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This paper examines the three largest flood events in terms of intensity and ground effects which affected the Bisagno Valley in the last three centuries: the flood of 25th October 1822, well documented by contemporary sources, the flood of 8th October 1970, undoubtedly the most tragic on record and the very recent event of 9th October 2014. For this purpose both scientific and historical-geographic methodologies were adopted, the latter particularly useful for the reconstruction of the flood event of 1822 and the landscape history of the Bisagno Valley in the 19th century.
This comparison shows that the Bisagno Valley is characterised by climatic and landform features which have been making the flood events historically common in the area. However, both recent climate change and land-use variations, including some irrational modifications of the catchment basin, have progressively determined an increase of flood hazard. Consequently, in recent decades a growth in the number of flood events occurred, to the extent that the Bisagno today is a famous case study on an international scale.

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The Bisagno stream catchment (Genoa, Italy) and its major floods (1822, 1970 and 2014): geomorphic and land use variations in the last three centuries

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Abstract

The city of Genoa (Liguria, Italy) and the Bisagno Valley are affected by frequent floods, often with loss of human lives. Historically characterised by high flood hazard, the Bisagno Valley was recently affected by a flood event on 9th October 2014, less than three years after the tragic event of 4th November 2011 when six people died, including two children. In the last 50 years four destructive floods occurred in the Bisagno Valley, in addition to some minor events which caused significant damage and economic losses.

This paper examines the three largest flood events in terms of intensity and ground effects which affected the Bisagno Valley in the last three centuries: the flood of 25th October 1822, well documented by contemporary sources, the flood of 8th October 1970, undoubtedly the most tragic on record and the very recent event of 9th October 2014. For this purpose both scientific and historical-geographic methodologies were adopted, the latter particularly useful

for the reconstruction of the flood event of 1822 and the landscape history of the Bisagno Valley in the 19th century.

This comparison shows that the Bisagno Valley is characterised by climatic and landform features which have been making the flood events historically common in the area. However, both recent climate change and land-use variations, including some irrational modifications of the catchment basin, have progressively determined an increase of flood hazard. Consequently, in recent decades a growth in the number of flood events occurred, to the extent that the Bisagno today is a famous case study on an international scale.

KEY-WORDS: Bisagno stream, Genoa, Geo-hydrological Hazard, Historical floods, Land-Use variations

1. Introduction

Research on urban floods is today a particularly relevant theme for the analysis of the hazard (Plate, 2002) and its management (Apel et al., 2008) aimed to reduce geo-hydrological risk. More recently this approach is directed to the increase of resilience amongst local communities (Committee on Increasing National Resilience to Hazards and Disasters, 2012; Fryirs et al., 2015). Some scholars stress the role that climate change has in influencing the flood hazard (Barrera-Escoda and Llasat, 2015), while others underline the influence of climate oscillation to explain historical floods in Asia and Europe (Yu et al., 2009; Likai and Jijun, 2010; Bohm et. al., 2014; Elleder, 2015). Landscape evolution is another important factor to consider when studying flood hazard, particularly land-use change (Latocha, 2009; Agnoletti et al., 2012; Boudou et al., 2016) or combined climate and land-use variations (Ward et al., 2009).

Important flood events have recently affected Central Europe (Grams et al., 2014) and research on flooding regime variations and comparisons with past events has been carried out (Blösch et al., 2013; Hall et al., 2014). In Southern European countries flood hazard is particularly high along the Mediterranean coast (Montanari et al., 2013; Jansà et al., 2014) and so the flash flood stream power (Marchi et al., 2016). In the last decades, flash floods in Southern Europe, Italy in particular, have been studied due to their remarkable intensification and the increase of rainfall intensity connected with recent climate change (Terranova and Cariano, 2014; Llasat et. al., 2014). Due to geologic, geomorphologic and climatic features, geo-hydrological hazard is here particularly common and its primary effects include serious damage to buildings, infrastructures and loss of life (Guzzetti and Tonelli, 2004; Luino, 2005).

In the Italian peninsula, the city of Genoa has been historically affected by geo-hydrological events since the Roman-Byzantine period, while important events historically documented in the annals of the Republic of Genoa occurred in 1404, 1407, 1414, 1416, 1420, 1452, 1465, 1582, 1746, 1780, 1787 and 1790. In the city centre, where the Bisagno stream catchment lies (**Fig. 1**), Faccini et. al. (2015a) demonstrated a recent increase in the number of floods and flash floods linked to both centennial climate oscillation and to massive land-use changes and modifications of both the main and other minor hydrographical networks. In the urban area of Genoa in particular an increasing trend of daily average rainfall (the ratio between the annual rainfall and the total number of rainy days in one year) and of the average temperature were measured (Faccini et al., 2015a; Pasquale et al., 1994; Russo et al., 2000). These variations match with the data of weather stations worldwide (IPCC, 2013). The city of Genoa and the Bisagno catchment in particular, show specific orographic and hydrographical features. Apennine peaks of over 1000 metres are found only at a short distance from the coast. The hydrographical network is characterised by particularly short streams within limited water basins, often less than 100 square kilometres: therefore, concentration time during heavy rainfall events is very short.

Tab. 1 a, b shows the most important flood events, which affected the Bisagno Valley in Genoa city centre from 19th century to present day. These important events were classified as both regular and flash floods (USA National Weather Service, 2008) and they occurred in the main stream and some minor tributaries. In the 19th century four floods occurred and, at least one, included a flash flood event. Of the eight floods occurred in the 20th century, three could be classified as flash floods, while in the 3rd millennium two flash floods have already occured, in 2011 and 2014.

If we consider all the catchments in Genoa metropolitan area, just in the last 50 years many other streams flooded: in 1977, 1993, 1994, 1995, 2000, 2007, 2010, 2013 and in 2014 (twice, 10th and 15th November) again with loss of life and serious damages and economic losses (Faccini et al., 2005; 2012; 2015a; 2015b). The extraordinary frequency of flood events and the consequent effects have made Genoa and the Bisagno stream in particular (**Fig. 1**) important cases study worldwide (Rosso and Rulli, 2002; Silvestro et al., 2012; 2015; Ferrari et al., 2014; Hally et al., 2015).

Since, according to historical data, the Bisagno flooded every 16 years averagely in the last two centuries (**Tab. 1 a and b**) (and floods in Genoa metropolitan area every 7-8 years), the aim of this work is to assess what has changed in the stream dynamics from 1800 to today. It is well known how historical and anthropogenic variations in catchments affect alluvial occurrences (De Roo et al., 2001; Chin, 2006; Garcia-Ruiz et al., 2008; Rhoads et al., 2015). For this purpose, three significant events in terms of intensity and ground effects were selected, one for the 19th century (25th October 1822), one for the 20th century (8th October 1970) and one for the 21st century, the recent flood of 9th October 2014. The first flood is significant as it occurred at the end of the Little Ice Age (Mann, 2002) in a different climate regime from today (Delile et al., 2016): moreover, the landscape was different from today as the flood happened before the industrial revolution of the second half of the C19th when the Genoese coast became one of the most important industrial center of Mediterranean area. The flood event of 1970 is certainly the most famous for its dramatic ground effects (Faccini et al., 2015a) which were also due to the effects of irrational urbanisation of the post-war period, while the event of 2014 indicates the current climatic and geomorphological situation in Genoa.

These flood events have been assessed through the reconstruction of rain histories and ground effects; the results provide interesting evidence on the consequences of landscape and climatic changes and allow us to learn useful lessons for the analysis of the flood events and management of geo-hydrological hazard.

Storm event day	Rainfall event	Discharge	Flood event	Damage losses and other damages
1822/10/25	812 mm / 24 h in the lower Bisagno catchment (Marassi)	1200 mc/s	Regular flood. 15 hours of violent rainfall a 3 h peak between 10 a.m. and 1 p.m.	Many streams flooded: two bridges on the Bisagno collapsed. Mud and water reached the second floor of the houses at Foce district. Serious damage to shops, farms, factories and the public aqueduct. Estimated damage around half a million of Savoy liras
1842/8/25	247 mm in less than 10 h at Genoa University	?	Regular flood. Violent rainfall hit the slopes behind the city: flooding of some streams in the Bisagno catchment and of the Bisagno at Foce	Not quantifiable by the historical sources
1872/10/17	350 mm/48h at Genoa University	More than 300 mc/s	Regular flood hit the Western Riviera and the Bisagno and Scrivia Valleys. Overflowing of the Bisagno stream at Marassi, S.Agata and Foce.	Not quantifiable by the historical sources
1892/10/08	The only measure is 181.3 mm/24hs at Genoa University, in the city centre. The data appear underestimated, probably due to an error in the measurement	460 mc/s at Foce	Flash flood. The Bisagno stream flooded at Molassana and Foce.	The event involved mainly the upper part of the catchment. Damage not quantifiable by the historical sources

Tab. 1a - Disaster flood features of the Bisagno Stream 19th century.

Storm Event Date	Rainfall event	Discharge	Flood events	Damage losses and other damages	Storm-related fatalities
1907/10/10	246 mm/24 h measured at Genoa University	500 mc/s	Regular flood. The Bisagno stream flooded at Molassana and Foce.	Not quantifiable by the historical sources	No reports of fatalities
1908/07/18	238,6 mm at Viganego rain gauge in 9 h with a peak between 4 - 6:30 a.m.	420-450 m^3/s at Foce	Regular flood. The Bisagno stream flooded in the medium-upper part of the catchment.	Damages not quantifiable by the historical sources	No reports of fatalities
1945/10/29	285 mm/24 h (PCAR)	Lower Bisagno catchment and right slope, 202 mm/6 h. 450 m3/s at Staglieno Cemetery, final culvert under pressure	Flash flood. Flood of the Bisagno, Fereggiano, Veilino and Geirato streams	Serious damages, today hardly quantifiable	5 fatalities
1953/09/19	206 mm/24 h (GEFC), 486/5 d (GEGR)	750-800 m3/s, end culvert under pressure	Flash flood. Flood of the Bisagno, Torbido, Geirato, Veilino and Fereggiano streams	39 million Euros equivalent	No reports of fatalities
1970/10/08	453 mm/24 h (PCAR), 394 mm/24 h (RGHI)	950 m3/s end culvert under pressure	Regular flood. Flood of the Bisagno, Torbido, Geirato, Veilino, Fereggiano and Mermi streams	55 million Euros equivalent 1000 people left homeless; 50,000 people without jobs	10 fatalities only in the Bisagno valley, 44 in the Genoa metropolitan area
1992/09/27	435/24 h (PCAR), 337/24 hrs (VIGA)	700 m3/s	Flash flood. Flood of the Bisagno stream	75 million Euros equivalent, 250 people left homeless	No reports of fatalities in the Bisagno basin, 2 fatalities in the close Sturla basin
2011/11/04	166/1 h, 499/12 h (GEQU)	700 m3/s, final culvert under pressure	Flash flood. Flood of the Bisagno e Fereggiano streams	150 million Euros, 150 people left homeless	6 fatalities
2014/10/09	141 mm/1 h (GEGR), 401/24 h (GEGR)	1000 m3/s, final culvert under pressure	Flash flood. Flood of the Bisagno e Fereggiano streams	300 million Euros, 250 people left homeless	1 fatality

Tab. 1b - Disaster flood features of the Bisagno stream 20th and 21st century. For acronym in rainfall event column see fig. 1.

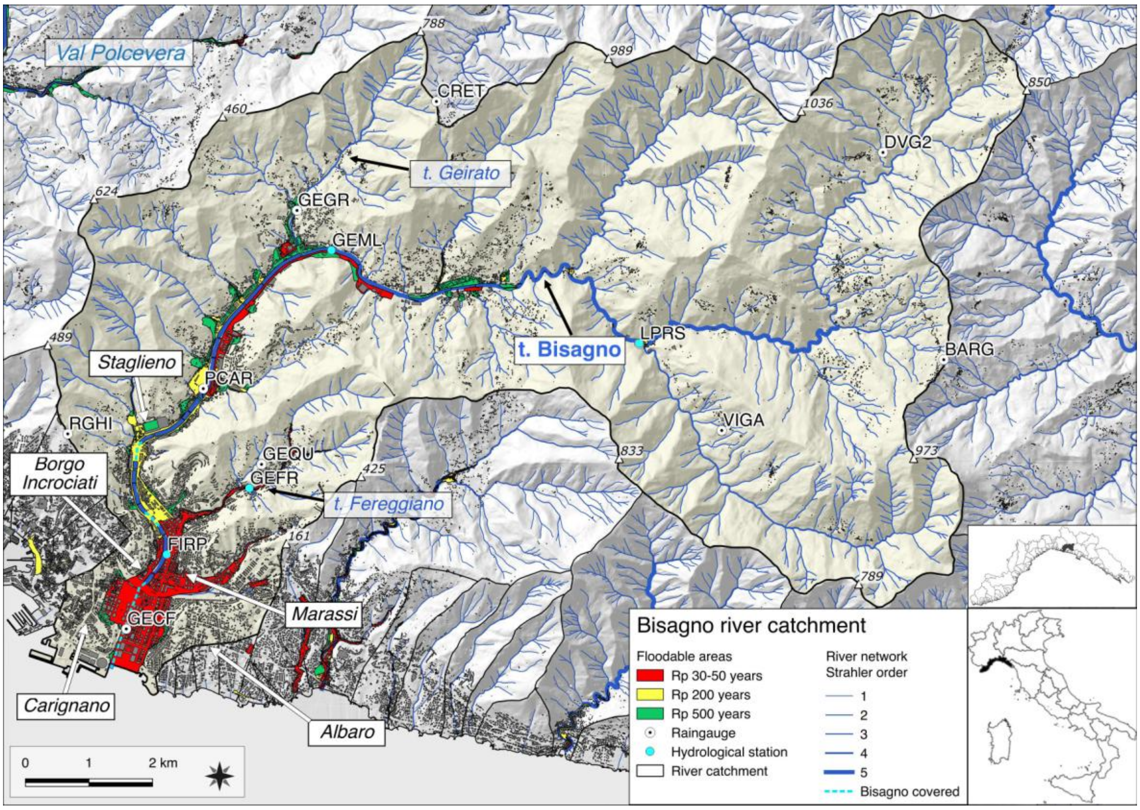


Fig. 1 - Bisagno stream catchment with rain gauges, hydrometric stations and flood hazard zones (red=high, yellow=medium, green=low) (modified from Città Metropolitana di Genova, 2015). GEFC= Centro Funzionale; FIRP= Passerella Firpo; GEQU= Quezzi; GEFR: Fereggiano; RGHI= Castellaccio; PCAR= Pontecarrega; GEGR= Geirato; GEML= Molassana; CRET= Creto; LPRS= La Presa; VIGA=Viganego; BARG= Bargagli; DVG2= Davagna.

2. Material and method

2.1 Geographical settings of the Bisagno catchment

The Bisagno stream rises near Scoffera Pass (675 m) and its drainage basin covers 95 square kilometres. The main stream has a total length of 25 km and its mouth is in Genoa city centre, east of the natural amphitheatre of the old town. The maximum elevation of the catchment is 1034 m and the average gradient is 31%. 10% of the territory has a gradient of more than 75%, while only 5% has a gradient of less than 10%. 60% of the territory has a gradient between 35% and 75%, while almost 70% of the total catchment is included between 0 and 500 m above the sea level. Today the urban area covers 15% of the total catchment. 57% of the territory is wooded and this represents the main land use category for the higher part of the valley which was almost entirely abandoned due to emigration and depopulation of the countryside since the end of the 19th century.

The Bisagno valley is geologically characterized by marly limestone flysch of Mt Antola (Upper Cretaceous) and related base complex of Montoggio shales. Ortovero Pliocenic clays feature only at the city centre. The main stream is subject to erosion for 11 km from the mouth, while the flood plain is heavily urbanised. The maximum width of the floodplain is roughly 300 m before it reaches the main culvert which encases the stream for the last 1.4 km as far as the stream mouth, while other minor culverts partially cover the stretch between the A12 motorway and Genoa football stadium. The whole basin is subject to intense erosion conditions affected by tectonic control. The reactivation of erosion processes is related to the last drop of the base level (Brancucci and Paliaga, 2005; Paliaga, 2004; 2015).

The hydrological regime is characterized by frequent drought events, particularly in the summer, and sudden floods, more frequent in autumn, with a time of concentration ranging from less than an hour to 3 hours. The maximum discharge of the Bisagno stream was estimated for different return periods (Cittá Metropolitana di Genova, 2015): for T50 the estimated discharge is 790 m^3/s (which already exceeds the capacity of the terminal culvert), for T200 it is 1300 m^3/s and for T500 it is 1785 m^3/s. Estimated solid transport is higher than 25,000 m^3/a ma, however, due to the intermittent flow regime, most of the sediment transport is brought during the floods (Cevasco et al., 2010) when, in addition to geomaterials (mainly sand, gravel, pebbles and boulders), trees and urban waste from illegal dumps are transported as well (Faccini and Vassalli, 2008).

The Bisagno catchment is affected by more than 300 landslides most of which occur in areas affected by deep-seated gravitational slope deformation. Sediment transport during flood events can be considerable, with reactivation of landslides after prolonged rainfall and debris flow events during flash floods (Tung-Chiung et al., 2010).

The coastal climate is characterised by short and mild winters (average temperature in January 8°C), temperate summers (average temperature in July 24 °C) and widespread rainfall in all seasons with the maximum occurring in autumn (150-200 mm in October) and the minimum in summer. The annual average rainfall ranges from 1100 mm to 1300 mm and the annual average temperature is just less than 16 °C. Overall, it is a humid-mild climate with short dry season restricted to one or two summer months (Sacchini et al., 2012; ARPAL, 2013).

Flood events, with consequent damages, have affected Liguria and Genoa Metropolitan Area in particular, with an apparent recent increase in their number and their effects. In terms of their meteorological character, these events are all related to a blocking anticyclone setting up a prefrontal flow in the warm branch of the perturbation coming from the Atlantic Ocean, which generates convective systems resulting in extremely intense and localized rainfall sufficient to generate flash floods (Russo and Sacchini, 1994; Faccini et al., 2015a).

2.2 Research methodology

Three flood events from 19th, 20th and 21st century were selected due to their importance in terms of intensity, historical significance and ground effects. The isohyets maps were realized from data recorded at different weather stations by local environmental authorities and from documentary sources. For the flood event of 2014, maps and meteorological data produced by ARPAL (Environmental Protection Regional Agency) were analysed, in addition to direct surveys carried out by the authors of this paper and online sources (documents and images). For the flood events of 1970 and 1822 both scientific literature (Bossolasco et al., 1971; Cati, 1971) and contemporary reports were taken into account. For 1822 the correspondence between a physician from the University of Genoa and other contemporary intellectuals and scholars was an important source of data. Written accounts by writers and poets living in Genoa during the flood, such as George Gordon Lord Byron and Mary Wollstonecraft Godwin Shelley were also consulted for their precise description of the flood event. Land-use changes since 1822 were reconstructed through the comparison of historical and modern maps, such as the *Minute di Campagna* of 1816-1829 (1:9.450) and the *Gran Carta degli Stati Sardi di Terraferma* produced between 1852-1874 (1:50.000), both produced by the Sardinian Kingdom. There is increasing attention in the use of visual sources for the reconstruction of past landscape dynamics (Gaynor and McLean, 2008; Piana et al., 2012). In addition to historical cartography, the landscape history of the Bisagno Valley in the first half of the 19th century was reconstructed using contemporary cadastral documents and topographical drawings and paintings produced by local painters such as Luigi Garibbo (1784-1869) and Pasquale Domenico Cambiaso (1811-1894). Recent landscape changes and urban sprawl were reconstructed by analysing the 1973 Ligurian Regional Technical Map and Google Earth™. Moreover, land use maps of 1976, the CE project, “Corine Land Cover” (European Environmental Agency, 2006) and the 2012 update (ISPRA, 2015) were analysed. The maps were geo-referenced using GIS software in order to reconstruct the land use variations occurred in the last three centuries. The urban growth was defined by examining the map of urban evolution produced by Regione Liguria (1986) integrated by ISTAT data (Istituto Italiano di Statistica, 2011), which categorizes the buildings by decade of their construction. Moreover, topographical maps published by Regione Liguria (Regional Map, 1990-2006) and aerial photographs produced by the same institution (1990-2004) integrated the data. Maps from different periods were overlaid and compared using known monuments, forts or churches as reference points.

The data were examined to investigate variations in the flood events of the last three centuries. For the climate aspects we used historical data from Genoa University weather station, established in Genoa city centre in 1833 and constantly in use ever since. In particular historical records for average annual temperature, annual rainfall, number of rainy days (rainfall > 0.2 mm) and annual precipitation rate, calculated as the ratio between the annual rainfall (mm) and the number of rainy days (n), were examined.

3. The main Bisagno stream disaster floods

3.1. The 25th October 1822 flood event

This disastrous flood event was reported in detail by Italian newspapers (*La Gazzetta di Genova 26th and 30th October 1822, Gazzetta Piemontese 31st October 1822 and 2nd November 1822, Gazzettino di Parma 2nd November 1822,* **Tab. 1a**). The flood event occurred on the 25th October, when part of Genoa was flooded, with severe damage to the roads and the shops, destruction of walls and cultivations and great loss of livestock for an estimated damage of around half a million of Savoy liras. All the bridges of the lower Bisagno Valley collapsed, as reported by Lord Byron who described the flood event as a "deluge", with the road being an "impassable cascade" and "all landscape under water" (Byron, 1980, Letter 10, pp. 28-30). Contemporary to Byron, Mary Shelley stated that in 20 minutes of rain the flood "sufficed […] to lay flat the walls which in that hilly country support the soil" (Shelley, 1844, p. 58).

The contemporary chronicles state that the Bisagno Valley was completely flooded from the walls of "Fronti basse" to the Hill of Albaro downstream of Marassi, with the houses submerged up to the second floor, the level of water which reached 12.5 palms (1 Genoese palm = 24.8 cm) and the St. Agata and Pila bridges swept away. The peak of the flood was probably between the Bisagno and Sturla Valleys and the left side of the Polcevera Valley (**Fig. 1**). Professor Antonio Pagani from the University of Genoa had been recording meteorological data for 25 years: on the 25th October 1822 his rain gauge, which was located in Marassi, measured 30 inches of rain (812 mm). This incredible data was the object of a correspondence with the Universal Library of Geneve aimed to find out how the rainfall measurement was obtained. This correspondence is also mentioned in the “Annales de Chimie et Physique” by Arago and Gay Lussac who defined Pagani as “observateur exacte” (exact observer, 1824, p. 406 vol. XXVII). The rain started in the night between the 24th and the 25th and lasted 15 hours. The phenomenon become more intense around 10 a.m. on the 25th, when the allotments of the Bisagno began to be flooded; the complete flood occurred around 11:30 a.m. and by 1 p.m. most of its worst ground effects had already happened. Mary Shelley reports that “a cloud, surcharged with electricity and water, burst above our heads in one torrent of what was rather a cataract than rain” (Shelley 1844, p. 58). Based on contemporary accounts, the flooded area was reconstructed and it is shown on a contemporary map (**Fig. 2a**). The descriptions suggest that, due to a stoppage situation between the cyclonic circulation over the Atlantic and the anticyclone between Eastern Mediterranean and Eastern Europe the intense rainfall started up in the warm pre-frontal sector of the perturbation. The pre-frontal phase was followed by another peak at 10 a.m., probably caused by a stationing convective super-cell stretched towards NNE along the Bisagno and Geirato Valleys, similar to the structure of other recent flood events in 2010 (Faccini et al., 2015b), 2011 and 2014 (Faccini et al., 2015a).

3.2. The 8th October 1970 flood event

In October 7-8, 1970 Genoa City suffered probably the most catastrophic flood event of its history when an anticyclone block generated recurring convective systems which hit Genoa city and the hinterland and above all the Bisagno Valley from the morning of 7th October to early hours of 9th October. Most of the streams and creeks in the Municipality flooded large urbanized areas in a very short time. The 1970 event in Genoa City was also the most dramatic in terms of damage, there were 44 fatalities and over 2000 individuals were evacuated.

On the evening of 7th October pre-frontal storms struck the western side of the city and the centre and the hinterland the day after. The storm affected Genoa before the arrival of the cold front due to an anticyclone block in Eastern Europe (Bossolasco et al., 1971). The heavy rainfall lasted more than 24 hours with highs at Bolzaneto rain gauge (Polcevera Valley, north-west of Genoa centre) where over 950 mm of rainfall in 24 hours were measured. The exceptional amount of rainfall measured in Bolzaneto indirectly confirmed the accuracy of Pagani's data for the flood of 1822. Over the city centre and the Bisagno Valley, 400 mm in 24 hours was recorded. The Bisagno stream channels overflowed submerging coastal areas and the city centre. Due to the absence of discharge gauge stations, the maximum flow rate of the Bisagno stream was estimated by Cati (1971) as 950 m^3/s (12 $m^3/s/km^2$) near the railway station of Genoa Brignole. The maximum flow rate capacity of the Bisagno coverage was approximately 700 m^3/s. The cumulated rainfall registered at other rain gauges of the Bisagno catchment show a sequence of flow peaks with concentration time around 2-3 hours. Overall, the flood event lasted 28 hours and the overflow of the Bisagno occurred at 3 p.m., c.1 hour after the peak rainfall measured in the centre of the catchment (Faccini et al., 2015a). The submerged area and water heights are reported in **Fig. 2b**. The map shows the Bisagno plain downstream of Marassi where the depths of flooding ranged from a few centimetres to up to 3 metres.

3.3. The 9th October 2014 flood event

Between October the 9th and 10th 2014 an intense and localized rainfall occurred. This flood event seems broadly comparable to those described in the recent past over the Ligurian Gulf *(*Faccini et al. 2012; 2015a; 2015b; Silvestro et al. 2012; Hally et al. 2015*)*, with repeated "self-regenerating" thunderstorms, stationing for several hours over the city and starting up in the warm pre-frontal sector of the perturbation. The rainfall was very intense in the Bisagno valley and in the closest surroundings and much lower in height over the rest of Liguria, with less disastrous effects on the ground. Satellite and radar images showed the persistence of storm cells, organized in “V-shaped” structures which were formed over the Liguria Gulf, southwest of Genoa, moving down towards the city and the hinterland, driven by the SW winds at 500 hPa (Faccini et al., 2015a). The flood event 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 baric figures a flow of currents from SW at high altitude and SE in the lower layers has settled. Furthermore, over the “Pianura Padana” (Po river floodplain) the anticyclone structure stretched causing the influx of cooler air that overflowed into the Liguria Gulf through low level (< 500 m asl) Apennine passes with northern winds. Immediately east of these situations of wind convergence to the ground the storm cells were developing. While a large high-pressure area was situated in the whole Italian peninsula and most of Liguria, a flood affected the city centre and the Bisagno Valley. The convergence to the ground and the shear *Scirocco* and *Libeccio* (SE and SW winds) favoured local atmospheric instability culminating in the event of the evening on October the 9th. The instability was also fuelled and supported by the contribution of very mild and humid air at 850 hPa (Faccini et al., 2015a*)*, the support of the still warm sea and the effect of the orographic barrier of the Apennines (Sacchini et al., 2012). This atmospheric configuration is typical and recurrent for each flood event in Liguria between the late summer and the early autumn (Russo and Sacchini, 1994).

The maximum rainfalls were recorded in the middle Bisagno valley. Rainfall peaks of about 140 mm/h were recorded in the Geirato Valley and a total of 754 mm/5 days. The isohyets' distribution showed the highest rainfall rates along a narrow band which followed the shape of the valley. The culmination of the event took place in the afternoon-evening of the 9th with the disastrous flooding of Bisagno and Fereggiano (its last left tributary) watercourses during the night. The concentration time was immediate and the water level reached its maximum after one hour from the rainfall peak. The maximum flow rate at Foce was estimated about 1000 m^3/s, a value that has a return time of 100 years (Città Metropolitana di Genova, 2015).

Near the Passerella Firpo bridge, the level of Bisagno stream recorded an increase of nearly 6 m. The final culvert under the city is inadequate in section; consequently, the flooding of the Bisagno stream in the terminal stretch between Genoa football stadium and the railway track near Genoa Brignole station occurred: in the city the water reached heights up to 2.5 m as a function of the topographic surface (**Fig. 2c**). The flood devastated homes and businesses over large areas of the lower Bisagno Valley where a fatality occurred. Shops, markets and craft activities in the centre of Genoa, just barely recovered from the flood on November the 4th 2011, were again devastated. The alluvial plain of the Bisagno stream in the city centre between Brignole (railway station), Foce and Via XX Settembre (the main commercial road in the city) was entirely affected by the flood: laminar and turbulent flows have caused water levels between 0.3 and 2 m (**Fig. 2c**) and stagnant water in lowest areas reached more than 2 m and up to 3 m in Borgo Incrociati.

From a meteorological point of view, the Gulf of Genoa is characterized by a typical circulation called "Genoa Low". 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, Ligurian Sea (Sáez de Cámara et al., 2011). This secondary depression linked to the arrival of Atlantic perturbations behind the Alps is formed on the Genoa Gulf primarily in the autumn-winter and spring periods (Anagnostopoulou et al., 2006). As a consequence, conditions of sharp thermodynamic contrast between hot humid Mediterranean air masses and cold air masses of continental origin are created. The Genoa Low toward the centre of the Gulf redirects the cold air masses over the Po Plain and behind the mountainous Ligurian arch, where the winds overflow into the Ligurian Gulf through the mountain passes, including the ones between Savona and Genoa, which reach modest altitudes, between 450 and 600 m asl. This typical circulation is responsible for the large amounts of rainfalls distributed over the region surrounding the Ligurian Sea (Sacchini et al., 2012). Between the end of summer and autumn, when the sea temperature is at its top, the thermodynamic contrast of similar air masses, together with the wind shear at different altitudes around the Genoa Gulf (N at sea level, SE at 850 hPa, SW at 500 hPa) are responsible for triggering of thunderstorm convective systems and sometimes super-cells (Silvestro et al. 2012; 2015). These convective systems originate in the Ligurian Sea and move to the inland area with a typical V-shape. The perturbations canalise along the valleys as far as the main mountain ridge which accentuates the precipitations. This is the cause of all the flood events which hit Genoa since at least 1970 and probably even the earlier ones, for which, however, no detailed meteorological data remain.

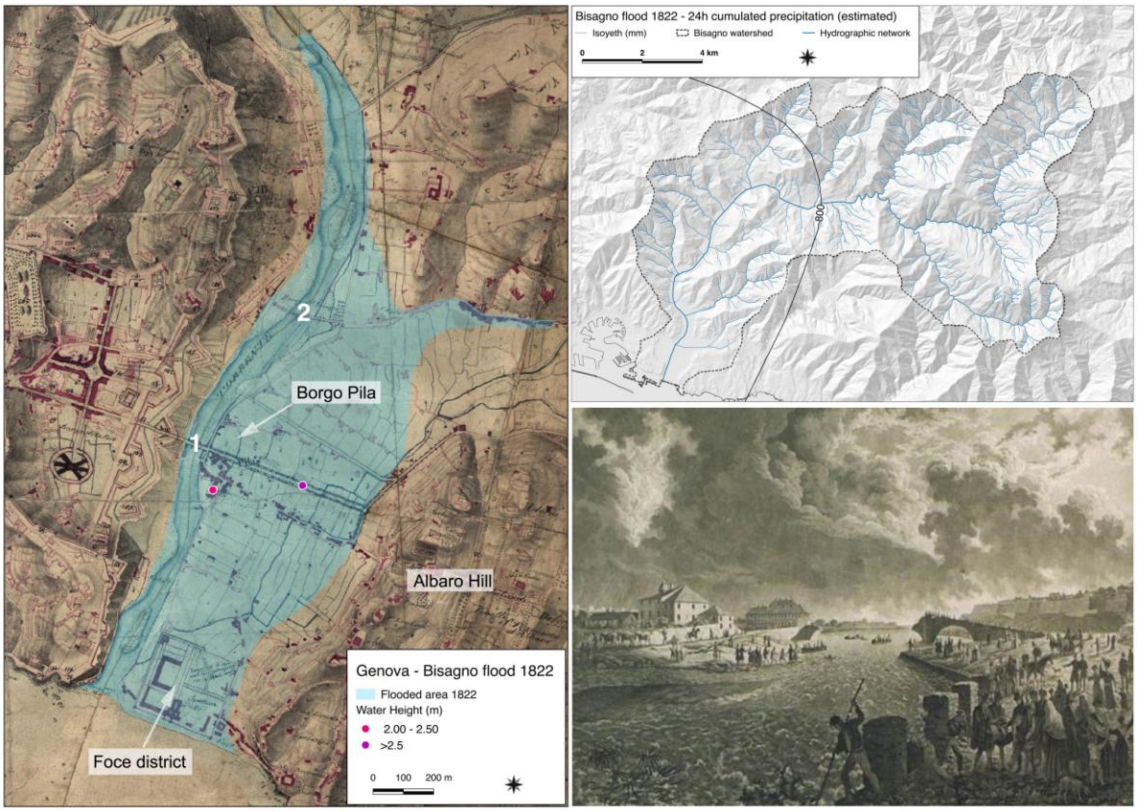


Fig. 2a - Water height and ground effect, rainfall 24 h, 25th October 1822 event (1: Pila Bridge; 2: St. Agata bridge). Rainfall: 812 mm/24 h at Marassi rain gauge; Max Water height: 12 Genoese palm (c. 3 m) downstream of Borgo Pila at Foce district; discharge: 1200 m^3/s at Ponte Pila. Print of the flood at Ponte Pila by Luigi Garibbo, '*Veduta del ponte della Pila sul Bisagno presso alle mura di Genova poco dopo il suo diroccamento per la gran piena del 26 Ottobre 1822*', Collezione Topografica del Comune di Genova

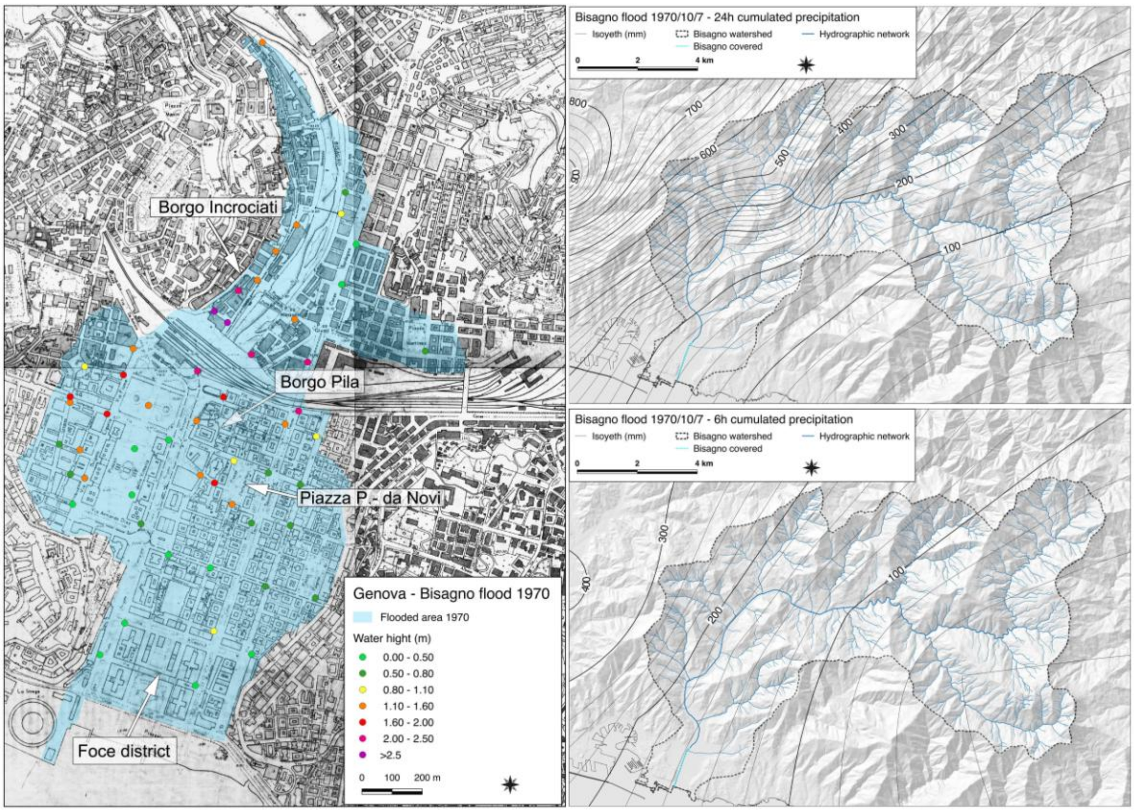


Fig. 2b - Water height and ground effect, rainfall 6 and 24h, 8th October 1970 event. Rainfall: 453 mm/24 h at Pontecarrega station; Max Water height: 2 m between Borgo Pila Church and Paolo da Novi Square at Foce district, 3.5 m at Borgo Incrociati; Discharge: 950 m^3/s at Borgo Incrociati.

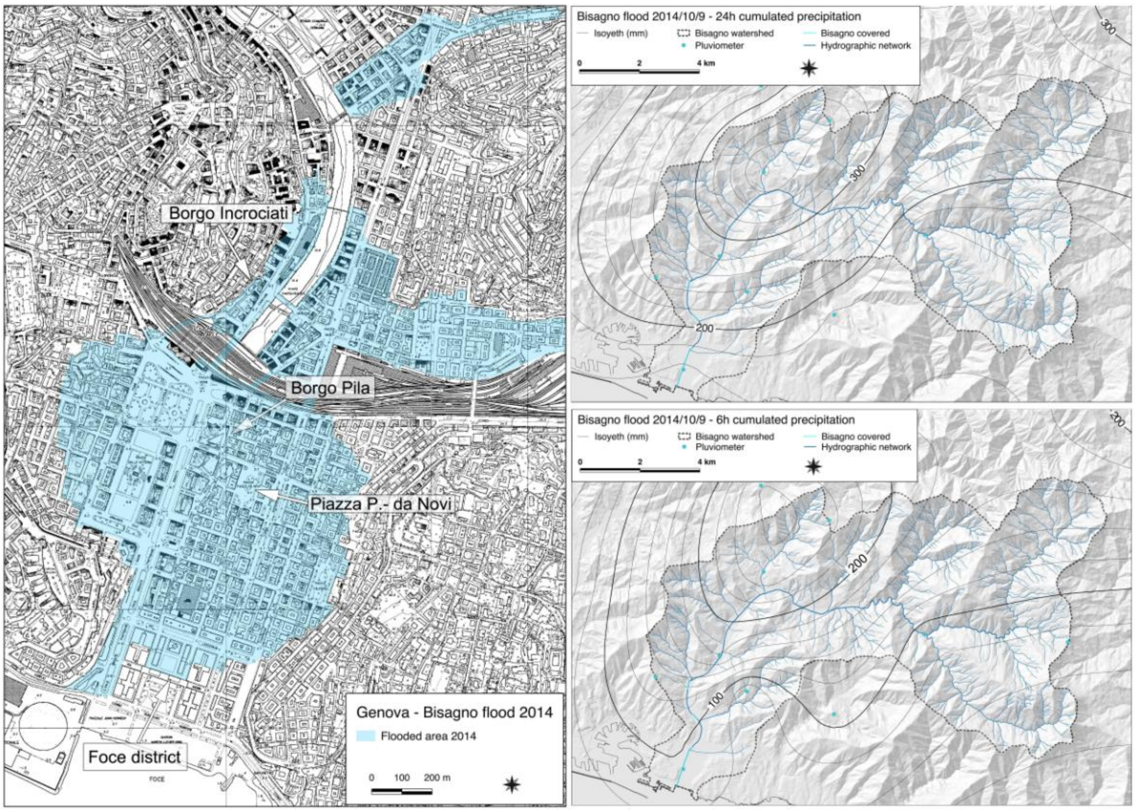


Fig. 2c - Water height and ground effect, rainfall 6 and 24 h, 9th October 2014 event. Rainfall: 392 mm/24 h at Geirato station; Max Water height: > 2m between Borgo Pila Church and Piazza Paolo da Novi at Foce district, 3 m at Borgo Incrociati; Discharge: 1000 m^3/s at Borgo Incrociati.

4. Geo-hydrological factors analysis

4.1. Urban sprawl

Genoa Municipality is one of the ten metropolitan cities of Italy, consisting of a total population of 1,600,000 living in the wide metropolitan area, of which 600,000 live in the city. The original structure of the city since before the Roman times and up to the 19th century was included between the small natural gulf where the harbour was built and the right side of the Bisagno Valley (**Fig. 1**), with hardly any settlement either on the alluvial plains of the streams and on the hills around. In the 19th century, when Genoa was annexed to the Savoy Kingdom (1815) and to the Italian Kingdom (1861) the urbanisation of coastal and alluvial plains began, particularly the Polcevera (west) and the Bisagno Valleys (east). While the area west of the historical centre lived a rapid industrial development, the Bisagno Valley has always been characterised by the presence of services such as Staglieno municipal cemetery. In the 20th century the urbanisation of the hillside area of the inland part of Genoa begun, with a peak between the 1950s and the 1980s and it is still partly continuing nowadays. Today more than 150.000 people live in the Bisagno catchment, where most of the commercial and artisanal businesses and city services are settled.

4.1.1. River bed changes

Fig. 3 shows the evolution of the city until 1986: it is integrated by the graphs, which document that the urban growth continued until at least 2006. From the natural amphitheatre around the historical centre, the built up surface in the late 19th century increased in the Bisagno plain where the buildings soon occupied the whole bottom of the valley. This process affected the lower-medium bottom valley before WW2 and successively the upper part of the valley and the hillside after WW2.

The map of soil consumption (**Fig. 4**) shows the urban growth by altitude, documenting that most of the consumed soil in the valley is included between 0-50 m of altitude in the lower Bisagno Valley, while its upper part is characterised by scarce density of built up surface, in accordance with what is shown in **Fig. 3**.

Fig. 5 shows the modifications of the Bisagno stream riverbed during three centuries. The riverbed has undergone a significant constriction in the channel width in the last 200 years. In 1822, the Bisagno stream occupied the entire alluvial plain from the city walls to the hill of Albaro. Its course was braided with many small channels. There were no buildings along the riverbed, apart from a leper hospital and the village of Borgo Pila. The Bisagno was crossed by some bridges, particularly St. Agata bridge along the ancient Roman route which linked Genoa with the Eastern Riviera and Pila bridge which lead to the city centre through Porta Pila gate (**Fig. 2a**). The name "Pila" is probably an ancient Ligurian word, which indicates the mouth of a stream, providing evidence of the evolution of the alluvial plain towards the actual location from the Bronze Age to present day, a process which is also confirmed by geological and archaeological data. Until 1822 Borgo Pila village was 5 metres higher than today, it was lowered at the end of the 19th century to facilitate the road link with the new road to the centre of Genoa (currently called Via XX Settembre) through Pila bridge. St. Agata bridge was approximately 280 m wide, while Pila bridge crossed a 120 m wide channel.

By 1970 the situation was completely different due to the urban sprawl to the East, which started when the municipalities of the Bisagno Valley were included in the Genoa Municipality (1873). In the same period the railway line from France to Tuscany was built (1868) and Genoa Brignole Station (1905). The Bisagno stream is embanked upstream of the station and completely covered downstream, parallel to the stream are two roads. The plain is completely built up.

The bridge of St. Agata is 70 m wide and only 5 arches remain of the original 28. Ponte Pila does not exist anymore and the riverbed is only 50 metres. The culvert of the Bisagno stream was decided in the 20th century: it was calculated by a group of three engineers on commission by the Genoa Municipality in 1908 (Inglese et al., 1909): using hourly values of precipitation definitely modest, they calculated that the maximum flow rate of Bisagno "could not exceed 500 m^3/s". In 1905 eng. Cannovale from the Municipality of Genoa, estimated more correctly a maximum range of about 1200 m^3/s; the data was based on the rainfall measurements of Prof. Pagani related to the flood of 1822. Unfortunately, they were thought to exaggerate the true rainfall and not taken into account by the pool of engineers during the design phase. This value is very close to the water flow peaks that, in recent years, the stream has reached during its violent floods. Based on the underestimated data of 1908, a large project of urban development was carried out during the fascist period and a large square was built which could celebrate the fascist regime. In 1936 the culvert was finished and in 1938 Mussolini could give a famous speech in Piazza della Vittoria. In the same period in Marassi the Fereggiano stream (the last left tributary of the Bisagno), was embanked first and then covered for more than 1 km from where it joins the Bisagno stream. The Fereggiano stream became sadly famous for the flood of 4th November 2011 when it caused much damage and six fatalities.

In 2014 urbanization is complete, the embankments are characterized by roads, warehouses and factories while the alluvial plain and the sides of the valley are heavily built up with residential buildings. Before Football World Cup of 1990, new culverts were built downstream of the cemetery of Staglieno at Genoa East motorway exit and near the football stadium. St. Agata bridge was repeatedly damaged and almost destroyed during the floods of 1970 and 1992. Of the ancient bridge only two arched remains, located upstream of the final culvert, which is 50 metres wide.

4.1.2. Land use variations in the catchment

The pie charts of **Fig. 6** summarise the land-use of the Bisagno stream basin in 1822, 1970 and 2014.

In 1822 the urban or built up area is only 2% of the entire catchment, while 22% of the area is characterised by cultivation, with many vineyards. The bare land, a category which also includes the pastures of the higher part, occupies 26%, while woodland, mainly managed fruit chestnut orchards, covers 21% of the valley. Due to lack of data for the period under consideration, the land use for 29% of the total surface of the Bisagno basin in the high valley remains unknown. These are mainly uplands over 700 m of elevation which today are scarcely wooded and partly terraced. Current field evidence, in addition to recent studies on the landscape history of the Apennines (Moreno and Cevasco, 2008) suggests that these were open areas used as pastures and cultivations or hayfields spread over terraces near the villages. In 1970 the situation is different, with 12% of urban area and only 17% of cultivated fields, with a remarkable reduction of the vineyards, from 7% in 1822 to 1% in 1970, while the wooded areas cover almost half of the catchment (44%). In 2014 the wood characterises more than half of the entire territory (57%) and the urban part has increased to 15%: there is further reduction of cultivated areas and bare land.

Three sites of the middle-lower Bisagno Valley were chosen as they show different landscape features: St. Agata, which was an ancient village of the lower valley, located just before the terminal culvert, Marassi close to the confluence with a small final tributary (Fereggiano stream) and Staglieno, in the medium part of the main valley,

For each site an investigation of the landscape evolution in the last 3 centuries was carried out. This analysis draws upon recent approaches to topographical art for landscape history (Barrell, 2013; Piana, 2015) consisting in the comparison and integration of a wide range of sources which, in addition to drawings and paintings, includes cartography, archival papers, historical photography and field data. The analysis of the landscape dynamics in three different case studies of the middle-lower stretch of the Bisagno shows a general reduction of the riverbed alongside with the progressive growth of the built-up surface and the reduction of managed fields and orchards, in accordance with the pie charts of **Fig. 6**.

Located less than 2 miles from the coast St. Agata was a village set immediately outside the seventeenth-century walls of Genoa in correspondence of a 280 m bridge on the historical route from Genoa to the Eastern Riviera and Central Italy. A watercolour by Pasquale Garibbo (c. 1825), taken from the hill of Carignano, shows the bridge in its entire width and the wide bed of the Bisagno stream (**Fig. 8.1-A**). The surrounding landscape is characterised by little clusters of buildings, scattered villas and terraces along the lower part of the slopes, providing evidence of the agricultural vocation of this area in the early C19th. If compared to Marassi and Staglieno, the area of St. Agata and the village of St. Fruttuoso behind show a higher density of buildings. The map of **Fig. 7.1-A** focuses on the area near the bridge, documenting the agrarian landscape which is mainly constituted by fields and a little olive orchard in an area called “la piana delle olive” (the plain of the olives). Before the building of Staglieno cemetery here was a mass grave which was partly destroyed during the flood of 1822, and contemporary accounts refer to skeletons and bones swept away by the river (Marcenaro and Repetto, 1970). Today the river bed is considerably narrower as is the bridge which partly collapsed after the floods of 1970 and 1992 and is now replaced by a modern bridge.

The second case study is Marassi, a few miles downstream from Staglieno, where a painting by Pasquale Garibbo (c. 1825) shows the Bisagno in foreground with the river bed bordered by an embankment wall (**Fig. 8.2-A**). The hamlet of Marassi, which is now part of Genoa city centre, consisted of a mixture of villas and farms around the parish church of St. Margherita. The background of the painting shows the bare mountains above Marassi traditionally used as common lands with pastures and wooded areas which were used for wood fuel (Cevasco and Moreno, 2014). Different types of cultivations included vineyards, traditionally kept on high trellis and fruit trees such as the mulberry tree. The almost contemporary map (1822, **Fig. 8.2-A**) depicts a landscape which is mainly rural, with predominance of vineyards, some olive orchards and bare land in the higher part of the side as in the watercolour by Garibbo. In the early 20th century Marassi still had a rural connotation, with cultivated fields and bare mountains clear of vegetation where the forts established in the 18th and 19th century to protect the city of Genoa stand on the top (**Fig. 8.2-B**). As in Sant'Agata, the maps of 1970 and 2014 (**Fig. 7.2-B and C**) and a current picture of the area (**Fig. 8.2-C**) show the changes occurred in the post-war period in terms of built-up surface and loss of agricultural landscape, with most of the territory which is now part of the city of Genoa. Today the church of St. Margherita is hidden behind high buildings to the extent that it is almost invisible from the same point of view of **Fig. 8.2 B and C**. The recent abandonment of traditional pastoral practices in the area resulted in the regrowth of vegetation on the higher part of the area, where only the top of the mountains, due to scarcity of soil and frequent fires is still bare and open. The last case study is Staglieno, where the cemetery of the city of Genoa was built in the mid-19th century. The map of **Fig. 7.3-A** shows the situation in 1822: the southern slope is characterised by extensive vineyards, often mixed with olive trees and bare land along the higher slopes. Bare land areas, called ‘gerbido’, were often common lands used for animal grazing or hay making as in the higher part of the slopes above Staglieno or Marassi. The opposite site of the valley is wooded, however, as shown below, the landscape is clear and various. A painting (Pasquale Domenico Cambiaso, c. 1840) depicts the area of Staglieno while the building of the cemetery of Genoa is taking place (**Fig. 8.3-A**). The territory is open, with bare mountains (common lands) in the background and a mixed landscape of cultivated fields and wooded parts. The painting shows how the left hand side of the Valley, very steep and facing North, is generally open with scattered groups of trees which contemporary documents identify as chestnuts. A photograph of C. 1930 shows the urban growth along the bottom of the valley and the cemetery which covers most of the hill of St. Bartolomeo (**Fig. 8.3-B**). In 1970 the map of **Fig. 7.3-B** provides evidence of the urban growth during the post-war period, when buildings and industries were established where once were cultivated fields, orchards and terraces. The vineyards are replaced by olive orchards, while the woodland of the left side is denser than in the 19th century but its size was reduced to build some factories and new buildings. These buildings are very evident in the current photograph (**Fig. 8.3-C**), which shows the impact of uncontrolled urbanisation in the area. As also shown by the current map (**Fig. 7.3-C**), there are still some managed fields in the area, mostly above the cemetery along the slope which faces South.

4.2. Climate change

Fig. 9 enables us to observe the distribution of the parameters relating to average annual air temperature and the daily rainfall rate over time (almost 200 years), as calculated from the historical data recorded from 1833 by the University of Genoa rain gauge that is located in the ancient city centre at 50 m asl**.** The average annual air temperature varies from a minimum of 14.1 °C, detected in 1956, to a maximum of 17.4 °C in 1865, with a mean value of 15.7 °C and a standard deviation of 0.6 °C. The series shows cyclical fluctuations and a significant increase in time. The rainfall rate, calculated as the ratio between the annual rainfall and the number of rainy days, shows a significant increase over time and a greater dispersion of data in the last 50 years, linked to the similar dispersion of the total annual rainfall (Russo et al., 2000). The test of Mann-Kendall (Mann, 1945) has been applied to them in order to assess the presence of a statistically significant trend. The average annual air temperature has a trend to 99% rising (+ 0.146 °C/y), and also the rainfall rate shows a trend to 99% in increase (+0,277 mm/y). The annual average temperatures shows at least 5 oscillations of higher order and a greater increase between 1910 and 1920, as calculated with Petitt's homogeneity test (Petitt, 1979*)*; the average intensity of daily rainfall shows a steady increase, above all from the 1920s and caused by the decrease of rainy days (Pasquale et al., 1994; Russo et al., 2000), followed by a marked decrease in the last decade. Floods in the Genoa area occur mostly in the autumn, because of the meteorological predisposing factors. However, as shown by the rain historical data, such flooding events occurred all through the year (Faccini et al., 2015a).

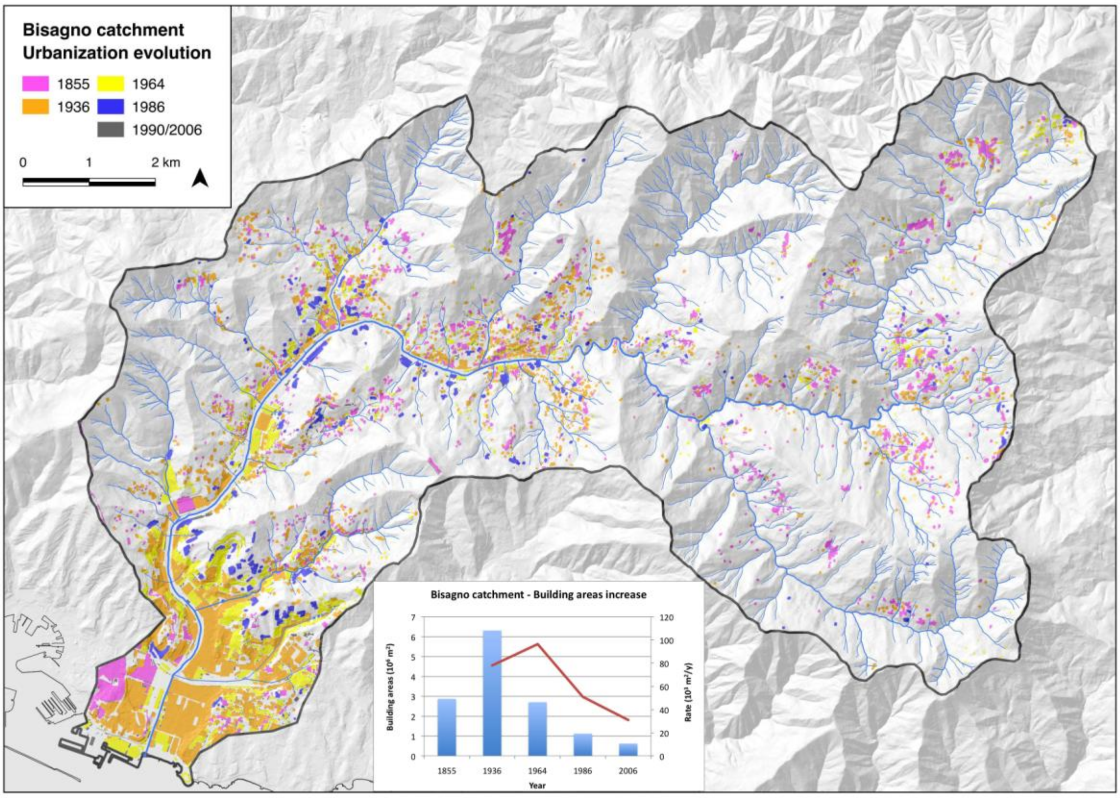


Fig. 3 - Map of the evolution of the urban area. Modified Regione Liguria, 1986 and updated with data from Regione Liguria “Edifici e Costruzioni”, Regional Map scale 1:5,000 – ed. 1990/2006.

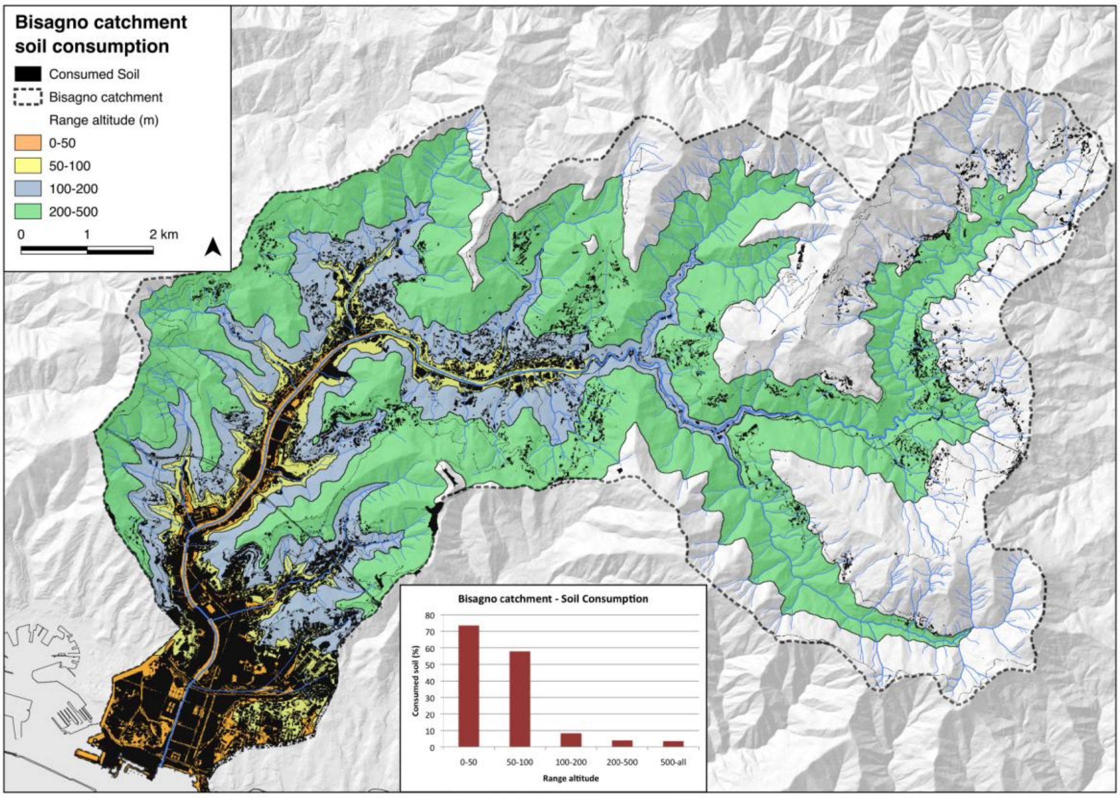


Fig. 4 - Map of the soil consumption by altitude. Data from ISPRA 2015, developed from DTM 2007-5 m resolution Regione Liguria, 2007.

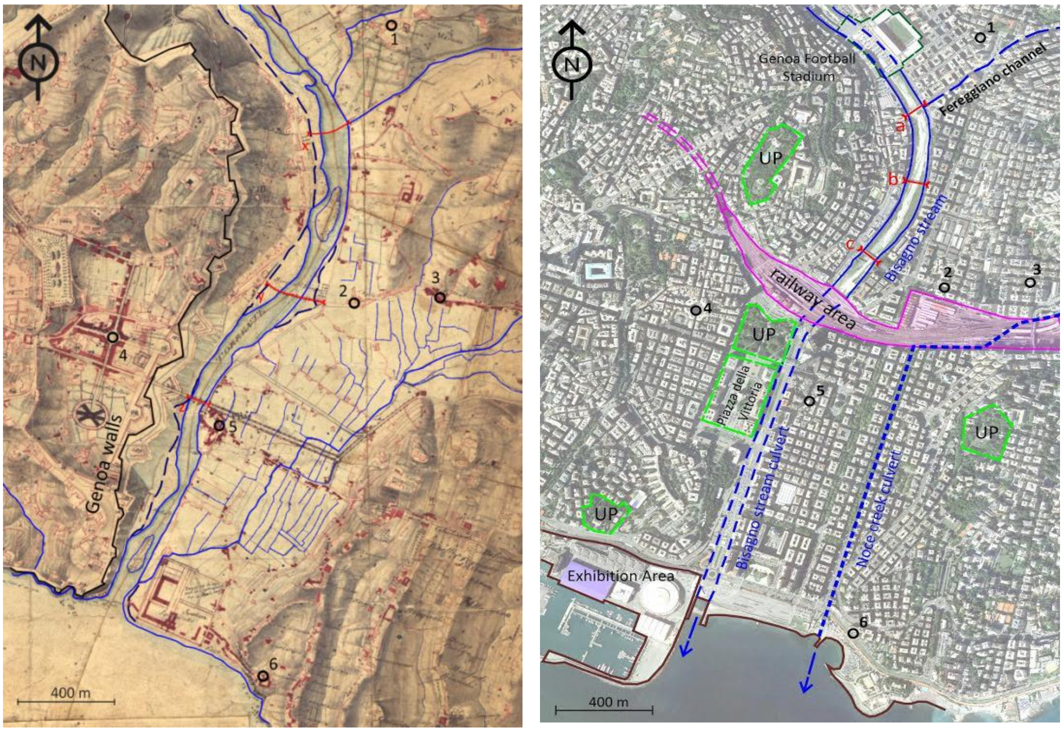


Fig. 5 - River bed changes in the final stretch from 1822 (left) to present day (right). It is possible to observe: the complete urbanisation of the alluvial plain between 1873 and 1950; the coverage of the Bisagno stream (between 1926 and 1936); the coverage of the Fereggiano stream (between 1892 and 1907); the demolition of Ponte Pila bridge for the coverage of the Bisagno and the narrowing of the river bed (from 120 to 50 metres); the narrowing of the river bed at Sant'Agata bridge (from 280 to 70 metres). 1: Convent of the Nuns of Marassi, 2: Convent of S. Agata, 3: Monastery of SS. Giacomo and Filippo, 4: Piazza Colombo, 5: Borgo Pila, Church of St. Zita, 6: Church of St. Pietro, UP: urban parks, x: Monticelli (today Serra) bridge, y: Sant'Agata bridge, z: Pila bridge, a: Serra Bridge, b: Firpo bridge, c: Sant'Agata bridge.

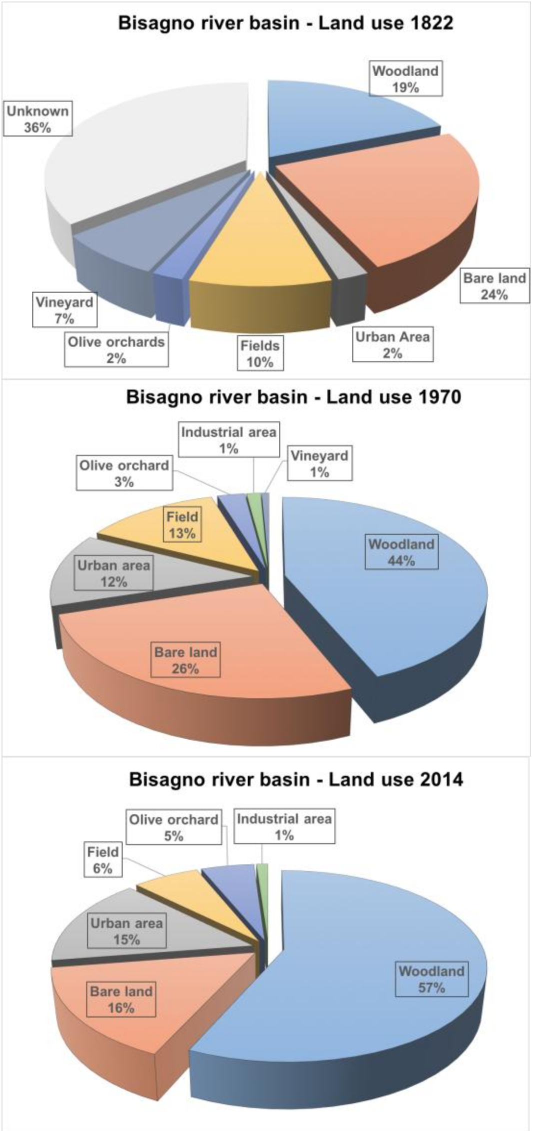


Fig. 6 - Land-use Bisagno catchment in 1822, 1970 and 2014, representative of the three flood events. Data elaborated from Italian Military Geographical Institute, Corpo di Stato Maggiore Sardo (1816-27), Regione Liguria (1970), Regione Liguria (2014).

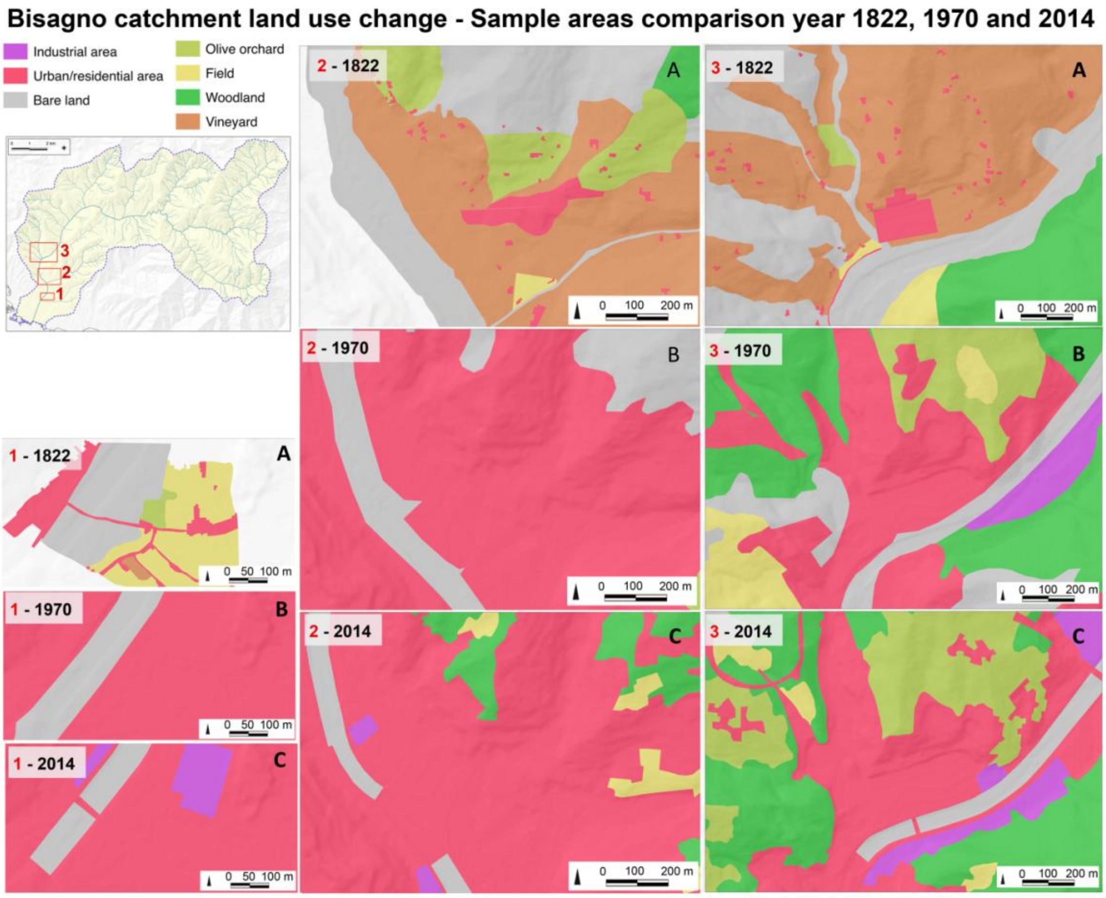
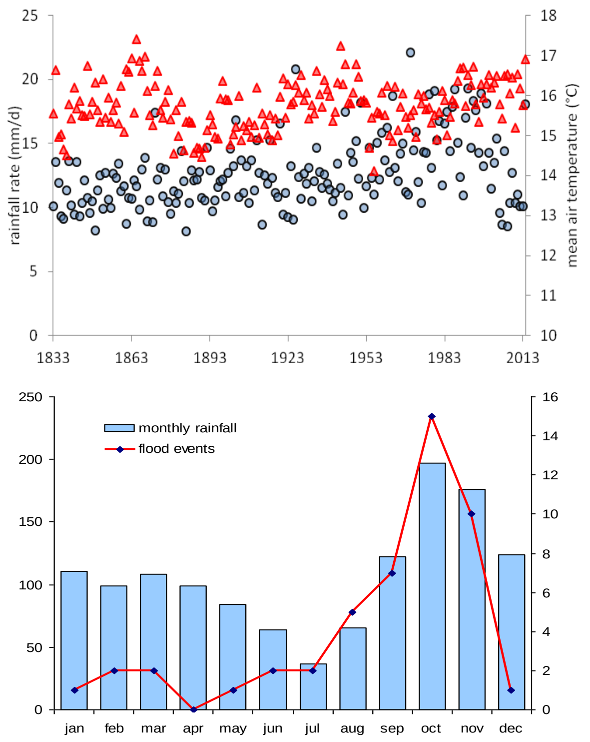


Fig. 7 - Land-use changes in 1822, 1970, 2014 in S.Agata (lower catchment, column 1), Marassi (middle-lower catchment, column 2) and Staglieno (middle catchment, column 3).

Fig. 8: Landscape changes in the final stretch (column 1), Marassi (column 2) and Staglieno (column 3). The sequence of images shows the progressive urban growth and decrease of the rural landscape associated to the building of the terminal coverage of the Bisagno. Images references: 1.A, Luigi Garibbo (Collezione Topografica del Comune di Genova); 1.B, image from www.genovavintage.it; 1.C, Pietro Piana (2014); 2.A, Luigi Garibbo (Collezione Topografica del Comune di Genova); 2.B, image from Lamponi (1982); 2.C, Pietro Piana (2014); 3.A, Pasquale Domenico Cambiaso (Collezione Topografica del Comune di Genova); 3.B, image from www.amicidipontecarrega.it; 3.C Pietro Piana (2014).



	annual rainfall	rainfall rate	mean air temperature	rainy days
tau Kendall	-0.080	0.277	0.146	-0.431
Score	-1214	443 0.05 6	2365	-6876
Var(S)	664268	664270	664221	663988
2 sided p-value	0.111	< 0.0001	0.004	< 0.0001
trend	*no trend*	*positive*	*positive*	*negative*

Fig. 9 - historical record rainfall rate (mean rains by year / average number of rainy days by year) and mean air temperature by year at Genoa University station. Rainfall regime by month with number of flood events by month in Genoa metropolitan area from XVII century to present day (modified from Faccini et al., 2015); Non parametric Mann-Kendall test table (Mann, 1945) data from Genoa-University station, 1833-2104 modified from Faccini et al., 2015a, significance level 95%.

5. Discussion and conclusion

The three flood events examined in this research show differences and similarities. From a meteorological point of view they all occurred in autumn, caused by the same atmospheric conditions. Persistent precipitations with significant peaks linked to convective systems generated in the Gulf of Genoa characterise these events. The cumulated rainfall can reach significant values such as in 1970 (800 mm/24h), while the last flood presents lower levels of precipitation but higher hourly peaks than in 1970, as already reported by Faccini et al., 2015a. The ground effects are similar, with the whole Bisagno alluvial plain submerged and similar water heights despite the landscape changes occurred in the last 189 years. The small differences in some areas are due to the levelling of the hill near Via XX Settembre, the lowering of Borgo Pila and the demolition of the lower walls and in general the total urbanisation of the area. The urban sprawl in the Bisagno catchment is an evident cause of the increased flood risk. The wider part of the alluvial plain at St. Agata is completely built up apart from the river bed which is 70 metres wide immediately before the railway bridge and the final culvert of the Bisagno. The modifications of the river bed consist of the channelling of the stream, the constriction of the discharge-section and the irrational final culvert which made the discharge-sections totally insufficient even for floods of a return time of 20 years The land use variations, the almost total urbanisation of the bottom of the valley and the riverbed modifications are all factors which increase the ground effects and the vulnerability.

The compared analysis of maps and drawings of the Bisagno Valley has shown the land-use changes of the last two centuries, documenting the progressive reduction of cultivated fields and managed orchards, the expansion of wooded areas and the urban growth of the last 50 years. The case study of the flood of 1822 is particularly interesting and it shows the importance of the use of historical documents, both written and iconographical, for the study of past flood events, opening up a fruitful multidisciplinary approach which involves both scientific and humanistic disciplines (Piana et al., 2012; Piana, 2015).

Historical land-use variations, with the total urbanisation of the alluvial plain and the sides of the lower valley reduced the concentration time. On the other hand, the abandonment of the countryside has contrasting effects: from one side there was an increase of woodland in the upper valley with possible positive effects on the development of the stream floods (Hjelmfelti, 1991). However, the abandonment of traditional practices such as river and terraces management has increased sediment transport and slope instability (USDA-NRCS, 2000; Brancucci and Paliaga, 2006; Kang and Marston, 2006; Ward et al., 2009).

The annual average temperature and the rainfall rate show an increasing trend in accordance with recent climate variations (IPCC, 2013). This trend starts between 1910 and 1920 indicating a new climatic phase (Faccini et al., 2015a*)*. Therefore, the data supports the observation that rainfall tends to concentrate in even shorter times with frequent flash floods. Today, global warming and hourly rainfall intensity on a catchment with very short concentration times contribute more effectively to the development of violent floods than in 1822 at the end of the little ice age.

Written and iconographical sources provide evidence of the historical frequency of floods in the Bisagno Valley. Both meteorological and geomorphological factors make the occurrence of floods and intense rainfall events in autumn particularly high. In addition to this, recent climate change and the urbanisation have contributed to increase respectively the hazard and the vulnerability; consequently, the number of short but very intense flood events has grown.

However, the land use variations due to the urbanisation of the area appear to have a greater impact on the floods than climate change.

Since re-establishing the original landscape conditions or managing the short-term climate is impossible, it is necessary to manage the hazard and defend goods and human lives with structural and non-structural measures. In particular, the reduction of sediment transport is of primary importance. The entire basin should be subject to constant hydraulic-forest management with the aim to decrease erosion and the times of concentration and improve the stability of the slopes. The terminal culvert of the Bisagno needs a complete renovation with increased hydraulic section. In addition measures should be developed to ‘re-naturalize’ some parts of the upper Bisagno and, where possible, re-manage the agrarian landscape according to historical land-use information provided by drawings, archival documents and maps. Moreover, any further soil consumption has to be stopped. From a meteorological and hydrological point of view these sudden hazardous weather events should be faced by using “now-casting” in addition to forecasting, and by monitoring in real time the formation of storm cells and the hydrometrical data produced by the weather stations of the catchment. From a civil protection point of view it is necessary to have detailed and diversified Municipality emergency plans for the various areas subjected to flood hazard. From a civil defence point of view flood warnings should be efficient and immediate, while campaigns on self-protection with simulations and practical training should be carried out, improving people’s resilience.

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