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# Rainfall variability from a dense rain gauge network in north-western Italy

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ABSTRACT: The aim of this study was to investigate the spatial and temporal distribution of rainfall in Piedmont, a region in north-western Italy, in order to evaluate the high intensity precipitation events that occurred in the 2004–2016 period. A daily precipitation series of 211 ground stations, belonging to 2 different meteorological monitoring networks, were analysed. As at first step, a quality control was performed on the daily precipitation series to evaluate the homogeneity of the series. The annual rainfall events were spatialised, using the ordinary kriging method, considering the whole set of weather stations. Moreover, 5 climatic areas were identified through a cluster analysis method. In order to better understand the extreme rainfall events, the main climatic precipitation indices were calculated, using ClimPACT2 software, and the thresholds by percentile were calculated for each cluster on a daily scale to identify the different precipitation types (weak, medium, heavy, very heavy [R95p]). Non-parametric (Kolmogorov-Smirnov and Wilcoxon) and parametric (Student's *t*-test) tests were applied to the annual and seasonal number of events observed for each rainfall class in order to study the statistical relationship between the clusters. The results lead to the conclusion that the investigated area is characterised by an increase in precipitation. Considering the extreme events, this methodology shows that even though the north sector is the wettest, central Piedmont is the area in which the highest number of extreme events was recorded.

KEY WORDS: Piedmont · Rainfall · Extreme events · Kriging · Cluster analysis

## 1. INTRODUCTION

Climate change is part of the natural 'life cycle' of our planet. In the history of the Earth, the climate has changed many times, even in a radical way. Much of the climate change that has been observed since 1950 has not only been dictated by natural causes, but also by human activities. In fact, many of these activities, which are mainly based on the exploitation of carbon and its derivatives, have had a strong and irreversible impact on global ecosystems (terrestrial, marine, freshwater) (IPCC 2014a). In the last few years, the Mediterranean region has been affected a great deal by climate change (Drobinski et al. 2016). Owing to the specific characteristics of this region, climate change may have a wide-ranging impact that could affect the socio-economic and production sectors as well as the environment (e.g. Fazzini et al. 2004, Davis & Hanna 2016). The effects of climate change are not only the result of a decrease in the total rainfall amount. In this regard, the increasing long periods without precipitation during the rainiest season, which have led to desertification in some areas in the world, are of particular interest (IPCC 2014b). For this reason, rainfall changes are widely recognised as an important factor in the control of environmental processes (Meersmans et al. 2016). In fact, it has been recognised that changes in precipitation patterns can have important financial, social and ecological consequences. In the Mediterranean region, these changes are a response to the climate change that took place in the 20th century (Queralt et al. 2009). However, observations of precipitation changes as a result of climate change remain un-

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clear. As stated by the IPCC (2013), 'confidence in precipitation changes averaged over global land areas since 1901 was low prior to 1951 and medium afterwards' (Scherrer et al. 2016). The study of precipitation events and their frequency is very important for understanding why they happen, and for determining whether there are any signs or periodicities (Boccolari & Malmusi 2013). In this context, the IPCC introduced a Special Report on Extreme Events (SREX) in which the main extreme events of relevance to society and ecosystems were registered in order to study the relationship between climate extremes and their impacts (Skansi et al. 2013). Moreover, the Expert Team on Climate Change Detection and Indices (ETCCDI) developed a set of climate change indices to facilitate the investigation of extreme temperature and precipitation events (Kharin et al. 2013). The development of the indices includes a free user-friendly software package written in R (ClimPACT2) and a website that has been developed to describe all the indices, the quality control procedures and references to relevant literature (Sillmann et al. 2013).

Several efforts have been devoted to the study of extreme rainfall events, and trends of these events have been obtained for southern and central America (Haylock et al. 2006, Zandonadi et al. 2016), Canada (Zhang et al. 2001), Japan (Iwashima & Yamamoto 1993) and Europe (Vicente-Serrano et al. 2010, Piccarreta et al. 2013). Several studies conducted on the rainfall trend in the Mediterranean area have shown conflicting results. Toreti et al. (2009) reported a decrease in the total precipitation in Italy. In fact, a reduction of about 10 to 20% was observed during the 1951–1995 period, with southern Italy showing a reduction of about 26%. Over a synchronous but longer period (1952–2002), Ciccarelli et al. (2008) showed no significant rainfall trends in northern Italy. Brunetti et al. (2004) indicated an increase in the period without wet days per year, which they linked to more intense precipitations, while the research of Boccolari & Malmusi (2013) showed a large increment in the rainfall amount. As far as the frequency of extreme wet events is concerned, Alpert et al. (2002) highlighted an increase in heavy and extremely heavy events (exceeding 128 mm $d^{-1}$) in Italy. On the other hand, Rodrigo (2010) showed a constant or decreasing number of extreme events. Over the last 50 yr or so, a tendency towards a decrease in number of rainy days and an increase in intensity has been found in Piedmont. Moreover, a significant increase in the number of events falling into the highest class-interval (comprising events above the 99th percentile) has been observed (Pinto et al. 2013). Piedmont is largely devoted to agriculture, and grape cultivation in particular; this region in fact produces some of the finest Italian red wines. More than 53000 ha of Piedmont are covered by vineyards, and they are mainly located in the plain and hilly areas (Biancotti et al. 2006). According to the results of a recent study (Acquaotta & Fratianni 2013), the increasing rainfall intensity trend in these sectors could have a serious effect on this type of cultivation. For this reason, this work could be considered a novel contribution to the study of extreme events in Italy, as the studies developed so far in Italy and Piedmont have only considered a limited number of meteorological stations (Ciccarelli et al. 2008, Bodini & Cossu 2010, Segoni et al. 2015), while we attempt here to provide a high-resolution analysis of extreme rainfall events throughout Piedmont. This is possible because rain gauges from 2 different meteorological monitoring networks are taken into account in order to obtain a high-density gauge network of stations spread over the whole study area. Furthermore, several studies have shown an increase in extreme events in the Mediterranean area in the last few years (Singh et al. 2013, Knapp et al. 2017), and these events have mainly been related to an increase in rainfall events, an extension of dry periods, and an increment in extreme wet and dry years. This study is an attempt, on the basis of the literature, to highlight the spatial and temporal distribution of extreme events in Piedmont (north-western Italy) over the period from January 2004 to December 2016.

The 2 main objectives of this study were:

- to make a climatic characterisation of Piedmont's plain and hilly zone, in order to quantify the spatial and temporal distribution of the annual and seasonal rainfall
- to analyse the spatial and temporal distribution of the current extreme rainfall events, and to identify the areas in Piedmont that are most affected by them

## 2. DATA AND METHODS

### 2.1. Study area

The area analysed in this work falls within the Piedmont region (north-western Italy). The region extends for 25402 km$^2$ and is made up of 3 geomorphological areas: mountains (43%), hills (30%) and plains (27%). The hilly area consists of the Turin, Langhe and Monferrato hills. The alpine mountain chain surrounds the region on 3 sides, and is located on the north-western border of Italy with France and

Switzerland. The plain area is in the central sector. It is made up of the Po plain, and is crossed by the Po river and its several tributaries (Garzena et al. 2015). The study area analysed in this work is characterised by 2 of the 3 aforementioned geomorphological areas: plains and hills. The selected rain gauges are located between 300 and 700 m above sea level (a.s.l.). Two main types of factors determine the thermal-pluviometric characteristics of Piedmont. The orography, which is the most important internal factor, controls Piedmont's climate, while the atmospheric circulation, with dry continental air flowing in from the Po Valley in the east and relatively moist Mediterranean and Atlantic air coming from the northwest, is the most important external factor (Fratianni et al. 2009, Giaccone et al. 2015). The annual distribution of precipitation in Piedmont is characterised by a bimodal trend, with 2 maxima (spring and autumn) and 2 minima (winter and summer). On the basis of the position of the main maximum, the secondary maximum and the main minimum, different types of pluviometric rates can be recognised in this area: a continental type, characterised by a main minimum in winter (prealpine, subcontinental and subalpine); and Mediterranean type, characterised by a main minimum in summer (subcoastal). Of these, 3 are continental (the main minimum in winter), while the fourth is Mediterranean (the main minimum in summer).

### 2.2. Dataset

One of the main problems with rainfall measurement is the low representativeness of a large area. Moreover, the observations made by a single station are only representative of a restricted area in the neighbourhood of a rain gauge (Lanza & Vuerich 2009, Mazza et al. 2014). For this reason, it is necessary to have a high density of rain gauges spread over the whole study area. Several networks, managed by public and local authorities, are available in Piedmont. In this study, the daily precipitation series of 2 independent automatic climate networks are analysed for the first time. These networks belong to:

- the Regional Agency for Environmental Protection (ARPA); this network was started in 1988 and is characterised by 400 monitoring stations, with a density of 1 instrument every 100 km$^{2.}$ The instrumentation used consists of a tipping bucket rain gauge, CAE PMB2, with a 1000 cm$^2$ diameter collector (Acquaotta et al. 2016)
- the agrometeorological network (RAM); this network has been active since the second half of the 1990s and is made up of 120 monitoring stations. These stations have been installed to support agricultural monitoring, and for this reason they are in the proximity of the main cultivation areas (e.g. vineyards, orchards). The RAM rainfall stations use a tipping-bucket SIAP UM7525 rain gauge with a 1000 cm$^2$ diameter collector

The selected rain gauges (Fig. 1) are located between 300 and 700 m a.s.l. According to the elevation zonation model described by Beniston et al. (2011), this is the lowest zone, known as the planar zone. Therefore, the selected stations identify the plain and hilly homogeneous area in Piedmont, 90 % of which is located between 300 and 500 m a.s.l. Rainfall over 700 m was not analysed, because the distribution of rainfall is affected to a great extent by the elevation, and for this reason the mountain climate is more variable than the climate in the plains and hills, which are characterised by orographic uniformity (Meersmans et al. 2016). A period of study was identified, 1 January 2004 to 31 December 2016, that provided a complete and homogenous database. Since the selected series come from 2 different meteorological

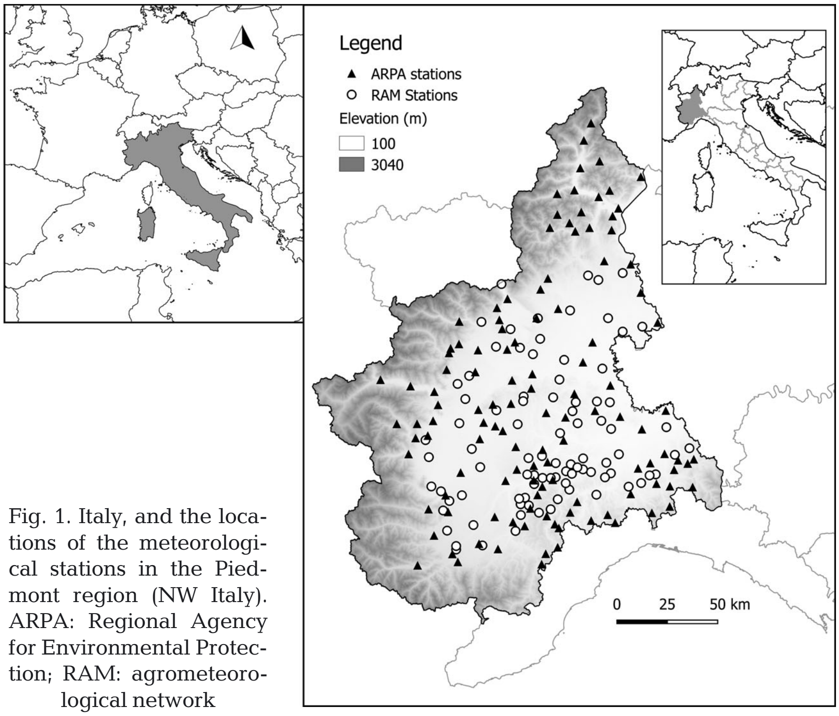

Fig. 1. Italy, and the locations of the meteorological stations in the Piedmont region (NW Italy). ARPA: Regional Agency for Environmental Protection; RAM: agrometeorological network

monitoring networks, it was necessary to verify whether they were comparable. The comparison was carried out using the free, open source script CoRain, which is written in R language (R Development Core Team 2011). This script uses an innovative analysis approach to compare 2 parallel rain series (with an overlapping period) (Guenzi et al. 2017) and is availed online (https://github.com/UniToDSTGruppoClima/CoRain) under GNU GPL v3 license (Free Software Foundation 2007). After having confirmed the comparability of each of the selected meteorological stations, accurate historical research was carried out to evaluate the homogeneity of the series. This involved detecting any breaks caused by changes in location or in the instruments in the stations during their activity. The historical research was carried out by consulting the registers of the stations, where any replacements of an instrument or changes in position are reported. The stations with such known problems were removed from the dataset. Fortunately no breaks were identified by historical research. Subsequently, each series was submitted to a quality control. For this, all questionable values, such as daily precipitation amounts of less than zero, were deleted. In addition, any daily rainfall data outliers were identified and flagged. An example of an outlier is a weekly accumulation being transcribed as the value for 1 day. The flagged outliers were compared with precipitation series from neighbouring stations (Klein Tank et al. 2009). Moreover, daily precipitation values of <1 mm in the series were deleted to prevent a set of small values that reflected changes in measuring precision from influencing the record (Wang et al. 2010). The obtained dataset was composed of 211 daily precipitation series measured in Piedmont from 1 January 2004 to 31 December 2016. In the first analysis carried out on the selected stations, the series showed continuity of the rainfall amounts over several years and <10% gaps. The average amount of daily rainfall data available for each series was 4290 values, and the total dataset was therefore composed of 905 000 values.

### 2.3. Data analysis

In this study, 211 daily precipitation series, recorded in Piedmont from 1 January 2004 to 31 December 2016, were analysed. Since rainfall offers a rather limited representativeness for large areas (Adhikary et al. 2015a), 2 geostatistical analyses were adopted: ordinary kriging and cluster analysis. First, considering the whole set of rain gauges, the annual precipitation data were spatialised on a regular 200 × 200 m cell grid, which had the following vertices, expressed in WGS84 UTM-32N cartographic coordinates: North 5159500 m 4871500 m South, East 562500 m 304500 m West (Pai et al. 2014). Because the selected stations in this study are located between 300 and 700 m, and elevation does not influence the rainfall distribution at this elevation, the spatial variation of precipitation was interpolated by means of the ordinary kriging method (Adhikary et al. 2015b, Ahmed et al. 2017), using the Automap package (Hiemstra & Hiemstra 2013), which is based on R software. This geostatistical approach is a well established rainfall spatial interpolation method (St-Hilaire et al. 2003, Webster & Oliver 2007). One advantage of kriging is its statistical manner, which improves the accuracy of estimates at grid points (Allard 2013). Once it was established that the rainfall was not homogeneously distributed in the study area, a cluster analysis (CA) was performed. CA is a statistical tool that is used extensively in climate studies to divide a study area into a limited number of homogeneous climate regions using, for example, rainfall data. Objects with the same features are classified in the same cluster, while dissimilar objects are assigned to different groups. Two types of clustering methods have been used in previous studies: hierarchical and non-hierarchical. The hierarchical method, which has been adopted in this study, is useful for a large volume of rainfall data (Ünal et al. 2003). Thus, different climatic areas were identified, based on the monthly rainfall amount, using Ward's method (Carvalho et al. 2016, Rau et al. 2017). This is an agglomerative technique where, starting from N clusters, the proximity matrix is calculated for the N clusters. In this matrix, the minimal distance between the clusters is measured and the 2 closest groups are combined. Once the matrix has been updated with the created cluster, this aggregation process is repeated until only 1 cluster remains (Iyigun et al. 2013). This method allows the optimum number of clusters to be identified through the depiction of a dendrogram, where the root represents a single cluster that contains all the data and the tops show each cluster generated by the partition (Türkeş et al. 2016). Climatic characterisation was then performed for each cluster, analysing the pluviometric regimes (Biancotti et al. 1998, 2005), the number of rainy days with rainfall ≥1 mm, the annual average precipitation and the annual rainfall density.

Moreover, in order to have a better understanding of the extreme rainfall events that occur in different climatic regions, the climate indices, established by the Expert Team on Climate Change Detection Monitoring and Indices (ETCCDMI 2003), were calculated for each daily precipitation series. (Sillmann et al. 2013). The ClimPACT2 software package (Alexander et al. 2015) was used for each series, and the following indices were observed on an annual basis:

- PRCPTOT, total precipitation in 1 yr; the sum of the precipitation amount measured in mm
- CWD, consecutive wet days; the number of consecutive wet days with precipitation ≥1 mm, measured in d
- SDII, simple daily intensity index; the total annual rainfall divided by the number of rainy days, measured in mm $d^{-1}$ (Acquaotta & Fratianni 2013, Skansi et al. 2013)

In order to establish the daily amount of rainfall that characterised each cluster, the thresholds by percentile were then calculated on a daily basis to identify the different precipitation types. The annual and seasonal percentiles of each cluster were calculated considering the daily series, and 4 classes of precipitation were established: weak, medium, heavy and very heavy (R95p) (Table 1) (Acquaotta et al. 2016). Once the daily thresholds had been identified, the annual and seasonal number of weak, medium, heavy and very heavy events that characterised each cluster was calculated. In order to compare the results obtained for each climatic area, the number of events was normalised, using the following equation: $S = n/d$, where $n$ is the number of recorded events and $d$ is the cluster dimension (number of stations). Finally, a statistical analysis was developed to evaluate the relationship between the normalised annual and seasonal number of event series of the 5 clusters. The parametric and non-parametric tests that were applied are:

- Student's *t*-test, which was used to evaluate whether each observed climatic area recorded the same mean of the normalised number of events
- the Kolmogorov-Smirnov test, which was adopted to evaluate whether the climatic areas had the same distribution for each rainfall class
- the Wilcoxon rank sum test, which was applied to observe whether the clusters had the same population medians

A p = 5% significance level was used for all tests. The selected tests were fitted so that the null hypothesis (H0) was that the 2 compared means, distribution or median are equal, while the alternative hypothesis (H1) was that the true differences in means, median or distribution are not equal to 0. If the p-value was >0.05 the alternative hypothesis (H1) was rejected.

Table 1. Names and ranges of the 4 precipitation classes, where R is the observed rainfall data

| Class | Range |
|---|---|
| Weak rain | R < 50th |
| Medium rain | 50th ≤R < 80th |
| Heavy rain | 80th ≤R ≤R95th |
| Very heavy rain (R95p) | R > 95th |

## 3. RESULTS AND DISCUSSION

In accordance with previous studies carried out by Acquaotta & Fratianni (2013) and the Piedmont Region (Biancotti et al. 1998), the annual average rainfall is greater in the northern part of the region, with peaks >1930 mm $yr^{-1}$ (recorded at Cicogna), while the driest area is the plain in the centre of Piedmont, with a total precipitation of <800 mm $yr^{-1}$ (Fig. 2b). The spatial interpolation also revealed that 2014 was the wettest year during the 2004–2016 period, while 2007 was the driest. The comparison with the annual average rainfall distribution shows that not only was the northern part of Piedmont characterised by abundant precipitation in 2014, but all the stations located in the south, at the foothills of the Ligurian Apennines, were also affected. The annual precipitation recorded in 2014 in these sectors was between 2000 and 3000 mm, much higher than the annual averages, which are between 1600 and 2300 mm. Furthermore, a drier area characterised by the stations located in the central plain of Piedmont was also observed in 2014. Between 900 and 1100 mm of rainfall was recorded in this area, 100 mm higher than the annual average rainfall (Fig. 2c). In 2007 (Fig. 2a), the spatialisation indicated a dry sector that was not limited to the Piedmont plain, but also extended to the Monferrato hills, where 300 to 400 mm of rainfall was recorded, 300 mm below the annual average rainfall distribution. The precipitation recorded in 2007 gradually increased towards the north, but no sector was observed where the rainfall amount was much higher than the surrounding area. A maximum of 1600 mm was observed in this surrounding area, which is significantly lower than the 2300 mm recorded for the annual average rainfall distribution. The spatial distribution of rainfall was improved through the cluster analysis (Fig. 3). The application of this method highlighted 5 clusters, corresponding to 5 climatic zones in Piedmont. Table 2 shows that there are 3 particularly rainy areas. The wettest is

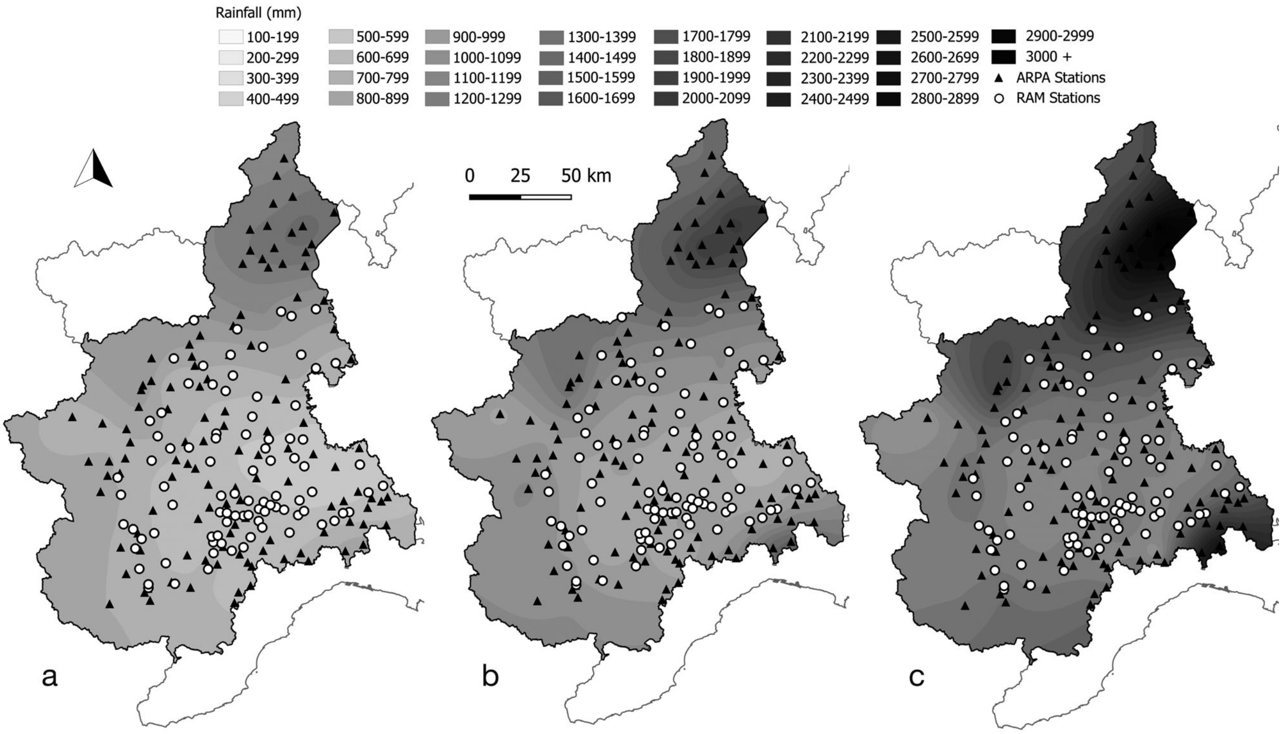

Fig. 2. Spatial distribution of rainfall in the Piedmont plains and hills for (a) the driest year (2007), (b) the study period (2004–2016) and (c) the rainiest year (2014). ARPA: Regional Agency for Environmental Protection, RAM: agrometeorological network

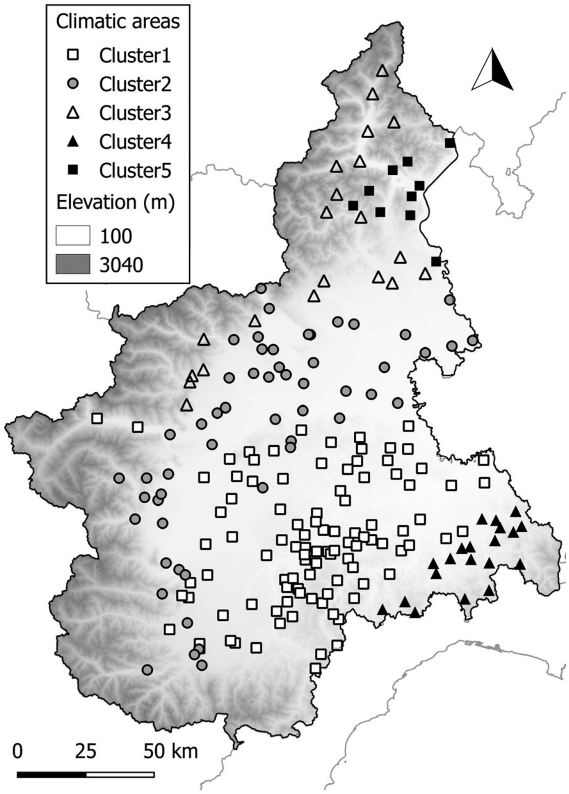

Fig. 3. Classification of rainfall into the 5 climatic regions that characterise the Piedmont region (NW Italy)

Cluster5, which includes the stations located in northern Piedmont. The annual rainfall is between 1699 and 1930 mm, and the precipitation is more concentrated, with an average density of 19 mm $d^{-1}$. The identified pluviometric regime is subalpine (maximum in autumn and spring, minimum in winter). The second wettest area is found in north-western Piedmont (Cluster3). The annual rainfall amounts are between 1500 and 1729 mm. The average density of precipitation is 14 mm $d^{-1}$, and the pluviometric regime is subalpine. The third area lies in the south-eastern part of the region (Cluster4), at the foothills of the Ligurian Apennines. The rainfall in this area is between 677 and 1800 mm. The average density is 12 mm $d^{-1}$, and the pluviometric regime is sublittoral (maximum in autumn, minimum in winter). The 2 driest areas are in the central part of Piedmont (Table 2). The first is Cluster1, which is characterised by an annual rainfall of between 618 and 950 mm. The average density is 11 mm $d^{-1}$, and the pluviometric regime is subalpine. The second includes the rain gauges located at the foothills of the Maritime and Graie Alps (Cluster2), and the annual amount of rainfall is between 815 and 1170 mm. The average density is 12 mm $d^{-1}$, and the observed pluviometric regime is prealpine (maximum in spring and minimum in winter).

Table 2. Maximum and minimum annual rainfall, density and seasonal rainfall distribution (pluviometric regime) recorded for each climatic region

| | Annual rainfall (mm) Max. | Annual rainfall (mm) Min. | Density (mm d$^{-1}$) | Pluviometric regime |
|---|---|---|---|---|
| Cluster1 | 950 | 618 | 11 | Subalpine |
| Cluster2 | 1170 | 815 | 12 | Prealpine |
| Cluster3 | 1729 | 1500 | 14 | Subalpine |
| Cluster4 | 1800 | 677 | 12 | Sublittoral |
| Cluster5 | 1930 | 1699 | 19 | Subalpine |

Table 3. Annual study of the daily rainfall thresholds using the 95th, 80th and 50th percentiles for each climatic region

| | 95th (mm) | 80th (mm) | 50th (mm) |
|---|---|---|---|
| Cluster1 | 35.8 | 17.2 | 6.2 |
| Cluster2 | 40.4 | 18.8 | 6.6 |
| Cluster3 | 51.6 | 22.6 | 7.4 |
| Cluster4 | 41.2 | 18.0 | 6.2 |
| Cluster5 | 68.2 | 29.0 | 8.8 |

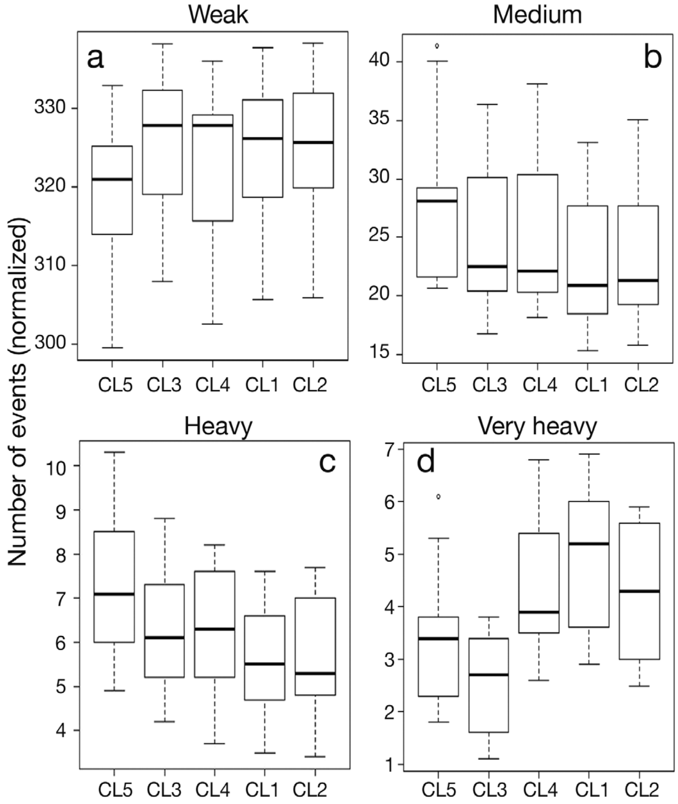

Fig. 4. The normalised annual number of rainfall events recorded in each climatic area for (a) weak events, (b) medium events, (c) heavy events and (d) very heavy events. Boxplots — midline: median; box: first and third quartiles; whiskers: maximum and minimum; circles: outliers

Compared with recent studies in northern Italy pertaining to the last few decades (Acquaotta & Fratianni 2013, Pieri et al. 2016), the results obtained from the index highlight an annual rainfall increment (PRCPTOT). This increase is more notable in the north (Cluster5), with 1906 mm yr$^{-1}$ recorded in the 2004–2016 period, and 1489.2 mm yr$^{-1}$ for the reference period (Acquaotta & Fratianni 2013). The value measured in central Piedmont (Cluster1) during the reference period was 639.4 mm yr$^{-1}$, and the annual rainfall average in the 2004–2016 period was 760 mm yr$^{-1}$. Moreover, a growth in the average density (SDII) was observed over the whole study area. This increase in density was only 1 mm d$^{-1}$ in the 2 driest clusters, while it was around 5 mm d$^{-1}$ in the north. Furthermore, neither an increase nor a decrease was noted for the number of rainy days (CWD). In fact, in the central part of Piedmont, the value was about 66 d for both periods, while 100 d were recorded in the north. A comparison with other Italian sites shows that the precipitation trends show remarkable differences overall, depending on the local conditions. In fact, Tomozeiu et al. (2006) reported an absence of or uncertainties in trends in north-western Italy for the period they analysed (1958–2000), as did Toreti et al. (2009) for a similar period (1960–2006). Diodato (2007) observed a decrease in precipitation in southern Italy since the 17th century, as did Liuzzo et al. (2016) during the period which started in 1910 and ended in 2010. As far as the central, western and eastern areas of the Mediterranean are concerned, Feidas et al. (2007) observed an annual decrease in rainfall for Greece for the 1955–2001 reference period, while Lorenzo-Lacruz et al. (2013) also observed a decrease in Spain during a similar period (1955–2005).

According to the spatial distribution, the annual rainfall classification shows that, for each precipitation type, the daily amounts were greater in Cluster5 than in Cluster1 or Cluster2 (Table 3). As far as weak rainfall is concerned, the box plot in Fig. 4a shows that the annual number of these recorded events was quite similar for each cluster, and was between 320 and 328 d. The statistical analysis, in agreement with the box plot, demonstrates that all the clusters are correlated with each other; the p-values of the *t*-test and the Kolmogorov-Smirnov and Wilcoxon tests are all >0.05 (see Table 5). Table 4 shows that the daily amount for weak rainfall events in each season was similar for each period, and the box plots show that the recorded number of these events in all the seasons was analogous for all the clusters. As far as the

Table 4. Seasonal study of the daily rainfall thresholds using the 95th, 80th and 50th percentiles for each climatic region

| | Daily rainfall threshold (mm) | | |
|---|---|---|---|
| | 95th | 80th | 50th |
| **Cluster1** | | | |
| Autumn | 45.4 | 20.8 | 7.6 |
| Spring | 34.4 | 18.2 | 6.6 |
| Summer | 33.6 | 15.4 | 5.6 |
| Winter | 30.2 | 13.8 | 5.0 |
| **Cluster2** | | | |
| Autumn | 52.2 | 22.8 | 8.2 |
| Spring | 39.0 | 19.6 | 6.8 |
| Summer | 37.0 | 16.6 | 5.8 |
| Winter | 34.1 | 15.8 | 5.6 |
| **Cluster3** | | | |
| Autumn | 70.2 | 28.2 | 9.0 |
| Spring | 50.0 | 23.8 | 7.8 |
| Summer | 45.0 | 19.4 | 6.8 |
| Winter | 40.6 | 18.2 | 6.2 |
| **Cluster4** | | | |
| Autumn | 57.8 | 22.1 | 7.4 |
| Spring | 35.1 | 16.8 | 6.2 |
| Summer | 33.4 | 16.6 | 5.6 |
| Winter | 36.6 | 16.8 | 5.4 |
| **Cluster5** | | | |
| Autumn | 92.6 | 40.8 | 10.8 |
| Spring | 62.3 | 29.8 | 9.6 |
| Summer | 62.2 | 25.2 | 7.6 |
| Winter | 45.2 | 22.2 | 7.8 |

Table 5. Annual p-values of the Student's *t*-test, and the Kolmogorov-Smirnov (KS) and Wilcoxon (W) tests for each rainfall class. A p = 5% significance level was used for all tests. In **bold** are p-values where the 2 compared series present a difference in means, median or distribution

| | Rainfall events | | | |
|---|---|---|---|---|
| | Weak | Medium | Heavy | Very heavy |
| *t*-test_CL5CL3 | 0.07 | 0.15 | 0.29 | 0.08 |
| *t*-test_CL5CL4 | 0.29 | 0.16 | 0.32 | 0.06 |
| *t*-test_CL5CL1 | 0.15 | **0.03** | **0.04** | 0.10 |
| *t*-test_CL5CL2 | 0.12 | 0.15 | 0.29 | 0.11 |
| *t*-test_CL3CL4 | 0.44 | 0.98 | 0.95 | **<0.001** |
| *t*-test_CL3CL1 | 0.71 | 0.38 | 0.42 | **<0.001** |
| *t*-test_CL3CL2 | 0.84 | 0.53 | 0.96 | **<0.001** |
| *t*-test_CL4CL1 | 0.70 | 0.37 | 0.38 | 0.48 |
| *t*-test_CL4CL2 | 0.58 | 0.52 | 0.98 | 0.69 |
| *t*-test_CL1CL2 | 0.87 | 0.80 | 0.36 | 0.27 |
| KS test_CL5CL3 | 0.29 | 0.59 | 0.57 | 0.57 |
| KS test_CL5CL4 | 0.57 | 0.30 | 0.57 | 0.29 |
| KS test_CL5CL1 | 0.29 | **0.03** | **0.04** | 0.13 |
| KS test_CL5CL2 | 0.57 | 0.30 | 0.57 | 0.13 |
| KS test_CL3CL4 | 0.88 | 1.00 | 1.00 | **0.01** |
| KS test_CL3CL1 | 1.00 | 0.59 | 0.88 | **<0.001** |
| KS test_CL3CL2 | 1.00 | 0.90 | 0.88 | **0.01** |
| KS test_CL4CL1 | 0.88 | 0.90 | 0.88 | 0.88 |
| KS test_CL4CL2 | 0.88 | 0.90 | 0.88 | 1.00 |
| KS test_CL1CL2 | 1.00 | 0.90 | 0.13 | 0.57 |
| W test_CL5CL3 | 0.29 | 0.59 | 0.57 | 0.57 |
| W test_CL5CL4 | 0.57 | 0.30 | 0.57 | 0.29 |
| W test_CL5CL1 | 0.29 | **0.03** | **0.03** | 0.13 |
| W test_CL5CL2 | 0.57 | 0.30 | 0.57 | 0.13 |
| W test_CL3CL4 | 0.88 | 1.00 | 1.00 | **0.01** |
| W test_CL3CL1 | 1.00 | 0.59 | 0.88 | **<0.001** |
| W test_CL3CL2 | 1.00 | 0.90 | 0.88 | **0.01** |
| W test_CL4CL1 | 0.88 | 0.90 | 0.88 | 0.88 |
| W test_CL4CL2 | 0.88 | 0.90 | 0.88 | 1.00 |
| W test_CL1CL2 | 1.00 | 0.90 | 0.13 | 0.57 |

medium (Fig. 4b) and heavy (Fig. 4c) rainfall events are concerned, the highest number of events was recorded in Cluster5. In fact, the annual number of medium precipitation events was 28 and was between 20 and 21 for the other clusters. The number of heavy events for Cluster5 was 7, while it was 5 for the other clusters. The number of heavy events for Cluster5 was 28 and was between 20 and 21 for the other clusters. The statistical analysis shows that there is no correlation between Cluster5 and Cluster1, while the other clusters are related to each other as far as the median, the average and the distribution of the number of events are concerned (Table 5). The seasonal study shows that the highest daily threshold for the 80th percentile was recorded in autumn (Table 4) and, according to the distribution of the annual rainfall, it was greater in Cluster5 with 40.8 mm d$^{-1}$. The box plots in Fig. 5 show that the medium and heavy events follow the annual distribution, while the statistical analysis reveals that Cluster5 is not correlated by the median, the average or the distribution of the number of events with the other clusters for medium events in summer. The heavy events in spring (Fig. 5) follow the annual statistic distribution, and there is no relationship between Cluster3 and Cluster1. This indicates that the 2 main rainiest clusters in spring are not correlated with the central area of Piedmont (Table 6). In fact, the main weather type in spring in north-western Italy, as observed by Nadal-Romero et al. (2014), is a perturbation from the north-east. This perturbation consists of low pressure over the Mediterranean area, and it affects the 2 sectors at the foothills of the western Alps in Piedmont. Finally, for very heavy events, the box plot (Fig. 4d) shows that, unlike the annual rainfall distribution, the highest number of these events was found in the driest sector (Cluster1). In fact, the annual number recorded in Cluster1 was 5, and was around 3 in Cluster5 and Cluster3. The statistical analysis, in agreement with what can be observed in the box plot (Fig. 4d), shows that there is a relationship between Cluster4, Cluster2 and Cluster1, while Cluster3 is not related to the central sector or to the southern one (Table 5). These high rates of very heavy rainfall in the central Pied-

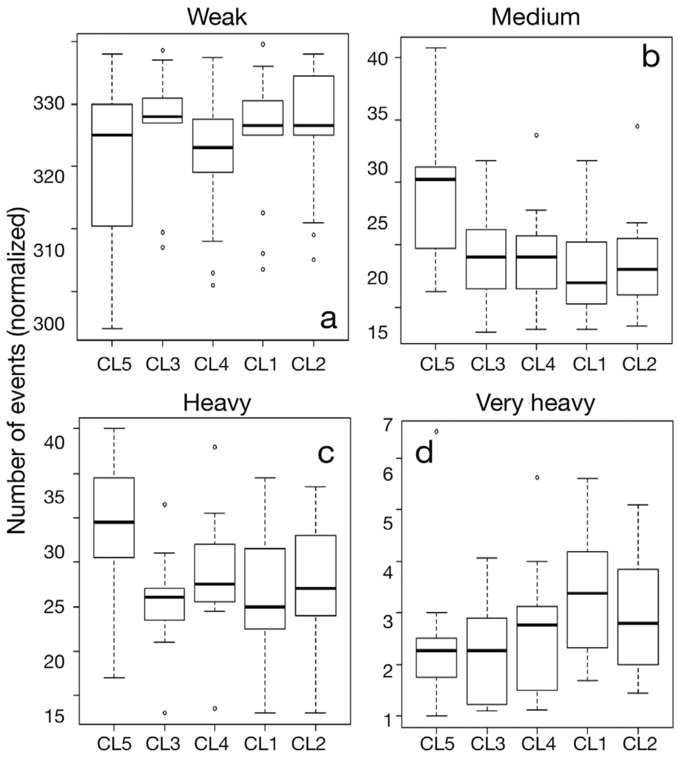

Fig. 5. The normalised seasonal number of rainfall events recorded in each climatic area for (a) autumn weak events, (b) summer medium events, (c) spring heavy events and (d) autumn very heavy events. Boxplots as in Fig. 4

mont area are the main climatic characteristic that make several crops, in particular grapes, vulnerable to erosion (Poesen & Hooke 1997). Several studies (Morvan et al. 2014, Biddoccu et al. 2016) have demonstrated that the vineyards in north-western Italy are located in the regions that have incurred the highest soil loss, which has been estimated as being between 47 and 70 t ha$^{-1}$ yr$^{-1}$ (Rodrigo Comino et al. 2015). This study has indicated that the rainiest season is autumn, and Table 4 shows that the highest daily amount was also recorded in this period. In fact, the very heavy rainfall in Cluster5 is much higher than that of the other groups. This area is in fact characterised by 92.6 mm d$^{-1}$, in contrast with the 52.2 mm d$^{-1}$ for Cluster2 and 45.4 mm d$^{-1}$ for Cluster1. The box plots (Fig. 5d) show that the highest number of extreme events was recorded in autumn, and like the annual distribution, they are more abundant in the driest sectors. In this regard, the statistical analysis confirms this pattern; in fact, statistically significant p-values can be observed for Cluster1 and Cluster2, but not for Cluster5. This distribution of extreme events, especially during autumn, makes the central Piedmont sector very vulnerable to erosion (Martínez Casasnovas et al. 2016). This area is largely devoted to wine production, and Biddoccu et al. (2016) observed the highest soil erosion rates in young vineyards in autumn, in particular during the months of September and October, due to the increase in the footprints of the wine growers. Rodrigo Comino et al. (2015) recorded high infiltration rates (almost 100%) and subsurface flows during very heavy events in this period. National and international studies of recorded extreme events have led to contrasting results. A general increase in the number of extreme events along the Mediterranean coast was reported by De Luis et al. (2009) for the second half of the 20th century, as well as by Acquaotta et al. (in press), who observed that recent extreme rainfall events have affected Liguria (NW Italy), and by Fernández-Montes & Rodrigo (2015), for the 1970–2007 period in the south-eastern Iberian Peninsula. Terzago et al. (2013), Fratianni et al. (2015) and Morán-Tejeda et al. (2016) detected an increase in the rain-on-snow precipitation amount for the 50 yr period of 1961–2010. Rodrigo (2010) reported a constant or decreasing number of extreme events, mainly in winter and spring, in inland areas during the second half of the 20th century. These differences could be due to the diverse microclimate and topography of the investigated sites. The changes in climate variability in the Mediterranean areas have been more pronounced, starting from 1980 (Pieri et al. 2016), probably as a result of the strengthening of the North Atlantic Oscillation (Lolis & Türke 2016).

## 4. CONCLUSION

In this study, we have characterised the spatial and temporal distribution of rainfall in Piedmont using a multivariate methodology. The analysis has highlighted an increase in precipitation, which is more marked in the north than in the central drier area. This, linked with the intensification of rainfall density and the constant number of rainy days, suggests that each single rainfall event in Piedmont in the 2004–2016 period was characterised by a higher rainfall amount than in the past. An innovative approach has been adopted in the detailed study of extreme events reported in this paper to classify these events over an extended area, such as Piedmont, using rainfall thresholds. This approach has in fact demonstrated that the distribution of rainfall, classified as wet, medium and heavy, is in agreement with the annual rainfall distribution. As far as heavy events are concerned, this methodology has shown that even

Table 6. Seasonal p-values of the Student's *t*-test, and the Kolmogorov-Smirnov (KS) and Wilcoxon (W) tests for each rainfall class. A p = 5% significance level was used for all tests. In **bold** are p-values where the 2 compared series present a difference in means, median or distribution

| | Rainfall events | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Autumn | | | | Spring | | | | Winter | | | | Summer | | | |
| | Weak | Medium | Heavy | V. heavy | Weak | Medium | Heavy | V. heavy | Weak | Medium | Heavy | V. heavy | Weak | Medium | Heavy | V. heavy |
| *t*-test_CL5CL3 | 0.20 | 0.18 | 0.90 | 0.61 | 0.15 | 0.43 | **0.01** | 0.15 | 0.75 | 0.94 | 0.81 | 0.90 | 0.11 | **0.01** | 0.07 | 0.06 |
| *t*-test_CL5CL4 | 0.64 | 0.18 | 0.30 | 0.65 | 0.13 | 0.09 | 0.13 | 0.13 | 0.44 | 0.49 | 0.93 | 1.00 | 0.12 | **0.01** | 0.04 | 0.36 |
| *t*-test_CL5CL1 | 0.26 | 0.12 | 0.97 | 0.15 | 0.06 | 0.07 | **0.03** | 0.08 | 0.42 | 0.99 | 0.38 | 0.35 | 0.11 | **<0.001** | 0.15 | 0.79 |
| *t*-test_CL5CL2 | 0.19 | 0.12 | 0.99 | 0.22 | 0.09 | 0.16 | 0.06 | 0.27 | 0.82 | 0.96 | 0.54 | 0.56 | 0.13 | **0.01** | 0.22 | 0.85 |
| *t*-test_CL3CL4 | 0.36 | 0.95 | 0.19 | **0.02** | 0.67 | 0.35 | 0.20 | **<0.001** | 0.63 | 0.52 | 0.87 | 0.89 | 0.72 | 0.73 | 0.82 | **0.01** |
| *t*-test_CL3CL1 | 0.86 | 0.22 | 0.85 | **0.01** | 0.98 | 0.28 | 0.64 | **<0.001** | 0.61 | 0.95 | 0.47 | 0.27 | 0.87 | 0.67 | 0.58 | **0.03** |
| *t*-test_CL3CL2 | 0.96 | 0.21 | 0.90 | **0.05** | 0.80 | 0.54 | 0.41 | **0.01** | 0.93 | 0.90 | 0.66 | 0.46 | 0.67 | 0.97 | 0.41 | **0.03** |
| *t*-test_CL4CL1 | 0.46 | 0.27 | 0.25 | 0.28 | 0.69 | 0.93 | 0.45 | 0.56 | 0.97 | 0.48 | 0.39 | 0.31 | 0.84 | 0.44 | 0.42 | 0.50 |
| *t*-test_CL4CL2 | 0.34 | 0.26 | 0.23 | 0.41 | 0.85 | 0.70 | 0.68 | 0.16 | 0.58 | 0.45 | 0.57 | 0.52 | 0.94 | 0.72 | 0.28 | 0.45 |
| *t*-test_CL1CL2 | 0.82 | 0.93 | 0.95 | 0.40 | 0.83 | 0.61 | 0.74 | 0.41 | 0.56 | 0.94 | 0.78 | 0.69 | 0.78 | 0.71 | 0.77 | 0.94 |
| KS test_CL5CL3 | 0.13 | 0.88 | 1.00 | 0.88 | 0.29 | 0.29 | **0.01** | 0.29 | 0.88 | 1.00 | 0.29 | 0.88 | 0.15 | **0.01** | 0.29 | 0.15 |
| KS test_CL5CL4 | 0.88 | 0.57 | 0.88 | 0.29 | 0.29 | 0.13 | 0.13 | 0.15 | 0.29 | 0.57 | 0.88 | 0.88 | 0.15 | **0.01** | 0.29 | 0.88 |
| KS test_CL5CL1 | 0.88 | 0.29 | 1.00 | 0.50 | 0.29 | 0.13 | **0.05** | 0.13 | 0.57 | 1.00 | 0.29 | 0.88 | 0.13 | **0.01** | 0.57 | 0.88 |
| KS test_CL5CL2 | 0.29 | 0.13 | 1.00 | 0.29 | 0.29 | 0.13 | 0.13 | 0.29 | 0.88 | 0.88 | 0.29 | 0.88 | 0.15 | **0.01** | 0.88 | 1.00 |
| KS test_CL3CL4 | 0.29 | 1.00 | 0.29 | **0.05** | 0.88 | 0.57 | 0.29 | **<0.001** | 0.88 | 0.88 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 | **0.01** |
| KS test_CL3CL1 | 0.57 | 0.88 | 1.00 | **0.05** | 1.00 | 0.57 | 0.88 | **<0.001** | 0.88 | 1.00 | 0.57 | 0.57 | 1.00 | 1.00 | 1.00 | **0.05** |
| KS test_CL3CL2 | 0.57 | 0.57 | 1.00 | **0.05** | 1.00 | 0.88 | 0.57 | **0.01** | 1.00 | 1.00 | 0.88 | 0.88 | 0.88 | 1.00 | 0.57 | **0.05** |
| KS test_CL4CL1 | 0.57 | 0.29 | 0.57 | 0.13 | 1.00 | 0.88 | 0.57 | 0.88 | 1.00 | 0.88 | 0.57 | 0.57 | 1.00 | 1.00 | 0.88 | 1.00 |
| KS test_CL4CL2 | 0.57 | 0.29 | 0.57 | 0.57 | 1.00 | 0.88 | 0.88 | 0.29 | 0.88 | 0.57 | 0.88 | 1.00 | 1.00 | 1.00 | 0.57 | 0.88 |
| KS test_CL1CL2 | 0.88 | 1.00 | 1.00 | 0.88 | 1.00 | 0.88 | 1.00 | 1.00 | 0.90 | 1.00 | 1.00 | 1.00 | 0.88 | 1.00 | 1.00 | 1.00 |
| W test_CL5CL3 | 0.13 | 0.88 | 1.00 | 0.88 | 0.29 | 0.29 | **0.01** | 0.29 | 0.88 | 1.00 | 0.29 | 0.88 | 0.15 | **0.01** | 0.29 | 0.15 |
| W test_CL5CL4 | 0.88 | 0.57 | 0.88 | 0.29 | 0.29 | 0.13 | 0.13 | 0.15 | 0.29 | 0.57 | 0.88 | 0.88 | 0.15 | **0.01** | 0.29 | 0.88 |
| W test_CL5CL1 | 0.88 | 0.29 | 1.00 | 0.15 | 0.29 | 0.13 | **0.05** | 0.13 | 0.57 | 1.00 | 0.29 | 0.88 | 0.13 | **0.01** | 0.57 | 0.88 |
| W test_CL5CL2 | 0.29 | 0.13 | 1.00 | 0.29 | 0.29 | 0.13 | 0.13 | 0.29 | 0.88 | 0.88 | 0.29 | 0.88 | 0.15 | **0.01** | 0.88 | 1.00 |
| W test_CL3CL4 | 0.29 | 1.00 | 0.29 | **0.05** | 0.88 | 0.57 | 0.29 | **<0.001** | 0.88 | 0.88 | 0.88 | 1.00 | 1.00 | 1.00 | 1.00 | **0.01** |
| W test_CL3CL1 | 0.57 | 0.88 | 1.00 | **0.05** | 1.00 | 0.57 | 0.88 | **<0.001** | 0.88 | 1.00 | 0.57 | 0.57 | 1.00 | 1.00 | 1.00 | **0.05** |
| W test_CL3CL2 | 0.57 | 0.57 | 1.00 | **0.02** | 1.00 | 0.88 | 0.57 | **0.01** | 1.00 | 1.00 | 0.88 | 0.88 | 0.88 | 1.00 | 0.57 | **0.05** |
| W test_CL4CL1 | 0.57 | 0.29 | 0.57 | 0.13 | 1.00 | 0.88 | 0.57 | 0.88 | 1.00 | 0.88 | 0.57 | 0.57 | 1.00 | 1.00 | 0.88 | 1.00 |
| W test_CL4CL2 | 0.57 | 0.29 | 0.57 | 0.57 | 1.00 | 0.88 | 0.88 | 0.29 | 0.88 | 0.57 | 0.88 | 1.00 | 1.00 | 1.00 | 0.57 | 0.88 |
| W test_CL1CL2 | 0.88 | 1.00 | 1.00 | 0.88 | 1.00 | 0.88 | 1.00 | 1.00 | 0.90 | 1.00 | 1.00 | 1.00 | 0.88 | 1.00 | 1.00 | 1.00 |

though the northern sector is the wettest, central Piedmont is the area where the highest number of extreme events has been recorded. Finally, this study may contribute to a better understanding of the dynamics between extreme wet events and spatial distribution in the Piedmont region, and of the possible impacts on ecosystems. Cortesi et al. (2012) have shown that precipitation is one of the main factors in the process of creating landscape and, in this context, different temporal and spatial distributions of extreme rainfall events can lead to various climatic conditions that can affect the landscape process, and can thus have an impact on natural and social processes, such as floods, soil erosion, cultivation and water arability.

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