FLOOD REGIMES OF MID-SIZED AND MIXED LAND-USE CATCHMENTS: CAN WE ASSESS THE URBAN CONTRIBUTION?

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ABSTRACT

This paper presents a study that aims to evaluate the impact of urban development on the flood regime of a small river. This research was conducted on the catchment of the Yzeron River in western Lyon. The Yzeron catchment is mid-size (130 square kilometres), characterized by a rapidly expanding, scattered suburban development. Statistical tests showed that both flood frequency and severity have increased in this catchment, between two distinct periods: the 1970s and the 1990s. Evaluation of the specific impact of urban development on the flood regimes requires the paying of attention to all possible contributing factors. For that purpose, we used a diachronic approach, with hydrologic and land-use data from the two periods. We used these data to calibrate a distributed hydrologic model and then to simulate the urban, sub-urban, and rural hydrologic contributions.

Simulation results suggest that the current increase in flood frequency and severity is due to a combination of causes, all operating in the same direction: stronger rainfall in the 1990s, increasing imperviousness, straightening of flow paths, and a decrease in grassland and farming areas. None of these factors alone would be sufficient to explain the observed increase in the flood regime. We conclude from this research that the:

- use of a simulation model, correctly calibrated, allows removal of the effects of inter-annual fluctuations in rainfall, which in turn allows analysis of urban effects;
- comparison of flood regimes based on flow-duration-frequency curves allows a more holistic evaluation of trends than the more classical ‘remarkable events comparison’ method;
- simulation of scenarios with increasing imperviousness shows a clear effect of urbanization on the flood regime when the relative increase is up to 14%. This result is confirmed by literature reports for smaller basins.

Key words: peri-urban, runoff, simulation model, flood regime

1. INTRODUCTION

There is now general concern regarding sustainable water resource development in urban environments. In industrial countries, almost 80% of the population is living in urban areas and it is expected that 60% of the worldwide population will live in towns by 2030 (Paul and Meyer 2001). In France, the last population survey indicates a significant expansion of main city areas (Chavouet and Fanouillet 2000) with 76% of inhabitants living in urban areas on 18% of national territory.

Suburban zones are characterized by an important rate of change in land usage over a ten-year timescale. They experience simultaneously an increase of impervious areas, straightening of natural water courses and runoff into pipes as well as desertion of farming lands that become fallow and finally turn into sporadic deciduous forests. The most visible changes occur around large cities during expansion and likely significantly modify rainfall transfer in sub-urban areas as well as runoff production for higher rates of urbanization. It is observed from experimental data and for small catchments of some squared kilometres that small- and medium-size floods begin to increase strongly from 10% of imperviousness (Hollis 1975).

For catchment sizes of one to several hundred square kilometres (here called mid-size basins), more complex effects are expected, depending on runoff pathways across mixed land-use areas.

In this situation a comparison of peak flood magnitudes, before and after an observed (or simulated) growth of urbanization, seems insufficient.

Urban hydrologists have developed suitable models to predict and quantify the effect of imperviousness in order to design storm runoff pipes and manage complex sewer networks (Leopold 1968, Bras and Perkins 1975, Chen and Wong 1993, 1989, Chocat 1978, 1991, 1994, 1997, Desbordes 1974, 1975, 1989). Complex models that intend to represent the hydraulic interaction between surface runoff and drainage systems in urban areas are also supported by geographical information system facilities (Dordevic et al. 1989, Grandjean and Zech 1991). However, suburban processes include a variety of situations with a mixing of effects between rural and urban flows. These effects are very difficult to represent in detail.

Nevertheless it seems increasingly obvious that sustainable water management can no longer ignore the specific hydrological behaviour of this dynamic. At the same time suburban areas offer spaces where flood mitigation and natural water quality improvement could take place, both today and in the future.

We must, however, demonstrate that these areas have a sensitive effect on the water balance and its dynamics. This research, therefore, focuses on high flow regimes, as a well-known – but not well-quantified – effect of uncontrolled runoff coming from suburban developments is the inundation of downstream densely urbanized areas.

2. DATA ANALYSIS

2.1 Study area

This study relates to the Yzeron catchment. It is a mid-size catchment, located to the west of Lyon, where heterogeneous urbanization has been observed over a number of decades. This evolution generally takes the form of the expansion of small urban centres from old villages, developing along road networks, and following the topographic constraints imposed by river networks. The upstream and western part of the basin is limited by a range of hills culminating at 800 metres and covered with coniferous vegetation. The intermediate part is covered mainly with grassland and cultivated lands, mixed with urban zones. Its mean elevation is about 300 metres above sea level. Thin green corridors covered with deciduous trees remain along rivers. The downstream part is mainly covered with densely urbanized areas. The outlet reaches the Rhône River at an elevation of 157 metres.

2.2 Available Data

Since 1969, discharge data have been recorded with a variable time step for the upstream station (drainage area of 50 km^2) and since 1988 for the downstream station (drainage area of 130 km^2). Since 1985, rainfall data have been recorded at a time step of 6 minutes at four rain gauge stations, distributed across the urban part of the basin. We also used a long-term record of daily rainfall data to check the evolution of the rainfall regime across the entire period spanning two decades. Discharge and rainfall data covering the years since 1988 were also available for two small basins of 2.8 and 8.2 km^2 with respectively sub-urban and rural land uses.

For land use codification we used aerial photographs from two surveys that took place on the years 1972 and 1996. The first survey was in black and white and the second in colour.

3. PRELIMINARY DATA ANALYSIS

3.1Discharge analysis

Figure 1 shows the discharge time series for the upper part of the basin between 1969 and 1999. The size of this sub-catchment is 50 km². The downstream urban area is flooded over a discharge threshold of 7 m^3/s (dashed line). We can see from this figure that five urban floods occurred during the 1990s, whereas none took place during the 1970s. We chose the 1990s and 1970s as reference periods for comparing flood regimes because we know the state of land use during these periods from aerial surveys (see previous section). We used a stationary test (Lang 1999, Fig.2) to check the number of large floods that occurred during a given period. This test has been applied to the upstream gauge discharge series. Accepting a confidence interval of 95%, the flood regime was declared to be non-stationary during the 1990s. Confronting this result with the magnitude of the floods during this period (Fig.1) indicates that fewer but more intense floods took place. This could be the effect of both rainfall features and land use changes.

3.2 Rainfall analysis

The application of the same stationary test to a daily rainfall time series spanning the entire period indicates a slight decrease in the number of large daily rainfall amounts during the 1990s. Checking for intensity (daily amount per day) versus frequency distributions of the largest amounts (Fig.3), we observed the 1990s were statistically higher than the 1970s for a confident interval of 90%. However, it is difficult to form conclusions on the daily rainfall feature changes and the increase in flood event magnitude because the rain gauge station is situated about 15 km east of the catchment, in a very different landscape.

3.3 Land uses

The aerial photographs from each period were assembled. We then used a transparent grid layer with a unit square cell size of 167 metres. Each cell was attributed a land use cover number corresponding to forest or grassland (including farming) or sub-urban or urban type. Sub-urban type was associated to any cell that contained impervious features such as roads, parking lots and houses, but for which the impervious rate was less than 20%. From figure 4 we can see that impervious cover cells grew, along the 1970s to the 1990s, from 20 to 30% of the total area. At the same time, we can observe a decrease of about 30% of grass and cultivated lands to the benefit of urban, suburban and forest areas respectively with an increase of 15, 12 and 5% for each.

4. METHOD

We used a method based on a numerical simulation to assess the respective contributions of land use evolution and rainfall difference to flood increase. The method was implemented as follows:

1) Build an hydrological distributed model, corresponding to the 1990s state of the basin, calibrate and validate this model;
2) Build a second hydrological distributed model, corresponding to the 1970s state of the basin, assuming that the hydrological behaviour of each type of surface (urban, sub-urban, grassland and forest) remained unchanged;
3) Use both models to simulate the 10 year-long series of rainfall observed during the 1990s and generate two series of hydrographs;
4) Analyse and compare the statistical properties of the two series, try to form conclusions on the influence of land use change.

4.1Hydrological model structure

To take into account the mixed land use evolution between the two periods, and to test the relative importance of an expected urban effect on the flood regime, we used a semi-distributed hydrological model called CANOE (Figure 5). The architecture of the model allows consideration of three differing hydrological functions whose combination leads to three types of hydrological units whose categories are strictly urban, semi-urban, and strictly rural.

The main steps of the construction of the distributed model are described below.

4.2 Sub-basins delineation

Three criteria were used to delineate sub basins: dominant land use, an outlet located on the perennial stream network, and finally, the number of basins should not exceed 30 so as to not alter the simulation process. The number of basins we finally retained was 23 with a mean size of 5 km^2. Imperviousness was estimated by the rate of the number of urban cells on the total number of cells in a sub-basin. Each sub-basin was then attributed a hydrological class according to the following rules: basins with less than 5% of imperviousness areas were declared as rural, basins with less than 25% as sub-urban, and basins over 25% as urban. For this purpose, forest and grassland covers were considered as rural hydrological units. We also used a statistical plot sampling method (Chocat and Seguin 1986) to assess the sub-basins imperviousness rate directly from maps in order to avoid any bias as a result of an arbitrary human cell codification. A good linear relationship was found between the imperviousness rates we calculated from these two methods. The correlation coefficient was 84% and only dominated rural basins exhibited different values.

4.3 Model calibration strategy

To calibrate the model, we chose 3 events for each season, and we used the Nash’s classical criteria. Firstly, we calibrated the parameters of rural areas (initial losses and Horton’s parameters) using flow data collected at the upstream stations. Afterward we calibrated the parameters of urban areas, using flow data collected at the downstream stations.

4.4 Validation / Statistical tests

To assess the quality of the calibration, we decided to use a method based on the analysis of the statistical properties of the distribution of some flood characteristics. Indeed, our aim was not to construct a model able to reproduce individually each flood, but to generate two series of virtual floods, presenting the same distribution as observed ones. We based our study on an holistic flood regime description, rather than on flood volume and peak ratios. This description is based on the analysis of discharge thresholds defined by durations during which a discharge threshold is continuously over-passed (Javelle et al. 1989, 2002). These flood characteristics are called ‘QCXd’ for discharge (Q) continuously exceeded on a ‘d’ duration. Qcxd is expressed in cubic metre per second (c.m.s-1), as a discharge. Sampling the ‘n’ greatest QCXs for several durations that encompass the basin flood dynamics, results in different sets of data that are expected to follow probabilistic laws when plotted versus their experimental frequency (Javel et al. 1999, Javel et al. 2002). Flood regimes are then summarized in terms of expected maximum intensities for different given durations. Then, classical non-parametric tests like Wilcoxon-Mann and Withney or Kolmogorov-Smirnov can be used to compare the simulated flood regime with the observed one, and then validate the model. The nul hypothesis we retained is ‘the two flood regimes belong to the same one’ Significance levels of 10, 5 and 1% were tested, to accept or reject the nul hypothesis.

We used the same method to compare the series of simulated hydrographs corresponding to the 1970s and the 1990s, and to assess the real influence of land-use evolution on the flood regime.

5. RESULTS

5.1 Some orders of magnitude

A literature review (Pherson 1974, Hollis 1975, Galea et al. 1993) gives an idea of the order of magnitude of the effects of rural to urban change in land use on the flood regime (Fig.7). The ratio between post-urbanization and pre-urbanization peak floods can reach 10 to 20 for small or frequent floods (less than one-year return period). It can reach 2 for a 100 year return period flood. Other studies shows that urban and rural flow peaks can remain in the same order of magnitude for a ten-year flood event. Turning from crops to forest land use can, in some cases, smooth the flood regime and compensate the effect of urban growth.

5.2 Power of test analysis

To discriminate the flood regimes we assessed the power of the statistical tests to detect independent differences between position and scale parameters of the QCXd distribution. We observed that QCX distributions did not belong to the same flood regime since there is a 15% difference between the position parameters and a 35% difference between the shape parameters. This corresponds to small shifts between the distribution of sampled QCXs for a same duration ‘d’. The tests are assumed to be very sensitive, the Wilcoxon test being more sensitive than the Kolmogorov test in this case. Here, we only present results from the Wilcoxon. In the case of urbanization, both the position and scale parameters of the QCXd distributions are expected to change.

5.3 Model validation for the last decade

The calibration performance was assessed using the statistical tests over several ‘d’ durations of 1, 3, 6, 12 and 24 hours. These durations are representative of the flood regime dynamics. The smallest durations describe properly the peak flood form and the largest ones give a good idea of the recession part of the flood curve. We reported in Table 1 the results of the nul hypothesis with ‘yes’ if it was accepted and ‘no’ if it was rejected. The nul hypothesis was rejected for the QCX duration of 24 hours. It reveals that the calibrated model is well-fitted to the short durations representative of urban dynamics. The 24-hour duration is mainly representative of the rural discharges that sustain the flood recession curve.

5.4 Comparison between pre and post urbanization periods

The two simulated flood series, corresponding to the two decades, have been compared using the statistical tests. The imperviousness rate increased by 15% over these periods. Such an increase was expected to have a significant effect on flood characteristics. Two sets of QCXd characteristics were used. The first (Table 2.a) only included the largest floods over a two-year recurrence interval, while the second one (Table 2.b) included small floods. In the first case, and in spite of the imperviousness increase, no statistical differences were observed between the flood regimes from the 1970s and the 1990s. When including the small floods, we observed that short duration QCX distributions (from 1 to 3 hours) were significantly different between the two periods. This result confirms the fact that urbanization increases mainly the frequency of small floods but does not alter large floods in a mixed land use basin where the rural area is dominant.

6. CONCLUSIONS AND PERSPECTIVES

This research allowed us to formalize a reproducible methodology that can be used to assess the influence of land-use evolution on flood regime for mid-size catchments.

In our specific case we demonstrated that the urbanization process significantly affects frequent floods (return period less than 2 years), but does not seem to have a major influence on larger ones (return period more than 10 years) as observed in the 1990s. To avoid any effect of the evolution of the rainfall regime we used the 1990s rainfall series in our model with 1970s and 1990s land covers. It seems that, in this case, other factors must be invoked. A 5% increase in forested areas seems too few, but a 12% increase in the suburban is not, as we can expect one main effect to be acceleration of flow transfer but not reduction in rural flood production. This is quite complex to capture with a model based on distributed hydrological units. The reason is that a range of suburban types exist where the artificial and natural drainage network patterns and interconnections are determinant factors in transferring rural floods (Li and Wong 1998). A key challenge would be to define hydrological signatures corresponding to typical suburban developments.

Large town fringe areas are rapidly growing and represent a main point of concern for urban water management in the coming decades. This research is a contribution to river basin management, especially with regard to land use evolution and its effect on the flow regime in developing suburban landscapes.

We now want to assess biological and ecological effects of urbanization at the same scale. Other methods, using tracers as oxygen isotopes, will be used to determine the origin of water during different periods of time. The hydrological model will be improved and its results compared with the ecological quality of different stations, using classical bio indicators. Collaboration with the US Long-Term Ecological Research network is planned to compare results with other urban ecology projects. The final aim is to develop a more holistic urban planning approach that encompasses ecological perspectives.

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Figure 1: Evolution in high flood occurrence between the 1970s and 1990s

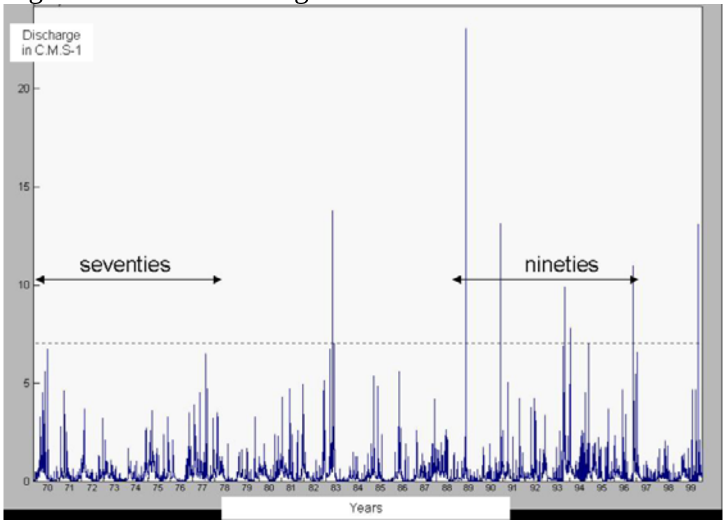

Figure 2: Stationary test on the number of maximum discharges between the 1970s and 1990s

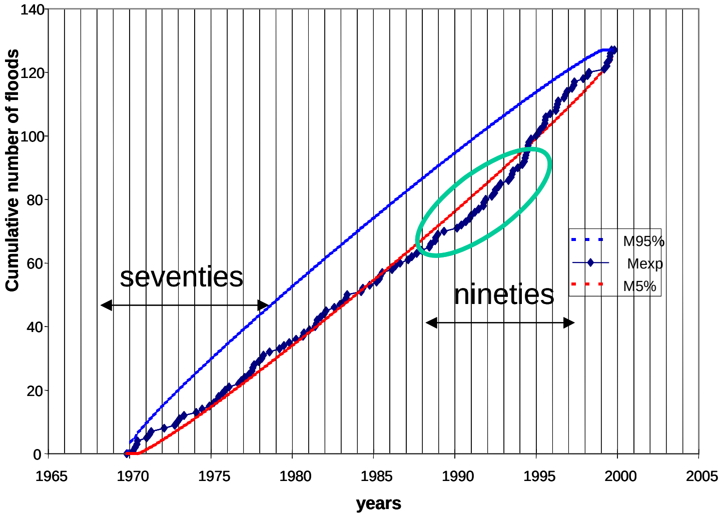

Figure 3: Distributions of maximum daily rainfall for the 1970s (black squares) and 1990s (grey triangles) with a 90% confident interval

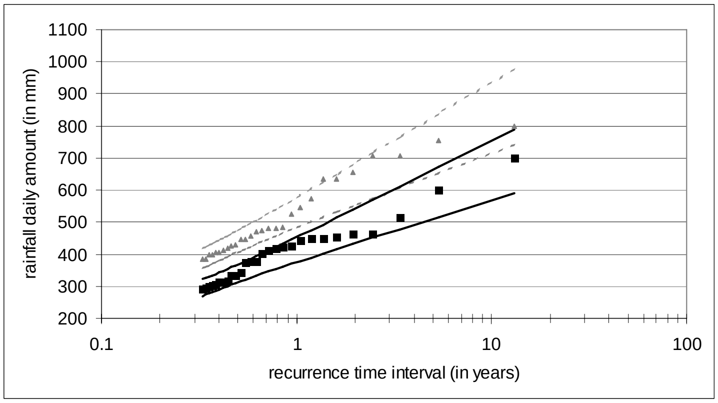

Figure 4: Histogram of the four main land uses during the 1970s and 1990s

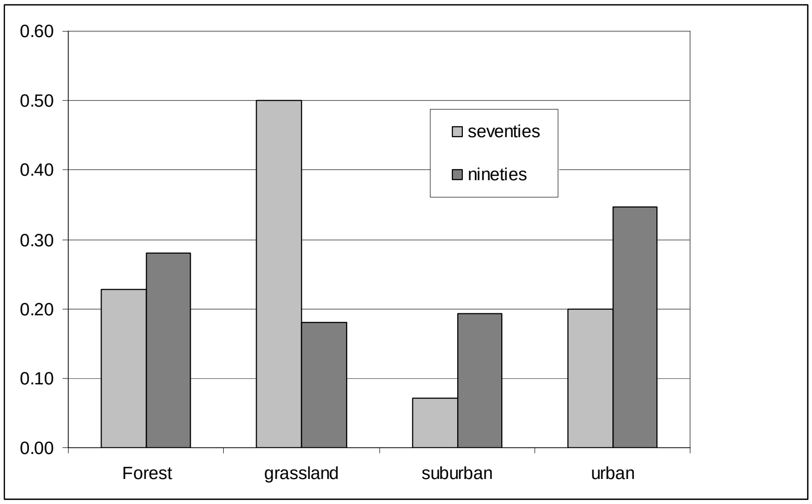

Figure 5: Map of the organization of production and transfer functions in the CANOE model

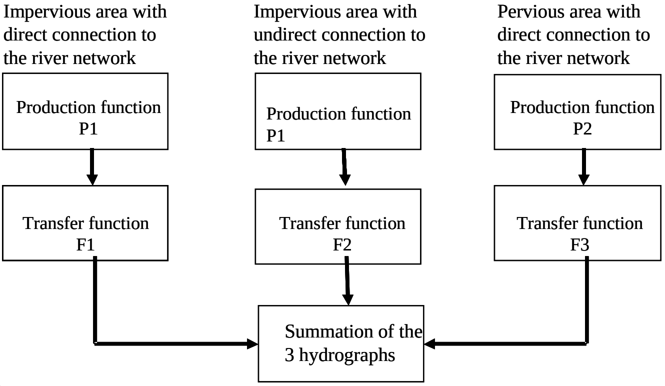

Figure 6: Somme magnitude orders for flood peaks in relation to land cover change types *(data collected from Hollis 1975 and Galea et. al., 1993)*

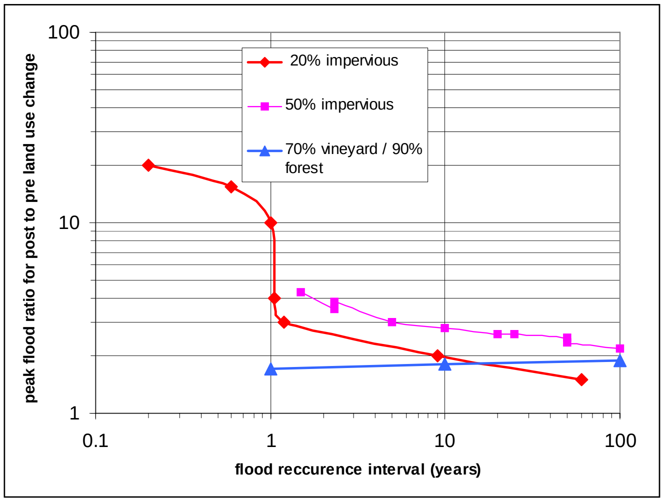

Table 1: Model validation using a comparison test on observed and simulated flood characteristics

Wilcoxon-Mann-Whitney / unilateral test			
significance level			
QCX durations	10%	5%	1%
1h	yes	yes	yes
3h	yes	yes	yes
6h	yes	yes	yes
12h	yes	yes	yes
24h	no	no	

Table 2: Comparison tests on simulated flood characteristics from the 1970s and 1990s (a) without small floods and (b) all floods included

(a)	Wilcoxon-Mann-Whitney / unilateral test		
	significance level		
QCX durations	10%	5%	1%
1h		yes	yes
3h		yes	yes
6h		yes	yes
12h		yes	yes
24h		yes	yes

(b)	Wilcoxon-Mann-Whitney / unilateral test		
	significance level		
QCX durations	10%	5%	1%
1h	no	no	yes
3h	no	yes	yes
6h	yes	yes	yes
12h	yes	yes	yes
24h	no	yes	yes