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# HEAVY RAINS TRIGGERING FLASH FLOODS IN URBAN ENVIRONMENT: A CASE FROM CHIAVARI (GENOA METROPOLITAN AREA, ITALY)

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## EXTENDED ABSTRACT

Il 2014 in Liguria sarà ricordato come l'anno record di pioggia cumulata: in alta Val d'Aveto sono stati infatti superati 4000 mm. Il 9-10 ottobre è esondato il T. Bisagno a Genova e il T. Scrivia a Montoggio, il 10 novembre sono esondati i corsi d'acqua nel chiavarese, il 15 novembre numerosi corsi d'acqua tra Genova e Imperia.

In questo contributo è stata fatta la ricostruzione dell'evento pluviometrico e analizzati gli effetti al suolo registrati con l'inondazione di Chiavari del 10 novembre 2014.

La piana di Chiavari è ubicata nella Liguria orientale e si estende per circa 2 km tra i torrenti Entella e Rupinaro. Il T. Entella presenta un bacino di 376 $km^2$ e una portata per T=200 anni di 2800 $m^3/s$. Il T. Rupinaro presenta una superficie di 11 $km^2$ e una portata per T=200 anni di 240 $m^3/s$. La piana di Chiavari è storicamente soggetta ad esondazioni: nel XX secolo si descrivono una quindicina di eventi da parte del T. Entella e/o del T. Rupinaro, mentre nel secolo attuale si ricorda l'alluvione del 24 novembre 2002.

Per la ricerca sono stati utilizzati i dati meteoclimatici della rete ARPAL, mentre gli effetti al suolo sono stati valutati tramite rilievi diretti post-evento. Sono state quindi analizzate le serie termo pluviometriche di Chiavari e di Diga Giacopiane per evidenziare trend climatici in atto. Lo sviluppo urbanistico e i cambiamenti dell'uso del suolo sono stati valutati attraverso un raffronto cartografico e fotografico multitemporale relativo agli ultimi 200 anni.

L'evento del 10 novembre è caratterizzato da una pioggia cumulata di 66 mm in 1 ora, 220 mm in 6 ore registrata a Panesi. La pioggia è legata alla risalita di aria umida e instabile dal Mar Tirreno verso la costa ligure che ha determinato la formazione di un sistema temporalesco sul Golfo del Tigullio. Fenomeni convettivi di questo tipo sono caratteristici dei mesi autunnali liguri e sono causati dalla particolare condizione meteorologica che insiste sul Golfo Ligure.

Gli effetti al suolo sono consistiti in esondazioni e frane: tra le 20:00 e le 23:00 il livello del T. Lavagna è risalito di oltre 6 m, del T. Graveglia di oltre 2 m, del T. Sturla di 4 m e infine del T. Entella di quasi 7 m. Si è verificata l'esondazione dei torrenti Lavagna, Entella e Rupinaro, con un tempo di ritorno dell'evento stimabile in 50 anni.

I danni calcolati sono di oltre 50 milioni di Euro solo per la città di Chiavari.

Il territorio di Chiavari è oggi quasi completamente urbanizzato: la prima espansione urbanistica è avvenuta agli inizi del XX secolo, ma la fase più intensa di consumo del suolo è avvenuta negli anni Sessanta, soprattutto nel tratto medio e terminale della piana del T. Rupinaro. Oltre alla realizzazione di nuove superficie impermeabili per edifici e infrastrutture, si è verificato il restringimento e la trasformazione dei corsi d'acqua in canali, la loro deviazione e la progradazione della fascia costiera per colmate.

L'analisi della serie termo pluviometrica registrata presso la stazione di Chiavari, in funzione dal 1877, mostra un trend positivo per la temperatura media dell'aria (15.4°C), una cumulata di pioggia annua intorno a 1200 mm e un numero di giorni piovosi (85) in trend negativo. Conseguentemente il tasso di precipitazione giornaliera mostra un trend positivo, che comporta pioggia più intensa e meno frequente. Questo trend è confermato dai valori in aumento dei massimi di pioggia di 1, 3, 6, 12, e 24 ore rilevati per la stazione di Diga Giacopiane.

Tutti i dati raccolti confermano che nel bacino del T. Entella gli eventi geo-idrologici sono in aumento negli ultimi 50 anni, per incremento della vulnerabilità e della pericolosità. L'espansione urbana e la costruzione in aree a rischio è avvenuta soprattutto nel dopoguerra: al Ponte della Maddalena il T. Entella è stato ristretto in tempi storici di oltre 150 m, mentre aree golenali del T. Rupinaro sono state occupate da edifici e infrastrutture. La variazione del regime delle piogge e l'aumento della temperatura dell'aria sono in accordo con i cambiamenti climatici globali.

L'area metropolitana Genovese è ormai diventata un caso studio internazionale per il rischio geo-idrologico a causa dell'alta probabilità di innesco di temporali autorigeneranti, della morfologia acclive dei bacini e della densa urbanizzazione nelle piane alluvionali. Interventi di mitigazione del rischio attraverso la riduzione della pericolosità e della vulnerabilità sono assolutamente indifferibili.

## ABSTRACT

Between 10th and 11th November, 2014, heavy rainfall over a short period fell on the eastern Genoa metropolitan area. The geo-hydrological event had important ground effects, among them the simultaneous flooding of Entella and Rupinaro streams, in Chiavari city. In lower Lavagna valley, the main tributary of the Entella, a landslide caused two casualties, while serious damage to buildings and infrastructures were registered in Chiavari's Old Town and in the nearby communities of Carasco and Cogorno. In the Entella basin, the rainfall peaked at 60 mm/hour and accumulated 220 mm in six hours. The levels of the streams rose instantly, showing concentration times of less than an hour. The Entella rose seven meters, flooding Carasco, Cogorno, and the Caperana neighborhood of Chiavari. Flash flooding of the Rupinaro stream caused water to rise to 1.5 m in Chiavari's historic core. Analyses were carried out of the weather conditions and the ground effects of the events; in addition, studies were made of the main causes of the geo-hydrological risk. In particular, variations in climate and uncontrolled urban development were the cause of increased geo-hydrological hazards and vulnerability of this area, historically subject to flooding. Such conditions of risk are unacceptable, and urgent measures are required to mitigate the effects of heavy rainfall events.


***Keywords:*** *geo-hydrological hazard, heavy rainfall, flood risk, Entella and Rupinaro catchments, Chiavari, Liguria*

## INTRODUCTION

Geo-hydrological risk is currently a subject of scientific interest due to its environmental, social and economic impact on the affected areas. Floods in particular are of interest throughout Europe (Hall *et alii*, 2014, Grams *et alii*, 2014, Blosh *et alii*, 2013), and the Mediterranean (Jansà *et alii*, 2014). The recent flooding which affected Europe and the Mediterranean area were studied by various authors concerning the role of climate variations (Barrera Escoda & Llasat, 2014; Bohm *et alii*, 2014; Elleder, 2015; Likai & Jijun, 2010), or variations in land use (Boudou *et alii*, 2015). Moreover, from a geological and geo-morphological point of view, in the Italian peninsula geo-hydrological catastrophes are very common (Guzzetti & Tonelli, 2004), causing damage to buildings and infrastructures and frequently also costing human lives (Guzzetti, 2000; Guzzetti *et alii*, 2004). Flash floods in particular have been studied in recent years in the Mediterranean area and in Italy due to their recent intensification (Llasat *et alii*, 2014; Terranova & Gariano, 2014), in part as a result of climate change. The metropolitan area of Genoa, especially in the last century, has experienced a trend of growth in annual rate of daily precipitation and average temperatures (Faccini *et alii*, 2015e; Russo *et alii*, 2000). This trend correlates with data in other stations around the world (IPCC, 2013). Furthermore, the Ligurian area has always been subject to geo-hydrological events, as evidenced by historical news documents and annals of the ancient Republic of Genoa. In recent times there has been an increase in such events, more and more often involving economic damage and the loss of human lives. The area of Chiavari and eastern Liguria in particular are frequently affected by flooding, most recently in 2000 and 2002 in the valley of the Entella stream (Fig. 1) (Faccini *et alii*, 2005) and in 2011 in the world-famous area of the Cinque Terre (Buzzi *et alii*, 2014), as well as again in 2013 and 2014 in the Entella valley. The year 2014 saw record rainfall in the entire Mediterranean area. In certain areas of eastern central Liguria, rainfall reached twice the average levels (Tab. 1), example g. 4000 mm in Barbagelata and Cabanne (Upper Aveto Valley), and between 3500 and 4000 mm in Torriglia (Upper Scrivia Valley), Belpiano and Cichero (Upper Sturla Valley) (Fig. 1). In autumn 2014 major flooding occurred in the Mediterranean and three serious floods affected the Ligurian territory. These took place between early October and mid-November: on 9 and 10 October the Bisagno stream overflowed in Genoa (Faccini *et alii*, 2015b) and a high number of landslides occurred in the Upper Scrivia catchment, especially affecting the village of Montoggio; on 10 November, both the Entella and Rupinaro overflowed in the city of Chiavari (Faccini *et alii*, 2015a), while on 15 November heavy rainfall in a short period caused the streams to overflow. That event affected a larger area of central-western Liguria located between the Impero stream in Imperia, to the west, and the Polcevera stream in Genoa to the east.The flash flood under study illustrates a high accumulation of rainfall (60 mm/hour, 220 mm in six hours) which affected the territory of the valleys of the Entella and Rupinaro on 10 November 2014 (Fig. 2), as well as the overflowing of the Lavagna stream in the lower sector of the Fontanabuona valley and the triggering of several landslides. This natural disaster also caused two fatalities in the municipality of Leivi. The aim of the research is to reconstruct the flood event which affected Chiavari on 10th November 2014 with respect to past rainfall and the consequent effects on the city's Old Town. This permits an evaluation of the conditions of geo-hydrological risk in the Entella stream catchment, especially with respect to other historical events in Chiavari, its largest town, both regarding risk and increased vulnerability. This study of the most recent flood may provide useful indications concerning flood analysis and risk reduction.

## RESEARCH METHODOLOGY

### *Entella catchment and Chiavari: geographical settings*

The city of Chiavari is located in the middle area of eastern Liguria, in a floodplain two km wide, between the Entella stream to the east and the Rupinaro stream to the west (Fig. 1). The Entella basin is one of the broadest in Liguria (372 km$^2$), distinguished by a network of short streams with narrow basins. The Entella rises in the locality of Prioria di Carasco, 4.5 km north of Chiavari, from the confluence of Graveglia (63 $km^2$), Lavagna (160 $km^2$) and Sturla (130 $km^2$) streams. The floodplain of the Entella averages 500 m in width, narrowing to 300 m in Rivarola and widening to 800 m in San Salvatore. The presence of the towns of Carasco, Chiavari, Cogorno and Lavagna, with a total population of 50,000, makes this area vulnerable. Based on rain gauge measurements (Tab. 1), the rainfall has sub-Mediterranean seasonal regime (Sacchini *et alii*, 2012), with minimums in the summer and maximums in the autumn. The weather station in Chiavari registers an average annual precipitation of 1184 mm over 85 days. In the hinterland the average rainfall increases with altitude (Tab. 1): average rainfall may be more than 1900 mm and autumn maximums around 200 mm / month. Most of the rainfalls between autumn and spring, determined by a local circulation which is characteristic of the area and is known as the Genoa Low; it is a secondary of depression orographic origin which originates downwind of the Ligurian Alpine-Apennine arc at the arrival of an Atlantic

| Raingauge Station | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Panesi (25 m) | 130 | 105 | 120 | 104 | 82 | 61 | 40 | 69 | 107 | 198 | 165 | 134 | 1115 |
| | *255* | *254* | *78* | *55* | *47* | *15* | *24* | *57* | *32* | *432* | *519* | *131* | *2048* |
| Cichero (615 m) | 123 | 79 | 118 | 97 | 94 | 59 | 45 | 94 | 83 | 198 | 103 | 130 | 1930 |
| | *362* | *300* | *86* | *90* | *40* | *17* | *44* | *123* | *29* | *657* | *530* | *148* | *3739* |
| Reppia (530 m) | 170 | 135 | 163 | 151 | 132 | 88 | 54 | 75 | 116 | 240 | 200 | 216 | 1990 |
| | *785* | *470* | *183* | *147* | *67* | *64* | *66* | *131* | *31* | *398* | *746* | *121* | *2805* |

*Tab. 1 - Monthly and annual average rainfall compared to 2014 data (in italics) in some rain gauges of the Entella catchment (see fig. 1 for their location)*

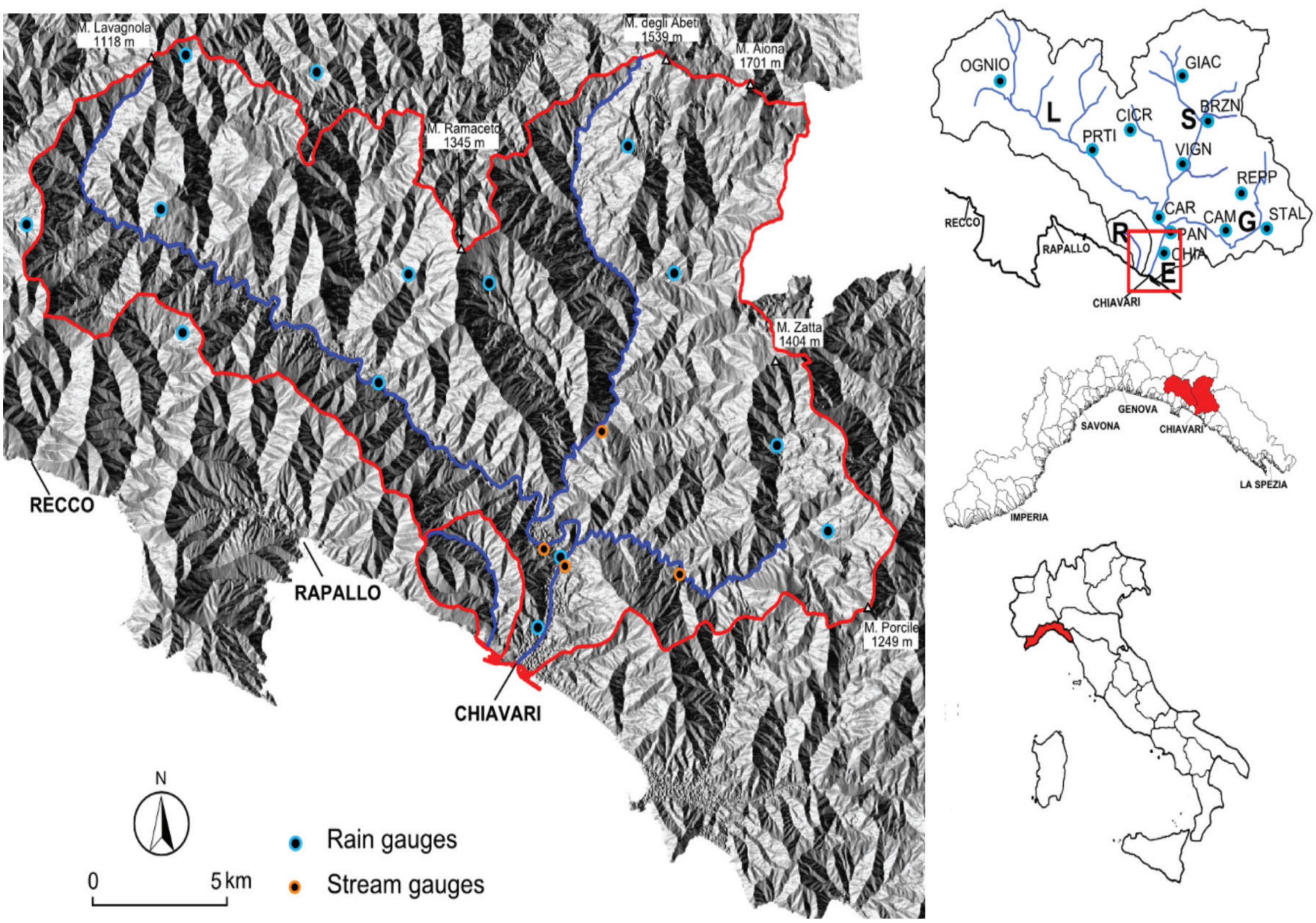


*Fig. 1 - Geographical sketch map of the Entella and Rupinaro streams catchment and the rain and/or discharge gauges of ARPAL network. LEGEND: L=Lavagna, S=Sturla, G=Graveglia, E=Entella, R=Rupinaro CHIA= Chiavari; PAN= Panesi; CAR=Carasco; CAM=Caminata; REPP= Reppia; STAL= Statale; VIGN=Vignolo; BRZN= Borzone; GIAC= Giacopiane; CICR= Cichero; PRTI= Pian dei Ratti; OGNIO= Ognio*

storm (Jansà *et alii*, 2014). Chiavari's average temperature at sea level is 15.4°C, with averages of 8°C in January and 24°C in July. Significant differences are registered inland, both in the immediate interior and in the hinterland: the former has a more continental climate, while the mountains behind the town rise rapidly to an altitude of 1700 m above sea level. Geologically, the plain is characterized by recent alluvial deposits as a result of the diversion of the Entella stream, currently banked along its entire length; recent and current alluvial terraced deposits create a plain along the water's course which becomes broader in the

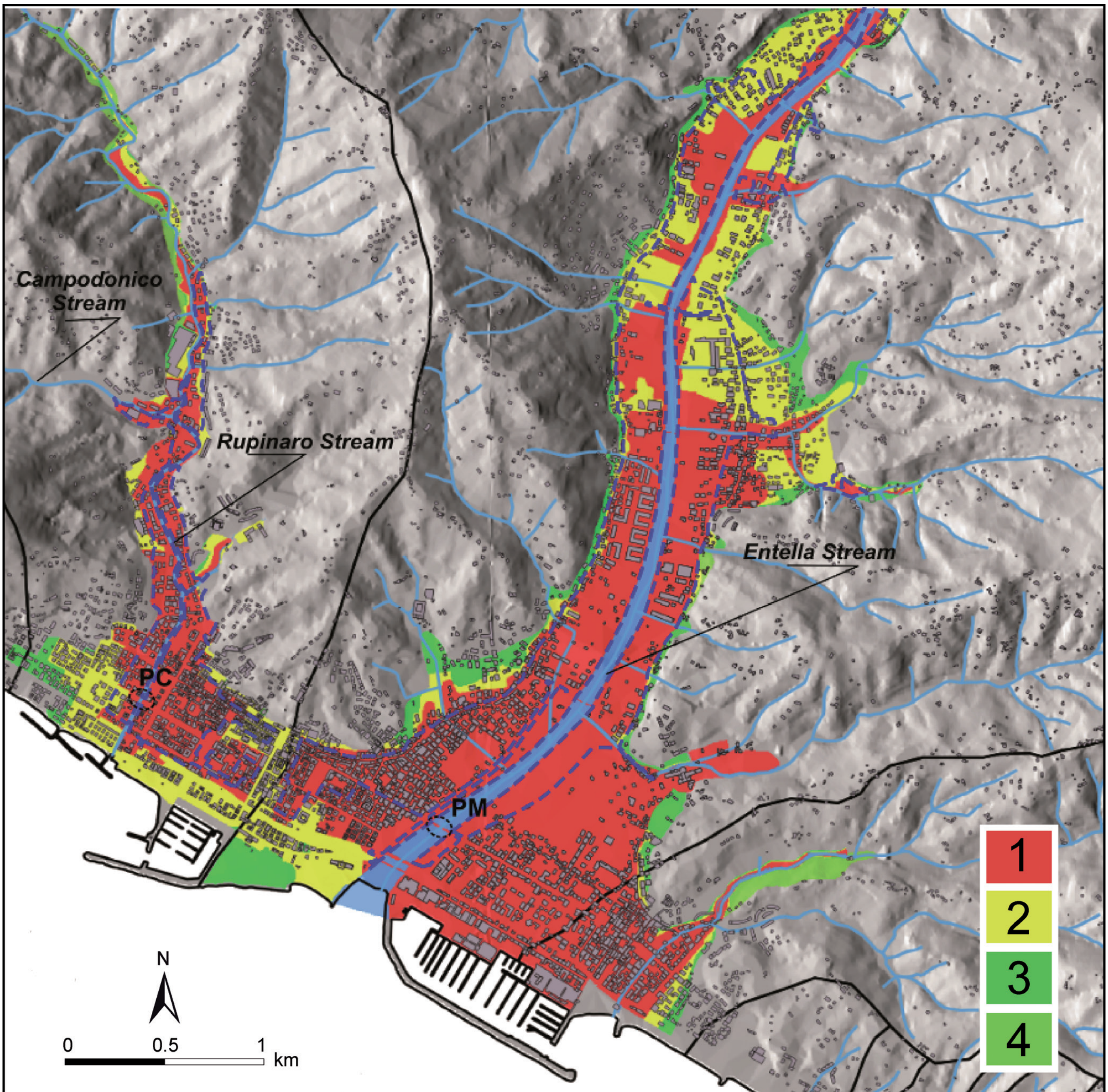


*Fig. 2 - Chiavari floodplain and related flood hazard zonation (1=high, 2=medium, 3=low, 4=historically flooded areas), modified from Provincia di Genova, 2013. The blue dashed line indicates the flooded area by the 10 November 2014 event.* Legend: *PM= Maddalena Bridge (ponte della Maddalena); PC= Castagnola Bridge (ponte di via Castagnola)*

lower sections. Both shores show moderate levels of alluvial fan. The maximum capacity at the stream's mouth, for a return period of 200 years, has been estimated at 2739 $m^3/s$ and at 1559 $m^3/s$ for a return period of 50 years (Provincia di Genova, 2013). The basin of the Rupinaro stream shows the typical characteristics of the numerous small Ligurian catchments: an area of 11 $km^2$, steeply slopes and a hydrographic pattern affected by tectonic lineations. The watershed is fairly close to the coastline and descends from an altitude of 547 m, on Mount Anchetta. The water flows for 4.5 km and the entire drainage network is affected by erosion. The discharge at flood is estimated at 242 $m^3/s$ for a return period of 200 years, and 167 $m^3/s$ for a return period of 50 years (Provincia di Genova, 2013). The Chiavari plain is historically subject to flooding (Sanguineti, 1953); in the last century alone (Tab. 2) numerous floods were registered, resulting in considerable damage. In this century, the most disastrous flood before the one under study in this paper occurred on 24th November 2002 at the mouth of the Rupinaro stream, causing one victim (Faccini *et alii*, 2005).

## *Methods*

The research was carried out using an analysis of the weather conditions on the ground during the event, using the maps of MetOffice and Wetterzentrale available on the web, as well as a study of radar images available on the site of the Agenzia Regionale per la Protezione dell'Ambiente in Liguria (ARPAL), the regional agency for environmental protection. The hourly rainfall was measured by several stations, supplemented by hydrographs which were correlated with the rainfall. Using the rainfall data, maps could be prepared of hourly isohyets during the event. The ground effects were determined on the basis of direct results registered soon after the event, added to bibliographic and amateur sources available on the web and from reports of the event (ARPAL, 2014). Historical and bibliographical sources were consulted, including chronicles and annals of the ancient Republic of Genoa, and records of past incidents of flooding were consulted (Sanguineti, 1953; Faccini *et alii*, 2005; Provincia di Genova, 2013). The most disastrous flooding events of the Twentieth and Twenty-first centuries were traced using the data on daily rainfall over five days which showed the cloudburst center in the area of the Entella stream basin. Finally, the bibliographic data of the Genoa Chamber of Commerce and the Municipality of Chiavari were used to evaluate the flood damage, together with data from the historical archives of the Società Economica (economic society) of Chiavari concerning past events. Subsequently a climate analysis was carried out using the century-old thermo-pluviometric series of Chiavari, gather

| Year/Month/Day-s | Rainfall peak | Rainfall event | River/Creek | Flooded city area/street/bridge/district | Damage |
|---|---|---|---|---|---|
| 1935 Nov 10-11 | 118 mm/3 h (Panesi) | 250 mm/5 d (Chiavari) | Rupinaro | Rupinaro district | economic activities, basement dwellings |
| 1936 Sept 25-26 | 201 mm/3 h (Chiavari) | 220.6 mm/48 h (Chiavari) | Rupinaro | Chiavari city western area | economic activities, basement dwellings |
| 1938 Sept 09 | 119.6/3 h (Chiavari) | 268 mm/48 h (S. Maria di Sturla) | Rupinaro | Rupinaro district and Chiavari lower districts | economic activities, basement dwellings |
| 1948 May 27-28 | 130.6/12 h (Neirone) | 223.8/5 d (Neirone) | Rupinaro and Entella | Rupinaro district | economic activities, historical buildings |
| 1948 Oct 26 | 112.6/1 h (Chiavari) | 160.8/24 h (Giacopiane) | Rupinaro and Entella | Rupinaro and Cadiborgo district, Lavagna river bank | economic activities, basement dwellings |
| 1953 Sept 19 | 100 mm/1 h (Neirone) | 362.3 mm/5 d (Ognio) | Entella | Caperana | economic activities, basement dwellings |
| 1953 Oct 15 | 154.6 mm/3 h (Chiavari) | 324 mm/5 d (Statale) | Entella | Caperana | 1fatality, economic activities, basement dwellings |
| 1963 Sept 04 | 158.4/3 h (Panesi) | 242.8/24 h (Panesi) | Entella and Rupinaro | Chiavari city, La Franca and Rupinaro district | economic activities, basement dwellings |
| 1979 Sept 21 | 113.6/3 h (Cassagna) | 316/24 h (Cassagna) | Entella and Rupinaro | Chiavari city, Castagnola bridge | economic activities, basement dwellings |
| 1982 Sept 22 | 113 mm/1 h (Tigliolo) | 551.8 mm/24 h (Tigliolo) | Entella | Chiavari eastern city | economic activities, basement dwellings |
| 1999 Oct 23-24 | 119 mm/3 h (Statale) | 240 mm/24 h (Statale) | Entella | Chiavari eastern city | economic activities, basement dwellings |
| 2000 Nov 06 | 199.4/3 h (Piana di Soglio) | 243 mm/24 h (Statale) | Entella | Caperana | economic activities, basement dwellings |
| 2002 Nov 24 | 93 mm/1 h (Chiavari) | 186 mm/24 h (Tigliolo) | Rupinaro | La Franca district, western Chiavari city | 1fatality, economic activities, basement dwellings |
| 2014 Nov 10 | 129 mm/3 h (Panesi) | 214 mm (24 h) | Entella and Rupinaro | Chiavari city, Castagnola bridge | 2 fatalities in Leivi, economic activities, basement dwellings |

*Tab. 2 - Disaster flood features and minor geohydrological events in Chiavari floodplain since XX century*

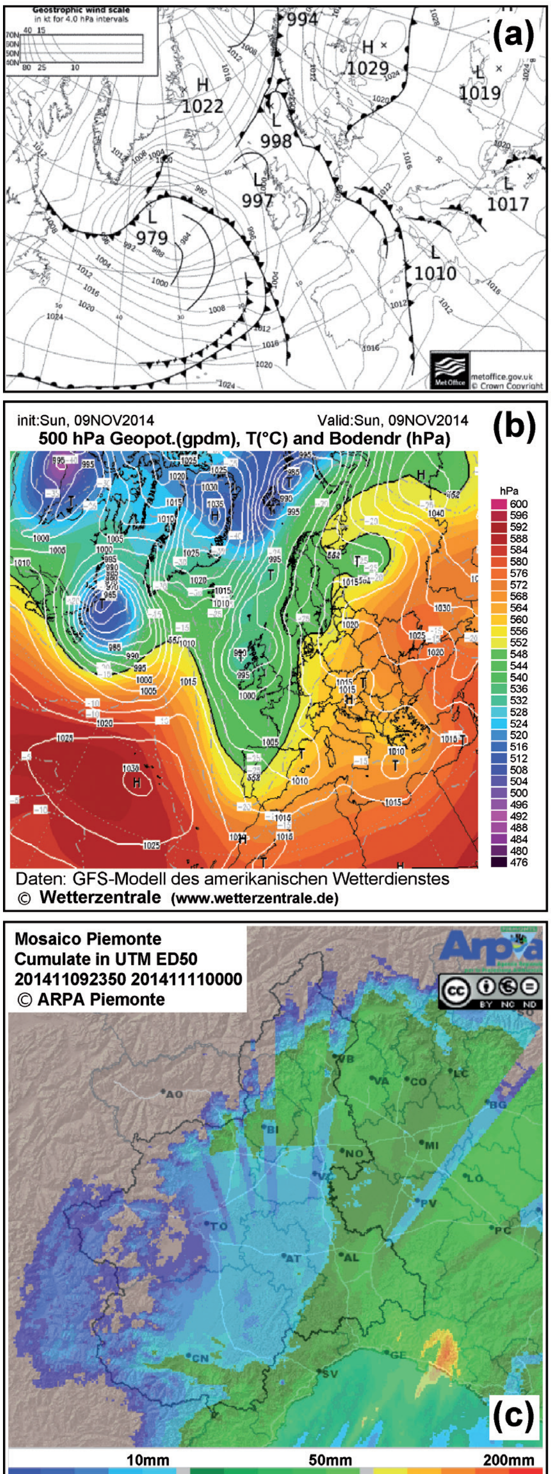


*Fig. 3 - Meteorological conditions on 10th November, 2014. a) Sea level pressure and fronts (Bracknell chart from Wetterzentrale.de); b) 500 hPa geopotential (from www.centrometeo.com); c ) Radar image at Mount Settepani (ARPAL, 2014)*

by a former ecclesiastical observatory currently managed by the Municipality of Chiavari and in use uninterruptedly since 1877. The climate analysis made it possible to reconstruct the historical series of annual rainfall, rainy days, daily rainfall rate and mean air temperature.The series were subjected to polynomial regression with the "LOWESS" graphic function (Becker *et alii*, 1988; Cleveland, 1979; 1981) to obtain a better fit of data which contain considerable historical variations. The series also underwent the non-parametric Mann-Kendall statistic test (Mann, 1945) to evaluate the presence of trends with a significance of 95 percent: this purpose "xlstat" software was used, evaluating the percentage of accuracy of the trend. The Mann-Kendall test is used in particular to highlight trends in the series of environmental data (Hipel & McLeod, 2005). Moreover, since the cloudburst centers of the flood events in the Entella stream are often located in the hinterland of Chiavari, on the mountains rising behind the city (Sacchini *et alii*, 2012), a climate analysis was made of the series of maximum rainfall at 1, 3, 6, 12 and 24 hours, measured by the raingauge installed on the dam on Lake Giacopiane in 1925, which has functioned uninterruptedly up to the present time. To evaluate the urban development and changes in land use, the following measures were applied: i) a multi-temporal comparison between a orthophoto from 2014and the "Map of the Sardinian States on the Mainland" dating from 1823; ii) statistical data, in particular the historical series, drawn from the census by the National Institute of Statistics (ISTAT) concerning population and buildings for the city of Chiavari. The climate analysis and the study of urban growth gave significant results concerning flood risk in Chiavari and the actions to mitigate the risk.

## THE DISASTROUS FLOOD OF 10 NOVEMBER 2014

### *Meteorological features*

On 10 November 2014, rain fell for 24 hours in the basin of the Entella stream, starting at 8 a.m. but reaching a paroxysmal phase by evening, between 17 h and 24 h (5 p.m. and midnight). The most intense rainfall was recorded by instruments in the location of Panesi, with 66 mm in one hour, 220 mm in six hours. The heavy rainfall which caused the disastrous flooding was linked to the "Genoa Low", a synoptic low-pressure weather system originating in the Ligurian Gulf and caused by the passage of an Atlantic front behind the Alpine range. In such cases masses of cold air from the northern Atlantic, together with a perturbation, meet the Ligurian Alpine-Apennine range and move down the Rhone Valley to reach the Mediterranean Sea. This causes the formation of the secondary orographic system of low pressure centered on the Gulf of Genoa (Jansà *et alii*, 2014). The Genoa Low thus formed gives rise to winds from the south toward eastern Liguria (Sacchini *et alii*, 2012). This extra-tropical cyclone is frequently accompanied by heavy

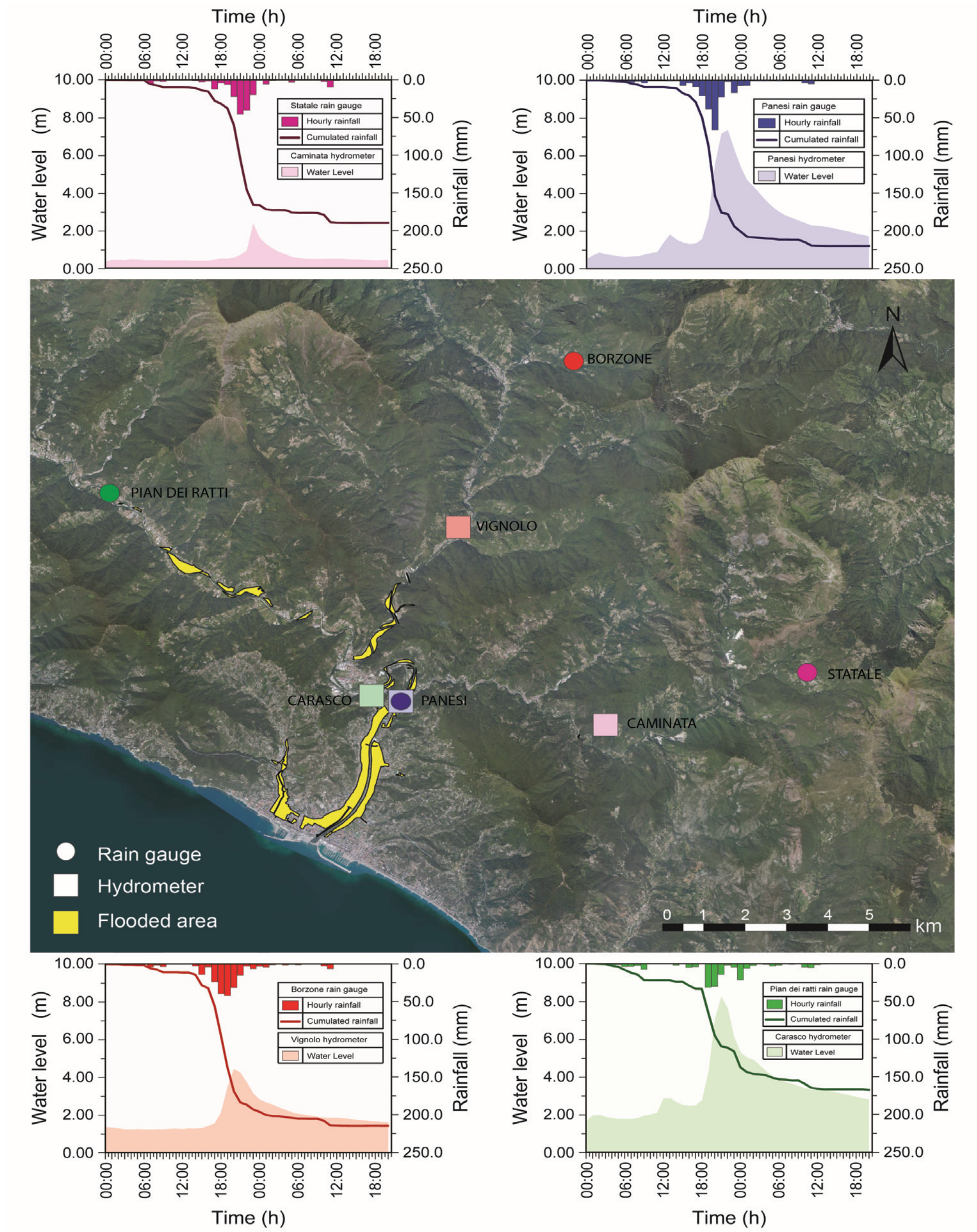


*Fig. 4 - Hourly rainfall, cumulated rainfall and water level on 10th -11th November 2014 in the rain gauges and stream gauges of Entella stream catchment. The circle and square shape (in four colors) represent the location of the rain gauge and hydrometer respectively.*

rainstorms of short (Fig. 3a-b) duration in concentrated areas (Saèz De Camara *et alii*, 2011). During the event the presence of the Entella valley, oriented on a north-south axis, on one hand facilitated the passage of storm cells along the valley pushed by south winds of 500 hPa; on the other hand it served as a barrier to the peaks of the northern Apennines, some of which are at an altitude of 1500 m above sea level.The simultaneous action of anti-cyclone block on eastern Europe (Fig. 3) also slowed the passage of the front and favored, in the warm part of the storm, a flow of stationary hot damp currents from the south. Due to the effects of orography and wind-shear caused by the converging of northern winds near the center of the gulf associated with the Genoa Low, a convective self-healing system was created, causing heavy rainfall over several hours in the concentrated area of the Entella valley (Fig. 3; Fig. 4; Fig. 5). These convective systems are fairly common in autumn in Liguria, and are mainly caused by this meteorological situation which persists in the Ligurian Sea. Examples of such

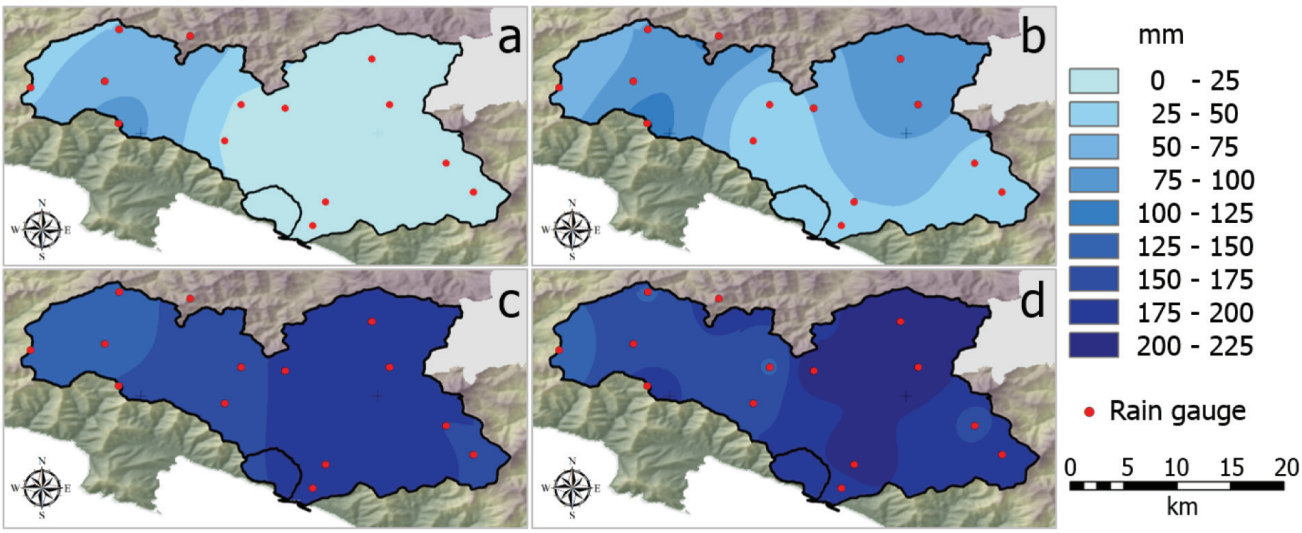


*Fig. 5 - The distribution of the hourly isohyets in the Entella catchment: a) 12:00 of 10 Nov; b) 18:00 of 10 Nov; c) 00:00 of 11 Nov; d) 06:00 of 11 Nov 2014*

meteorological conditions which determine catastrophic events in Liguria occurred numerous times in recent years: in Varazze and the Sestri Ponente section of Genoa on 4 October 2010; in the Cinque Terre and Val di Vara on 25 October 2011; in Genoa on 4 November 2011 and 9 October 2014; in the eastern metropolitan area of Genoa and Savona on 15 November 2014. More rarely, these convective systems are triggered at the beginning of the summer season (Buzzi *et alii*, 2014; Faccini *et alii*, 2015c and 2015d). The effect of the concentrated rains along the storm structure identified by the radar image in Figure 3 is clearly visible in the distribution of the hourly isohyets shown in Figure 5.The distribution of the accumulations of rainfall during the most intense phase of the storm shows the maximum recorded in the area of the Entella basin, in particular between the mouth of the Entella stream and the Sturla valley. Accumulated rainfall measuring 170 mm over 6 hours was recorded in the upper Graveglia valley and in the mid and lower Lavagna valley. In the upper portion of the Lavagna basin, accumulated precipitation measured 150 mm over 6 hours (red circle in Fig. 4), (Fig. 5).The accumulated rainfall registered in the basin of the Entella stream is far higher than the average monthly levels. The instrument in Panesi recorded 640 mm in the entire month of November, compared to an average of 135 mm. In addition, the barrier effect of the high waves on the downward flow of the flooded river toward the sea must be taken into consideration, especially since the flow would also have been partially blocked by the port's docks and tourist craft just offshore; the strong south winds in fact had whipped up waves 1.8 m high on the evening of the flood, measured by the ondametric station of eastern Liguria (Faccini *et alii*, 2012b). In recent decades Chiavari, and the basin of the Entella Stream in general, have been frequently hit by heavy rains: the most significant events in terms of quantity of rainfall and subsequent effects on the ground occurred on 22 September 1982, 23-24 October 1999, 6-7 November 2000, 24 November 2002, and 21-22 October 2013 (Tab. 2), (Fig. 10).

### *Ground effects and damage evaluation*

The recorded effects on the ground consisted mainly of flash floods and shallow landslides: between 20 h and 22 h (8 p.m. and 10 p.m.) major flooding was recorded along all the main waterways in the basin of the Entella stream. The level of the Lavagna stream, recorded by the hydrometric station at Carasco, rose 6 m; the Graveglia near the Caminata bridge rose more than 2 m; the Sturla at the Vignolo bridge rose more than 4 m, and the Entella stream registered by the hydrometer at Panesi rose more than 7 m (violet square in Fig. 4). The hydrographs provide immediate results on an hourly basis. Consequently the flooding was registered at the following sites: the Lavagna flooded the plain between San Colombano Certenoli and Carasco, while the Entella flooded the plain between San Salvatore and Cogorno and the eastern section of Chiavari, where the high-water level exceeded 1.5 m. The Rupinaro overflowed its banks in the western section of Chiavari along three different areas between the confluence with Campodonico stream and the mouth of the main stream. The readings of the effects on the ground and the immediate results suggested that one of the peaks of precipitation during the event could be located at the point where the Campodonico stream flows into the Rupinaro stream. The Rupinaro at that time was not equipped with instruments for measuring the stream's level; its overflow can be deduced through flood-level markers (Mertz *et alii*, 2007) such as stains on buildings, or through the use of photos or video images: the water overflowed the bridge on Via Castagnola by more than one meter, and the neighborhood known

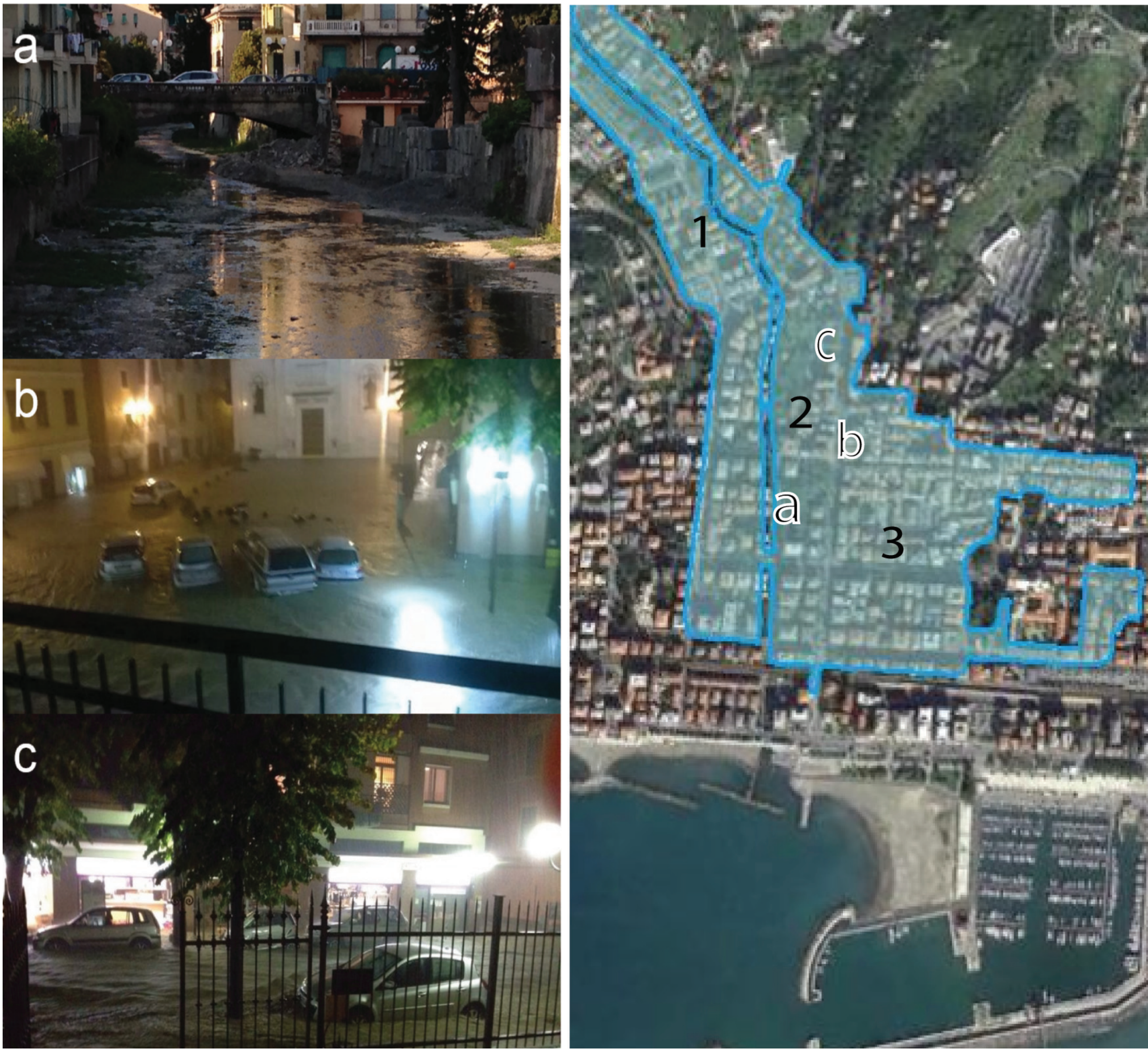


*Fig. 6 - Flooded areas in Chiavari of the 2014 Nov 10th event. Places mentioned in the text: 1) La Franca, 2) Rupinaro district, 3) Chiavari old town. Photos of a) damage to the riverbank of Rupinaro stream , b) flood of the main square of Rupinaro district, c) flood of the main street of Rupinaro district*

as Rupinaro was flooded, evidenced by water some 1.5 m high in its main square (Fig. 6). Numerous shallow landslides were noted in the lower section of the Lavagna stream, in the Sturla valley, in the Graveglia valley. The estimated discharge of water was some 1600 $m^3/s$ for the Entella stream, and some 170 $m^3/s$ for the Rupinaro stream, corresponding to a return period of 50 years for both watercourses.The estimated cost (updated to April 2015) of the damage caused by the flood of 10 November 2014 is some 52.4 million Euros for the city of Chiavari alone. A breakdown of the costs according to the type of damage and source of information indicates that the damage to economic activity assessed by the Chamber of Commerce in Chiavari amounts to 27.8 million Euros, based on the claims for damage. Estimated costs for urgent interventions and losses to private citizens (real estate and other property) were assessed by the Municipality of Chiavari at 24.6 million Euros. Comparing that disaster with the earlier ones in 2000 and 2002 (Faccini *et alii*, 2005), it can be noted that the weather conditions, the areas of rainfall and its effects on the ground were similar. During the flood in 2000 the heaviest rainfall was not more than 50 mm/h and the Entella stream overflowed its banks. In the 2002 flood, downpours of 100 mm/h were recorded, disastrous for the smaller Rupinaro stream, which in 2000 had not overflowed, although the conditions of rain were similar but spread out over a longer period. With regard to landslides, the areas most affected by the flood in 2002 (Faccini *et alii*, 2005) were equal in type, location and orientation to the event in 2014, but nonetheless it caused the death of two people in Leivi who were buried in their home by a landslide.

## GEO-HYDROLOGICAL RISK FACTORS

### *Chiavari urban development*

The territory of Chiavari today is almost completely urbanized. Figure 7 shows the comparison between the hydrographic network of early XIX century and of the present situation. It is noteworthy that until 1855 the areas surrounding the two main watercourses were free of construction. The plain of the Rupinaro stream was subjected to urban sprawl, and the stream

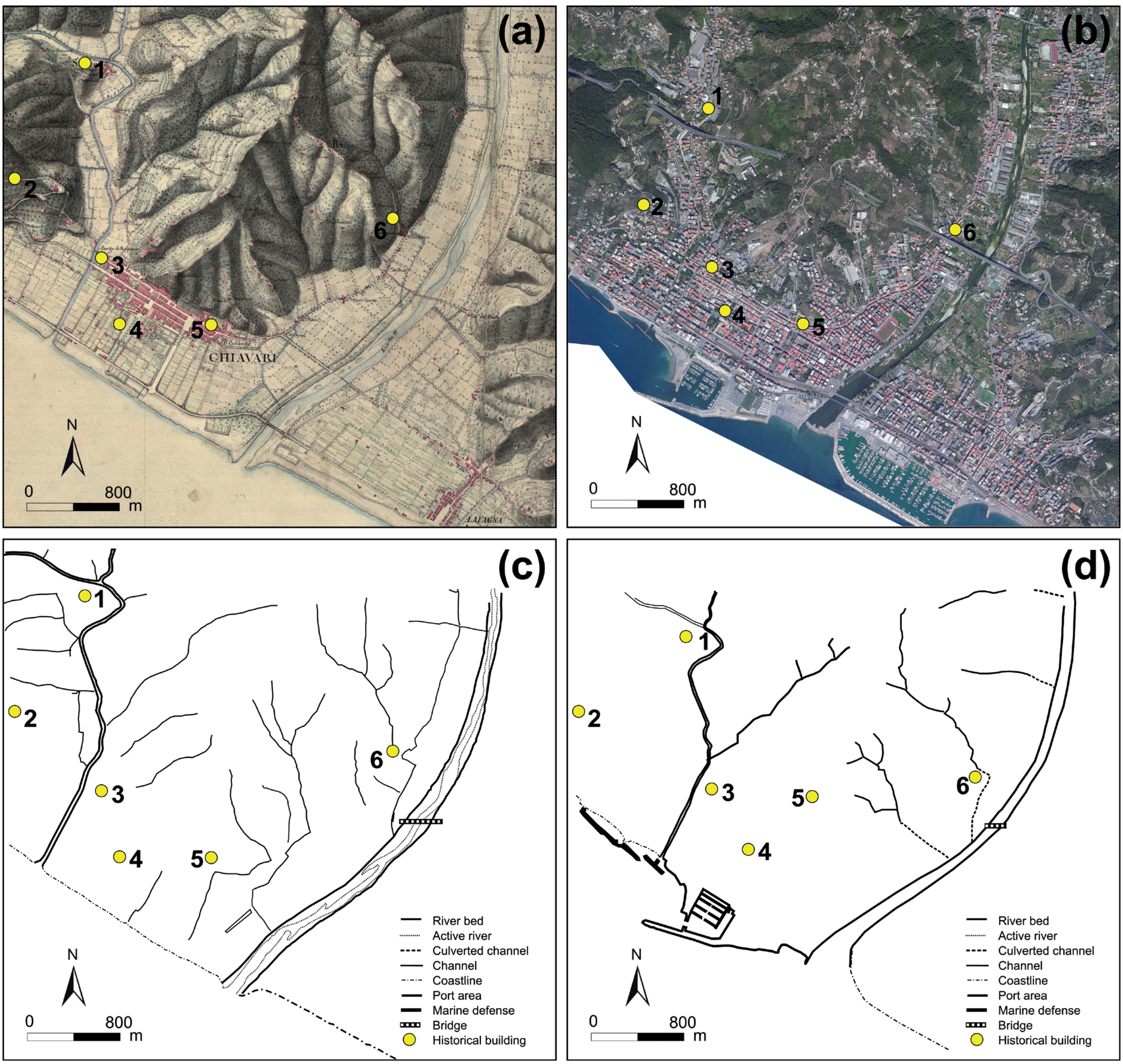


*Fig. 7 - Maps comparison of the Chiavari floodplain. Legend: a) early XIX century (From Stati Sardi, Italian Military Geographic Institute Archive 1815-1823), b) present day situation (from Bing Maps, 2014), c) hydrographic network in 1823, d) hydrographic network in 2014. Legend of historical building: 1. San Pier di Canne; 2. Bacezza church; 3.San Giacomo di Rupinaro church; 4. Madonna dell'Orto cathedral; 5.Cadiborgo church; 6. Chiesanuova*

was narrowed and confined by the surrounding buildings. The floodplain of the Entella, which until 1855 had hosted arable land, greenhouses and gardens, over the following century was cluttered with buildings, hangars, military barracks all close to the stream, with no space left for the floodplain. The number of buildings tripled in the period between the end of World War I and the end of the 1960s; the population peaked in 1971 with some 30,000 inhabitants, but has since decreased. Development was especially intense around the Old Town, resulting, during World War II, in its total cementification. According to the latest report on soil consumption (ISPRA, Munafò, 2015), Chiavari is among the worst cities in Liguria, with fully 24 percent of its area built up, compared to a regional average of 8 percent. Istat data also indicate Liguria as the region which loses the most land to cement despite a loss of population; between 1990 and 2005 the available hectares decreased from 249 000 to 135 570 inhabitants. In order to evaluate the changes in land use in Figure 7, multitemporal images are shown of the territory of Chiavari, from 1823 to the present. The urban expansion of Chiavari is evident from the area at the base of the mountain, which was historically inhabited, to the full urbanization of the plain and the anthropic expansion toward the sea. In particular the urbanization is complete in the area of the Rupinaro stream which is narrowed and covered. In the last forty years especially there has been a complete anthropization of the coastline, with buildings on the beach and the construction of port areas, a tourist port and a series of public works for marine defense.

### *Climate analysis*

Figure 8 shows the historic series of mean annual temperatures, annual rainfall, number of rainy days and daily rainfall rate (the ratio between annual rainfall and number of rainy days) from 1877 to the present in Chiavari.The temperature averages 15.4°C, with a variation of 0.6°C and an increase over time indicated by the graphic function "LOWESS", in particular from the 1950s.

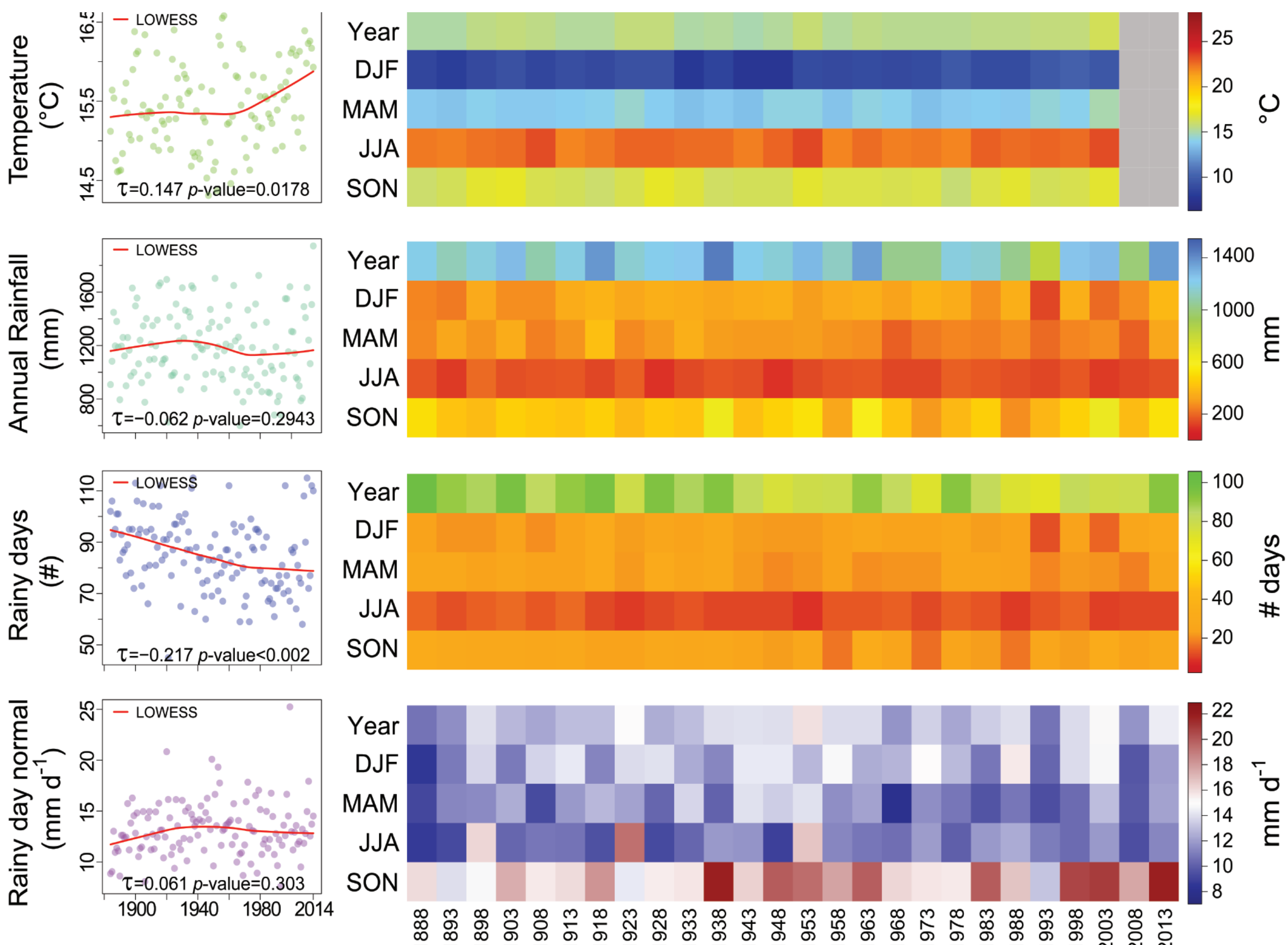


*Fig. 8 - Climate series of temperature, annual rainfall,rainy days and rainfall rate in Chiavari weather station from 1877 to 2014 (left column). For each variable, the figure shown the mean values of 5 years for the annual period (Year), winter period (DJF), spring period (JJA) and autumn period (SON)*

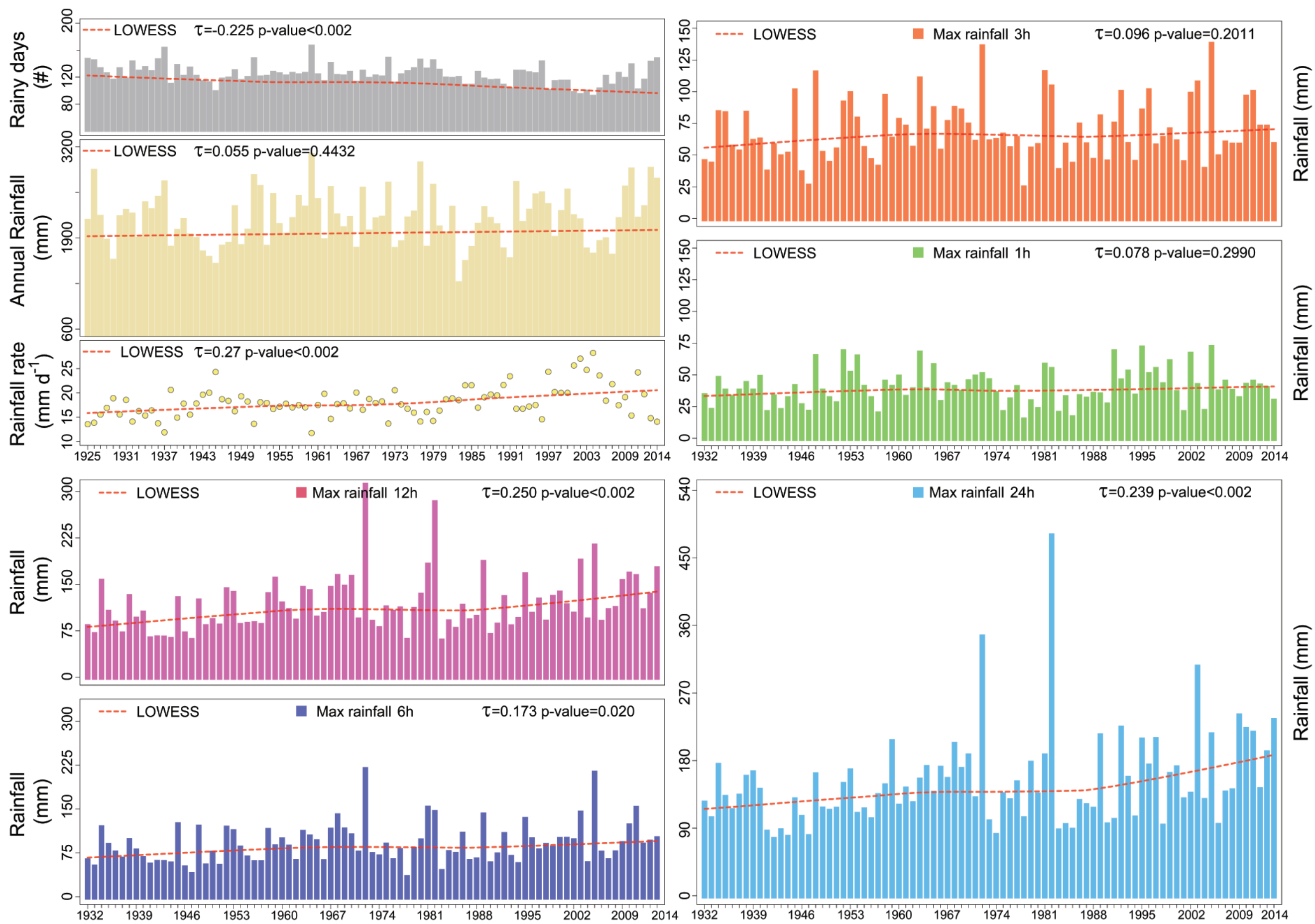


*Fig. 9 - Climate series of annual rainfall, rainy days and rainfall rate in Diga Giacopiane weather station from 1925 to 2014 (top left. Maximum annual rainfall for 1, 3, 6, 12 and 24 h at Diga di Giacopiane rain gauge from 1932 to 2014)*

The Mann-Kendall test shows a growth trend with a level of significance above 99 percent, spread over all the seasons.The annual rainfall shows an average of 1184 mm and a variation of 269 mm and a cyclical progress over a century without trends. The average number of rainy days per year in the series is 85, with a variation of 14. The series shows continual oscillations over time and a continual negative regression from the beginning of the series, which tends to diminish beginning in the 1970s. The Mann-Kendall test shows a negative trend with a level of significance of more than 99 percent, due especially to the spring trimester. The daily rainfall rate shows important oscillations from one year to another and a positive regression caused by the diminution of the number of rainy days. The Mann-Kendall test, nonetheless, does not show acceptable statistically significant trends either of annual values nor of seasonal values (at most 82 percent significance for the autumn trimester). For the purpose of evaluating whether there are significant variations in the modes of rainfall in the mountainous interior, where the main cloudburst centers are located which determine the flooding of Chiavari and along the final tract of the Entella stream, in Figure 9 the historical series of annual rainfall, rainy days and rainfall rate were studied, along with the series of maximum yearly precipitation at 1, 3, 6, 12, and 24 h at the weather station at Giacopiane. The historical series of annual data show a decrease in rainy days and an increase in yearly rainfall and in rainfall rate, with a continual regression throughout the entire series.The rainy days tested with Mann-Kendall show a diminishing trend of 99 percent, in the same way that the rainfall rate shows an increasing trend with a significance of more than 99 percent. The series of maximum hourly intensity of rainfall show a positive regression for all five graphs and in particular a statistically significant trend for the maximum rainfall at 6 h (98 percent significance), 12 and 24 h (significance greater than 99 percent).

## DISCUSSION

The analyses carried out, the archival information and the measures available since the Nineteenth Century demonstrate that

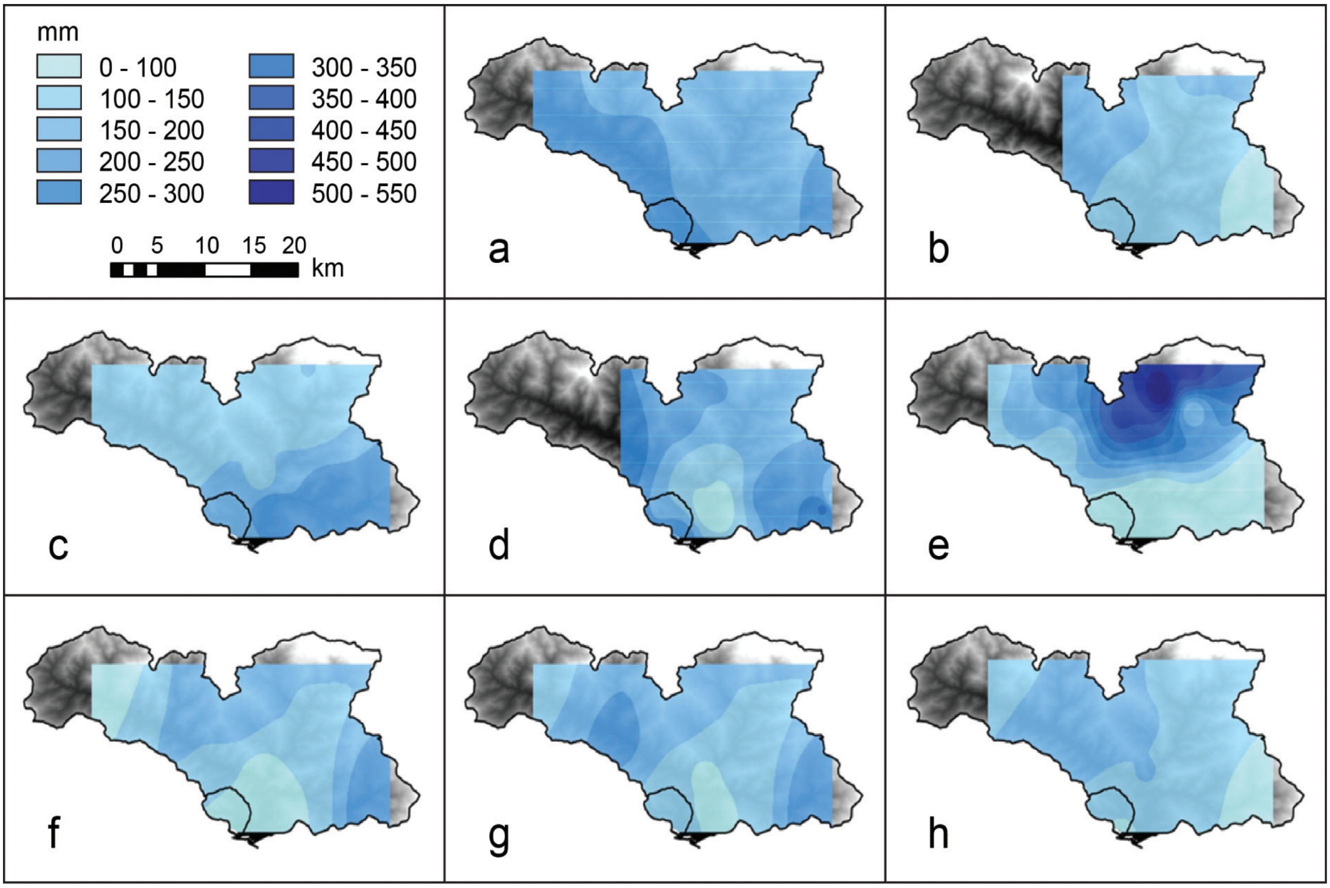


*Fig. 10 - The distribution on 24hours isohyets in the Entella catchment for major floods in Chiavari floodplain. a) 26 October 1948, b) 19 September 1953, c) 4 September 1963, d) 21 September 1979, e) 22 September 1982, f) 23 October 1999, g) 6 November 2000, h) 24 November 2002*

the Entella basin has always been prone to frequent flood events (Fig. 10a-h): from three to ten events every 50 years, with an increase starting in the Twentieth Century (Tab. 2). Concerning vulnerability, important effects are due to demographic growth in the 1900s, linked to an extensive overbuilding of the areas at greatest risk. Using historical maps, images and pictures of the last two centuries, it is possible to identify four main factors determining the vulnerability of Chiavari, based on geomorphological features linked to urban growth: 1) variations in land use from mainly agricultural to urban, with some localized covering of water courses (Disse & Engel, 2001; Luino *et alii*, 2012; Nirupama & Simonovic, 2007); 2) variations in width of riverbeds and nearby floodplain areas, with an overall reduction in area available for overflow (Baioni, 2011; Corominas & Alonso, 1990; Faccini *et alii*, 2015c); 3) extension of the coastal plain toward the sea with landfill (Kellens *et alii*, 2013; Petrucci *et alii*, 2012); 4) diversion of certain sections of riverbed and construction of new and narrower canals. Since at least the Seventeenth Century the function of irrigation and water recuperation in the plain of Chiavari was guaranteed by a network of canals connected to the two main bodies of water, the Entella to the east and the Rupinaro to the west. This network has become inadequate for regulating the runoff in recent times (Faccini *et alii*, 2015a); the system of canals caused the mouth of both the Entella and the Rupinaro to shift eastward. In the lower basin of the Entella stream, the ongoing abandonment of traditional agricultural activity meant a lack of maintenance to the water system. The urban build up of the Chiavari plain in areas historically subject to flooding and in the lowlands caused the narrowing of the riverbed (Fig. 7). A significant example is the "Ponte della Maddalena" (Maddalena bridge, cited by Dante Alighieri in the Divine Comedy) over the Entella stream, originally 250 meters long and with 15 arches, currently shortened to 100 meters and with six arches. The Rupinaro stream, for its part, has undergone a major narrowing of its area in the lower section, from the confluence of the smaller Campodonico stream to its mouth. The entire Chiavari plain has been the victim of successive steps in a disastrous policy of land use approved in the 1970s which permitted the construction of buildings in areas historically subject to flooding (Faccini *et alii*, 2012a). The situation of the so-called "La Franca" is emblematic: this area, left free until after World War II to serve as floodplain to absorb the periodic overflow of the Rupinaro, today is so incorporated into the urban fabric that it is covered by the swathes of cement which form the access ramps of the motorway at Chiavari. The construction of the small-craft port of Chiavari also resulted in an extension of the coastal plain resulting in an advance of the coastline on the order of several dozen meters; a breakwater brought with it the double disadvantage of blocking the beach nourishment and causing accumulation of sediment at the mouth of the stream, further limiting its flow into the sea. In many areas such situations determine an increased vulnerability compared to the past. Moreover, the progressive overbuilding on the floodplain which has been matched by a significant increase in population and infrastructures and has led to a reduction of space for discharge also results in a reduction in concentration times and a greater vulnerability. The addition of urban sprawl to an increased geo-hydrological risk (Fig. 7), seems clear in terms of increased vulnerability of property and persons (EEA, 2006). The annual average temperature shows a clear increase matched by recent climate changes and with a significant trend (Fig. 8). The rainfall rate shows a slight increase, caused by a reduction in the annual number of rainy days, matching the previous studies on the Genoa Metropolitan Area (Faccini *et alii*, 2015d; Pasquale *et alii*,1994; Russo *et alii*, 2000). The data from the dam at Giacopiane show that the yearly maximums of rain from 1 to 24 hours are on the increase, as well as a positive trend for the rainfall rate. Therefore the territory registers hourly downpour and maximum daily intensity of rainfall, increasingly intense especially in autumn months. The data therefore concur in establishing that the rains tend to be concentrated in shorter and shorter time periods. The increase in average temperatures is confirmed by the data from other stations (i.e. Genoa, Faccini *et alii*, 2015c) which demonstrate the global warming (IPCC, 2013). The higher rainfall rate may also be an effect of global warming, whose causes and effects are worth examining in depth in other climate studies. The increased conditions of hazard and vulnerability can be evaluated in terms of casualties (Tab. 2) and property potentially exposed to the risk of floods. The economic damage caused by floods, evaluated at the start of the Twentieth Century, has been increasing to reach more than 50 million euros for the most recent disasters. These are high costs, considering that such events, because of weather and orographic conditions, generally hit with maximum intensity in a contained area involving only a few dozen square kilometers. As a consequence, the geo-hydrological risk determined by hazard and vulnerability is increasing progressively due to climate change which influences a pre-existing high level of hazard, and an ongoing urban growth which increases vulnerability. The resulting increase in damage, economic costs and victims cannot be considered acceptable (Nielsen *et alii*, 1994).

## FINAL REMARKS AND RISK REDUCTION STRATEGIES

Since the first decade of the Twenty-first Century, the Liguria Region has been affected by more than 70 geo-hydrological events which have caused a total of 28 deaths (Faccini *et alii*, 2015c). The majority of cases took place in the east-central section of the region, due to meteorological and geo-morphological factors described above. Liguria in general and the Genoa metropolitan area in particular represent a case study at an international level because of the geo-hydrological risk and the uncontrolled building in a Mediterranean setting (Faccini *et alii*, 2014d; Ferrari *et alii*, 2014; Hally *et alii*, 2015; Rosso & Rulli, 2002; Silvestro *et alii*, 2012; 2015). Three factors, in part natural and in part man-made, predispose the Genoa metropolitan area to a high geo-hydrological risk when they occur together: 1) the high probability of the initiating trigger and development of "self-regenerating" storms with heavy rainfall, increasingly frequent due to changes in rainfall patterns; 2) a topography of steep slopes which makes flood propagation rapid and unpredictable; 3) dense urbanization in the floodplain area. The disaster of 10 November 2014 is only the latest in a historical pattern which appears to be increasing in the current century. The causes must be sought in a hazard increase determined by climate changes under way and an increase in vulnerability resulting from urban sprawl. A comparison of recent events highlights the fact that the way in which triggering occurs and the location of the stricken areas repeat themselves, therefore favoring the possibility of forecasts, the resilience of inhabitants (Committee on increasing national resilience to hazards and disasters, 2012) and the possibility of action.Technical measures aimed at reducing geo-hydrological risk can no longer be postponed, and must involve remedies both to the hazards and the vulnerability (Faccini *et alii*, 2015c; 2015d). This means that structural measures on the waterways must be planned and carried out to improve discharge and remove obstacles in the riverbed and any other obstructions to the water flow in flood conditions. Such a plan must provide for the delocalization of buildings and infrastructures at high risk. These measures must be accompanied by ongoing maintenance of the territory, indispensable both for the riverbanks and the waterways along their entire length. Maintenance of the slopes must include repair and upkeep of terraced lands, which represent not only a distinctive element of the Ligurian landscape but also an important factor in land preservation.The network of meteorological-hydrological monitors must be improved; the current network is barely adequate for the rainfall stations and seriously inadequate for measuring the level of the waterways: such statistics are also necessary if a detailed plan of civil protection is to be put into practice. Geo-hydrological events and their impact on the inhabitantsare no longer merely an element of scientific interest but have become a social problem as well. Only through an informed perception of the natural risks to be faced will it be possible to lower the level of risk by activating the awareness of all citizens.

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