Post-flood field investigations in upland catchments after major flash floods: proposal of a methodology and illustrations

E. Gaume¹ and M. Borga²

¹ Laboratoire Central des Ponts et Chaussées, Nantes, France
² University of Padova, Padova, Italy

Correspondence:
E. Gaume, Laboratoire Central des Ponts et Chaussées, Division Eau et Environnement, BP 4129–44341 Bouguenais Cedex, Nantes, France
Tel. 33-(0)240845884
Email: gaume@lcpc.fr
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Abstract
Post-event survey and investigation is one way to gain experience on natural hazards. The importance of the systematisation and standardisation of such investigations and re-analysis is progressively recognised in all the geophysical sciences as shown by the growing number of scientific papers and programs on the subject. But how to proceed in the case of a flash floods, what type of data should be collected for what type of analyses and to explore which particular issues? To give a first answer to these questions, a methodology for post-flash flood field investigations has been developed under the EC FLOODsite project and tested under the EC HYDRATE project. This paper presents shortly the principles of this methodology and illustrates its application for the study of two major flash floods that occurred in November 1999 and September 2002 in the South of France.

Introduction
Are field investigations conducted after major flash flood events really useful and what for? The question formulated in that manner may appear a little surprising. In fact, flash floods, sudden floods with high peak discharges produced by severe thunderstorms that are generally of limited areal extent (IAHS, 1974), rank as the most destructive process among weather-related hazards in many parts of the world. Forgoing studying these extreme events, because no measured data are directly to hand, or because data that exist are not considered as sufficiently accurate, or even because it is time consuming and limiting the hydrological analyses to moderate events on gauged watersheds, would be focussing on the trivial while skipping the essential (Figure 1).

Post-flood surveys appear clearly as a necessity to increase the existing knowledge on such events to provide adapted methods of analysis and technical solutions for flood prevention and control. The questions are rather how to proceed, what type of data can and should be collected for what type of analysis and what questions should be explored.

Past experience show that two main types of post-flood investigations can be distinguished that differ by their objectives and context. The first type is generally commissioned by the local or national authorities after a major catastrophe. The main objective is to answer questions raised by the public and local stakeholders on the causes of the floods, the possible human impacts on the flood magnitude and frequency, but also on the management of the crisis, the efficiency of the flood mitigation measures and the solutions to recover from the flood and to limit the future risks (Huet, 2005). Typical examples are the investigations conducted after the major 1987 floods in Switzerland (Bundesamt für Wasserwirtschaft, 1991) or more recently in France (Lefrou et al., 2000; Huet et al., 2003). The purposes of such investigations are well defined and limited to the raised questions. Scientists are generally involved either to conduct studies on some specific questions or to take part in scientific support groups. Research activities may be conducted during such investigations, but it is then a by-product. The objective is mainly to draw the lessons of the event at the local scale and not to increase the overall scientific and technical knowledge.

A second type of post-flood investigations is conducted more systematically by technical services like the US Geological Survey (Bowers, 2001; Juracek et al., 2001; Carter et al., 2002; Winston and Criss, 2002), the Istituto di Ricerca per la Protezione Idrogeologica in Italy for instance or by research institutions (Hemain and Dourlens, 1989; Gilard and Mesnil, 1995). The aim is then to document the extreme events. Most of the past works have been limited to a description of the event through the available measured data (rain gauge or river gauge measurements) and some field observations as cross-section surveys and corresponding peak discharge estimates generally for one single selected river reach (Costa, 1987a; Jarrett, 1987; Gutknecht, 1994; House and Pearthree, 1995; Rico et al., 2001). Sometimes the description of the sediment...
transfer processes, of their localisation and the estimation of the transferred volumes is provided (Caredio et al., 1998; Alcoverro et al., 1999). A detailed rainfall–runoff analysis including the identification of the major runoff-producing areas on the affected watersheds and the study of the relation between the time sequences of the floods and of the rainfalls is rarely done due to the lack of measured rainfall and discharge data.

The inventory of extreme events and of their peak discharge values is of course important to define the range of the possibilities, to build envelope curves and to study the regional patterns of the river flood extreme peak discharges (Pardé, 1961; Perry, 2000; O’Connor and Costa, 2003), or to reduce the uncertainties in flood frequency analyses (Payrastre et al., 2005).

But the recent developments of the measurement networks, especially weather radar networks, open new perspectives for the analysis of flash floods. Weather radar provides rainfall estimates at appropriate space and time resolutions. It seems therefore now possible to undertake an analysis of the rainfall–runoff dynamics (Smith et al., 1996; Ogden et al., 2000; Belmonte and Beltran, 2001; Gaume et al., 2003a,b, 2004; Delrieu et al., 2004; Sächsisches Landesamt für Umwelt und Geologie, 2004; Borga et al., 2007). This opens the possibility to answer questions such as:

- What are the rainfall–runoff dynamics during a flash flood, and what is the influence of the watershed characteristics, of the initial soil moisture or ground water recharge conditions on this dynamics?
- As a subsidiary question, what type of watershed characteristics (slopes, land use, geology, soil types, etc.) should be considered in a regional flood frequency analysis?
- What are the dominant flood-generating processes during a flash flood?
- Is the answer to this question dependent on the land use and geomorphological properties of the watershed?
- What part of the catastrophe can be attributed to anthropogenic factors (change in land use, deforestation, agricultural drainage, imperviousness, road network, river management)?
- Are the dominant processes the same during flash flood events and medium flood events, and is it possible to extrapolate tendencies observed on medium flood events (flood frequency distributions, rainfall–runoff models)?
- What is the influence of ‘artificial’ processes such as blockages and their breaking ups, or of the sediment load (i.e. mainly water flood versus hyperconcentrated or even debris flow) on the peak discharge and the shape of the rising limb of flood hydrographs?
- How do the existing flood forecasting models perform on such events?

Owing to the time–space characteristic scale of flash flooding, the majority of the upstream catchments affected by these floods are not gauged. In addition, the peak discharges can be spatially highly heterogeneous, even within small catchments: cross-section surveys and peak discharge estimates are also useful to map the discharges on gauged watersheds. A detailed flash flood study should not be limited to the few gauged river cross sections if some exist. Flash floods are by definition rare events. If an intensive research activity is to be set up on these hydrological events, which seems to be the case according to the recent European research calls for proposals, it is necessary to develop specific methods to collect and analyse the existing information about the floods when and where they occur and not to limit the analysis to the few events affecting gauged watersheds.

This paper, based on past experience of post-flood studies, is a first attempt to propose some guidelines on how to identify, collect and analyse data available after a major flash flood event. Three main types of data will be considered.

- **Indicators of the peak discharge values**: mainly cross-section surveys based on flood marks but also clues of flow velocities (video movies, witness observations, water supererelevations in river bends or in front of obstacles). The paper presents and criticizes various indirect post-flood peak discharge estimation methods and puts the emphasis on validation procedures.
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- **Indicators of the time sequence of the flood**: mainly eyewitness accounts where no stream gauge measurements are available. Accounts from eyewitnesses are occasionally cited in flash flood studies; they have seldom been, to our knowledge, systematically collected and analysed.

- **Sediment transfer processes (erosion and deposition on slopes and in river beds, hyperconcentrated, mud or debris flow)**: mainly focus of the post-flood investigation but also as an indication of the local runoff generation processes and flow energy and velocity.

Information on socio-economic aspects can also be collected such as geo and time references of accidents, qualitative description of public behaviour, and effectiveness of warning broadcasts, nature and extension of the damages caused to bridges, roads and buildings, but will not be discussed herein.

This paper is based on illustrations of the hydrological valuations of the collected data. This, we hope, will convince the readers that the conclusions that can be drawn from post-flood investigations are worth the time spent to collect and analyse the data. Our common knowledge on flash floods will only grow through the multiplication of post-flood field surveys for two main reasons. The conclusions drawn on one single event, based on inaccurate and partial data may be questionable and will be consolidated on the basis of repeated post-flood analyses. Various case studies are needed to determine whether the hydrological behaviour described for one flash flood is a general pattern for the considered region or type of watershed or is an outcome of spatial and temporal-specific circumstances (i.e. rainfall pattern, wetness state of the soils, soil types, geology of the watersheds, etc.).

The paper is structured into two parts: (i) the presentation of a proposed post-flood investigation methodology and (ii) illustration of post-flood hydrological analyses. We hope that the guidelines presented herein will contribute to the systematization of post-flash flood field investigations.

### Principles of a methodology

The proposed methodology is presented in detail in a research report published within the European research project FLOODsite (Gaume, 2006). This report can be downloaded on the Floodsite Web site or directly obtained from the authors of the present paper.

Table 1 summarizes the proposed procedures for the collation and the analysis of the field data. We will here shortly add some additional comments about post-flood investigations and develop on some specific aspects of peak

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Steps of the proposed data collation and analysis procedures</th>
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<tr>
<td><strong>Data collation process</strong></td>
<td><strong>Data analysis process</strong></td>
</tr>
<tr>
<td><strong>Phase 1</strong>: Just after the flood</td>
<td><strong>Step 1</strong>: Peak discharges estimation and mapping</td>
</tr>
<tr>
<td>- Collect the data on the rainfall event (rain gauge measurements, radar images) to locate the affected areas.</td>
<td>- Based on the cross sections surveyed, peak discharges and specific discharges can be estimated at various locations of the considered river and of its tributaries and reported on a map.</td>
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<td>- If possible, first reconnaissance visit of the affected areas, pictures (flood marks, large debris, river bed state) can be taken, but no survey work can generally be conducted during the crisis time.</td>
<td>- Test of the spatial consistency of the estimates and comparison with rainfall data to get a first idea of possible runoff rates.</td>
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<td><strong>Phase 2</strong>: A few weeks after the flood</td>
<td>- A comparison with rainfall, geological, land use maps gives some first idea of the possible factors affecting the flood magnitude.</td>
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<td>- The cross-section surveys can begin as well as some interviews of witnesses depending on the local atmosphere.</td>
<td><strong>Step 2</strong>: Rainfall–runoff dynamics</td>
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<td><strong>Phase 3</strong>: A few months after the flood</td>
<td>- Where radar quantitative precipitation estimates appear reliable and where complete or partial flood hydrographs can be retrieved from measured data or accounts or documents (dated pictures) from the witnesses, they can be compared with simple rainfall–runoff (RR) simulations to get a better idea about the RR dynamics, especially about the evolution of runoff rates during the flood.</td>
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<td>- It is certainly the best period for the survey work especially for the interviews. The area is fully accessible and the stress has fallen again. The river beds and marks may have been cleaned out; this is why the pictures taken in phase 1 or 2 are important.</td>
<td><strong>Step 3</strong>: Comparison with previous floods</td>
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<td>- Collect additional data useful for the analysis (river gauge measurements, digital terrain model, soil, land-use, geological map, soil moisture measurements, satellite or pictures taken by plane, flood mark inventories, etc.).</td>
<td>- If step 2 could be performed, the same RR simulations can be conducted for previous large floods that occurred on the same catchment if it is gauged or on nearby similar gauged catchments.</td>
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<tr>
<td>- Preparation of the rainfall–runoff simulations to support the interpretations.</td>
<td><strong>Step 4</strong>: Accompanying processes</td>
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<tr>
<td><strong>Phase 4</strong>: The year after the flood</td>
<td>- When the runoff is described, accompanying processes such as erosion intensity on hill slopes, sediment transport or local flow characteristics can be studied.</td>
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<tr>
<td>- Owing to the inaccuracy of the available data, a post-flood investigation has some similarities with police inquiries. It is a long-lasting work, requiring cross-checking and possibly returns to the phase 3.</td>
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discharge estimation methods and of the use of sediment transfer and erosion evidences.

Three important ingredients are needed for an efficient field survey to be conducted. First, the survey must be well prepared. This preparation includes organizational aspects but also the collation and criticism of the available data (geology, hydrogeology, soils types, measured rainfall rates and discharges, previous conducted hydrological studies on the area, etc.) previously to the field work. The field survey must rely on knowledge of the analysed watersheds and some initial questions concerning their hydrological behaviour. Therefore, a field survey campaign can hardly be conducted immediately after the flood event. Nevertheless, it is preferable to make a first-round tour of the area just after the flood and take pictures to locate flood marks that can rapidly be removed and to have a clear reference state of the river system since river beds are generally rapidly cleaned up after a major flood event.

The second important aspect is the standardization of the type of data collected and of their storage formats and analysis procedures. This facilitates intercomparisons and data archiving. Moreover, it is important to store all the raw data for an a posteriori criticism and discussion of their interpretation. The exact location of the surveyed cross sections, or interviews should be clearly indicated, pictures taken and stored showing the local environment and specific reference points mentioned by interviewed people or hydraulic singularities which could have influenced the water levels, the surveyed values as well as the details of peak discharge computations and the accompanying hypotheses should be included, as the name of the persons who produced the document. Standard cross-section survey and interview summary forms have been therefore proposed and are presented in Appendix A.

Finally, a post-flood field survey can never be an automatic application of a recipe. Each case study has its own specificities. Like in any inquiry on complex situations, it is necessary to develop a terrain observation skill for the selection of the most suited cross sections for peak discharge estimations and for the detection and the valuation of any possible clue: flood marks, erosion evidences on hill slopes or in the river beds, films and pictures, etc. Also discharge estimation validation, consistency testing and the search for additional information to confirm the first guesses or conclusions should be a constant concern in post-event field surveys. The following two examples illustrate this principle.

**Peak discharge estimation approaches**

Peak discharges can be estimated in ungauged sites after a major flood event on the basis of flood marks and surveyed river cross sections. Without direct current meter measurements, these estimates rely on hydraulic modelling and on sound engineering judgment. The sources of uncertainties and errors are numerous: choice of the appropriate surveyed river reaches that must not have been too much modified by sediment movements (erosion or deposition) and not affected by mud or debris flow or blockages, estimate of water levels or water longitudinal profiles through flood marks, choice of the roughness coefficient values.

Flood marks for instance may either indicate the water level in still water areas or the total hydraulic head on obstacles located in the flow. Flood marks in vegetation on river banks or in the flood plain where the flow velocity is reduced should be preferred. Moreover, marks may have been deposited on vegetation temporarily bent by the flow, may have slid down a smooth support, or be the result of water projections. To reduce uncertainties, as many as possible flood marks should be surveyed in a given cross section. Concerning the roughness coefficient, tabulated values (Benson and Dalrymple, 1967) and empirical equations (Chow, 1959) exist. But they were established in cases of moderate floods and low-gradient streams and it seems that the apparent roughness of a stream has to be significantly increased for extreme floods to obtain realistic discharge estimates (Jarrett, 1987; Jarrett, 1990; Gaume et al., 2004).

For all these reasons, it is necessary to seek for various sources of information to enable a cross-checking and to reduce uncertainties and avoid significant errors: select more than one cross section for each river reach with significantly different cross-sectional shapes and areas, test the upstream–downstream consistency of the estimated discharges on a watershed and also evaluate directly the possible flow velocity ranges on films and pictures, use sediment transport and erosion indicators, and test the rainfall–runoff consistency. Some examples of discharge estimation checking and validation are presented in the next section.

Field surveys provide cross-sectional wetted areas, which accuracies depend on the accuracy of the flood marks. Velocity profiles or average velocities must be determined to evaluate the corresponding discharge values. This is mainly where the hydraulic models are needed. In rivers with shallow slopes – typically 1/1000 or less – one-dimensional hydraulic models are necessary owing to the distance over which backwater effects propagate (see Naulet, 2002, for an illustration): i.e. most generally the flow is subcritical even during extreme flood events except in some specific cross sections (Jarrett, 1987). Note that the definition of the downstream boundary condition is in this case an additional source of uncertainty. In complex cross-section shapes, in the surroundings of bridges or in urban areas, two-dimensional hydraulic models may be needed to capture the complex pattern of transversal and longitudinal velocity profiles (see Denlinger et al., 2001, for an illustration).
In the case of relatively steep river channels in headwater catchments affected by flash floods – slopes typically larger than 0.5% – a uniform flow assumption may provide fair velocity estimates if compared with one-dimensional hydraulic models, provided that the selected section is sufficiently far (some hundred metres) upstream or downstream an obstacle or change of shape or slope of the channel. Moreover, the cross-sectional shape of these headwater streams is generally simple: a trapezoidal main channel with floodplain of limited extent. The flow is basically one-dimensional.

For these reasons, the most commonly used method to evaluate peak-discharge values after major flash flood events in headwater catchments is the so-called slope conveyance method or the slope area method, which is an extension of the former (Costa, 1987a; Webb and Jarrett, 2002). It is based on the application of the Manning–Strickler empirical formula, with an assumption of uniform flow (friction slope $S_f$ equal to the river bed slope $S$).

$$V = \frac{Q}{A} = KR^{2/3}S_1^{1/2}$$

where $V$ is the so-called average velocity (m/s), $Q$ is the discharge in (m$^3$/s), $A$ is the wetted cross section (m$^2$), $R$ is the hydraulic radius ($R = A/P$, with $P$ the wetted perimeter in m) and $K$ known as the Manning–Strickler roughness coefficient depending on the river cross-section characteristics, which generally takes its values between 5 and 100. The parameter $n = 1/K$ is also often used in the technical and scientific literature.

In cases where the flow is not confined in the main river channel but covers also a flood plain, the section has to be subdivided into a main channel area and a right and left overbank flow area, and the discharge calculated separately for each of the subareas (Chow, 1959).

The slope conveyance method also has the great advantage to be rapid and enables the evaluation of a large number of peak discharge values for a single flood event and hence the mapping of the flood flows over the area of the affected watershed and reveal the spatial heterogeneities of the runoff, which is one of the objectives of post-event surveys (see illustrations presented in 'Illustration of some interpretation results').

Independently on the hydraulic model chosen, it is important to keep in mind that the data collected are necessarily incomplete and affected by uncertainties, that some local flow characteristics (backwater effect, obstacles limiting the flow in the flood plain, etc.) may be missed out during the field survey, and that the methods used, especially the Manning–Strickler formula, are empirical approximations that may not be extrapolated reliably to the extreme flow conditions encountered during extreme flash flood events (high velocities, significant sediment concentrations). Therefore, peak discharge estimates after flash flood events cannot be only based on a single site and single method approach. It is absolutely necessary to search for additional information to check and validate the proposed peak discharge estimates. The next two sections give some examples of how this additional information can be evaluated.

Finally, even after a thorough validation, it is the opinion of the authors that an uncertainty bound of at least 30–50% should be added to the peak discharges estimated after flash flood events occurred on headwater catchments. According to the magnitude of the observed flows during such events and to the important spatial and temporal gradients, this large uncertainty does nevertheless not prevent further analyses (see 'Illustration of some interpretation results’ and especially Figure 7).

**Discharge estimation checking and validation**

Among the possible sources of additional information for discharge estimation checking, pictures and films taken by eyewitnesses are now often available after major flood events. On these images, superelevations in front of obstacles located in the flow as trees or piers of bridges may be visible (Figure 2). This superelevation is linked to the flow velocity. The application of the Bernoulli formula gives the

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**Figure 2**

Example of a superelevation in front of bridge piers located in a river bend and showing a lateral velocity gradient: 0.8–1 m in front of the left bank pile, about 0.5 in front of the central pile and negligible on the right bank pile. July 2007, Mill Burn, Northumberland, Great Britain.
range of possible values for the flow velocity in the vicinity of the obstacles, a value that can be compared with the estimated average flow velocity $Q/A$ computed for nearby cross sections.

$$y_1 + \frac{V_1^2}{2g} = y_2 \Rightarrow V_1 = \sqrt{2g(y_2 - y_1)}$$

(2)

With $y_1$ and $V_1$ the water depth and mean velocity in the area surrounding the obstacle, and $y_2$ the water depth in front of the obstacle.

This method has the greatest advantage to be nonparametric unlike the Manning–Strickler formula, and the superelevation is relatively sensitive to the velocity. It makes it possible to distinguish between moderate velocities, < 2 m/s and superelevation lower than 20 cm, high velocities, 3–4 m/s corresponding to superevolutions between 40 and 80 cm, and extremely high velocities, more than 1 m of superelevation. In Figure 2, the superelevation in front of piers of a bridge can be seen. They indicate that the flow velocity may have exceeded 4 m/s on the outside bank of the river bend in front of the bridge and that the average velocity must have been close to 3 m/s under the bridge, about 50 cm superelevation in front of the central pile and almost no velocity on the inside bank of the bend (pictures taken just after the flood peak).

Image-tracking methods can also be used to assess water surface velocities and hence discharges on films (Fourquet, 2005). But their application on films taken by eyewitnesses with a generally moving camera requires a preparation survey of the filmed river reach and the identification of the viewpoints of the camera. To our knowledge, this method has only been applied on controlled cross sections with fixed cameras for the moment (Creutin et al., 2003).

Likewise, when possible, a consistency test of the estimated peak discharges and of the measured rainfall rates available on the watersheds upstream of the considered river cross sections should also be conducted. It can at least reveal peak discharge overestimations: except if an important dam breach occurred during the flood event, the comparison of peak discharges and rainfall intensities should not lead to runoff rates significantly greater than 1. Two methods can be used to test this consistency: (i) application of the so-called ‘rational method’ and comparison of the specific peak discharge (in mm/h) and the event maximum rainfall intensity over a time period close to the estimated time of concentration of the considered watershed, (ii) rainfall–runoff simulation with a constant runoff rate value taken equal to 1 (see Figures 7 and 8).

Table 2 presents some data produced by the US Geological Survey concerning extreme flash floods that occurred in the United States (taken from Costa, 1987b). In each case, the application of the rational method reveals that the estimated discharges are dubious when compared with the reported measured rainfall intensities. The time of concentration of the Bronco creek is for instance comprised between 1 and 2 h according to its area. The estimated discharge value would require an average spatial rainfall intensity at least twice as high as the maximum reported point rainfall intensity over 0.75 h. This is of course not impossible, the watershed may have been affected by much more intense rainfall not captured by the rain gauge network, but very unlikely. The possible overestimation of the peak discharge value has been confirmed by other studies for this specific flood event (House and Pearthree, 1995).

Likewise, the same procedure leads to some doubts concerning the three other peak discharge estimates. In each case, the estimated peak discharges require that the majority of the measured rainfall amount has fallen homogeneously in space over the watersheds during a reduced duration corresponding to the time of concentration of the watershed: 70 mm over 10 min for the Humbolt river tributary, 85 mm over 30 min for the Meyers canyon and 180 mm over 2 h for the Jimmy camp creek. Such rainfall rates are really exceptional, especially in the conterminous United States (Costa, 1987a) and particularly if they represent spatial mean rainfall rates rather than point rainfall intensities.

### Sediment transport or erosion evidences

Sediment transport phenomena may be a central topic of a post-flood field survey. They may also reveal active hydrological processes or local flow characteristics. In river reaches where clear evidences of bed load sediment transport exist and the sediment size is homogeneous, it is possible to use the Shields relation between the characteristics of the flow, critical shear stress and characteristics (diameter) of the
particles of the river, to assess the possible range of a critical flow velocity that can have led to the displacement of these particles. Of course, there is a risk of underestimation because the river bed deposits visible after the flood event may not be representative of the flood peak, but may have been deposited during the decreasing limb of the flood. Moreover, this approach is highly uncertain. It must not be used to deliver a first guess of peak discharge value in a river reach but as one possible approach to check discharge values estimated otherwise.

It is admitted that significant bed load is induced when the Shields parameter exceeds 0.047 [Eqn (3)].

\[ \tau^* = \frac{\gamma_w R S_f}{(\gamma_s - \gamma_w) d} > 0.047 \]  

(3)

with \( d \) the diameter of the particles and \( (\gamma_s - \gamma_w)/\gamma_w \) the ratio between the volumetric weights of the water and the solid particles, generally close to 1.6 for mineral particles.

Combining Eqn (3) and the Manning–Strickler formula Eqn (1) with the hypothesis that the river bed and banks’ roughness is determined by the size of the particles, i.e. the river bed is flat, with \( K = 21/d^{1/6} \) (Degoutte, 2006), leads to the empirical Eqn (4).

\[ V = 5.8 R^{1/6} d^{1/3} \]  

(4)

In the example presented in Figure 3, the river bed material has undoubtedly been deposited during the flood event. The river gravel diameters are relatively homogeneous, sign that no bigger particles were transported during the flood. The water depth during the peak of the flood was approximately equal to 2.5 m according to the flood marks (\( R = 1.25 \) m). The diameter of the river bed material is comprised between 10 and 20 cm, which leads to a flow velocity estimation using Eqn (4) of 3–3.5 m/s, consistent with the slope conveyance estimation.

Moreover, erosion processes on hill slopes may reveal active hydrological processes and particularly the saturation of the soil necessary to induce slope failures and subsurface flows. As an example, the analysis of the data collected during the recent post-flood investigation conducted after the September 2007 flood on the Selscica Sora river in Slovenia has revealed low runoff rates and conversely high infiltration rates into the soils of the watershed as well as a rapid release of a significant part of these infiltrated volumes after the storm, sign of an efficient drainage of the hill slopes. Such a hydrological response is surprising for a mountainous watershed with steep slopes, shallow soils and a bed rock mostly composed of schist stones.

As illustrated in Figure 4, the storm event induced shallow slope failures and erosion rills on almost every hill slope of the watershed. They confirm that the soil and weathered bed rock covering the hill slopes have been saturated during the storm event. The erosion rills also reveal an active subsurface flow in fractures of the bed rock. The drainage of the hill slope through these fractures may explain the observed rapid release of one part of the infiltrated water volumes just after the flood event.

The two previous illustrations concerning peak discharge estimates and sediment transport and erosion evidence valuations have shown the variety of information sources that can be mobilized after a major flash flood event. The next section presents some examples of the type of hydrological lessons that can be drawn from post-flood investigations.

Illustration of some interpretation results

The data analysis illustrations will be mainly based on two flash flood examples well known by the authors: the 2002 floods in the Gard region and the 1999 floods in the Aude region, both major events that occurred in the south of France. These are the floods on which the post-flood investigation methodology presented herein has been developed and tested. To our knowledge, among the published works on flash floods, these two case studies led to the most detailed rainfall–runoff interpretations. The majority of the data and analyses presented hereafter have already been published (Gaume et al., 2003b; Delrieu et al., 2004; Gaume and Bouvier, 2002; Gaume et al., 2004). Our aim here is to show what type of knowledge can be acquired based on post-flood investigations. The focus will be put on two main questions: (a) what does the spatial pattern of peak discharge values reveal about the rainfall–runoff processes and (b) what is the rainfall–runoff dynamics and its variability during extreme floods? More recently, other post-flood field investigations have been conducted in Italy (Borga et al., 2007) and in Slovenia within the European research project...
HYDRATE. These two case studies will be referred to in the conclusions of this paper. They reveal significantly different reactions of south Alpine watersheds to extreme rainfall events.

**Spatial pattern of peak discharge values: where did the flood generate?**

The estimated peak discharge values can be used to identify the relative contributions of the various subareas of watersheds affected by flash floods. A first example is given in Figure 5 for a 300 km² watershed affected by the 1999 storm events in the Aude region in France. In this case, the mapped peak specific discharges clearly show a high spatial heterogeneity of the runoff contributions. The estimated peak discharge is about 50 times higher downstream Tuchan than upstream of Padern (9 versus 0.2 m³/s/km²) for similar watershed areas and while the two locations are separated by < 10 km. This peak discharge distribution is consistent with the observed rainfall amount repartition. The western part of the watershed received about 200 mm of rainfall within 24 h while the north-eastern received more than 400 mm. A desktop application of the 'rational method' with estimated time of concentration of the watersheds indicates that the runoff rate has probably remained lower...
than 10% upstream of Padern and must have been close to 100% around Tuchan to explain the estimated discharges. The observed high spatial heterogeneity of the peak discharges reveals the nonlinearity of the rainfall–runoff reaction of these watersheds, linked, as we will be able to see in the next section, to the high initial infiltration and storage capacities of their soils and subsoils.

A second example of a peak discharge map is given in Figure 6 for the three main river systems of the Gard region affected by the 2002 storm event. The spatial pattern appears here much more homogeneous but with at least two exceptions. In the north-east, the peak discharge of the upper Alzon river (number 16 in Figure 6) appears as significantly lower as the ones of the surrounding watersheds. This area is highly karstified, and the karstic aquifer feeds a perennial source located a few kilometres upstream the surveyed cross sections. This Fontaine d’Eure source is one of the most important of the region and had therefore been harnessed by the Romans to supply the Nîmes city with drinking water through the famous Pont du Gard aqueduct. The mapped results appear to show that this extended karstic system has had a significant attenuating effect on the flood of this watershed. Another outlying watershed appears in the south of the considered area on the Vere stream (number 2 in Figure 6). After exchanges with local geologists, it was apparent that this stream has been fed by the overflow of the karstic aquifer, which covers a large area located in the north of this watershed. Pictures taken on the Vere watershed indicate that some karstic resurgence appeared during the 2002 flood and were still active a few days after the storm event.

These two examples illustrate how spatial heterogeneities as a sign of differentiated hydrological processes can be revealed through a detailed mapping of peak discharge values.

Variability of the rainfall–runoff dynamics: how has the flood been generated?

In some cross sections, it is possible to identify various water levels referenced in time, owing to the number of witnesses and the level of detail of their accounts: typically the time of the river bank overflow, of a bridge overflow and the time of the various flood peaks. These points of reference can be compared with the outputs of very simple rainfall–runoff models fed with radar quantitative precipitation estimates to evaluate the range of possible runoff rates over the flood.
One example is shown in Figure 7. The information gathered through interviews appears as bars. The vertical range represents the uncertainty in the discharge estimates – relatively large – and the horizontal span, the uncertainty in time evaluated after validation of witnesses’ accounts (Gaume et al., 2004) (+\(\pm\) 15 min with regard to the time indicated by the witnesses). The rainfall–runoff model is a distributed model combining a Soil Conservation Service-curve number (SCS-CN) production function (Soil Conservation Service, 1973) and a kinematic wave transfer function (Gaume et al., 2004). The main adjustment parameter is the so-called curve number CN, taken homogeneous over the watershed area and representing a water storage capacity \(S\) on the watershed:

- \(CN = 100\) means \(S = 0\) mm,
- \(CN = 70\) means \(S \approx 100\) mm,
- \(CN = 50\) means \(S \approx 250\) mm.

The comparison of the points of reference and of simulated flood hydrographs for two headwaters affected by the 1999 storm in the Aude regions reveals two main characteristics of the flash floods. First, over bank flow, first bar on the two graphics, occurs late in the storm event and reveals that despite the high rainfall intensities, a large proportion of the initial rainfall volumes did not produce significant runoff and were stored on both watersheds, probably infiltrated in the soils and subsoils. The adjusted CN value leads to an evaluation of the runoff deficit of about 250 mm (CN = 50). This value is relatively high but confirmed by other data collected on the Aude flood (Gaume et al., 2004) and in accordance with values estimated for other flash floods (Cosandey, 1993; Belmonte and Beltran, 2001; Borga et al., 2007). On these watersheds, high-intensity rainfall rates seem not to be sufficient to trigger a flash flood, but a rainfall accumulation (i.e. a certain level of saturation) is necessary. Despite the relatively high rainfall intensities (more than 50 mm/h), the 1999 flash floods producing processes seem not to be of the hortonian type. Second, the Tournissan and Verdoul watersheds have the same type of bedrock but while 50% of the Tournissan watershed area is covered by vineyards, the Verdoul watershed is essentially covered by forest and scrub. According to the level of accuracy of the available data, it is not possible to reveal a clear difference in the rainfall–runoff dynamics of both watersheds. The land use type may have an influence on the rainfall–runoff response, but it is not a first-order effect for this specific flash flood.

Figure 8 shows another example of rainfall–runoff analysis for two headwaters affected by the 2002 floods.
the Gard region. In these cases, the complete flood hydrographs could be relatively accurately reconstructed using existing water level measurements in flood control dam spillways. The comparison with the same simple rainfall–runoff model leads to significantly different conclusions, illustrating the variability of the rainfall–runoff responses depending on the watersheds. The adjusted CN value for the Crieulon stream (70) indicates a moderate water retention capacity of the soils and subsoils, about 100 mm, much lower as in the Aude case study. Moreover, the rainfall–runoff model is not able to reproduce the flood hydrograph of the Vidourle watershed. Its runoff coefficient never seems to exceed 50%: the watershed still has some rainfall water retention capacities even during the peak of the flood. Moreover, unlike what is observed on the Crieulon, a relatively high discharge, not simulated by the rainfall–runoff model, remains after the rain event has ceased indicating that a part of the temporary stored rainwater is rapidly returned to the stream after the event. About one-third of the flood volume is released during the few days after the flood event in the case of the Vidourle river. Taking into account this late released volume, the retention capacity of the Vidourle watershed appears also to be about 100 mm.

The geology and the corresponding soil types can be put forward to explain those clear differences in the rainfall–runoff reactions of both watersheds. The Vidourle watershed is mainly composed karstified limestone, which may explain its large retention capacities during the flood but also the rapid release of one part of the water stored in the karst after the flood. As for the Crieulon catchment, it is mainly composed of marls. The analysis of data collected on other headwaters revealed a reaction similar to that of the Crieulon for all the watersheds on marls, highly variable dynamics of karstic areas and a surprise. The watersheds located in the mountainous part of the Gard region with steep hillslopes and bedrocks composed of granite or schists reacted in a way very similar to karstic areas: high infiltration and retention capacities during the storm event and rapid release of one part of the stored water volumes of the flood. Further field investigations and infiltration tests have revealed that the upper schist and granite layers are highly fractured and weathered and have confirmed the very high retention volume and permeability of this layer (Ayral, 2005). This is consistent with the conclusions of recent post-flood studies conducted in the Adige region in Italy (Borga et al., 2007) and Slovenia that revealed huge infiltration and storage capacities on south alpine watersheds with limestone but also schist bedrocks. Steep slopes and a priori impervious plutonic or metamorphic bedrocks are not necessarily associated with rapid runoff during high-intensity rainfall events! Such counter-intuitive results reveal the gaps in the hydrological knowledge and the need for further post-flood analyses.

**Conclusions**

We hope that these few examples have convinced the readers of the usefulness of post-flash flood surveys. It is a tedious and difficult task. We have shown here that recent surveys have revealed important and sometimes unexpected aspects of flash floods: the importance of the geology and soil types, counter-intuitive behaviours of some areas, limited impact of the land use type, limited contribution of Hortonian runoff processes in vegetated catchment even during intense rainfall events. These observations may also lead to a better understanding of the underlying flood-generating processes.

A post-flood survey procedure has been suggested herein as well as some analysis methods. It is a first proposal that certainly will be amended. But beyond the procedure and methods, it is important to keep in mind the general philosophy: the data collected are necessarily inaccurate, no method is perfect and the very first concern must be to verify, cross-check, verify and cross-check again. It is the only way to limit the risks of errors on peak discharge estimates for instance as illustrated herein. Moreover, a written methodology is a necessary condition for efficient post-flood surveys. The outcome of such investigations also depends highly on the observational skill of the involved hydrologists, on their ability to depict indices and clues (flood and erosion marks) in the landscape, to ask the right questions to the eyewitnesses and technical services. This skill has to be developed based on practice and the initiative taken within the European research projects Floodsite and HYDRATE aiming at exchanging between research teams and conducting common surveys at the European scale is therefore very welcome. Field surveys are also an excellent exercise for young or even senior hydrologists to maintain and extend their expertise.

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References


Appendix A

The cross-section survey form (Figure A1) has been developed to apply the so-called slope-conveyance discharge estimation method using digital theodolite measurements of cross sections and flood marks. Note that the measured data (cross section, high water marks, water surface slope) and the detail of the computations leading to the peak discharge estimate are clearly separated. A sensitivity analysis of this estimate to various sources of uncertainty is conducted and a range of possible discharge values is proposed. The details of the computation are given, to be criticised and discussed. The empirical Manning–Strickler formula is used for the estimation. The main river bed and the right and left bank flows are considered separately for the roughness coefficient and hydraulic radius estimations. It is not directly the discharge that is estimated but the mean velocity that can possibly also be evaluated by other means and therefore criticised: analysis of video documents, erosive power of the flow, superelevation, etc. The witness interview account synthesis from (Figure A2) contains a summary of the description of the flood by the eyewitness, other possible information given by the witness (location of runoff sources on hill slopes, velocities, role of blocages …) and possible references to previous major floods.

Figure A1  River cross-section survey form.
River: The Lionnais, right hand tributary of the Alzon river

Witness: Mr and Mrs Maury

Coordinates: X=754681.2, Y=1962451 (Lambert II etendu)

Established by: Olivier Payastre (CEREVE)

Date: 17 January 2003

Description of the site: House located on the left bank.

Summary of the interview:

- The rainfall began on Sunday the 8th of September during the day, and lasted without interruption until the Monday in the morning.
- During the night, around midnight, the house of M. Boilot, our neighbour, which is closer to the Lionnais, began to be flooded. He drove his car in our garden, and at one o’clock, M. Boilot left his house to take refuge in our house for the rest of the night. The water level seems to have risen progressively between midnight and one o’clock.
- The maximum water level - level of the mailbox of M. Boilot - occurred on Monday between 5:00 and 6:00.
- The water level dropped rapidly after 6:00. Within a quarter of an hour there was no water left on the road in front of the house.

Other observations:

- -

Information about past floods:

- The road in front of the house has been flooded twice: in 1958 and in 1995. But the maximum water level has never been so high than in 2002.

Figure A2 Witness interview account synthesis form.