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Extreme Storm Precipitations Events in a Changing Climate: How to Define and Analyze (Case of the Lake Maggiore Watershed)

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Summary

The magnitude and the frequency of extreme events are great concerns of our time in light of possible change or variability in climate. In recent years we are assisting in Alpine region to a profound change in rainfall typology and distribution. In particular, we can observe an increase in consecutive non-rainy days, and an escalation of extreme rainy events which are short and very intense.

In this study, the historical extreme rainfall series with high-resolution from 5 to 45 min and above: 1, 2, 3, 6, 12 and 24 h collected at different gauges located at representative sites in the watershed of Lake Maggiore, have been computed to perform regional frequency analysis of annual maxima precipitation based on the L-moments approach, and to produce growth curves for different return-period rainfall events.

Moreover, I used rainfall statistic methodology to check whether the automatic equipment (Tipping-Bucket Rain Gauges) was working effectively during specific extreme events. In four selected stations in our study are (Pallanza, Domodossola Lunecco and Monte Mesma) we noticed an underestimation of extreme events due to the loss of rainwater during, because of the movement of the bucket blocked up.

Then I carried out an automatic conversion of rain data from paper records into digital numerical format regarding four sites: Pallanza, Vercelli, Lombriasco and Bra. Using this method we obtained long time series of precipitation with high temporal resolution: 5, 10, 15, 20 and 30 minutes and above 1, 2, 3, 6 and 12hour.

Finally I examined the long-term historical change in frequency and amplitude of extreme precipitation events collected and digitized in four stations situated in Piedmont region (the previous stations mentioned above). We adopted two indices of extremes and also Peaks-Over-Threshold approach. The application of Mann-Kendall test showed that we have a statistically significant positive trend of the extreme frequency index and spring maximum precipitation for the station of Bra and Lombriasco. The temporal change of growth curve proved that extreme short rainfall events have risen during the last 20 years of our time series (1984-2003) in the station of Vercelli.

KEY WORDS: extreme events, regional frequency analysis, Tipping-Bucket Rain Gauges, trend.

Riassunto

La grandezza e la frequenza degli eventi estremi sono una preoccupazione del nostro tempo alla luce del possibile cambiamento o variabilità del clima. Negli ultimi anni stiamo assistendo, nella regione alpina, a un profondo cambiamento nella tipologia e nela distribuzione delle precipitazioni. In particolare, si può osservare un aumento di giorni non piovosi consecutivi, e un incremento degli eventi estremi di pioggia brevi e molto intensi.

In questo lavoro, le serie storiche di precipitazione estreme ad alta risoluzione da 5 a 45 min e oltre: 1, 2, 3, 6, 12 e 24 ore raccolte in diversi sensori situati in siti rappresentativi nel bacino imbrifero del Lago Maggiore, sono state elaborate per eseguire l'analisi regionale di frequenza di precipitazioni intense in base all'approccio degli L-moments, e per produrre delle curve di crescita per i diversi periodi di ritorno.

Inoltre ho usato una metodologia statistica per verificare l'accuratezza dei sensori automatici di misura di pioggia (Pluviometro a doppia vaschetta basculante) durante specifici eventi estremi. In quattro stazioni selezionate nella nostra area di studio (Pallanza, Domodossola Lunecco e Monte Mesma) abbiamo notato una sottostima degli eventi estremi a causa della perdita di acqua piovana durante il movimento delle vaschette che non riescono a basculare abbastanza in fretta.

In seguito abbiamo eseguito una conversione automatica dei dati di pioggia da documenti cartacei in formato digitale numerico per quanto riguarda quattro siti: Pallanza, Vercelli, Lombriasco e Bra. Usando questo metodo abbiamo ottenuto una lunga serie di precipitazioni con alta risoluzione temporale: 5, 10, 15, 20 e 30 e sopra 1, 2, 3, 6 e 12 ore

Dopo di che, ho esaminato il cambiamento a lungo termine in frequenza e in ampiezza degli eventi estremi di precipitazione raccolti e digitalizzati nelle quattro stazioni sopra citate utilizzando indici degli estremi e l'approccio dei Peaks-Over-Threshold. L'applicazione del Mann-Kendall test ha dimostrato che c'è una tendenza positiva statisticamente significativa del'indice di frequenza estrema e del massimo di precipitazione in primavera per le stazioni di Bra e Lombriasco. La variazione temporale della curva di crescita ha dimostrato che gli eventi estremi di pioggia di breve durata sono aumentati nel corso degli ultimi 20 anni della serie storica (1984-2003) della stazione di Vercelli.

Parole chiave: eventi estremi, analisi regionale di frequenza, Pluviometro a doppia vaschetta basculante, tendenza

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Introduction

In the recent past many analyses have claimed the possible presence of non-stationarity, produced by the presence of either trend or long-term climatic fluctuations, in some historical hydrometeorological records observed in Europe as well as in other countries. Such non-stationarity might exert a remarkable effect on the estimation of the frequency distribution of the extreme events. However, it is well known that a reliable assessment of the presence of non-stationarity in hydrological records is not an easy task, because of the limited extension of the available data sets. And this often does not allow a reliable identification of patterns in the data.

These efforts have been mainly motivated by the results of some meteorological and hydrological research studies which claimed the possible presence of irreversible climatic change, due to global climate forcing, such as increasing atmospheric CO2. (Jones et al., 1986; Hansen and Lebedeff, 1987). The awareness of the significant effects that such a global change exert influence even at the optimal design of urban and land drainage networks and flood protection works has motivated a number of studies in order to detect evidences of climatic changes even at local scale.

A significant number of rainfall series were recently analysed in Italy, where some long precipitation records are available such as, for instance, the daily rainfall series observed in Padova (Camuffo, 1984), which covers a very long observation period (since 1725) and is one of the longest daily rainfall record available in the world. Camuffo (1984) gave evidence that precipitation amount show a wavy trend of different period, not always in phase with the frequency trend and also a cyclical variation of the precipitation intensity. The periodic pattern of the oscillations found by Camuffo

(1984) highlights the particular care that should be taken when analysing short climatic records, since increasing or decreasing trends detected in a short series might be the effect of a longer cycle, thus not leading to irreversible changes.

Burlando (1989) analysed the series of daily rainfall data observed in Florence (Italy). He collected data observed since 1813 (another of the longest daily rainfall records available today in Italy). He found significant changes along time of the extreme storms structure and, in particular, a decrease of the number of storm events and a corresponding increase of their intensity in the latter decades. Similar results were found by Montanari (1998) who analysed four long rainfall series observed in the cities of Sondrio, Milan, Florence and Genoa (Italy). These results might explain the apparent increase of the magnitude of the extreme storm events in the recent past.

In order to verify whether or not the detected trends might be due to long-term climatic fluctuations, rather than non-stationarity, Montanari et al. (1996) performed a long-term analysis on the available data in Italy. They concluded that the detected trends in the precipitation amounts are never statistically significant. The results of this analysis highlighted that the estimation of trends and tendencies, when dealing with hydrometeorological variables, should always take into account the effects of the possible presence of long-term persistence.

Recently, a decrease in total precipitation in Italy over the past two centuries has been highlighted in Brunetti et al. (2002) and Brunetti et al. (2006) from a dataset of 111 homogenised precipitation series. This decrease has become more accentuated, though less significant, in recent decades. A final data set was clustered into regions and Italy was divided into six sub-regions: Northwest, Southeast, the southern part of Northeast, the northern part of Northeast, south and centre.

In the world, extreme precipitation had increased in the US, China, Australia, Canada, Norway, Mexico, Poland and the ex-Former Soviet Union (Groisman et al., 1999). No clear tropics-wide trends have emerged in the number of tropical storms; Nicholls et al. (1998) found a slight increase in the number of intense tropical cyclones in the Australian region since 1969, while Landsea et al. (1996) reported a decline in the number of intense Atlantic hurricanes over a similar period. There is little evidence of a change in extra-tropical storms, but only a limited amount of data have been analysed. Fewer studies have examined trends in climate extremes, other than changes in mean values, largely a result of the extra demands of good quality and quantity data.

The outcomes of this latter analysis highlighted that the detection of climate change at local scale, and therefore of non-stationarity in hydrological records, has relevant implications in the design of the river engineering and drainage facilities, and consequently is not only a matter of ecological concern. Although it is still not clear whether or not the detected tendencies are indication of global climate change, they are worth analysing and assessing from an operational point of view.

The present study first of all performs a regional frequency analysis of extreme storm precipitation based on the L-moments approach and using historical series with high-resolution from 5 minutes to 45 minutes and above: 1, 2, 3, 6, 12 and 24h collected at different gauges located at representative sites in the watershed of Lake Maggiore. This helped to produce growth curves for different return-period rainfall events.

The regional frequency analysis is generally based on (Caporali et al. 2008): (a) selection of the regionalization method, combining the extreme rainfall with geomorphological and meteoclimatic characteristics, (b) selection of the probability distribution of the annual maximum rainfall depth of the analyzed duration, relating to the extreme rainfall. We used data recorded in digital format regarding the last 20 years, selected from regional and CNR-ISE rain gauge networks

Regional frequency analysis, using L-moment approach, assumes that the standardised variant has the same distribution at every site in the selected region, and that data from a region can thus be combined to produce a single regional rainfall frequency curve that is applicable anywhere in the region (Hosking and Wallis 1997; Gabriele and Arnell 1991). This method is widely used for the regional frequency analysis of extreme storm precipitation. Adamowski et al. (1996) applied L-moment for the regional frequency analysis of annual extreme series of precipitation for assumed durations of 5, 10, 15, 30, 60 and 120min from 320 meteorological stations in Canada. Flower and Kilsby (2003) carried out a regional pooling of 1, 2, 5 and 10 day annual maxima for 1961 to 2000 from 204 sites across the United Kingdom and estimated maximum rainfall over different return periods. Lee and Maeng (2003) applied L-moments for the regional frequency analysis of annual maximum daily rainfall in 38 Korean stations. Di Baldassarre et al. (2006) used the L-moments method for the regionalization of annual precipitation from 15 min to 1 day in northern central Italy.

The study area is the Lake Maggiore watershed, which extends for 6599 km2 shared between Italy (3299 km2), in the two Region of Piedmont and Lombardy, and Switzerland (3369 km2) (Ciampittiello 1999). This zone is characterized by a distinctive climatic regime. The presence of the Alps causes heavy rainfall in the area, often with extreme events (Frei and Schär 1998). Indeed the average of precipitation is higher than the Italian average, 1700 mm as opposed to 940 mm. Numerous flood events have occurred since the 18th century with a frequency of minor event every 2-3 years; the most important happened in the years 1993 and 2000.

In the second part we carried out an inter-comparison in the field to single out the counting errors associated with automated tipping-Bucket Rain (TBR) gauge (instrument used for precipitation measurement in the first part of this study), during extreme events, so as to help the understanding of the measured differences using as reference instrument the Bulk precipitation samplers (Vuerich et al. 2009; Lanza and Vuerich, 2009) and also to understanding if data collected with this automatic instrument are valid and good enough correct to base our trend analysis of extreme rainfall and to use into long time series. Errors in measurements from traditional and recently developed rain gauges are reported by various authors (Habib et al. 2001; Calder and Kidd 1978; Marsalek 1981; Siek et al. 2007). Over the last 50 years the World Meteorological Organization has launched many large-scale international programs to develop adjustments to regular precipitation measurements. Since 2006 this organization has studied rain gauges and worked on checking their good functioning (WMO report n° 84 2006 and Report n°99 2009).

To check whether our automatic equipment was working effectively during specific extreme events, we confined our study to the Lake Maggiore region. Rainfall data from four (4) different stations was analysed over the course of approximately 20 years (1991-2010).

Finally in the third part we have tried to understand if the extremes rainfall are changing in the last 20 years, respect to the past. One of the major problems examining the climate record for changes in extremes is a lack of high-quality long-term data (Easterling et al. 2000). According to the World Meteorological Organisation (WMO) climatic observations of at least thirty years are needed in order to obtain representative climatic data (Peterson et al. 2001). It was not simple to found this data; in the catchment of Lake Maggiore, only for one station (Pallanza). So we investigated the variability of precipitation data collected also in other three different sites in the Piedmont region–Italy (Lombriasco, Vercelli and Bra). The historical extreme rainfall series with high-resolution from 5 minutes to 30 minutes and above: 1, 2, 3, 6, and 12h collected at different gauges have been computed to perform a statistical analysis to determine whether the recent changes in frequency and magnitude of the rainfall extremes can be considered statistically significant. Trends are analysed both at the annual and at the seasonal scale. Current interest in trends of extreme weather phenomena relates to their potential for severe and adverse impacts on human life, civil infrastructure, and natural ecosystems.

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Chapter 1

The Climatic Characteristics of Extreme Precipitations for Short-term Intervals in the Watershed of Lake Maggiore

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The climatic characteristics of extreme precipitations for short-term intervals in the watershed of Lake Maggiore

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Abstract Alpine and Mediterranean areas are undergoing a profound change in the typology and distribution of rainfall. In particular, there has been an increase in consecutive non-rainy days, and an escalation of extreme rainy events. The climatic characteristic of extreme precipitations over short-term intervals is an object of study in the watershed of Lake Maggiore, the second largest freshwater basin in Italy (located in the north-west of the country) and an important resource for tourism, fishing and commercial flower growing. The historical extreme rainfall series with high-resolution from 5 to 45 min and above: 1, 2, 3, 6, 12 and 24 h collected at different gauges located at representative sites in the watershed of Lake Maggiore, have been computed to perform regional frequency analysis of annual maxima precipitation based on the L-moments approach, and to produce growth curves for different return-period rainfall events. Because of different rainfall-generating mechanisms in the watershed of Lake Maggiore such as elevation, no single parent distribution could be found for the entire study area. This paper concerns an investigation designed to give a first view of the temporal change and evolution of annual maxima precipitation, focusing particularly on both heavy and extreme events recorded at time intervals ranging from few minutes to 24 h and also to create and develop an extreme storm precipitation database, starting from historical sub-daily precipitation series distributed over the territory. There have been two-part changes in extreme rainfall events occurrence in the last 23 years from 1987 to 2009. Little change is observed in 720 min and 24-h precipitations, but the change seen in 5, 10, 15, 20, 30, 45, 60, 120, 180 and 360 min events is significant. In fact, during the 2000s, growth curves have flattened and annual maxima have decreased.

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1 Introduction

Rainfall studies are very important for understanding of the evolution of water resources and in developing a correct approach to environmental management and the activities and safety of people. Rainfall is also an environmental parameter of great importance and complexity. The frequency analysis of extreme precipitation events on sub-daily timescales, which depend on the topographical and meteorological characteristics of a particular region or territory (Gajic-Capka 1991), represents one of the challenges in climatological studies and is the first step towards clarifying climate change and predicting its future evolution. The risks of such events are difficult to predict, but their impacts might well be severe.

Because the extreme precipitation events are rare and the data record is often short, it is difficult to estimate their frequency. There are thus many hydrologic and climatic studies trying to find and develop methods for the regionalization of extreme hydrologic and climatic events. It is clear that when data at a given location are insufficient for a reliable estimation of the quantiles, a regional frequency analysis must be performed.

The regional frequency analysis of extreme storm precipitation of a given duration is generally based on (Caporali et

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al. 2008): (a) selection of the regionalization method, combining the extreme rainfall with geomorphological and meteoclimatic characteristics; (b) selection of the probability distribution of the annual maximum rainfall depth of the analysed duration, relating to the extreme rainfall.

In the process of regional frequency analysis, the sites must be assigned to homogeneous regions, because approximate homogeneity is required to ensure that regional frequency is more accurate than at-site analysis (Hosking and Wallis 1997; Alila 1994; Lin and Chen 2005).

In literature, a decrease in total precipitation in Italy over the past two centuries has been highlighted in Brunetti et al. (2002, 2006) from a dataset of 111 homogenised precipitation series. This decrease has become more accentuated, though less significant, in recent decades. A final dataset was clustered into regions that are climatically homogeneous in terms of precipitation, by means of a principal component analysis. Italy was divided into six regions: northwest, southeast, the southern part of northeast, the northern part of northeast, south and centre.

A project for flood evaluation in Italy called Valutazione delle Piene in Italia (VAPI; flood evaluation in Italy) has been carried out by the National Group for Defence from Hydrogeological Catastrophes (Gabriele and Iiritano 1994). A hierarchical three-level regionalization approach was adopted. This approach is based on the two-component extreme value distribution (TCEV) introduced by Rossi et al. (1984) and generalises the most common index flood method.

Since the introduction of L-moments by Hosking and Wallis (1997), many studies have used L-moments for the regionalisation of hydroclimatic variables. Hosking and Wallis showed the good property of regionalization based on L-moments ratios, which represent a linear combination of the ratio of probability-weighted moments, called L-moments.

The purpose of this paper is to use the L-moments to develop a regional rainfall frequency model for computing design storms at gauged stations. The statistic analysis is performed using annual maximum rainfall data from 15 stations located in the watershed of Lake Maggiore for storm durations of 5, 10, 15, 20, 30, 60 min and 2, 3, 6, 12, 24 h. The regional rainfall frequency model is developed in four stages (Hosking and Wallis 1997), to be precise: screening data, identification of homogeneous regions (cluster analysis), choice of the regional parent distribution and estimation of its parameters.

2 Study area

Lake Maggiore (Fig. 1), located in North-western Italy, is the second largest freshwater basin in Italy and one of the most important lakes of the European Community. Lake Maggiore is one of several large lakes in the southern alpine lake district (which includes Lakes Como, Garda and Iseo); it has an area of 212.2 km^2 (80 % in Italy and 20 % in Switzerland) and a water volume of 37.5 km^3 (Ciampittiello 1999).

The Lake Maggiore watershed extends for 6,599 km^2 shared between Italy (3,299 km^2), in the two Region of Piedmont and Lombardy, and Switzerland (3,369 km^2; Ciampittiello 1999). The lake's catchment contains many streams and rivers, some natural alpine lakes and numerous reservoirs created by the damming of rivers for hydroelectric power. Other important lakes in the Lake Maggiore catchment are Lugano, Varese, Orta and Mergozzo.

The highest point of the catchment is the Dufour Peak (4,634 m above sea level (asl)) in the Monte Rosa Massif,

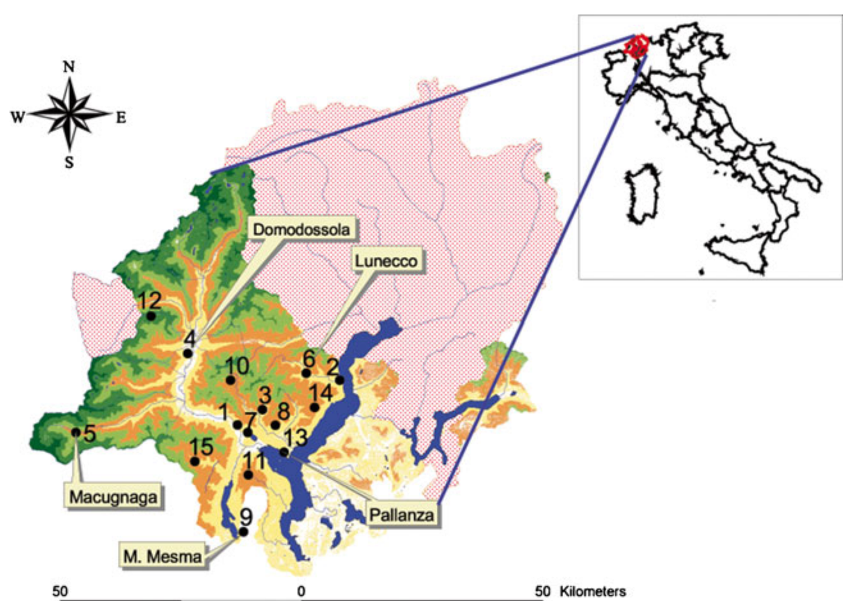

Fig. 1 Study area: Lake Maggiore Watershed and meteorological stations

and its average altitude, extracted from the hypsographic curve, is 1,270 m asl. The lowest point is the height of the lake above sea level, 193 m. Six percent of the catchment is above 2,500 m asl (Barbanti 1994).

The Lake Maggiore catchment is characterised by a distinctive climatic regime. The presence of the Alps causes heavy rainfall in the area, often with extreme events (Frei and Schär 1998). Indeed, the average of precipitation is higher than the Italian average, 1,700 mm as opposed to 940 mm. Numerous flood events have occurred since the eighteenth century with a frequency of minor event every 2–3 years; the most important happened in the years 1993 and 2000, the latter with a return period of 100 years (Provenghi 2002). These exceptional precipitations are especially significant for a number of practical aspects, like the study of erosion processes, water resource management and hydraulic infrastructure design, and are also essential for a definition of the hydrological regime of water bodies. The pluviometric regime, calculated as mean monthly distribution during an annual period, is defined as "*sub-littoral alpine*" (Contessini 1956), characterised by two *maxima* in spring and autumn and two *minima* in winter and summer.

Rainfall is distributed over the Lake Maggiore catchment in different groups of precipitation dividing the catchment into areas of major or minor rainfall (Ciampittiello and Rolla 2008) analysed in our study.

By analysing the maxima precipitation, from 1 to 5 consecutive days, over a long time period (1921–1950) in the River Po Basin, where the Lake Maggiore catchment is situated, it is possible to divide the area into different zone according to rain features (Cati 1981). The Lake Maggiore catchment is situated in the zones B and C.

3 Data collection

The Lake Maggiore catchment contains a number of meteorological stations at different altitudes and in different valleys, divided homogeneously throughout Italian and Swiss territory, to a total of 99 pluviometric stations with a density of one station every 66.7 km^2 (Ciampittiello 2009). These stations show great differences as regards the number and type of data available: some are automatic and some are manual, some data have been generated digitally, while others, the oldest, are still on paper. Our study analyzes the data collected by the Italian automatic station in the Piedmont Region, which have been available since 1980.

The extreme rainfall database consists of the annual series of precipitation maxima with durations of 5, 10, 15, 20, 30 and 45 min; 1, 2, 3, 6, 12 and 24 h obtained from 15 stations situated in the watershed of Lake Maggiore. Table 1 reports the major characteristics of the meteorological stations used in this study.

The choice of this station is based:

- on the possibility to have long time series recorded continuously at the same station in the same place
- on time series of at least 20 years
- on the presence of other station around the one selected, in the same 5 km wide area and at the same altitude, with a data period overlap of at least 10 years
- on the covered of different altitude, because of the different distribution of the precipitation in the large Lake Maggiore catchment

At the moment, we are using data recorded on the computer series regarding the last 20 years in digital format, selected from regional and CNR ISE rain gauge networks.

Table 1 Description of the 15 meteorological stations located in the project area and used for the homogenisation and extreme events analysis

Station code	Station name	Easting	Northing	Elevation (m asl)	River/Lake Catchment
1	Candoglia	455,382	5,091,683	201	Toce
2	Cannobio	476,626	5,101,249	220	Cannobino
3	Cicogna	460,527	5,094,840	770	San Bernardino
4	Domodossola	445,070	5,106,511	277	Basso Toce
5	Fornarelli	421,939	5,090,075	1,185	Anza
6	Lunecco	469,645	5,102,406	415	Cannobino
7	Mergozzo	457,529	5,090,130	195	Lake Mergozzo
8	Miazzina	463,252	5,091,628	721	San Bernardino
9	Monte Mesma	456,616	5,069,516	575	Lake Orta
10	Mottac	453,935	5,100,948	1,690	San Bernardino
11	Mottarone	457,656	5,081,294	1,491	Lake Orta
12	Paione	437,475	5,114,095	2,269	Bogna
13	Pallanza	465,025	5,086,015	211	Lake Maggiore
14	Piancavallo	471,381	5,095,332	1,240	San Giovanni
15	Sambughetto	446,531	5,084,133	800	Strona

Each station is identifiable in Fig. 1 by its code

These data have been provided by CAE-Bologna instrument (Environmental Monitoring Company). But in the future, we intend to transform and use data from before the 1980s, which are still recorded on paper, and improve the long time series of extreme events, to analyse better the trend of climate change in the different zones of the Lake Maggiore catchment and in different season.

To carry out statistical analysis and studies on the time series in order to detect any trend in the extreme series, we need to have a certain number of historical daily, hourly and sub-hourly data (Djerboua et al. 2004; Pal and Al-Tabbaa 2009).

One of the major problems examining the climate record for changes in extremes is a lack of high-quality long-term data (Easterling et al. 2000). In our case, we need data series able to produce a time series long enough for analysis from the perspective of climate change. According to Gajic-Capka (1990), climatic observations of at least 50–60 years are needed, in case of short-term precipitation, in order to obtain representative climatic data. The longer are the sample sizes of rainfall depth, the more reliable the statistics analysis will be (Aronica et al. 2002).

4 Regional frequency: an approach based on L-moments

4.1 Regional rainfall frequency analysis

L-moments are a recent development in mathematical statistics facilitating the estimation process in the frequency analysis (Noto and La Loggia 2009; Onibon et al. 2004); they represent an alternative set of scale and shape statistics of a data sample or a probability distribution (Hosking and Wallis 1997). Their main advantages over conventional product moments are that they are able to characterise a wider range of distribution, and when estimated from a sample, are less subject to bias in estimation and more robust to the presence of extreme values and outliers. Introduced by Hosking (1990), this approach is increasingly being used by hydrologists.

For example, this method is widely used for the regional frequency analysis of extreme storm precipitation. Adamowski et al. (1996) applied L-moment for the regional frequency analysis of annual extreme series of precipitation for assumed durations of 5, 10, 15, 30, 60 and 120 min from 320 meteorological stations in Canada, identifying 28 homogeneous regions and suitable distribution for each region. Flower and Kilsby (2003) carried out a regional pooling of 1-, 2-, 5- and 10-day annual maxima for 1961–2000 from 204 sites across the UK and estimated maximum rainfall over different return periods. This study showed that the frequency of extreme rainfall changed over parts of the UK in the period 1961–2000. Nine regions were defined taking into account physiographic character and spatially coherent rainfall variability.

Smithers and Schulze (2001) employed the L-moments approach to define regions using 175 rainfall stations across South Africa. They found 15 relatively homogeneous regions for which the generalised extreme value (GEV) distribution was identified as a parent distribution.

Modarres and Sarhadi (2011) investigated the spatial pattern of rainfall frequency function over Iran using the annual rainfall of 137 stations for the period of 1952–2003. The hierarchical method identified eight rainfall regions over Iran. Guttman (1993) and Guttman et al. (1993) defined 111 regional rainfall groups within the 48 contiguous USA using L-moments and calculated the regional quantile value for eight durations.

Lee and Maeng (2003) applied L-moments for the regional frequency analysis of annual maximum daily rainfall in 38 Korean stations. Di Baldassarre et al. (2006) used the L-moments method for the regionalization of annual precipitation from 15 min to 1 day in northern central Italy. Casas et al. (2007) used 145 pluviometric stations for the regional estimation of extreme rainfall in Catalonia using L-moments. More recently, Yurekli et al. (2009) found GEV and three-parameter log normal distributions as the regional distribution function for the maximum daily rainfall of the Cekerec watershed, Turkey, through the L-moment approach.

The L-moments method has also been used for regional flood frequency analysis. Noto and La Loggia (2009) analysed the annual maximum peak of flood discharge data recorded from more than 50 stream flow gauging sites in Sicily in order to derive regional flood frequency curve. Sicily was divided into five sub-regions and hydrometric homogeneity was confirmed using a heterogeneity measure test based on L-moments.

Adamowski (2000) and Kumar and Chatterjee (2005) performed regional analysis of annual maximum peak flood data, respectively, from hydrometric sites in Ontario and Quebec provinces in Canada and in the north Brahmaputra region of India using the L-moments approach.

Regional frequency analysis assumes that the standardised variate has the same distribution at every site in the selected region, and that data from a region can thus be combined to produce a single regional rainfall frequency curve that is applicable anywhere in the region (Hosking and Wallis 1997; Gabriele and Arnell 1991). This approach can also be used to estimate events at an ungauged site where no information exists.

4.2 L-moments

Hosking and Wallis (1997) defined L-moments as linear functions of probability weighted moments (PWM), which are robust to outliers and virtually unbiased for small samples. Greenwood et al. (1979) summarised the theory of PWM and defined them as follows:

$$\beta_r = E\{X[F(X)]^r\} \quad (1)$$

Where $F(X)$ is the cumulative distribution function of X and β_r is the rth order PWM. Starting from PWMs, Hosking (1990) suggested the use the L-moment defined as the linear combination of probability weighted moments. The $(r+1)$th L-moment is defined as:

$$\lambda_{r+1} = \sum_{k=0}^{r} p^*_{r,k}\beta_k \quad where\, p^*_{r,k} = (-1)^{r-k}\binom{r}{k}\binom{r+k}{k} \quad (2)$$

In particular, λ_1 is the mean of the distribution; λ_2 is a measure of the scale or dispersion; and λ_3 and λ_4 are measures of skewness and kurtosis, respectively.

In the regional frequency analysis, dimensionless ratios between L-moments, called L-moments ratios (indicated as LMRs), are particularly useful. The LMRs are L_{cv}, L_{skew} and L_{kurt} and they are analogous to the usual coefficient of variation, coefficient of skewness and coefficient of kurtosis. In particular, the coefficient of variation is equal to $\tau=\lambda_2/\lambda_1$ while the other two LMRs (L_{skew} and L_{kurt}) are given by

$$\tau_r = \frac{\lambda_r}{\lambda_2} \quad r = 3, 4(L_{skew}\text{ for } r = 3 \text{ and } L_{kurt}\, for\, r = 4) \quad (3)$$

The sample estimation of L-moments can be expressed by:

$$l_{r+1} = \sum_{k=0}^{r} p^*_{r,k} b_k \quad (4)$$

With

$$b_k = \frac{1}{n}\sum_{i=1}^{n}\frac{(i-1)(i-2)...(i-k)}{(n-1)(n-2)....(n-k)}x_i, k > 1, \text{and } b_0 = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (5)$$

Where x_i for i=1,…, n is the ordered sample and n is the sample size.

The sample estimations of β_r and λ_r are unbiased while the following estimation of the L-moments ratios τ and τ_r (L_{cv} and L_r) are consistent but not unbiased (Hosking and Wallis 1997).

$$t = L_{cv} = \frac{l_2}{l_1} \quad (6)$$

$$t_3 = L_{skew} = \frac{l_3}{l_2} \quad (7)$$

$$t_4 = L_{kur} = \frac{l_4}{l_2} \quad (8)$$

The values of l_1, l_2, t, t_3 and t_4 are useful summary statistics of data sample and can be used to delineate homogenous regions, to judge which distributions are consistent with a given data sample and to estimate parameters when fitting a distribution.

4.3 Delineation and statistical testing of homogeneous regions

4.3.1 Screening data: discordancy test

Given the group of 15 sites situated in the Lake Maggiore watershed, the aim is to identify the so-called "unusual sites", which are grossly discordant with the group as a whole. Discordancy is measured in terms of the L-moments of the sites data (Hosking and Wallis 1993). A high value of the discordancy measure indicates that a site may be discordant within the pooling group, but this may be caused by only a few unusual rainfall events. These unusual sites merit close examination.

The discordancy measure of site (1) was defined by Hosking and Wallis (1993) as

$$D_i = \frac{1}{3}(u_i - \overline{u})^T S^{-1}(u_i - \overline{u}). \quad (9)$$

with

$$S = (N-1)^{-1}\sum_{i=1}^{N}(u_i - \overline{u})^T(u_i - \overline{u}) \quad (10)$$

and

$$\overline{u} = N^{-1}\sum_{i=1}^{N} u_i \quad (11)$$

and

$$u_i = \left[t^{(i)}, t_3^{(i)}, t_4^{(i)}\right]^T \quad (12)$$

This discordancy test was applied to each extreme storm precipitation from 5 min to 1 day.

4.3.2 Tests of regional homogeneity

The second step of the regional frequency analysis of extreme storm precipitation was identifying the homogenous regions, defined as a set of gauge sites whose frequency distributions are approximately the same after appropriate scaling operations (Noto and La Loggia 2009). It can be assumed that the LMRs are the same for data from all the sites within this statistically homogeneous region. The homogeneity of the proposed region is usually calculated by using a summary statistic of at-site data and then comparing their variability with what would be expected for a homogeneous region, following the approach proposed by Hosking and Wallis (1997). Another test, the S statistic test (Alila 1999), was used for this purpose.

– Homogeneity test (H; Hosking and Wallis 1997)

Supposing that the proposed region has N sites, with site i having record length n_i and sample L-moment ratios $t^{(i)}$ (L-CV), $t_3^{(i)}$ (L-skewness) and $t_4^{(i)}$ (L-kurtosis) of maximum annual k minute (5, 10, 15, 20, 30, 45, 60, 120, 180, 360, 720 and 1,440) precipitation.

The test statistic is

$$H_1 = \frac{V_1-\mu_v}{\sigma_v}, \text{where} V_1 = \sqrt{\frac{\sum_{i=1}^{N} n_i\left(t^{(i)}-t^R\right)^2}{\sum_{i=1}^{N} n_i}},\ t^R = \frac{\sum_{i=1}^{N} n_i t^{(i)}}{\sum_{i=1}^{N} n_i} \tag{13}$$

μ_v and σ_v are determined from simulation (500 realisations of a homogeneous region with N sites, each having a four-parameter kappa distribution with L-moments ratios equal to t^R, t_3^R and t_4^R and the at-site mean equal to 1) as the mean and the standard deviation of the simulated value of V_1.

Two other analogous tests are based on L-skewness t_3 (test statistic H_2) and L-kurtosis t_4 (test statistic H_3) instead of L-CV. The region is regarded as "acceptably homogenous" if $H<1$, "possibly heterogeneous" if $1\leq H<2$, and "definitely heterogeneous" if $H\geq 2$ (Hosking and Wallis 1997).

– Homogeneity test S (Alila 1999)

The test statistic is

$$S_1(\%) = \frac{\sigma_1^2-\mu_{\sigma^2}}{\sigma_1^2}\times 100, \text{ where } \sigma_1^2 = \frac{\sum_{i=1}^{N} n_i\left(t^{(i)}-t^R\right)^2}{\sum_{i=1}^{N} n_i} \tag{14}$$

And $\mu_\sigma{}^2$ is determined from simulations as the mean of the simulated value of $\sigma_1{}^2$. S_1 represents the percentage of signal that is evident in the network and the percentage of noise (sampling error) in the network is thus equal to $100-S_1$. A high value of S_1 means high heterogeneity. Two other analogous tests are based on L-skewness t_3 (test statistic S_2) and L-kurtosis t_4 (test statistic S_3) instead of L-CV.

4.3.3 Identification of homogeneous sub-regions (cluster analysis)

Cluster analysis, a standard method of statistical multivariate analysis for dividing a dataset into groups, has been successfully used to form regions for the regional frequency analysis of extreme storm precipitation (Smithers and Schulze 2001; Lin and Chen 2005; Kysely et al. 2005).

To identify homogeneous regions, Hosking and Wallis (1997) recommended using Ward's method, which is a hierarchical clustering method, based on minimising the Euclidean distance in site-characteristics space within each cluster.

A data vector is associated with each site, and sites are partitioned or aggregated into groups according to the similarity of their data vectors. The data vector can include at-site statistics or site characteristics. We prefer to use combinations of the two.

The variables used have to be carefully selected and weighted according to their importance for the actual problem. Since the attributes, chosen for the distance measure, have different units and, in most case, also different magnitudes, standardisation of the attribute data had to be performed before calculating the distance measure (Hosking and Wallis 1997; Smithers and Schulze 2001). Several methods of standardisation are conceivable, for example methods based on a range or standard deviation and/or substraction of the mean. A number of different transformations of the sites characteristics which gave satisfactory results and which were implemented are summarised in Table 2.

The site characteristics selected in this study for each site included: latitude, longitude and the altitude of the stations. Table 1 shows the site characters for 15 stations selected in the watershed of Lake Maggiore. We also used to perform this cluster analysis, mean annual precipitation (Alila 1999), and at-site characteristics like L_{cv}, L_{skew} and L_{kurt} for each storm duration.

4.4 Choice and estimation of regional frequency

After the correct identification of the homogeneous regions, the subsequent step was to select an appropriate regional frequency distribution; this was done by comparing the moments of the distributions to the average moments statistics obtained from regional data. The aim was to find from a number of candidate distributions the one giving the best fit to the observed data.

L-moments ratio diagram An L-moment diagram of L-kurtosis versus L-skewness is useful for distinguishing groups of sites with similar frequency behaviour of extreme storm precipitation and identifying the statistical distribution that can adequately describe them (Rahnama and Rostami 2007).

Table 2 Final transformation of site characteristics

Site characteristics X	Cluster variable Y
Latitude (m)	$y = \frac{x-x_{\min}}{x_{\max}-x_{\min}}$
Longitude (m)	$y = \frac{x-x_{\min}}{x_{\max}-x_{\min}}$
Altitude (m)	$y = \frac{x}{x_{\max}}$
Mean annual precipitation (mm)	$y = \frac{x}{x_{\max}}$
L-cv	$y = \frac{x}{x_{\max}}$
L-skew	$y = \frac{x}{x_{\max}}$
L-kurt	$y = \frac{x}{x_{\max}}$

Table 3 Summary statistics test results for 5 min precipitation measured in all sites

Site	Site name	*N*	Mean	L_CV	*t*_3	*t*_4	*t*_5
1	Candoglia	22	9.9545	0.1804	0.1860	0.2577	0.1508
2	Cannobio	9	10.1333	0.1096	0.1757	0.1643	0.0557
3	Cicogna	24	14.8417	0.2684	0.4282	0.4586	0.3639
4	Domodossola	11	7.9818	0.2720	0.3892	0.1848	0.0307
5	Fornarelli	12	5.2333	0.1691	0.0274	0.6016	0.0034
6	Lunecco	20	11.2600	0.1906	0.0343	0.0993	0.1392
7	Mergozzo	19	10.6421	0.1811	0.1970	0.2090	0.0211
8	Miazzina	22	11.6818	0.2321	0.3272	0.4234	0.3300
9	Monte Mesma	12	7.8833	0.3654	0.1470	0.0710	0.0002
10	Mottac	20	8.3200	0.2024	0.0983	0.2346	−0.0450
11	Mottarone	24	10.5000	0.2126	0.1882	0.1223	0.0751
12	Paione	13	6.0923	0.1229	0.0467	0.1438	−0.1364
13	Pallanza	18	14.5778	0.2742	0.5523	0.5376	0.5022
14	Piancavallo	23	10.8087	0.2306	0.2101	0.3520	0.1114
15	Sambughetto	21	10.7143	0.2475	0.1469	0.2566	0.0498

Goodness-of-fit test The goodness-of-fit test described by Hosking and Wallis (1997) is based on a comparison between sample L_{kurt} and population L_{kurt} for different distributions. The test statistic is termed Z^{DIST} and given as

$$Z^{\mathrm{DIST}} = \frac{\left(\bar{t}_4 - t_4^{\mathrm{DIST}}\right)}{\sigma_4} \tag{15}$$

where DIST refers to the candidate distribution, $\bar{t}_4$ the regional average of L-kurtosis and σ_4 the standard deviation of $\bar{t}_4$. A given distribution is declared a good fit if $|Z^{\mathrm{DIST}}| \le 1.64$. When more than one distribution qualifies for the goodness-of-fit measurement criteria, the preferred distribution will be the one that has the minimum $|Z^{\mathrm{DIST}}|$ value (Hosking and Wallis 1997). The criterion corresponds to acceptance of the hypothesised distribution at a confidence level of 90 % (Hosking and Wallis 1997).

A goodness-of-fit test was not applied to the Wakeby distribution because it has the ability to assume the wide variety of skewed shapes that the extreme precipitation distribution exhibits (Guttman et al. 1993; Park et al. 2001).

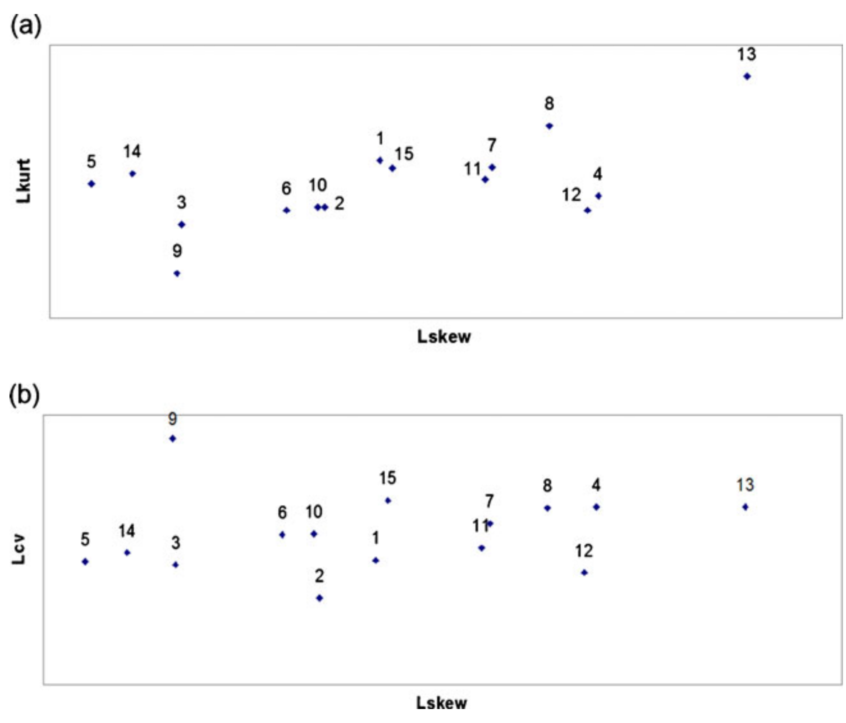

Fig. 2 Example of L-moments ratio diagrams for 10 min storm precipitations. **a** L_{cv} against L_{skew}, **b** k_{urt} against L_{skew}

Table 4 Result of discordancy test D_i in all sites for all 12 durations from 5 min to 24 h

Duration (min)	5	10	15	20	30	45	60	120	180	360	720	1,440
Candoglia	0.13	0.28	0.43	0.71	0.80	1.45	0.76	1.10	0.88	1.12	0.61	0.70
Cannobio	1.49	1.14	0.85	1.72	0.49	0.12	2.98	2.31	2.25	1.47	1.94	2.25
Cicogna	0.86	0.62	0.74	0.61	1.41	0.28	0.22	1.05	0.71	0.46	0.64	0.81
Domodossola	0.98	0.97	1.09	1.01	1.75	0.76	0.97	2.35	2.96	1.13	1.66	0.32
Fornarelli	**3.32**[a]	1.33	2.99	2.34	1.26	1.72	2.16	1.44	0.52	0.65	0.94	2.17
Lunecco	0.62	0.13	0.28	0.22	0.40	0.63	1.20	0.51	0.03	0.41	0.58	0.68
Mergozzo	0.22	0.13	1.50	1.93	0.49	0.35	0.78	0.09	0.34	0.92	1.56	0.74
Miazzina	0.36	0.77	0.29	0.82	1.04	1.43	1.10	1.16	1.97	1.00	0.51	0.83
M. Mesma	**3.11**[a]	**3.52**[a]	**4.03**[a]	**3.85**[a]	**3.72**[a]	2.24	0.87	0.35	0.15	1.84	2.41	1.09
Mottac	0.21	0.09	0.14	0.37	0.23	0.64	0.90	0.32	0.48	0.96	0.57	0.75
Mottarone	0.35	0.21	0.37	0.18	0.46	0.32	0.11	0.51	0.30	0.48	0.49	0.78
Paione	0.94	1.94	0.41	0.23	0.64	1.19	0.09	0.52	0.37	0.85	1.88	2.59
Pallanza	1.98	2.33	0.11	0.18	1.80	2.42	1.27	1.84	2.76	1.13	0.21	0.57
Piancavallo	0.14	1.17	0.08	0.44	0.13	0.60	0.41	1.11	0.96	2.15	0.93	0.09
Sambughetto	0.29	0.38	1.70	0.36	0.37	0.85	1.06	0.33	0.33	0.42	0.10	0.66

[a] D_i higher than critical value: 3

5 Results and discussion

The time series of multi-annual extreme rainfall at rain gauges in the zone were used. The multi-annual rainfall extremes for different durations were extracted from the historical data series collected (Crisci et al. 2002) distinguishing between the extreme events with high resolution: from 5 to 45 min (Molnar and Burlando 2008), and above: 1, 2, 3, 6, 12 and 24 h. The duration of the rainfall extremes is important for an evaluation of the precipitation law and for defining the rain time distribution.

A complete regional analysis of high-resolution precipitations was carried out using data collected in 15 sites situated in the Italian part of the Lake Maggiore watershed. The first step of the regional analysis (screening, data quality) is a close scrutiny of the data so that gross errors and inconsistencies can be eliminated. The second step involves delineating the homogeneous regions within the area of study and testing for homogeneity within each region. The delineation of homogeneous regions is based on the use of L-moments ratios. The third step of the procedure deals with the identification of the regional distribution, and the fourth step consist of the estimation of its parameters.

– Screening data: discordancy test

The discordancy test was applied to each extreme storm precipitation from 5 min to 1 day. Record lengths and L-moment ratios for the 15 sites are given in Table 3 and illustrated in Fig. 2.

Table 5 Results of the H and S statistical tests of homogeneity

Storm duration (min)	L-CV		L-skewness		L-kurtosis	
	H_1	S_1 (%)	H_2	S_2 (%)	H_3	S_3 (%)
5	0.86	18	0.22	−5	0.92	31
10	0.66	16	2.18	44	1.73	22
15	0.47	14	0.95	30	1.22	29
20	−0.07	−2	1.68	36	1.89	37
30	−0.61	−31	0.92	29	2.15	38
45	−0.07	−8	0.12	−1	0.02	−16
60	**1.48**	**30**	1.80	37	0.70	−85
120	0.33	9	−0.09	−16	−0.32	−49
180	0.80	19	−0.73	−45	−1.05	−46
360	**2.48**	**51**	1.47	9	1.47	36
720	**2.21**	**51**	2.60	50	3.43	57
1,440	0.63	18	1.38	47	2.27	55

Table 6 Results of heterogeneity test for the three clusters obtained for 60, 360 and 720 min storm durations

Storm duration (min)	Sub-region	Heterogeneity measure (H_1)
60	A	−0.01
	B	0.02
	C	0.87
360	A	0.32
	B	0.44
	C	0.60
710	A	0.65
	B	0.68
	C	0.75

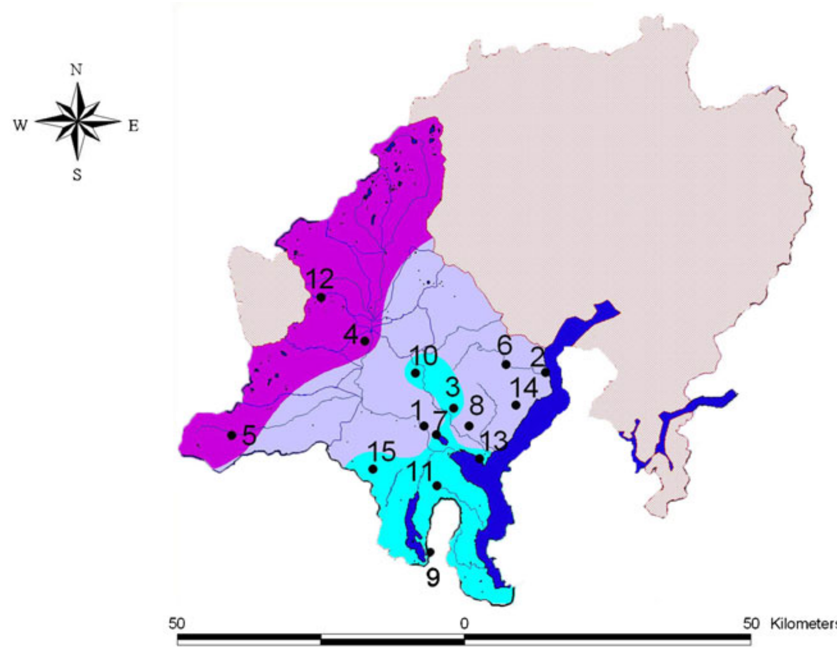

Fig. 3 Result of identification of homogenous regions for regional frequency analysis: sub-region A (*grey*), sub-region B (*blue*) and sub-region C (*purple*)

For 5 min storm precipitation, the critical value, 3, is exceeded by two sites (Table 4): Fornarelli (station 5) and Monte Mesma (station 9). The high value of discordancy test result for the station of Fornarelli, is caused by single unusually low annual maxima precipitations on 17 April 2005.

For the meteorological station of Monte Mesma (station 9) this critical value, is exceeded for 5-min storm precipitations and also for the storm durations of 10, 15, 20 and 30 min. This site has the highest L-CV of any in the group but this is not the only factor causing the high discordance measure (D_i) value. As Fig. 2 suggests, the discordancy arises because the combination of high L-CV and low L-skewness and L-kurtosis is discordant with the pattern of the other sites.

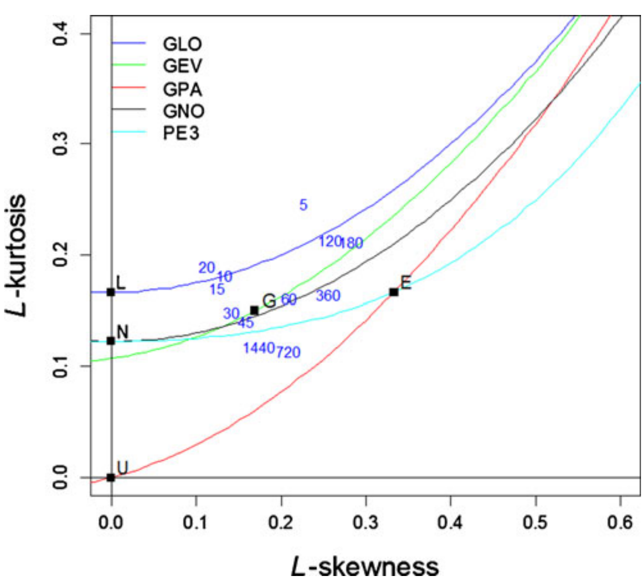

Fig. 4 Identification of frequency distribution using L-moment ratio diagram for the 5, 10, 15, 20, 30, 45, 60, 120, 180, 360, 720 and 1,440 min precipitations and theoretical L-moment ratio diagram. *GLO* generalised logistic, *GEV* generalised extreme value, *GPA* generalised Pareto, *GNO* generalised normal, *PE3* Pearson type III

In contrast, for this kind of precipitation, Pallanza (station 13), with extremely high values of L-CV, L-skewness and L-kurtosis and Fornarelli (station 5), with extremely low values of L-CV, L-skewness and L-kurtosis are not particularly discordant with the other sites. At the Monte Mesma site, the high discordancy measure for 5, 10, 15, 20 and 30 min precipitations results from single unusually low annual maxima precipitations in 2005.

Initially, the Lake Maggiore watershed was assumed to be a homogenous region in terms of extreme storm precipitations for all durations from 5 min to 24 h. If this is the case, it might be worthwhile to shift Monte Mesma Station to another group but there is no evidence of gross errors in the data and the entire group of sites is at this stage a plausible candidate for being a homogenous region.

– Tests of regional homogeneity

Initially, the study area as a whole was assumed to be homogenous region, the truthfulness of this assumption being tested using the two tests, *H* and *S*.

The values of heterogeneity measures computed by carrying out the 500 simulations mentioned above, based on the data of 15 sites are shown in Table 5.

H_2, H_3, S_2 and S_3 statistics lack the power to discriminate between homogenous and heterogeneous regions while the

Table 7 Result of the *Z* goodness of fit for rainfall data at all station

Duration (min)	5	10	15	20	30	45	60	120	180	360	720	1,440
GLO	−2.37	**−0.04**	**0.39**	**−0.92**	1.97	2.17	1.56	**0.30**	0.52	2.01	4.39	4.32
GEV	−3.41	−1.77	−1.48	−2.75	**−0.18**	0.21	**0.09**	−0.54	**−0.26**	0.86	2.62	2.36
GNO	−3.78	−1.79	−1.47	−2.74	−0.25	**0.03**	−0.31	−1.03	−0.80	**0.29**	2.13	1.93
PE3	−4.47	−2.12	−1.78	−3.06	−0.72	−0.52	−1.12	−1.89	−1.73	−0.75	**1.15**	**1.03**
GPA	−5.92	−5.44	−5.42	−6.61	−4.77	−4.08	−3.35	−2.71	−2.36	−2.05	−1.57	−2.16

GLO generalised logistic, *GEV* generalised extreme value, *GNO* generalised normal, *P3* pearson type III, *GPA* generalised Pareto distribution

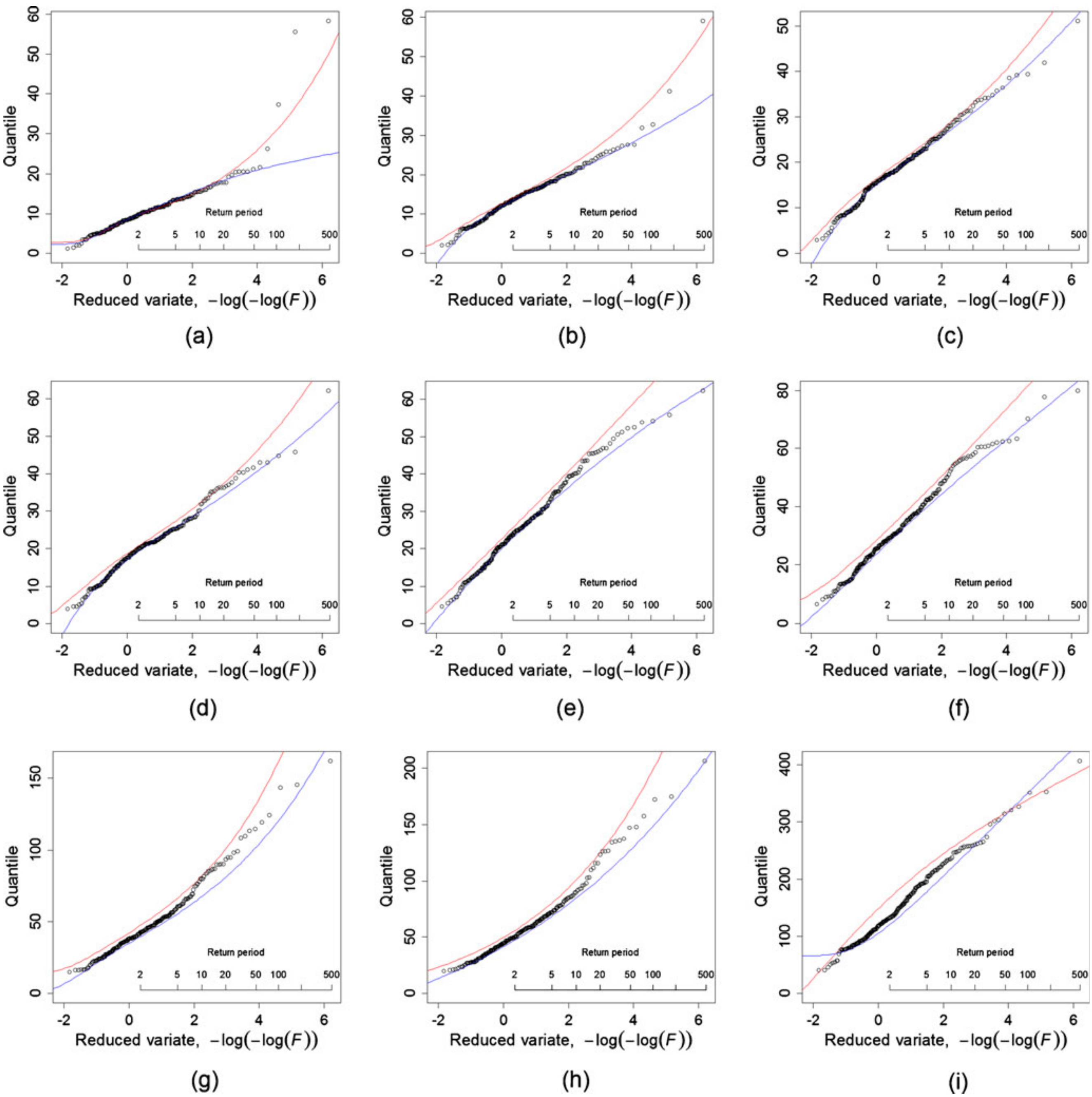

Fig. 5 Example of temporal changes in annual maxima precipitation using parent distribution, 10-year moving window and the fixed decades of 1990–2099 (*red*) and 2000–2009 (*blue*): **a**5 min, **b** 10 min, **c** 15 min, **d** 20 min, **e** 30 min, **f** 45 min, **g** 120 min, **h** 180 min, **i** 24 h

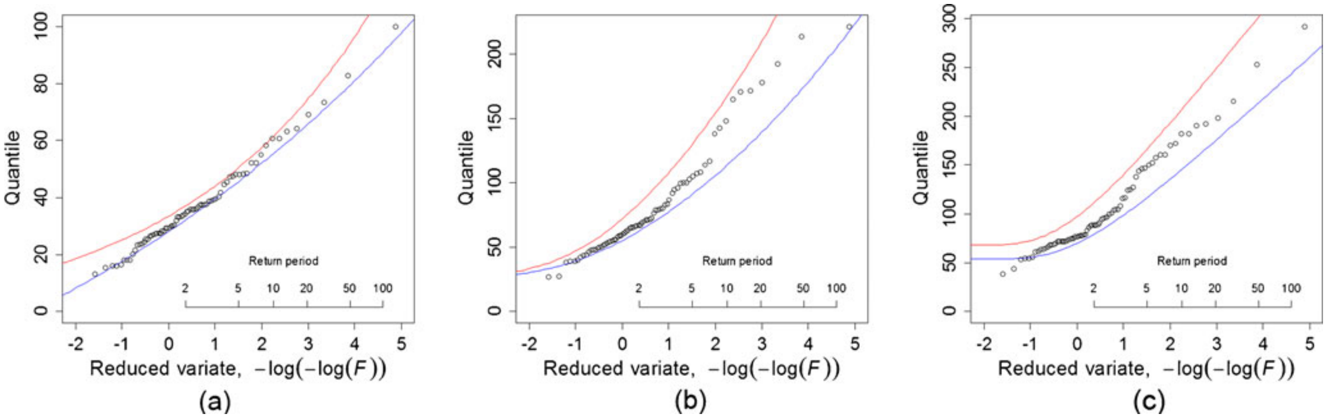

Fig. 6 Example of temporal changes in annual maxima precipitation for homogeneous sub-region A using parent distribution; 10-year moving window and the fixed decades of 1990–1999 (*red*) and 2000–2009 (*blue*): **a** 60 min and GEV distribution, **b** 360 min and GNO distribution, **c** 720 min and PE3 distribution

H_1 statistic has much better discriminatory power (Hosking and Wallis 1997).

For the above reasons, since the H_1 statistic measure for the Lake Maggiore watershed, using the data of 15 sites, was found to be greater than 1 for storm durations of 60, 360 and 720 min, thus one can assert that the entire watershed is not identifiable as a homogenous region for storm durations of 60, 360 and 720 min, and homogeneous for the others. This initial finding was confirmed by the high value of the S_1 statistic respective to this kind of precipitation.

– Identification of homogeneous sub-regions (cluster analysis)

Using the method described in 4.3.3 and based also on L-moments ratio diagrams (Fig. 2) the project area was divided into three regions (A, B and C).

After identification of the homogeneous region, using Hosking's method, D_i and heterogeneity measure H_1 were applied for each sub-region. Table 6 shows the result of the heterogeneity test for the three clusters A, B and C. Figure 3 shows the location of gauging sites and homogeneous regions in the watershed of Lake Maggiore.

The three proposed homogeneous sub-regions are:

– Sub-region A: including Cannobio, Lunecco, Miazzina, Piancavallo
– Sub-region B: including Cicogna, Mergozzo, Monte Mesma, Mottac, Mottarone, Pallanza, Sambughetto
– Sub-region C: including Candoglia, Domodossola, Fornarelli, Paione.

The value of H_1 based on the proposed regional subdivision (Table 6) identifies the three sub-regions as homogeneous ($H_1 < 1$).

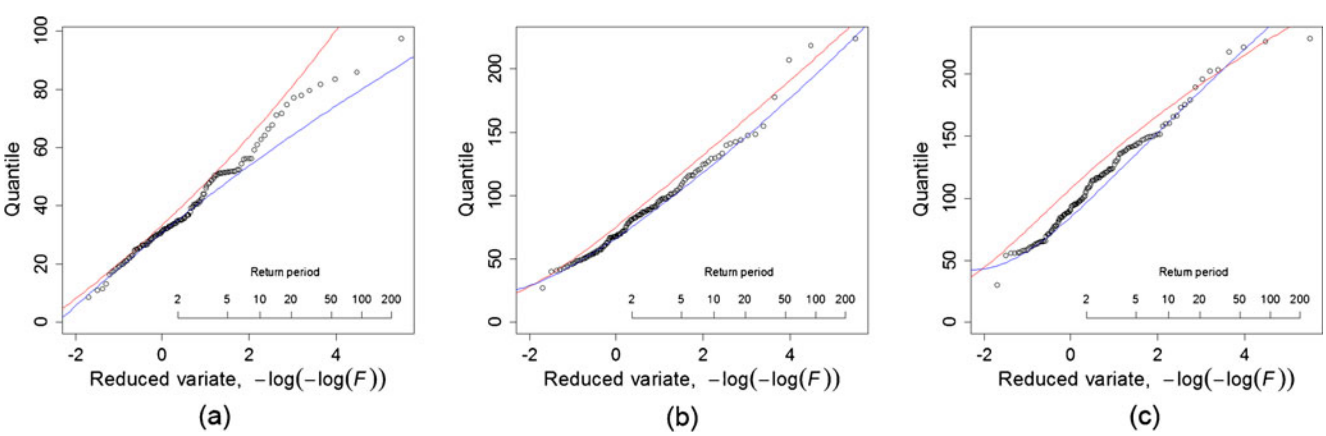

Fig. 7 Example of temporal changes in annual maxima precipitation for homogeneous sub-region B using parent distribution; 10-year moving window and the fixed decades of 1990–1999 (*red*) and 2000–2009 (*blue*): **a** 60 min and GEV distribution, **b** 360 min and GNO distribution, **c** 720 min and PE3 distribution

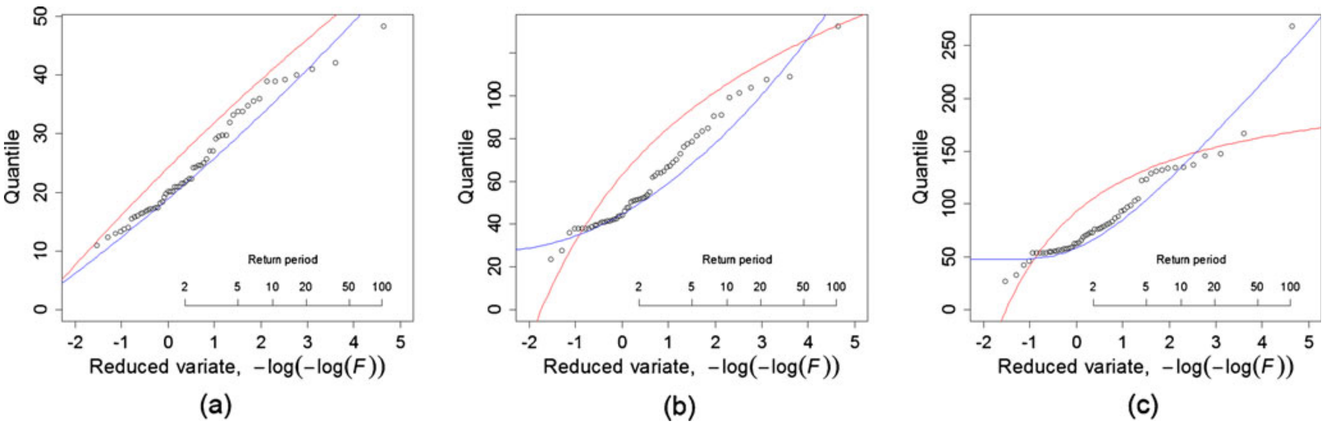

Fig. 8 Example of temporal changes in annual maxima precipitation for homogeneous sub-region C using parent distribution, 10-year moving window and the fixed decades of 1990–1999 (*red*) and 2000–2009 (*blue*): **a** 60 min and GEV distribution, **b** 360 min and GNO distribution, **c** 720 min and PE3 distribution

The usefulness of this rainfall regionalisation is that it can be used to extend rainfall data to regions where rainfall data are not available.

– Choice and estimation of regional frequency

Figure 4 shows the L-moments ratio diagram for all precipitation durations from 5 to 1,440 min. As the samples L-moment are unbiased, the sample point should be distributed close to the theoretical line of a suitable distribution (Hosking and Wallis 1997).

– Goodness-of-fit test

The choice of distribution should be influenced by considerations of robustness. It is particularly important to use a distribution that is robust to moderate heterogeneity in the at-site frequency distributions. By applying the goodness-of-fit test and plotting the L-moment diagram, it appears that the generalised logistic (GLO) is appropriate for 10, 15, 20 and 120 min precipitation, the GEV is appropriate for 30, 60 and 180 min precipitation, the generalised normal is appropriate for 45 and 360 min precipitation and Pearson type III (PE3) is appropriate to 720 and 1,440 min precipitation.

In the case of 5-min precipitation, the regional L-moments (Fig. 4) does not lie between two operationally equivalent distributions. It lies above the GLO and $|Z^{\mathrm{DIST}}|>1.64$ (Table 7) for all the candidate distributions. In this case, no three parameters distribution is acceptable (Hosking and Wallis 1997) and a more general distribution such as the Kappa or Wakeby should be used. We opted to use the Wakeby distribution as parent distribution for the 5-min precipitation data.

– Derivation of the regional growth curves

After the regional distributions were selected and the parameters of these distributions were estimated by the L-moments, growth curves were derived for each extreme event.

Changes in regional growth curve parameters which imply temporal changes in extreme storm precipitation are examined with L-moments using both a 10-years moving window and the fixed decades 1990–99 and 2000–2009. Growth curves for the 5, 10, 15, 20, 30, 45, 60, 120, 180, 360, 720 min and 24-h precipitation are shown in Figs. 5, 6, 7 and 8.

There was a two-part change in occurrence of extreme events across the study area from 1987 to 2009. Few decadal level changes are seen in all extreme storm precipitation events. From 5- to 180-min precipitations, the growth curves have flattened and annual maxima have decreased (Fig. 5). However for 24-h precipitations (Fig. 5i), the growth curves have steepened and annual maxima have risen.

Using 5-, 10-, 15-, 20-, 30-, 45-, 60-, 120-, 180-min data precipitations from 15 stations located in the watershed of Lake Maggiore, regarded as a single, homogeneous group for this kind of event, we can deduce that recent short rainfall events have been less extreme than those previously recorded and that for 24-h precipitation, these events have increased in the last decade.

In terms of regional frequency change, the regional changes in growth curves are markedly different between sub-regions A, B and C and are mainly seen at 60, 360 and 720 min precipitations. In sub-regions A and B, growth curve became flatter over the last decade from 2000 to 2009. Growth curves for 60, 360 and 720 duration in sub-region A and B are shown in Figs. 6 and 7, respectively. In the sub-region C, the opposite change occurs, with the growth curve increasing in gradient spatially for the extreme events of 360 and 720 min (Fig. 8).

We found that recent extreme events during the 2000s have been less extreme than events recorded before. The annual maxima series also reveal many extreme events lasting less than 24 h in the 1990s. The decade from 2000 to 2009 was in fact, highly unusual in terms of 24 h precipitations over the whole study area and in terms of 360 and 720 min with reference only to sub-region C of the Lake Maggiore Watershed (stations: Candoglia, Domodossola, Fornarelli, Paione).

Taking account of these results and examining the historical data recorded, we found that the unusually high annual maxima precipitations during the 1990s are related to single events observed at a single station such as the event of 1 June 1998, when 55.6 mm of precipitation was recorded in 5 min at the station of Pallanza. During the 2000s, there were high annual maxima in 2000, related to the event of 14 October 2000. This resulted in Lake Maggiore flooding and caused great damage in Piedmont, with very large 1-day rainfall at some sites. At Paione, for example there was 406.8 mm rainfall, 4.6 times more than the decadal site median. Rainfall approximating 232.6 mm also occurred at Fornarelli, 204.8 mm at Sambughetto and 184.4 mm at Cicogna.

6 Conclusions

Do we really have a changing climate in the Lake Maggiore catchment? The impression from the international literature is that no one, in this region (Lake Maggiore), has ever found significant non-stationarity in extreme hydrological data, and this may merely be a scare story promoted by environmentalists exploiting the confusion between the natural phenomenon itself and the cost implications of the consequences of a flood.

This paper accordingly describes the regional frequency analysis, based on L-moments techniques, of annual maximum rainfall depths for storm durations ranging from 5 to 45 min and from 1 to 24 h observed in 15 stations across the watershed of Lake Maggiore with an average of 20 years of observations.

It would be remiss not to mention that many studies continues to emphasise the need for long-term period data for trend analysis of very rare events (Frei and Schär 1998). Indeed, one of the biggest problems in performing analysis of extreme climate events is the lack of long-term climate data with good quality (Easterling et al. 2000) and with the time resolution appropriate for analysing extreme events. Furthermore, much high resolution data remains undigitized. For our study, longer datasets are needed. Consequently, we have to use a methodology that consent to digitise numerous data on paper.

The large time variability of short-term precipitation requires that a sufficiently long-time series of rainfall input is used for this kind of hydrological calculations. Long rainfall series with high resolutions are necessary in order to observe a trend within the uncertainty margins (Vaes et al. 2002).

It is necessary to underline that the shortness of the period did not permit to do a rigorous statistical analysis; nevertheless, it provides important information in order to explain regional precipitation feature, especially extreme events and, above all, it concerns high temporal resolution data extended to the whole Lake Maggiore watershed.

Our study shows little change in the frequency of extreme rainfall over parts of the study area and recent short rainfall events have been less extreme than events recorded before. This may due to natural climatic variability, climate change or both.

The study area can be regarded as one homogeneous region for some short term rainfalls (5, 10, 15, 20, 30, 45, 120, 180 min and 24 h) and heterogeneous for others (60, 360 and 720 min). Given this heterogeneity and using site characteristics, L-moments and Ward's method the study area was divided into three acceptably homogeneous regions.

The identification of a suitable regional distribution for each storm event was based on the L-moment diagram and a goodness-of-fit test. Growth curves were developed for each of 12 durations ranging from 5 min to 24 h. The estimated regional growth curves were different for the three sub-regions A, B and C, confirming the non-homogeneity of the whole region in terms of 60, 360 and 720 min precipitation. In fact, this approach can be regarded as a valid alternative to the VAPI (Arnell and Gabriele 1988; Gabriele and Arnell 1991; Gabriele and Iiritano 1994) project procedure (Italian regional frequency analysis carried out with TCEV distribution).

The results of this statistical analysis will be useful for sustainable territory management at local or larger scales, for the hydrologic design of structures that control storm runoff, and also for modelling water course systems and drainage.

It is anticipated that the research presented in this paper will be built upon to examine the further possibilities of:

- When the oldest data available (before the 1980s), currently in paper format, have been transformed to digital format, it will be possible to have a more complete view of evolution and trend of precipitation distribution, with particular focus on both heavy and extreme events.
- A comparison of the results of regional frequency analysis of extreme storm precipitation in the watershed of Lake Maggiore based on L-moments, with a regional analysis based on the TCEV.

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Chapter 2

Extreme rainfall events: Evaluation with different instruments and measurement reliability

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Extreme rainfall events: Evaluation with different instruments and measurement reliability

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Abstract

With regard to extreme events, it is well documented that an intensity of about 1 mm/min already represents an extreme intensity. Under alpine conditions, a precipitation event with an intensity of 3 mm/min has occurred. Therefore the rain gauges in this region have to be able to measure in this and even in higher intensity ranges. This study deals with basic automated Tipping-Bucket Rain (TBR) gauge, and Bulk precipitation samplers, which are able to hold more than 95% of the cumulative rainfall that are verified within the space of the week without losses during the extreme events and with minimal evaporation loss. Bulk samplers collected more rainfall than TBR gauges in 110 of 221 extreme events analysed over the past 10 years. In 17 extreme events an underestimation greater than 10% was evaluated. The objective was to single out the counting errors associated with TBR gauge, during extreme events, so as to help the understanding of the measured differences between instruments in the field. We want to determine if the automated precipitation gauge can provide a reliable and precise measurement of precipitation with particular interest regarding heavy and extreme events.

Keywords: extreme events, tipping-bucket rain gauge, Bulk sampler, underestimation, reliable

1- Introduction

The attention paid to accuracy and reliability in rainfall measurements is currently increasing, following the increased popularity of scientific and practical issues related to the assessment of possible extreme events trends and the mitigation of natural disasters like storms and floods (Lanza and Stagi 2009).

Errors in measurements from traditional and recently developed rain gauges are reported by various authors (Habib et al. 2001; Calder and Kidd 1978; Marsalek 1981; Maksimović et al. 1991; La Barbera et al. 2002; Molini et al. 2002; Siek et al. 2007), together with suitable proposed methods for either a posterior correction of the measured figures (Molini et al. 2005b) or calibration of the gauges (Humphrey et al. 1997; Lombardo and Stagi 2004). Tipping-bucket rain gauges are the most popular recording rain gauges used by many weather and hydrological agencies. Tipping-bucket rain gauges are known for providing high accurate measurements of low to intermediate intensity rainfalls. This type of gauge produces rainfall data in digital form which can be readily processed by computers. However tipping-bucket rain gauges are known to underestimate the rainfall at higher intensities because of the loss of rainwater during the movement of the bucket. Then at high rain rates a tipping-bucket gauge may suffer from underestimation problems due to the fact that it cannot keep up with heavy rain during a severe extreme event (Vasvári 2005). Allis et al. (1963) compared several rain gauges and concluded that, although differences were sometimes statistically significant, they were frequently so small in absolute magnitude that they were a little practical concern. La Barbera et al. (2002), Molini et al. (2001) and Habib et al. (2008) investigated the propagation of measurement errors in the most common statistics of rainfall extremes and found that mechanical errors of Tipping-Bucket Rain gauges may lead to biases in the assessment of the return period T of short duration and high intensity events quantified as 100% for T=100 years. The problems associated with adjusting the dynamics of these instruments (Russo et al. 1997) has been documented extensively. Molini et al. (2005a) present a methodology to minimize measuring errors particularly for heavy rainstorm events. Over the last 50 years the World Meteorological Organization has launched many large-scale international programs to develop adjustments to regular precipitation measurements. Since 2006 this organization has studied rain gauges and worked on checking their good functioning (WMO report n° 84 2006 and Report n°99 2009). A 2010 work session in Helsinki (WMO – N°1064, 2010) discussed the necessity for evaluating the methods and instruments used for measurements in the meteorological field, focusing on the need to obtain correct, homogeneous data, both for the statistical use of extreme events or of long time series based on correct data. As such, From 1 October 2007 to 26 June 2009, the Department for Meteorological Experimentation of the Air Force (ReSMA) of Vigna di Valle (Roma), in collaboration with Genoa University, conducted assessment of rainfall measuring instruments.

The main objective of this intercomparison in the field was to assess and compare counting and catching errors of both catching and non-catching type of rainfall intensity gauges (Vuerich et al. 2009; Lanza and Vuerich, 2009), with special consideration given to high rainfall intensities. Further objectives were to offer advice on improvements of instruments and precipitation measurements.

2- Precipitation measurement instruments:

Rain gauges are classified into recording and non-recording types. The latter include cylindrical and ordinary rain gauges, and measurement of precipitation with these types is performed manually by the observer (case of Bulk precipitation collector). Some recording types such as tipping-bucket rain gauges have a recorder attached to them, and remote readings can be taken by setting an automatic recorder at a site distant from the gauge itself to enable automatic observation. This study focuses on basic automated tipping-bucket rain gauge CAE-PMB2 and Bulk precipitation collector.

- CAE-PMB2 Rain gauge:

This type of rain gauge generates an electric signal for each unit of precipitation collected. The PMB2 is a tipping-bucket rain gauge with a resolution of 0.2 mm and collector area of 1000 cm2 +- 0.5%. The automated precipitation gauge CAE-PMB2 proved to be a reliable and precise device of automated measurements of liquid precipitation. The CAE sensor is conforming to standard W.M.O.

Technical Data of Rain gauge PMB2

- Resolution: 0.2 mm of rain
- Tipping-bucket with knife support
- Rain collection vessel surface: 1000 cm^2
- Reed magnetic contact
- Measurement range: 0-300 mm/h
- Working temperature: 0-60 ° C
- Size: 358x584 cm
- Weight: 7 Kg

- Bulk precipitation collector

The bulk collector consists of a funnel (plastic in our case) connected to a sampling bottle, which may be changed daily, weekly or even monthly. The main body of the collector (which contains the 2 litre bottle) is constructed from 195-145 mm diameter pipe depending on the rainfall of the area (fig. 1). This system is simple and does not require electrical power. It was designed to collect samples of precipitation falling as rain for chemical analysis in our institute but in addition it may be used as a reasonably accurate rain gauge like in our study.

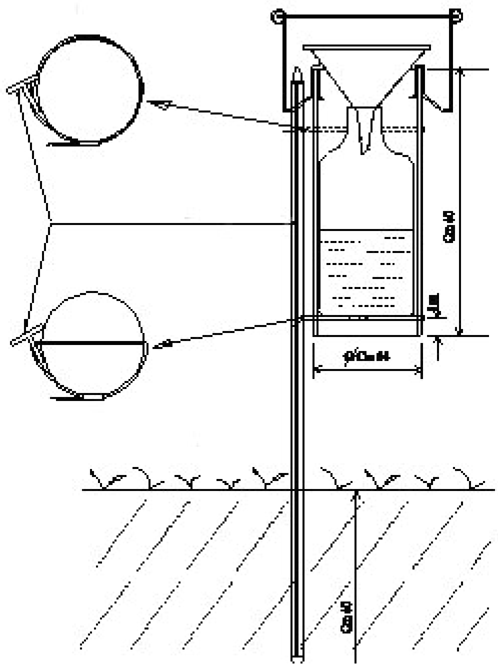

Figure1. Bulk precipitation Collector (Tartari et al., 2002)

3- Context and case study description

To check whether our automatic equipment (tipping-bucket rain gauges) was working effectively during specific extreme events, we confined our study to the Lake Maggiore region. Rainfall data from four (4) different stations was analysed over the course of approximately 20 years (1991-2010).

Approximately 99 meteorological stations were distributed fairly homogeneously inside the Lake Maggiore area (Fig. 1 - chapter 1) (Ciampittiello 2009a); these were and still are used to evaluate both the annual and seasonal evolution of the pluriannual rainfall trends. Some stations (Fig. 2) were selected to be checked for the correct functioning of the tipping-bucket rain gauges. Their characteristics and the data used are given in Table 1.

The selected stations are located in areas which differ both in altitude and geographical characteristics. Two are located at low altitudes (Pallanza and Domodossola) and two at a medium altitude (Monte Mesma and Lunecco) (Fig. 2) compared with the area in which they are located (Table 1). The Domodossola station is characterised by a more continental climate (Ciampittielo 1999b), while the Lunecco station is located in an enclosed, narrow valley (the Cannobino Valley).

Table 1 – Pluviometric stations used to check some extreme events.

ID	Stations	Altitude (m a.s.l.)	Catchment area	Data used
1	Pallanza	211	Lago Maggiore	1992-2009
2	Monte Mesma	575	Lago d'Orta	1999-2010
3	Domodossola Rosmini	277	Lower River Toce	2000-2010
4	Lunecco	662	Cannobino Stream	1991-2010

These stations were selected not only for their ability to continuously provide data, but also for their range of geographic and altitudinal characteristics.

However, they were selected primarily because they are close to a tipping-bucket rain gauge of the type PMB2 – CAE, and to a BULK rain gauge. Thus, we were able arrive at the total effective quantity of precipitation during the events studied. The height of the containers meant that more than 95% of the rainfall events occurring in a week can be retained, with no loss during the event and with a minimal loss through evaporation (CESI 2004). Tipping-bucket gauge measured and recorded 0.2 mm of rain each, whereas the Bulk was emptied weekly at all the stations, except for Pallanza, where they were emptied at the end of each rainfall event. The major events investigated are given in Table 1. Of duration between 5 minutes and 5 days, they are converted to weekly values to make them comparable with the rainfall collected by the Bulk and gauges.

Figure 2 – Monte Mesma. Pluviometric station, tipping-bucket rain gauge and Bulk

4- Data Retrieval

The continuously recorded tipping-bucket gauge data were analysed using a programme devised for the calculation of all intense events (every 5, 10, 15, 20, 30, 45, 60, 120, 180, 360, 720, 1440 minutes) starting from binary data, and aggregations for 1, 2, 3, 4, 5 days. The rainfall data were downloaded in binary format and processed from the modules of the CAE stations of Pallanza, Monte Mesma, Domodossola Rosmini, and Lunecco.

Binary data resulting from the memory module, were transformed into text format, then transferred automatically to an Excel archive at a daily, hourly and sub-hourly rate; a further, specially devised procedure was used for calculating and analysing short, intense periods of rainfall. This procedure allowed for data to be processed directly from all four station modules, as well as calculated the values of short, intense rainfall events for varying periods.

Using this system we produced tables at intervals of 5, 10, 15, 30 and 45 minutes, 1, 2, 3, 6, 12 and 24 hours, 1, 2, 3, 4 and 5 days for the stations of Pallanza, Monte Mesma, Domodossola and Lunecco for the period 1991-2010. From the different events considered, we checked the data and their effective duration: for example, a 5-minute event may be continued for longer, until we arrived at the reduction and the identification of the events in a single week, for each station and for the years analysed, so that we could compare these continuously measured data with those collected weekly in Bulk rain gauges.

5- Rainfall Statistics (Methodology)

A statistical analysis has been applied to paired variables (Tokay et al. 2008; Tokay et al.2010) represented by extreme rain events registered by CAE-PMB2 rain gauge and Bulk precipitation collector. The statistical analysis takes into account the Pearson correlation coefficient ρ , which is the ratio of the sample covariance of the two variables (x and y) to the product of the two standard deviations. It is expressed as

$$\rho = \frac{\mathrm{Cov}(x, y)}{\left[\mathrm{Var}(x)\mathrm{Var}(y)\right]^{1/2}} \qquad (1)$$

The Pearson correlation coefficient is neither robust nor resistant (Wilks 1995). It is not robust because a strong but nonlinear relationship between the two extreme events may not be recognized. It is not considered resistant because it is relatively sensitive to a single or few outlying point pairs. Since a high correlation coefficient alone does not guarantee a good agreement between the paired variables, a low bias should be satisfactory in this situation. Bias is indicative of the position of paired variables with respect to the diagonal (one to one) line (Tokay et al. 2008), and if one of the variables is taken as a reference, the bias indicates the underestimation or overestimation of the other variable like in our case of study. If the points were scattered at both sides of the one-to-one line, then the bias would be small but this does not guarantee good agreement in the absence of a high correlation coefficient. In this study, the bias β between the two variables is defined as:

$$\beta = \frac{1}{n}\sum_{k=1}^{n}(x_k - y_k) \qquad (2)$$

Where n is the number of paired variables (number of events). The standard deviation of the difference (SD) between the two paired of precipitation value provides a measure of the agreement between the two in terms of their distribution. Low standard deviation is one of the indications for the agreement between the considered paired of variables. The SD is expressed as:

$$SD(x - y) = \sqrt{Var(x) - Var(y) - 2Cov(x, y)} \qquad (3)$$

We consider one of the instruments as a reference (Bulk collector), then we can calculate the measurement error of the second instrument (CAE-PMB2 rain gauge). We employed absolute bias to quantify the measurement error of the CAE-PMB2 instruments. The bias in Eq. (2) equally weights all the paired variables. Extreme rainfall events with higher accumulation are of large significance, as they can result in flooding (Tokay et al., 2008). The weighted absolute bias $|\beta_w|$ is then calculated as

$$|\beta_w| = \sum_{k=1}^{n} w_k |x_k - y_k| \qquad (4)$$

Where w_k is the weighting function and is calculated based on the reference instrument

$$w_k = \frac{x_k}{\sum_{k=1}^{n} x_k} \qquad (5)$$

Unlike the correlation coefficient, the statistics used in this package are not normalized and carry the units of the variables (mm of precipitation in our case). Although the magnitude of the mean absolute difference between the two variables is significant in rainfall, the percent absolute bias, a normalized quantity, is widely used in rainfall statistics. If variable x is considered to be a reference, the percent absolute bias $\left|\beta_{percent}\right|$ becomes:

$$\left|\beta_{percent}\right| = \frac{\sum_{k=1}^{n}\left|x_k - y_k\right|}{\sum_{k=1}^{n} x_k} \qquad (6)$$

The criterions to judge the degree of agreements between the PMB2_CAE rain gauge and Bulk collector are:

- Bias < 5% Excellent
- 5% < Bias < 10% Very Good
- 10% < Bias < 15% Good
- 15% < Bias < 20% Reasonable
- 20% < Bias Poor

6- Results

6- 1-Dispersion and relative deviation

Tipping-bucket rain gauges identified 63 extreme events at the Pallanza station, 49 events at the Monte Mesma station, 55 events at the Domodossola station, and 54 events at the Lunecco station. We then compared the data measured by the different rain gauges available, for each event and for each station, for a total of 221 events.

This comparison revealed that of the total of 221 events, there were 110 (50%) in which the Bulk collectors recorded a greater quantity of rain than was recorded by the tipping-bucket gauges; this occurred specifically in 24 events at Domodossola and Lunecco, 28 at Pallanza and 34 at Monte Mesma. It is hypothesized that the Monte Mesma station received a higher frequency of extreme events than the other stations analysed.

Figure 3 shows all the events at all stations during which the Bulk collectors recorded greater quantities of rain than the tipping-bucket gauges; this trend was more marked after 2002.

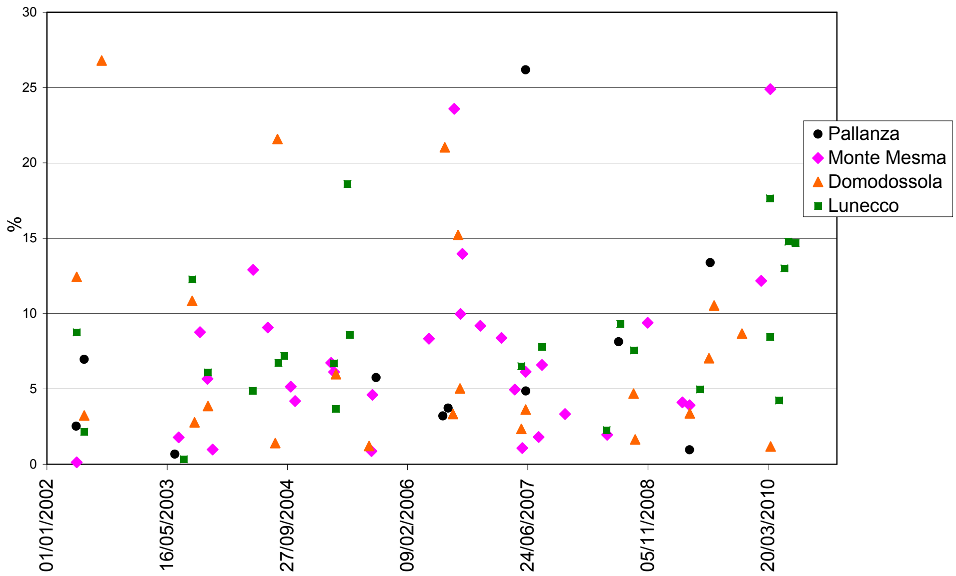

Figure 3. Percent deviation of the quantity of rainfall measured during intense events by Bulk collectors compared with PMB2 – CAE tipping-bucket gauges.

The graph shows that most events analysed had between 0 and 10% deviation (81 global events, or 76%); 11 events showed a deviation between 10 and 15%, with four events at the Lunecco station alone; 3 events had a deviation between 15 and 20%, of which 2 were at the Lunecco station, and 3 events recorded at Pallanza, Monte Mesma and Domodossola had a deviation between 25 and 30% although these were recorded in different years.

As for the intensity of the events recorded, this datum can be obtained only from the tipping-bucket gauges, and is therefore subject to underestimation (Tropeano and Turconi 2004; Turconi et al. 2008). Thus, it must be explored further. In summary, according to the events analysed up to now, the greatest deviation between the two different rainfall measurements occurred mainly at Domodossola, followed by Monte Mesma and Lunecco. The Pallanza station had a higher number of deviations but with percent values lower than those at the other stations. The data can be analysed on monthly and annual basis.

- Monthly deviations

The relative deviation of tipping-bucket rain gauges was negative across all stations, which implies that this instrument underestimated precipitation. (Fig. 4). Relative deviations of Monte Mesma, Domodossola and Lunecco show the highest underestimation of measured precipitation, even up to 20 %. Pallanza raingauge deviations are uniform and below 10% with only one exception in July (the lowest monthly amount of extreme events in Pallanza)

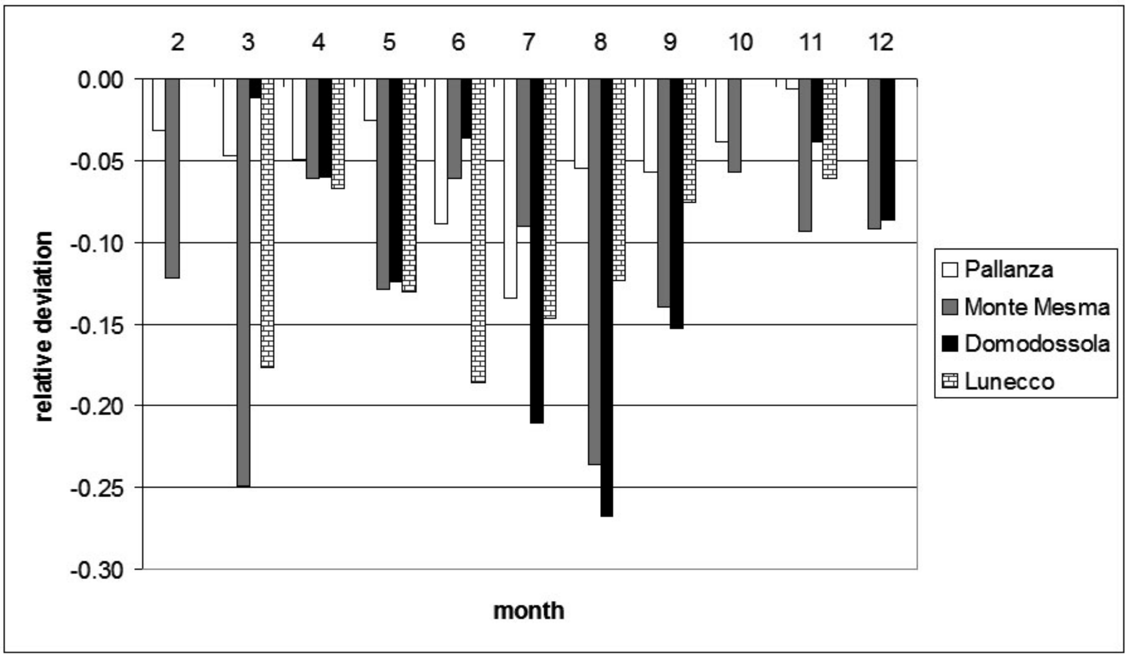

Figure 4. Monthly relative deviations of different stations rain gauges to the Bulk precipitation collector.

- Annual deviations

Figure 5 presents annual relative deviation. As with the monthly data, annual data also shows negative deviation, further supporting the fact that tipping-bucket rain gauge underestimates precipitation. Again Domodossola, Monte Mesma and Lunecco show the highest relative deviations.

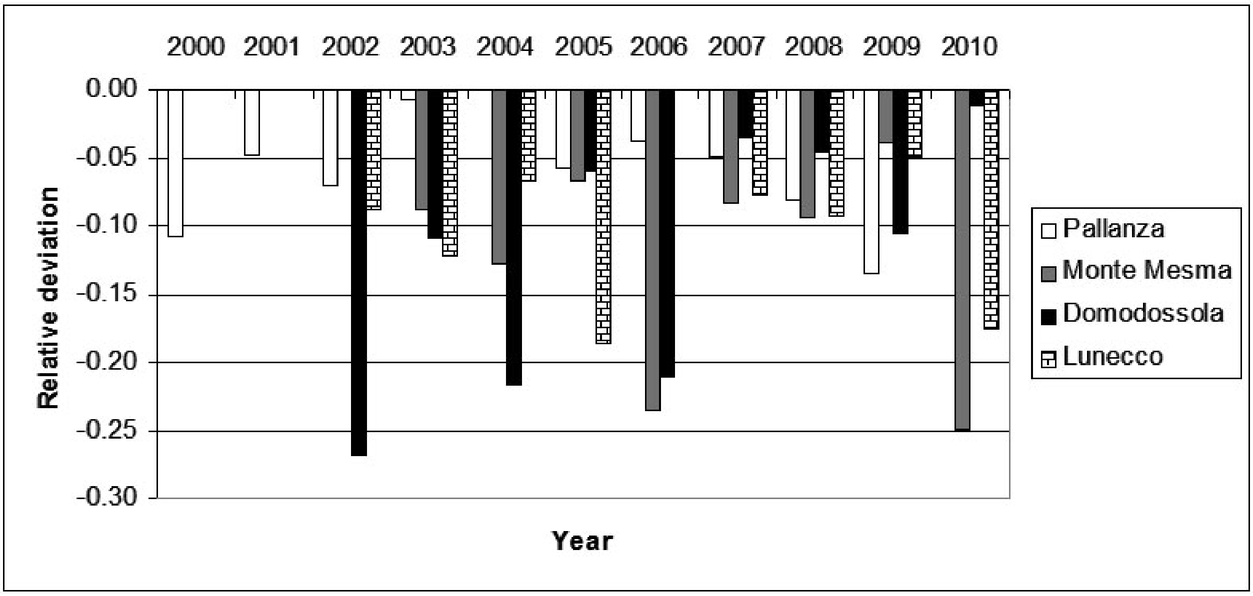

Figure 5 Annual relative deviations of different stations rain gauges to the Bulk precipitation collector.

- Dispersion of relative deviation:

The analysis of the range of the relative deviations is shown in Figure 6. Ends of the bar represent mean values ±1 standard deviation. Generally higher dispersion of the relative deviations is seen in July and August: this is likely due to lower amounts of precipitation in these months.

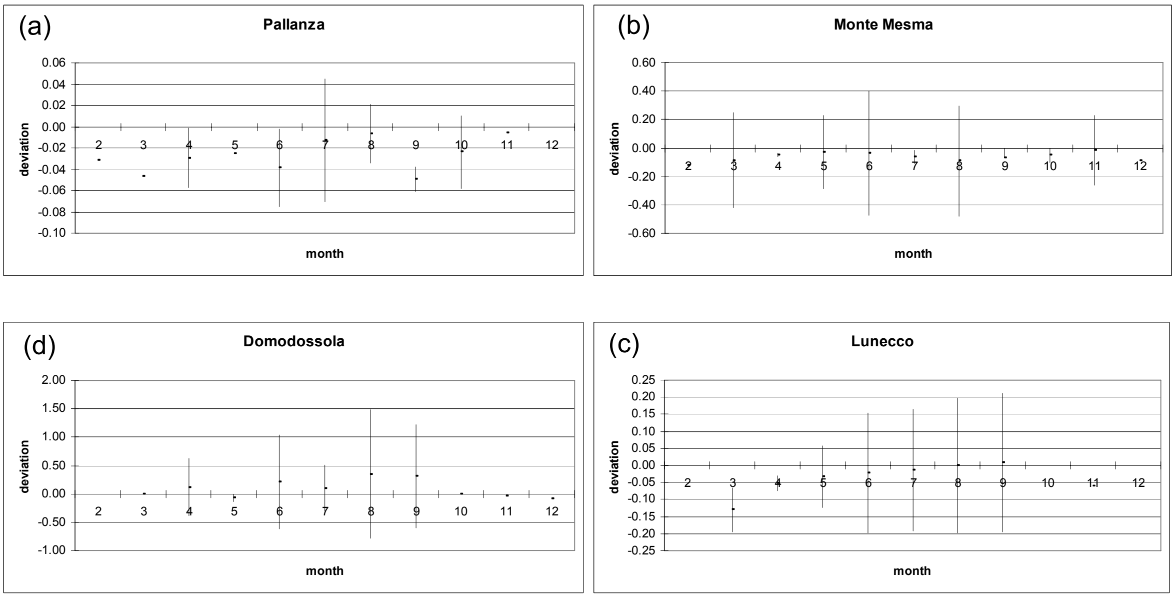

Figure 6 . Dispersion (mean +/- 1 stdev) of relative deviations of different rain gauges (a) Pallanza (b) Monte Mesma (c) Lunecco (d) Domodossola

6-2. Rainfall Statistics package

The results of rainfall statistics package are presented in Figure 7, 8, 9 and 10 for the four stations of this study.

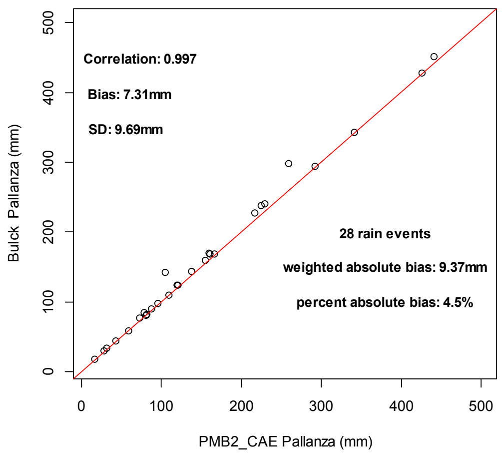

Figure 7. Comparison of rain events Pallanza

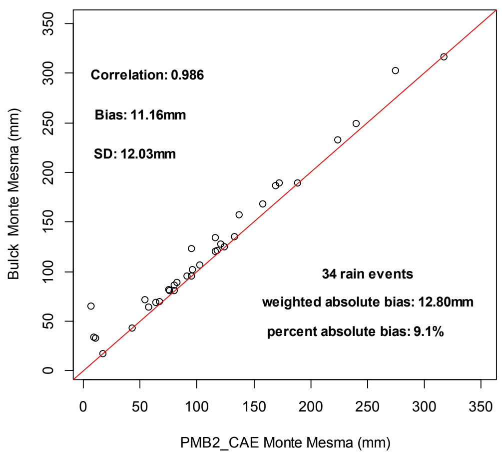

Figure 8. Comparison of rain events Monte Mesma

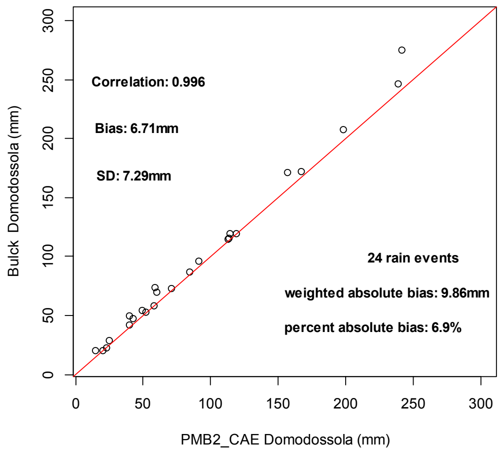

Figure 9. Comparison of rain events Domodossola

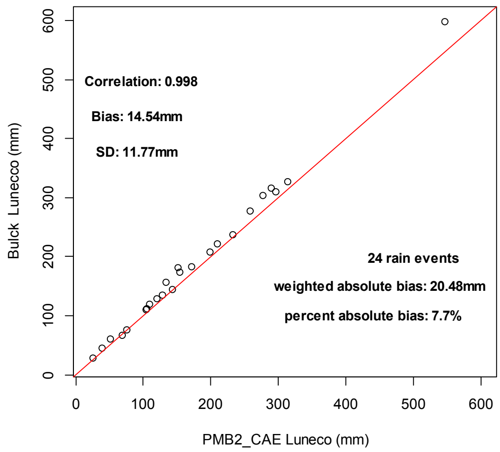

Figure 10. Comparison of rain events Lunecco

Considering the event-by-event comparisons for the station of Pallanza, the two different gauges, PMB2_CAE and Bulk, had excellent agreement with high correlation (fig. 7) and had a low absolute percent bias of 4.5%.

Despite the underestimation of extreme rainfall events registered by the PMB2_CAE gauges of Monte Mesma, Domodossola and Lunecco stations (fig. 4 and 5) the gauges were still highly correlated (figure 8, 9 and 10).

Statistically speaking, the stations of Pallanza, Monte Mesma, Domodossola and Lunecco proved a good agreement between the extreme precipitation values collected by the two different instruments. This shouldn't obscure the fact that difference in measured catches were apparent and in some cases with very high magnitude. The bias induced by systematic mechanical errors of tipping-bucket gauge (PMB2_CAE) is usually neglected in the hydrological practice, based on the assumption that it has little influence on the total recorded rainfall depth. Since the error increases in the case of extreme events, the assumption is not acceptable for the assessment of rainfall in hydrological applications.

7. Conclusions

In this study, it was generally found that CAE-PMB2 Rain gauge underestimated precipitation. Due to relative deviation comparison it could be said that rain gauges deployed in Domodossola and Monte Mesma showed the highest underestimation of measured precipitation. The registrations of these two stations showed the least regularity. Uniformity in registration was found for Pallanza rain gauge and its registration was the closet to Bulk precipitation collector may be because the latter is emptied at the end of each rainfall event.

The high number of intense events – 110 – which were underestimated (on average by about 7%) by the tipping-bucket rain gauges, makes it necessary to perform further research into the methods of measuring rainfall data, especially for extreme events. The importance of measuring extreme events using different methods at the same time and in different areas derives from the requirement to be able to provide correct, accurate measurements on which to base models, predictions of phenomena, and critical thresholds. Further comparison and investigations will be done.

This paper is intended to emphasize the intention of the scientific community to apply the results of studies in a specialised, concrete examination of the data, which can provide a reliable reconstruction of precipitation; it is also designed to highlight a critical evaluation of methods used to measure extreme data.

It is only through evaluations of this kind of data, and by a serious exploration of the situation, that we can further model specific phenomena, which are closely connected with meteo-pluviometrical events.

Despite the underestimation of extreme events by the PMB2_CAE gauge, a strong relationship between the two gauges in this study raised the authors' confidence to consider that other investigations and intercomparison of more than two different instruments is necessary and should be done in the future.

It's concluded that, while the measured values of precipitation during extreme event from the PMB2_CAE tipping-bucket gauge in the watershed of Lake Maggiore are satisfactory, the recorded values may not be reliable.

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Chapter 3

Trend in long term series of extreme rainfall events

Trend in long term series of extreme rainfall events

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Abstract

Intensification of heavy precipitation foreseen in climate change studies has become a public concern, but it has not yet been examined well with observed data, particularly with data at short temporal scale like hourly and sub-hourly data.

In this research we digitalized sub-hourly precipitation recorded at the stations of Vercelli (since 1927), Bra (since 1933), Lombriasco (since 1939) and Pallanza (since 1956) in order to investigate historical change in extreme short precipitations.

Besides seasonal and yearly maximum of precipitation we adopted two indices of extreme rainfall: the number of events above an extreme threshold (extreme frequency) and the average intensity of rainfall from extreme events (extreme intensity).

The results showed a statistically significant increase of the extreme frequency index and spring maximum precipitation for the station of Bra and Lombriasco. The extreme intensity index presented by the mean of events above 95th percentile is decreasing for Bra regarding hourly precipitation and increasing for Lombriasco regarding 20 minutes extreme events. For the station of Vercelli we noticed only a positive trend of the number of extreme events for hourly precipitation.

Thereby it cannot be said that recent sub-hourly and hourly precipitation has become unprecedently strong or frequent for all the stations and for all the extreme events duration.

Key words: trend, sub-hourly precipitation, extreme frequency, extreme intensity

1 Introduction:

Trend detection is an active area of interest for both hydrology and climatology in order to investigate climate changes scenario and improve climate impact research. The assumption of stationarity seems to be invalid as a result of anthropogenic influence and the natural variability of the climate system (Karpouzos et al. 2010). Therefore, trend detection in precipitation time series is crucial for planning regional water resources management and civil defence.

Climate simulations indicate that a warmer climate could result in an increase in the proportion of precipitation occurring in extreme events (karl et al. 1995). It seems to be generally accepted that the expected climatic changes are not necessarily associated with a higher intensity of extreme values, but rather with a higher frequency of the occurrence of extreme values. Recent studies (Easterling et al. 2000) analyzed the changes in observed heavy precipitation, based on daily precipitation, resulting in the detection of an increase in heavy precipitation at many parts of the world, with a decrease at some parts of the world. Due to the limitation of available digitalized records, as described above, daily precipitation has been the major material for analysis so far.

Some studies about the variation of heavy and extreme events were performed for the USA (Karl et al. 1995; Karl and Knight, 1998; Trenberth, 1998; Kunkel et al., 1999), Japan (Iwashima and Yamamoto, 1993), eastern and northeastern Australia (Suppiah and Hennessy, 1998; Hennessy et al. 1999; Plummer et al. 1999), South Africa (Mason et al. 1999), the UK (Timothy et al. 199, Osborn et al. 2000) and Italy (Brunetti et al., 2004, Brunetti et al., 2006).

Karl et al. (1995) and Karl and Knight (1998) observed a significant positive trend in the frequency of extreme rainfalls (greater than 50 mm per day) over the last few decades in the USA. For Australia, Suppiah and Hennessy (1996, 1999) showed a significant increase in the 90th and 95th percentiles, while Hennessy et al. (1999) and Plummer et al. (1999) showed increases in the 99th percentile. Iwashima and Yamamoto (1993) found that, in Japan, more stations recorded their highest precipitation events in recent decades. Brunetti et al. (2004, 2006) confirmed a strong decrease in precipitation trends over Italy, with a rainfall reduction of about 135 mm in the southern regions during the last 50 years.

Groisman et al. (1999) performed a study on heavy precipitation over a wide area comprising Canada and Norway (for the period 1900–1995), the USA and Australia (spanning the period 1910–1999), the Ex-former Soviet Union (1936–1994), Mexico, China, Alaska and Poland (whose data are available for the post-World War II period). They found an increase both in summer rainy days and in heavy precipitation frequency over the past century for the USA, Norway and Australia, but they found no significant trend for any other country where the series are shorter and/or have many missing data. In most of the analysed areas, the positive trend observed in rain intensity is generally associated with an increase in total precipitation. Groisman et al. (1999) studied the relationship between the increase in total precipitation and the frequency of heavy rain events.

Typical temporal scales of precipitation phenomena may suggest us to analyze precipitation records of shorter resolution than a day. Kanae et al, (2004) digitalized and investigated the hourly precipitation record since 1890 measured at the Tokyo observatory and proved an upward trend in heavy precipitation over Japan. They report that "many hourly heavy precipitation events (above 20 mm/hour) occurred in the 1990s compared with the 1970s and the 1980s".

In Alpine region the evidence is growing stronger that climate warming is accompanied by an increase frequency of intense precipitation events (Frei and Schär 1998, Frei and Schär 2000). Some previous studies (Saidi et al. 2012) took the advantage of utilizing sub-daily precipitation data for analysis of regional changes in precipitation in the watershed of Lake Maggiore where the Alps are the cause heavy and extreme events. The periods of the utilized data are generally limited to a few decades due to the availability of digital data. Recent progresses on digitalization method of old climatic data point out to us the importance of studying the changes in hydrological cycle with a longer record.

The purpose of this work is to investigate the variability of precipitation data collected in 4 different sites in the Piedmont region -Italy. The historical extreme rainfall series with high-resolution from 5 minutes to 30 minutes and above: 1, 2, 3, 6, and 12h collected at different gauges have been computed to perform a statistical analysis to determine whether the recent changes in frequency and magnitude of the rainfall extremes can be considered statistically significant. Trends are analysed both at the annual and at the seasonal scale. The implications of changes at the seasonal scale are particularly significant for water resource management processes related to seasonal cycles.

2 Data:

Understanding climate change demands attention to change in climate variability and extremes, but knowledge of the behaviour of these variables has been limited by the unavailability of long-term high-resolution data. The extending spread of new technological techniques over meteorological stations has made it possible to have high temporal resolution data (i.e. hourly and sub-hourly) and to collect them automatically.

Very few such stations are operated before 1980. Hence the time period available with sub-daily rainfall totals is quite short for conducting analyses on long-term changes we decided to transform the oldest data available, currently in paper format, to digital format. It will be possible to have a more complete view of evolution and trend of extreme events.

Given that still now we have only one station (Pallanza), in our study area (Lake Maggiore watershed), with sufficient data record length to justify a trend detection study, so we decided to add three other stations situated in Piedmont region: Vercelli, Bra and Lombriasco to verify and calibrate better the model analysis of long time series of extreme events. All the station are situated in plain and good allocated in the flat total area. Details of the location and the period of observation have been reported in table 1

Table 1. Main characteristics of meteorological station:

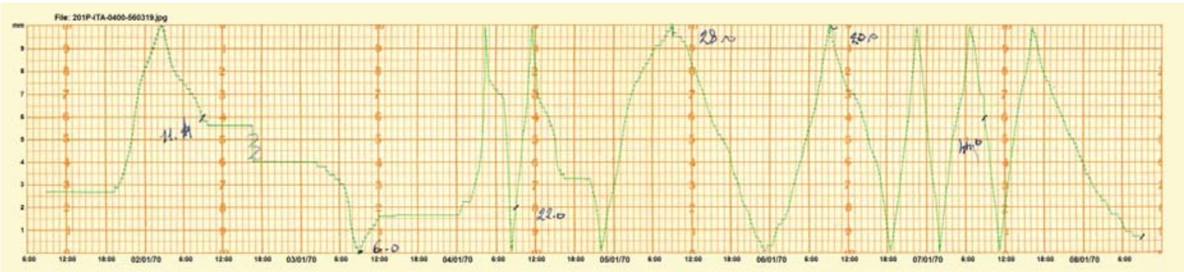
Station name	**Elevation m a.s.l**	**Location**		**Observation period Year**
		UTM_X	**UTM_Y**	
Pallanza	211	465025	5086015	1956-2003
Bra	290	409124	4950561	1933-2003
Vercelli	135	450886	5019210	1927-2003
Lombriasco	241	392509	4966637	1939-2003

As a matter of fact, several software dedicated to data digitization are available which allow the transcription of the paper-recorded data onto text files, after the acquisition of the tracks by a scanner as an image file (figure 1).

We used two kind of software, called Plot2data (Leonardi et al. 2006) and GetData Graph Digitizer (http://getdata-graph-digitizer.com), dedicated to the completely automatic reading of scanned images of records of precipitation. The same software provides the immediate storage of the resulting data on text files.

The conservation of the cartograms represents a critical factor. In fact, as years pass by, the paper gets dusty, spoiled and worm-eaten, while the tracks fade and become less and less readable, so that the longer is the delay in digitizing the cartograms, the more difficult is the retrieval of the recorded data and of the meteorological information stored therein.

The strip chart is converted into a file by means of a scanner as a true-colour (24 bit) image with a resolution of 150 to 200 depending on the size and quality of the cartogram.



.Figure 1. Exemple of rain gauge recorder chart

The tracks impressed on graph paper, once transformed into image files with the use of a scanner, are converted rapidly and accurately into numeric data files of a format chosen by the useradopting sampling times as low as 5 minutes.

By means of this software we obtained observations every 5 minutes interrupted by a brief gap every Mondays, corresponding to the time taken by the manual procedure necessary to replace the paper form on the rotating drum.

Then it's possible to recover within reasonable times the vast information stored in the voluminous paper archive from chosen stations: Pallanza, Lombriasco and Vercelli. Rainfall data from the stations of Bra are manually extracted from the charts. In the last case (Bra) the highest temporal resolution for the manually work is 1 h.

Quality check was applied to the digitalized dataset such as calculating daily totals from the dataset and comparing them with another independent daily precipitation dataset. The above procedure was carried out for the prevention of mistype.

3 Methods:

The definition of what constitutes an extreme event is debated. An extreme event may be selected based on frequency, intensity or threshold exceedance and physical expected impacts (Ntegeka and Willems, 2008). It depends on the intended use in design or future planning. Afterwards we explained which kind of indices we adopted in this study.

3.1 Indices of climate extremes:

In addition to yearly and seasonal maxima, two indices of extreme rainfall (Haylock and Nicholls, 2000) were calculated for each year in the period: the number of events above the long-term 95th percentile, referred to as the extreme frequency and the average intensity of rain falling in the highest events, referred to as the extreme intensity.

The extreme frequency index examines changes in the number of extreme events. In calculating this index, the authors selected to use the mean 95th percentile (which varies for each station), rather than following the method of Karl et al. (1995) involving a fixed threshold for all stations. A fixed threshold is impractical for our study area with a high spatial variation in rainfall intensity. The index is calculated by counting the number of events in the year with intensities above this threshold. This approach is similar to that used by Karl and Knight (1998) who considered changes in frequencies or probability of events above specified long-term percentiles. They proved that increases of total precipitation are strongly affected by increases in both frequency and intensity of heavy extreme precipitation events and the proportion of total annual precipitation derived from heavy and extreme precipitation events have increased relative to more moderate precipitation (not heavy precipitation).

The extreme intensity index incorporates changes in all events above the upper percentile. This index was calculated using two different methods: averaging the highest four events for each year and averaging all events above the long-term 95th percentile.

3.2 Mann-Kendall test:

All trends have been calculated using the test statistic Mann-Kendall test. Where a trend is indicated as 'significant', it has at least 95% significance using this test.

Mann–Kendall test (Kendall, 1962; Sneyers, 1990) is based on the comparison between the observed number of increases and decreases (jumps) and the values expected from random series. The occurrence of a trend is suggested if the null hypothesis of no trend is rejected when the level of significance is below a given threshold (here set at value $\alpha = 0.05$).

In this test, for each element y_i the number n_i of element y_j preceding it (i>j) is calculated such that $y_i > y_j$.

The test statistic t is then given by the equation:

$$t = \sum_i n_i$$

And its distribution function, under the null hypothesis is asymptotically normal, with mean and variance:

$$E(t) = \frac{n(n-1)}{4} \quad \text{and} \quad \mathrm{var}(t) = \frac{n(n-1)(2n+5)}{72}$$

The null hypothesis must therefore be rejected for high values of $|u(t)|$ with:

$$u(t) = \frac{[t - E(t)]}{\sqrt{\mathrm{var}(t)}}$$

In particular, if the probability α_1 is determined using a standard normal distribution table such that

$$\alpha_1 = P(|u| > |u(t)|)$$

The null hypothesis is accepted of rejected at the level α_0, depending on whether we have $\alpha_1 > \alpha_0$ or $\alpha_1 < \alpha_0$.

When the values of $u(t)$ are significant, an increasing or decreasing trend can be observed depending on whether $u(t)$ >0 or $u(t)$ <0

3.3 Peaks-Over-Threshold:

One of commonly used extreme value sampling is to pick the highest value per year, hence it generate annual maximum series whose sample size is identical with the number of years (Ny). It does not include all extreme values because any second highest would be dropped out of Ny samples. The other procedure is called Peaks-Over-Threshold (POT).

In this case extremes are extracted from a series by applying a threshold (in section 3.1 the threshold was 95% long term percentile), which implies that the analysis is valid only for those values above a certain return period. The selection of the threshold is, however, subjective. There is no universal technique used for the selection of the threshold. Lang et al. (1999) proposed that the selection of the threshold should be based on the distribution of the Peaks-Over-Threshold values and the hypothesis of the independency. Pickands (1975) stated that independent extremes extracted from a univariate series after applying a threshold can be fitted to a Generalized Pareto distribution (GPD).

Therefore, for practical applications, the threshold needs to be high enough to ensure that the extremes can be fitted to the extreme value distribution.

In the present study, the independency criterion is based on a procedure for extracting Peaks-Over-Threshold (POT) values for rainfall which is similar to that of extracting Peaks-Over-Threshold values for flows (Ntegeka and Willems, 2008). The independency criterion for rainfall events states that two consecutive events are independent if the occurrence of one event does not affect the occurrence of the other event. Ntegeka and Willems (2008) proposed for extreme value analysis based on rainfall series a minimum of 12 h inter-event time considering two events happening within the same day or night as one event.

The theoretical background of the POT method is based on the following fact: Excesses over a high threshold u can be modelled by a generalized Pareto distribution with the following distribution function:

$$G_{\xi,\beta}(x) = 1 - \left(1 + \xi \frac{x}{\beta}\right)^{-1/\xi} \quad \text{if} \quad \xi \neq 0$$

$$G_{\xi,\beta}(x) = 1 - \exp\left(-\frac{x}{\beta}\right) \quad \text{if} \quad \xi = 0$$

The procedure consists of choosing the subsequence { Xj } from the basic sequence that exceeds a threshold u, calculating the values { X_j -u } for those values that exceed the threshold u and estimating parameters ξ and β either by the L-moment method presented in Chapter 1.

4- Results and discussion

- Mann-Kendall test:

As mentioned above we tried to adopt several indices for heavy precipitation analysis, since there is not an only index to clarify the changes in the time series of heavy precipitation. Seasons were defined according to the standard meteorological definition: winter (DJF), spring (MMA), summer (JJA), autumn (SON).

A summary of the trends in extreme indices are summarized in table 2, 3 and 4 for all the stations.

It can be stated that the frequency of hourly heavy precipitation in case of the station of Vercelli is increasing (figure 2). For all the other series regarding this station the results showed no statistically significant (table2).

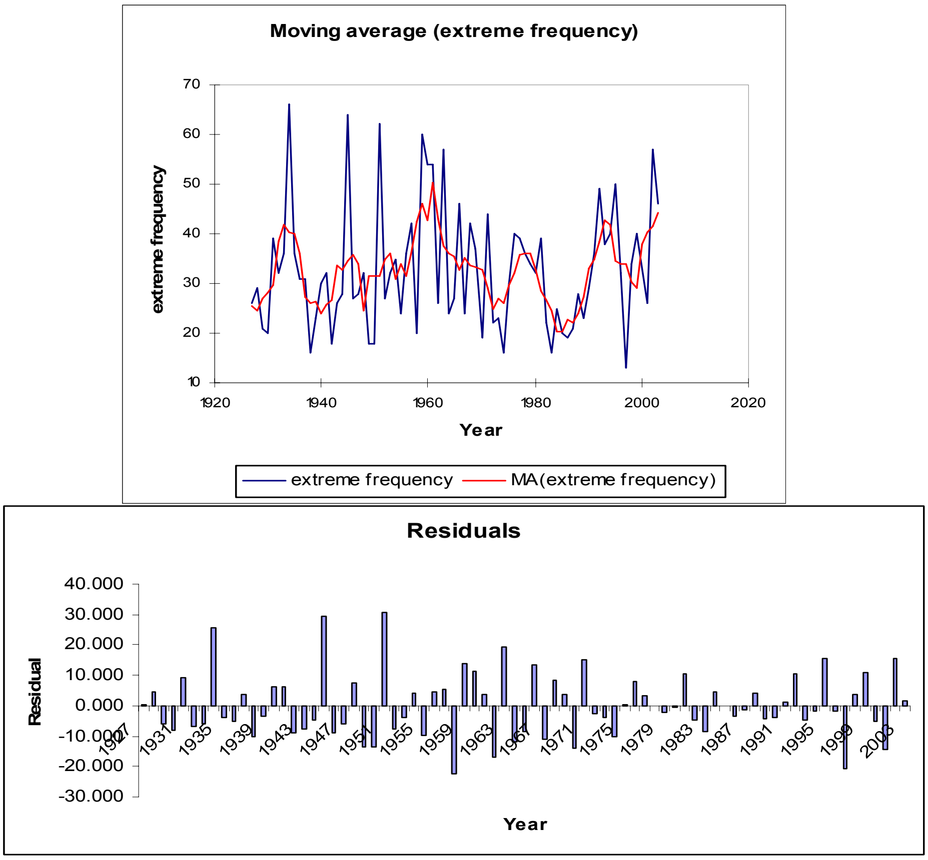


Figure 2. 5 year moving average of extreme frequency index for Vercelli (1hour precipitation) and residuals.

Of note is that, although statistically not significant, the test values, regarding many aggregation levels less than 1 hour (10min, 15min, 2min and 30min), indicated an increase of intensity and a decrease of frequency of this kind of extreme events registered in the station of Vercelli.

Table 3 and 4 show an increase in the extreme frequency index regarding the stations Bra (figure 3) and Lombriasco.

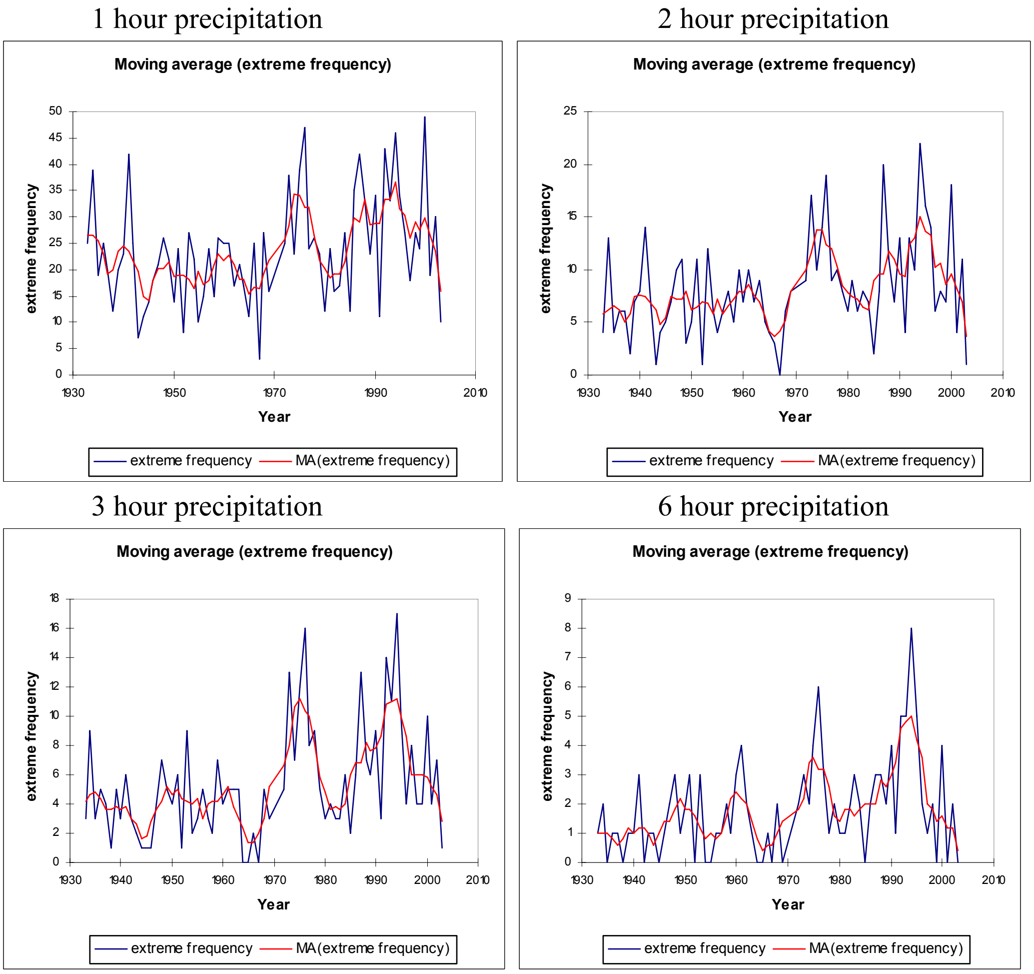


Figure 3. 5 year moving average of extreme frequency index for Bra (1, 2, 3, and 6 hour precipitation)

The mean of events above 95th percentile (extreme intensity) decreased in the case of heavy hourly precipitation for the station of Bra (figure 4)

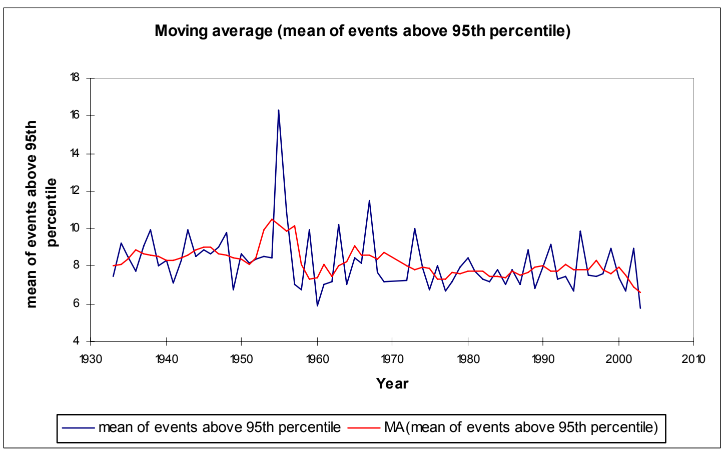


Figure 4. 5 year moving average of extreme intensity index for Bra (mean of events over 95th percentile:1 hour precipitation)

These trends imply significance change of the mean of the highest four event (extreme intensity) and the yearly maximum precipitation with duration of 12hours for the station of Bra (figure 5).

Frequently the trends are most similar between the index calculated from the four highest events and the events exceeding the long-term 95th percentile. The trend is generally strongest when the index is calculated using the average of events above the 95th percentile.

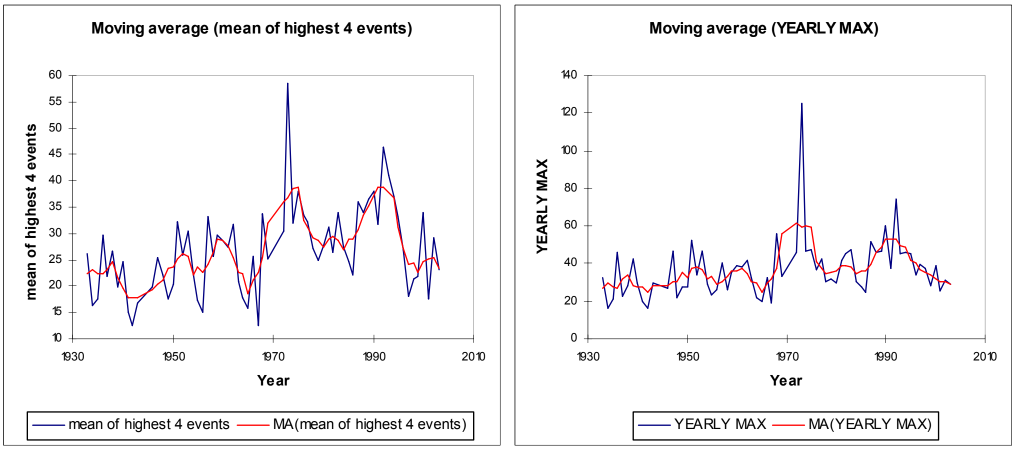


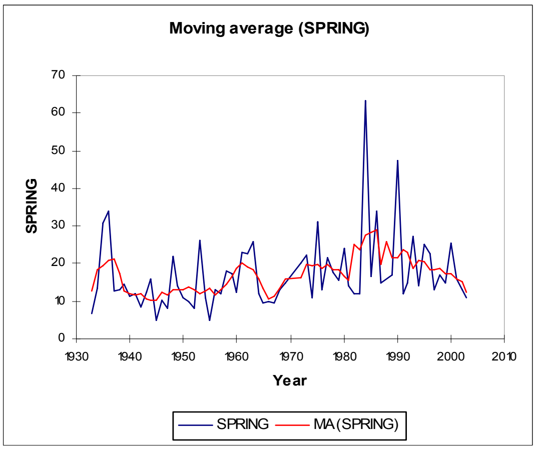
Figure 5. 5 year moving average of mean of highest 4 events and yearly maximum precipitation for Bra (12 hour precipitation)

In most cases, the positive sign of the trend in the extreme intensity index matches the trend in spring maximum precipitation (figure6).

Changes and increase of extreme precipitation frequency coincide with decrease of storm intensity in the case of heavy hourly precipitation registered in the station of Bra. This may pose a number of problems for water resource managers.

3 hour precipitation

6 hour precipitation



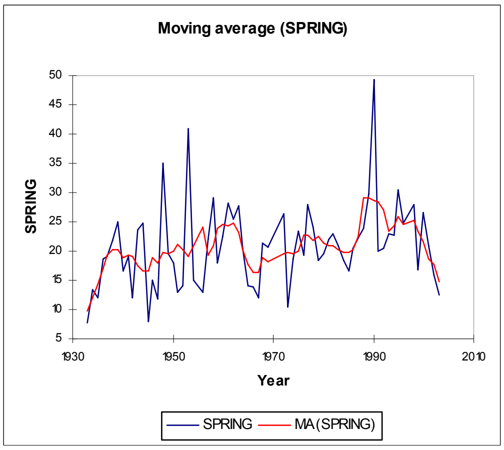


Figure 6. 5 year moving average of spring maximum precipitation for Bra (3 and 6 hour precipitation)

Table 2: Result of the application of Mann-Kendal test to Extreme precipitation indices for the station of Vercelli

Site	duration	index		Kendall's tau	Significance level (Upper threshold :0.05)	Series with significant trend
Vercelli	5min	WINTER		-0.014	0.880	NS
		SPRING		0.074	0.394	NS
		SUMMER		0.121	0.167	NS
		AUTUMN		0.013	0.882	NS
		YEARLY MAX		0.138	0.112	NS
		extreme frequency		0.022	0.799	NS
		extreme intensity	mean of events above 95th percentile	0.042	0.626	NS
		extreme intensity	mean of highest 4 events	0.108	0.209	NS
Vercelli	10min	WINTER		-0.014	0.883	NS
		SPRING		0.030	0.728	NS
		SUMMER		0.120	0.172	NS
		AUTUMN		0.056	0.516	NS
		YEARLY MAX		0.137	0.116	NS
		extreme frequency		-0.018	0.835	NS
		extreme intensity	mean of events above 95th percentile	0.106	0.219	NS
		extreme intensity	mean of highest 4 events	0.115	0.183	NS
Vercelli	15min	WINTER		-0.051	0.578	NS
		SPRING		0.095	0.271	NS
		SUMMER		0.040	0.652	NS
		AUTUMN		0.030	0.731	NS
		YEARLY MAX		0.068	0.434	NS
		extreme frequency		-0.001	0.995	NS
		extreme intensity				
			mean of events above	0.073	0.401	NS

			95th percentile			
			mean of highest 4 events	0.086	0.319	NS
Vercelli	20min	WINTER		-0.083	0.359	NS
		SPRING		0.087	0.316	NS
		SUMMER		0.034	0.695	NS
		AUTUMN		0.061	0.488	NS
		YEARLY MAX		0.053	0.539	NS
		extreme frequency		-0.025	0.780	NS
		extreme intensity	mean of events above 95th percentile	0.081	0.348	NS
			mean of highest 4 events	0.070	0.417	NS
Vercelli	30min	WINTER		0.005	0.963	NS
		SPRING		0.044	0.618	NS
		SUMMER		0.068	0.434	NS
		AUTUMN		0.027	0.762	NS
		YEARLY MAX		0.061	0.480	NS
		extreme frequency		-0.055	0.533	NS
		extreme intensity	mean of events above 95th percentile	0.126	0.146	NS
			mean of highest 4 events	0.057	0.513	NS
Vercelli	1h	WINTER		0.015	0.846	NS
		SPRING		0.054	0.495	NS
		SUMMER		0.017	0.833	NS
		AUTUMN		0.080	0.307	NS
		YEARLY MAX		-0.014	0.857	NS
		extreme frequency		**0.163**	**0.043**	**increase**
		extreme intensity	mean of events above 95th percentile	0.096	0.218	NS
			mean of highest 4 events	0.042	0.595	NS
Vercelli	2h	WINTER		0.017	0.829	NS
		SPRING		-0.002	0.986	NS
		SUMMER		0.040	0.607	NS

		AUTUMN		0.153	0.050	NS
		YEARLY MAX		0.034	0.666	NS
		extreme frequency		0.083	0.300	NS
		extreme intensity	mean of events above 95th percentile	0.050	0.521	NS
			mean of highest 4 events	0.079	0.310	NS
Vercelli	3h	WINTER		0.036	0.644	NS
		SPRING		0.007	0.929	NS
		SUMMER		0.004	0.965	NS
		AUTUMN		0.148	0.059	NS
		YEARLY MAX		0.048	0.538	NS
		extreme frequency		0.037	0.652	NS
		extreme intensity	mean of events above 95th percentile	0.066	0.398	NS
			mean of highest 4 events	0.046	0.559	NS
Vercelli	6h	WINTER		0.021	0.798	NS
		SPRING		0.020	0.798	NS
		SUMMER		0.069	0.391	NS
		AUTUMN		0.019	0.816	NS
		YEARLY MAX		0.066	0.401	NS
		extreme frequency		0.078	0.347	NS
		extreme intensity	mean of events above 95th percentile	-0.012	0.891	NS
			mean of highest 4 events	0.071	0.365	NS
Vercelli	12h	WINTER		0.009	0.913	NS
		SPRING		0.066	0.417	NS
		SUMMER		0.044	0.733	NS
		AUTUMN		0.099	0.224	NS
		YEARLY MAX		0.094	0.230	NS
		extreme frequency		0.138	0.122	NS
		extreme intensity	mean of events above 95th percentile	-0.168	0.160	NS

			mean of highest 4 events	0.102	0.191	NS

NS: non significant
In bold: significant level grater than 95%

Table 3: Result of the application of Mann-Kendal test to Extreme precipitation indices for the station of Bra

Site	duration	indices		values of u	Significance level (Upper threshold :0.05)	Series with significant trend
Bra	1h	WINTER		-0.157	0.062	NS
		SPRING		0.122	0.142	NS
		SUMMER		-0.088	0.288	NS
		AUTUMN		-0.027	0.752	NS
		YEARLY MAX		-0.034	0.686	NS
		extreme frequency		**0.195**	**0.020**	**increase**
		extreme intensity	mean of events above 95th percentile	**-0.212**	**0.010**	**decrease**
			mean of highest 4 events	-0.029	0.729	NS
Bra	2h	WINTER		0.019	0.828	NS
		SPRING		0.138	0.096	NS
		SUMMER		0.084	0.319	NS
		AUTUMN		0.069	0.410	NS
		YEARLY MAX		0.055	0.507	NS
		extreme frequency		**0.206**	**0.015**	**increase**
		extreme intensity	mean of events above 95th percentile	-0.020	0.816	NS
			mean of highest 4 events	0.095	0.250	NS
Bra	3h	WINTER		-0.032	0.704	NS
		SPRING		**0.210**	**0.011**	**increase**
		SUMMER		0.085	0.305	NS
		AUTUMN		0.059	0.475	NS
		YEARLY MAX		0.060	0.468	NS
		extreme frequency		**0.238**	**0.005**	**increase**
		extreme intensity				
			mean of events above	-0.049	0.569	NS

			95th percentile			
			mean of highest 4 events	0.110	0.183	NS
Bra	6h	WINTER		0.047	0.593	NS
		SPRING		**0.210**	**0.012**	**increase**
		SUMMER		-0.026	0.805	NS
		AUTUMN		0.142	0.085	NS
		YEARLY MAX		0.122	0.143	NS
		extreme frequency		**0.231**	**0.010**	**increase**
		extreme intensity	mean of events above 95th percentile	0.065	0.492	NS
			mean of highest 4 events	0.230	0.005	NS
Bra	12h	WINTER		0.147	0.138	NS
		SPRING		**0.204**	**0.025**	**increase**
		SUMMER		-0.047	0.795	NS
		AUTUMN		0.108	0.226	NS
		YEARLY MAX		**0.211**	**0.012**	**increase**
		extreme frequency		0.224	0.022	NS
		extreme intensity	mean of events above 95th percentile	-0.051	0.723	NS
			mean of highest 4 events	**0.292**	**0.0005**	**increase**

NS: non significant
In bold: significant level grater than 95%

Table 4: Result of the application of Mann-Kendal test to Extreme precipitation indices for the station of Lombriasco

Site	duration	index	Kendall's tau	Significance level (Upper threshold :0.05)	Series with significance trend
Lombriasco	5min	WINTER	-0.072	0.536	NS
		SPRING	-0.090	0.389	NS
		SUMMER	0.008	0.941	NS

		AUTUMN		0.099	0.335	NS
		YEARLY MAX		-0.002	0.993	NS
		extreme frequency		0.146	0.152	NS
		extreme intensity	mean of events above 95th percentile	0.092	0.368	NS
			mean of highest 4 events	0.065	0.527	NS
Lombriasco	10min	WINTER		-0.093	0.427	NS
		SPRING		-0.041	0.703	NS
		SUMMER		0.064	0.533	NS
		AUTUMN		0.103	0.313	NS
		YEARLY MAX		0.100	0.331	NS
		extreme frequency		0.127	0.212	NS
		extreme intensity	mean of events above 95th percentile	0.121	0.240	NS
			mean of highest 4 events	0.146	0.152	NS
Lombriasco	15min	WINTER		-0.170	0.107	NS
		SPRING		-0.032	0.762	NS
		SUMMER		0.114	0.267	NS
		AUTUMN		0.096	0.349	NS
		YEARLY MAX		0.167	0.098	NS
		extreme frequency		0.157	0.125	NS
		extreme intensity	mean of events above 95th percentile	0.112	0.276	NS
			mean of highest 4 events	0.146	0.152	NS
Lombriasco	20min	WINTER		-0.033	0.782	NS
		SPRING		0.034	0.747	NS
		SUMMER		0.070	0.491	NS
		AUTUMN		0.093	0.364	NS
		YEARLY MAX		0.182	0.074	NS
		extreme frequency		0.128	0.215	NS
		extreme intensity	mean of events above 95th percentile	**0.213**	**0.038**	**increase**

			mean of highest 4 events	0.155	0.126	NS
Lombriasco	30min	WINTER		-0.063	0.588	NS
		SPRING		0.111	0.291	NS
		SUMMER		0.080	0.436	NS
		AUTUMN		0.046	0.653	NS
		YEARLY MAX		0.185	0.069	NS
		extreme frequency		0.085	0.413	NS
		extreme intensity	mean of events above 95th percentile	0.104	0.311	NS
			mean of highest 4 events	0.131	0.199	NS
Lombriasco	1h	WINTER		0.018	0.847	NS
		SPRING		0.094	0.276	NS
		SUMMER		0.054	0.535	NS
		AUTUMN		0.059	0.494	NS
		YEARLY MAX		0.147	0.088	NS
		extreme frequency		-0.055	0.533	NS
		extreme intensity	mean of events above 95th percentile	0.126	0.146	NS
			mean of highest 4 events	0.057	0.513	NS
Lombriasco	2h	WINTER		0.027	0.765	NS
		SPRING		0.082	0.342	NS
		SUMMER		0.091	0.289	NS
		AUTUMN		-0.012	0.894	NS
		YEARLY MAX		0.169	0.050	NS
		extreme frequency		0.146	0.098	NS
		extreme intensity	mean of events above 95th percentile	0.058	0.502	NS
			mean of highest 4 events	0.131	0.129	NS
Lombriasco	3h	WINTER		0.043	0.632	NS
		SPRING		**0.182**	**0.034**	**increase**
		SUMMER		0.059	0.504	NS
		AUTUMN		0.060	0.487	NS

		YEARLY MAX		0.126	0.143	NS
		extreme frequency		**0.228**	**0.010**	**increase**
		extreme intensity	mean of events above 95th percentile	0.070	0.417	NS
			mean of highest 4 events	0.161	0.060	NS
Lombriasco	6h	WINTER		0.075	0.413	NS
		SPRING		**0.311**	**0.0003**	**increase**
		SUMMER		-0.154	0.118	NS
		AUTUMN		0.054	0.531	NS
		YEARLY MAX		0.164	0.057	NS
		extreme frequency		**0.241**	**0.0090**	**increase**
		extreme intensity	mean of events above 95th percentile	-0.001	0.990	NS
			mean of highest 4 events	0.163	0.057	NS
Lombriasco	12h	WINTER		-0.030	0.769	NS
		SPRING		-0.016	0.862	NS
		SUMMER		-0.017	0.965	NS
		AUTUMN		-0.137	0.155	NS
		YEARLY MAX		0.040	0.647	NS
		extreme frequency		0.086	0.395	NS
		extreme intensity	mean of events above 95th percentile	0.043	0.747	NS
			mean of highest 4 events	0.061	0.483	NS

NS: non significant
In bold: significant level grater than 95%

- Peaks-Over-Threshold series:

In this study we apply the POT model to rainfall data collected in the station of Vercelli (the longest historical time series available: 1927-2003) in order to investigate changes in growth curve in the last 20 years comparing the whole long time series which imply temporal changes in extreme storm precipitation (growth curves are examined with L-moments like in chapter 1). The peak-over-threshold extremes are extracted using R software (http://www.r-project.org/).

As this is a time series, we must select independent events above a threshold. First, we fix a relatively low threshold to extract more events. Thus, some of them are not extreme but regular events. This is necessary to select a reasonable threshold for the asymptotic approximation by a GPD.

From figure 7 a threshold value of 10mm should be reasonable for series of 1 hour precipitation. The selected threshold must be low enough to have enough events above it to reduce variance while not too low as it increases the bias. Thus, we can now re-extract events above the threshold 10mm.

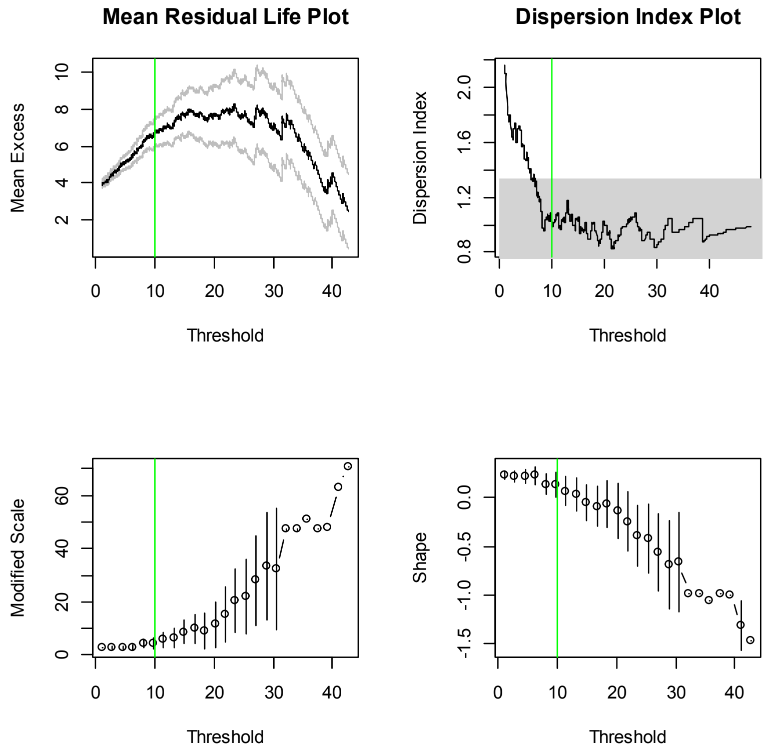


Figure 7. Threshold selection for 1 hour precipitation (Vercelli)

Figure 8 shows graphic diagnostics for the fitted model. It can be seen that this model seems to be appropriate.

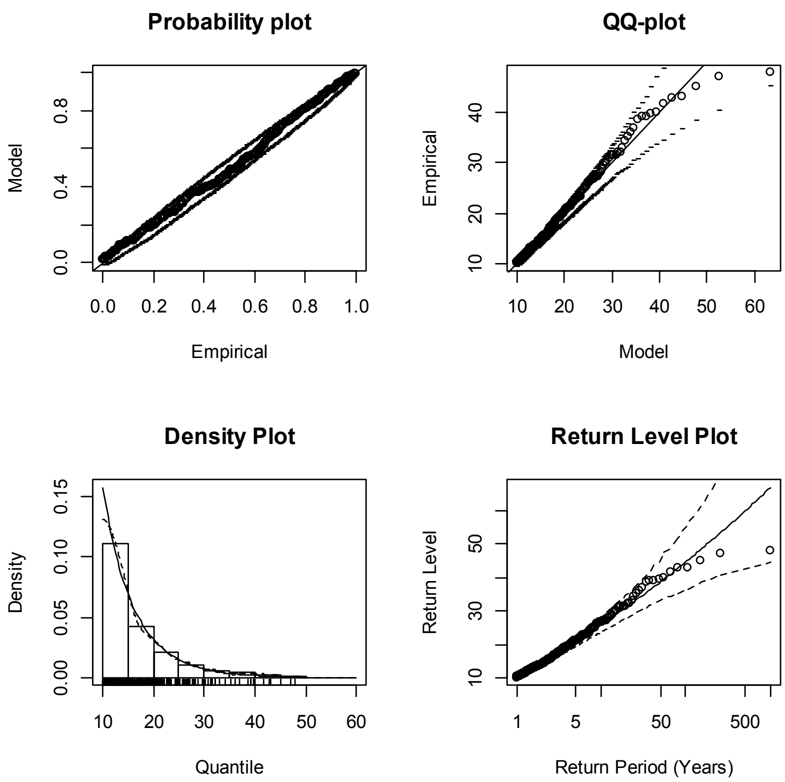


Figure 8. Graphic diagnostics for 1 hour precipitation (Vercelli)

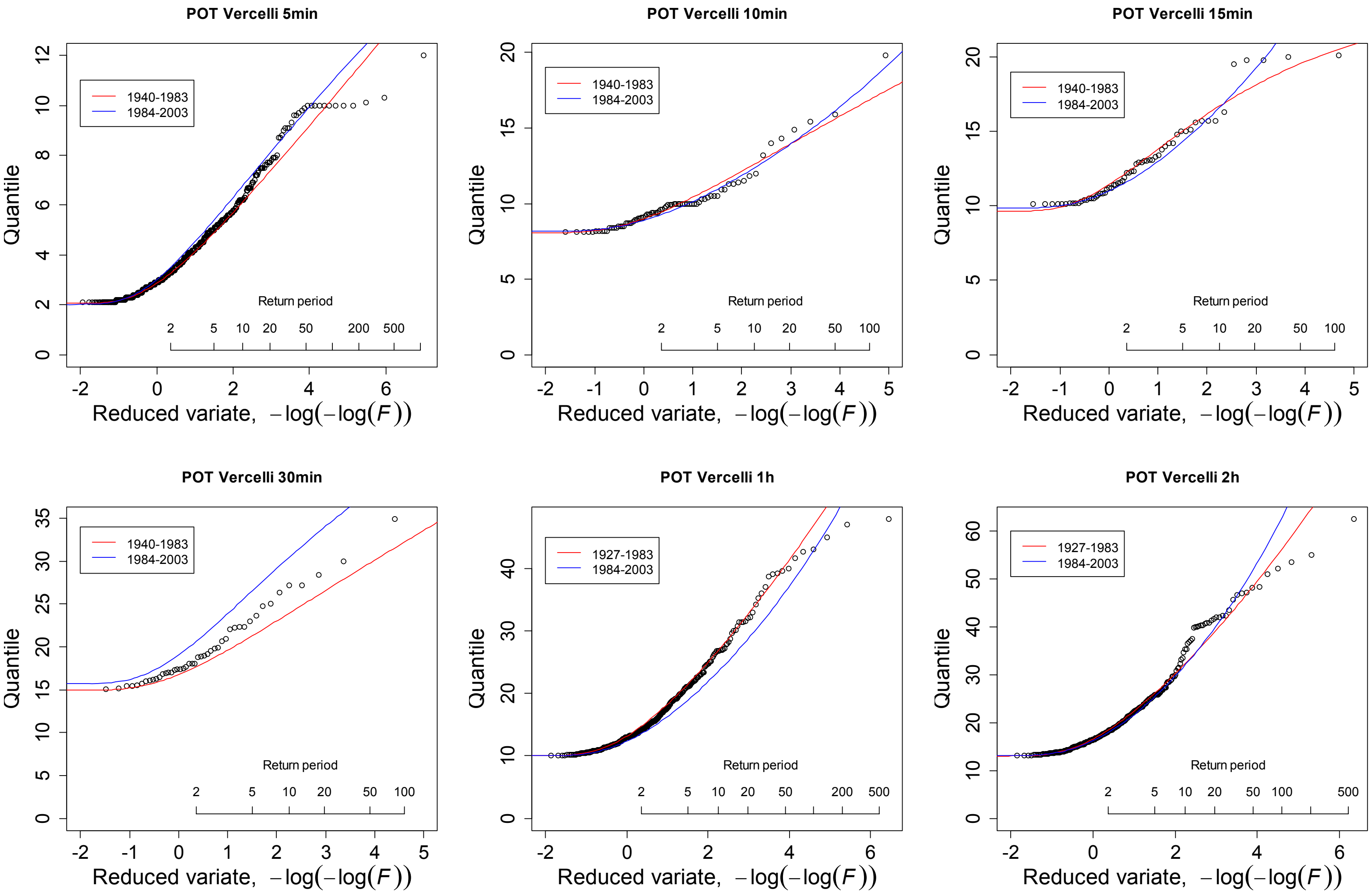
Table 5 shows the selected thresholds for the stations of Vercelli. These values are starting point for calculating POT series for every timescale.

Table5. Example of threshold above which POT series were derived: Vercelli

Timescale (h)	1	2	3	6	12
Threshold (mm)	10	13	15	25	34

POT series extracted from precipitation data collected in the station of Vercelli with high resolution (5, 10, 15, 20, 30 minutes and 1, 2, 3, 6, 12 hour) is used to produce growth curves with an extreme value distribution.

Figure 9 shows that growth curves has steepened and recent short rainfall events have risen during the last 20 years of our time series (1984-2003) except for POT series derived from 1 and 12 hour precipitations where we noticed a decrease of theses events.


POT Vercelli 5min
1940-1983
1984-2003
Return period
2 5 10 20 50 200 500
Quantile
Reduced variate, −log(−log(F))
POT Vercelli 10min
1940-1983
1984-2003
Return period
2 5 10 20 50 100
Quantile
Reduced variate, −log(−log(F))
POT Vercelli 15min
1940-1983
1984-2003
Return period
2 5 10 20 50 100
Quantile
Reduced variate, −log(−log(F))
POT Vercelli 30min
1940-1983
1984-2003
Return period
2 5 10 20 50 100
Quantile
Reduced variate, −log(−log(F))
POT Vercelli 1h
1927-1983
1984-2003
Return period
2 5 10 20 50 200 500
Quantile
Reduced variate, −log(−log(F))
POT Vercelli 2h
1927-1983
1984-2003
Return period
2 5 10 20 50 100 500
Quantile
Reduced variate, −log(−log(F))

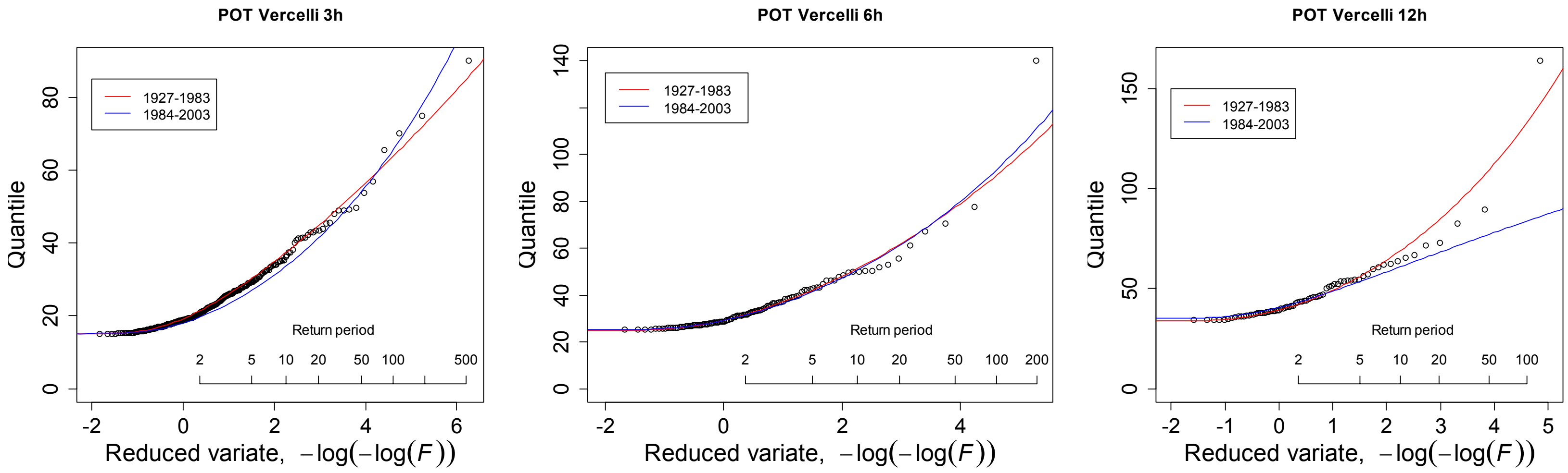


Figure 9. Changes in POT series compared to last 20 years (1984-2003

5- Conclusions

The aim of the present study was to analyse rainfall time series, detecting potential trends and assessing their significance. It's well known that one of the biggest problems in performing analyses of extreme climate events for most of the globe is a lack of access to high-quality, long-term climate data with the time resolution appropriate for analyzing extreme events.

We adopted an automated recovery of rain data from paper records of tipping-bucket rain gauges regarding four sites: Pallanza, Vercelli, Lombriasco and Bra situated in the Piedmont region in the north west of Italy. We obtained long time series of precipitation with high temporal resolution: 5, 10, 15, 20 and 30 minutes and above 1, 2, 3, 6 and 12hour.

For intense precipitation in Lombriasco and Bra the trend analysis has yielded substantial evidence of increasing trends in the extreme intensity index of this event. The increase was found also for spring, season that is characterized by high synoptic weather activity.

Globally we can say the analysis of extreme short precipitation series from 4 stations (Lombriasco, Vercelli, Bra and Pallanza) gave the following principal results:

- The extreme frequency index seems to have a positive trend for the station Bra and Lombriasco for only hourly heavy precipitations registered in the station of Vercelli.
- The extreme intensity index presented by the mean of events above 95^{th} percentile is decreasing for Bra regarding hourly precipitation
- On a yearly basis, maximum precipitation increased only for Bra with a time scale of 12 hour.
- On a seasonal basis, there is significant positive trend in spring maximum precipitation for Bra and Lombriasco.
- On a sub-hour scale we noticed a significant increase of the mean of events above 95^{th} percentile (extreme intensity) of precipitation with duration of 20 minutes registered in the station Lombriasco.

The use of Peaks-Over- Threshold method showed that extreme events have risen in the last 20 years (1984-2003) in the station of Vercelli.

The results obtained are consistent with those provided by Brunetti et al. (2004) for Italy and Burlando (1989) for Florence.

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Conclusions

In the **first Part** we described the regional frequency analysis, based on L-moments techniques, of annual maximum rainfall depths for storm durations ranging from 5 to 45 min and from 1 to 24 hour observed in 15 stations across the watershed of Lake Maggiore with an average of 20 years of observations. The study area can be regarded as one homogeneous region for some short term rainfalls (5, 10, 15, 20, 30, 45, 120, 180min and 24hours) and heterogeneous for others (60, 360 and 720min).

Given this heterogeneity and using site characteristics, L-moments and Ward's method the study area was divided into three acceptably homogeneous regions. The identification of a suitable regional distribution for each storm event was based on the L-moment diagram and a goodness-of-fit test. The results therefore affirm that our study manifests a little change in the frequency of extreme rainfall over parts of the study area and recent short rainfall events have been less extreme than events recorded before. This may due to natural climatic variability, climate change or both. Hence the time period available with sub-daily rainfall totals is quite short for conducting analyses on long-term changes we decided to transform the oldest data available (**third part** of this study**)**, currently in paper format, to digital format. It was possible to have a more complete view of evolution and trend of extreme events.

In the **second Part**, the inter-comparison of rainfall intensity gauges regarding automated tipping-Bucket Rain and Bulk precipitation samplers in four selected stations in our study (Pallanza, Domodossola Lunecco and Monte Mesma), during extreme events, shows that in 17 extreme events an underestimation greater than 10% was evaluated if we consider the Bulk sampler as reference instrument.

Due to relative deviation comparison it could be said that rain gauges deployed in Domodossola and Monte Mesma showed the highest underestimation of measured precipitation. In that cases the registrations of these two stations showed the least regularity. Uniformity in registration was found for Pallanza rain gauge and its registration was the closet to Bulk precipitation collector may be because the latter is emptied at the end of each rainfall event.

The importance of measuring extreme events using different methods at the same time and in different areas derives from the requirement to be able to provide correct, accurate measurements on which to base models, predictions of phenomena, and critical thresholds.

Finally in the **third Part** we adopted an automated recovery of rain data from paper records of tipping-bucket rain gauges regarding four sites: Pallanza, Vercelli, Lombriasco and Bra situated in the Piedmont region in the north west of Italy. Using this technique we obtained long time series of precipitation with high temporal resolution: 5, 10, 15, 20 and 30 minutes and above 1, 2, 3, 6 and 12hour.

The analysis of trend of extreme events, performed by the Mann-kendall test and some indices of climate extremes, gave the following principal results:

- The extreme frequency index seems to have a positive trend for the station Bra and Lombriasco for only hourly heavy precipitations registered in the station of Vercelli.
- The extreme intensity index presented by the mean of events above 95th percentile is decreasing for Bra regarding hourly precipitation
- On a yearly basis, maximum precipitation increased only for Bra with a time scale of 12 hour.
- On a seasonal basis, there is significant positive trend in spring maximum precipitation for Bra and Lombriasco.
- On a sub-hour scale we noticed a significant increase of the mean of events above 95th percentile (extreme intensity) of precipitation with duration of 20 minutes registered in the station Lombriasco.

It is anticipated that the research presented will be built upon to examine the further possibilities of:

- A comparison of the results of regional frequency analysis of extreme storm precipitation in the watershed of Lake Maggiore based on L-moments, with a regional analysis based on the Two-Component Extreme Value procedure (TCEV).
- Linking trends in rainfall extremes to trends in floods using various case studies.
- Verify if even weak trends in the mean of a distribution, which can go unnoticed, can cause surprising changes in the probability of exceedance of larger events and, hence, substantial changes in flood risk

Moreover, this kind of changes in the frequency and intensity of extreme events are surely having more impacts on environment and human activities than changes in the mean climate. Losses of life and very high economic damages have been experienced during recent flooding events in the last decade in Italy e especially in the watershed of Lake Maggiore. A vital question not only for our study area but also in all the world is, therefore, whether such events will occur stronger and more frequently in the future.