Analysis of the hydrological functioning of an urbanizing river

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Abstract

Due to the expansion of urbanization, peri-urban zones face a quick land-use change. The control over this phenomenon has become a major issue for flood and water pollution management. Nevertheless, so far we are still on the pursuit of a well adapted model to these particular basins. We aim to develop such model by studying the Chézine basin, in the framework of the French national project AVuPUR (ANR-VMCS, 2008-2010). A 7-year data analysis unveils a specific behavior: first, rain events displaying one single peak produce one or two distinct peak discharge on the hydrograph ; second, the lag-time of the basin, usually close to 1 hour, sometimes exceeds 6 hours. Based on geomorphologic and hydro-meteorological data analyses we made some hypotheses to explain the different shapes that the hydrological response of the Chezine Bassin may present. The localization of urbanization throughout the basin and its pre-event moisture state seem to play a crucial role on the variability of hydrological responses. The application of the First Differenced Transfer Function confirms the existence of different shapes of transfer functions for the basin according to its initial moisture state. Therefore we conclude that the hypotheses here presented should not be neglected in the current pursuit to develop a well adapted model for suburban river basinsWrite your abstract here here

Keywords

Flooding, modelling, suburban, runoff, drainage network

INTRODUCTION

Suburban catchments have been facing many problems due to the fast land-use change that accompanies the worldwide phenomenon of urbanization. Conversion of land into industrial and residential uses significantly alters hydrological characteristics of land surfaces modifying pathways and rates of water flow. Bhaduri and al. (2000) assessed many impacts faced by basins located in urbanizing areas, emphasizing the increase of downstream flooding and the decrease of long-term deep and shallow groundwater supply. They also suggested that these consequences are enhanced by faster runoff from impervious surfaces and engineered drainage systems.

In spite of these important issues, peri-urban rivers have been the object of only few studies so far. O'Loughlin et al (1996) raise important points to consider when combining rural and urban models. To keep it short, here we mention two of them: (1) topography, soils and vegetation have an important influence on the hydrological impacts of urban development; (2) urban impacts are greatest for low intensity storms because in rural areas losses small storms are relatively large, but impervious areas will always produce runoff.

Valeo (2000) considered these remarks developing TOPURBAN, a modified version of the well known model for rural catchments TOPMODEL (Beven and Kirkby, 1979) so that the new model is also adapted to urbanized areas. Her model introduces a linear reservoir for describing the runoff over impervious areas, as in classical urban models (Nash, 1957; Cruise and contractor, 1980; Rao et al, 1972), but keeps the variable source area concept (Dunne *et al.* 1975;

O'Loughlin 1996) largely used for rural and natural catchments. These source areas correspond to the saturated surfaces that produce runoff immediately under rainfall. The spatial distribution of these saturated contributive areas is commonly based on a topographic index (eq.1) used to determine and localize the regions that are more likely to saturate before the others; either because they drain a greater area, or because the region has a weaker slope than the others.

$$TI = \ln \frac{upstream\ area}{slope} \qquad \text{eq. 1}$$

TOPURBAN presented better results over urbanizing basins than TOPMODEL and other conventional hydrological models (Valeo, 2000). Nevertheless, studies reveal that its simulations do not reach high verification efficiencies (Valeo, 2000). Thus the hydrological response of suburban catchments has still not been successfully reproduced by existing models so far.

An example of this particular kind of basin is the Chezine river basin (Nantes, France), in which urbanization spreads heterogeneously over natural surfaces. The purpose of this paper is to explain particularities observed in the outflow hydrographs of the Chezine basin, capturing the essential features of the catchment's hydrological response. This work has been carried out within the context of the research project "Assessing the Vulnerability of Peri Urban Rivers" (ANR-AVuPUR), which aims to improve the knowledge in urbanizing catchments and ultimately develop an entirely adapted hydrological model for suburban river basins (Braud *et al.*, 2009).

A classical method to apprehend the hydrological response of a basin based on observed data is the First Differenced Transfer Function – Excess Rainfall and Unit Hydrograph by a deconvolution Iterative Identification technique (FDTF –ERUHDIT, Duband *et al.* 1993). The FDTF applies the classical unit hydrograph concept for river basins, identifying the transfer function according to observed rainfall-runoff data. The method has been the object of several research studies (Nalbantis et al 1995, Rodriguez -Iturbe & Valdes, 1979) and has been applied in different contexts (Wendling, 1992; Rodriguez *et al.*, 2003). We can thus assume that the method is a good indicator to verify the pertinence of our hydrological functioning hypothesis.

This paper is organized in five sections: the first one provides an overview of the research area. The second section describes the most important results of the database analysis leading to some hypotheses on the catchment's hydrological functioning. These hypotheses will lead us to a 3-step methodology based on geomorphologic data. The description of this simple model will then be followed by the results of the FDTF applied on 2 different types of rainfall events that were identified among the Chezine hydrological responses. Finally, the last section presents conclusions and the perspectives for the ongoing project and related studiesTitle style = Major Headings Introduction - describing the background of the work and its aims.

The Chézine catchment

Covering an area of 29 km^2, the Chezine river basin is located in the northwestern suburbs of Nantes, France. The Chezine River follows a south-easterly course and covers a distance of 15km from it's source at Saint Etienne-de-Montluc to it's confluence with the Loire River at Nantes. The watershed receives approximately 800mm of precipitation annually and the amount of cumulated rainfall is in general almost two times greater during the winter than in summer. The region has a mild year round temperature. The average temperature during the winter is 5°C and during the summer, the average is around 18.5°C (www.meteofrance.fr, 2009). Due to these climate differences according to the season, the catchment is drier in the summer and quite wet during the winter. This wetness variation is clearly noticeable on field observation and has a relevant influence on the catchment's hydrologic behavior. The predominant rainfall type over the region is the frontal rainfall, from west to the east. Given the position and size of the catchment, the spatial structure variation of the precipitations is thus negligible in most of the cases. Nevertheless, whenever we find a particular behavior that cannot be explained by the topography and morphology of the basin, we set the data apart to be carefully analyzed with radar images.

The systematic analysis of radar images for all events will be performed later on in the project, for simulations with the complete hydrological model that will be developed.

The basin is equipped by a rain gauge and a hydrometric station both run by Nantes Metropole since January 2001. The rain gauge measures the total amount of rainfall every five minutes while the hydrometric station has a variable time step measurement, according to the variation of the water level (it takes measures every minute when the water level is changing and every hour when it doesn't detect enough variation on the water level).

The topographically-defined Chezine catchment (Figure 1) is extracted from a 20m resolution digital elevation model (DEM), supplied by Nantes Métropole. A complete urban database (roads, buildings, etc) has also been made available by the same local administration for this research project. The analysis described in the next section is essentially based on this dataset.

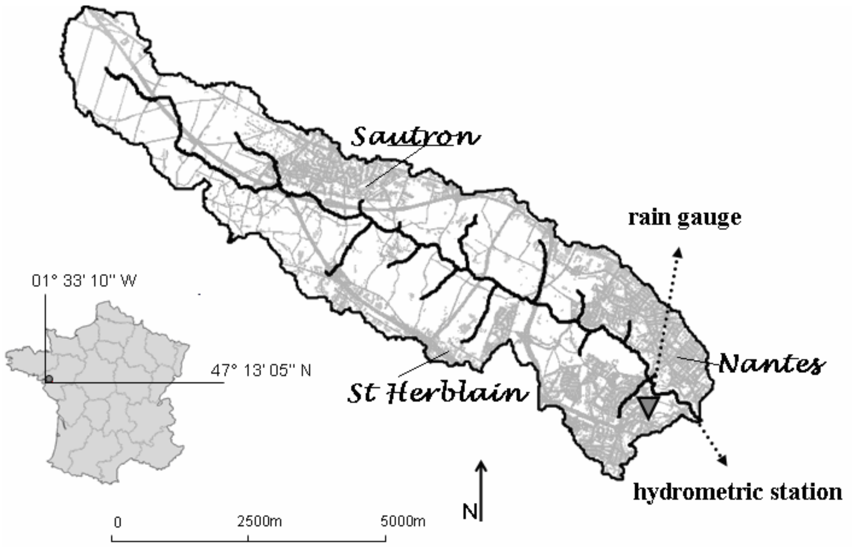
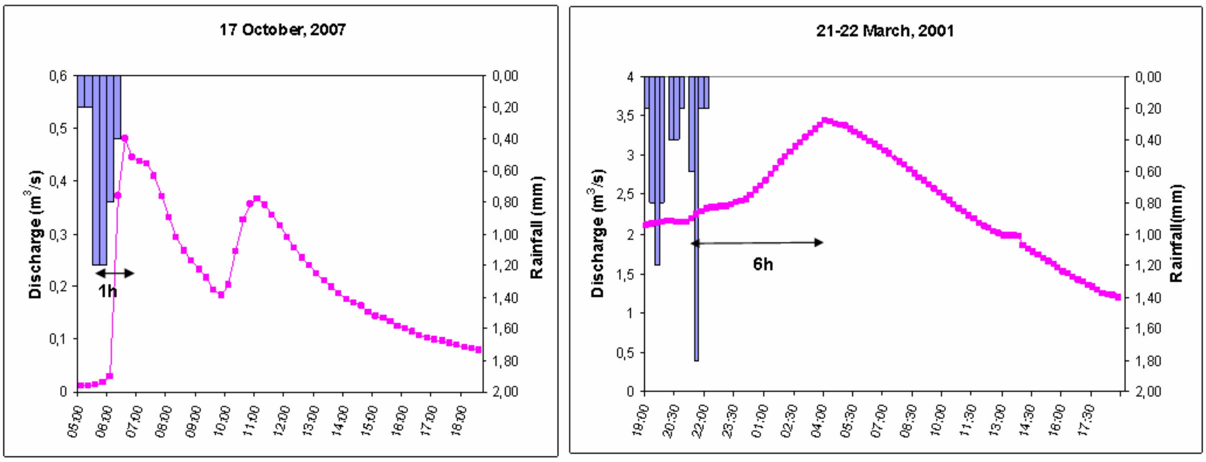


Figure 1. Chezine catchment indicating the location of the rain gauge and the hydrometric station at the outlet. The grey areas correspond to the urban database layers superposed (roads and buildings).

DATABASE ANALYSIS

The main objective of the database analysis was to identify particular behaviors and simple predictors to characterize them. From the 7-year rainfall-runoff available data set 295 events have been extracted, presenting a total precipitation superior than 2mm. 50 events among them were then selected. The criterion for their selection was to have an exploitable set of measures. Events that are superposed to others or those that have even one single bad measure for rainfall or outlet flow were rejected. Too long rainfall episodes or too weak outflow values have also been excluded.

The observed hydrogrammes unveil a specific behavior. First, rain events displaying one single peak can produce two distinct discharge peaks on the hydrograph. It can be observed for instance on the event of october 2007 represented by the hydrograph on figure 2.a. Second, the lag-time of the basin, usually close to 1 hour, sometimes exceeds 6 hours, as shown on figure 2.b.



(a) (b)

Figure 2. Observed discharge (m3/s) in pink lines and averaged 15 min observed rainfall (mm) represented by blue bars on (a) 17 October 2007 and (b) on the 21st -22nd of March 2001. The time-lag is indicated by double arrows.

In order to explain these behaviors, the start point of the study was evaluating the variability of the flow coefficient for different rainfall episodes on the Chezine basin. The flow coefficient (FC) is a traditional practical tool in engineering hydrology (Gottschalk et Weingartner, 1998). In the classical 'rational formula' (Dooge, 1957) it is considered to be a constant, differing in value according to the catchment's morphology and land cover. Here, it is defined as the proportion of discharge volume from the total rainfall volume for each rainfall episode (equation 2).

Erreur ! Des objets ne peuvent pas être créés à partir des codes de champs de mise en forme. eq. 2

A potential indicator of the basin dynamics is the pre-event discharge at the outlet (PED), which is commonly used to represent the soil moisture before each rainy episode. The PED is frequently considered as a proxy of state of the groundwater store (Graeff et al, 2009).

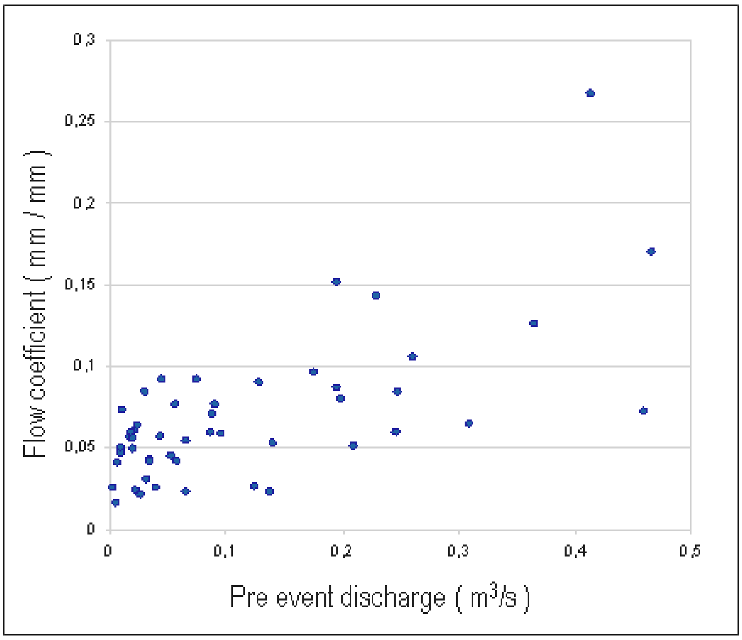


Figure 3. Correlation between the flow coefficients and the pre-event discharges for 50 rainfall episodes over the Chezine basin in the period from 2001 to 2007.

The relation observed between PED and FC for the Chezine dataset (figure 3) suggests that the events could be devised into 2-groups with different behaviors: "dry episodes" and "wet episodes". In figure 6, the 37 dry episodes, with a PED inferior than 0,2 m^3/s, are represented by the bar on the left. To the right, the larger bar represents the 13 events that have a PED superior or equal to 0,2 m^3/s. The 37 "dry episodes" present a RC close to 0.05, the mean RC value of the group, whereas the "wet" ones are more dispersed.

A hypothesis to explain the uniformity of the first group is the presence of a relatively constant proportion of runoff generating surfaces. If we assume that rural (or natural) surfaces in a dry condition retain or infiltrate all the precipitated water, the "constant portion" generating runoff would be the urbanized impervious surface. Meanwhile, when the soil is already wet before the rainfall episode, saturated rural surfaces of variable extension also contribute for the runoff generation. The definition of the extension and localization of these saturated rural surfaces was based on the variable source area, widely used by hydrologists in TOPMODEL (Beven and Kirkby, 1979) as it mentioned before. The next section describes how these hypotheses were considered for elaborating a simple method for simulating the discharge at the outlet due to the runoff generation distribution.

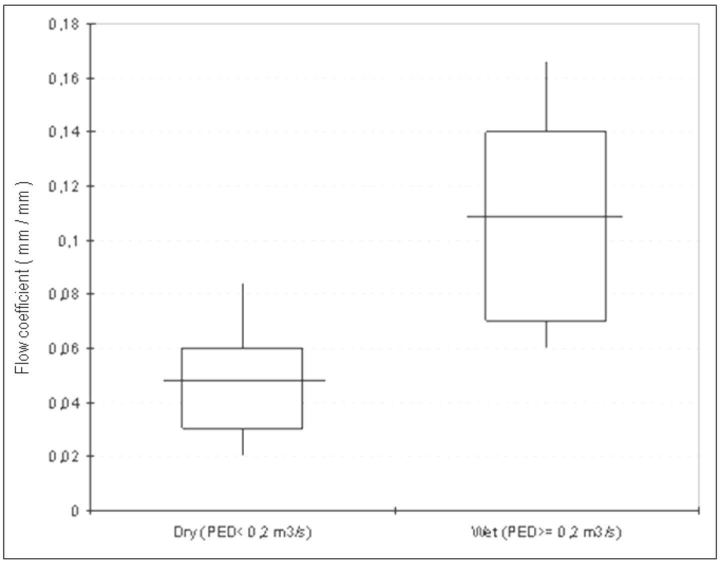


Figure 4. : Flow coefficient values for dry events (PED <0.2 m3/s) and for wet events (PED>=0.2 m3/s). The bars represent the interval of values for 50% of the events. The vertical extension lines represent the edges for 80% of the events. The horizontal lines represent the mean FC value of each group.

METHODOLOGY

The model is based on a natural water pathway guided by its topography and respecting the gravity law. Using a digital elevation model (DEM) with 20m resolution mesh and the unidirectional D8 algorithm (O'Callaghan J. and Mark D., 1984) we have extracted the catchment's topography and its hydrological network.

The objective of the simulation developed at this point is not to achieve the most precise results but to apprehend the overall hydrograph shape based on a simple physical model. In order to verify the hypothesis listed in the last section, our choice was to reproduce the dynamics of the runoff over the basin with a simple 3-step geomorphologic model, known as 'isochronal simple transfer' as described by Estupina (2004). Using neither complex theories nor over-parameterized calibrations the aim is to minimize misleading factors to better apprehend essential processes and features of the hydrological responses observed in this suburban catchment.

The first step of the methodology consists on the determination of the pixels that produce quick flow. Next, we calculated the hydrological distance to the outlet from each of these 'contributive' pixels. Finally, in order to obtain the time evolution of the outflow we affected a constant flow velocity for the stream channels and another slower one for hill slope flows. Urban runoff coefficient corresponds to the angular coefficient of the linear adjusted graphic on figure 7. Thus the urban coefficient is 0,06. The initial losses over urban areas are estimated by the interception of the graphic with the horizontal axis (2mm). Meanwhile, over natural surfaces, the losses vary depending on the initial moisture state of the catchment.
According to the hypothesis defined on the previous section, the impervious urban portion of the cells is always a source of runoff. For defining the imperviousness of each cell of the catchment mesh, a GIS layer of streets and a layer of buildings were taken from the urban data bank. These impervious surfaces correspond to the contributive pixels for dry episodes, and thus the first step of the model for this case (dry moisture state) is defined.
The distribution of these pixels according to their distance to the outlet is represented on figure 8. This morphological signature is known as Impervious Function (Gironas, 2007), and it is similar to the Width function (Rodriguez-Iturbe & Valdes, 1979), but only considers the impervious surfaces of the catchment. It is possible to identify the first peak of the graphic corresponding to the city of Nantes and Saint Herblain (figure 1), that are found at the third sector closest to the outlet (within 5km). The second elevation corresponds to Sautron (figure 1), that is the urbanization node located at about 10km from the outlet. The overall shape of the imperviousness function is coincidently bimodal suggesting that the source of the dual mode hydrographs often found among the analyzed events may come from the distribution of imperviousness throughout the catchment, at least for episodes when the initial moisture state is rather dry.

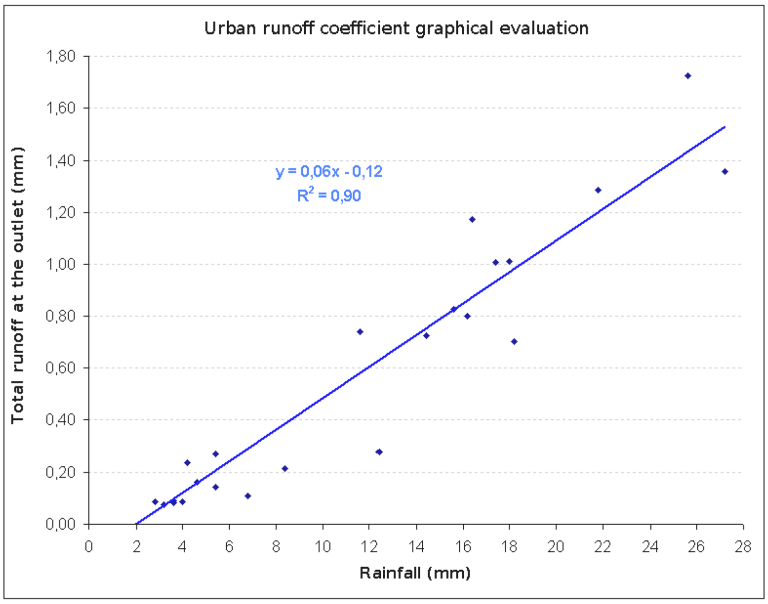


Figure 5. The angular coefficient of the linear adjusted graphic (total runoff versus precipitation) is an estimation of the urban runoff coefficient. There are 2mm of initial losses over the urban zone according to this graphic.

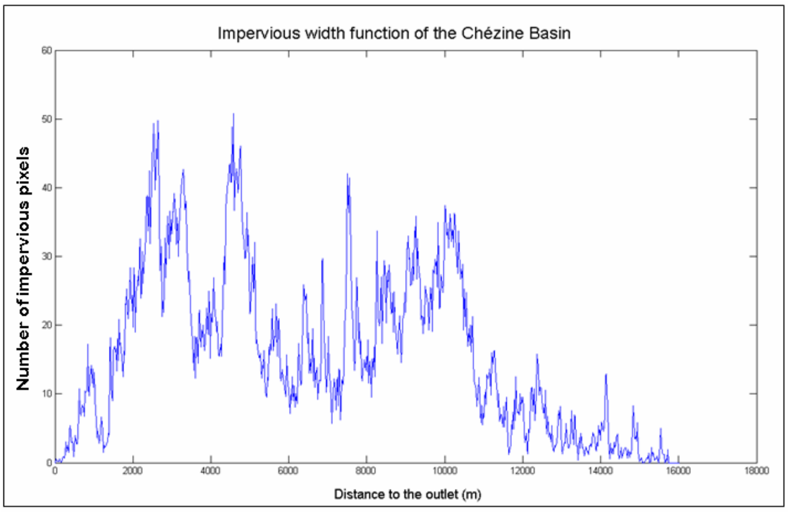


Figure 6. The Impervious width function of the Chézine basin

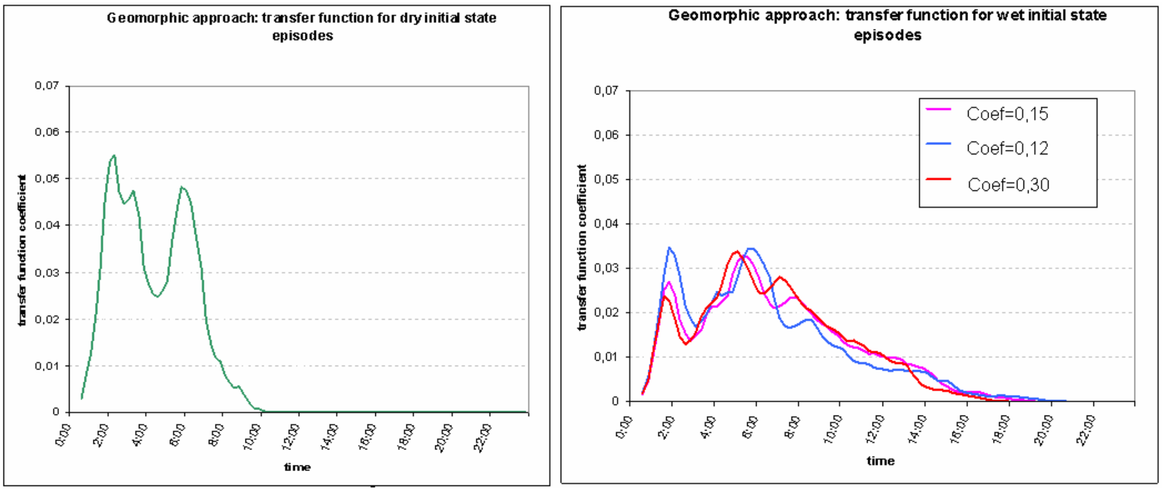
Another hypothesis drawn from the dataset analysis (section 2) was that urban contribution is constant for all events. By doing so, we can compute the rural variable source area extension by subtracting urban contribution from the observed total flow coefficient.

The second step of the model requires defining the spatial localization of the contributive area: the impervious cells and the natural saturated cells. The first ones have been mapped from the urban GIS data bank. In order to localize the natural cells that are more likely to saturate before the others, we used the concept of topographic index (Beven & Kirkby, 1979). It depends on the upstream contributing area of each pixel and decreases with its slope (eq.1). A topographic index threshold is calculated for each class of episodes depending on their flow coefficient. All the natural pixels with a topographic index superior to the threshold determined for the event are considered to be saturated and thus contribute to the runoff.

The third step of the model was accomplished in a very simplified way because the objective was to first investigate the sources of runoff production before going further into flow dynamics issues. Velocity values most usually found in the literature for hill slope and channel stream flows were tested and compared to observed data for model calibration. Rural hill slope flow was considered to be about 10 times slower than channel stream flows (river and urban pixels). The velocities that produced the best results, according to the Nash criterion (Nash & Sutcliffe, 1971) were then chosen to be applied on further simulations.

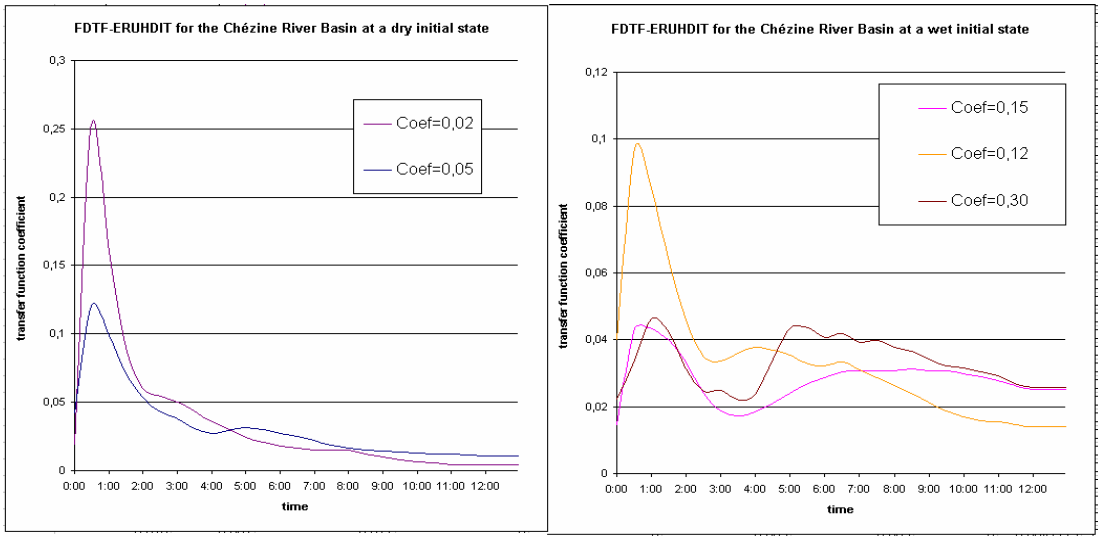
RESULTS AND DISCUSSION

According to the methodology presented in the last section, the outlet discharge responses were obtained (figure 7) for a unit rainfall applied in different wetness contexts. The moisture state is represented by the flow coefficient, remembering that their relation has been discussed on section 3 (figures 3 and 4). The hydrograph observed on figure 7.a may explain bimodal responses as the one shown on figure 2a. The two peaks have been identified in the description of the impervious function (figure 6). As the flow coefficient increases, the second peak grows bigger and becomes relatively more important than the first peak, as shown on figure 7. While the first peak is composed essentially by runoff from the first urban agglomeration closer to the outlet (figure 1), the second peak is probably composed partially by the flow that comes from the second urban agglomeration (Sautron, figure 1) and in addition by rural saturated areas when its moisture is wetter. The saturated rural zones are determined according to the variable source area (Beven and Kirkby, 1979). The wetter the soil is the larger the source area will be. Moreover, the second peak occurs 6 hours after the rainfall. This may explain why the lag time seem to be postponed 6h when the soil is wet before the rainfall event. The first peak being much smaller than the second one ends up 'disappearing' from the hydrograph by the effect of the dispersion of the rainfall peak (figure 2b).



(a) **(b)**

Figure 7. Comparison among different geomorphological transfer function according to the runoff coefficient value



(a) **(b)**

Figure 8. Comparison among different FDTF according to the runoff coefficient value.

Figure 8 shows the FDTF for different groups of rainfall event types, once again according to their flow coefficients. The hydrological response when the catchment is rather dry and the flow coefficient is weak (around 0.02) presents a clear peak an hour after the rainfall impulsion. As we take stronger flow coefficients, the first peak is still found an hour after the rainfall impulsion but it relatively 'decreases' comparing to the rest of the hydrograph, specially comparing to the second elevation of the curve.

Therefore we can conclude that the tendency of these curves, as the coefficient increases, is quite similar to the results obtained with the geomorphologic simple transfer presented on figure 7. The second peak also appears and grows bigger as the first peak retracts with the increase of the flow coefficient value that characterizes each group of episodes.

The main difference between the two groups of unit hydrographs (geomorphologic on figure 7 and FDTF on figure 8) is the second peak of dry events that appears on geomorphologic transfer function and not on the FDTF one. When we deal with weak rainfall over a rather dry soil, the contribution of the second node of urbanization upstream (Sautron on figure 1) is probably

weakened by the effects of diffusion that have not yet been included to the simple transfer methodology applied in this work.
Results and Discussion - a clear presentation of experimental results obtained, highlighting any trends or points of interest.

CONCLUSIONS

In the context of the research that ultimately aims to develop a well adapted hydrologic model for suburban basins, this work focused on determining the main contributive sources of runoff over the catchment. Our objective is to explain some particular behaviors observed by investigating this process and find indicators that trigger different hydrological responses to rainfall on a basin.
The Chezine rainfall-runoff hydrographs showed that the basin often presents a bimodal response. Another interesting observation is that the peak time can vary from 1h to 6h. We have used a simple model to explain these particularities, identifying relevant parameters and features that must be considered in a future model.
Based on the results of a hydro-meteorological dataset analysis, two hypotheses have been drawn to describe the behavior of the basin according to its initial moisture state. When the soil is dry, natural surfaces infiltrate, store and evaporate all the rainfall. Therefore runoff is produced entirely over impervious surfaces. However, when the basin is wetter, part of the rural (or natural) surfaces are saturated and generate runoff as well. We thus complete the second remark extracted from O'Loughlin et al (1996) in the introduction of this paper: urban impacts are greatest not only for low intensity storms, but also for a drier initial wetness state of the basin. Both factors are extremely important because they imply relatively large losses over rural areas and thus the most important contribution to the outlet flow variation comes from the urban zones.
The simple 3-step geomorphologic model allowed us to draw based on these hypotheses different unit hydrographs according to the flow coefficient, which was shown to be closely related to the initial moisture state. This study suggested, by the means of the imperviousness function (Gironas, 2007), that the localization of imperviousness over the basin could be responsible for the dual-mode response for dry initial state episodes, when urban contribution is preponderant. When the basin is wetter the contribution of the rural saturated areas increases in addition to the second urban zone upstream (Sautron, figure 1). The greater the flow coefficient is the bigger second peak will be. This might explain why the lag time seems to increase in some events (as the one on figure 2.b): the first peak (an hour after the rainfall), being much smaller than the second one (6h after the rainfall), probably ends up 'disappearing' from the hydrograph by the effect of dispersion.
The application of the FDTF produced a similar trend of curves as it was observed on simulations, corroborating the hypotheses made on runoff generation for drawing these geomorphologic transfer functions. The differences observed can be explained by the diffusion effects of the routing that were not yet considered at this point. For a complete attempt of hydrological model it is thus important to consider the diffusion effects using for instance the kinematic wave theory (Moussa, 1996) instead of the simple transfer for routing the water flow.
This work was meant to identify important characteristics that must be considered when developing a complex, detailed model for suburban catchments. It was shown that it is indeed essential to distinguish and well represent both urban and rural areas. The role of the soil wetness initial state in models for peri-urban basins has also been proved to be crucial, as we have different transfer function shapes depending on their flow coefficient that varies according to the basin initial moisture state.
Acknowledgements: The AVuPUR project was funded by the French Agence Nationale de la Recherche (ANR) under contract ANR-07-VULN-01.

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