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Abstract

The October 2014 rainfall event centered on the Bisagno basin and the consequent flooding effects are analyzed. This event was characterized by violent downpours and the levels of the watercourses rose rapidly causing a flash flood that flooded the final stretch of the river, where the Bisagno is culverted for the last 1.4 km. In the successive steps of the paper, the characteristics of floods from 1945 to today have been compared to assess possible changes in flood risk factors. The methods have been applied to national and international weather maps, the rainfall and hydrometric data recorded in Bisagno Valley. The authors have analyzed both natural hazards and the human impact on the environment, two important aspects of environmental geology. The series of maximum rainfall intensity was studied by means of the standardized anomaly index and a cluster analysis. The urban sprawl in the Bisagno basin has been defined by a cartographic and photographic multi-temporal comparison. The predisposing factors of the Genoa floods are determined by the orography and the meteorological conditions of the Genoa Gulf. A comparison of the rainfall and discharge of selected events demonstrates an increasing intensity of the flash floods due to the modifications of the rainfall regime. Otherwise, the progressive historical changes in the extension of the urban area and land use variations are most important causes. This necessitates rapid intervention for flood risk mitigation.

Keywords	Heavy Rainfall; Flood Risk; Historical Floods; Genoa City; Liguria.

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Dear Prof. Hoalst-Pullen and dear Prof. Patterson
Editor-in-Chief of Applied Geography

We would like to submit the attached files related to manuscript of: “RAINFALL REGIME AND URBAN SPRAWL VARIATIONS IN A MEDITERRANEAN RIVER CATCHMENT PRONE TO HISTORICAL FLOODS” for a possible publication in your Journal.

The authors are coming from a research group born 5 years ago between Italian National Research Council of Turin (ITALY) and the Department of Earth, Environmental and Life Sciences, University of Genoa (ITALY). Two years ago, it also started the collaboration with the Mountain Centre, University of Savoy (FRANCE).
Many similar geomorphological processes are involving these two countries. One of these is urban flooding. Genoa city is the capital of Liguria and the sixth largest city in Italy: 600.000 people live within the city's administrative limits. Genoa was hit many times in the last years and in Italy it is now the greatest problem for the Italian Government from the point of view of natural risk.

This research presents an original approach to the Genoa's flood problems due to the orography and the particular meteorological conditions of the Genoa Gulf. The methodological approach involved the aerial photo interpretation, bibliographical research, field work and the use of data kept at many different archives; an original base map was produced by using a DTM raster (5 m) and vector layers for the different cartographical elements. The output shows an example of geocartography that could contribute to the implementations of useful maps for a conscious and sustainable tourism. The authors consider both natural hazards and the human impact on the environment, two important factors of environmental geology. The increase of events with violent rainfall and the immediate response of the watercourses often narrowed in concrete channels under the houses and streets added to a terrible urban sprawl have caused a constant increasing of the flood risk from 1970 to date.

In order to evaluate the features of the main flood events in the last 70 years, a cluster analysis has been performed. The authors analyzed both the maximum rain intensities in the 1, 3, 6, 12 and 24 hours intervals for the whole series and the maximum hourly values and the maximum discharge values registered during flood events. The cluster analysis allowed to point out the rainy features that characterize the flood events and to differentiate between the 1945, 1951 and 1953 episodes and the latter ones in 1970, 2011 and 2014.

The manuscript covers 7822 words (title, abstract, key-words and references excluded), 8 figures and 2 tables.

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The potential reviewers suggested above have no conflict of interest with any of the authors of the paper being submitted.
This paper has not been published or accepted for publication. It is not under consideration at another journal.

Sincerely,

Fabio Luino and Francesco Faccini

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RAINFALL REGIME AND URBAN SPRAWL VARIATIONS IN A MEDITERRANEAN RIVER CATCHMENT PRONE TO HISTORICAL FLOODS

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ABSTRACT

The October 2014 rainfall event centered on the Bisagno basin and the consequent flooding effects are analyzed. This event was characterized by violent downpours and the levels of the watercourses rose rapidly causing a flash flood that flooded the final stretch of the river, where the Bisagno is culverted for the last 1.4 km. In the successive steps of the paper, the characteristics of floods from 1945 to today have been compared to assess possible changes in flood risk factors. The methods have been applied to national and international weather maps, the rainfall and hydrometric data recorded in Bisagno Valley.
The authors have analyzed both natural hazards and the human impact on the environment, two important aspects of environmental geology. The series of maximum rainfall intensity was studied by means of the standardized anomaly index and a cluster analysis. The urban sprawl in the Bisagno basin has been defined by a cartographic and photographic multi-temporal comparison.
The predisposing factors of the Genoa floods are determined by the orography and the meteorological conditions of the Genoa Gulf. A comparison of the rainfall and discharge of selected events demonstrates an increasing intensity of the flash floods due to the modifications of the rainfall regime. Otherwise, the progressive historical changes in the extension of the urban area and land use variations are most important causes. This necessitates rapid intervention for flood risk mitigation.

KEY WORDS: Heavy Rainfall; Flood Risk; Historical Floods; Genoa City; Liguria.

1 Introduction

For the catchments in Genoa City (Liguria, Italy), Faccini et al. (2015a) have demonstrated an increase in floods and in particular flash floods during the last 50 years. This increase is both linked to a centennial climatic cycle (Russo et al. 2000) and to important changes in land use. In less than 50 years four major floods with loss of lives and very serious economic damage have occurred. After previous flood events in 1970, 1992 and 2011 the Bisagno River overflowed its banks again on October 9, 2014 flooding the city center of Genoa. If we consider all the streams and rivers surrounding Genoa City for the same period additional flooding can be noted in 1993, 1994, 2002, 2010 as well as in November 2014 with more victims and serious damages (Faccini et al. 2015a, 2015b). During the last half of the century, the four major floods of the Bisagno River are similar both from a meteorological perspective and in the extension of flooded areas.
In 2014 intense and prolonged rainfall was recorded during all 12 months of the year with consequent triggering of landslides and floods (Faccini et al. 2016). Average annual precipitation in the lower Bisagno Valley (in the center of Genoa) lies slightly above 1,200 mm, but in 2014 values close to and even above 2,000 mm were recorded (Table 1).

In the Bisagno Valley annual rainfall, which has higher average values of 1,700-1,800 mm (Sacchini et al. 2012) showed a cumulative excess of 3,000 mm. The recurring periodicity and the severe effects in the urban areas caused by such phenomena have made Genoa (Fig. 1), and the Bisagno River in particular (Figs. 1 and 2), an internationally emblematic case study (Rosso and Rulli 2002; Silvestro et al. 2012; 2015; Ferrari et al. 2014; Hally et al. 2015; Dunaieva et al. 2014).

The Bisagno River is the most well known case study in Italy because each of its floods affects the city center, causing serious damage often with fatalities. During the second last flood that occurred on November 4, 2011, six people lost their lives, including some children. Furthermore, similar conditions have been recorded in other basins in the Genoa area (Faccini et al. 2015a). Ancient historical data on floods and flooding are also available for this watercourse flowing through a densely populated part of the city.

The Bisagno River seems to be affected by more frequent and more intense floods than in the past (Faccini et al. 2016). On the other hand, the width of the riverbed in the final stretch and at the confluence with the sea was once much larger than currently. Urbanization leading to rapid urban sprawl occurred above all in the first half of the twentieth century without any appropriate city planning.

Various authors have studied numerous recent flood events that have affected Europe (Kvočka et al. 2016) and the Mediterranean area with relation to climate variations (Barrera Escoda and Llasat 2015) or changes in land use (Tsanakas et al. 2016; Boudou et al. 2016). Issues related to historical variations have been highlighted by other authors, emphasizing changes linked to historical climate cycles (Böhm et al. 2014) or flood frequencies in Europe (Elleder 2015) or rainfall variations in the last 43 years in Asia (Likai and Jijun 2010). Studies on monitoring of urbanization processes and urban sprawl that highlight their influences on floods were recently carried out above all in China, using geoprocessing tools integrated by remote sensing in GIS (Lv et al. 2011) or by analyzing the rapid urban growth to improve the response of climate models (Hu et al. 2015).

Flash floods are increasingly studied not only in Europe (Terranova and Cariano 2014; Llasat et al. 2014; Petrović et al, 2015; Diakakis et al., 2016) due to their recent intensification, but also in other zones of the world (Tripathi et al., 2014; Al Mamoon and Rahman, 2016; Mahmood et al. 2016; Rahman et al., 2016), as well as their response to current climate change. For geographical conditions similar to Liguria, Marafuz et al. 2015 analyzed flash floods in a limited catchment in Portugal including their concentration times, water balance and surface runoff towards critical areas or exposed features. They found an increase in urban flood events linked to rapid urban sprawl. From a climatic point of view there is a secular trend of increase in annual precipitation and average temperatures in the Genoa area (Faccini et al. 2015a; Pasquale et al., 1994; Russo et al. 2000). This trend is well correlated with data from other worldwide stations (IPCC 2013).

In this paper, we analyze the meteorological conditions that triggered the event on October 9, 2014 and its effects on the ground. The aim of this paper is to examine interactions between man and the environment and how the associated geo-hydrological risk is increased. According to Alexander (1989) and Luino and Castaldini (2012), geo-hydrological risk is the geo-hydrological hazard which can potentially cause loss of the exposed elements at risk. Geo-hydrological hazard (flood, mud-debris flows and landslides, Canuti et al. 2001), derives from natural earth processes related to the interactions between meteorological phenomena and the geological environment. Elements at risk include population, properties, buildings, transport infrastructures and economic activities (Norén et al, 2016).

The study approach is typical for environmental geology (Keller, 1999) and in this context the interactions between natural hazards and human impacts on the environment are analyzed (Haraguchi and Lall, 2015; Noy, 2015). We compare the floods that have affected the Bisagno basin in the post-war period (Table 2) after the main hydraulic modifications of the watercourse in order to define which risk factors have changed over time. We also explain the intensification of floods according to influences of the environment on man (such as changes in the rainfall regime) and of man on the environment (such as urban sprawl). This study could be useful for defining these type of interactions in other contexts of geo hydrological risk and to outline how risk mitigation should be urgently implemented.

2. Materials and methods

2.1 Study area

Genoa City is characterized by a peculiar orographic location, narrowly enclosed by the Alps-Apennines mountain arc and by a thin coastal strip (Fig. 1). Its hydrographic network is represented by short streams with a virtually instantaneous hydrological response to precipitation. The Bisagno River originates in the hinterland of Genoa, near the Passo della Scoffera saddle, at 675 m a.s.l., and has a catchment extending over an area of 95 km^2. Its geology consists predominantly of flysch formations of the Cretaceous outcrop and subordinate shales of the base complex with Pliocenic marls outcrops near the city center.

After a length of only 25 km the Bisagno flows into the center of Genoa ("Foce" quarter), east of the natural amphitheater of the historic city. The highest point in the basin is the Mount Candelozzo (1034 m) and its lowest point is at sea level. 60% of the territory includes slopes from 35% to 75% (the average gradient is 31%). The most represented altitudinal range (70%) is between 0 and 500 m. More than 80% of the basin is wooded, but this is almost entirely abandoned due to urban migration that started in the late nineteenth century. At present 13% of the basin is urban area. The main stream has a propensity to erode from its source up to 11 km upstream from its confluence. Its predominantly depositional final reach corresponds to the strongly urbanised part of the catchment. The maximum width of the floodplain is about 300 meters just upstream of the main stretch where the Bisagno River becomes covered. In fact, the riverbed disappears from the view over its last 1,400 meters up to its confluence with the sea, while other concrete coverage is visible between the motorway junction A12 Genoa East and the Genoa Football Stadium.

The main tributaries of Bisagno River: on its left bank include the Lentro creek in suburban band and the Mermi and Fereggiano creeks. On the right bank they include the Canate creek in suburban area as well as the Geirato, Trensasco and Veilino creeks. The last creek flows near the Staglieno monumental cemetery.

The Bisagno River network is characterised by a strong hierarchical anomaly and by strong variabilities in the bifurcation ratio reaching high values between stream orders 3-4 and 4-5 (respectively 4 and 9) according to Strahler (Brancucci and Paliaga 2005). Such variability and high values indicate intensive/severe erosion conditions in the basin that is supposed to be affected by tectonic control. The reactivation of erosion processes is related to the last drop of the base level (Brancucci and Paliaga 2005).

The Bisagno has a torrential hydrological regime. It frequently has low flow in summer but it can produce sudden floods, especially in autumn, with response times from between less than an hour to 3 hours. The coverage of the final river stretch reaches its maximum capacity at a discharge of about 700 m^3/s. The flood discharge at the beginning of the coverage has been estimated for different return periods "T" by means of hydraulic model tests. For T=50 years the estimated range is 790 m^3/s, for T=200 years it is 1,300 m^3/s and for the T=500 years it is 1,785 m^3/s (Città Metropolitana di Genova 2015).

In terms of fluvial geomorphology, suspended sediment and bedload transport is estimated at over 25,000 m^3 per year. However, due to its torrential regime the greatest part of the sediment is transported during floods (Città Metropolitana di Genova 2015). In addition to sediments (mainly sand and gravel, together with pebbles and boulders) long trees and urban waste from illegal dumps are transported violently downstream and often jammed under bridges. In addition, covered river sections may reduce the useable flow perimeter (Faccini and Vassalli 2008).

Landslides may also play an important role in the Bisagno basin (Sacchini et al. 2016): more than 300 are active and many of them are located in areas affected by deep-seated gravitational slope deformations.

The contribution to sediment transport during flood events can be substantial, with remobilization of landslides in the case of long-lasting rainfall and the triggering of violent debris flows in the case of flash floods (Turconi et al. 2013).

Genoa is one of the ten metropolitan cities in Italy with an urban area exceeding 500 km^2 and 600,000 inhabitants living within the more extensive metropolitan area, covering a total of 4,000 km^2. It hosts a population of 1.5 million of inhabitants distributed within the central sector of the Ligurian coastal arch.

Urbanization of the coastal plains and valley floors began only during the second half of the 19^{th} century when the ancient maritime republic was annexed first to the Kingdom of Sardinia and then to the Italian State.

It started first with industry, then with settlements followed by the expansion of the city from the historical center out towards the side valleys.

In the 20^{th} century, urbanization of the mountain slopes in the hinterland commenced. It reached its maximum in the post World War II reconstruction period until about 1985. Urbanization still continues today but less noticeably, especially in the Bisagno basin which has a population of more than 150,000 people and where the most important commercial and handcraft activities are located, together with city services.

2.2 Meteorology and climatology

The Genoa Gulf is characterized by a typical circulation referred to as the “Genoa Low” or Ligurian Depression. It is a Mediterranean cyclone of orographic origin (Jansà et al. 2014) that forms or intensifies from a pre-existing cyclone to the south of the Alps over the Gulf of Genoa in the Ligurian Sea (Sáez de Cámara et al. 2011). This secondary depression, linked to the arrival of Atlantic perturbations behind the Alps, is formed over the Gulf of Genoa primarily in the autumn-winter and spring periods (Anagnostopoulou et al. 2006). Consequently, conditions of sharp thermodynamic contrast are created between the hot humid Mediterranean air masses and the cold air masses of continental origin. The cold air masses over the Po Plain and behind the mountains of the Ligurian arc are redirected by the Genoa Low towards the center of the Gulf, where they stream through the mountain passes included between Savona and Genoa and reach modest altitudes of between 450 and 600 m a.s.l. (Figs. 1 and 2). This typical circulation is responsible for large amounts of precipitation distributed over the region surrounding the Ligurian Sea (Sacchini et al. 2012). Between the end of summer and mid-November, when sea temperatures are at their highest level, thermodynamic contrast of similar air masses and wind shear at different altitudes over the Genoa Gulf trigger convective thunderstorm cells and sometimes even supercells (Silvestro et al. 2012). These convective systems, born over the sea, move with their typical "V-shape" towards the hinterland along the valleys. Following the direction of the winds they can cause heavy rainfall with altitude, accentuated by the orographic barrier. The warm and moist maritime air masses flowing from the SE along the land surface and from the SW at high altitudes converge with the northern temperate continental airflow. From the Passo dei Giovi saddle (476 m) it flows through the Polcevera Valley and from the Passo della Crocetta d'Orero saddle (465 m) it squeezes into the Geirato Valley and into the Bisagno Valley up to the sea (Fig. 1). Over the sea, right to the East of these structures of convergence, convective self-regeneration systems can be produced. They converge in the Bisagno Valley, pushed by winds blowing from the SW at medium altitudes, causing heavy rainfall and sometimes floods.
The coastal climate is a humid temperate with a dry season restricted to one or two summer months (Sacchini et al. 2012; ARPAL 2013). It is characterized by short and temperate winters (average January temperature of 8°C), temperate summers (average July temperature of 24°C) and widespread rainfall over all seasons with the maximum occurring in autumn (150-200 mm in October, Table 1). The annual average rainfall ranges from 1,100 mm to 1,300 mm and the annual average air temperature lies just below 16°C.

2.3 Research methodology

The study is based on a meteorological reconstruction of the event after Llasat et al. (2003) including: i) an analysis of synoptic maps relative to sea level pressure and weather fronts on the ground, obtained from the UKMO (www.metoffice.gov.uk); and ii) on an analysis of radar images during the event, obtained from the site of ARPAL (www.arpal.gov.it).
The responses of raingauges distributed over the most affected area were analyzed, in particular those located in the Bisagno valley. Rainfall data were compared with the resulting flood hydrographs recorded in the Bisagno River (Herget et al. 2014). Interpolation based on the Kriging methodology was applied to calculate the 6 and 24 hrs isohyets for the event Those values deemed as the most representative for the event were examined more closely. We then analyzed: i) the environmental impacts, ii) the water depths in the city center (Barroca et al. 2006), obtained from images and citizen videos; iii) the report of the event made by the Regional Agency for the Ligurian Environment Protection (ARPAL 2014); iv) the results of the surveys carried out shortly after the event (Diakakis et al. 2011).
The hydrological and rainfall data were collected from the weather stations of ARPAL and Genoa's municipality. The situations that occurred in previous floods (Barredo 2007) were compared with the 2014 event including: meteorological, pluviometrical and hydrometrical conditions, the isohyets maps, as well as hydro-geomorphologic impacts.
In particular, we compared hourly rainfall sums at 1 to 24 hourly intervals for the flood events that have affected the Bisagno River in the last 70 years and the discharge measured or estimated for various events. In fact, the

final coverage of the Bisagno River was completed in 1935 and ten years later the first flood occurred when the post-war reconstruction was about to start. Therefore, in order to differentiate the possible causes of the observed variations between different flood events, climate data and changes in urban planning conditions were analyzed.
The climate data recorded directly in the Bisagno basin, at the Pontecarrega raingauge station, have allowed us to observe some variations in the annual events of maximum rainfall sums for 1, 3, 6, 12 and 24 hour intervals. The data were presented through the application of the Standardized Anomaly Index (SAI), which expresses the anomaly of the parameter compared to the mean value of the reference period (Coles 2001). The index was calculated on an annual basis by averaging the standardized anomalies analyzed for all parameters. In detail, the annual value of the SAI is obtained using the relation of average annual parameter-value to standard deviation parameter. The series considered for the Pontecarrega raingauge begins in 1945. The meteorological station, considered representative of the rainfall in the basin, is located in the middle of the Bisagno Valley, near the building of the company that manages the Public Aqueduct (Fig. 2).
In order to investigate possible similarities in the maximum annual rainfall at 1, 3, 6, 12 and 24 hourly intervals from 1945 to 2014, a cluster analysis was performed both for the Pontecarrega sequence and for the Bisagno flood for the set of stations. The cluster analysis has been achieved with the average linkage method in Eucledian metrics.
Urban sprawl in the Bisagno basin was studied preliminarily using the historical evolution of the urban area mapped first at a scale of 1:50,000 and then superimposed with later maps at higher resolution (Regione Liguria 1986): i) Carta degli Stati di S.M. Sarda (Savoy Kingdom Maps) with a 1:50,000 scale (1855), ii) Carta d'Italia IGMI (Italian Military Geographic Institute) with a 1:25,000 scale (1936), iii) aerial photographs EIRA (Ente Italiano Riprese Aeree) with a 1:13,500 scale (1964), iv) Carta Tecnica Regionale (Regional Technical Map) with a 1:25,000 scale (1986). The chart has been updated with information from regional technical maps of the period 1990-2006, even taking into account the number of buildings on the basis of the decennial census of ISTAT (Italian Institute of Statistics) and variations in land use (Rosso and Rulli 2002) and soil consumption (Munafò et al. 2015).
The analysis allowed us to define the main anthropological and environmental factors contributing to the increase of geo-hydrological risk in the Bisagno Valley, permitting us to identify appropriate methodologies for risk mitigation.

3. The October 9, 2014 flood event and its effects in the basin

Between the 9th and 10th of October 2014 intense and localized rainfall occurred in Genoa and its Apennine hinterland. This flood event seems broadly comparable to those events described in the recent past over the Ligurian Gulf (Faccini et al. 2009; 2012; 2015a; 2015b; Russo and Sacchini, 1994), with repeated "self-regenerating" thunderstorms, stagnating for several hours over the city (Fig. 3a). They initiated in the warm pre-frontal sector of the perturbation (Fig. 3b). Very intense torrential rainfall resulted in the Bisagno valley and their immediate surroundings but it was much less intense over the rest of Liguria, with less disastrous effects. Radar images show the persistence of storm cells organized in "V" shaped structures, which were formed over the Ligurian Gulf, southwest of Genoa and moved down towards the city and its hinterland, driven by southwesterly winds at 500 hPa. The rainstorm developed into a blocking situation between the cyclonic circulation over the Atlantic and the anticyclone between the Eastern Mediterranean and Eastern Europe. Between the two figures depicting pressure, a flow of currents from SW at high altitude and SE in the lower layers settled into place (Fig. 3b). Furthermore, the anticyclonic structure extended over the "Pianura Padana" (Po river floodplain) causing the influx of cooler air that overflowed into the Liguria Gulf through the "Passo del Turchino", the "Passo dei Giovi" and the "Passo della Crocetta d'Orero" (Fig. 1) backed by northerly winds. Immediately east of these situations of wind convergence to the ground storm cells were developing. Although throughout Italy and most of Liguria a summer anticyclone was dominating, a flood was occurring over the city centre and over the Bisagno Valley (Fig. 3a).
These convective systems have already recently affected different locations over the Ligurian Gulf (Faccini et al. 2012) causing flash floods arising from rainfall intensities exceeding 500 mm/6 hrs or 180 mm/1h. The most recent of these events occurred twice so far in November 2014 in the Genoa Metropolitan area (Faccini et al. 2015a). These phenomena are recurring and have been violent in recent years, especially the last events that

effected in Varazze and Genoa-Sestri Ponente in 2010 (Faccini et al. 2015b), Cinqueterre (Buzzi et al. 2013) and the Genoa-Bisagno valley in 2011 and 2014 (Faccini et al. 2016).

The raingauge analysis (Figs. 3c and 3d) shows how the central rainfall burst develops along the axis of the Bisagno River with rainfall peaks of about 140 mm/h and 380 mm/6 hrs over Geirato and a total of 550 mm/24 hrs and 754 mm/5 days in the period between 7-11 October. We observe that the isohyet distribution of the event at 3, 6 and 24 hourly intervals follows a narrow strip parallel to the valley shape, accentuating the rate of extreme rainfall speed of the full (Figs. 3c and 3d).

The culmination of the event took place between the afternoon-evening of October 9 and the early hours of October 10, causing disastrous flooding of the Bisagno and Fereggiano (its last tributary) watercourses in Genoa during the night. The rainfall of October 9, amounted to 400 mm/24 hrs in the Bisagno basin. The amount of energy accumulating in the system was testified by lightning storms that hit the area in the two periods 06:00-15:00 and 17:00-00:00 (UTC) with a total amount of 14,459 lightning strikes (data courtesy of SIRF-CESI, the Italian lightning detection system).

It is possible to observe the immediate response of the gauges that cover the whole basin because they reached their peak discharge only about an hour after maximum precipitation (Fig. 4). The estimated maximum discharge at the "Foce" exceeded 1000 m^3/s (by means of gauges and hydraulic models), with a return period corresponding to about 100 years (Città Metropolitana di Genova 2015).

In Genoa La Presa (upper catchment) and Genoa Molassana (middle catchment) the Bisagno water level increased by approximately 3 m, preceded by four minor peaks, from 06:00 pm on October 7 to 12:00 am on October 9, while in the Geirato stream the waters increased by about 3 m. The Fereggiano stream increased by about 2 m. Finally, near the Passerella Firpo footbridge, the river gauge of the Bisagno River recorded an increase of nearly 6 m. Consequently, there was extensive flooding of the Bisagno River (Figs. 5a and 5b) in the final reach between the Genoa football stadium and the railway track near the Genoa Brignole station (Fig. 5c). In the city, water levels reached up to 2.5 m as a function of the topographic surface (Fig. 5d).

The flood impacts (Fig. 6a) and the most impacted areas in the city center of Genoa were comparable to the episode of November 4, 2011 (Silvestro et al. 2012; Hally et al. 2015). The rivers were unable to absorb the sudden through flow of water along their narrow riverbeds and through the culverts under the city, which are under dimensioned. The floods devastated residential and industrial buildings over large areas of the mid-east district, especially in the lower Bisagno valley where a victim was swept away in the flood. Serious damage was recorded, even in the most important municipal market downtown. Shops and manufacturing activities in this central district of Genoa that had just barely recovered from the flood on November 4 2011, were again devastated by water levels ranging from 0.3 to more than 2 meters. The first evaluation of damages was in the order of 250 million euro.

The alluvial plain of the Bisagno River in the city center between Brignole (railway station), Foce and via XX Settembre (the main commercial street in the city) was entirely impacted by the flood. From a hydrological perspective, the response of Bisagno River and its tributaries was almost immediate, with an estimated concentration time of less than 1 hour (Fig. 4).

4. Results

4.1 Rainfall regime variations

Compared with the dynamics of the previous flood discharges and flood areas over the last 70 years, we can observe that the October 2014 event has similar characteristics to those of the largest flood disaster in the history of Genoa in October 1970, as well as the October 1822 event, which, however occurred under different conditions of land use and urbanization from nowadays (Rosso and Rulli 2002; Faccini et al., 2016).

Fig. 6a depicts rainfall intensity for the maximum precipitation at 1, 3, 6, 12 and 24 hour intervals, recorded at the Pontecarrega raingauge during the main floods that have affected the Bisagno River including inundation of the city in the last 70 years (1945, 1951, 1953, 1970, 1992, 2011, 2014), as well as the values of the Standardized Anomaly Index (SAI) of the annual maximum precipitation levels at 1, 3, 6, 12 and 24 hourly intervals (6b-6f). The events of 2011 and 2014 show the highest values for shorter duration rainfall, whereas the event of 1970

demonstrate the highest values for higher duration rainfall, while the events prior to 1970 have overall lower values. 1992 have not significant rainfall intensities at 1 hr, but high values at 3, 6, 12 and 24 hour intervals.
The annual maximum daily rainfall measured at Pontecarrega (Figs. 6b and 6f) shows an increase in maximum precipitation for 1, 3, 6, 12 and 24 hour intervals and is positively correlated with an angular coefficient of the average regression line of 0.01. However, the Mann Kendall test shows that it is not possible to accept the hypothesis of the presence of trends with a significance level of 95%. In the series there are obvious peaks related to the most recent floods of Bisagno River (1970, 1992, 2011, 2014), particularly for the 24 hour rainfall sums. For the 6 hour precipitation sums only the historical floods of 1945 and 1953 are highlighted, whilst for the 3 hour sums the recent floods of 1992, 2011 and 2014 are emphasized apart from the event of 1993, which, however, did not cause flooding of the Bisagno, but only in some basins further west (Faccini et al. 2015a). At a seasonal level it was observed that the maximum annual rainfall peaks occur especially between August and December, with a prevalence of 3, 6 and 12 hour maximum during the autumn. Fig. 6g shows rainfall data for the Pontecarrega gauge from 1945-2014 for 1, 3, 6, 12 and 24 hourly intervals and results from the cluster analysis. Apart from 1951, the Bisagno flood events coincide with red and yellow groups. Fig. 7a shows the rainfall intensity in mm/h for 1, 3, 6, 12 and 24 hour intervals registered during a central rainfall burst in the Bisagno Valley as opposed to the overall duration of rainfall. The central rainfall bursts in the valley are then localized and the rainfall recorded for 1, 3, 6, 12 and 24 hour intervals versus the year of the event. We can observe significant changes in the intensity of hourly rainfall over the last century. Rainfall previous to 1970 generally has lower intensities than in the following years (< 300 mm/24 hrs) while rainfall since 1970 always has an intensity higher than 400 mm/24 hrs. We can therefore observe that third millennium flash floods are caused by intense rainfall of short duration with extremely high precipitation over 1, 3 and 6 hour periods (more than 100 mm/h and more than 300/6 hrs) which obviously affect the 12 and 24 hour totals. Torrential rainfall during the 3 hour interval inherent to the 1992, 2011 and 2014 flood, increases compared with the previous period. As a result, flood discharge is much higher for the events after 1970 (Fig. 7b). Fig. 7c shows rainfall data at the maximum intensity gauge for the Bisagno flood events during the period 1945-2014 at 1, 3, 6, 12 and 24 hour intervals as well as the maximum discharge. The cluster analysis differentiates the 1945, 1951 and 1953 events from those after 1970.
The discharge monitored for the 1945 and 1951 events lay theoretically within the capacity of the final culvert of the Bisagno, while that of 1953 reached the limit. In 1951 the river exceeded bankfull discharge only just at the confluence with the tributary rivers. In contrast, in 1945 and 1953 flooding close to the coverage could be related to problems of ordinary maintenance which led pressure at the entry. For floods from 1970 onwards discharges close to or above 1000 m^3/s were recorded. This lies slightly below the measured value of the 2011 event, whose main centre of rainfall burst was located on the Fereggiano tributary stream causing major damage and casualties. For the 1970 Genoa event the main centre of rainfall burst was located more to the west rather than in the expected centre of the Bisagno basin (Pontecarrega). Interestingly, since the centre of the 2014 event was located in the middle Bisagno Valley (Geirato), it resulted higher discharge at slightly lower rainfall intensity.

4.2 Urban sprawl

Variations in the urbanization of the basin were analysed (Fig. 8), based on a map of the evolution of urban space in the Liguria Region. Appropriate colours (Fig. 8a) highlight constructions in the middle of the nineteenth century, in the first half of the twentieth century (1936), in the 1960’s (1964), the 1980's (1986) and finally between the 1990's and the XXI C (2006). For the last years, based on the number of buildings shown in the decennial census and considering the most recent studies on land-use (Rosso and Rulli 2002; Munafò et al. 2015; Faccini et al., 2016), the figure illustrates that urbanization is continuing, albeit at a much more reduced rate (Fig. 8c). We can see complete urbanization of the valley plains from the late nineteenth century onwards, as the lower Bisagno valley was being absorbed by the city of Genoa. This coincided with the total coverage of the last stretch of the Bisagno River to its confluence with the sea, completed in 1935. The inner part of the valley and the slopes underwent urbanization mainly after the Second World War during post-war reconstruction phase and the period of the Italian “economic boom”. Concrete constructions continued spreading up the slopes and covering the valley floors during the entire 1980's, sparing only the mountainous part of the basin without a flat

valley floor. Urbanization still continues in the twenty-first century with some more suburban buildings, new roads and industrial complexes along the river banks up to the limit of the mountainous part of the basin.
The soil consumption as a function of the distance from the stream is represented in Fig. 8b: it is possible to observe the full occupation of the areas close to the river axis and a percentage of soil consumption decreasing moving away from this (Fig. 8d). The values are close to 80% in the first 15 m away and are 40% just over 150 m away from the river.

5. Discussion

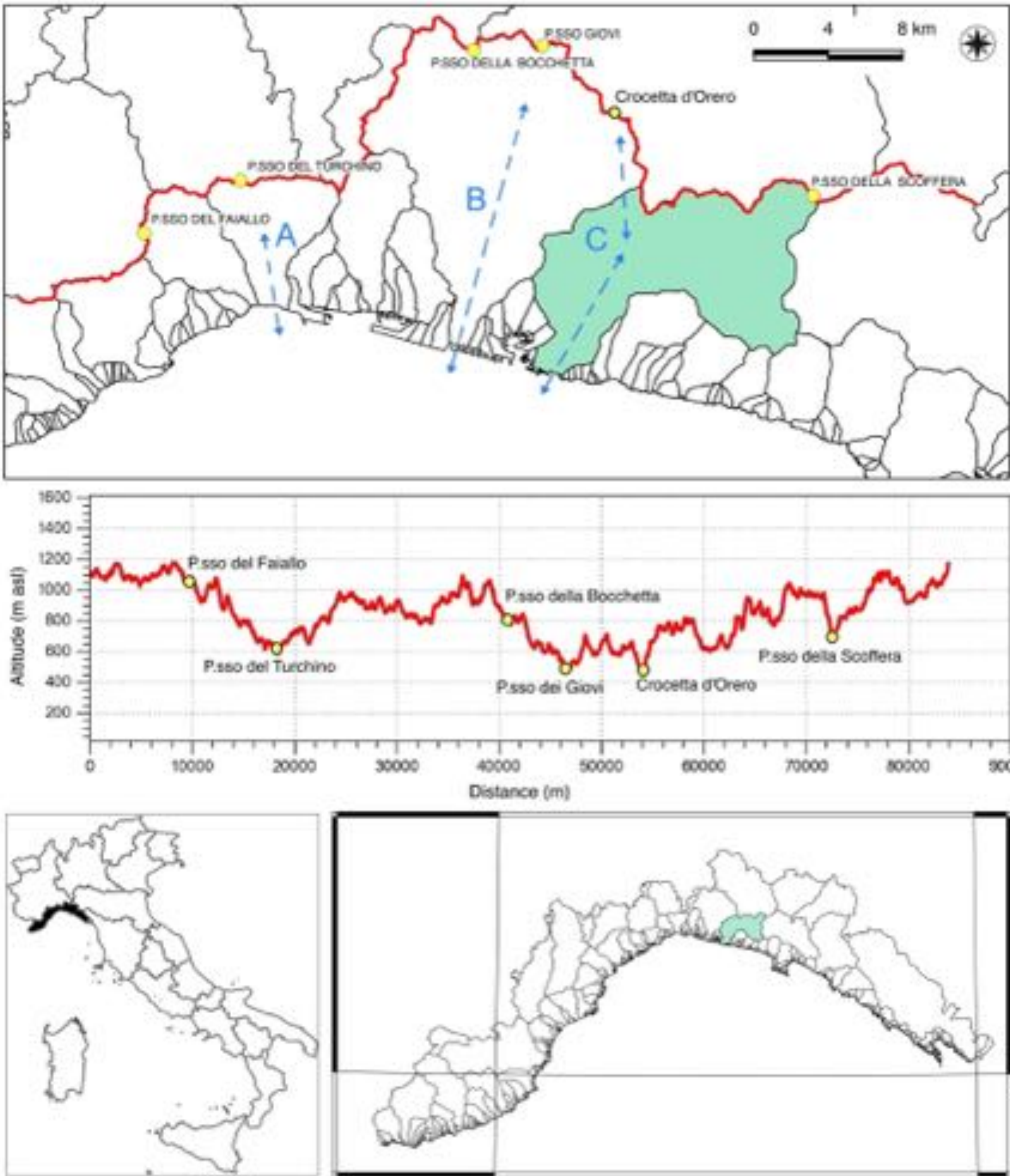
The analysis of collected and processed data suggests that geo-hydrological risk in the Bisagno Valley has increased over the years. From a meteorological and orographic perspective there are predisposing conditions for geo-hydrological risk over the Genoa area and in particular over the Bisagno Valley (Figs. 2 and 3).
The distribution of self-regenerating storms not only follows the orography, but also fits the morphology of the valleys; as such events are triggered by the convergence that takes place at the sea near the area where air from North is attracted and channelled into the valleys along the Apennines (Fig. 1).
This, in turn, strongly influences the convergence over the Bisagno Valley with air from the North following the direction of the pre-quaternary riverbed (Sacchini et al. 2015) that cuts across the Polcevera valley towards the valley of the Bisagno River and particularly that of the Geirato creek (Figs. 1 and 2). The hydrological response of the Bisagno basin, for the last floods, has been almost immediate and posed great difficulties for the preparation of civil protection interventions (Fig. 4).
The already particularly rainy weather in the Bisagno valley in autumn shows an increase of rainfall events of short duration with an increase in the maximum intensity of short rainfall and in the intensity of flood events (Faccini et al. 2015a). This has serious impacts on Genoa's water courses and the Bisagno River in particular (Faccini et al., 2016).
From a climate perspective, it should be highlighted that the maximum annual rainfall over 1 to 24 hour intervals is increasing. Hourly recorded rainfall bursts and maximum daily intensities of rainfall are becoming increasingly powerful (Figs. 6b-6f), especially in the autumn months. The intensity of flood events has increased over the past 70 years, in particular after the final coverage of the terminal reach of the Bisagno River in 1935. A comparison of the last 4 floods in the Bisagno Valley shows that in the middle valley the event of October 1970 presents the maximum daily rainfall; the one of September 1992 presents the maximum 12-hourly rainfall, that of October 2014 has particularly intense rainfall measured over 1, 3 and 6 hours, whilst the event in November 2011 has all the major characteristics of a flash flood (Diakakis et al. 2011) exceeding all other floods in terms of hourly and three-hourly rainfall (Fig. 6a).
The cluster analysis performed allowed to point out three groups both for the complete sequence at Pontecarrega and for the Bisagno flood rainfall at the maximum rainfall station set. For the Pontecarrega series the flood events coincide with the groups in red and in yellow (Fig. 6g), with the exception of the 1951 event. These two groups are quite homogeneously distributed in the 1945-2014 series.
For the Bisagno flood data (Fig. 7c) at the maximum rainfall intensity station, the cluster analysis points out the similarity between the first three rainfall events (1945, 1951 and 1953) and the ones including and after 1970. Among the latter the 2011 one differs considerably for its maximum rainfall characteristics.
The centre of the rainfall burst in the last event was concentrated in the middle valley of the Bisagno (Figs. 3 and 7), in particular at the Geirato station, whereas the rainfall peak of 2011 occurred in the side valley of the left tributary, the Fereggiano creek. The September 1992 and October 1970 were the events with the most significant rainfall respectively at the 6, 12 and 24 hourly intervals. Their rainfall burst centres occurred more to the west, in the area of the Polcevera Valley. The location of the centres of rainfall burst is important for the concentration time and for the subsequent development of the flood peak (Fig. 4). The event of 2014, although less intense than that of 2011 when considering the one-and three-hourly rainfall duration, was optimally located for a prompt hydrological response of the stream, therefore leading to a higher discharge.
Urban sprawl and soil consumption (Fig. 8) clearly reduce concentration times and increase the vulnerability of goods and people (EEA, 2006; Fuchs et al, 2012). In particular, the values of land consumption show the largest growth in the 19th century, mainly due to the industrial development in the beginning of the century and to the post-war reconstruction (Faccini et al., 2016). The settlement areas have been preferably concentrated around the

water course in particular within a distance of 50 m from the riverbed where over 70% of the soil is now urbanized. These areas are the most flat and next to road network and therefore the most interesting for the urban development.
The St. Agata's bridge, just upstream of the final coverage of the Bisagno River had 28 arches and a width of about 280 m until the beginning of the 19th century - now it is reduced to only 70 m in width. Finally, it is necessary to underline: i) the effects of the coverage of the Bisagno's final stretch, completed in the 1930's and followed by seven flood events and ii) the coverage of the Bisagno close to the Genoa football stadium (realized for the football World Cup Italy in 1990) and followed by three flood events; iii) the coverage of some stretches of the main Bisagno's tributaries (like Fereggiano and Veilino Streams), suffering many flood events in conjunction with the main Bisagno floods. It should be emphasized, however, that since the Bisagno River had already been covered in 1945, this factor did not negatively affect the increased flood risk recorded for the period immediately after World War II up to date. The effect of increasing urbanization nevertheless accelerates the hydrological response in a pre-prepared meteorological and geomorphological setting and in a climate context that increases the intensity of rainfall floods. So, both Man and the Environment contribute to a higher geo-hydrological risk.

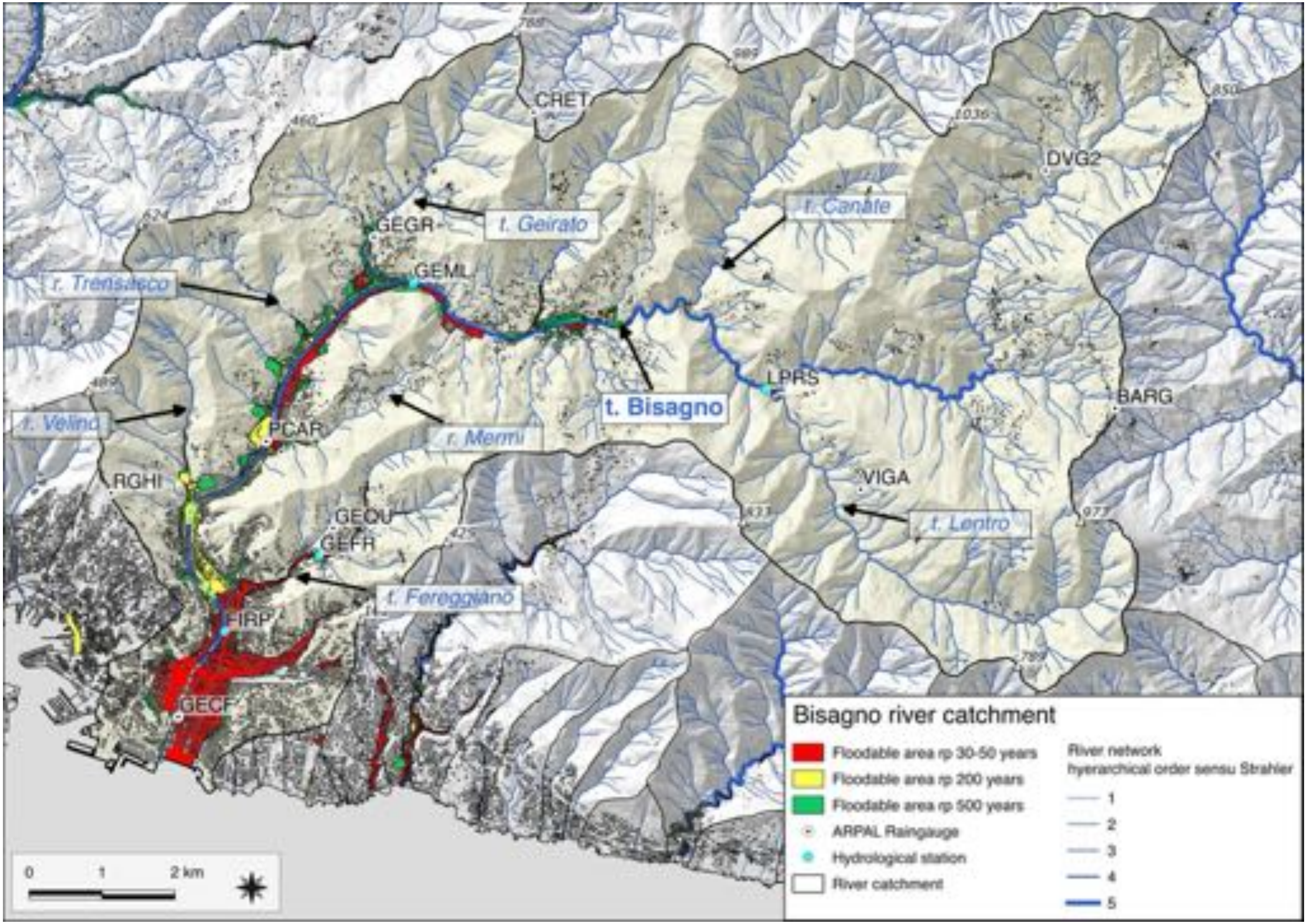
6. Conclusions

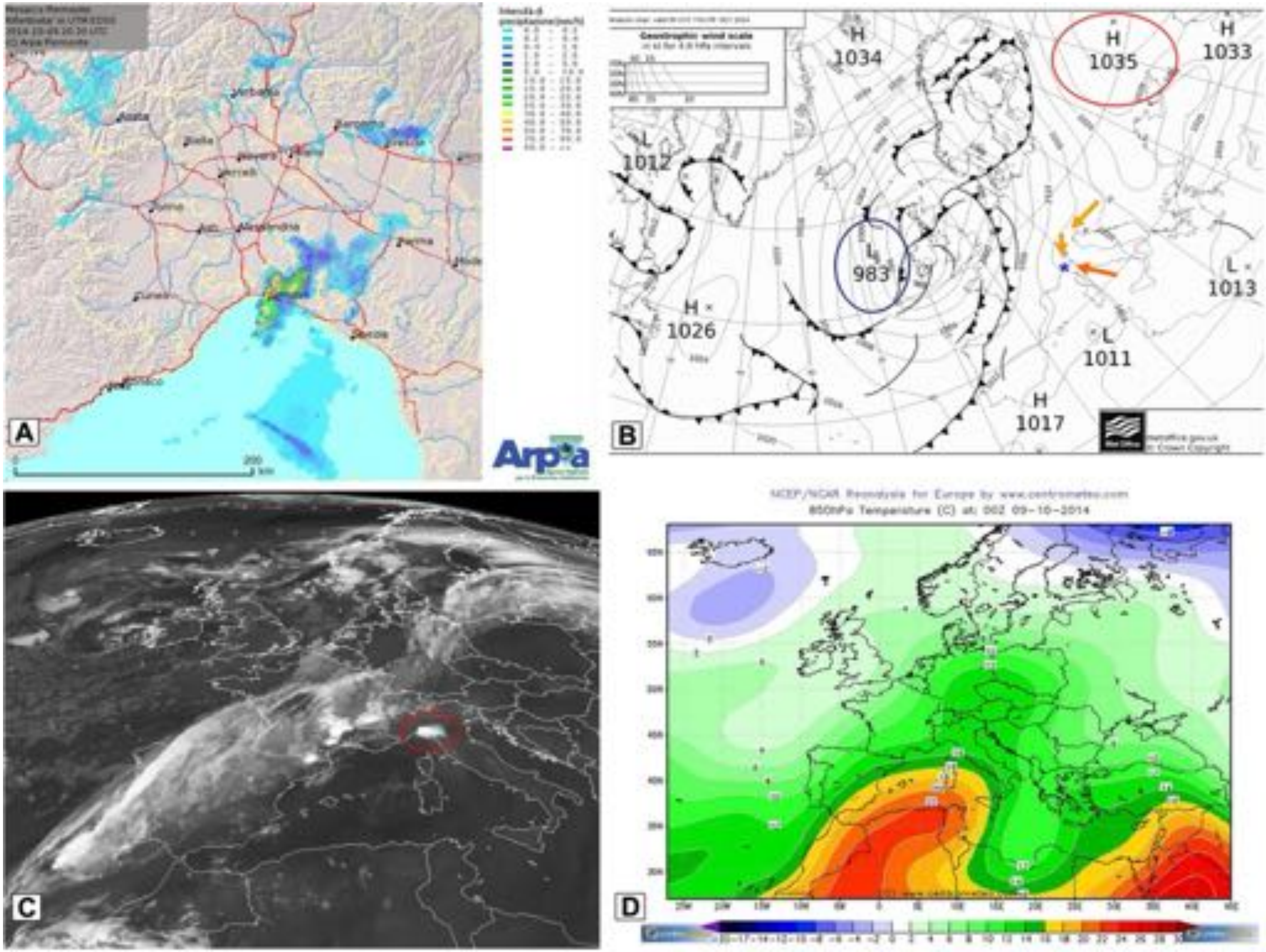
The October 9, 2014 event had such specific characteristics that it would be difficult to integrate into forecast modeling (ARPAL 2014). Even as the event was occurring, the hydrological alert was not sufficiently fast and widespread, thus making Civil Protection action ineffective. There are a multitude of causes determining the frequency of flooding disasters of Genoa including weather-topography (Çelik et al, 2012), climate (Benito et al. 2003; Arnell and Gosling 2016), urban density (Peiser 1989; Luino et al. 2012) and hydraulic (Pinter et al. 2002) issues.
Genoa is probably the most exposed Mediterranean town to violent storms (with a rainfall intensity of > 100 mm/h) due to its geographical location enclosed by a mountain arc adjacent to the sea, frequently subject to unstable hot and humid air circulations coming from the southern quadrants between September and November.
The sudden amounts of precipitated water are conveyed in a very short time from the slopes to the central coastal strip now populated by more than 100,000 inhabitants in the municipality. The short coastal plains are completely urbanized and the Apennine streams, transformed into channels, now flow in riverbeds much narrower than what they were previously to the urban sprawl that began in the late 19th century. For example, the Bisagno riverbed just upstream the culvert stretch, measured on the St. Agata bridge, has been reduced from 280 m to the present 70 m, while the final coverage is barely 50 m wide. A group of three engineers commissioned by the Genoa Municipality in 1908 calculated the coverage (Inglese et al., 1909). Using definitely modest hourly values of precipitation, they calculated that the maximum discharge of the Bisagno River "could not exceed 500 m^3/s". Earlier in 1905, Cannovale from the Municipality of Genoa had estimated more correctly a peak discharge of approximately 1,200 m^3/s, which unfortunately was considered exaggerated and not taken into account during the design phase. This value is very close to the flow peaks that the river has reached in recent years, during its violent floods.
Risk mitigation can be developed through multiple activities and policy options including weather-hydrological analysis, civil protection, structural investigations and maintenance of the territory.
With regard to the changes in land use in the non-urbanized areas, contrary to the findings reported by Rosso and Rulli 2002, it seems that the extension of forested areas in the mountainous parts of the basin is not a prerogative of the 21th century, but is linked to mountain depopulation during more recent periods (Hjelmfelti, 1991). In addition, the role of forests in landslide and water regulation is not always viewed positively (Latocha, 2009). Mountain depopulation could hence cause a negative effect on flow concentration times and on solid transport even in the presence of a larger-scale wooded areas.
Surely the use of nowcasting from real-time radar observations of the formation of convective storm systems based on the analysis of rainfall intensity from multiple hydrometric stations in a catchment could allow the detection of sudden flood wave influxes. This is a useful system, if preventively managed and interpreted by qualified technicians, for giving prompt alarms to the population. The conditions of soil saturation necessary for assessing runoff heights could be incorporated into hydrological models as performed by.

Similarly, the conditions leading to an important increase in solid transport in the basin and to the exceedance of flood-triggering rainfall thresholds may be modeled (Faccini et al. 2012). Furthermore, land-use and urban sprawl, strictly linked to top soil saturation can also be modeled.
Another forecast technique that could be developed is based on the lightning that precedes the onset of the self-regenerating storm. Lightning strikes recorded in the hours before the flood, could precisely delimit the basin that will be impacted by floods a few hours later. Real-time observations of lightning, radar and gauges could be relevant for forecasting the position of the convective system up to a few hours in advance. The triggering of self-regenerating thunderstorms, especially between September and November, should be considered as a sufficiently high risk situation to issue an early warning or alert status. In that case real-time monitoring can help to identify the most critical areas for the population. In case of emergency, targeted plans diversified for various city sectors should be implemented and early-warning should be widespread and reliable, with information campaigns on self-protection including “square bashing” (avoiding public places).
Regarding the Bisagno River, the final part of coverage urgently requires an increased hydraulic section and periodic interventions of arrangement and maintenance. In addition, the entire basin should be subject to constant hydraulic-forest maintenance.
In Italy, as in other countries, flood events of the last decades have highlighted the lack of a proper town-and-country planning (Luino et al. 2012; de Jong 2014) and now we are paying the consequences. The zones next to the riverbeds have been urbanized and waterproofed, with the construction of buildings, shopping centers, parking and even underground garages without taking into account the flood risk. If from the beginning of the 1950’s onwards, when the uncontrolled urbanization of the most attractive areas started, a higher awareness of the exposure level to the geo-hydrological risk would have been taken into account, an adequate policy of forecasting and prevention designed to reduce the territory vulnerability could have been put into place.
Until now, post-flood reconstruction, in the wake of the emergency, has always been oriented to redesigning the same defense strategies. The consequence has been that, when new successive floods occurred, there has been an inevitable increase in damage and public expenditure allocated to them.
In Genoa, the costs of the floods are in the order of several hundred million euros for localized events resulting from flash floods, while soaring over a billion euros for larger floods (Faccini et al. 2015a).
The Ligurian Water Basin Authority decided to implement an underground drainage canal that could divert the floods of the Bisagno from the city center as the main means for mitigating risk (Ferrari et al., 2014). However, at the present time inhabitants are still waiting for the repair works from the last flood to be funded and implemented. Furthermore, this does not completely reduce the flood risk. It remains important to redefine the interaction between man and the environment and in particular between man and the river and slope system that have been entirely compromised by decades of unruly urban sprawl. All of the above considerations suggest the necessity to invest human and financial resources into scientific research in order to perform detailed studies and then targeted interventions. A flood can damage assets, infrastructures and crops but it is unacceptable that under the socio-economic and territorial cohesion of a civilized country it assumes the characteristics of a disasters causing dozens of casualties.
The increased geo-hydrological risk conditions caused both by urban sprawl and by climatic change necessitate new policies for land use and city planning that are respectful of the dynamics of natural systems.
The problem of recurring flooding in Genoa city is certainly difficult to solve. Some authors and bodies (Werritty et al, 2007; Luino et al., 2012; Munich Re, 2016; FEMA, 2016) for several years have been suggesting two non-structural actions depending on the geo-hydrological process and the urbanized areas involved: i) relocation of property, ii) subscription of an insurance. The first solution in Genoa is frankly impossible because it would mean moving thousands of people, to create for them new homes in suitable areas and then to destroy big and historic buildings along the Bisagno River to give it back to the Bisagno River the right amplitude able to flow the discharge evaluated in these last years. Therefore, the second solution appears to be the most viable, although with many difficulties: in fact, in Italy it does not exist yet the possibility to subscribe an insurance for ensuring property against flooding as in other countries and second, it should be verified the real availability of insurance companies to offer insurance coverage for the inhabitants of an area so exposed to the risk.

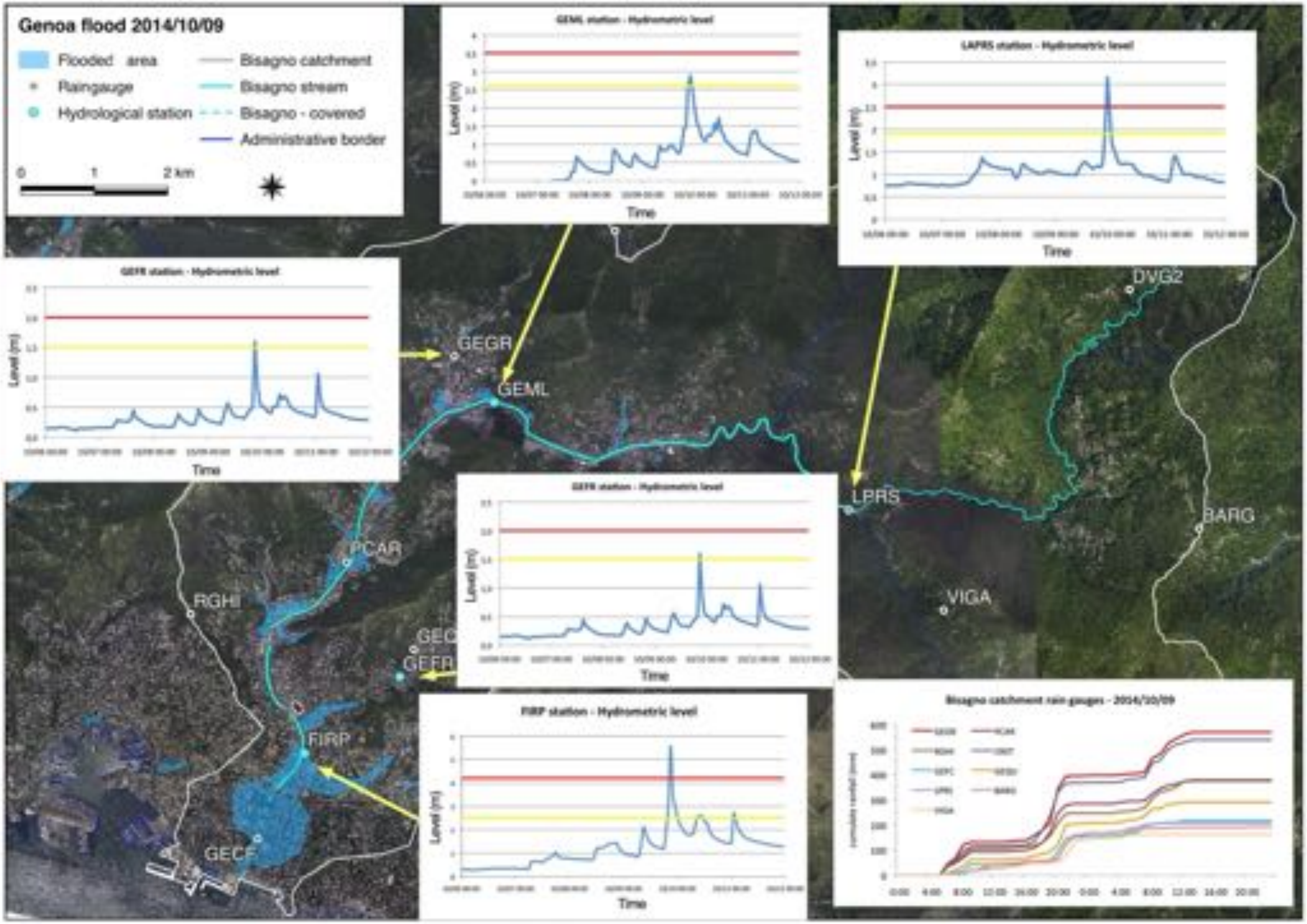


0
4
8 km
P.SSO GIOVI
P.SSO DELLA BOCCHETTA
Crocetta d'Orero
P.SSO DEL TURCHINO
P.SSO DELLA SCOFFERA
P.SSO DEL FAIALLO
A
B
C
1600
1400
1200
1000
800
600
400
200
Altitude (m asl)
P.sso del Faiallo
P.sso della Bocchetta
P.sso del Turchino
P.sso dei Giovi
Crocetta d'Orero
P.sso della Scoffera
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
Distance (m)
8°E
10°E
44°N

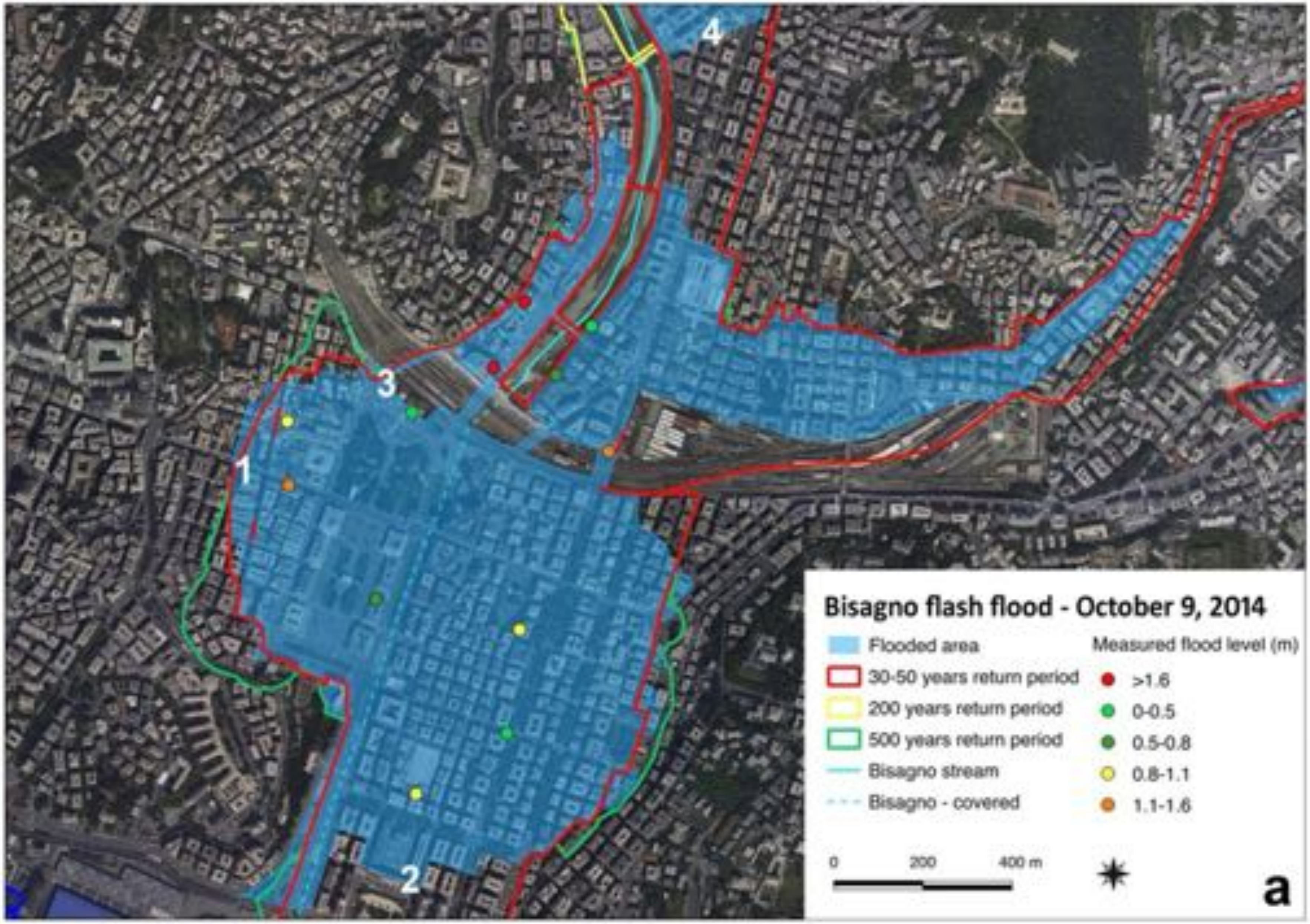

CRET
DVG2
GEGR
t. Geirato
t. Canate
GEML
r. Trensasco
LPRS
BARG
t. Velino
PCAR
r. Mermi
t. Bisagno
RGHI
VIGA
GEQU
GEFR
t. Lentro
t. Fereggiano
FIRP
GECF
Bisagno river catchment
Floodable area rp 30-50 years
Floodable area rp 200 years
Floodable area rp 500 years
ARPAL Raingauge
Hydrological station
River catchment
River network
hyerarchical order sensu Strahler
1
2
3
4
5
0
1
2 km



A
Arpa
B
H 1034
H 1035
H 1033
L 1012
L 983
H 1026
L 1013
L 1011
H 1017
C
NCEP/NCAR Reanalysis for Europe by www.centrometeo.com
850hPa Temperature (C) at: 00Z 09-10-2014
D



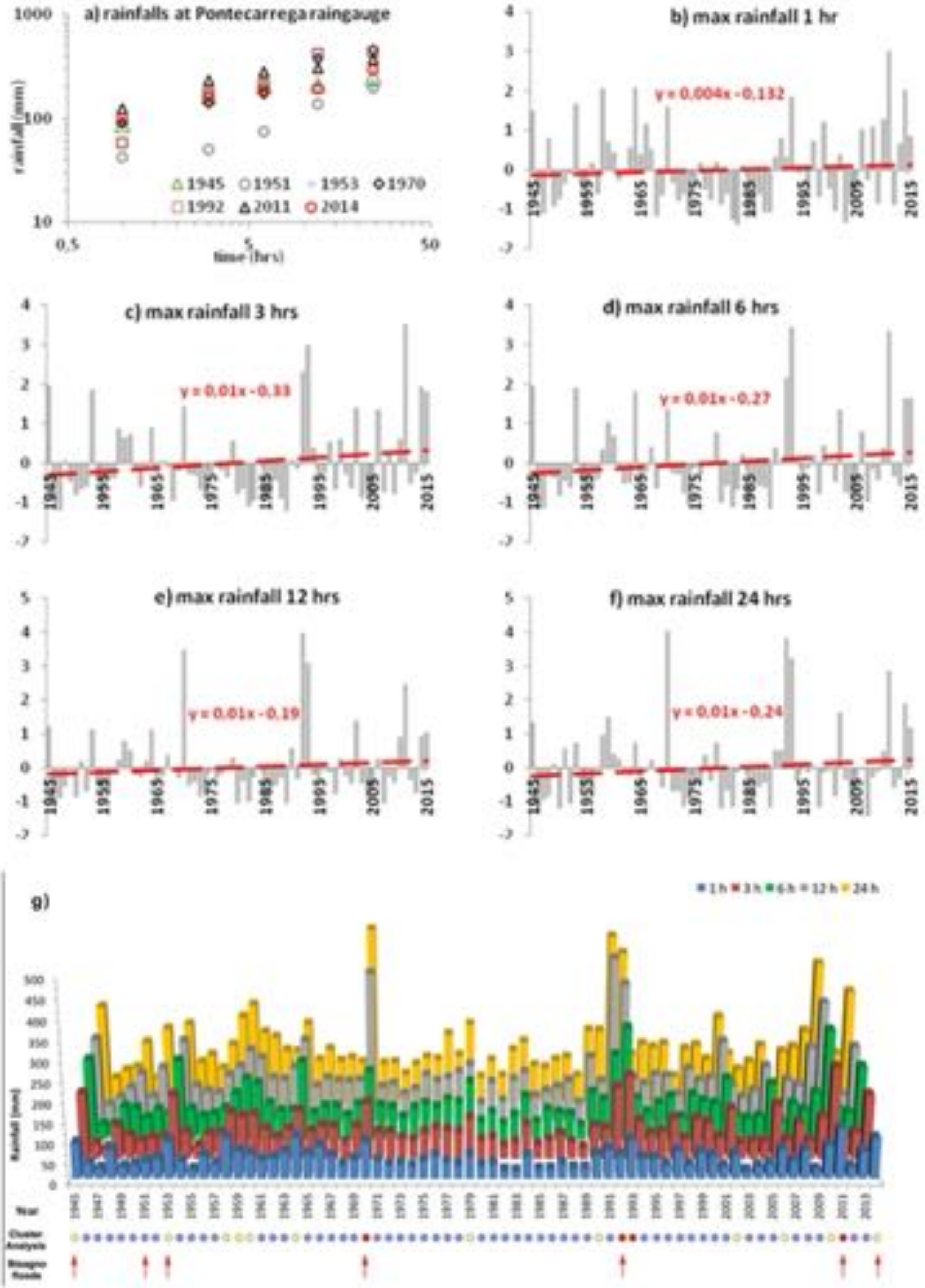
Genoa flood 2014/10/09
Flooded area
Raingauge
Hydrological station
Bisagno catchment
Bisagno stream
Bisagno - covered
Administrative border
0
1
2 km
GEML station - Hydrometric level
LAPRS station - Hydrometric level
GEFR station - Hydrometric level
FIRP station - Hydrometric level
Bisagno catchment rain gauges - 2014/10/09
Level (m)
Time
GEGR
GEML
DVG2
LPRS
BARG
PCAR
RGHI
VIGA
GEC
GEFR
FIRP
GECF


4
3
1
2
Bisagno flash flood - October 9, 2014
Flooded area
30-50 years return period
200 years return period
500 years return period
Bisagno stream
Bisagno - covered
Measured flood level (m)
>1.6
0-0.5
0.5-0.8
0.8-1.1
1.1-1.6
0
200
400 m
a

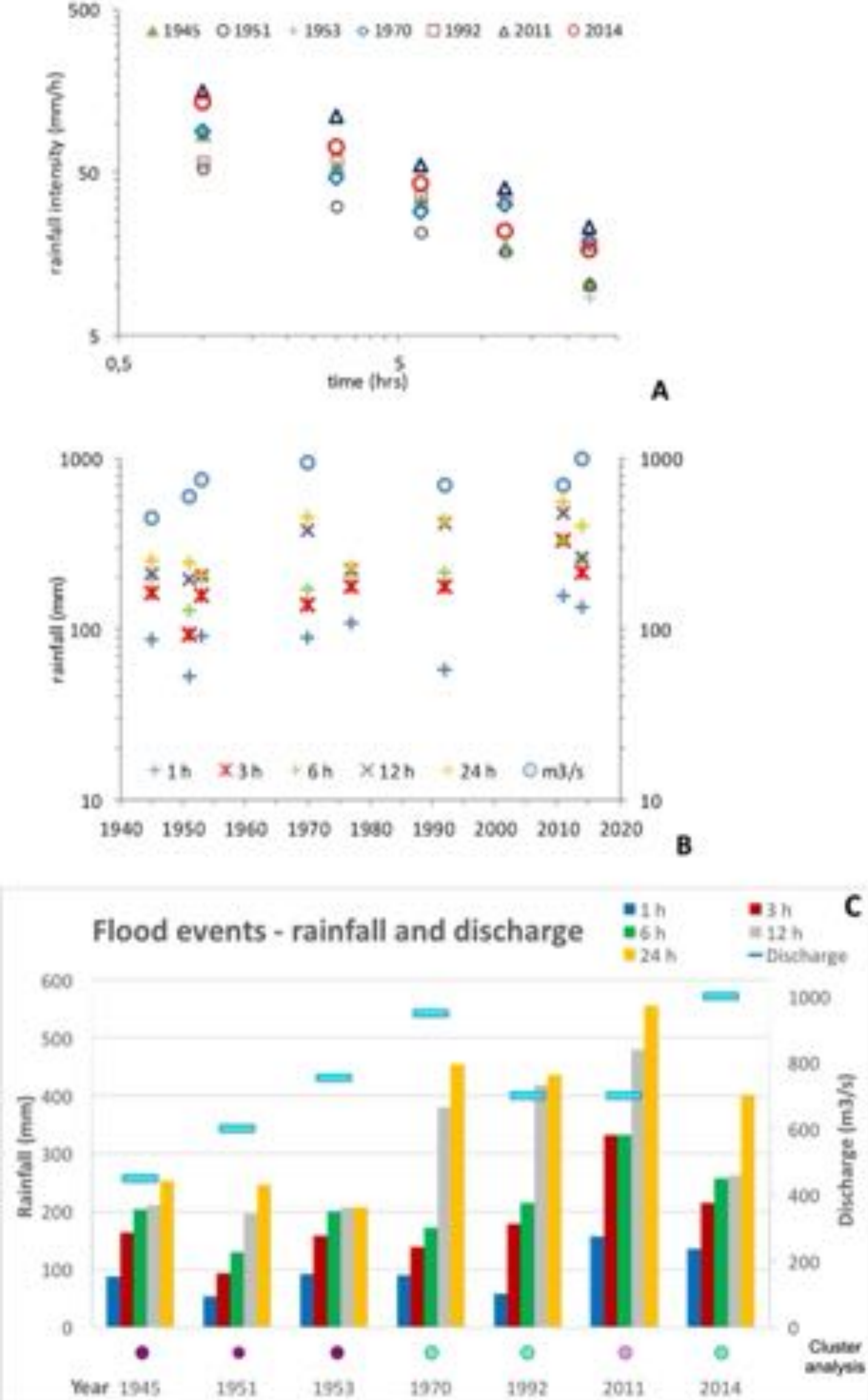

b


C

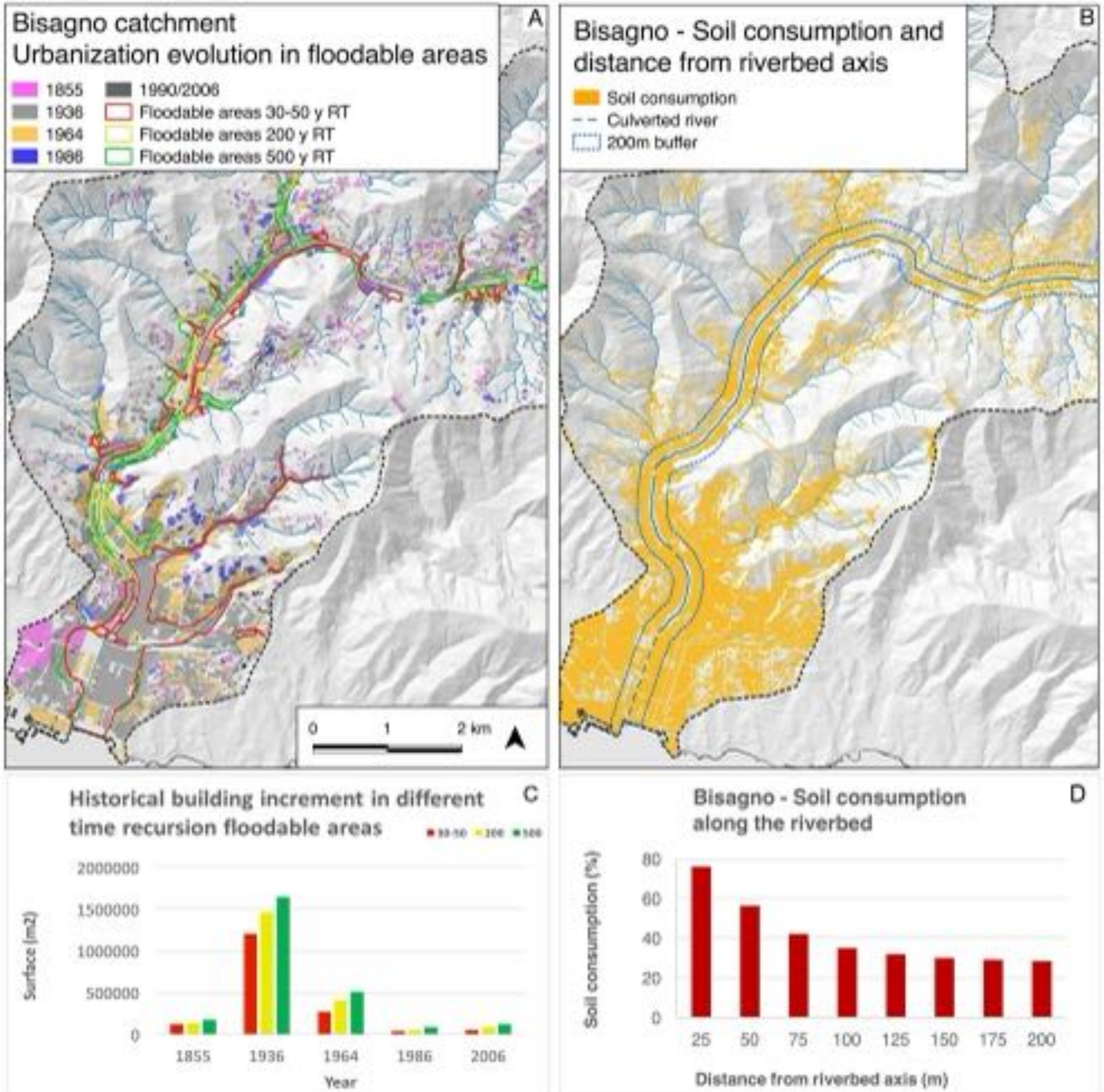

water level



a) rainfalls at Pontecarrega raingauge
rainfall (mm)
time (hrs)
1945
1951
1953
1970
1992
2011
2014
b) max rainfall 1 hr
y = 0,004x - 0,132
c) max rainfall 3 hrs
y = 0,01x - 0,33
d) max rainfall 6 hrs
y = 0,01x - 0,27
e) max rainfall 12 hrs
y = 0,01x - 0,19
f) max rainfall 24 hrs
y = 0,01x - 0,24
g)
1 h
3 h
6 h
12 h
24 h
Rainfall (mm)
Year
Cluster Analysis
Bisagno floods



A
rainfall intensity (mm/h)
time (hrs)
1945
1951
1953
1970
1992
2011
2014
500
50
5
0,5
5
B
rainfall (mm)
1 h
3 h
6 h
12 h
24 h
m3/s
1000
100
10
1940
1950
1960
1970
1980
1990
2000
2010
2020
C
Flood events - rainfall and discharge
1 h
3 h
6 h
12 h
24 h
Discharge
Rainfall (mm)
Discharge (m3/s)
Cluster analysis
Year
1945
1951
1953
1970
1992
2011
2014



A
Bisagno catchment
Urbanization evolution in floodable areas
1855
1936
1964
1986
1990/2006
Floodable areas 30-50 y RT
Floodable areas 200 y RT
Floodable areas 500 y RT
0
1
2 km
B
Bisagno - Soil consumption and distance from riverbed axis
Soil consumption
Culverted river
200m buffer
C
Historical building increment in different time recursion floodable areas
30-50
200
500
Surface (m2)
2000000
1500000
1000000
500000
0
1855
1936
1964
1986
2006
Year
D
Bisagno - Soil consumption along the riverbed
Soil consumption (%)
80
60
40
20
0
25
50
75
100
125
150
175
200
Distance from riverbed axis (m)

CAPTIONS

Fig. 1
Geographical sketch maps of the studied area. Top: the Bisagno stream catchment (colored area) and the Genoan hydrographic network. A is the axe Passo del Turchino -Leiro Stream-Sea, B Passo dei Giovi-Polcevera Stream-Sea and C Passo della Crocetta d'Orero-Bisagno Geirato Stream-Sea. Red line evidences the main watershed in plan and section (below).

Fig. 2
Bisagno stream catchment: flood hazard zones (red=high, yellow=medium, green=low) are shown (modified from Città Metropolitana di Genova, 2015). With colored dots are evidenced the rainfall and discharge gauges of the ARPAL net: GEFC=Centro Funzionale (Functional Centre); FIRP=Passerella Firpo; GEQU=Quezzi; GEFR=Fereggiano; RGHI=Castellaccio; PCAR=Pontecarrega; GEGR=Geirato; GEML=Molassana; CRET=Creto; LPRS=La Presa; VIGA=Viganego; BARG=Bargagli; DVG2=Davagna.

Fig. 3
Meteorological conditions on October 9, 2014. A: Radar image at Mount Settepani (Arpal, 2014). B: Sea level pressure and fronts: note the high pressure and the convergence of currents over the Gulf of Liguria (Bracknell chart from Wetterzentrale.de, from Arpal, 2014). C and D: Isohyets map of the rainfall for 6 hrs and 24 hrs in the Bisagno Valley.

Fig. 4
Hydrograms recorded in the stations located in the Bisagno Valley from 6 to 12 October 2014 (see Fig. 2 for further information about the stations). The yellow line indicates the ordinary flood, as the water flows fully inside the whole riverbed, with local levels lower than the amount of the banks or the ground level. The red line shows the extraordinary flood as the amount of water cannot flow inside the riverbed, causing over flooding. Low on the right the cumulated rainfall recorded on October 9, 2014 by the weather station of Bisagno stream basin.

Fig. 5
a) Flooded areas of the 2014 event in Genoa city: the measured points are shown with colored dots. Fluvial zones T30, T50 and T200 coincide in the area downstream Genova Brignole. Places mentioned in the text: 1) via XX Settembre, 2) Foce, 3) Genova Brignole, 4) Marassi. The snapshots on the right refer to: the paroxysmal moment of the flood event in via XX Settembre (a), cars piled up near the Brignole metro station (c), the level of the water (arrow) in an old street of the city (d).

Fig. 6
Critical rainfall values of the flood events occurred in the Bisagno valley (6a) and annual maximum rainfall recorded at Genoa Pontecarrega (see fig. 2 for location) represented by Standardized Anomaly Index in the 1945-2015 period (6b-6f). Rainfall data at Pontecarrega gauge for the period 1945-2014 at 1h, 3h, 6h, 12h and 24h. Bisagno flood events coincide with red and yellow groups, apart from the 1951 one (Fig. 6g).

Fig. 7
A) Rainfall intensity (mm/h) for the maximum rainfall recorded at 1, 3, 6, 12, 24 hrs during flood events since the post-war period and recorded in the burst centres (1945, Castellaccio; 1951; 1953 Functional Centre; 1970; 1992 Pontecarrega; 2011 Fereggiano; 2014 Geirato, see fig. 2 for location). B) Rainfall values for 1, 3, 6, 12, 24 hrs measured in the burst centre of floods from 1945 to 2014 and estimated discharge of the event. C) Rainfall data at the maximum intensity gauge for the Bisagno flood events in the period 1945-2014 at 1, 3, 6, 12, 24 hrs. On the right axis the maximum discharge. The Cluster analysis differentiate between the 1945, 1951 and 1953 events and the ones after 1970.

Fig. 8
Maps of urbanization of Bisagno basin: A) historical evolution of urbanization in the floodable area (modified by Regione Liguria, 1986); B) soil consumption and distance from the riverbed (data from ISPRA, 2015); C) historical surface building increment in the Bisagno valley floodable area; D) Percent of soil consumption vs distance from the riverbed.

Table 1
Long term average and 2014 rainfalls (italic) in three rain gauges of the Bisagno Valley (fig. 2 for location)

Raingauge Station	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*Annual Average*
GE Centro Funzionale	130 *255*	105 *254*	120 *78*	104 *55*	82 *47*	61 *15*	40 *24*	69 *57*	107 *32*	198 *432*	165 *519*	134 *131*	1286 *1906*
Pontecarrega	123 *362*	79 *300*	118 *86*	97 *90*	94 *40*	59 *17*	45 *44*	94 *123*	83 *29*	198 *657*	103 *530*	130 *148*	1223 *2435*
Viganego	170 *785*	135 *470*	163 *183*	151 *147*	132 *67*	88 *64*	54 *66*	75 *131*	116 *31*	240 *398*	200 *746*	216 *121*	1740 *3238*

Table 2
Disaster flood features and minor geo-hydrological events of the Bisagno Stream since 1945. Minor events in the Bisagno catchment in 1951, 1966, 1977, 2000 and 2002

Date of the Meteorological Event (yyyy/mm/dd)	*Rainfall peak*	*Discharge*	*Flood event*	*Storm-related Deaths*	*Damage losses and other damages (updated 2015)*
1945/10/29	285 mm/24 hrs (PCAR)	450 m^3/s at Staglieno Cemetery, final culvert under pressure	Regular flood, overflowing of Bisagno River, Fereggiano, Veilino and Geirato streams	5 fatalities	Serious damage, today hardly quantifiable
1951/11/08	245 mm/24 hrs (GEFC), 420/5 days (PCAR)	600 m^3/s	Regular flood, Bisagno, Fereggiano and Geirato floodings	No reports of casualties	17 million Euros
1953/09/19	206 mm/24 hrs (GEFC), 486/5 days (GEGR)	750-800 m^3/s, final culvert under pressure	Flash flood, overflowing of Bisagno, Torbido, Geirato, Veilino, Fereggiano	No reports of casualties	39 million Euros
1970/10/08	453 mm/24 hrs (PCAR), 394 mm/24 hrs (RGHI)	950 m^3/s final culvert under pressure	Regular flood, overflowing of Bisagno, Torbido, Geirato, Veilino, Fereggiano, Mermi	10 fatalities	55 million Euros 1,000 people homeless; 50,000 people without jobs
1992/09/27	435/24 hrs (PCAR), 337/24 hrs (VIGA)	700 m^3/s	Flash flood, overflowing of Bisagno River	No reports of casualties in the Bisagno basin, 2 deaths in the neighbourhood Sturla basin	75 million Euros, 250 people homeless
2011/11/04	166/1 hr, 499/12 hrs (GEQU)	700 m^3/s, final culvert under pressure	Flash flood, overflowing of the Bisagno and Fereggiano	6 fatalities	150 million Euros, 150 people homeless
2014/10/09	141 mm/1 hr (GEGR), 401/24 hrs (GEGR)	1,000 m^3/s final culvert under pressure	Flash flood, overflowing of the Bisagno and Fereggiano	1 fatality	300 million Euros, 250 people homeless

RAINFALL REGIME AND URBAN SPRAWL VARIATIONS IN A MEDITERRANEAN RIVER CATCHMENT PRONE TO HISTORICAL FLOODS

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