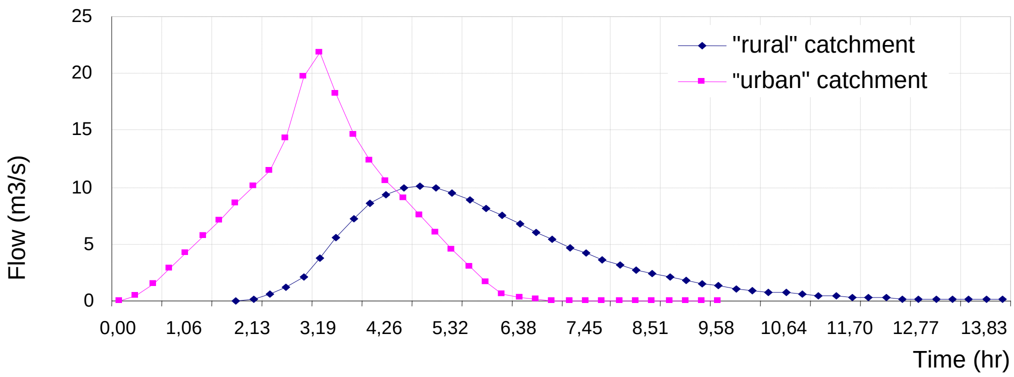

Figure 6: Hydrographs in the outlet of the catchment

The hydrological responses of the "urban" catchment and the "rural" catchment to the fifty years return period rainfall are represented by the hydrographs in the outlet (Figure 6). The obtained results express the effect of the urbanization on the hydrological response of the catchment. We observe that the urbanized catchment distinguishes itself by elevated flows, by a short lag time and by a very pronounced flood peak. The lag time of the “urban” catchment is equal to 0.27 hours. It is five lower than that of the “rural” catchment. In the local context, since the capacity of the evacuation work of the rain waters is insufficient, one considers the downstream of the basin as flooded.

4. Conclusion

The work was by the study of the effect of the urbanisation on the hydrological response of the small catchment area (2.78 km^2) to a shower of return period of 50 years. The modelling of the process of the hydrological response was made in two stages: the modelling of the rain and the modelling of the transformation runoff-flow.
The comparison of the hydrographs at the outlet of the “urban” and “rural” catchments showed the impact of the urbanization, which results in the impermeabilisation of soils, on the hydrological response. Thus, impermeabilisation of soils increases the runoff coefficient and, consequently, the volume of the hydrograph. In addition, it decreases the concentration time. The reduction in this last appears by a short response time and a very marked flow peak of the hydrograph. So the urbanization of a catchment area and especially that predisposed to the floods, increases the risk of floods by runoff, generated by the frequent showers of return periods going from 10 to 100 years.
Also, in this study a detailed attention was carried out to the modelling of the synthetic design storm through IDF (intensity-duration-frequency) curves of precipitations for a weather station of mediterranean climate. The proposed methodology of establishment of IDF curves comprises several stages. Initially, one adjusts a statistical law to the annual maximum values of short duration precipitations, and on determines their quantiles for the specified return periods. Next, one models the IDF curves. By applying a statistical test, it was shown that the annual maximum values of the precipitations, raised in a station of Mediterranean climate, follow the function of Gumbel distribution. The empirical model with two parameters is appropriate to describe the variations of the maximum average intensity of precipitations for the considered station. The reliability of this model has been demonstrated acceptable values of the relative mean square error, calculated for the specified return periods.
In the proposed methodology, the maximum intensity of precipitations in a climatic station is expressed according to the quantiles of maximum annuals daily precipitations and of the relative average intensity (i_o). This approach can be used, in view, for the regionalization of IDF curves. The objective of this regionalization will be the establishment of IDF curves from the regional model of the relative intensity, for a station having no data on short duration precipitations.

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