Describing actual and future flood hydrological regimes

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Abstract

This paper presents a Flood Frequency Analysis (FFA) which takes into account the notion of duration: the “flood-duration-frequency” (QdF) method. Two applications are presented. The first one concerns its application to describing observed flood regimes in a case study of a hundred French catchments. Different types of floods are defined and represented on a map of France. The second application illustrates the potential for describing the impact of a presumed climate change, by analysing simulated discharges. Results for the whole Rhone basin (86 200 km²) will be soon available in the framework of the GICC-Rhone project. This will allow impacts of climate change to be spatially represented and critical areas identified.

Key words

Flood Frequency Analysis (FFA), flood-duration-frequency approach (QdF), flood volume analysis, hydrograph shape, impact of climate change.

Résumé


Mots clefs

Analyse fréquentielle des crues, approche débit-durée-fréquence, volume de crue, forme d’hydrographe, impact du changement climatique.
1. Introduction

In these last decades, new challenging hydrological problems have emerged, such as predicting the impact of a predicted climate change or of human activity on the behaviour of rivers. More than ever, there is a need for tools to describe in a concise way the hydrological regime. Because of their devastating potential, this paper focuses more specifically on floods, but other aspects of the hydrological regime (such as low flows) can be treated in the same way.

Flood Frequency Analysis (FFA) is a commonly used tool for describing the flood regime. However, most often, FFA characterises a flood event only by its instantaneous peak or its maximum daily flow. This information is essential but insufficient for many purposes. Flood severity is not only defined by its peak value, but also by its volume and duration.

This paper presents a FFA method which takes into account the notion of duration: the “flood-duration-frequency” (QdF) approach. It shows its application to describing observed flood regimes in a case study of a hundred French catchments. Its potential for describing the impact of presumed climate change on flood behaviour is also illustrated.

2. The flood-duration-frequency (QdF) approach

2.1 Brief review

As mentioned in introduction, most often, FFA describes a flood event only by its peak. However, more complete methods exist. One has been initiated by Ashkar (1980) and called “peak-volume analysis”. For each observed flood, a starting and an ending date are defined. Flood peak, volume and duration are then determined and analysed as random variables. Using the Gumbel mixed model, Yue et al. (1999) give a joint distribution, a conditional probability functions and the associated return periods for these variables. Ouarda et al. (2000) develop a regional flood frequency procedure based on canonical correlation analysis which can give estimates for ungauged basins.

Another similar approach, mentioned by Cunnane (1988) under the term “Volume over threshold analysis”, is based on partial duration series (PDS). The data involved consists of volume of flow exceeding a threshold $Q_0$, where $Q_0$ is the existing within-bank or within-levee flow or a proposed design channel flow. According to Cunnane (1988), theoretical derivations of distribution of flood volumes has been discussed by Todorovic (1978), Askar and Rousselle (1982) and Correia (1987).

This present paper deals with a third FFA approach which takes into account the duration notion and is called QdF analysis. Unlike the peak-volume approach, the duration is not considered as a random variable, but as a fixed parameter. QdF analysis is similar to the intensity-duration-frequency (IdF) analysis commonly utilised for rainfall. First, averaged discharges are computed over different fixed durations $d$. Then, for each duration, a frequency distribution is fitted to the maxima of these averaged discharge values. This approach is similar to the “Flood volume over different durations” approach mentioned in the Flood Studies Report (NERC, 1975), but was abandoned in the recent Flood Estimation Handbook (Institute of Hydrology, 1999). Only a limited number of papers focus on QdF analysis: Sherwood (1994), Balocki and Burges (1994), Galéa and Prudhomme (1997).
This paper deals with the QdF formulation presented by Javelle et al. (1999). This model was tested with good results on more than two hundred catchments: in France (Javelle et al., 1999; Javelle et al., 2000), Martinique (Meunier, 2001), Guadeloupe (Galea and Javelle, 2001), Burkina-Faso (Mar et al. 2002), Romania (Mic et al., 2002) and Canada (Javelle et al., 2002).

### 2.2 Methodology and QdF curves formulation

Instead of studying only the maximum peak flood ($Q_{\text{max}}$), the QdF approach considers maximal flood volumes over different durations noted $d$. Maximal volumes are divided by $d$ in order to deal with m$^3$/s and noted noted $V_d$. In this way, $V_d$ represents a mean flow, and instantaneous peak flood is the $V_d$ limit case, when $d$ tends to zero (Figure 1).

![Figure 1: Variables definition](image)

$V_d$ values are sampled using a procedure described by Lang (1995), which is now completely automatic. A moving average with a window length $d$, is computed over the whole instantaneous streamflow time series $Q(t)$, providing a new time series $Q_d(t)$:

$$Q_d(t) = \frac{1}{d} \int_{t-d/2}^{t+d/2} Q(\tau) d\tau$$

(1)

$V_d$ values are sampled by selecting maximal values of this new time series. Different methods can be carried out, as in any Flood Frequency Analysis (i.e. Peak-Over-Threshold or Annual Maximum analysis). Repeating these steps for $N$ different durations $d$, $N$ samples of $V_d$ values and $N$ corresponding distributions $V_d(T)$ are fitted. The limit case $d=0$ corresponds to the original time series of instantaneous values (if available).

The aim of the QdF modelling is to describe these $N$ mean flow distributions in one general framework, by fitting to them a unique formula $V(d,T)$ as a function on $d$, the length of the averaging window, and $T$ the quantiles return period.

The sketch of Figure 2 summaries the two described steps:

a) A frequency distribution is fitted to the maximal values of the $Q_d(t)$ (1) time series. Here, the sizes of the averaging window are $d_1$, $d_2$ and $d_3$ respectively and no assumption is made about a specific probability distribution;

b) A $V(d,T)$ formulation is fitted, allowing quantiles to be represented as a function of $d$, for different return period $T$, respectively $T_1$, $T_2$ and $T_3$. 

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We can establish the link with the IdF approach by indicating that the maximum runoff volume \( V_d \) multiply by \( d \) and the maximum mean streamflow \( V_d \) are respectively equivalent to the depth and the intensity of precipitation.

This study uses the following formula:

\[
V(d, T) = \frac{V(d = 0, T)}{1 + d / \Delta}
\]

Where \( V(d=0,T) \) is the distribution corresponding to instantaneous peak discharges, \( \Delta \) is a parameter which determines the curvature of the hyperbolic relationship in Figure 2b. These parameters are fitted on sampled data (Javelle et al., 2002).

This relationship concerns flood analysis, but a similar QdF approach exists for low flows (Galéa et al., 2000).

3. Value of the QdF approach and his \( \Delta \) parameter

The value of the QdF approach is briefly illustrated by the following case study. Both studied basins are part of the database presented in paragraph 4: the Jabron River at Souspierre (85 km², located in South of France) and the Nied Allemande river at Faulquemont (187 km², located in the north). Instantaneous streamflow time series are available for a period of 27 and 14 years, respectively.

Figure 3 shows the results of the peak flood analysis (peak-over-threshold values fitted by an exponential distribution). For both studied examples, distributions are similar.
Despite the similarity in peak values, the flood hydrograph shapes are completely different, as illustrated by Figure 4 which for each catchment shows an actual flood hydrograph with a peak of approximately 10-year return period. This result is confirmed by an analysis of all the sampled floods, Figure 5. Each flood is plotted as a point, with its peak discharge along the x-axis and a time parameter denoted as $t_{1/2}$ on the y-axis. $t_{1/2}$ corresponds to the time during which the discharge exceeds half the value of the peak. For the 10-year flood, $t_{1/2}$ is equal to 12 hours for the Jabron River and 4 days for the Nied Allemande (Figure 4).

Figure 4: Hydrographs of the observed 10-year flood
In term of water resource management, it is clear that both catchments have completely different flood regimes. However, as illustrated by Figure 3, a classical flood frequency analysis, considering only peak floods, would miss this point.

The same catchments are now studied according the QdF methodology described in paragraph 2, concentrating on mean discharges over durations $d$, successively equals to 0 (instantaneous streamflow), 1, 2 and 5 days. It can be seen that now, the analysis is able to make the distinction between the different behaviour of the two catchments (Figure 6).

In the case of the Jabron River, the whole set of distributions shows considerable spread, while for the Nied Allemande River they lie within a narrow sector. In the first case, floods contain relatively small volumes, while on the second case, high volumes are involved (Figure 4). Consequently, when studying mean flows over the same durations (i.e. 5 days), the distribution obtained for the Jabron River is lower than for the Nied Allemande.
The difference between both examples is also characterised when studying the fitted QdF curves, represented as a function on $d$ (Figure 7). Widely spread distributions of Figure 6 leads to curved hyperbolas, while more concentrated distributions leads to flat hyperbolas.

![Figure 7: $V(d,T)$ formulation fitting](image)

According to the $V(d,T)$ formulation (2), it appears that hyperbola shape is controlled by the $\Delta$ parameter: the flatter hyperbolas are, the higher $\Delta$ is. For example, a value of 1.3 days is obtained from fitting QdF curves to the Jabron River, and 11 days for the Nied Allemande River. Consequently, this parameter is a very good indicator of the flood dynamic behaviour. Compared with other characteristic durations manually obtained from hydrographs analysis, this parameter can be calculated in an objective and automatic manner.

### 4. Application in France for characterising different actual flood regimes

The QdF approach described in the previous sections was applied to 103 French catchments. Their areas range from 7 to 9387 km², and the available length of streamflow records ranges from 9 to 33 years. Javelle et al. (1999) showed that the fitted $V(d,T)$ formulation gives acceptable results.

Two flood regime indicators are identified:

- the $\Delta$ duration,
- the 10-year-return period instantaneous peak flood, $V(0,10)$, simply noted $Q10$

The $\Delta$ duration is a good indicator of the flood dynamic behaviour, as it has been explained in the previous section. $Q10$ gives an information about peak flood. The 10-year-return period is chosen because its seems to be a good compromise between the rarity of the event (we want to study extreme events), and the data availability (due to record length, longer return period, i.e. 100 years, would lead to larger uncertainties).

Figure 8 shows $Q10$ and delta as a function of the area of each studied catchment (in logarithmic scales). Area explains 70% of the $Q10$’s variance, while only 17% of the $\Delta$’s variance is explained. This result is mainly due to the fact that delta reflects the transfer processes within catchments. For a same rainfall amount, these processes depends on the surface area, but also on many other characteristics, such as topography, soil type, land use, etc.
In order to compare \( Q10 \) and \( \Delta \) for catchments of different sizes, both regime indicators have been divided by the area raised to the power of a coefficient deduced from the slope of the log-linear regression line between the variables. (Figure 8).

\[
Q10^* = Q10 / A^{0.83} \quad (3)
\]

\[
\Delta^* = \Delta / A^{0.22} \quad (4)
\]

Figure 9 represent the 103 studied basins as a function of their two scaled regime indicators, \( Q10^* \) and \( \Delta^* \). Plots, each representing one catchment, seems to follow an imaginary hyperbola, from top-left to right-down part of the graphic. Catchments located in top-left have a regime characterised by very intense and short floods (flash floods) and conversely, catchments located in the bottom-right are characterised by less intense and slower floods.

Three groups have been graphically delineated on Figure 9: one group for strong and quick floods, one for weak and slow floods, and one intermediate group. Then, each catchment has been represented on a map of France, with a symbol depicting its flood regime.
(Figure 10). It can be seen that flash floods basins are mainly located in the south east France. This expected result is explained by the fact that the Mediterranean region is known for its heavy precipitation occurring on very small areas, especially in autumn. For example, these kind of events caused huge damages in the Aude region, in 1999.

![Legend](Legend.png)  
Legend:  
- Strong and quick floods  
- Intermediate  
- Weak and slow floods

Figure 10: French studied catchments location according to their flood typology

5. Characterising the impact of a climate change on the flood regime

The QdF approach may also be used to characterise flood regime modifications, due to changes in climate, or land use. The idea is to carry out the same QdF analysis on streamflows generated by a rainfall-runoff model using climatic model outputs.

5.1 Data and methodology

The presented application is based on results provided by the GICC-Rhone project (Leblois, 2002). This ongoing project studies the impact of the climate change on the French Rhone basin (86 200 km²). The climate change scenario modelled is a doubling of the CO₂ concentrations, following the predictions of the Intergovernmental Panel on Climate Change (IPCC, 2001). Four Global Circulation Models (GCMs) have been tested. Simulations indicated that the doubling of CO₂ concentrations will induce an increase of rainfall total amount in winter. For being used by distributed hydrological models, these results were downscaling using the "perturbations" method. More details are provided by Boone et al. (2000).

During a former project (Gewex-Rhone), two distributed hydrological models were calibrated and validated using atmospheric forcings derived from meteorological database over the period 1981-1995 (Golaz-Cavazzi et al., 2001). Sauquet and Leblois (2001) showed that models were able to reproduce observed hydrological regimes. The GICC-Rhone project applies these models with six different climate change scenarios with equal probability (all assume a CO₂ doubling, but results depend on GCMs and resolutions). In the following application, results are shown for the standard MODCOU hydrological model and for one climate scenario. In the
future, all available hydrological models and climate scenarios should be considered in order to have an idea of the possible variability in the possible responses.

5.2 Application

The application is illustrated for one example: the Lanterne River at Fleurey-lès-Faverney, a tributary to the north part of the Rhone basin. The QdF model is used to describe the flood regime for this 1020-km² basin:
- measured discharge time series over the period 1981-1995 (Figure 11a)
- discharge time series simulated by the MODCOU model over the same period 1981-1995 for validation under past conditions (Figure 11b)
- discharge time series simulated by the MODCOU model forced by a climate change scenario (Figure 11c).

QdF curves derived from the reconstituted time series (b) are close to the observed ones (a). This indicates that the hydrological MODCOU model can correctly reproduce the actual flood regime. Comparison of graphs a and c indicates that the considered climate change scenario leads to a significant increase of the floods magnitude.

Figure 11: Comparison of QdF curves for the Lantern River at Fleurey-lès-Faverney, (a) derived observed streamflow measurements, (b) reconstituted times series estimated by MODCOU and (c) expected under climate change

Figure 12 represents the flood regime of (a), (b) and (c) cases, as a function of the magnitude and the dynamic of floods: $Q_{10}$ and $\Delta$ respectively (see Figure 9, section 4). This graph confirms that the observed flood regime (a) and thus simulated by the MODCOU model (b) are very close. Concerning the impact of a possible climate change (c), results indicate that floods magnitude ($Q_{10}$) may increase significantly, while their dynamic behaviour ($\Delta$) may remains constant. Several reasons may explain the stability of $\Delta$:
- a flood seasonality analysis under climate change indicates that the Lantern River still demonstrates rainfall-fed hydrological regime (i.e. floods are still generated by rain in winter);
- the same runoff and sub-surface processes are expected due to the unchanged surface status of the basin.

Results for the whole Rhone basin are soon expected in the framework of the on-going GICC-Rhone project.
Figure 12: Characterisation of the climate change impact for the Lantern River at Fleurey-lès-Faverney

6. Conclusion

This paper presented a FFA method which takes into account the notion of duration: the QdF approach. On this basis, different flood typologies have been defined for a hundred French catchments. The possibility to characterise the impact of a climate change has also been illustrated. Both applications, concerning actual and future flood regimes, have shown the potential of the QdF approach. However, different points need to be investigated further and research is ongoing.

The flood typology presented in section 4 has been empirically derived and can be improved. Other catchments, under different climatic conditions, have to be studied. Furthermore, the relationship between flood hydrographs and QdF curves needs to be better understood.

Concerning the climate change study, results for the whole Rhone basin area (86 200 km\(^2\)) will be soon available in the framework of the GICC-Rhone project. This will allow the flood regime map presented in section 4 to be established for future regimes. Climate change impacts could be spatially represented and critical areas (hot-spots) identified. Furthermore, work on the uncertainties of the involved models should be attempted. Indeed, this difficult task is essential for determining if observed modifications are significant or not.

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