Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood

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Summary The main objective of the study is to characterize the severity of a flash flood generating storm occurred on August 29, 2003 on the upper Tagliamento river basin, in the eastern Italian Alps. This storm was characterized by extraordinary rainfall amounts and large spatial variability. Regional frequency analysis based on the index variable method and L-moments is utilized to analyse short duration annual maximum precipitation for the Friuli-Venezia Giulia region, in north-eastern Italy, which includes the storm location. It is shown that the regional growth curves based on the Kappa distribution may be useful for the subregions specified. This analysis provides a framework to investigate the frequency characteristics of the August 29, 2003 flash flood generating storm for various rainfall durations. Radar rainfall estimates, adjusted by using a physically-based methodology and data from a raingauge network, are used to characterize the return period of the storm rainfall amounts, highlighting the importance of considering its spatial dimension. Severity graphs are developed to visualise the return periods and their variability for different rainfall durations within the storm. It is shown that adjusted radar rainfall estimates may suffer for considerable uncertainty and that the uncertainty magnifies in the evaluation of the relevant return periods. The analysis shows also that (i) attributing a single return period to a storm event is not realistic, and (ii) the severity of flash flood generating storms is poorly captured by using conventional raingauge networks. The reported results show that estimates obtained by using careful adjustment of radar observations may be useful to evaluate the severity of the storm for ungauged basins and to evaluate the spatial dimension of the frequency characterization.

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Introduction

A common problem in ex-post flood risk analysis is that of estimating the rarity of events such as extreme floods or precipitation. Design, implementation and operation of measures and instruments for effective and sustainable flood risk reduction require knowledge of the flood risk mitigation system under extreme events. The evaluation of the extreme flood events is therefore an important basis for learning processes during ex-post evaluation of interventions in support of future development of strategies and strategic options in flood risk management. Due to the scarcity of discharge data for flash flood events, rainfall frequency estimates are often used to describe the characteristics of a flood event. In these cases, the return period of the greatest point rainfall intensity within the storm is taken as the return period of the storm (Ramos et al., 2005). However, lack of reliable raingauge coverage frustrates the hazard characterization of flash flood generating storms, which develop at space and time scales that conventional rain observation system are not able to monitor (Creutin and Borga, 2003). Radar observations have large potential to improve the monitoring of flash flood generating storms. In the last decade, several studies have shown that adjusted radar rainfall estimates, corrected for the dominant observation error sources, may be used for flood and flash flood analysis (Borga et al., 2000; Borga, 2002; Gaume et al., 2004; Delrieu et al., 2005; Borga et al., 2007). It is therefore interesting to evaluate the feasibility of using adjusted radar observations for hazard characterization of flash flood generating storms. This study focuses on the use of both regional frequency analysis and radar rainfall observations to assess return periods for an extreme flash flood-producing storm for various rainfall durations.

On August 29, 2003, an extreme storm and flood occurred on the 600-km² wide Fella watershed, a tributary of the Tagliamento river basin in the eastern Italian Alps. Rainfall produced by the August 2003 storm resulted in severe flooding throughout the Fella river basin. The storm produced catastrophic flooding at drainage areas up to 80–90 km², with dominance of debris floods at basin scale up to some tens of km². The flash flood led to the death of two people and caused damages for almost 1 billion Euro (Borga et al., 2007). Most of the basins hit by the flood are not instrumented with a raingauge network. Radar rainfall estimates, adjusted by using a physically-based methodology and data from a raingauge network, are used to characterize the return period of the storm rainfall amounts, highlighting the importance of considering its spatial dimension.

Regional frequency analysis methodology

Frequency analysis of extreme storms usually implies extrapolations well beyond the range of the available at-site data. Regional frequency analysis is therefore used to provide a framework for hazard characterization of these extremes. The regionalization concept, introduced by Dalrymple (1960), “trades space for time” by using data from nearby or similar sites to estimate quantiles of the underlying variable at each site in the homogenous region of consideration (Stedinger et al., 1993). The concept was continuously developed since, and new approaches were regularly developed by researchers (e.g. Benson, 1962; Matras and Gilroy, 1968; Vicens et al., 1975; National Environment Research Council (NERC), 1975; Greiss and Wood, 1981; Rossi et al., 1984; Hosking et al., 1985; Lettenmaier et al., 1987; Burn, 1990; Buishand, 1991; Stedinger and Lu, 1995; Hosking and Wallis, 1997; Reed et al., 1999; Sveinson et al., 2001; Koutsoyiannis, 2004). A common method for pooling summary statistics from different sites is the index variable procedure, referred to also as the “index flood” from early studies (Dalrymple, 1960) that used flood data when implementing the procedure. The main assumption of an index variable procedure is that the sites in a homogeneous region have an identical frequency distribution apart from a site-specific scaling factor, the index variable. The index variable is usually the mean of the site-specific data (Hosking and Wallis, 1997). Regional analysis involves the following steps: (i) identification of the region, i.e. the sites that belong to the region, and testing whether the proposed region is homogeneous, (ii) choice of the distribution to fit the regional data, and (iii) estimation of parameters and quantiles.

Cunnane (1988) reviewed twelve different methods of regional frequency analysis and rated a regional algorithm based on probability weighted moments (PWMs) as the best one. PWMs were introduced by Greenwood et al. (1979). Hosking (1986, 1990) defined L-moments as a linear combination of PWMs. L-moments are less influenced by the effects of sampling variability than conventional moments and can in some cases yield more efficient parameter estimates than other estimation methods, such as the method of maximum likelihood or the conventional product moments method. Schaefer (1990) developed a regional procedure for annual maximum rainfall of the state of Washington based on L-moments and two regression curves relating the coefficient of variation and the coefficient of skewness of the data to mean annual precipitation.

The methodology used here for deriving rainfall quantiles for the Eastern Italian Alps is an index variable regional frequency analysis approach as outlined by Hosking and Wallis (1997) (called “HW methodology” hereinafter) and based on annual maximum data. The procedure assumes that sites from a homogeneous region have an identical frequency distribution apart from a site-specific scaling factor represented by the mean of the site-specific data. Three models based on this methodology are considered: a generalized extreme value (GEV) distribution, a generalized logistic (GLO) distribution and a Kappa distribution. Analogously to the usual method of moments, the method of L-moments obtain parameter estimates for a p-parameter probability distribution by equating the first p sample L-moments to the corresponding population quantities. Hence, the parameters of the three-parameter distributions (GEV, GLO) and of the four-parameter distribution (Kappa) are obtained by using the first three and four sample L-moments, respectively (Hosking, 1990; Hosking and Wallis, 1997). The relationships for parameter estimations are reported in the following sections. In the following, $r$ indicates the L-CV of a frequency distribution, while $\lambda_r$ and $r_r$ indicates the rth L-moment and the rth L-moment ratio of a frequency distribution, respectively.
Parameter estimation for GEV distribution

The CDF of the generalized extreme value (GEV) distribution with parameters $x$ (location), $\beta$ (scale) and $\kappa$ (shape) is given by

$$F_X(x) = \exp \left\{ -\left[ 1 + \frac{\kappa}{\beta} (x - x) \right]^{1/\kappa} \right\}, \text{ if } \kappa \neq 0,$$

(1)

where $x + \beta/k < x < \infty$ if $\kappa < 0$ and $-\infty < x < x + \beta/k$ if $\kappa > 0$.

The quantile estimate is then

$$x_q = x + \beta \left\{ 1 - \left[ 1 - q \right]^{1/\kappa} \right\}, \text{ if } \kappa \neq 0.$$

(2)

The shape parameter $\kappa$ is estimated numerically from the L-skewness relation

$$t_3 = -3 + \frac{2(1 - 3^{-n})}{(1 - 2^{-n})},$$

(3)

with relative accuracy better than $9 \times 10^{-4}$ for $-0.5 \leq t_3 \leq 0.5$ using (Hosking and Wallis, 1997)

$$\kappa = 7.8590C + 2.944C^2,$$

(4)

where $C = 2/(t_3 + 3) - \ln 2/\ln 3$ and $t_3$ = sample L-skewness.

Given an estimate of $\kappa$, estimates of $\beta$ and $\alpha$ are obtained from

$$\beta = \frac{\lambda_q \kappa}{(1 - 2^{-\beta})} \Gamma(1 + \kappa),$$

$$\alpha = \lambda_1 + \frac{\beta}{\kappa}\left[ 1 - \Gamma(1 + \kappa) \right],$$

where $\Gamma(.)$ = gamma function.

Parameter estimation for GLO distribution

The CDF of the generalized logistic (GLO) distribution with parameters $x$ (location), $\beta$ (scale) and $\kappa$ (shape) is given by

$$F_X(x) = \frac{1}{1 + \exp \left\{ \kappa \cdot \log \left[ 1 - \kappa (x - x) / \beta \right] \right\}}, \text{ if } \kappa \neq 0,$$

(6)

where $x + \beta/k < x < \infty$ if $\kappa < 0$ and $-\infty < x < x + \beta/k$ if $\kappa > 0$.

The quantile estimate is then

$$x_q = x + \beta \left\{ 1 - \left[ 1 - q \right]^{1/\kappa} \right\}, \text{ if } \kappa \neq 0.$$

(7)

The parameters are estimated using L-moments as follows:

$$\kappa = -t_3,$$

$$\beta = \frac{\lambda_2 \sin \kappa \pi}{\kappa \pi},$$

$$\alpha = \lambda_1 - \beta \left[ 1 - \frac{\pi}{\sin \kappa \pi} \right].$$

(8)

Parameter estimation for Kappa distribution

The CDF of the Kappa distribution with parameters $x$ (location), $\beta$ (scale), $\kappa$ and $h$ is given by

$$F_X(x) = \left\{ 1 - h \left[ 1 - \frac{\kappa (x - x)}{\beta} \right]^{1/n} \right\}^{1/h},$$

(9)

where $x + \beta/k < x < \infty$ if $\kappa < 0$ and $h < 0$. The quantile estimate is then

$$x_q = x + \frac{\beta}{\kappa} \left\{ 1 - \left[ 1 - \frac{q}{h} \right]^{1/n} \right\}, \text{ if } \kappa \neq 0 \text{ and } h \neq 0.$$

(10)

To enable the four-parameters of the distribution to be estimated from the first four L-moments, the parameter space must be restricted, so that only one set of parameters corresponds to a given set of the first four L-moments. This corresponds to the following conditions on the parameters (Hosking, 1994):

(a) $\kappa > -1$;

(b) if $h < 0$, then $\kappa \cdot h > -1$;

(c) $h > -1$;

(d) $\kappa + 0.725h > -1$.

Conditions (11a) and (11b) ensure the existence of the L-moments; conditions (11c) and (11d) ensure the uniqueness of the parameters, given the four L-moments. No explicit equations are available for the determination of the parameters based on the L-moments. However, Hosking (1996) provided a Newton–Raphson algorithm for the determination of $\kappa$ and $h$ in terms of $t_3$ and $t_4$. This procedure is used here for parameter estimation.

The four steps of the HW regional frequency analysis methodology

The HW regional frequency analysis is articulated into four steps: (i) screening of the data, (ii) testing of regional homogeneity, (iii) identification of the regional distribution, and (iv) development of regional storm frequency relationships for gauged and ungauged sites. Since these procedures are presented in detail by Hosking and Wallis (1997), only a summary is reported below.

Screening of data using discordancy measure test

The first step in the procedure is to test for gross outliers, inconsistencies, shifts, and trends. Furthermore, a discordancy measure (Hosking and Wallis, 1997) is used to identify those sites from a group of given sites that are grossly discordant with the group as a whole. The discordancy measure is a single statistic based on the difference between the L-moment ratios of a site and the average L-moment ratios of a group of similar sites. This statistic can also be used to identify erroneous data. The discordancy measure is useful only for regions with $N \geq 7$. A site is declared to be discordant if the discordancy measure is large and the definition of large depends on the number of sites in the group. Thus a site is regarded as discordant if the measure exceeds the critical value given in tabular form (Hosking and Wallis, 1997).

Identifying homogeneous regions

The purpose of this step is to form groups of stations that satisfy the homogeneity condition—that is, stations with frequency distributions that are identical apart from a station-specific scale factor. A heterogeneity measure called the $H$-statistic is then used to compare the between site variation in sample L-moments for a group of sites with
Figure 1  Location of the study area with DTM of North-Eastern Italy. The locations of the raingauge stations used in the study are also reported.

Figure 2  a–c: Maps of point average of maximum yearly rainfall for durations of (a) 1 h, (b) 6 h, and (c) 24 h, for the Friuli region.
what would be expected for a homogeneous region (Hosking and Wallis, 1997). To determine what would be expected, repeated Monte Carlo simulations of a homogeneous region with sites having record lengths equal to those of the observed data are performed. A large positive value of the $H$-statistic indicates that the observed L-moments ratios are more dispersed than is consistent with the hypothesis of homogeneity.

There are three measures of the $H$-statistic. The first, $H(1)$, is the standard deviation, weighted according to record length, of the at-site L-CVs. The second measure, $H(2)$, is the average distance from the site coordinates to the regional average on a plot of L-CV versus L-skewness. The third measure, $H(3)$, is the average distance from the site coordinates to the regional average on a plot of L-skewness versus L-kurtosis. In this work, heterogeneity is tested using $H(1)$ and $H(2)$ because the L-CV and L-skewness are required for fitting pooled growth curves with a GEV or GLO. Note, however, that Hosking and Wallis (1997) found that $H(2)$ is a weaker test of heterogeneity than $H(1)$. A region is declared ‘acceptably homogeneous’ if $H < 1$, ‘possibly heterogeneous’ if $1 < H < 2$, and ‘definitely heterogeneous’ if $H > 2$ (Hosking and Wallis, 1997). The heterogeneity measure $H(2)$ is used also by the FEH (Institute of Hydrology, 1999). According to the FEH, a region is said to be heterogeneous if $2 < H(2) \leq 4$; it is described as strongly heterogeneous if $H(2) > 4$.

Identifying a robust regional frequency distribution

Regional frequency analysis requires determining the underlying probability model of the variable under consideration. For this purpose, a number of goodness-of-fit techniques are available in the literature. In our study, we compare the relation of L-Kurtosis versus L-Skewness for various commonly used distributions duration with the corresponding relations obtained from the at-site and regional data. Furthermore, we use the $Z$-statistic introduced by Hosking and Wallis (1997). This statistic was developed for three-parameter distributions and measures how well the theoretical L-kurtosis of the fitted distribution matches the regional average L-kurtosis of the observed data. The fit of the distribution is considered satisfactory if $|Z| \leq 1.64$, corresponding to an acceptance of the hypothesised distribution at a confidence level of approximately 90% (Hosking and Wallis, 1997).

Data analysis and results

The region considered in this study (Fig. 1) includes a portion of the central chain of eastern Alps and the Alpine foreland region. The arc-shaped mountainous range of the eastern Alps constitutes the major topographic feature within the analysis domain. The most prominent valleys are aligned along the main ridge in the west–east direction for some tens of kilometres. The area is included within the Friuli-Venezia Giulia region, which borders to the north with Austria, to the east with Slovenia and to the west with Veneto. The region is characterized by three distinct pluviometric regimes: (i) the upper plain area, with mean annual precipitation (herewith called MAP) ranging from 1200 to 1500 mm; (ii) the Alpine foreland area, where MAP increases up to 3300 mm, which represents the highest mean values for the Alps; (iii) the inner Alpine area, where MAP decreases to 1600–1800 mm, due to rain shadow effect of the southern ridges.

Daily rainfall amounts exceeding 500 mm may be locally recorded in this area in a 20–30 years time span (Villi et al., 1986; Ceschia et al., 1991). For instance, 617 mm and 543 mm daily precipitation were recorded in Oseacco, close
to Moggio Udinese, on October 9, 1933 and on November 14, 1969, respectively. During late fall, winter and spring, heavy precipitations are normally related to synoptic circulations and to southerly humid flows. During summer and partially during fall, the contribution from convective or mesoscale rainfall becomes significant or even prevailing. Due to the rugged topography of the region, together with its densely fractured bedrock and its high seismicity (Querini, 1984), heavy convective precipitations result often in flash floods, associated to diffused landsliding, debris flows and sediment transport.

The total number of stations used in the analysis is 63 with an average usable record length of 51 years. The screening procedure using discordancy measure was implemented to identify gauges the sample statistics of which were markedly different from the majority of gauges. The test based on discordancy measures was repeated both at the regional and at the subregional level, according to the regional subdivision reported below. Suspicious gauges and data were checked to verify the validity of records. This led to remove 6 stations, which included data clearly erroneous.

### Spatial mapping of at-sites means

The spatial mapping of the at-site means has been carried out by using the multiquadratic surface fitting technique (Borga and Vizzaccaro, 1997). Results are reported in Fig. 2 for duration of 1-, 6- and 24-h. The maps show clearly

<table>
<thead>
<tr>
<th>Duration</th>
<th>Subregion A</th>
<th>Subregion B</th>
<th>Subregion C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_1$</td>
<td>$H_2$</td>
<td>$H_1$</td>
</tr>
<tr>
<td>1</td>
<td>0.22</td>
<td>0.64</td>
<td>1.58</td>
</tr>
<tr>
<td>3</td>
<td>1.61</td>
<td>-0.32</td>
<td>1.89</td>
</tr>
<tr>
<td>6</td>
<td>2.44</td>
<td>0.53</td>
<td>-0.09</td>
</tr>
<tr>
<td>12</td>
<td>2.37</td>
<td>1.29</td>
<td>0.08</td>
</tr>
<tr>
<td>24</td>
<td>1.34</td>
<td>-0.52</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Values exceeding the heterogeneity threshold ($H = 2$) are marked in bold.

**Figure 4** a–c: Identification of subregional frequency distribution using regional L-skewness L-kurtosis diagram: (a) Subregion A; (b) Subregion B; (c) Subregion C. Notation: GEV: generalized extreme value; GLO: generalized logistic; PE3: Pearson type III; LN3: lognormal-3; G: Gumbel.
(i) the relatively high values of these rainfall accumulations, and (ii) the orographic control on the spatial distribution of the average values. It is interesting to note that the highest values for 6-h duration are located on the Alpine foreland area, while for 1-h duration high values are also found on the south-eastern coastal plain. The maps reveal also a marked decrease of the average annual precipitation maxima values (for all durations) in the inner Alpine region.

A quantitative measure was required to evaluate the relative accuracy of the spatial estimation procedure. This is difficult in all studies of this type because the true value of the at-site means are unknown, since sample values of the station at-site means will differ from the true population values due to sampling variability. Therefore, this problem was approached by cross-validating estimates obtained by the interpolation technique against the actual observed

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**Figure 5**  
*a–e: Subregion C growth curves for Kappa, GLO and GEV distributions compared with regional normalised sample for five durations: (a) 1 h, (b) 3 h, (c) 6 h, (d) 12 h and (e) 24 h. Normalised data marked in bold result from the storms of August 29, 2003, June 22, 1996 and September 11, 1983.*
ones. We used a leave-one-out cross-validation procedure, which is the limiting case and probably best form of the Jackknife validation (Miller, 1974). With this procedure, the interpolation technique is used to produce an estimated value at each of the observation locations using data only from the other stations. The accuracy of the surface fitting technique has been evaluated by computing the bias and the RMSE of the standardised residuals

\[
SR_i = \frac{S_i - P_i}{P_i},
\]

where \(S_i\) is the cross-validated estimate and \(P_i\) is the observed value at each site \(i\). Bias range from 0.5% at 1-h duration to 1.1% at 24-h duration; RMSE range from 9.6% at 1-h duration to 13.5% at 24-h duration. The decrease in accuracy with increasing rainfall duration is due to the higher spatial variability of the rainfall fields at longer duration.

**Partitioning the region and estimation of regional growth curves**

The whole region was initially considered as a candidate homogeneous region for the analysis. However, this selection exhibited high heterogeneity measures \(H\) statistics for several durations, suggesting large site-to-site variation in statistics. Thus, this selection was deemed inappropriate for a regional frequency analysis. Orographic differences between the Alpine foreland area and the upper plain area, shadow effect, establishment of orographic convective bands during Mesoscale Convective Systems over the eastern inner Alpine area are all factors influencing the frequency of extreme precipitation. Recognizing that interaction between warm moist air masses from south and south-west direction and orography are major driving force behind rainfall intensity for the considered area, three regions were identified. Hence, the southern plains and the Alpine range are considered as two subregions. In addition, to account for the effects of convective orographic bands over the north-eastern portion of the region, the Alpine range was further subdivided into two subregions depending on aspects. Thus, three subregions are considered (Fig. 3): Subregion A, with 24 stations located in the southern plain region; Subregion B, which includes 21 stations located in the alpine foreland area and the upper Tagliamento basin closed upstream the junction with the Fella; Subregion C, which includes 12 stations within and around the Fella basin. Heterogeneity measures \(H(1)\) and \(H(2)\) are reported for the three subregions in Table 1.

Examination of results reported in Table 1 shows that \(H(2)\) exceeds the heterogeneity threshold only in the Subregion C for rainfall maxima of 12-h. Furthermore, \(H(1)\) exceeds the threshold in Subregion A for durations of 6 h and 12 h. A number of negative values are also found, particularly for \(H(2)\) and for Region B. According to Hosking and Wallis (1997), these indicate that there is less dispersion among the at-site statistics than would be expected of a homogenous region with independent at-site frequency distributions. This is usually an indication of large cross-correlation between the sites’ frequency distributions. Research is ongoing to quantify these effects for the various rainfall durations.

**Table 2** Values of the normalised rainfall maxima exceeding a threshold value of 3.0 for Subregion C

<table>
<thead>
<tr>
<th>Station</th>
<th>1-h</th>
<th>3-h</th>
<th>6-h</th>
<th>12-h</th>
<th>24-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avisacco</td>
<td></td>
<td>-</td>
<td>-</td>
<td>4.47</td>
<td>-</td>
</tr>
<tr>
<td>Moggio Udinese</td>
<td>3.78</td>
<td>-</td>
<td>-</td>
<td>3.83</td>
<td>3.43</td>
</tr>
<tr>
<td>Paularo</td>
<td>3.27</td>
<td>4.0</td>
<td>-</td>
<td>3.54</td>
<td>-</td>
</tr>
<tr>
<td>Pontebba</td>
<td>4.72</td>
<td>4.84</td>
<td>-</td>
<td>3.93</td>
<td>3.51</td>
</tr>
<tr>
<td>Timau</td>
<td></td>
<td>3.36</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Arnoldstein</td>
<td></td>
<td>-</td>
<td>3.17</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The sampling stations and the generating event are reported for each data.

a September, 11, 1983.
b June, 22, 1996.

**Table 3** Z statistic reported for GEV and GLO distribution for the three Subregions and the five durations

<table>
<thead>
<tr>
<th>Duration</th>
<th>Subregion A</th>
<th>Subregion B</th>
<th>Subregion C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GEV</td>
<td>GLO</td>
<td>GEV</td>
</tr>
<tr>
<td>1</td>
<td>-0.88</td>
<td>2.46</td>
<td>-1.29</td>
</tr>
<tr>
<td>3</td>
<td>-0.32</td>
<td>2.44</td>
<td>0.85</td>
</tr>
<tr>
<td>6</td>
<td>-0.39</td>
<td>1.96</td>
<td>-0.95</td>
</tr>
<tr>
<td>12</td>
<td>-0.24</td>
<td>2.27</td>
<td>-1.80</td>
</tr>
<tr>
<td>24</td>
<td>-1.25</td>
<td>1.14</td>
<td>-1.37</td>
</tr>
</tbody>
</table>

For each region and duration, the lower value of goodness-of-fit criterion is marked in bold.

**Table 4** Normalised quantities obtained based on Kappa distribution for various rainfall durations and return periods for Subregion C

<table>
<thead>
<tr>
<th>TR (years)</th>
<th>1-h</th>
<th>3-h</th>
<th>6-h</th>
<th>12-h</th>
<th>24-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.234</td>
<td>1.217</td>
<td>1.207</td>
<td>1.220</td>
<td>1.229</td>
</tr>
<tr>
<td>10</td>
<td>1.486</td>
<td>1.472</td>
<td>1.462</td>
<td>1.459</td>
<td>1.472</td>
</tr>
<tr>
<td>20</td>
<td>1.756</td>
<td>1.766</td>
<td>1.760</td>
<td>1.724</td>
<td>1.731</td>
</tr>
<tr>
<td>50</td>
<td>2.151</td>
<td>2.240</td>
<td>2.254</td>
<td>2.129</td>
<td>2.106</td>
</tr>
<tr>
<td>100</td>
<td>2.486</td>
<td>2.684</td>
<td>2.727</td>
<td>2.489</td>
<td>2.422</td>
</tr>
<tr>
<td>200</td>
<td>2.856</td>
<td>3.220</td>
<td>3.311</td>
<td>2.903</td>
<td>2.768</td>
</tr>
<tr>
<td>1000</td>
<td>3.877</td>
<td>4.944</td>
<td>5.263</td>
<td>4.129</td>
<td>3.710</td>
</tr>
</tbody>
</table>

Results from Table 1 lead to investigate causes for \(H(2)\) being high. For the rainfall duration of 12-h and Subregion C, the plausible cause is the rainfall maximum recorded for the event of August 29, 2003 by the station located in Pontebba. The value of \(H(2)\) for this duration is the most sensitive to the outlier represented by the rainfall depth recorded on August 29, 2003 (as shown by a sensitivity analysis conducted by either including and excluding the 2003 maximum from the evaluation). We retained this value into the analysis, because a representative heterogenous region is better than one that has been made homogeneous by
removing similar sites with unusual rainfall amounts (Hosking and Wallis, 1997).

Fig. 4a–c shows the moment ratio diagrams, L-Skewness versus L-Kurtosis, for the three subregions, where the regional averages of the L-Skewness and L-Kurtosis for the three subregions are plotted together with the L-Skewness - L-Kurtosis relations for different distributions. The average points exhibit a shift towards larger values of L-Skewness and of L-Kurtosis when moving from the plains (Subregion A) to the inner eastern alpine area (Subregion C). This is consistent with the idea that changes in elevation, shadow effect and aspect are reflected in different climatic response, i.e. different extreme rainfall regimes. More than half of the points for all durations lie above the GEV curve, with the Subregion C point for the 6-h lying over the GLO curve. This suggests that either GEV or GLO may provide a good fit to the data, depending on rainfall duration. For instance, in the case of Subregion C the GEV model may be a good choice for 1-h and 24-h, whereas the GLO model may be a better model for the 3-h, 6-h and 12-h data.

The GEV and the GLO are suitable distribution for estimation of precipitation quantiles out to 500-year recurrence interval. If quantiles estimates are desired for more extreme events than the 500-year recurrence interval, it would be worthwhile to refine the selection of the regional probability distribution. In these cases, it may be better to use a four-parameter distribution such as the Kappa distribution, which is more robust to misspecification of the frequency distribution (Wallis et al., 2007). The Kappa distribution can mimic both the GEV and the GLO and produce a variety of regional growth curves intermediate between the GEV and the GLO. The L-moments of the Kappa distribution cover a large area of the moment ratio diagram (L-Skewness versus L-Kurtosis); in Fig. 4a–c, the L-moments of the Kappa distribution cover the area below the curve corresponding to the GLO distribution. Therefore, the choice of the Kappa distribution is consistent with the arrangement of the empirical average moment ratio points for the various Subregions. Given these considerations, it was decided to use the four-parameter Kappa distribution for Subregion C, which includes the storm location.

Subregional C growth curves for the Kappa, GEV and GLO distributions along with the empirical growth curves based on the APL plotting position (Stedinger et al., 1993) are shown for all durations of annual maxima precipitation in Fig. 5. In Fig. 5, growth curves for the Kappa match closely

![Figure 6](image_url) Location of the OSMER radar and location of the 15 rain gauges used for analysis of the storm event (PB: Pontebba; PP: Pramollo).
those for the GEV in the case of 1-h and 24-h durations, and those for the GLO in the case of 6-h and of 3-h durations. For 12-h duration, the growth curve from the Kappa is intermediate between GEV and GLO.

In Fig. 5, the normalised sample data exceeding 3.0 are marked in bold. It is interesting to note that all these extremes result from three flash flood—generating storm events, occurred on September 11, 1983, June 22, 1996 and August 29, 2003, sampled by 6 stations (Table 2). These events appear to dominate the upper tail of the precipitation frequency distribution. Furthermore, the data reported in Table 2 show clearly an effect of intersite dependence for these extreme storms. Intersite dependence has not been explicitly addressed in this study and is the subject of on going investigation in the study region.

Values of the Z statistic are reported in Table 3 for GEV and GLO for the three subregions. In agreement with the

![Figure 7](image_url)

**Figure 7** Storm total rainfall (mm) for the August 29, 2003 event.

![Figure 8](image_url)

**Figure 8** Catchment map of the upper Tagliamento river basin with location of the Fella’s subbasins. (1): Uqua at Ugovizza; (2) Fella at Pontebba; (3) Fella at Dogna; (4) Raccolana at Raccolana; (5) Resia at Borgo Povici; (6) Fella at Moggio Udinese; (7) Tagliamento at Venzone; (8) Rio del Lago at Cave del Predil; (9) Slizza at Tarvisio.
observations reported above, the values show a shift from GEV to GLO when moving from Subregion A to Subregion C. Only for Subregion C and 6-h, the frequency distributions used here appear to provide a goodness-of-fit criterion larger than 1.64. This is due to the large value of both L-skewness and L-kurtosis. Results from Fig. 5 confirm that the Kappa distribution, which is intermediate between GEV and GLO, is appropriate for quantile estimation for Subregion C. Quantiles for various return periods and rainfall durations obtained from the application of the Kappa distribution are reported in Table 4.

Even though the statistic $H(2)$ in the Subregion C exceeds the heterogeneity threshold only for rainfall maxima of 12-h, we wanted to examine the effect of reducing the amount of heterogeneity on the computed quantiles. We analysed a further smaller subregion, composed by 8 stations in Subregion C chosen based on geographical proximity. This new subregion was tested for homogeneity. The amount of heterogeneity is less than for Subregion C, as expected. The statistics $H(1)$ and $H(2)$ are always less than 1.3, with the exception of $H(2)$ for 12-h duration, which amounts to 1.9. The Kappa distribution was fitted to these data and precipitation quantiles were computed for the return periods reported in Table 4. The precipitation quantiles for the new smaller subregion are somewhat larger than for the Subregion C. However, the relative difference between 500-yr quantiles for the various durations is less than 8%. This suggests that the reduction of the amount of heterogeneity obtained by redefining the region has a relatively minor effect on the computed quantiles. Taking into account that with the smaller subregion the analysis of the August 2003 storm implies extrapolations beyond the range of the cumulative record length, we decided to use Subregion C for estimation of regional growth curve (Table 4).

The August 29, 2003 flash flood generating storm

On August 29, 2003, at the end of a prolonged drought, a Mesoscale Convective System affected the study area, starting at 10:00 LST (Local Standard Time) and lasting for approximately 12 h. The storm affected a 1500 km$^2$ wide area, and caused loss of lives and substantial disruption of the local economy, with damages close to 1 billion Euro (Tropheano et al., 2004).

Radar and raingauge observations are used to derive rainfall fields for the August 2003 storm. Five-minute raingauge data were collected at 15 raingauges (Fig. 6), whereas storm total rainfall was available at further six daily raingauges. Twelve out of the 15 raingauges are located within the Fella watershed closed at Moggi Udinese (623 km$^2$) and the nearby Slizza watershed (73.1 km$^2$), that is an average density of about one rain gauge per 50 km$^2$. In spite of the density of the raingauge network, only two raingauges (Pontebba and Pramollo) sampled the high intensity area of the storm.

Volume scan reflectivity data from the Doppler, dual-polarised C-band OSMER radar station, located at Fossalon di Grado (Fig. 6) (time resolution of 5 min and spatial resolution of 250 m in range by 0.9° in azimuth), were used to derive radar rainfall rates. The radar measures the reflectivity in two orthogonal (horizontal and vertical) polarizations, $Z_h$ and $Z_v$, respectively. When the two reflectivities are measured in an approximately simultaneous fashion, the differential reflectivity (in decibels) can be derived by $\text{dBZ}_{\text{DR}} = 10 \log_{10}(Z_h/Z_v)$. In this study, rainfall rates were estimated based on horizontal-polarised observations; $Z_R$ values were use to discriminate ground clutter from rainfall observations. A number of procedures were applied to the reflectivity data to correct for the following error sources: (i) ground clutter; (ii) partial beam occlusion; (iii) path attenuation. Hail was not observed during the event, so no correction was implemented to remove hail contamination.

An algorithm based on a three-step decision tree, based on Doppler velocity, clear air echo statistics and $Z_R$ variance, was used to flag clutter contaminated data in the polar volumes (Bechini et al., 2002). Correction for beam occlusion is based on off-line computation of the percentage of beam power intercepted by the orography by using a model of beam propagation and a digital description of the orography (Borga et al., 2000; Pellarin et al., 2002). Path attenuation due to precipitation (which can generate large errors at C-band at high rainfall rates – Delrieu et al., 2000) is corrected by using a variational method with gauge accumulations as external constraints and the Hitchens-Bordon (1954) equation as model (Berenguer et al., 2002).

Rainfall estimation was based on reflectivity observations from the 2.06° beam elevation, which is the lowest elevation affected by minimal beam occlusion over the study area. Effects due to non uniform reflectivity along the vertical were not included in the analysis and correction procedure, due to the difficulties of separating the effects of attenuation from those generated by vertical variability of reflectivity and of beam occlusion for localised storms. After correction, the reflectivity factor $Z$ was converted to rainfall rate $R$ through an empirical $R-Z$ power function of the form $R = aZ^b$. The $R-Z$ parameters used are $a = 0.022$ and $b = 0.67$ for $R$ in mm h$^{-1}$ and $Z$ in mm$^6$m$^{-3}$. These parameter values are used in this region for estimation of convective events and are similar to those used in the so-called NEXRAD convective relationship (Ogden et al., 2000).

<table>
<thead>
<tr>
<th>Duration</th>
<th>Maximum rainfall depths (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pontebba</td>
</tr>
<tr>
<td>1-h</td>
<td>88.6</td>
</tr>
<tr>
<td>3-h</td>
<td>233.4</td>
</tr>
<tr>
<td>6-h</td>
<td>343.0</td>
</tr>
<tr>
<td>12-h</td>
<td>389.6</td>
</tr>
<tr>
<td>24-h</td>
<td>396.2</td>
</tr>
</tbody>
</table>
Comparison of hourly rainfall obtained from raingauges and radar-based estimates after adjustment shows a general good agreement; the largest rainfall accumulations are accurately portrayed by radar. The squared correlation coefficient for hourly accumulation is 0.73, while for rainfall accumulation on 12 h it raises to 0.94. The radar estimates after adjustment show a slight positive bias, with an overestimation around 10%. The storm total precipitation (Fig. 7) exhibits three local peaks of rainfall accumulations exceeding 320 mm. The most extended accumulation is over the upper Aupa basin; the second peak is close to the Uqua basin and near the Italian–Austrian border; the third one (and also the less extended) is located over the extreme eastern portion of the study area. The position of the Aupa and Uqua catchments is shown in Fig. 8.

A striking characteristic of the event is its organization in four well defined banded structures. Some of the bands persisted in the same locations for the duration of the event. The steadiness of these rainbands led to highly variable precipitation accumulations; the rain gauge at Pontebba recorded 389.6 mm of precipitation in 12 h, while San Giorgio di Resia, located just 15 km to the south but not directly

![Figure 9](image-url)
under a band, recorded only 68.4 mm during the same period. Extreme spatial gradients in precipitation accumulations up to 80 mm/km can be recognised in Fig. 7.

The size of the storm measured at the Pontebba raingauge, close to the core of the precipitation event, was 88.6, 233.4, 343.0, 389.6, and 396.2 mm for the 1-, 3-, 6-, 12- and 24- maximum, respectively. Except for the 24-h these were the largest precipitation events ever recorded at Pontebba since 1928, when precipitation monitoring started. Previous largest recorded events were 78.4, 155, 199.6, 345.6 and 465 mm, for the 1-, 3-, 6-, 12- and 24-h maximum, respectively, all recorded during the previous June 22, 1996, flash flood event. Comparing the above figures, it is evident that what made the August 29, 2003 event so extraordinary (at least in Pontebba) was the excessive precipitation for the durations in the range between 3 and 12 h.

Analysis of storm severity

This section aims to analyse the spatial distribution of storm point return periods, for various rainfall durations, for the August 29, 2003 storm event. The analysis is based on rainfall estimates obtained by using both raingauge measurements and radar observations. As a first step, a

Figure 10  a–d: Return time patterns for rainfall maxima corresponding to (a) 1 h, (b) 3 h, (c) 6 h and (d) 12 h. The bold triangle represent the position of the Pontebba raingauge station.
comparison has been carried out to evaluate the quality of the point return period estimates obtained by using adjusted radar observations. To this purpose, the maximum rainfall depths for the different rainfall durations have been computed for the raingauges of Pontebba and Pramollo from both raingauge measurements and adjusted radar estimates. The classical moving-window procedure for rainfall accumulation was adopted to select the maximum rainfall depth observed for each duration. To account for possible errors in the computation of the geographical position of the radar observations, maximum rainfall depths over different rainfall durations were computed by selecting, for each duration, the maximum rainfall depth over a 3 × 3 km kernel centered on the 1-km size grid cell of interest. Rainfall maxima obtained from raingauges and from radar observations are reported in Table 5. Inspection of these data show that adjusted radar estimates are generally in good agreement with raingauge data, with errors ranging between −14% for 3-h at Pontebba to +12% for 12-h at Pramollo. Since cumulated raingauge data were used in the adjustment procedure of the radar observations, a good correspondence is expected for 12-h maxima between the two measures; the agreement for shorter durations provides an indication of the feasibility of using radar rainfall estimates for rainfall maxima analysis of extreme storms. Return periods were computed for these data based on Kappa distribution specified for Subregion C. According to the terminology introduced by Ramos et al. (2005), the graphs obtained by associating, for a given station, the return periods of maximum rainfall intensities to the different rainfall durations have been named here severity graphs. Severity graphs obtained from adjusted radar estimates

Figure 11 a,b: Severity graph for two catchments in the upper Fella basin: (a) Uqua; (b) Aupa.
and raingauge measurements are reported in Fig. 9a and b for Pontebba and Pramollo, respectively. These graphs show clearly that even small-to-moderate errors in rainfall estimation (as are those implied in the radar–raingauge comparison reported above) amplify strongly in the return period estimation. With a 15% under/overestimation, return periods for Pontebba may be under/overestimated by more than 50–60% (depending on rainfall durations). This shows clearly that the main outcome of a radar-based evaluation of storm hazard is an analysis of patterns of relative severity, rather than a determination of absolute values of return periods.

Maps of point return periods are reported in Fig. 10a–d for durations of 1-h, 3-h, 6-h and 12-h. The map for 24-h is not reported because the corresponding depths are the same as those reported for 12-h. Examination of the maps reveals large differences both among various durations and in space for a given duration. First of all, it is shown that extreme rainfall is concentrated on the right-hand tributaries of the river Fella system. Return periods for 1-h are generally comprised between 100 and 300 years (the station of Pontebba recorded a rainfall depth in this range), with peaks exceeding 300 years over the Uqua basin, on the mid Pontebbana and over the mid Aupa basin. 3-h and 6-h maps are pretty similar, showing three peaks exceeding 600 years over the eastern portion of the study area, the Uqua basin and on the area ranging between mid Pontebbana and mid Aupa. 12-h map reveals a different pattern, with two peaks exceeding 600 years over mid Aupa and the eastern portion of the area. A synthesis of this information is reported in Fig. 11a and b, which shows the envelope of the severity graphs for the grids covering the Uqua and Aupa catchments in terms of 10%, 50% and 90% percentiles. The graphs show clearly that the severity

![Figure 12](image_url)  
Figure 12 a–d: Ratio of point to areal rainfall maxima for rainfall duration of (a) 1 h, (b) 3 h, (c) 6 h and (d) 12 h.
peak over the Uqua is concentrated on 3-h and 6-h durations, whereas severity on the Aupa show a peak at 12-h duration.

Globally, this analysis shows that attributing a single return period to a storm event is not realistic, even for a storm developing at a relatively small spatial scale such as the one considered here. The analysis shows also that the severity of this flash flood generating storm is poorly captured by using conventional raingauge networks.

A comparison between the mapped damages and the return period patterns (Tropeano et al., 2004) shows a remarkable agreement for the Uqua basin and nearby catchments. In these basins, the relatively large duration of extreme rainfall explains also why the event was associated to widespread shallow landsliding and debris flows. Rainfall duration and infiltration amounts were evidently adequate to produce the positive pore pressures necessary to initiate large mass movements (Borga et al., 2002). However, less damages were recorded over the Aupa basin, in spite of the severity of the relevant precipitation. This prompted to analyse the spatial character of the hazard evaluation.

Actually, severity graphs provide only partial information regarding the potential for flooding, emphasising the point scale of storm rarity (Konrad, 2001). It is the timing and spatial distribution of precipitation within a basin that are the key factors in determining whether a flooding will be observed (Hirschboeck et al., 2000). In order to gain a deeper view of the spatial extent and of the simultaneity of the intensities in the storm, we analysed the ratio between point and areal precipitation. Areal precipitation were computed over a support of $11 \cdot 11 \text{km}^2$, this area being the upper threshold for basin scales, which reproduce the shape of the central convective band and experienced extreme flooding during the event. For each rainfall duration, the following steps were taken:

(i) For each grid characterized by a return period greater than 50 years, the maximum rainfall depth over the area of $11 \cdot 11 \text{km}^2$ centered on the grid was computed according to the moving window procedure.

(ii) The ratio was computed between the point and areal rainfall depths and mapped over the region (Fig. 12a–d).

Values of the ratio close to one imply simultaneity of the rainfall across the area investigated and for the considered duration. On the contrary, low values of the ratio imply a high degree of heterogeneity and loss of simultaneity of the rainfall depth across the area. Ratios are reported in Fig. 12a–d for the four durations of 1-h, 3-h, 6-h and 12-h, respectively. As expected, ratios for shorter durations (1-h and 3-h) are generally lower than for longer durations (6-h and 12-h). Ratios for 6-h an 12-h show also a remarkable spatial pattern with values consistently higher over the Uqua basin and the upper Fella basin (with values in the 0.6–0.8 range, with peaks close to one), and lower values over the mid Pontebbaana and the Aupa (with values in the range 0.4–0.6). This helps to explain the explosive character of the flooding (and corresponding damages) over the Uqua and nearby basins with respect to the Aupa catchment, where the rainfall rates peaked at different times across the basin.

### Summary and conclusions

Regional frequency analyses were conducted on AMP data using the index variable method. The study area was the Eastern Italian Alps. AMP data were collected at 63 stations for durations of 1, 3, 6, 12 and 24 h. The region was analysed as composed by three smaller subregions, namely, (i) the southern plains, (ii) the alpine foreland area and the upper Tagliamento basin closed upstream the junction with the Fella and (iii) the region within and around the Fella basin. The last region was of particular interest because it includes the area hit by an exceptional flash flood event occurred on August 29, 2003. The subregions passed a regional homogeneity test and were treated as homogeneous. L-moments analysis suggests that either GEV or GLO may provide good fit to the data, depending on rainfall duration. For instance, in the case of the Fella-centered Subregion the GEV model may be a good choice for 1-h and 24-h, whereas the GLO model may be a better model for the 3-h, 6-h and 12-h data.

The GEV and the GLO are suitable distribution for estimation of precipitation quantiles out to 500-year recurrence interval (Wallis et al., 2007). If quantiles estimates are desired for more extreme events than the 500-year recurrence interval, it would be worthwhile to refine the selection of the regional probability distribution. Given this consideration, it was decided to use the four-parameter Kappa distribution, which can mimic both the GEV and the GLO and produce a variety of regional growth curves intermediate between the GEV and the GLO. The Kappa distribution was used to estimate growth curves for the Fella-centered region for various rainfall durations, providing a framework to investigate the frequency characteristics of the August 29, 2003 flash flood generating storm for various rainfall durations. Rainfall maxima from the Pontebba station, which recorded the highest rainfall depths, were characterized by return periods in the range 200–500 years for 1-h and 24-h durations, and in the range 500–1000 years for 3-h, 6-h and 12-h durations.

Radar rainfall estimates, adjusted by using a physically-based methodology and data from a raingauge network, were used to characterize the return period of the storm rainfall amounts, highlighting the importance of considering its spatial dimension. Severity graphs were developed to visualise the return periods and their variability for different rainfall durations within the storm. The analysis shows that (i) attributing a single return period to a storm event is not realistic, and (ii) the severity of this flash flood generating storm is poorly captured by using a conventional raingauge network, which is too sparse to provide adequate sampling. It has been shown that adjusted radar rainfall estimates may suffer for considerable uncertainty and that the uncertainty magnifies in the evaluation of the relevant return periods. Whereas this call for development of standard procedures for evaluation of uncertainties in radar rainfall estimation, the reported results show that these estimates may be useful to evaluate the severity of the storm for ungauged basins and to evaluate the spatial
dimension of the frequency characterization. Both these features represent important basis for learning processes during ex-post evaluation of interventions in support of future development of strategies and strategic option in flood risk management in the study area.

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