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Climate change impact on flood generation process

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Abstract This study aims to assess the impact of climate change on flood frequency and severity in a meso-scale catchment in France. The research was conducted on the catchment of the Yzeron River in western Lyon. First statistical tests showed that both flood frequency and severity increased between the two distinct periods in the 1970s and 1990s. During the same period an increase in accumulated rainfall amount over several days and an increasing urbanisation from 20 to 35% of the catchment area was observed. In order to assess the influence of each change a diachronic approach was used with rainfall and land-use data from the two periods of the 1970s and 1990s. The data were used to calibrate a distributed hydrologic model. The simulations showed the respective effect of both, climate change (through rainfall regime change) and urban development on flood frequency and flood risk.

Key words climate change; simulation model; flood regime

PRELIMINARY DATA ANALYSIS

This study relates to the Yzeron catchment (western Lyon, France) which is 130 km^2 in area and characterized by a rapidly expanding, scattered suburban development.

Discharge analysis

The 1990s and 1970s were chosen as reference periods for comparing flood regimes because the state of land use during these periods from aerial surveys was known. We used a stationary test to check the number of large floods that occurred during a given period. 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 indicates that fewer but more intense floods took place. This could be the effect of both rainfall features and land-use changes.

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, we observed the 1990s were statistically higher than the 1970s for a confidence interval of 90% (Radojevic & Breil, 2000).

Land uses

The aerial photographs from each period were assembled. Then a transparent grid layer with a unit square cell size of 167 m was used. Each cell was attributed a land-use cover number corresponding to forest or grassland (including farming) or peri-urban or urban type. Peri-urban type was associated to any cell that contained artificial flow-paths such as draining ditches, pipes and artificial runoff surfaces with impervious features such as roads, parking lots and houses, but for which the impervious rate was less than 20%.

METHOD

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

- Build an hydrological distributed model, corresponding to the 1990s state of the basin, calibrate and validate this model;

- 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;
- Use in the two land-use state models the same 10-year-long time series of rainfall observed during the 1990s to simulate two series of hydrographs; this allowed removing the effect of the rainfall on the flood regimes response.
- Analyse and compare the statistical properties of two generated flood regimes, try to form conclusions on the influence of land-use change.

Hydrological 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, a semi-distributed hydrological model called CANOE (Chocat, 1978) was used. The architecture of the model allows consideration of three differing hydrological functions whose combination leads to three types of hydrological units whose categories are totally urban, semi-urban, and totally rural. The main steps of the construction of the distributed model are described below.

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 not to 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 impervious 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.

Model calibration and validation

To calibrate the model, we chose three events for each season and used 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. Following this the parameters of urban areas, were calibrated using flow data collected at the downstream stations.

To assess the quality of the calibration, it was decided to use a method based on the analysis of the statistical properties of the distribution of the 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 the observed ones. We based our study on a holistic flood regime description, rather than on a selection of flood events characterized by their volume and peak. For the purpose we used the so-called peaks-over-threshold method (POT) to select a partial duration series (Stedinger *et al.,* 1992) made of the "n" greatest independent observed floods. In our case the description is completed by the analysis of discharge thresholds defined by durations during which a discharge threshold is continuously over-passed (Galéa & Prudhomme, 1997). These flood characteristics are called "QCXd" for discharge (Q) continuously exceeded on a "d" duration. QCXD is expressed in cubic metre per second (m^3 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. Flood regimes were summarized in terms of expected maximum intensities for different durations. Then, the Wilcoxon-Mann test for paired data is used to compare the simulated flood regimes with the observed one, and then validate the model. The null hypothesis we retained is "the two flood regimes belong to a same one". The same method was used 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.

Flood risk evolution

The flood risk can be defined as the mix of flood hazard and vulnerability. In our case the objective was to get a basin scale view of the cross-effect of the imperviousness increase and of the land-use evolution along the stream courses. We used for the purpose a simple metric of the vulnerability which corresponds to the flooding frequency that is acceptable for a given land use. Mean recurrence intervals of 0.5, 5 and 10 years were attributed to green land, periurban and urban land uses, respectively. Frequencies of flood hazard and vulnerability were then compared.

Floodable area boundaries were determined from a digital elevation model (DEM) analysis considering at least all grid cells connected to a water course with no more than an arbitrary given height of 1 m above a stream-cell elevation. Due to the 15 m cell size definition, this was only an approximation, but the objective was to compare the vulnerability evolution between the two observed periods. For this, the weighted amount of vulnerability at each period multiplying the land-use type vulnerability by its area was calculated.

RESULTS

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. 1). The ratio between post-urbanization and pre-urbanization peak floods can reach 10–20 for small or frequent floods (less than one-year return period). It can reach 2 for a 100-year return period flood. Other studies show that urban and rural flow peaks can remain in the same order of magnitude for a 10-year flood event. Turning a significant part of a basin area from crops to forest land use can, to some extent, smooth the flood regimes and compensate the effect of urban growth. In our case the forest compensation effect would only concern suburban sub-basins but not the whole basin, which only changed from 5% crop to forest.

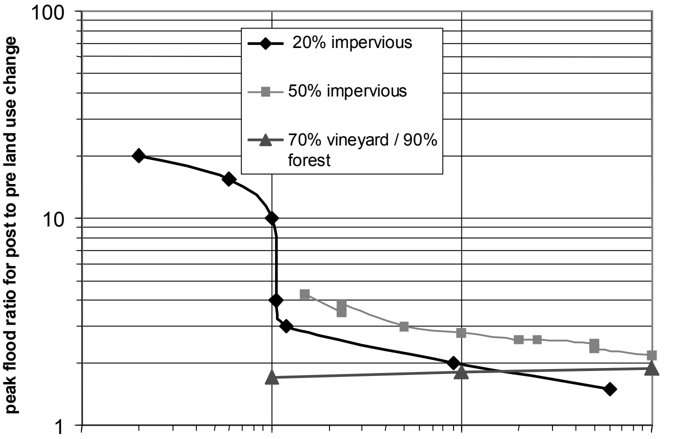

Fig. 1 Some magnitude orders for flood peaks in relation to land cover change types (data collected from Hollis, 1975 and Galea *et al.*, 1993).

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 h. These durations are representative of the flood regime dynamics. The smallest durations describe the peak flood form properly and the largest ones give a good idea of the recession part of the flood curve. Figure 2 illustrates how observed and simulated distributions fit quite well together.

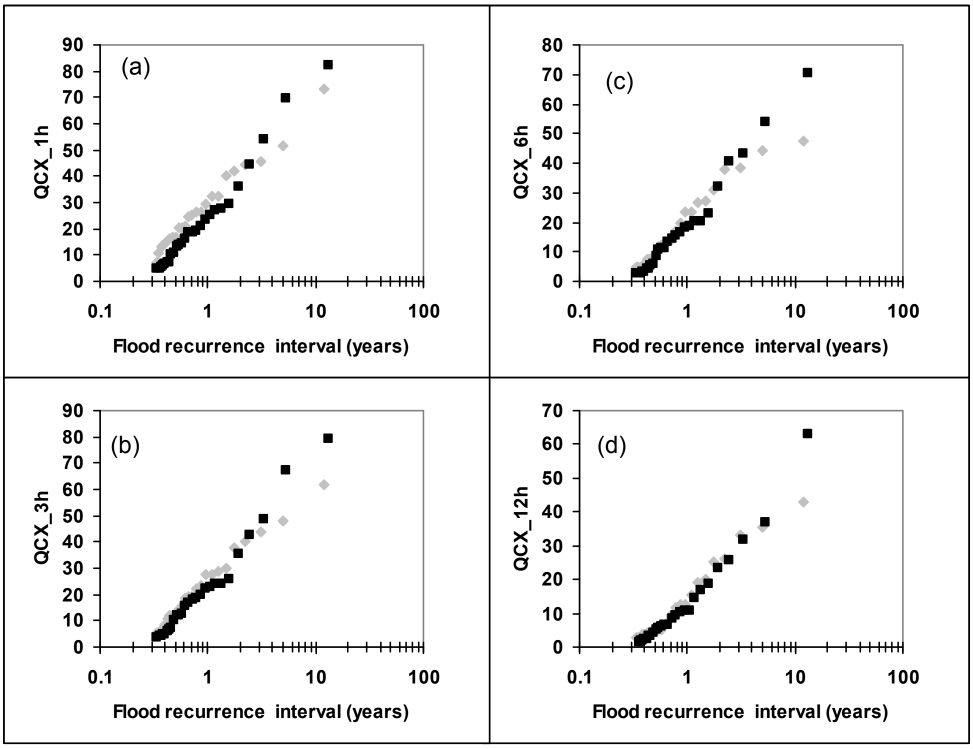

Fig. 2 Model validation comparing observed (grey diamonds) and simulated (black squares) flood QCX for duration from (a) 1 h, (b) 3 h, (c) 6 h and (d) 12 h.

In Table 1 the reported results of the zero hypothesis with "yes" if it was accepted and "no" if it was rejected are shown. The Wilcoxon test seems to be very sensitive as it rejects the model fitting for flood characteristics of 1 hour when it is accepted for 3, 6 and 12 hours. The zero hypothesis was also rejected for the QCX duration of 24 hours but they are in fact very different (not presented here). It reveals that the calibrated model is well-fitted to the short durations representative of peak floods and the earlier urban response during these events. The 24-hours duration is mainly representative of the rural discharges that sustain the flood recession curve.

Table 1 Model validation using Wilcoxon bilateral test for paired data of observed and simulated flood characteristics.

Significance level $\alpha/2$	0.05	0.025	0.01
QCX_1h	No	No	No
QCX_3h	No	Yes	Yes
QCX_6h	Yes	Yes	Yes
QCX_12h	Yes	Yes	Yes
QCX_24h	No	No	No

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 increased by 15% over the whole period of three decades. 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 one-year return period, while the second (Table 2(b)) also included small floods whose frequency and magnitude are very sensitive to the urban increase, as first demonstrated by Hollis (1975). 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, except for 24 h duration as a result of the poor fitting of the model for this duration. When including the small floods, we observed that short duration QCX distributions (from 1 to 3 h) were significantly different between the two periods. This result confirms the fact that urbanization mainly increases the frequency of small floods, but does not alter large floods in a mixed land use basin where the rural area remains dominant.

Flood risk evolution

As a consequence of the land use change in the vicinity of the stream corridor the global amount of acceptable flooding return period has doubled from years 79 to 96 showing the need for protection (see Table 3). This means that at the Yzeron basin scale the flood risk has mainly increased as the result of the increase in vulnerability rather than in the flood hazard itself.

Table 2 (a), (b) Comparison tests on simulated flood characteristics from the 1970s and 1990s, (a) without floods less than 1 year return period, and (b) with all floods included.

(a)

Significance level $\alpha/2$	0.05	0.025	0.01
QCX_1h	Yes	Yes	Yes
QCX_3h	Yes	Yes	Yes
QCX_6h	Yes	Yes	Yes
QCX_12h	Yes	Yes	Yes
QCX_24h	No	No	No

(b)

Significance level $\alpha/2$	0.05	0.025	0.01
QCX_1h	No	No	No
QCX_3h	No	No	No
QCX_6h	Yes	Yes	Yes
QCX_12h	Yes	Yes	Yes
QCX_24h	No	No	No

Table 3 Land use evolution from 1979 to 1996 in the floodable area at the whole basin range. Vulnerability quotation with land use and change in total amount of vulnerability between the two periods.

Land use type in floodable areas	Area in km^2		Negotiated acceptable flooding return period (VC)	Vulnerability amount in years (area *VC)	
	Year 79	Year 96	Vulnerability coeff. in years	Year 79	Year 96
Forest	0.7	1.3	0.5	0.4	0.7
Grassland	2.7	0.5	0.5	1.4	0.2
Periurban	0.3	1.3	5.0	1.7	6.3
Urban	0.8	1.4	10.0	7.7	14.3
Total	4.5	4.5		11.1	21.6

CONCLUSIONS AND PERSPECTIVES

This research allowed us to formalize a reproducible methodology that can be used to separate climate and land-use change influence on flood regime.

In our specific case we demonstrated that the urbanization process significantly affects frequent floods, but does not seem to have a major influence on larger ones. Also the peri-urban expansion was based on the diffuse growing of the imperviousness with a very sensitive effect on the flood risk "amount".

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