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ORIGINAL PAPER

Increased flash flooding in Genoa Metropolitan Area: a combination of climate changes and soil consumption?

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Abstract

The Genoa Metropolitan Area (GMA) has been historically affected by floods for two reasons, namely meteorological conditions and the city's geographical arrangement. In the past few years in GMA, an increase in flash floods has been registered; among the causes, climate variations have been analysed. In 2014, several floods took place. In some areas of the hinterland, the cumulative annual rainfall exceeded 4000 mm. This research analyses the rainfall statistics collected by Genoa University and Chiavari stations (GMA along the coast) and at Isoverde and Diga Giacopiane stations (hinterland of GMA). The analysis was based on the mean annual, seasonal and monthly rainfall and rainy days for the four stations and daily series for Genoa University. Furthermore, annual maximum data of hourly rainfall for the Pontecarrega station were analysed. The annual rainfall does not show any trend. The monthly analysis highlights significant decreases for rainfall and rainy days between spring and summer. Climate indices recorded on daily data at Genoa University station show a certain increase in rainfall intensity in recent years. Additionally, hourly rainfall at 1 and 3 h increased, and the series showed a change point in the 1990s. Furthermore, urban sprawl has continually increased until now, and its contribution has already been accepted. These facts can be related to the intensification of flash flood events measured in the last decade. Furthermore, historical data from several sources confirm an increase in the number of events and casualties. These conditions determine a clear need for monitoring potentially hazard situations.

1 Introduction

Urban risks from flash floods are an important issue in the Mediterranean area and Italy due to their recent intensification (Llasat et al. 2014; Guenzi et al. 2017a). Various authors have studied recent and numerous floods that have affected some parts of the world, Europe and the Mediterranean area (Zandonadi et al. 2016; Alexander et al. 2006) and stress the role of climate variations (Barrera-Escoda and Llasat 2015). Historical variations have been highlighted by other authors, emphasizing the changes linked to climate cycles (Elleder 2015), circulation patterns (Terzago et al. 2013) and changes in land use (Slobodan et al. 2016).

The extraordinary occurrence of phenomena and the effects on the ground have made the Genoa Metropolitan Area (GMA) an internationally emblematic case study (Silvestro et al. 2015; Hally et al. 2015; Faccini et al. 2015; Acquaotta et al. 2018). The GMA is historically affected by flash floods for two main reasons, namely the meteorological conditions due to the "Genoa Low" (also known as 'Ligurian Gulf Depression') and the city's geographical layout, which is dominated by a narrow coast bounded by steep mountains (Fig. 1). In addition, urban sprawl developed particularly in the twentieth century without rational land planning.

From a meteorological point of view, the Genoa Gulf is characterized by a typical circulation, the Genoa Low. This circulation is a cyclone that forms or intensifies from a pre-existing cyclone to the south of the Alps with an orographic effect (Jansà et al. 2014) over the Gulf of Genoa,

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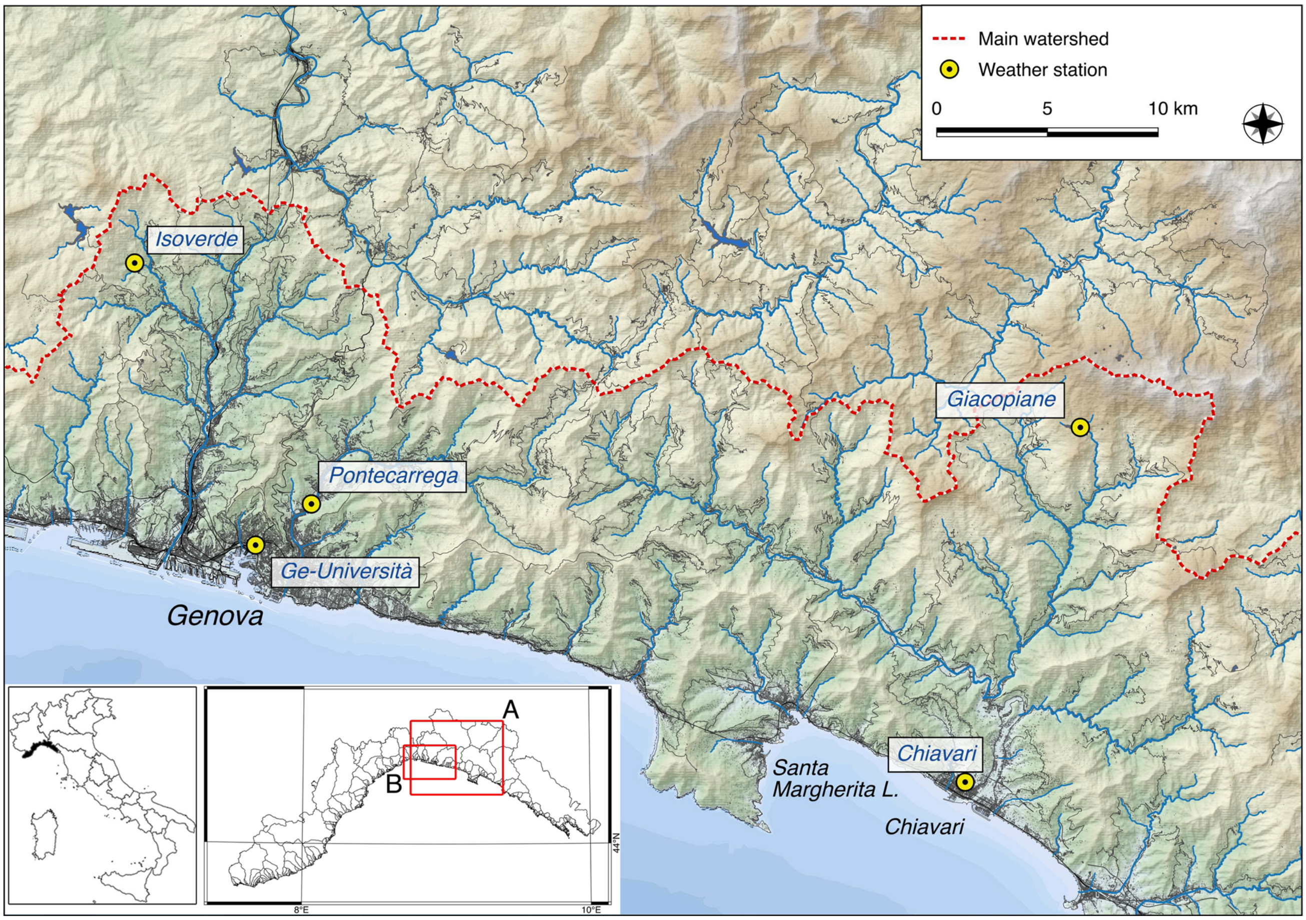

Fig. 1 Studied area and selected weather stations. *A* is the Genoa Metropolitan Area, and *B* is the Genoa Municipality

Ligurian Sea. This cyclone generally remains stationary but can sometimes determine the weather in Central Europe (Saéz de Càmara et al. 2011) and in the Italian peninsula (Trigo et al. 1999) according to the "Vb" and "Vd Van Bebber cyclone tracks" (Bartholy et al. 2006). This secondary depression is linked to the arrival of the Atlantic perturbations behind the Alps and is formed on the Gulf primarily in the autumn–winter and spring periods. This typical circulation is responsible for the large amounts of rainfall distributed over the region surrounding the Ligurian Sea (Sacchini et al. 2012).

The morphology of the Ligurian Gulf and the orographic barrier also contributes to rainfall events that may be very intense, especially at the end of the summer or autumn, when Atlantic perturbations may be blocked by the European continental anticyclone.

The convergence between the air mass stationed over the warm Mediterranean basin and the colder air masses moving from the Po basin triggers the development of convective systems and sometimes storm supercells (Silvestro et al. 2015). These convective systems have recently affected different locations over the Ligurian Gulf, causing flash floods arising from rainfall intensities of over 500 mm/6 h or 180 mm/1 h. The most recent of these events occurred on October 2014 in Genoa and on its eastern coast and on November 2014 in its western hinterland. These phenomena have been recurring and particularly violent in recent years, especially the events that took place in Varazze and Genoa-Sestri Ponente in 2010, Cinqueterre and Genoa-Bisagno Valley in 2011 and 2014.

In recent years, an increase in the number of flash floods in the GMA has been recorded: according to Faccini et al. (2016), this increase is related to man-made landforms (mainly irrational urbanization) and to climate change (mainly changes in rainfall regime). Only in 2014 did several floods occur in the entire area: in the hinterland, the cumulative yearly rainfall exceeded 4000 mm, while 2000 mm fell along the coast.

The objectives of the current study are as follows: to (1) analyse long rainfall series in different weather stations in the GMA to highlight significant trends; (2) analyse historical floods and casualties in the GMA to highlight trends or critical periods; (3) evaluate possible relationships between rainfall regime variations and the recent increase in flood events; and (4) evaluate a possible contribution by urban sprawl. Finally, the results obtained allow us to suggest some proposals for flood risk reduction activities on the GMA.

2 Materials and methods

2.1 Geographical settings

Genoa is an ancient pre-roman city in which urban development was concentrated in the twentieth century (Faccini et al. 2015, 2016). Genoa is the main harbour in Italy and serves a transit point between the Mediterranean Sea and Europe. Consequently, Genoa is one of the ten metropolitan cities of Italy: the metropolitan area covers a total amount of 4000 km^2 and hosts a population of 1.5 million inhabitants distributed in the central sector of the Ligurian coastal arch.

The area of Genoa is characterized by a complex morphology determined by the Alpine–Apennine system, which hosts relief extending from peaks between 1000 and 2000 m asl and rapidly descends towards the Ligurian Sea. The resulting hydrographic network consists of numerous steep and short watercourses that can attain a concentration time of less than an hour during floods. It is a humid temperate climate with a limited dry season restricted to 1 or 2 summer months. The climatic classification based on the Köppen–Geiger scheme defines this area as Mediterranean Csa (Hot temperate).

The coastal climate is characterized by short and temperate winters (average January 8 °C) and temperate summers (average July 24 °C).

Climate variations linked to temperature increase have been highlighted in nearby French regions (Eveno et al. 2016), in other parts of the world (Fortin et al. 2017) and in Italy (Colombo et al. 2016; Giaccone et al. 2015). The GMA shows a positive trend in air temperature that is statistically significant (Faccini et al. 2015). At Genoa University, the most important station because of the long-time series, the mean air temperature is 15.8 °C, but the series rises from approximately 15 °C in the early nineteenth century to a current value of more than 16 °C (Acquaotta et al. 2018). At the Isoverde weather station, the mean air temperature is 12.7 °C, but there is an increasing trend from approximately 12 °C in the 1920s to the current 13 °C with a significant increase in winter air temperature. In Chiavari city, the mean air temperature is 15.5 °C and the series show a positive trend increasing from 15.2 °C in the second half of the nineteenth century to the current 15.7 °C (Faccini et al. 2017a). Last, at the Diga Giacopiane weather station, the mean air temperature result was 10.2 °C, and the time series showed a positive trend from approximately 10 °C in the 1920s to 11 °C with an important increase in the maximum air temperature (Faccini et al. 2017b).

2.2 Data and methods

This research analyses the thermo-pluviometric statistics collected over time in four selected weather stations listed below (Fig. 1):

1. Genoa University, located at 21 m asl in Genoa historical city and active since 1833, representative of the central part of the studied area;
2. Chiavari, located at 6 m asl in the old city and active since 1877, representative of the Eastern sector of the GMA;
3. Isoverde, located at 270 m asl in the upper Polcevera Valley and active since 1921, representative of the hilly part of the Central-Western Genoese district;
4. Diga Giacopiane, located at 1030 m asl in the upper Sturla valley and active since 1925, representative of the mountainous environment of the Eastern Genoa Area.

These were all stations of the Italian National Hydrographic Service until 1999, and they were managed by the Regional Agency for the Environment (ARPAL). These bodies validate all data and guarantee their quality. For this study, the analysed period is 92 years from 1925 to 2016.

The first analysis was based on monthly, seasonal and annual rainfall and rainy days, or days with precipitation ≥ 1 mm.

For the monthly rain series, a HOMER test was carried out to identify the discontinuity in the series. The HOMER shows the breaks in the series and, if necessary, corrects the breaks (Mestre et al. 2013). The test allows us to evaluate the homogeneity of a series (Venema et al. 2013). A series is homogeneous when the variations are due only to variations in climate (Acquaotta et al. 2016; Guenzi et al. 2017b). The test was carried out on the same time period from 1925 to 2016 for all meteorological stations.

The Theil-Sen Approach (TSA) was carried out on the annual, seasonal and monthly series to calculate the amount of change over time (Fratianni et al. 2015). The non-parametric Mann–Kendall test at the 95% significance level was also used to determine the percentage of reliability of the trend.

The TSA was applied by package ‘zyp’ of the *R Project*, a free environmental software for statistical computing and graphics (Baronetti et al. 2018). In the output, the trend dp during the period and Sen’s trend over the time period were calculated.

For the Genoa series, the climate indices were also calculated. The indices are used to extract information from daily weather observations. The indices show aspects of the climate system that affect many human and natural systems with particular emphasis on extremes (Alexander and Herold 2016). Such indices reflect the duration and amplitude of extreme rainfall intensity and frequency and of measures of extremely wet and dry periods (Peterson and Manton 2008). For the daily series of Genoa, we selected ten indices created and organized by the ETCCDI, Expert Team on Climate Change Detection and Indices. The ten indices were calculated on an annual scale. The percentile indices, r95p and r99p, use threshold closely linked with the peculiarity of the station. The thresholds, equal to the 95th and 99th percentiles, are calculated on the reference period from 1981 to 2010. The period has been chosen as the most recent trentennial period according to reference periods of the World Meteorological Organization (Table 1).

For every index and variable, the standardized anomaly indices (SAIs) were calculated. The SAI are calculated by dividing anomaly, values minus mean, by the standard deviation. The mean and standard deviation were estimated for the same reference period from 1981 to 2010. The SAI shows the anomalies of the variable because the influences of dispersion have been removed. Between the SAIs, the correlation coefficient to highlight the intensity of the linear connection was calculated.

In addition, for autumn, where major floods happened, the SAI of the r95p indices and the relationship with the SAI of flooding were calculated.

In addition, the annual maximum rainfall intensity at 1, 3, 6, and 12 h from 1950 was analysed to highlight more recent variations in rainfall intensity. In particular, data were collected from the Pontecarrega rain gauge, which is representative of the Bisagno valley, 3 km into the hinterland of Genoa (probably the most hazardous in the GMA for the frequent floods) (Faccini et al. 2015). The station lies in the seat of the society, which manages the public aqueduct and belongs to the network of stations of the National Hydrographic Service (the ARPAL), which guarantees the quality of data.

The trends are calculated by TSA, and the sequential Mann–Kendall (SMK) test was carried out to detect the potential turning points in the time series. SMK calculates a progressive and a retrograde series of Kendall normalized tau's points where the two lines cross are considered as approximate potential trend turning points. When either the progressive or retrograde row exceeds certain confidence (95%) limits before and after the crossing points, the turning point trend is considered significant (Sneyers 1990).

To evaluate historical and recent increases in floods and flash floods, we analysed the number of floods and casualties in the GMA since 1600. F. The Italian Vulnerable Areas Inventory (AVI project) collects data on floods of the last millennium, which are recorded and published (online: http://avi.gndci.cnr.it/) by the Italian National Research Center for geo-hydrological protection (CNR-IRPI). In this analysis, the national catalogue data were extracted from the beginning of 1600 for the area of interest and integrated to include 2016, drawing from various other sources such as Basin Master Plans in the GMA, the Interreg IIc European Project, publications on individual events, the observatory of geo-hydrological risks of the Genoa Metropolitan Area, the census realized as a result of Ligurian Regional Laws and other data available online. All data refer to floods that broke or overlapped the river embankments and resulted in at least local inundation of the plain.

The results obtained could lead decision makers to better monitor and highlight the possible prevention measures.

3 Results

The HOMER test carried out on the four-monthly series, which were validated by the National and Regional Official Bodies, did not show any breaks. Overall, the series did not present discontinuities. The pairwise detections do not show a break in the same position between candidates, the series to be homogenized, and the reference series (Fig. 2).

Table 1 Indices used for daily data analysis

Short name	Long name	Definition	Units
cdd	Consecutive dry days	Maximum annual number of consecutive dry days (when rain < 1.0 mm)	Days
cwd	Consecutive wet days	Maximum annual number of consecutive wet days (when rain ≥ 1.0 mm)	Days
r10 mm	Number of heavy rain days	Annual number of days when rain ≥ 10 mm	Days
r20 mm	Number of very heavy rain days	Annual number of days when rain ≥ 20 mm	Days
rx1 day	Max 1-day rain	Maximum 1-day rain total	mm
rx3 day	Max 3-day rain	Maximum 3-day rain total	mm
rx5 day	Max 5-day rainRl	Maximum 5-day rainRtotal	mm
r95p	Total annual rain from heavy rain days	Annual sum of daily rain > 95th percentile	mm
r99p	Total annual rain from very heavy rain days	Annual sum of daily rain > 99th percentile	mm

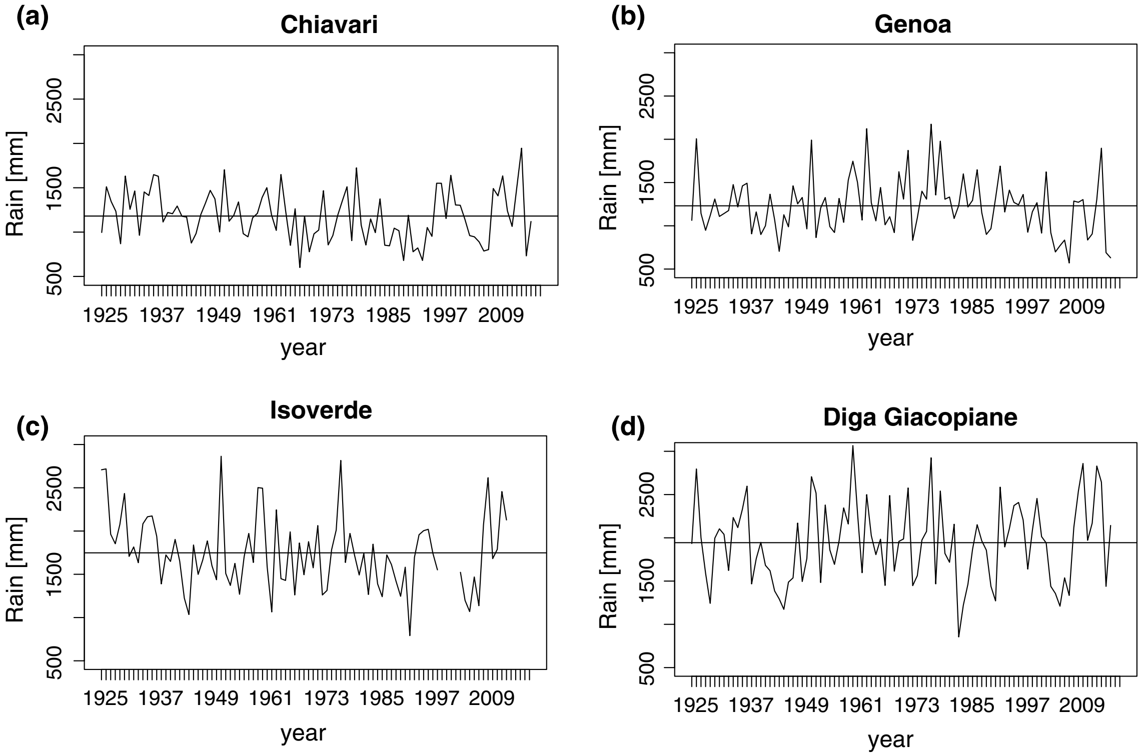

Fig. 2 Annual rain of Chiavari (**a**), Genoa (**b**), Isoverde (**c**) and Diga Giacopiane (**d**) from 1925 to 2016. In the plots, the black lines are the mean values

In contrast to other European stations (Gocic et al. 2016), the annual rainfall (1925–2016) does not show any significant trend for the selected weather stations: there is a persistent mean value of approximately 1270 mm for Genoa University, 1770 mm for Isoverde, 1190 mm for Chiavari and 1946 mm for Diga Giacopiane. The precipitation trends do not show a statistically significant slope. In Chiavari, Isoverde and Genoa, the trends decrease, while in Diga Giacopiane, the slope increases, but at this station, a significant contribution of fresh snow in winter is possible (Table 2).

In the Genoa historical centre, there is an average of 101 annual rainy days, at Isoverde weather, station there are 95 rainy days/year, while in Chiavari city, the mean annual rainy days is 85, and last, at Diga Giacopiane, there is an average of 111 annual rainy days. In addition, for this variable, the trends are not statistically significant and, in all locations, the slopes diminish (Table 2).

The trends calculated for the seasons have highlighted common behaviours in the stations (Table 2). In spring, the trends are negative, but only in Chiavari, Isoverde and Genoa are the trends statistically significant. The maximum decrease, − 2.31 mm/year, was calculated in Isoverde following Chiavari with − 1.11 mm/year (Fig. 3, left). Additionally, for the rainy days in spring, the trends are negative, but only

Table 2 The annual and seasonal trends for rainfall, *R* (mm), and daily rain, DR (number days) at Genoa, Chiavari, Isoverde, Diga Giacopiane

Station	Variable	Trend	Trend dp	Winter	Spring	Summer	Autumn
Chiavari	DR	− 0.10	− 8.90	0.00	− 0.05	0.00	0.00
	R	− 2.24	− 206.60	− 0.80	**− 1.11**	0.27	− 0.26
Isoverde	DR	− 0.12	− 11.50	0.00	**− 0.08**	0.00	0.00
	R	− 3.50	− 322.00	− 0.41	**− 2.31**	0.33	− 0.68
Giacopiane	DR	− 0.12	− 11.10	0.02	− 0.06	**− 0.03**	− 0.03
	R	1.05	96.60	0.95	− 1.24	0.15	1.09
Genova	DR	− 0.06	− 5.70	0.00	**− 0.06**	0.00	0.00
	R	− 1.06	− 97.53	− 0.44	**− 0.95**	− 0.09	− 0.21

In bold, the trend was statistically significant, 95%. Trend dp (during the period) is the Sen's slope (annual trend) over the time period

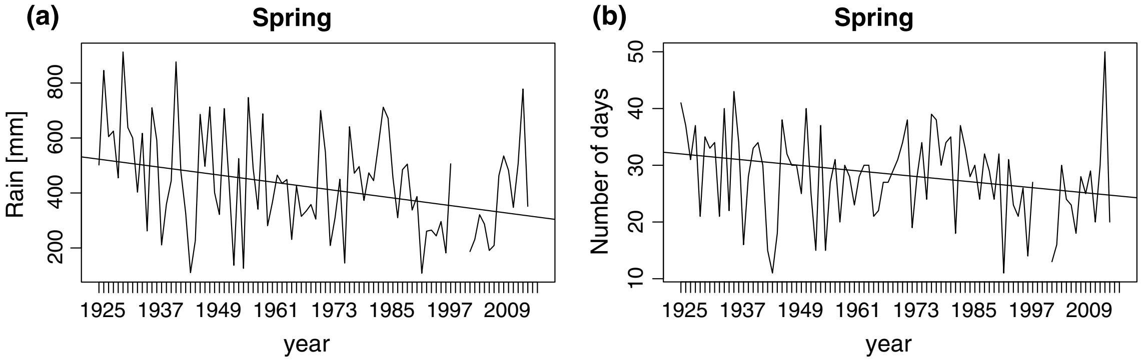

Fig. 3 Spring rain (left) in Isoverde and autumn rain (right) in Diga Giacopiane from 1925 to 2016. The black lines show the trends

in Isoverde and Genoa are the trends statistically significant. On a monthly scale, these reductions are recorded mostly in May (Table 3). In all stations in this month, both the trends of precipitation and rainy days are decreasing and statistically significant. Averages of − 0.64 mm/year for rain and − 0.03 days/year for rainy days are observed. For precipitation, the months with positive but not statistically significant trends are January, July, August, September and October. The maximum trend is calculated in August with an average of 0.21 mm/year, followed by October and January with 0.10 mm/year (Table 3). An autumnal increase is highlighted for the mountain station of Giacopiane (Fig. 3, right). The monthly rainy days do not show trends, and the slopes are near zero except in May.

The indices calculated on daily values for Genoa have shown two distinct behaviours, without trends and with increasing trends. For cdd (consecutive dry days), cwd (consecutive wet days), r10 mm (days with rain > 10 mm), r20 mm (days with rain > 20 mm) and r99p (annual sum of rainy days > 99 percentile), the trends are equal to zero (Table 4, Fig. 4). For rx1 day (maximum 1 day rain), rx3 day (maximum 3 days of rain), rx5 day (maximum 5 days of rain) and r95p (sum of rainy days > 95 percentile), the trends are increasing but not statistically significant. The maximum trend, 0.41 mm/year, was calculated for the heavy rain, r95p, precipitation major exceeding the 95th percentile, followed by rx5 day with 0.28 mm/year. The trend dp of r95p indicates an increase of 37.9 mm over 92 years for the heavy precipitation, while the rain over 5 days increased by 25.5 mm over 92 years (Table 4).

The correlation coefficients between the SAI calculated on the climate indices and the SAI estimates on the number of floods showed a good correlation between rx3 day, rx5 day and the number of floods (Table 4). The maximum value, 0.72, was estimated between rx1 day and flood, followed by rx5 day and flood, with 0.71. For these indices, the trends are increasing but not statistically significant.

The plot of SAI of flood and extreme precipitation, r95p, in autumn (Fig. 5) shows a correlation of data and a recent increase in extreme precipitation and autumnal flood in Genoa from 2009. The SAI values are positive; in particular, the maximum value was calculated in 2014, which had six floods and three extreme precipitation events.

The analysis of hourly rainfall shows a general increase in the trends. Only for 12 h rain is the slope decreasing, but in all cases are the trends not statistically significant (Table 5). The maximum value is calculated for 6 hourly rainfall, 0.15 mm/h, followed by 3 hourly rainfall. On the hourly series, the SMK (sequential Mann–Kendall) was carried out. For all series, two periods, approximately 1988 and approximately 1993, were detected as potential turning points. For 1 and 3 h in the first period, from 1950 to 1988, the trends decreased and, in the second period, from 1993 to 2016, the trends increased (Table 5). For the 1 h series, the

Table 3 The monthly trends for rainfall, *R* (mm), at Genoa, Chiavari, Isoverde, Diga Giacopiane and the mean values of the coefficients

Rain	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Chiavari	− 0.17	− 0.18	− 0.53	0.12	**− 0.60**	0.00	0.00	0.05	− 0.25	0.28	− 0.19	− 0.38
Isoverde	0.13	− 0.21	− 0.78	− 0.45	**− 0.88**	− 0.03	− 0.02	0.50	0.03	− 0.37	− 0.08	− 0.19
Giacopiane	0.40	0.07	− 0.69	− 0.08	**− 0.68**	− 0.19	0.13	0.17	0.16	0.50	0.02	− 0.01
Genova	0.03	− 0.19	− 0.35	− 0.11	**− 0.42**	− 0.07	0.00	0.13	0.16	− 0.03	− 0.19	− 0.43
Mean	0.10	− 0.13	− 0.58	− 0.13	− 0.64	− 0.07	0.03	0.21	0.02	0.10	− 0.11	− 0.26

The trends in bold are statistically significant at the 95% level

Table 4 Annual trends calculated on the indices for the Genoa station

Indices	Unit	Trend	Trend dp	Mean	Min	Max	Cor_coef
cdd	Days/year	//	//	36	15	69	−0.20
cwd	Days/year	//	//	6	4	13	0.20
r10 mm	Days/year	//	//	35	16	58	0.27
r20 mm	Days/year	//	//	19	7	35	0.32
rx1 day	mm/year	0.17	15.8 mm	129.5	44.4	451.0	0.66
rx3 day	mm/year	0.21	19.2 mm	183.5	60.8	480.2	0.72
rx5 day	mm/year	0.28	25.5 mm	211.5	86.8	588.0	0.71
r95p	mm/year	0.41	37.9 mm	333.9	0.0	903.6	0.51
r99p	mm/year	//	//	120.4	0.0	532.2	0.61

The trends are not statistically significant. Trend dp (during the period) is the Sen's slope (annual trend) over the time period, 1925–2016. The mean, mean, minimum, Min, and maximum, Max, values of the indices were reported. Additionally, in Cor_coeff, the correlation coefficients between the SAI calculated on the indices and the SAI calculated on the number of flood events are reported

//, no trend

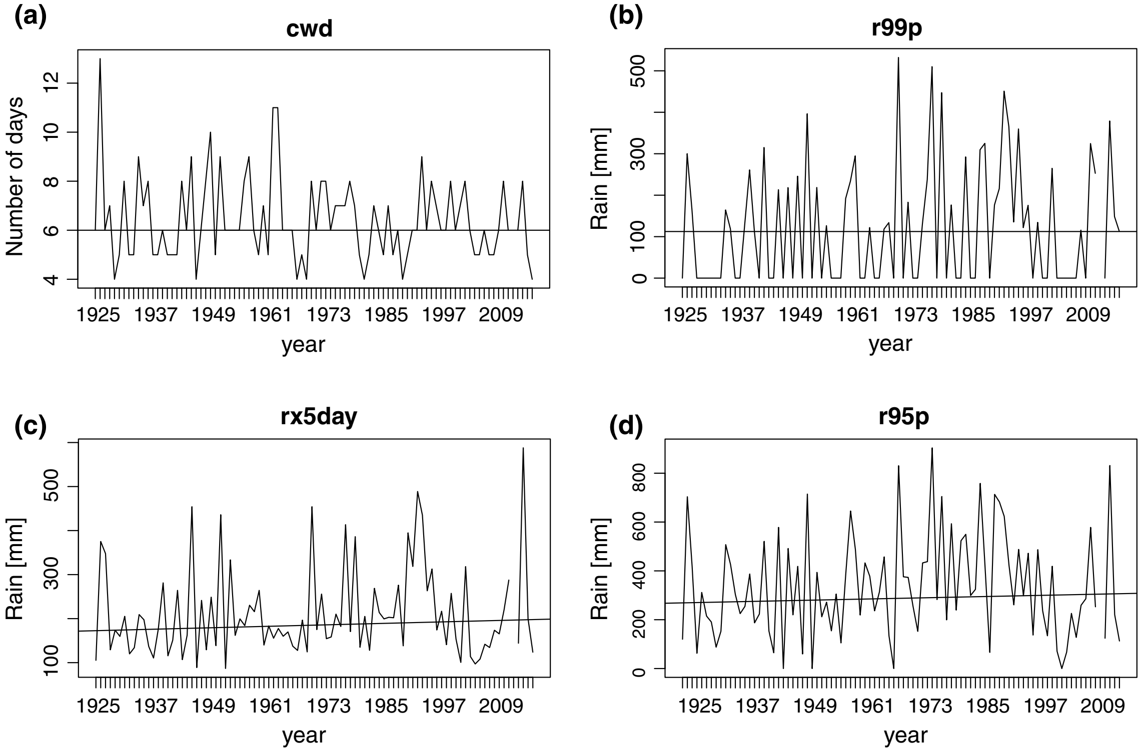

Fig. 4 Annual behaviours of cwd, consecutive wet days, r99p, total annual rain from very heavy rain days, rx5 day, max 5-day rain, and r95p, and total annual rain from heavy rain days at the University of Genoa weather station. The black lines show the trends

increase is equal to 20.1 mm for the event, while for 3 h, it is equal to 0.87 mm (Fig. 6). For 6 and 12 h in the two periods, the trends are decreasing. Only for 12 h in the first period, the trend is statistically significant, with a decrease equal to −28.1 mm for the event.

The data show that historically, floods have always hit the GMA, with many events taking place in particular years. The data from 1925 onwards show a significant increase in the recorded floods (Fig. 7). According to the compilers of the data, the increase is due to a sudden change in the patrimonial property and quality in the territory but also to a greater awareness of natural disasters and the positive changes in the process of analysis related to the change in the method of gathering data. A further increase is recorded in approximately 1950.

It is interesting to note that by merely evaluating the most critical years, the threshold is shifted to approximately 1950. We note, moreover, that the year 2014 was the year most

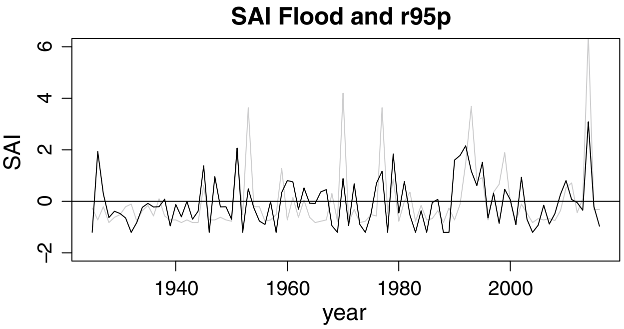

Fig. 5 The SAI of flood values in grey and the SAI of r95p indices calculated in autumn in black

Table 5 Trends calculated on the hourly series, namely, 1, 3, 6 and 12 h, and the change points calculated by SMK test for Pontecarrega station

Pontecarrega (h)	1950–2016		1950–1988	1993–2016
	Trend (mm/h)	Change point	Trend (mm/h)	Trend (mm/h)
1	0.02	1987/1993	**−0.73**	0.83
3	0.10	1988/1993	**−0.57**	0.04
6	0.15	1989/1992	−0.39	−0.24
12	−0.06	1958/1987/1993/2014	**−0.72**	−0.69

The trends are calculated for the entire period from 1950 to 2016 and for two sub-periods, 1993–2016 and 1950–1988. In bold, the trend was statistically significant, 95%

affected by the floods surveyed, followed by 1970, 1993 and 1977, when important floods happened. In recent years, many events have been recorded. Additionally, casualties (Fig. 7) can be observed in the whole series and are linked to particularly strong events. The count for the casualties should identify the most critical years with greater precision than the simple distribution of events. Moreover, this aspect allows us to evaluate the intensity of flooding. The year 1702 had the highest causalities in the observed period (50 casualties), followed by 1626 and 1970. However, the increase in information has been confirmed since 1900 and, in particular, since 1936, especially for lower energy events. It is also interesting to note the decrease in tragic events over the centuries. The data show a recent concentration of events, although maxima were recorded in other historical periods.

Furthermore, the number of floods has been correlated with 1 h of rainfall at Pontecarrega (Fig. 8). The equation is y (floods) = 0.52 * (Pontecarrega 1 h) − 7.62. The coefficient is 0.46 and is statistically significant according to the Mann–Kendall test (Table 6), with a p value much lower than 0.001.

4 Discussions and conclusions

The data highlight some rainfall regime variations in the GMA and, in particular, rainy days decrease. There is no significant trend in increasing rainfall intensity at the yearly or monthly scales. Regarding rainfall intensity, the study noted the following:

- a positive trend for Genoa University indices, in particular for r95p and rx5 day, representing the most intense rainfall that typically triggers floods;
- a positive trend since 1993 for precipitation at 1 and 3 h at Pontecarrega (near Genoa University) for rainfall intensities typical of flash floods;
- a significant correlation between rainfall at 1 h and floods at Pontecarrega;
- an increase in rainfall at Pontecarrega and since 2009 for Genoa in autumn, when floods often hit the GMA.

These findings agree with Faccini et al. (2015, 2016) for Genoa city and with Faccini et al. (2017a, b) for Chiavari and Giacopiane as well; these authors measured an increase in maximum precipitation at 1, 3, 6, and 12 h over time. For

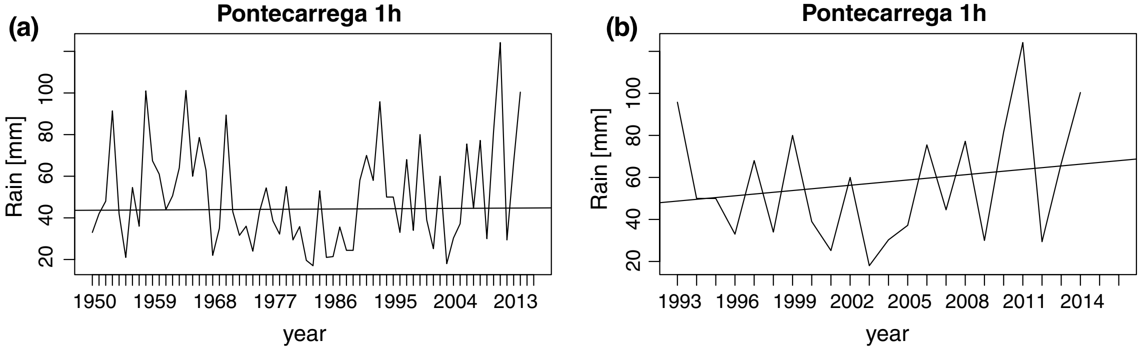

Fig. 6 Maximum annual rainfall at 1 h at Pontecarrega from 1950 to 2016 (left) and from 1993 to 2016 after the change point (right). The black lines show the trends

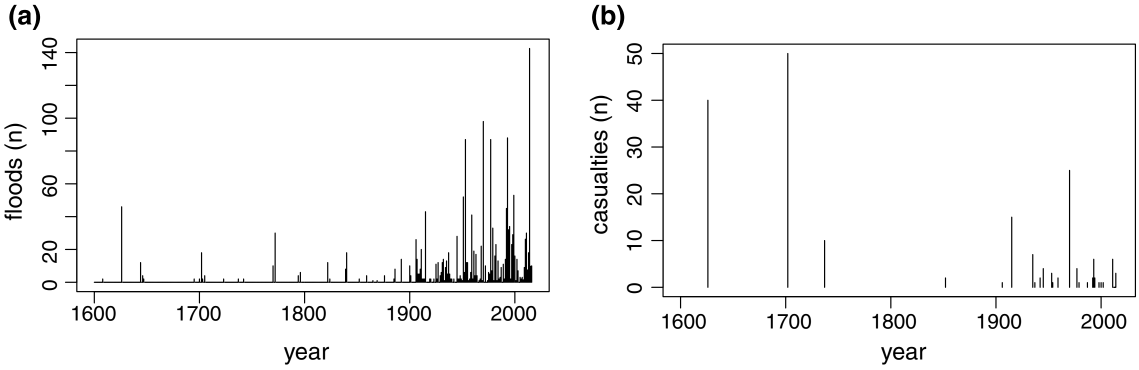

Fig. 7 (Left) flood annual values from 1600 (left axis) and casualties by floods (right axis) in Genoa Metropolitan Area from 1600 to 2016

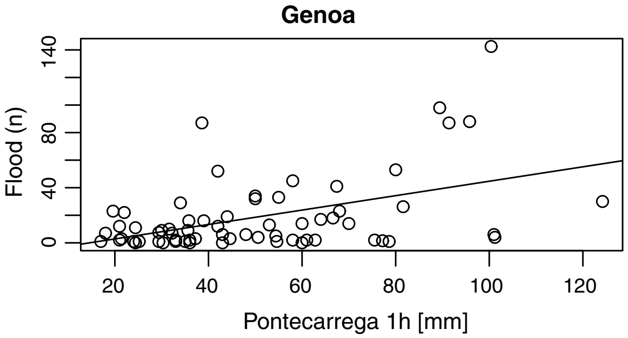

Fig. 8 Number of floods and maximum 1 h rainfall at Pontecarrega. The black line shows the regression

Table 6 Trend, relative error and correlation coefficient for flood and hourly data of Pontecarrega

1950–2016			
Floods/Pontecarrega	Trend (mm/h)	Error (mm/h)	Correlation coefficinte
1 h	**0.52**	± 0.13	0.46

Statistically significant value is shown in bold

geographic reasons, these stations are particularly sensitive to high amounts of rainfall (Flocchini et al. 1992).

Furthermore, Faccini et al. (2015) found that the annual rainfall rate (annual precipitation/annual number of rainy days) increases at Genoa University station with a significant trend, and the series shows a turning point in approximately 1925. These authors highlighted a variation in the rainfall regime in the GMA, where dry periods alternate with more intense rainfalls. Furthermore, the increase in r95p agrees with Norrant and Douguédroit (2006) for the Mediterranean region.

Finally, the correlation between the SAI of floods and the SAI indices (rx1 day and rx5 day) and the correspondence of autumnal plots of the SAI of floods and the r95p index suggest the possible start of a period of more intense autumnal rainfall, such as those recorded in the recent floods that hit GMA and Liguria from 2010 to 2016. This pattern is consistent with climate observations worldwide and with the measured increase in floods and flash floods in the Mediterranean area and in flash floods in recent years in Liguria in particular (Faccini et al. 2015).

Thus, an increase in strong events seems to occur, and this increase can be related to the recent trend of more flood events.

Because climatic trends are often not significant but increases in floods are, urban sprawl and soil consumption should have a more important role (Faccini et al. 2016). Figure 9 highlights how the landscape has been managed since the beginning of the twentieth century, how intensively soil consumption has been, how surface impermeabilization has increased and how major infrastructure, such as road networks and railways, together with widespread river culverts, influences natural collector systems.

We cannot say whether the historical increase in surveyed flooding is due to the growth of civil construction and the effects thereof on shores of streams or the improvement of the analysis related to changes in data acquisition mode (e.g. the increase in the availability of web data over the past decade). However, the 2014 record is consistent with severe precipitation derived from the increase in rainfall intensity. In addition, Faccini et al. (2016) highlighted that the urban sprawl in the GMA flood plains and soil consumption have remained similar since 1950, while an increase in floods has been recorded.

Thus, we can state that climate variation could be one of the causes of the GMA flood increase, as has already been discussed for nearby locations (Carrega 2016).

The number of casualties during floods highlights different behaviours in time. In fact, assuming that the number of casualties is correlated with the distribution of

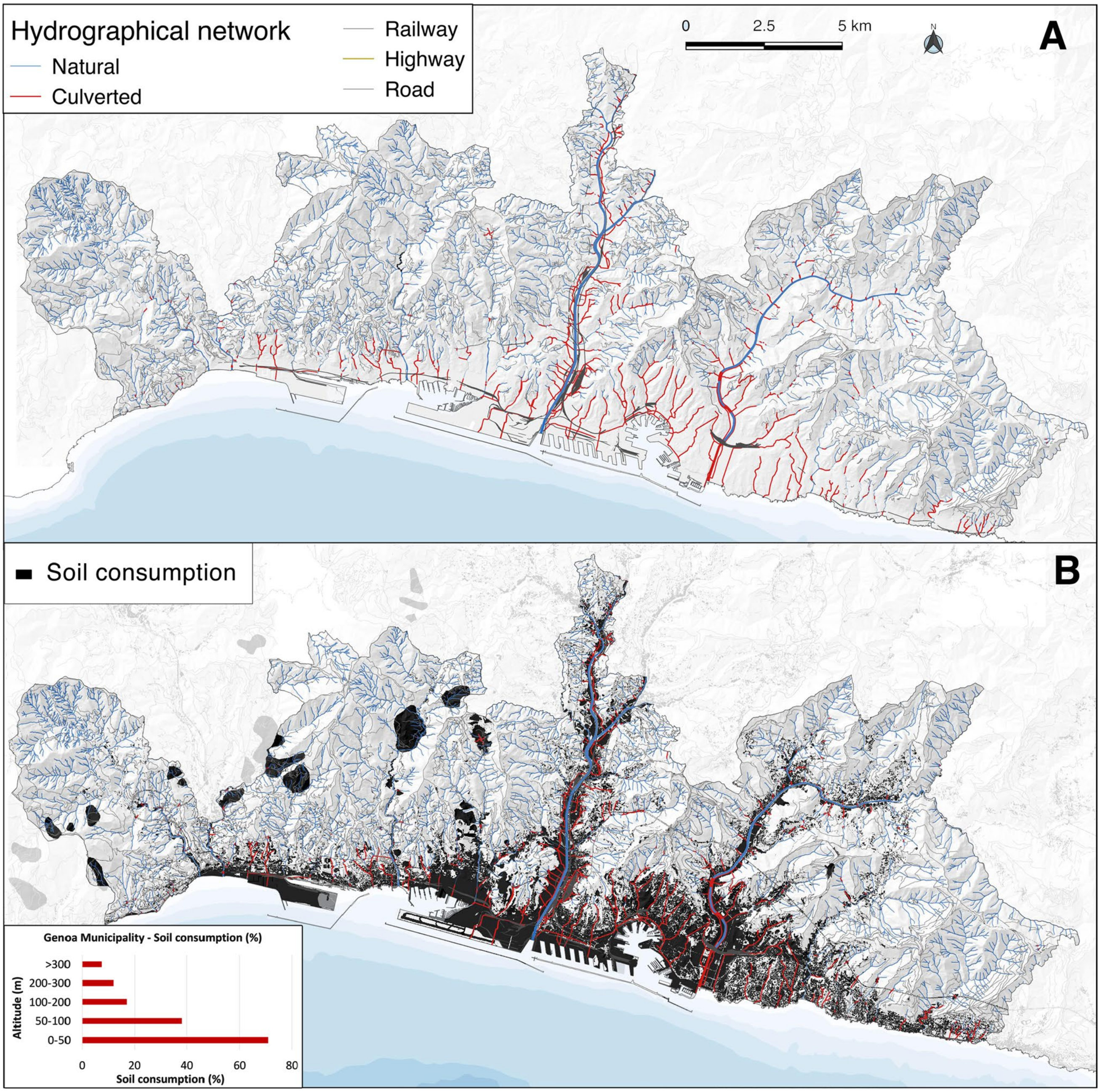

Fig. 9 Main infrastructures (**a**) and soil consumption (**b**) in Genoa Municipality; the inset diagram shows statistics for elevation belts

events, the frequency of events seems to be underestimated for the years prior to 1900.

A different explanation might relate to the recent, although modest, increase in stream accommodations made in the GMA (between the mid-90s and 2010), the increase in effectiveness of the civil protection measures, or the rules introduced on land use through basin master plans. If further studies can confirm the casualty distribution decrease, then it would be an encouraging example of climatic change adaptation.

Strategies to adapt to climate change and geo-hydrological risk reduction are crucial. The intent would be to reduce vulnerability by increasing community resilience to future hazardous events, resilience being ‘the ability to prepare and plan for absorb, recover from, and more successfully adapt to adverse effects’ (Committee on Increasing National Resilience to Hazards and Disasters 2012). Reducing the risk posed by future geo-hydrological events requires not only knowledge about the hazards but also taking action to use that knowledge (De Graff et al. 2015). Adaptation strategies to climate changes in the field of geo-hydrological risk are no longer delayable (European Commission 2013). In this framework, future developments could both limit and potentially reduce existing vulnerability as developmental opportunities cause the replacement and modification of urban features. This is obviously a long-term effort involving both governmental and private institutions, which will depend on the knowledge gained from the study of past geo-hydrological events to properly design, arrange and alter urban development in Genoa with plans avoiding hazardous areas (Bartholy et al. 2006). Increasing resilience will result in a decrease in vulnerability and, in turn, reduce the risk of future flood and related phenomena events. To this end, the monitoring and mitigation of heavy rainfall effects (reductions in instability processes and solid transport along water courses) should be planned and initiated. After a preliminary study at the basin scale to recognize the geo-hydrological instabilities, a series of interventions may be identified and managed on the basis of the decision support system model. Sensitizing the adaptation of populations to flood risk phenomena is also essential. Socio-geographical analysis and perceptual maps can adapt the risk perception and the related behaviours of the exposed people.

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