Determination of bankfull discharge magnitude and frequency: comparison of methods on 16 gravel-bed river reaches

O. Navratil,* M-B. Albert, E. Hérouin and J-M. Gresillon
CEMAGREF, Hydrology Hydraulic Research Unit, 3 bis quai Chauveau, CP 220, F-69336 Lyon Cedex 09, France

Abstract
Bankfull discharge is identified as an important parameter for studying river morphology, sediment motion, flood dynamics and their ecological impacts. In practice, the determination of this discharge and its hydrological characteristics is not easy, and a choice has to be made between several existing methods. To evaluate the impact of the choice of methods, five bankfull elevation definitions and four hydrological characterizations (determination of duration and frequency of exceedance applied to instantaneous or mean daily data) were compared on 16 gravel-bed river reaches located in France (the catchment sizes vary from 10 km² to 1700 km²). The consistency of bankfull discharge estimated at reach scale and the hydraulic significance of the five elevation definitions were examined. The morphological definitions (Bank Inflection, Top of Bank) were found more relevant than the definitions based on a geometric criterion. The duration of exceedance was preferred to recurrence intervals (partial duration series approach) because it is not limited by the independency of flood events, especially for low discharges like those associated with the Bank Inflection definition. On average, the impacts of the choice of methods were very important for the bankfull discharge magnitude (factor of 1.6 between Bank Inflection and Top of Bank) and duration of exceedance or frequency (respectively a factor 1.8 and 1.9 between mean daily and instantaneous discharge data). The choice of one combination of methods rather than another can significantly modify the conclusions of a comparative analysis in terms of bankfull discharge magnitude and its hydrological characteristics, so that one must be cautious when comparing results from different studies that use different methods. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: bankfull discharge; gravel-bed rivers; recurrence interval; flow duration

Introduction

The bankfull discharge corresponds to the river level just before it starts to flow out of its main channel and over its floodplain (Wolman and Leopold, 1957; Kilpatrick and Barnes, 1964; Riley, 1972; Pickup and Reiger, 1979; Williams, 1978; Harrelson et al., 1994; McCandless and Everett, 2002).

The scientific community has largely adopted the bankfull discharge (magnitude and frequency) as one of the important concepts in the analysis of river morphology, flood events and ecological systems. Firstly, this parameter can be used to compare the morphology of river reaches, and to quantify human influences (Leopold et al., 1964; Gregory and Park, 1976; Pizzuto et al., 2000; Doll and Wise-Frederick, 2002). Secondly, bankfull discharge provides important information for the ecological functioning of the river. Above bankfull discharge, all in-channel secondary channels and in-channel wetlands are generally hydraulically connected. So a radical change in the biological processes occurs, for example the possible migration of fishes onto the floodplain for reproduction or feeding (Thoms, 2003), or the exchanges of carbon and nutrients that influence the productivity of the entire river system (Junk et al., 1989). Bankfull discharge is obviously useful for flood management, as above this discharge human activities can be impacted. Thirdly, the transition between in-bank and over-bank flow conditions leads to additional energy losses attributed to the interaction between the main-channel and floodplain flows (Knight and Shiono, 1996). The friction change and the floodplain storage occurring above bankfull discharge are determinant for flood wave propagation.
(Wong and Laurenson, 1983) and attenuation (Archer, 1989). Finally, according to several authors, bankfull discharge is highly correlated with the effective discharge, i.e. the discharge that transports the largest proportion of the sediment load over a long period (Wolman and Miller, 1960; Dunne and Leopold, 1978; Carling, 1988; Emmett and Wolman, 2001; Torizzo and Pitlick, 2004). Moreover, incipient motion discharge is generally expressed in the literature as a percentage of the bankfull discharge that varies between 30 per cent to 50 per cent (Emmett, 1975; Torizzo and Pitlick, 2004). From a management perspective (e.g. river restoration), bankfull discharge can be used as an indirect approach for estimating the flows that maintain the morphology and the function of the river channel and aquatic habitats (Ryan et al., 2002; Schmidt and Potyondy, 2004).

However, even if the bankfull discharge concept introduced by Wolman and Leopold (1957) is appealing, in practice the estimation of bankfull discharge magnitude and frequency remains difficult.

### Determination of bankfull discharge magnitude

The determination of bankfull discharge is more relevant at river reach scale than at a local scale (Wolman and Leopold, 1957; Williams, 1978). Indeed, the main-channel morphology can present significant variations over a short distance, whereas many features of the channel morphology (e.g. pool–riffles, meanders) show remarkable consistency at river reach scale. A survey reach length of about 15 to 20 bankfull widths is generally recommended in the literature (Leopold et al., 1964).

The identification of the bankfull elevation in the field is very often ambiguous. At the cross-section scale, local characteristics of erosion, sediment deposition, bank stability and vegetation interact to produce a non-obvious transition between the main-channel banks and the flat floodplain. This complexity of the main-channel morphology explains the various definitions for estimating the bankfull elevation. A first category of definitions is based on recognition of the geomorphic features in the field, such as a break in the channel bank’s slope (Leopold et al., 1964; Harrelson et al., 1994; Castro and Jackson, 2001; Dury, 1961; Andrews, 1980; Hupp and Osterkamp, 1996). A second category requires surveyed cross-sections and consists in applying a geometric criterion to identify the bankfull elevation (Wolman, 1955; Harvey, 1969; Pickup and Warner, 1976; Richards, 1982; Carling, 1988; Riley, 1972; Williams, 1978). Definitions based on a change in sediment or vegetation composition (Speight, 1965; Woodyer, 1968; Radecki-Pawlik, 2002) also exist, but are quite removed from morphological characteristics, and have been criticized for their lack of consistency within the same reach and between reaches (Riley, 1972). Williams (1978) showed that different morphologically based definitions applied to the same reach lead to highly variable bankfull discharge estimations and associated recurrence interval. Indeed, a slight difference in interpreting bankfull elevation can lead to significantly different discharges (Leopold et al., 1964). Therefore, this wide variety of definitions makes comparison between the various studies difficult (Richards, 1982).

### Determination of bankfull discharge frequency and duration

Many studies have found that bankfull discharge occurs at a recurrence interval of about 1–2 years on the basis of the annual maximum flood (AMF) approach (Nixon, 1959; Leopold et al., 1964; Dury, 1976; Harman et al., 1999; Castro and Jackson, 2001). The peak annual sample is constructed by extracting the maximum peak discharge of each year from a series of flows. This recurrence interval has been questioned in many studies (Kilpatrick and Barnes, 1964; Harvey, 1969; Hey and Davies, 1975, Woodyer, 1968; Williams, 1978; Petit and Pauquet, 1997), as the AMF approach mathematically always gives recurrence intervals of more than one year. For lower recurrence intervals, the bankfull discharge frequency can only be analysed with the partial duration series (PDS). The PDS approach consists in retaining all independent peak discharges that exceed a threshold discharge (Lang et al., 1999). However, methodological difficulties remain in defining the threshold discharge and the criteria for selecting independent peak discharges (Petit and Pauquet, 1997; Lang et al., 1999), and few methodological guidelines are available in the literature for bankfull discharge frequency analysis. The flow duration (FD) approach is another classic way to analyse bankfull hydrological characteristics (Nixon, 1959; Dury, 1961; Emmett, 2001; Sweet and Geratz, 2003). It provides the total duration of bankfull discharge exceedance over the period of records.

Instantaneous discharge data are not commonly used for bankfull frequency determination, although they are the most reliable data type for this analysis. However, the previous approaches are generally conducted with mean daily discharge data because of their availability over longer periods of time (Petit and Pauquet, 1997; Sweet and Geratz, 2003; Page et al., 2005). As the choice of data used could significantly modify the estimations of bankfull hydrological characteristics, its influence has to be examined.

This work is concerned with the comparison of different methods for estimating bankfull discharge and its hydrological characteristics, in order to highlight the methodological reasons explaining their variability between studies.
The aim of this paper is to test and analyse the sensitivity of: (1) bankfull discharge magnitude according to the choice of bankfull elevation definition at river reach scale; (2) bankfull discharge duration and frequency of exceedance according to the hydrological analysis, the data type, and the bankfull definition.

**Study Reaches and Methods**

**Methodological framework**

Five bankfull definitions based on morphological criteria were applied at all natural cross-sections surveyed on 16 river reaches. The two definitions that are more commonly used are geomorphic (Table I): Top of Bank (ToB) and Bank Inflection (BI). They are based on field expertise of the incipient overflow indicated by morphological breaks. The three other definitions are geometric (Table I): Wolman (WOL), Williams (WIL) and Riley (RIL). They are based on mathematical criteria in order to free the assessment from operator dependency, but require measured cross-sections. Nevertheless, the WIL definition is based on a visual change on a curve, which does not completely suppress operator dependency.

For each definition, the bankfull discharge was estimated with Fluvia (Baume and Poirson, 1984), a one-dimensional backwater flow model, by fitting the water surface profile to the bankfull elevation profile for the entire reach length. To assess if a discharge can be associated with a bankfull elevation profile with enough consistency at river reach scale, the five definitions were evaluated on each reach with two indicators: (1) the mean absolute difference (EM) between the fitted water surface profile and the bankfull elevation profile; (2) the reach length (LC) required to obtain a convergence of bankfull discharge with increasing reach length.

EM provides the reach-scale variability of each bankfull definition, whereas LC provides a comparison of the measuring efforts required for each definition.

Next, to determine if each definition retained the same hydraulic significance in terms of flooded area between reaches, we plotted for each reach the five bankfull discharges on the graph showing the change in the flooded area (including the main-channel area) with discharge.

Finally, for each definition, the bankfull discharges were characterized by their total duration of exceedance (with the FD approach) and their frequency of exceedance (with the PDS approach), applied to instantaneous and mean daily discharge data.

**Study reaches**

The study reaches were located in three major river basins in France: 13 in the Loire River basin, two in the Seine River basin and one in the Garonne River basin (Figure 1 and Table II). The reaches examined varied with respect to average reach gradient, drainage basin area, and geology. Most of the rainfall regimes of the drainage basins are oceanic or continental. The mean annual rainfall in the area of most reaches ranges from 620 to 1000 mm with an average value of about 760 mm. Only the Goudesch River reach, located in the Cévennes mountain region, has a pluvio-nival regime with a very high precipitation, its mean annual rainfall being about 1880 mm.

All reaches were located at or near stream gauging stations maintained by the different Regional Environmental Departments. Long-term (about 20 years) hydrological records were available for most reaches. At each gauged station, a reliable rating curve associated with a range of validity was available for in-bank and over-bank flows (Table II).

Additional criteria for reach selection included no flood regulation, lack of major channel modification (no dykes, no enroachment work except in the vicinity of bridges, river not trained), and ease of access. All study reaches were referred to as 'study reaches'.

**Table I. Definitions of the bankfull elevation at a cross-section**

<table>
<thead>
<tr>
<th>Identification</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI</td>
<td>Bank Inflection</td>
<td>Break in bank slope, i.e. the end of the abrupt part of the channel’s bank.</td>
</tr>
<tr>
<td>ToB</td>
<td>Top of Bank</td>
<td>Beginning of the floodplain, i.e. a relatively horizontal area.</td>
</tr>
<tr>
<td>WOL</td>
<td>Wolman (1955)</td>
<td>Channel width to mean depth minimum ratio.</td>
</tr>
<tr>
<td>WIL</td>
<td>Williams (1978)</td>
<td>Significant change in the relation between the wetted area and the top channel width.</td>
</tr>
<tr>
<td>RIL</td>
<td>Riley (1972)</td>
<td>First maximum local bank slope (Riley Bench Index Ri), from upper to lower elevation.</td>
</tr>
</tbody>
</table>
self-formed single-thread channel reaches with mobile gravel beds, stable banks and well-defined floodplains along at least one side of the channel. Even if most of the reaches have retained an almost natural state, some of them were cleared at the end of the 1970s (Olivet, Ozanne and Bouzanne River reaches).

Sidebars and middle channel gravel bars covered by annual vegetation were generally present in the main channel. Only the Indre River reach showed well-developed meander forms and point bar deposits on convex banks. The floodplain areas were well-developed except for the Semme and Goudesch River reaches that were confined by the valley sides. Old river terraces were present in Graulade, Indrois and Ozanne River reaches about 1–2 m higher than the active floodplain elevation. Vegetation patterns in the study reaches were similar: riparian vegetation was generally composed of trees such as poplars (*Populus* spp.), alders (*Alnus glutinosa*), beeches (*Fagus silvatica*) and shrubs (*Rubus* spp., *Crataegus* spp.), while the floodplains were dominated by short grass or cultivated areas.

**Field surveys**

Topographic and water level measurements were conducted on each river reach in 2002–2004 in the vicinity of the gauged station, using an electronic, digital, total-station theodolite. Topographic data were expressed in terms of height above gauge zero. About 20 cross-sections were surveyed along the river reaches in order to describe the main morphological features of the main channel and adjacent floodplain (Table II). Reach lengths varied from 12 up to 40 bankfull widths in order to include at least three pool–riffle sequences. At this scale there were no tributaries, and no flooded backwaters or lateral channel floodplain.
### Table II. Characteristics of the 16 river reaches and their basins

<table>
<thead>
<tr>
<th>River: reach location</th>
<th>Drainage area (km²)</th>
<th>Geology</th>
<th>Mean discharge (m³ s⁻¹)</th>
<th>Mean gradient (m m⁻¹)</th>
<th>Reach length (in bankfull width)*</th>
<th>Number of cross-sections</th>
<th>Flow discharge surveyed (m³ s⁻¹)</th>
<th>Range of validity of rating curve†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andour: Folles</td>
<td>131</td>
<td>granite</td>
<td>1.7</td>
<td>0.0047</td>
<td>32</td>
<td>19</td>
<td>1.8–2.06–7.43</td>
<td>0.14–19</td>
</tr>
<tr>
<td>Gartempe-downstream: Bessine</td>
<td>570</td>
<td>granite</td>
<td>6.2</td>
<td>0.0025</td>
<td>23</td>
<td>21</td>
<td>4.87–12.8</td>
<td>1.14–32.8</td>
</tr>
<tr>
<td>Gartempe-upstream: Mazeras</td>
<td>380</td>
<td>granite</td>
<td>4.5</td>
<td>0.0005</td>
<td>20</td>
<td>22</td>
<td>3–32</td>
<td>0.19–65</td>
</tr>
<tr>
<td>Graulade: Montaigut</td>
<td>19</td>
<td>granite</td>
<td>0.3</td>
<td>0.0125</td>
<td>38</td>
<td>14</td>
<td>0.22–1.26</td>
<td>0.08–2.29</td>
</tr>
<tr>
<td>Semme: Droux</td>
<td>177</td>
<td>granite</td>
<td>2.1</td>
<td>0.0044</td>
<td>15</td>
<td>32</td>
<td>1.85–2.41</td>
<td>0.08–21</td>
</tr>
<tr>
<td>Olivet: Beaumont</td>
<td>76</td>
<td>limestone</td>
<td>0.4</td>
<td>0.0018</td>
<td>22</td>
<td>21</td>
<td>0.18–1.13–1.72–1.99</td>
<td>0.47–19</td>
</tr>
<tr>
<td>Indrie: Genillé</td>
<td>396</td>
<td>limestone</td>
<td>2.3</td>
<td>0.0003</td>
<td>18</td>
<td>26</td>
<td>0.76–1.75–5.65</td>
<td>0.20–130</td>
</tr>
<tr>
<td>Loir: St-Maur</td>
<td>1160</td>
<td>limestone</td>
<td>3.4</td>
<td>0.0006</td>
<td>14</td>
<td>28</td>
<td>1.27–2.25–24.4§</td>
<td>1.30–111</td>
</tr>
<tr>
<td>Yerre: Bechereau</td>
<td>282</td>
<td>limestone</td>
<td>0.5</td>
<td>0.0012</td>
<td>16</td>
<td>17</td>
<td>0.89</td>
<td>0.14–50</td>
</tr>
<tr>
<td>Braye: Valennes</td>
<td>270</td>
<td>limestone</td>
<td>1.8</td>
<td>0.0005</td>
<td>24</td>
<td>15</td>
<td>1.05–6§</td>
<td>0.2–29.3</td>
</tr>
<tr>
<td>Ozanne: Trizay-les-Bonneval</td>
<td>268</td>
<td>limestone</td>
<td>1.6</td>
<td>0.0024</td>
<td>27</td>
<td>26</td>
<td>0.19–0.33–0.8–11.5§</td>
<td>0.01–4.34</td>
</tr>
<tr>
<td>Indre: St-Cyrin-du-Jambot</td>
<td>1712</td>
<td>mixed‡</td>
<td>11.6</td>
<td>0.0018</td>
<td>12</td>
<td>20</td>
<td>5.85–7.16–14.9§</td>
<td>1.15–192</td>
</tr>
<tr>
<td>Bouzanne: Velles</td>
<td>434</td>
<td>mixed‡</td>
<td>2.9</td>
<td>0.0011</td>
<td>21</td>
<td>25</td>
<td>0.56–1.117§</td>
<td>0.015–58</td>
</tr>
<tr>
<td>Avenelles: Boissy-le-Chatell</td>
<td>45</td>
<td>limestone</td>
<td>0.3</td>
<td>0.0060</td>
<td>20</td>
<td>25</td>
<td>0.15</td>
<td>0.002–14.5</td>
</tr>
<tr>
<td>Orgnac: Le Thel</td>
<td>104</td>
<td>limestone</td>
<td>0.6</td>
<td>0.0047</td>
<td>30</td>
<td>36</td>
<td>0.21</td>
<td>0.001–29</td>
</tr>
<tr>
<td>Goudesch: Cepède</td>
<td>10</td>
<td>granite</td>
<td>0.52</td>
<td>0.0087</td>
<td>14</td>
<td>17</td>
<td>0.11–0.25–38.22§</td>
<td>0.003–19</td>
</tr>
</tbody>
</table>

* The bankfull width was estimated with the BI definition.
† Lowest and highest bounds (in m³ s⁻¹).
‡ Mixed geology: a part of the drainage basin is composed of limestone, and the other part of granite.
§ Peak flood discharge associated with surveyed flood mark elevations.
To obtain a reliable description of river morphology, we surveyed cross-sections covering a wide range of morphological variations in the main channel and floodplain. In addition to longitudinal variability of the cross-sections (pools and riffles), topographic measurements included the description of hydraulic works such as bridges or weirs. Each cross-section was described by about ten points to detect the main morphological breaks in the main channel and the floodplain. Following the idea of Heritage et al. (2001), we paid particular attention to morphological features that could be traced throughout the river reaches (Figure 2). The axis (AX) feature corresponds to the lowest point in the cross-section. Bottom of Bank (BoB) corresponds to the point where the bank becomes steeper. The Bank Slope Break (BSB) corresponds to a change in slope of the main-channel banks and was detected in seven reaches in about two-thirds of surveyed cross-sections. This feature was associated either with the top of a point bar elevation (Indre River reach), the limit of the active channel or erosion lines. The Bank Inflection (BI) corresponds to the main change in bank slope, i.e. the end of the abrupt part of the bank, whereas Top of Bank (ToB) corresponds to the beginning of the horizontal floodplain. They indicate respectively the lower and upper limit of the transition zone between the main channel and the floodplain. BI and ToB were located for all cross-sections on at least one bank, depending on floodplain configuration and channel pattern.

To build a reliable flow model, we also surveyed the water surface profile at different flow discharges (Table II). If obvious, we recorded the heights of flood marks in the form of sediment and vegetation deposits in the floodplain. These elevations associated with the peak discharge provided rough but useful information on over-bank flow conditions at reach scale. On the other hand, the rating curves provided the water level at the gauged cross-section for in-bank and over-bank discharges.

Flow modelling

The 16 river reaches were modelled with Fluvia, a one-dimensional, open-channel, steady and step backwater model (Baume and Poirson, 1984). Normal water depth was assumed to be the downstream boundary condition, except for the Goudeschen River reach, for which the presence of a weir implied the use of critical water depth for the whole range of flows.

Values of Manning’s $n$, considered as function of discharge, were determined by calibrating the model. For each surveyed discharge (Table II), a single $n$ value along each reach was determined. This assumption was considered relevant for in-bank and over-bank flows (see example in Figure 3), as the averaged mean absolute difference between the measured and modelled water surface profiles was 4 cm for the 16 reaches (standard error of 2 cm).

The variation of the Manning’s $n$ value with discharge was determined by fitting the water level to the rating curve at the gauging station generally located at the upstream end of the reaches. These relations between Manning’s $n$ value and discharge were valid for flows varying within the range of validity of the rating curve (Table II).

Bankfull discharge magnitude was estimated by fitting the modelled water surface profile to the bankfull elevation profile, by minimization of the mean absolute difference $EM(Q)$ defined as:

(a) Cross-section in a straight segment

(b) Cross-section in a meandering curve

Figure 2. Location of the main points of a cross-section (described in the text and in Table I).
Comparison of bankfull discharge determination methods

Figure 3. Water surface profile modelled (lines) and surveyed (circles) at two discharges in the Ardour River reach: $Q = 1.8 \text{ m}^3\text{s}^{-1}$ (open circles) and $7.4 \text{ m}^3\text{s}^{-1}$ (filled circles). Manning’s $n$ values are respectively 0.058 and 0.055 (EM = 4 cm).

\[ EM(Q) = \frac{1}{N} \sum_{i=1}^{N} |Z_{\text{water}}(Q_i) - Z_{\text{bf}}| \]

where $N$ is the number of cross-sections considered, $Z_{\text{water}}(Q_i)$ is the water elevation at cross-section $i$ and discharge $Q_i$, and $Z_{\text{bf}}$ is the bankfull elevation at cross-section $i$. Cross-sections corresponding to bridges and local embankments were taken into account only to run the hydraulic model, but not to determine the bankfull discharge. Only cross-sections free to adjust their shape and size to the flow regime were studied. If present on both sides of the channel, the lowest bankfull elevation between the two banks was retained (Tabata and Hickin, 2003).

The bankfull discharge at reach scale QBFR and the associated residuals EM, i.e. the fitting accuracy, were determined by considering the entire surveyed reach length (Table II). To estimate the length of convergence (LC), bankfull discharge $Q_{BF(D)}$ was computed using the fitting method described previously for different reach lengths ($D$) varying from the two upstream cross-sections to the entire surveyed reach length (Table II). To conduct a consistent comparison between reaches of different sizes, $Q_{BF(D)}$ and $D$ were normalized respectively by QBFR and the mean channel width (estimated with the BI definition). LC was established when $|1 - Q_{BF(D)}/QBFR|$ fell below and remained less than 10 per cent. The comparative analysis between bankfull definitions was conducted by considering the mean LC value between the 16 reaches. For the reaches for which $Q_{BF(D)}$ did not converge, the LC value was taken as equal to the maximum reach length.

The hydraulic model was also used to calculate the changes in the flooded area with discharge for each reach. To achieve this, the water surface profile calculated by the hydraulic model was plotted on a gridded topographic model at each discharge, allowing the calculation of the extent of the flooded area. These curves were analysed in relation to the entrenchment ratio. This parameter was defined by Rosgen (1994) as the ratio between the floodplain width (the width surveyed at twice the bankfull maximum depth) and the bankfull width. In this study, reach-averaged widths and depths were considered, and bankfull widths and depths were estimated with the BI definition.

Hydrological characteristics of the five bankfull definitions

The total duration and frequency of bankfull discharge exceedance were estimated by using instantaneous and mean daily discharge data. The flow duration (FD) curve associates with each discharge the percentage of time it is exceeded. In this study, the duration of flows in excess of bankfull discharge (QBFR) was expressed as an average number of days per year (inter-annual). The annual maximum flood (AMF) approach is unsuitable for estimating recurrence intervals of less than 1 year, therefore only the partial duration series (PDS) approach was considered here. The PDS approach is based on the selection of independent peak discharges over a fixed threshold (Lang et al., 1999). Peak discharge independence is assured by two criteria: a minimum duration ($C_1$) must separate two peak discharges, and the intermediate flows between two consecutive peaks must drop below a percentage ($C_2$) of the lowest of these two peak discharges.

The threshold discharge must be obviously less than or equal to the bankfull discharge value. In this study, it was chosen as being equal to bankfull discharge. $C_1$ was defined as the characteristic flood duration, i.e. the mean duration (at 50 per cent of the peak discharge) of the largest floods (Robson and Reed, 1999). This choice allowed us to take...
into account the flood dynamics of each river basin studied. C2 was chosen at 75 per cent following the recommendations of Lang et al. (1999).

In the literature, no clear agreement is made about the choice of the threshold discharge and the independence criteria (Petit and Pauquet, 1997; Lang et al., 1999). In this study, a test of the sensitivity of bankfull discharge frequency was conducted depending on the choice of these parameters. Two other methods were applied: (1) the method proposed by Sweet and Geratz (2003) considering a threshold discharge equal to bankfull discharge, C1 equal to one day and no C2 conditions; (2) the method proposed by Petit and Pauquet (1997) considering a threshold equal to 0·6 bankfull discharge, C1 equal to four days and C2 equal to 50 per cent. Differences in results were analysed only for ToB and BI definitions.

Results
Application and consistency of the five bankfull definitions

The five bankfull definitions were applied to each cross-section and provided five bankfull elevation profiles on each river reach (see example in Figure 4 of the application of the three geometric definitions).

We first examined the variability of bankfull discharge estimated at each cross-section throughout the entire reach. For all reaches, the mean ratio between the maximum and minimum bankfull discharges was about 8 (9 for Wolman (WOL), 6 for Williams (WIL), 14 for Riley (RIL), 3 for Top of Bank (ToB) and 4 for Bank Inflection (BI) definitions), and could be as high as 90. These results confirm that the concept of bankfull discharge is not relevant at the cross-section scale, and has to be considered at the reach scale.

Bankfull discharge at reach scale (QBFR) was very dependent on the bankfull definition (Table III). The choice of the definition used can lead to very different conclusions when comparing bankfull discharge between reaches. For example, if the ToB definition was used, bankfull discharge was greater for the Gartempe River reach than for the Orgeval River reach; however, the opposite was the case when the BI definition was used.

The local residuals did not depend on the location in the reach (see example in Figure 5), so that there was no trend. On average, BI, ToB, WOL and WIL elevation profiles did not differ very much in terms of fitting accuracy to a water surface profile (EM about 0·2 m), and only the RIL definition was significantly less accurate (EM of 0·31 m). For the WOL definition, the greatest difference (0·56 m) occurred at the Indre River reach. On straight segments of this reach, the WOL definition roughly corresponded to BI elevation, whereas on meander curves it corresponded to the top of the point bar elevation. The difference between these two elevations was large, so that a water surface profile could not be well fitted. Thus, the WOL definition was not consistent for this reach. The RIL definition generally showed local maxima that could be attributed to different breaks in the bank’s slope, and that depended greatly on the upper limit of the surveyed cross-section. For example in Figure 4c, the second maximum would have been more relevant for defining the bankfull elevation.

In nearly all cases, QBF(D) converged before the entire surveyed reach length (Figure 6). The length required depended on the bankfull definition. ToB and BI definitions converged systematically before the entire surveyed reach length (respectively seven and eight bankfull widths on average for the 16 reaches), and on shorter distances in comparison with the geometric definitions. The WOL definition also converged for the 16 reaches, but required a longer reach length (on average 12 bankfull widths). The WIL definition converged for ten bankfull widths on average, but did not converge for one reach before the entire surveyed reach length. The RIL definition converged for longer reach length (17 bankfull widths on average), but in three cases it did not converge. This result is consistent with the high values of EM found for the RIL definition (Table III).

Hydraulic significance of the five bankfull definitions in terms of flooded area

The analysis of variations in flooded areas showed that three ranges of discharge could be identified: the main-channel flows, transitional flows, and floodplain flows. The range of transitional flows depended on the slope of the floodplain and on the channel banks, the scour of channel banks or local depositions. In the example of the Ardour River reach (Figure 7), the first discharge range corresponded to flows contained within the main channel (discharges less than 4 m$^3$ s$^{-1}$). The second discharge range showed small pools of water at the transition zone between the main channel and the floodplain (discharges from about 4 up to 7 m$^3$ s$^{-1}$). The third discharge range showed a small overflow area throughout the reach, increasing up to a well-developed flooded area (discharges more than 7 m$^3$ s$^{-1}$).

These boundaries between the three ranges of flows were more or less obvious, depending on each reach configuration. In most river reaches (Figure 8) the transition zone was large, as was observed previously for the Ardour River.
reach (Gartempe upstream and downstream, Graulade, Indrois, Yerre, Indre, Bouzanne, Avenelles Loir and Orgeval River reaches). The flooded area remained almost unchanged as long as the flow remained in the main channel. At higher discharges, the flooded area increased slowly. To determine precisely the beginning of this range of discharge was quite difficult. Above this transitional zone, the flooded area showed a significant increase as the flow was onto the floodplain. These river reaches had a narrow floodplain, i.e. an entrenchment ratio varying from 3 to 7. At the Olivet, Braye and Ozanne River reaches, the flooded area versus discharge relation showed an obvious break point. The transitional zone between the main channel and floodplain was then reduced. These reaches had a wide floodplain, i.e. an high entrenchment ratio varying from 9 to 18. For the Semme and Goudesch River reaches, the different ranges of flows cannot be easily distinguished. Such behaviour could be explained by a very narrow floodplain, i.e. an entrenchment ratio of about 2.

The different changes in flooded area versus discharge at reach scale between the study river reaches showed that the definition of bankfull elevation was much more complex than the incipient point of overflow onto the floodplain. Indeed, the flood did not occur abruptly at each cross-section and at the same discharge throughout a reach, even over a short distance and for the simplest overflow configuration.

Figure 4. Application of the bankfull geometric definitions at a cross-section in the Ardour River reach.
Table III. Bankfull discharge at river reach scale QBFR (in m$^3$ s$^{-1}$) and mean absolute difference EM (in m) between water surface profile and bankfull elevation profile for the five bankfull definitions

<table>
<thead>
<tr>
<th>Reach</th>
<th>WOL QBFR</th>
<th>WOL EM</th>
<th>WIL QBFR</th>
<th>WIL EM</th>
<th>RIL QBFR</th>
<th>RIL EM</th>
<th>ToB QBFR</th>
<th>ToB EM</th>
<th>BI QBFR</th>
<th>BI EM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ardour</td>
<td>6·8</td>
<td>0·15</td>
<td>7·2</td>
<td>0·18</td>
<td>15·0</td>
<td>0·26</td>
<td>7·1</td>
<td>0·15</td>
<td>4·1</td>
<td>0·13</td>
</tr>
<tr>
<td>Gartempe, downstream</td>
<td>23·0</td>
<td>0·19</td>
<td>25·4</td>
<td>0·22</td>
<td>37·3</td>
<td>0·41</td>
<td>29·4</td>
<td>0·13</td>
<td>17·0</td>
<td>0·19</td>
</tr>
<tr>
<td>Gartempe, upstream</td>
<td>19·2</td>
<td>0·12</td>
<td>16·9</td>
<td>0·13</td>
<td>11·5</td>
<td>0·85</td>
<td>26·0</td>
<td>0·08</td>
<td>13·0</td>
<td>0·10</td>
</tr>
<tr>
<td>Graulade</td>
<td>1·1</td>
<td>0·12</td>
<td>1·4</td>
<td>0·11</td>
<td>2·9</td>
<td>0·23</td>
<td>1·5</td>
<td>0·08</td>
<td>1·0</td>
<td>0·09</td>
</tr>
<tr>
<td>Semme</td>
<td>8·5</td>
<td>0·16</td>
<td>7·9</td>
<td>0·18</td>
<td>11·2</td>
<td>0·73</td>
<td>14·4</td>
<td>0·26</td>
<td>6·0</td>
<td>0·10</td>
</tr>
<tr>
<td>Olivet</td>
<td>3·9</td>
<td>0·32</td>
<td>4·9</td>
<td>0·15</td>
<td>5·6</td>
<td>0·18</td>
<td>5·2</td>
<td>0·12</td>
<td>3·6</td>
<td>0·28</td>
</tr>
<tr>
<td>Indrois</td>
<td>14·2</td>
<td>0·35</td>
<td>16·8</td>
<td>0·34</td>
<td>22·2</td>
<td>0·32</td>
<td>15·9</td>
<td>0·26</td>
<td>13·7</td>
<td>0·24</td>
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<tr>
<td>Loir</td>
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<td>0·08</td>
<td>13·1</td>
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<td>0·16</td>
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<td>11·1</td>
<td>0·07</td>
<td>5·8</td>
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<td>Braye</td>
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<td>0·08</td>
<td>8·9</td>
<td>0·06</td>
<td>9·2</td>
<td>0·08</td>
<td>10·2</td>
<td>0·15</td>
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<td>0·15</td>
</tr>
<tr>
<td>Ozanne</td>
<td>8·2</td>
<td>0·16</td>
<td>9·4</td>
<td>0·19</td>
<td>13·2</td>
<td>0·13</td>
<td>10·3</td>
<td>0·11</td>
<td>7·7</td>
<td>0·20</td>
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<td>Indre</td>
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<td>0·56</td>
<td>40·3</td>
<td>0·33</td>
<td>45·2</td>
<td>0·15</td>
<td>47·5</td>
<td>0·14</td>
<td>40·5</td>
<td>0·25</td>
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<tr>
<td>Bouzanne</td>
<td>30·2</td>
<td>0·24</td>
<td>37·8</td>
<td>0·13</td>
<td>43·0</td>
<td>0·67</td>
<td>34·6</td>
<td>0·29</td>
<td>25·3</td>
<td>0·31</td>
</tr>
<tr>
<td>Avenelles</td>
<td>5·2</td>
<td>0·41</td>
<td>8·4</td>
<td>0·36</td>
<td>10·5</td>
<td>0·30</td>
<td>9·5</td>
<td>0·16</td>
<td>6·8</td>
<td>0·24</td>
</tr>
<tr>
<td>Orgeval</td>
<td>14·2</td>
<td>0·35</td>
<td>20·2</td>
<td>0·20</td>
<td>24·2</td>
<td>0·18</td>
<td>23·2</td>
<td>0·13</td>
<td>16·6</td>
<td>0·28</td>
</tr>
<tr>
<td>Goudesch</td>
<td>4·3</td>
<td>0·10</td>
<td>4·6</td>
<td>0·12</td>
<td>7·5</td>
<td>0·18</td>
<td>10·5</td>
<td>0·18</td>
<td>5·5</td>
<td>0·17</td>
</tr>
<tr>
<td>Mean EM</td>
<td>0·22</td>
<td>0·18</td>
<td>0·31</td>
<td>0·15</td>
<td>0·19</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Water surface profile fitted with the flow model (line) to the Wolman bankfull elevation profile (open circles) in the Ardour River reach.

The hydraulic significance in terms of flooded area can be assigned to each bankfull definition by locating it on the flooded area–discharge curve (Figure 8). BI and WOL definitions always corresponded to low variations in the flooded area with discharge. The associated flows were generally contained within the main channel. The WIL definition was more variable as it corresponded sometimes to the limit of in-channel flows (e.g. Ozanne River reach), and other times to a well-developed flooded area in the floodplain (e.g. Olivet River reach). This definition gave discharges generally higher than the BI definition (mean factor of 1·3), but lower than the ToB definition (mean factor of 0·8). The ToB definition was associated with the beginning of flooding. It corresponded to a large increase in the flooded area with discharge. Above this discharge, the flooded area was well-developed. The RIL definition was the most remote from the transitional zone, and was very variable between the different study reaches. Discharges associated with this definition often corresponded to a significant flooded area.
BI and ToB definitions had the greatest hydraulic significance as they characterized the lower and upper limit of the transition zone between the main channel and the floodplain. On average between reaches, the mean difference between the ToB and BI elevations was about 30 cm (varying from 15 to 50 cm), and did not depend on bankfull depth. It corresponded to a difference of about a factor 1·6 on average for bankfull discharges (varying from 1·2 to 2·4), and of about a factor 1·7 on average for reach-averaged bankfull channel widths (varying from 1·1 to 3·2).
Sensitivity of bankfull discharge duration and frequency according to the discharge data type

The median durations of exceedance did not depend significantly on the use of instantaneous or mean daily discharge data (Figure 9a). The factor between median durations using both types of data varied from 0.85 to 1.32 according to the bankfull definition used. The median frequencies were more dependent on the type of data used (Figure 9b). The factor between median frequencies using both types of data varied from 1.43 to 1.94 according to the bankfull definition used.

Reach by reach, the sensitivity to the type of data used was more important, especially for the duration of exceedance (illustrated in Figure 10a for ToB definition). In this case, the ratio between the medians was very low (1.03), but it hid great differences in the duration on each reach individually, the ratio between the maximum and minimum duration being 1.3 on average (varying from 1 up to 1.8). For example, the bankfull duration at the Loir River reach increased when mean daily data were used instead of instantaneous data (ratio equal to 1.8), whereas it decreased at the Olivet River reach (ratio also equal to 1.8). This observation can also be made for the frequencies (Figure 10b), but was less hidden by the factor between medians. Indeed a frequency estimated with instantaneous data will always be greater than a frequency estimated with mean daily data, so that there was no compensation effect. The ratio between the maximum and minimum frequency was 1.9 on average (varying from 1 up to 4.7). The great variability of the influence of the type of data makes the classification of the reaches unstable. For example, the Olivet River reach had a higher frequency than the Indre river reach when instantaneous data were used, but the reverse when mean daily data were used.

Comparison of bankfull discharge duration and frequency according to the bankfull definition (based on instantaneous discharge data)

The variability of bankfull discharge duration and frequency was high and of the same order for the five definitions used (Figure 9): the normalized interquartile range (the ratio between the interquartile range and the median value)
Figure 8. Position of the five bankfull discharges on the flooded area versus discharge curves. River reaches are ranked according to their increasing entrenchment ratio (ER).

The median durations and frequencies between the 16 reaches varied with the bankfull definition used. RIL and ToB definitions corresponded to the lowest durations (Figure 9a); the median values between the 16 reaches were respectively 4·5 and 5·3 days per year. They also corresponded to the lowest frequencies (Figure 9b), the bankfull discharge being exceeded respectively 3·5 and 4·2 times per year (median values). Discharges corresponding to WIL and WOL definitions were exceeded respectively 6·8 and 8·3 days per year (median values), and respectively 5 and 6·1 times per year. Durations of exceedance and frequencies associated with the BI definition were the highest (median values of 11·5 days per year and 7·4 times per year).

The variability of these estimations according to the definition used made the comparison between reaches unstable (Figure 10c and d). For example, the bankfull discharge duration of exceedance was lower for the Gartempe River...
Sensitivity of bankfull frequency estimations according to the different PDS approaches

The choice of threshold discharge and independence criteria for the PDS approach influenced the estimation of bankfull discharge frequency (Figure 11). The discharge threshold and independence criteria that we used and those used by Petit and Pauquet (1997) led to different bankfull frequency estimations. Differences in results depended on the bankfull definition and hydrological data used. They were large (ratio between the frequency estimations equal to 0·70 on average) when the BI definition and instantaneous discharge data were used (Figure 11a). Conversely, they were low (ratio equal to 0·93 on average) when the ToB definition and mean daily discharge data were used (Figure 11d). The choice of a low discharge threshold can make the distinction of flood events difficult. For example, the 0·6 bankfull discharge threshold used by Petit and Pauquet (1997) was often incompatible with the use of the BI definition, as this threshold discharge was too low in the flow series. Thus, it prevented the selection of independent flood events (in the cases of the Ardour, Graulade, Semme, Loir and Bouzanne River reaches). On the contrary, this threshold was well adapted when used with the ToB definition. The Sweet and Geratz (2003) threshold discharge and criteria were quite similar to ours, so the results were close (ratio between frequencies estimated with Sweet and Geratz criteria and ours equal to 0·96 on average), even if great differences occurred in a few cases. For example, the choice of C1 equal to 0·5 day for the Olivet River reach (Figure 11a), compared to a 1-day duration, significantly influenced the frequency estimation when instantaneous discharge data were used (ratio of 1·46).

Discussion

Determination of bankfull discharge magnitude

On the 16 reaches, the high variability of bankfull discharge at cross-section scale (a factor 3 on average for the more stable definition between the lower and the higher values) corroborates previous studies and remarks, and confirms the now widely accepted fact that bankfull discharge can only be determined at the reach scale (Williams, 1978; Richards, 1982).

The reach lengths required to ensure an accuracy of 10 per cent on our 16 sites are about 15 BI widths for all definitions except for WOL and RIL definitions (these two last definitions required longer reach lengths). These lengths are very similar to the 15–20 bankfull widths recommended by Leopold et al. (1964).
Figure 10. Comparison of bankfull duration and frequency between the 16 reaches. Each arrow links the ToB duration (a) and frequency (b) determined on each river reach with instantaneous and mean daily discharge data, or the bankfull durations (c) and frequencies (d) determined on each reach with ToB and BI definitions with instantaneous discharge data.

Though the WOL definition can be considered the most objective definition as it is based on a minimum criterion, it is not consistent for cross-sections located in meander curves, as already pointed out by Riley (1972). The criterion selected a level near the BI elevation in the straight portions of the reach, and the top of point bar elevation in meander curves. As already pointed out by Radecki-Pawlik (2002), the RIL definition generally showed local maxima that could be related to different breaks in the bank’s slope, and the bankfull level determined depended greatly on the upper limit of the surveyed cross-section. Moreover, the RIL definition was less accurate than the others and did not correspond to the over-bank processes.

The WIL definition corresponded to the incipient overflow, but showed a variable hydraulic significance (from small to large variations in flooded area with discharge), fluctuating between BI and ToB definitions for the different reaches.

BI and ToB definitions correspond respectively to the lower and upper limits of the transition between main channel and floodplain. They also had good fitting accuracy and required shorter survey lengths. Thus, the eye of the expert required by the geomorphic definitions still seems to be better than the blind mathematical criteria on cross-section shape used by the geometric ones. This can be at least partially explained by the great variability in shape between the cross-sections in a river reach. So, we recommend choosing one of these two definitions among the five tested.

The estimation of the BI discharge will probably be more reliable than the ToB discharge, because the hydraulic models are generally more accurate for in-bank flows (equal to or less than BI discharge), rather than for over-bank flows (from BI to ToB discharge and more). Indeed, the geometry and the vegetation at the interface between the main channel and the floodplain make the flow structures complex (Knight and Shiono, 1996), and introduce more uncertainty in the stage–discharge relation, especially if no gauging is performed at high water flow conditions.
Figure 11. Box and whisker plots of the ratio between bankfull discharge frequency estimated with Sweet and Geratz (2003) or Petit and Paquet (1997) methods, versus bankfull discharge frequency estimated in this study (applied to ToB and BI definitions, and combined with instantaneous and mean daily discharge data).

Determination of bankfull discharge duration and frequency

The annual maximum flood (AMF) approach is unsuitable for examining bankfull discharge frequencies as they are generally sub-annual, even when the ToB definition and mean daily discharge data are used (Figure 9b).

The test of different uses of the PDS approach found in the literature (Petit and Paquet, 1997; Sweet and Geratz, 2003) has shown significant variations of bankfull frequency according to the choice of discharge thresholds and independence criteria. As the peak discharge independence was easily verified when the ToB definition was used, the choice of this bankfull definition rather than the BI definition appears more relevant when the PDS approach is used. Furthermore, a C1 duration of one or four days is not suitable for a wide range of river basins with a wide variation in flood duration: from 0.5 day (Olivet River reach) to seven days (Indre River reach) in our study. The use of a C1 duration that depends on the river basin dynamics seems to be more relevant. The ToB definition combined with the use of mean daily discharge data seems attractive, because the results are less sensitive to the sampling criteria (Figure 11c). However, it has to be kept in mind that the frequency estimations based on mean daily discharge are scale-dependent because a systematic bias is certainly introduced for river reaches associated with short flood durations (in the range of our study reaches).

Moreover, according to the definition of bankfull as ‘the river level just before it starts to flow out of its main channel and over its floodplain’, the use of instantaneous discharge data are better suited to represent the overflowing process. Thus, we recommend the use of instantaneous discharge data for both FD and PDS approaches.

The flow durations (FD) approach does not require the selection of independent flood events, providing more robust results than frequency analysis, especially for low discharges. Thus, this approach is suitable for both BI and ToB definitions. Furthermore, the duration of exceedance of bankfull discharge could be more relevant for sediment budget (Emmett, 1999), because a discharge and a duration allow calculation of a volume.
Comparison of bankfull discharge determination methods

The use of different combinations of methods can lead to significant differences in estimations of bankfull discharge and its frequency. For example, between BI and ToB definitions, the small difference between bankfull elevations of about 30 cm on average leads to significant differences in terms of discharge (factor 1.6 on average). If the factor 1.6 is combined with the factor 1.9 observed on average between instantaneous and mean daily based frequencies (using our method), the factor between frequencies of the BI elevation using instantaneous data and the ToB elevation using mean daily data is about 3 on average. Moreover, the conclusions of a comparative analysis on a set of river reaches can be very different if the combinations of bankfull definitions and hydrological data type used are different. Indeed, the bankfull durations and frequencies of study reaches were not ranked in the same order.

Therefore, to make a consistent comparison of regional bankfull discharges or to detect the impact of human interference on river morphology, the bankfull elevation definition, the hydrological method, and the data type must be the same and clearly specified.

Our results are consistent with other studies for both bankfull duration and frequency of exceedance (Table IV). However, a more precise comparison is often difficult as different bankfull definitions are often used (Dury, 1961; Sweet and Geratz, 2003). When a single definition is used, the comparison can be relevant. For example, durations of bankfull discharge exceedance estimated in this study (with ToB definition and mean daily discharge data) are greater and more variable than in Nixon’s (1959) study.

Petit and Pauquet (1997) used the ToB definition and mean daily discharge data. Thus, the comparison with our results is possible. The bankfull frequency of our study is on average greater and more variable than in Petit and Pauquet’s study (Table IV).

The great variability in bankfull hydrological characteristics among our 16 reaches confirmed previous studies showing no fixed duration or frequency of exceedance for bankfull discharge (Williams, 1978; Petit and Pauquet, 1997).

Conclusion

Using a backwater model, we showed on 16 river reaches that the transition between main channel and floodplain does not occur at a single discharge, which could be defined without ambiguity as the bankfull discharge. In fact, a transition range of discharges was observed, explaining the numerous bankfull definitions that can be found in the literature. We compared five of them on the 16 surveyed reaches.

Each bankfull definition was relevant at reach scale and could be associated with a discharge. The two geomorphic definitions (Bank Inflection and Top of Bank) were more relevant than the geometric ones (Wolman, Williams and Riley), because their longitudinal profiles fitted better to the water surface profiles, and they required shorter survey

<table>
<thead>
<tr>
<th>Authors</th>
<th>Bankfull definition</th>
<th>Number of reaches</th>
<th>Minimum</th>
<th>Median</th>
<th>Maximum</th>
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</thead>
<tbody>
<tr>
<td>Our study</td>
<td>ToB</td>
<td>16</td>
<td>0</td>
<td>5.1</td>
<td>27.3</td>
</tr>
<tr>
<td>Our study</td>
<td>BI</td>
<td>16</td>
<td>0.03</td>
<td>13.5</td>
<td>46.8</td>
</tr>
<tr>
<td>(Dury, 1961)</td>
<td>ToB and BI</td>
<td>24</td>
<td>1</td>
<td>na</td>
<td>40</td>
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<tr>
<td>(Nixon, 1959)</td>
<td>Probably ToB</td>
<td>29</td>
<td>0.4</td>
<td>1.8</td>
<td>11</td>
</tr>
<tr>
<td>(Sweet and Geratz, 2003)</td>
<td>ToB, BI, highest scour lines, point bar</td>
<td>1.4</td>
<td>3.6</td>
<td>18.1</td>
<td></td>
</tr>
</tbody>
</table>
lengths. They corresponded respectively to the lower and upper limits of the transition between main channel and floodplain.

Bank Inflection and Top of Bank discharges differed on our reaches by a factor 1.6 on average (from 1.2 to 1.4), while the associated water levels differed by 0.3 m (from 0.15 to 0.50 m), and the channel widths by a factor 1.7 (from 1.1 to 3.2). The choice between both definitions depends on the purpose of the study. Bank Inflection will better characterize the main-channel morphological processes and the channel width, while Top of Bank will be more suitable when interactions with the floodplain are of interest.

The determination of bankfull discharge frequency is not easy because the classic hydrological methods developed for floods reach their limits. Annual maximum flood (AMF) analysis, broadly referred to but also widely criticised, should absolutely be avoided. The AMF analysis is mathematically incapable of providing sub-annual recurrence intervals, whereas even Top of Bank discharges occurred several times per year in most of our 16 surveyed reaches. Only partial duration series (PDS) can be used to determine bankfull discharge recurrence interval. Nevertheless, the PDS approach should be used carefully because of the difficulty of ensuring independence of the peak discharges, especially for the Bank Inflection definition and instantaneous discharge data.

This analysis leads us to prefer the use of the flow duration (FD) approach as the determination of the duration of exceedance does not require the selection of independent peak discharges.

Although they are less easy to obtain, the use of instantaneous discharge time series should be preferred to the mean daily ones. Indeed, they are suited for precisely determining the durations or the frequencies of the river just flowing out of its main channel and over its floodplain.

The choice of a combination of methods rather than another can significantly change the conclusions of a comparative analysis between reaches. To allow a relevant comparison between different studies, the bankfull definitions and hydrological analysis used (including the type of discharge data) should be specified in detail, as the results can significantly change from one combination to the other.

Acknowledgements

The authors are grateful to Celine Boudard, Guillaume Dramais, Thierry Fournier, Pascal Roger, Mickaël Lagouy and Shamsidine Sebea for the topographic surveys on the various river reaches; Eric Sauquet and Simon Duplès for the hydrological analysis. We also wish to thank the managers of the gauging stations: Maxime Ghio, André Chinn, Yves Dedusseau, François Fourrier, Patrick Fayard and Claude Martin, Jean-François Didon (CNRS UMR 6012). This paper has benefited greatly from reviews by Nicolas Lamouroux, Pascal Breil, Jean-Philippe Vidal and Hen Britton.

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