Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins

Daniele Norbiato a, Marco Borga a,*, Silvia Degli Esposti a, Eric Gaume b, Sandrine Anquetin c

a Department of Land and Agroforest Environment, University of Padova, Agripolis, via dell'Università, 16, Legnaro IT-35020, Italy
b Ecole Nationale des Ponts et Chaussees (ENPC), Avenue Blaise Pascal 6-8, Cite Descartes, Champs sur Marne, Marne la Vallée, France
c Laboratoire d’Etude des Transferts en Hydrologie et Environnement – LTHE (CNRS-UMR 5564, UJF, INPG, IRD), Rue de la Piscine 1023-1025, Grenoble, France

Received 17 November 2007; received in revised form 2 July 2008; accepted 30 August 2008

KEYWORDS
Flash flood;
Flash flood guidance;
Flash flood forecasting and warning;
Ungauged basins

Summary The main objective of this paper is to evaluate a threshold-based flash flood warning method, by considering a wide range of climatic and physiographic conditions, and by focusing on ungauged basins. The method is derived from the flash flood guidance (FFG, hereafter) approach. The FFG is the depth of rain of a given duration, taken as uniform in space and time on a certain basin, necessary to cause minor flooding at the outlet of the considered basin. This rainfall depth, which is computed based on a hydrological model, is compared to either real-time-observed or forecasted rainfall of the same duration and on the same basin. If the nowcasted or forecasted rainfall depth is greater than the FFG, then flooding in the basin is considered likely. The study provides an assessment of this technique based on operational quality data from 11 mountainous basins (six nested included in five larger parent basins) located in north-eastern Italy and central France. The model used in this study is a semi-distributed conceptual rainfall–runoff model, following the structure of the PDM (probability distributed moisture) model. Two general questions are addressed: (1) How does the efficiency of the method evolve when the simulation parameters can not be calibrated but must be transposed from parent gauged basins to ungauged basins? (2) How sensitive are the results to the method used to estimate the initial soil moisture status? System performances are evaluated by means of categorical statistics, such as the critical success index (CSI). Results show that overall...
Introduction

A flash flood is a flood that follows the causative storm event in a short period of time. The term "flash" reflects a rapid response, with water levels in the drainage network reaching a crest within minutes to a few hours after the onset of the rain event, leaving extremely short time for warning (Georgakakos, 1992; Creutin and Borga, 2003; Collier, 2007). Flash floods are localized phenomena that occur in basins of few hundred square kilometres or less, with response times of a few hours or less (Borga et al., 2007). In many cases, such basins respond rapidly to intense rainfall because of steep slopes and impermeable surfaces, saturated soils, or because of anthropogenic forcing or fire-induced alterations to the natural drainage.

Europe experienced several catastrophic flash floods in the last decades. Data concerning a number of flash flood events occurred since 1950 have been reported by Gaume et al. (2008). Examination of these data shows that (i) flash floods occur in any of the hydroclimatic regions of Europe, even though three regions appear to be characterised by high flash flood potential: Mediterranean, Alpine Mediterranean and Inland Continental Europe; (ii) space and time scales of flash floods increase systematically when moving from Inland Continental to Mediterranean regions, while seasonality shifts accordingly from summer to autumn months. According to these data, heavy rainfall accumulation is a necessary but not sufficient condition for inducing flash floods, since hydrology critically controls flash flood triggering. Soil moisture initial conditions are among the most important hydrological properties affecting flash flood triggering. Without hydrological analysis, it is impossible to evaluate the flash flood potential of storms, particularly in the fringe of the flood/no flood threshold.

Given the specific space–time scales of flash flood events, at least two features characterise flash flood forecasting with respect to riverine flood forecasting and point out to their larger uncertainty. These are: (i) the short lead time, which implies both the integration of meteorological and hydrologic forecast, and the difficulties of using data assimilation procedures based on real-time-observed discharges to reduce uncertainty in hydrologic predictions, and (ii) the need to provide local forecasts, which means that, on one hand, the rainfall must be monitored and forecasted on a wide range of space/time scales, and, on the other hand, every tributary of a monitored basin can be considered as a potential target for flood warning. In this sense, flash flood forecasting exemplifies the ungauged basin prediction problem under extreme conditions.

The assessment of the susceptibility to flash flood, by taking initial soil moisture status into account, is a critical step to anticipate the locations of the river system which may be hit by the flood. Even though the occurrence, location and (or) timing of the flash flood is still uncertain, this information may provide enough lead time so that flash flood mitigation measures can be planned and managed in an anticipatory rather than responsive manner. The provision of information about susceptibility to flash flood is one of the objectives of the flash flood guidance method, which is operating in the United States since 1970s (Mogil et al., 1978). According to Georgakakos (2006), the US National Weather Service relies routinely on flash flood guidance (FFG, hereinafter) computations to produce flash flood watches and warnings. FFG is the depth of rain of a given duration, taken as uniform in space and time on a certain basin, necessary to cause minor flooding at the outlet of the considered basin. This rainfall depth, which is computed by running in inverse mode a hydrological model, is compared to either real-time-observed or forecasted rainfall of the same duration and on the same basin. If the nowcasted or forecasted rainfall depth is greater than the FFG, then flooding in the basin is considered likely. As such, the FFG is not a forecast quantity; rather, it is a diagnostic quantity. Its use for the development of watches and warnings requires assessment of a present or imminent flash flood-inducing rainfall accumulation. Georgakakos (2006) provided the theoretical basis of developing operational FFG techniques by using analytical methods. Ntelekos et al. (2006) analysed uncertainty propagation within a simplified FFG technique. Even though FFG is operationally implemented in the United States by using the Sacramento soil moisture accounting model, in principle FFG can be estimated by using generic hydrologic models capable to describe in a continuous way the hydrological cycle.

Apart from their extensive use in the United States (Georgakakos, 2006) and in Central America (Georgakakos, 2004; Sperfslage et al., 2004), in Europe, the HYDRATE Project (http://www.hydrate.tesaf.unipd.it) among others aims at assessing the advantages for using the rainfall threshold approach for flash flood risk management. Alternatives to the FFG have been proposed in the last years, generally taking advantage from the development of spatially distributed hydrological models (Moore et al., 2006; Martina et al., 2006; Reed et al., 2007; Borga et al.,...
The objective of this paper is to evaluate a threshold-based flash flood warning approach based on FFG by considering a wide range of climatic and physiographic conditions, and by focusing on ungauged basins. Data from 11 basins (six nested included in five larger parent basins) located in north-eastern Italy and central France is used in the study. The model used in this study to compute the FFG is a semi-distributed conceptual rainfall–runoff model, following the structure of the PDM (probability distributed moisture) model (Moore, 1985).

Specific attention is drawn to the assessment of the FFG method under different conditions of data availability. More specifically, two questions are addressed: (1) How does the efficiency of the method evolve when the simulation parameters can not be calibrated but must be transposed from parent gauged basins to ungauged basins? (2) How sensitive are the results to the method used to estimate the initial soil moisture state?

The FFG method is therefore evaluated at gauged interior sites that were not used to calibrate the hydrological model. At these sites, the model parameters are regionalised by transposition from the parent basin. Results derived in this way are considered indicative of expected performance at ungauged locations, under the conditions that model calibration may be carried out at larger spatial scales and that computed parameters may be transposed at smaller spatial scales.

Likewise, two alternative ways to compute soil moisture status are considered. First, we evaluate results obtained by transposing soil moisture status, further than model parameters, from parent basins to interior basins. This technique has obvious advantages in terms of operational implementation, by reducing computational efforts to obtain FFG at several interior sites. However, soil moisture status may be biased when used at the scale of the specific interior basin, due to use of precipitation and evaporation estimates which are representative at the scale of the parent basin but potentially not at the scale of the interior basins. As a second alternative, we evaluate the use of time-constant soil moisture status as an input to the threshold-based flash flood warning system. This allows one to evaluate the decrease in accuracy associated to lack of information about the temporal variation of soil moisture status before the flood event.

The next section provides a description of the basins and data used in the investigation. Section “The flash flood guidance method” describes the hydrological model and the FFG method applied in the study. Section “Hydrological model application assessment” illustrates the results obtained by means of the hydrological model; assessment of the application of the FFG is reported in Section “FFG assessment”. Concluding remarks are in Section “Conclusions and future work”.

Study areas and data

Data from two distinct European regions were used in this study: north-eastern Italy (with eight basins) and central France (with three basins). Fig. 1 shows the location of the basins. Table 1a provides more detailed basin information, with Table 1b and 1c providing information on the length period with hourly data available and division among calibration and validation period. Table 2 provides the information about the topological connection between parent basins and nested basins. Two parent basins contain two nested basins each, and other two parent basins contain one nested basin each.

Drainage area is comprised between 116 km² and 3244 km² for the parent basins, and between 7.3 km² and 233 km² for the nested basins. The size of the largest basin (Loire river at Bas-en-Basset, with 3244 km²) is at the limit of the spatial scales usually met for flash flood analysis. This case has been used here to assess the performance of the method with increasing the basin scale. The second largest basin is the Dunierés at Vauberlet, with 233.4 km².

The topography of these basins is in general rather complex, with some high altitude basins (Ridanna, Cordevole at Saviner, Cordevole at Vizza), characterised by top altitudes exceeding 3000 m a.s.l., and elevation range comprised between 800 m and 2000 m. Snow-related processes are important elements for characterisation of the seasonal hydrological balance in these basins. We decided therefore to include dynamics of snow accumulation and melt in the modelling strategy.

In general, the river regime of these river systems is altered in a negligible way by management activities, such as artificial reservoirs and diversions. However, the regime of the Brenta river is influenced by two relatively large natural lakes (Caldonazzo and Levico), with 77 km² area drained by the lakes. In this case, the influence of the natural lakes on the river regime has been taken into account by subdividing the basin into subunits and simulating the effects of the lakes. Artificial reservoirs exist on the Loire river. The 200 km² upstream part of the Loire watershed is equipped with dams for hydropower plants and 350 km² of the Loignon watershed downstream Le Chambon sur Lignon is controlled by a dam built for the water supply of the City of Saint Etienne. These reservoirs are managed to have as low as possible impact on floods; as a consequence, their influence on magnitude and timing of flood flows is very limited, especially at Bas-en-Basset. No significant reservoirs exist on the Gagne and Duniere´ s river systems.

Sedimentary deposits prevail in the Posina, Brenta and Cordevole river systems, whereas metamorphic crystalline rocks are found in the Ridanna basin. Karstified aquifers influence the runoff response for specific portions of the Posina and Brenta river systems. A more detailed presentation of the geologic and land use setting for the Italian basins is reported by Norbiato et al. (submitted for publication). A more complex geology is found for the Upper Loire basins, with both crystalline rocks (mainly schist and gneiss) and sedimentary deposits.

Annual runoff coefficient range from rather low values (around 0.42) for the French basins to relatively high values for some Italian high altitude basins (0.8 for Ridanna). We
applied the Budyko’s climatic classifications scheme (Budyko, 1974) to compare and contrast the climatic characteristics of these basins. This is achieved by presenting the specific response of each of these basins on the Budyko curve (Fig. 2), which is a plot that expresses \( E/P \), the ratio of average annual actual evapotranspiration (\( E \)) to average annual precipitation (\( P \)) as a function of \( EP/P \), the ratio of average annual potential evapotranspiration (\( EP \)) to average annual precipitation (\( P \)). Actual evapotranspiration (\( E \)) for each basin was derived as the long-term difference between \( P \) and \( R \) (runoff) for the basins. Fig. 2 shows clearly the Italian basins (2, 3, 4, 5, 8, and 10) represent a wet climate,
whereas the French basins (1, 6, and 7) have a temperate climate.

Fig. 2 shows also significant climate variability among parent and nested basins. This is the case for Cordevole at Saviner (2) and at Vizza (8), where differences are mainly due to different elevation ranges among parent and interior basin, and for Posina at Stancari (3) and Rio Freddo (10), where differences are mainly due to the differentiated impact of the karstified aquifer.

<table>
<thead>
<tr>
<th>Table 1a</th>
<th>Basins characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station name</td>
<td>Basin number</td>
</tr>
<tr>
<td>Loire at Bas-en-Basset</td>
<td>1</td>
</tr>
<tr>
<td>Cordevole at Saviner</td>
<td>2</td>
</tr>
<tr>
<td>Posina at Stancari</td>
<td>3</td>
</tr>
<tr>
<td>Brenta at Borgo</td>
<td>4</td>
</tr>
<tr>
<td>Ridanna at Vipiteno</td>
<td>5</td>
</tr>
<tr>
<td>Gagne at Pandreaux</td>
<td>6</td>
</tr>
<tr>
<td>Dunieres at Vauberlet</td>
<td>7</td>
</tr>
<tr>
<td>Cordevole at Vizza</td>
<td>8</td>
</tr>
<tr>
<td>Posina at Bazzoni</td>
<td>9</td>
</tr>
<tr>
<td>Rio Freddo at Valoje</td>
<td>10</td>
</tr>
<tr>
<td>Brenta at Levico</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1b</th>
<th>Periods with data available: parent basins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station name</td>
<td>Basin number</td>
</tr>
<tr>
<td>Loire at Bas-en-Basset</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1c</th>
<th>Periods with data available: interior points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station name</td>
<td>Basin number</td>
</tr>
<tr>
<td>Gagne at Pandreaux</td>
<td>6</td>
</tr>
<tr>
<td>Dunieres at Vauberlet</td>
<td>7</td>
</tr>
<tr>
<td>Cordevole at Vizza</td>
<td>8</td>
</tr>
<tr>
<td>Posina at Bazzoni</td>
<td>9</td>
</tr>
<tr>
<td>Rio Freddo at Valoje</td>
<td>10</td>
</tr>
<tr>
<td>Brenta at Levico</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Relationship among parent and nested basins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent basins</td>
<td>Nested basins</td>
</tr>
<tr>
<td>1</td>
<td>6, 7</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>9, 10</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>5</td>
<td>–</td>
</tr>
</tbody>
</table>
The length of the hourly record of streamflow, precipitation and temperature data ranges from 5 to 13 years, with a total of 101 years. The data were quality controlled and as a result part of the record was set to missing. Basin-averaged precipitation estimates were obtained based on rain gauge stations by using a Thiessen technique, with densities ranging from one station per 15 km$^2$ (Brenta river basin) to one station per 140 km$^2$ (Loire river basin).

The stage–discharge relationship at the interior streamflow gauge of Brenta at Levico is considered exceedingly uncertain for low flows. Due to this reason, only flood discharge data were used.

Digital elevation model (DEM) at four different resolutions were used in the study: 75 m for the French basins, 30 m for Brenta and Ridanna, 25 m for Cordevole and 20 m for Posina.

**Rationale for basins selection**

The study basins in Fig. 1 were selected for several reasons. First, these basins had the data required to conduct the intercomparison, with concurrent time series of hourly rainfall, temperature and discharge data made available for the basin outlets and selected interior points. The quality of the data available is representative of operational conditions, subject to complexities due to rough orography and high space–time variability. Lack of significant modification of the streamflow due to reservoirs and diversions simplifies the intercomparison study.

A second critical criterion for selection is the observation of past flash flood events in these basins and their representativeness of conditions leading to flash floods. In both Italian and French regional setting, flash flood events occur during the fall season, and are mainly due to convective storm events. In the Brenta and Ridanna river system flash flood events are also reported in the summer season. Larger spatial extension and longer duration are reported for flash flood events observed in the Upper Loire with respect to those recorded in the central Italian Alps (Gaume et al., 2008). Differences in spatial scale between the two flash flood regimes are accounted for the selection of the study basins, which are larger in the French region.

The selected parent basins contain internal points having observed streamflow data, allowing to develop study questions regarding the prediction of interior hydrologic processes. The Ridanna basin has no interior gage locations. This basin represents an additional case for testing the threshold methodology over a high altitude alpine basin frequently hit by small scale flash flood, usually triggering shallow landsliding and debris flows.

Lastly, the hydrometeorology of flash flooding in these areas has been widely studied. Dinku et al. (2002) analysed estimation uncertainties of flood-generating storms based on raingauges and radar observations for the upper Astico river system (Posina). In the same region, Borga et al. (2000) and Hussain et al. (2004) examined the impact of errors in radar-based rainfall estimates on flood prediction uncertainty.

**The flash flood guidance method**

The FFG is the depth of rain of a given duration, taken as uniform in space and time on a certain basin, necessary to cause minor flooding at the outlet of the considered basin. FFG is estimated each day over a region to diagnose flash flood susceptibility during the following 6–24 h. FFG is conditional to the soil moisture conditions computed by using a continuous soil moisture accounting hydrological model. To support flash flood computations and using these initial conditions, the model runs off-line in ‘what if’ scenario runs with increasing amounts of rainfall input of a given duration. FFG for different durations are then compared to either real-time-observed or forecasted rainfall of the same duration and on the same basin. The warning is issued based on the comparison between the FFG and either the real-time-observed or the forecasted rainfall. If the nowcasted or the forecasted rainfall depth is greater than the FFG, then flooding in the basin is considered likely. It is important to recognise that the FFG technique does not predict flash flood timing, but only that a flood threat is imminent. The main objective with the FFG is the correct assessment of the flood threshold exceedance, while the correct timing forecast is left to the monitoring activity triggered by the flash flood alert.

Three elements are therefore included in the FFG method: (i) the continuous soil moisture accounting model, (ii) the computations of the FFG, and (iii) the flood threshold conditions. These elements are described in the next sections.

**Description of the hydrological model**

The model used in this study is a semi-distributed conceptual rainfall–runoff model, following the structure of the PDM (probability distributed moisture) model (Moore, 1985). The model is routinely used within the flood forecasting system in some river systems of north-eastern Italy, and for this reason has been chosen for the FFG assessment. The model runs on an hourly time step and consists of a snow routine, a soil moisture routine and a flow routing routine.
The snow routine represents snow accumulation and melt by using a distribution function approach based on a combined radiation index degree–day concept. Snow melt is computed as follows:

\[ M = \begin{cases} f_m \text{EI}(T_h - T_0) & T_h > T_0 \\ 0 & T_h \leq T_0 \end{cases} \]  

(1)

where \( M \) is the melt rate (mm h\(^{-1}\)), \( T_h \) is the hourly mean temperature (°C), \( T_0 \) (°C) is a threshold temperature beyond which melt is assumed to occur, \( f_m \) is a melt factor and \( \text{EI} \) (J m\(^{-2}\) h\(^{-1}\)) is an energy index which represents the potential radiation energy (variable in time) for a given site in the basin. EI is computed for each topographic element of the basin taking into account solar altitude angle, optical depth of the atmosphere, elevation, aspect, slope and shading effects. The basin is subdivided into temperature bands (generally ranging 200 m in elevation), and for each band the empirical distribution of the energy index is used in the lumped form of the snow melt module.

Catch deficit of the precipitation gauges during snowfall is corrected by a snow correction factor, SCF. A threshold temperature interval TR–TS is used to distinguish between rainfall, snowfall and a mix of rain and snow. The model includes a routine for computing runoff produced during rain-on-snow events.

Potential evapotranspiration is estimated by using the Hargreaves and Samani method (Hargreaves and Samani, 1982), based on earlier applications of the method on the study basins (Degli Esposti, 2006).

The soil moisture routine uses a probability distribution to describe the spatial variation of water storage capacity across a basin. Saturation excess runoff generated at any point in the basin is integrated over the basin to give the total direct runoff entering the fast response pathways to the basin outlet. Drainage from the soil enters slow response pathways. Storage representations of the fast and slow response pathways yield a fast and slow response at the basin outlet which, when summed, gives the total basin flow. The PDM model configuration used here employs a Pareto distribution of storage capacity, \( c \). This has the distribution function

\[ F(c) = 1 - (1 - (c/c_{\text{max}})^b)^k \]  

(2)

where \( c_{\text{max}} \) (mm) is the maximum storage capacity in the basin and the parameter \( b \) (–) controls the degree of spatial variability of storage capacity over the basin. The instantaneous rate of fast runoff generation from the basin is obtained by multiplying the rainfall rate by the proportion of the basin where storage capacity is saturated.

Losses due to evaporation are calculated as a function of potential evaporation and the status of the soil moisture store. The dependence of evaporation loss on soil moisture content is introduced by assuming the following simple function between the ratio of actual to potential evaporation, \( E/EP \), and soil moisture deficit, \( S_{\text{max}} - S(t) \)

\[ \frac{E(t)}{EP(t)} = 1 - \left( \frac{S_{\text{max}} - S(t)}{S_{\text{max}}} \right)^{b_v} \]  

(3)

where \( S_{\text{max}} \) (mm) is the total available basin storage, \( b_v \) (–) is an exponent coefficient and \( S(t) \) (mm) is the basin moisture storage at time \( t \). Drainage to the slow flow path, \( d \) (mm h\(^{-1}\)), is represented by a function of basin moisture storage \( S(t) \) such that

\[ d = (k_g)^{-1}|S(t) - S_b|^{b_g} \]  

(4)

where the parameters are a time-constant \( k_g \) (h mm\(^{b_g+1}\)), an exponent coefficient \( b_g \) (–) and a threshold storage \( S_b \) (mm) below which there is no drainage. The slow or base flow component, \( q_s \) (mm h\(^{-1}\)), of the total runoff is assumed to be routed through an exponential store such that

\[ q_s = \exp \left( \frac{S_b(t)}{k_g} \right) \]  

(5)

where \( S_b \) (mm) is the depth of storage and \( k_g \) (mm) is the decay parameter of the store.

Direct runoff from the proportion of the basin where storage capacity has been exceeded is routed by means of a geomorphology-based distributed unit hydrograph. With this procedure, a geomorphologic filter based on a threshold drainage area \( A_{\text{th}} \) (m\(^2\)) is used to distinguish hilltops and channel network starting from the space-filling representation of the drainage system directly obtainable from DEMs (Da Ros and Borga, 1997a). The routing time of each site in the basin is evaluated assigning different typical velocity values in each pixel pertaining to the basin and classified as hillslope or channel. The two velocities, \( v_h \) (m s\(^{-1}\)) and \( v_c \) (m s\(^{-1}\)), used to describe the flow routing process in each of the two components of the drainage system are assumed here constant; they maintain a physical meaning as the average velocities on hillslopes and in channel network. Total runoff is computed as the sum of slow and fast runoff.

The model application requires therefore specification of 14 parameters: three for the snow accumulation and melt module, eight for the PDM module and three for the runoff propagation module.

**FFG computation**

Five rainfall durations are considered for computing the FFG: 1, 3, 6, 12 and 24 h. The model is run continuously in time, and five values of FFG are computed each day (at 12:00) for each considered basin. Selection of the time during the day when the FFG is computed has been shown to have negligible impact on final results. For the considered day, the FFG values are compared with the maximum estimated areal precipitation over the corresponding five durations. The technique predicts the exceedance of the threshold flooding (i.e., a flash flood warning would be issued) when estimated precipitation exceeds the FFG for at least one precipitation duration.

**Threshold flooding conditions**

In this study the FFG is computed based on two different threshold flooding conditions. The first one (called hereafter high threshold – HT) is based on the bankfull flow, characterised by 2-year return time. Carpenter et al. (1999) suggest that a 2-year flood is a reasonable threshold to use for flood warnings given that the flood flow associated with damage or hazard is often a little higher than bankfull flow. Use of this definition led to identification of 55 flood events exceeding the basin-specific thresholds, over the
whole archive of streamflow data. However, use of this definition may give rise to sampling problems for the basins characterised by short data record length, due to the small number of local flood events. Owing to this reason, we used also a low threshold (LT), characterised by a return time around 0.5 year, corresponding to 223 flood events exceeding the threshold.

Hydrological model application assessment

Three different strategies were considered to implement the hydrological model within the FFG method: (i) model parameter calibration on gauged basins; (ii) model parameter transposition from parent basin to interior sites; (iii) model parameter and soil moisture status transposition from parent basins to interior points. These strategies and the relevant results are described in the following sections.

Gauged basins: calibration and validation

The goal of calibration is to adjust the model’s parameters to decrease the difference between observed and simulated streamflow values. The closeness of fit can be checked qualitatively (e.g. plots of observed and simulated hydrographs) or quantitatively (residual statistics such as the Bias, Nash–Sutcliffe efficiency, etc.). In this study, the Shuffled Complex Evolution-University of Arizona (SCE-UA, Duan et al., 1992) global optimization algorithm was used for calibration of the hydrological model parameters over the five parent basins. In an effort to improve the description of soil moisture conditions before the flood events, we placed equal weight to the representation of low flows and floods. The following objective functions were used during the optimization process for this study:

1. The Nash and Sutcliffe (1970) coefficient of efficiency defined as

\[ E_{NS} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - O_{ave})^2} \]

where \( O_i \) is the hourly \( i \)th observed discharge, \( S_i \) is the simulated discharge, and \( O_{ave} \) is the mean value of the observed discharges. The coefficient of efficiency was selected because it is dimensionless and is easily interpreted. If the model predicts observed streamflow with perfection then \( E_{NS} = 1 \). If \( E_{NS} < 0 \) then the model’s predictive power is worse than simply using the average of the observed values.

2. The relative bias (RB) defined as

\[ RB = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n}O_i} \]

RB is a measure of total volume difference between observed and simulated streamflows, and is important in the evaluation of simulations from continuous hydrologic models.

A simple split sample test (Klemes, 1986) was considered for calibration and validation of the hydrological model. The test involves dividing the available data into two sets, one used for parameter estimation (calibration period) and the other for validation (validation period).

Results from the calibration and validation of the model are reported in Table 3a, which reports both the coefficient of efficiency \( (E_{NS}) \) and the relative bias \( (RB) \) for the calibration and validation period, as well as for the whole data period. The overall coefficient of efficiency computed over the whole simulation period for the various parent basins amounts to 0.74. Efficiency values for calibration and validation are relatively homogeneous, with the exception of Brenta at Borgo, where the validation period was considerably wetter than the calibration period. Efficiency is lower than average for the largest basin considered in the study (Loire at Bas-en-Basset, 1) and for Brenta at Borgo (4). For the Loire basin, this suggests that there may be a mismatch between time and space scales of the hydrological model representation for this basin. In other words, the size of this basin and its inherent spatial variability are such that a lumped representation of precipitation and hydrological processes does not ensure a correct description of hourly streamflow dynamics. In the case of the Brenta river, relatively poor model accuracy is due to the combined influence of lake storage, on one hand, and karstified aquifer, on the other.

Ungauged basins: model parameter transposition

The process of transferring information (such as catchment model parameter values) from neighbouring catchments to

<table>
<thead>
<tr>
<th>Parent basins</th>
<th>Calibration period</th>
<th>Validation period</th>
<th>Whole simulation period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( E_{NS} )</td>
<td>RB (%)</td>
<td>( E_{NS} )</td>
</tr>
<tr>
<td>1</td>
<td>0.72</td>
<td>7</td>
<td>0.65</td>
</tr>
<tr>
<td>2</td>
<td>0.72</td>
<td>5.35</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>0.76</td>
<td>1.1</td>
<td>0.77</td>
</tr>
<tr>
<td>4</td>
<td>0.71</td>
<td>2.64</td>
<td>0.54</td>
</tr>
<tr>
<td>5</td>
<td>0.80</td>
<td>1.36</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Parent basins.
the catchment of interest is generally referred to as hydrological regionalisation (Blöschl and Sivapalan, 1995). Numerous regionalisation methods have been proposed in the literature for the case of catchment model parameters (Blöschl, 2005). Merz and Blöschl (2004) examined the performance of various methods of regionalising the parameters of a conceptual catchment model in 308 Austrian catchments. They concluded that the methods based on spatial proximity performed better than those based on physiographic catchment attributes. Similar finding were reported by Kokkonen et al. (2003) and Parajka et al. (2005). Kokkonen et al. (2003, p. 2219), concluded that “when there is a reason to believe that, in the sense of hydrological behaviour, a gauged catchment resembles the ungauged catchment, then it may be worthwhile to adopt the entire set of calibrated parameters from the gauged catchment instead of deriving quantitative relationships between catchment descriptors and model parameters”. One of the advantages of the similarity approach may be that the complete set of model parameters is transposed from a donor catchment.

In this study, we used a similarity approach for the parameter estimation of the interior gauges based on transposing the model parameters from the parent basin to the interior basin. According to this method, parameters of the three different modules of the soil moisture accounting model (snowmelt accumulation and melt module, PDM model and runoff propagation model) were calibrated on the parent basin and then transposed to the interior basin.

Assessment of the parameter transposition method affords to obtain results which are indicative of expected performance at ungauged locations, under the conditions that model calibration may be carried out at larger spatial scales (the scale of the parent basins).

Inspection of results reported in Table 3b the interior gauges by using transposition of model parameters shows that efficiencies are generally degraded. Comparing overall efficiency computed on the whole simulation period shows that the coefficient of efficiency decreases by 23%, from 0.74 to 0.57. Note that results obtained by calibrating the model on interior gauges, which are not reported here for the sake of brevity, show that score statistics obtained on interior basins are within the range of those of parent basins. Ranking of efficiencies is not always respected when moving from parent to interior points: efficiency of model application at interior points with high (low) parent efficiency, is not always high (low). For instance, Rio Freddo at Valoje (10) is characterised by the lowest efficiency (0.40), whereas the parent (Posina at Stancari, (3)) has the highest efficiency (0.86). This may be due to the effect of the karstified aquifer, which influences Rio Freddo more significantly than its parent. The bias (both high and low) is also inflated when moving from parent to interior points.

In spite of these observations, it is interesting to note that for three interior basins efficiency is larger than 0.6. This supports the view than transposing parameters from a donor to a similar catchment has the potential to ensure reasonable performances in regionalisation efforts, even at the hourly time step used in this study.

**Ungauged basins: model parameter and model soil moisture status transposition**

With this strategy, FFG values are obtained at interior sites based on transposing both model parameters and soil moisture status from the parent basin. This implies that the model is run based on input data (precipitation and temperature) for the parent basin. This methodology has obvious advantages in terms of operational implementation, by reducing computational efforts to obtain FFG at several interior sites. The model is run only at the level of the parent basin, and FFG computations are carried out for the specific interior sites. On the other hand, the quality of the model-based soil moisture status estimates obtained in this way may be altered. Biases in rainfall and temperature accumulate over weeks and months and soil moisture status are not as accurate as those obtained by running the model over the specific interior basins.

**Fig. 3** shows one year of simulation results at the outlet for the Cordevole basin at Vizza. **Fig. 3a** shows simulation results with model parameter transposition from Cordevole at Saviner, whereas **Fig. 3c** shows simulation results with model parameter and soil moisture status transposed from Cordevole at Saviner simulation residuals. **Fig. 3b** and d reports simulation result in the two cases, respectively. These figures show that for this basin the two approaches yield hydrologically acceptable representations of the watershed behaviour. At this scale, the two hydrographs appear visually similar. Only small differences can be seen, e.g. model with parameter transposition is biased low during the autumn floods (October), whereas model with parameter and soil moisture status is biased high during the same period.

### Table 3b  Model validation results

<table>
<thead>
<tr>
<th>Interior points</th>
<th>Parameter transposition</th>
<th>Parameter and soil moisture transposition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{NS}$</td>
<td>RB (%)</td>
</tr>
<tr>
<td>6</td>
<td>0.64</td>
<td>-4.3</td>
</tr>
<tr>
<td>7</td>
<td>0.46</td>
<td>-8.1</td>
</tr>
<tr>
<td>8</td>
<td>0.69</td>
<td>1.4</td>
</tr>
<tr>
<td>9</td>
<td>0.65</td>
<td>-6.2</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
<td>9.3</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interior points.
Figure 3  One year (01.10.1992–30.09.1993) of hourly results at the outlet for the Cordevole river at Vizza: (a) simulation results with model parameter transposition from Cordevole at Saviner; (b) simulation residuals; (c) simulation results with model parameter and soil moisture transposition from Cordevole at Saviner; (d) simulation residuals and (e) relative soil moisture content of the PDM storage obtained from model parameter transposition at Vizza and from model simulation at Saviner.
Fig. 3e shows relative soil moisture content of the PDM storage obtained from model parameter transposition at Vizza and from model simulation at Saviner. This figure shows clearly that there is a large difference between the two soil moisture statuses during the period from October, when snow accumulation starts on the basin, to late March when snowmelt begins. This difference is due to the different impact that solid precipitation has on the hydrological behaviour. For Vizza, almost all precipitation after October fall in solid phase, providing negligible input to the soil moisture store. On the contrary, on the lower basin closed at Saviner most of the precipitation falls in liquid form and feeds the PDM storage. However, this bias has apparently a negligible impact on the simulation of the summer and fall floods, since the hydrological status of the two basins is reset during snowmelt. A smaller bias can be identified during the summer period, this being explained by the different precipitation and evaporation accumulations on the two basins.

Inspection of Table 3b shows that transposition of both model and soil moisture status values parameters is associated to a further slight degradation of efficiency (from 0.57 to 0.53) and to a large inflation of bias, with RB values up to 18.2%. This is clearly an effect of using biased soil moisture values in the model framework.

**FFG assessment**

Assessment of the quality of flash flood warnings based on FFG estimates is obtained by using contingency tables. Contingency tables are highly flexible methods that can be used to estimate the quality of a deterministic forecast system (Mason and Graham, 1999) and, in their simplest form, indicate its ability to anticipate correctly the occurrence or non-occurrence of predefined events. A four-cell contingency table can be constructed which depicts the relationship between the forecasts and the events. Consider a set of forecasts that can have only two alternatives (e.g., yes, no) (Table 4). Let:

- \(X\) denote the number of positive forecasts that correspond to an occurrence of the event (hits),
- \(Y\) denote the number of events that occurred in conjunction with a negative forecasts (missed events),
- \(Z\) denote the number of positive forecasts that were not accompanied by an event (false alarms), and
- \(W\) denote the number of negative forecasts that did not have any associated events.

Three statistics can be used to summarise the contingency table. The probability of detection (POD) is the ratio of correctly forecasted events to the total number of events:

![POD equation]

The range of values for POD goes from 0 to 1, the latter value being desirable. A POD of one means that all occurrences of the event were correctly forecast.

The false alarm rate (FAR) is the ratio of the number of false alarms to the total number of predicted events:

![FAR equation]

The range of values for FAR goes from 0 to 1, the former value being desirable. A FAR of zero means that in the verification sample, no non-occurrences of the event were forecast to occur.

Neither POD nor FAR can give a complete picture of forecasting success; it is therefore desirable to include a statistic depending on both POD and FAR. This is the critical success index (CSI) (Schaefer, 1990; Wilks, 1995). The CSI is the ratio of correctly forecasted events to the total number of event forecasts that were either made \((X + Z)\) or needed \((Y)\):

![CSI equation]

For either a zero POD or a unit FAR, the value of CSI is uniquely equal to zero, since there are no hits. The range of values for CSI goes from 0 to 1, the latter value being desirable.

Results obtained from the threshold-based methodology are compared with corresponding results from two alternatives methodologies. With the first alternative, FFG is contrasted with the temporal-detailed hydrological model (Model, hereafter). This provides the study with an evaluation of the assumption of time-uniform rainfall implied by the FFG. Scores statistics are obtained by comparing streamflow predicted by the model with the observed events, for each day, in terms of exceedance of the flooding threshold.

With the second alternative, FFG is contrasted with use of a time-constant soil moisture status as an input to the threshold-based flash flood warning system. This alternative is representative of time-constant depth-durations precipitation thresholds (Constant, hereafter). These constant depth-duration precipitation values are derived by setting the values of the model soil moisture status to those corresponding to the annual average discharge value. Assessment of this procedure allows the study to evaluate the degradation of accuracy associated to the loss of information about the temporal variation of antecedent soil moisture status.

The assessment strategy comprises therefore three different procedures for model implementation, three different procedures for FFG assessment, and two threshold flooding conditions. FAR and POD scores are reported for each basin in Fig. 4a–c, for (i) gauged (parent) basins, (ii) ungauged (interior) points with model parameters transposition, and (iii) ungauged (interior) points with model parameter and soil moisture status transposition, respectively. For each type of model application, the three different strategies of FFG assessment and the two flooding thresholds are considered. Corresponding CSI values are reported in

---

**Table 4** Four-cell contingency table used in the study

<table>
<thead>
<tr>
<th>Events</th>
<th>Forecasts</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>X</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Z</td>
<td>W</td>
<td></td>
</tr>
</tbody>
</table>

---
Figure 4  Evaluation of the threshold-based technique for: (a) parent basin with model calibration; (b) interior basins with model parameter transposition and (c) interior basins with both model parameter and soil moisture status transposition. POD and FAR scores are plotted.
Fig. 5a–c, which report scatter plot of CSI values from FFG versus CSI values obtained from model application and use of constant threshold.

**Gauged basins: model parameter calibration**

Results reported in Fig. 4a with application of the flash flood guidance shows that good results are generally obtained for the high flooding threshold (HT). In this case, POD is always higher than 0.6, and FAR is less than 0.5 (with the exception of Brenta, with FAR equal to 0.72). For two basins (Posina at Stancari (3) and Ridanna (5)), POD is larger than 0.64 and FAR is less than 0.19. Performances are slightly degraded for some basins when using the low flooding threshold (LT). This is the case for Posina (3) and Ridanna (5), with an increase of FAR, and for Cordevole (2), with a decrease of POD. However, this does not occur for the Loire (1) and for Brenta at Borgo (4). Inspection of model simulations (not reported here) shows that this is an effect of modelling uncertainties of relatively small rain-on-snow events during the snowmelt season. As such, these effects have more impact on basins more affected by snow-related processes. The influence of these events is larger for the LT scenario than for the HT scenario.

Comparison of score statistics obtained by using the FFG with those resulting from direct model application shows a slight degradation of system performance. This provides an indication that the use of time-uniform rainfall in the FFG context has a limited impact on forecast accuracy, at least for the parent basin. CSI values in Fig. 5a for Model application range between 0.4 and 0.8, whereas corresponding values for FFG range between 0.22 and 0.7. It is interesting to note that the CSI ranking is very similar to the ranking of the same basins in terms of model efficiencies, with Posina (3) and Ridanna (5) ranking high and Loire (1) and Brenta (4) ranking low. This means that, as expected, high (low) efficiency in model application translates into high (low) CSI values.

System performances degrade considerably when a constant depth-duration precipitation threshold is used. In this case, POD is always less than 0.6, and FAR may be as high as one. CSI values are less than 0.4, with most of the basins comprised between 0 and 0.3. This shows, as expected, that information on antecedent soil moisture status is essential for flash flood forecasting in these humid to medium climate basins.

**Ungauged basins: model parameter transposition**

Results reported for the interior points by using transposition of the model parameters from the parent basins show that the variability in performances increases considerably among the various basins, with respect to the case of parent basins. Whereas this may be due to differences between parent and interior basins, we note here that absence of local calibration may introduce random error and bias which translate into inflated variability in performances between basins. For two interior basins (Dunières (7) and Brenta at Levico (11)) CSI is rather low, with values less than 0.3 for both FFG and Model. One of these basins, Dunières, ranks low also in terms of model efficiency. The three basins

![Figure 5](image)

**Figure 5** Evaluation of the threshold-based technique for: (a) parent basin with model calibration; (b) interior basins with model parameter transposition and (c) interior basins with both model parameter and soil moisture status transposition. CSI scores are plotted.
which rank high in terms of model efficiency (Cordevole at Vizza (8), Posina at Bazzoni (9) and Gagne (6)) have also relatively high CSI. In general, CSI at interior points with high (low) parent CSI, is also high (low).

Basin size and climate have apparently no impact on CSI. Medium size basins, characterised by humid and medium climate, may exhibit high (Gagne (6) and Posina at Bazzoni (9)) and low (Brenta at Levico (11) and Dunières (7)) CSI values. A small size basin like Cordevole at Vizza (8) range in between these two extremes.

For interior points, results obtained from FFG are generally comparable with those obtained the model, as already observed for parent basins. However, one exception can be noted: Cordevole at Vizza (8). This interior points have the smallest catchment area compared to the other basins. Since small spatial scale implies reduced response times, this means that safe implementation of the FFG concept, as described in this study, may be limited by scale considerations, at least with comparison to model application.

As observed for parent basins, CSI degrades markedly when using a constant depth-duration precipitation threshold.

Ungauged basins: model parameter and soil moisture status transposition

Use of soil moisture status transposition from parent basins (added to use of parameter transposition) produces a remarkable deterioration of system performance with respect to parameter transposition, as can be noted in the CSI plots. This is due to the biased character of these estimates, which are obtained by using estimates of precipitation and temperature from the parent basins.

Even in this case, it is observed that CSI degrades markedly when using a constant depth-duration precipitation threshold. This suggests that even a poor estimate of temporal variability of soil moisture, as the one derived from the parent basins, may improve markedly above the condition of no-information on antecedent soil moisture status.

Overall score statistics

Analysis of results reported in the previous sections show that score values obtained for the high flooding threshold exhibit always more dispersion than corresponding scores obtained for the low threshold. This is clearly an effect of the sampling problem which arise in these computations. Use of a high flooding threshold generally results in the analysis of a small sample of events which may prevent reliable characterisation of the system performance. Lowering the threshold incorporates more events into the analysis, hence mitigating the sampling problem. However, this choice exposes one to the risk of including small flood events which are not representative of the dynamics under study. To increase reliability of high threshold statistics, we analyse overall score statistics computed on all the considered basins. Overall score statistics are computed based on one overall contingency table generated from all basins considered in the study. The overall score statistics are reported in Figs. 6 and 7, for POD/FAR and CSI, respectively.

For parent basins and the high threshold, FFG is characterised by a POD of 0.76 with FAR of 0.48. In this case, CSI is equal to 0.43. Note that CSI increases to 0.55 by removing the basin of Brenta at Borgo, influenced by lake and karst effects (which are difficult to describe accurately with the hydrological model). For interior basins and high threshold, with parameters transposed by parent basins, POD increases...
to 0.85, but at the expenses of increasing FAR to 0.68. The overall CSI is equal to 0.28, in this case. This shows that the deterioration of performances following application of FFG to ungauged basins (with parameter transposition) is not negligible, and amounts to 35% (assuming that overall system performances on parent basins is comparable to the one that would have been attained on interior basins, in the case of model parameter calibration). However, one should note that CSI increases to 0.51 when removing the interior point of Brenta at Levico, which is heavily influenced by lake effects.

For interior basins, with parameters and soil moisture status transposed by parent basins, POD reduces to 0.64, while FAR increases to 0.73. The overall CSI is equal to 0.22 in this case and shows a decrease of 21% with respect to the case of parameter transposition.

Differences between FFG and direct model application are rather modest, and decrease with decreasing the accuracy of model application. The percent difference amounts to 18% for the parent basins, to 15% for interior basins with parameter transposition, and to 12% for interior basins with parameter and soil moisture status transposition. This is not unexpected, showing that the impact on system performances due to the use of time-uniform precipitation reduces when other sources of uncertainties, related to lack of calibration and biases in the soil moisture estimations, become more significant.

Performance differences between FFG and use of constant depth-duration precipitation threshold are very high for the parent basins and decrease with decreasing the model accuracy. The percent difference amounts to 53% for the parent basins, to 25% for interior basins with parameter transposition, and to 19% for interior basins with parameter and soil moisture status transposition.

It is noted that differences between results obtained for the high and the low threshold are relatively low for the case of parent basins and for interior basins with parameter transpositions. These differences become comparable to those which arise among the various procedures for the case of model parameter and soil moisture status transposition.

Conclusions and future work

A threshold-based flash flood warning approach, based on the FFG method, has been developed and tested on a wide range of climatic and physiographic conditions, and by focusing on ungauged basins. The FFG is the depth of rain of a given duration, taken as uniform in space and time on a certain basin, necessary to cause minor flooding at the outlet of the considered basin. This rainfall depth, which is computed based on a lumped hydrological model, is compared to either real-time-observed or forecasted rainfall of the same duration and on the same basin. If the nowcasted or forecasted rainfall depth is greater than the FFG, then flooding in the basin is considered likely.

The study investigates the efficiency of the method when the simulation parameters can not be calibrated but must be transposed from parent gauged basins to ungauged basins, and the sensitivity of the results to the method used to estimate the initial soil moisture status. System performances are evaluated by means of categorical statistics, such as the critical success index (CSI), based on data from 11 basins (six nested included in five larger parent basins) located in two European regions: north-eastern Italy and central France. The model used in this study is a semi-distributed conceptual rainfall–runoff model, following the structure of the PDM (probability distributed moisture) model.
Comparison of score statistics obtained by using the FFG with those resulting from direct model application shows a slight degradation of system performance. Differences between FFG and direct model application are rather modest, and decrease with decreasing the accuracy of model application. The percent difference amounts to 18% for the parent basins, to 15% for interior basins with parameter transposition, and to 12% for interior basins with parameter and soil moisture status transposition. This is not unexpected, showing that the impact on method performances due to the use of time-uniform precipitation reduces when other sources of uncertainties, related to lack of calibration and biases in the soil moisture estimations, become more significant.

Comparison of FFG application over gauged and ungauged basins shows that the overall CSI decreases from 0.43 over the parent basins, where the hydrological model has been calibrated, to 0.28 for the interior basins, where model parameters are transposed from parent basins. This shows that the deterioration of performances following application of FFG to ungauged basins (with parameter transposition) is not negligible, and amounts to 35% (assuming that overall system performances on parent basins is comparable to the one that would have been attained on interior basins, in the case of model parameter calibration). This deterioration of performances is likely due to the complex orography of the study catchments and its associated large hydrologic variability. However, since the complex orography is one of the influencing flash flood triggering factors, it is important to develop further parameter regionalisation methods which can be used for FFG estimation.

Results reported in this study show that there still exists potential for improving the regionalisation methods by identifying more relevant physiographic controls. However, one should note that the overall CSI exceeds 0.5 for both gauged and ungauged basins when removing from the assessment a single basin. This basin is heavily influenced by lake and karst effects, which are difficult to describe accurately with the model used in this study. These scores are encouraging and show promise for operational applications in flood warning systems, with focus on ungauged basins.

For interior basins, with parameters and soil moisture status transposed by parent basins, CSI reduces to 0.22 and shows a decrease of 21% with respect to the case of parameter transposition.

Performance differences between FFG and use of constant depth-duration precipitation threshold are very high for the parent basins and decrease with decreasing the model accuracy. The percent difference amounts to 53% for the parent basins, to 25% for interior basins with parameter transposition, and to 19% for interior basins with parameter and soil moisture status transposition. This suggests that even a relatively poor estimate of temporal variability of soil moisture, as the one derived from the parent basins, may improve markedly above the condition of no-information on antecedent soil moisture status.

Overall, these results show clearly that improving the performance of the FFG system on ungauged basins hinges on the improved representation of the hydrological system dynamics (i.e., better parameter regionalisation) for the accurate representation of the initial soil moisture conditions. On one hand, this can be achieved by improving parameter regionalisation methods or by developing spatially distributed approaches to the problem of FFG estimation. On the other hand, improvements could be expected by additional work on real-time updating of model status. A natural choice would be to adjust the catchment soil moisture status by making use of runoff data in a real-time mode. The rationale of this is that runoff is usually an excellent indicator of the catchment soil moisture state. An updating method widely used is the Kalman Filter which consists of weighting measurements and simulation, the weight (or Kalman gain) being a function of the measurement error and the model error (Da Ros and Borgia, 1997b). Additional work should focus on the value of real-time updating for ungauged basins (i.e., by transposing updated soil moisture status to interior points) and at various spatial scales.

Acknowledgments

This work was supported by the European Community’s Sixth Framework Programme through the Grant to the budget of the Integrated Project FLOODsite, Contract GOCE-CT-2004-505420 and in part by the STREP Project HYDRATE, Contract GOCE 037024. The Direction Régionale de l’Environnement de la Région Centre and the Etablissement Public Loire kindly provided the data for the Loire river basin. Data for the Adige and Brenta river systems were kindly provided by Provincia Autonoma di Bolzano — Ufficio Idrografico and by Provincia Autonoma di Trento — Servizio Bacini Montani, respectively. ARPA – Regione Veneto kindly provided the data for the Bacchiglione and Piave river systems. In addition, the writers extend their thanks to three unknown reviewers for making important suggestions that improved the text.

References


