Nat. Hazards Earth Syst. Sci. Discuss., 3, 2451–2492, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/2451/2015/
doi:10.5194/nhessd-3-2451-2015

Natural Hazards and Earth System Sciences
Open Access
Discussions

Geo-hydrological hazard and urban development in the Mediterranean area: an example from Genoa City (Italy)

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Received: 3 March 2015 – Accepted: 19 March 2015 – Published: 10 April 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Ligurian area has always suffered from significant geo-hydrological events causing casualties and serious damage. The atmospheric circulation in autumn and winter coupled with landform peculiarities are the main causes this hazard becoming a risk to human life, structures, and infrastructures. Genoa city and the surrounding metropolitan area are commonly subject to heavy rainfall that induces violent flash floods and many shallow landslides. The most recent rainfall events occurred on 9–10 October and 15 November 2014, again causing loss of human lives and widespread damage. A troubling trend since the beginning of the new century, is the recurrence of such events with greater frequency than in the past.

The city of Genoa serves as a very interesting case-study for geo-hydrological risks. Cloudbursts of few hours seem to have a rainfall intensity basically greater than in the past; that causes increase of hydrometric levels of the watercourses that quickly reach alarming values close to the overflowing. This meteorological factor, added to growing urbanization of the valley floors and slopes located north of Genoa, has inevitably produced a general trend of increasing risk for the city. Urbanization is particularly notable for the narrowing process in all cross-sections of Genoa's watercourses, both in the main ones and in the secondary streams that flow directly into the Gulf of Genoa. The narrowing of the sections resulted from the increasing demand for new spaces owing to both industrial development (which started initially at the coastal areas of Genoa), and the growth of the Genoa population. The number of inhabitants grew from fewer than 200 000 at the beginning of the 19th century tool a peak of over 800 000 in the 1970s modifying the water balance of the basins and increasing the geo-hydrological risk in an unacceptable way.

Among the important topics analyzed in this paper are: (i) the meteorological characteristics of these events, (ii) the changes in the rate of daily precipitation, and (iii) the most significant periods of the urban land development determining important changes of the territory above all on the hydrographic network.

1 Introduction

From a geological and geomorphological point of view, the Italian peninsula can be considered a young landscape and a very "fragile" territory (Almagià, 1907; Govi and Turitto, 1997). Geo-hydrological processes are very common in Italy: every year landslides, debris flows and flooding affect different areas and cause severe damage to structures and infrastructures and often claim human lives (Luino, 2005). Archival documents and maps can attest to the widespread areas of the peninsula damaged by this phenomena and their frequency extending from to the Roman Age to present. Table 1 reports some of the notable recent events affecting Italy. Within the Italian peninsula, Genoa city mirrors the impacts of geo-hydrological processes documented as early as 589 BC and characterized by significant events in 1404, 1407, 1414, 1416, 1420, 1452, 1465, 1582, 1746, 1780, 1787, and 1790. Table 2 describes severe events affecting Genoa city since the beginning of the 19th century.

In 7–8 October 1970 Genoa City suffered one of its most catastrophic flood events when an anticyclonic block generated recurring thunderstorm supercells which hit Genoa city and the hinterland between Voltri and the Bisagno Valley from the morning of 7 October to early hours of 9 October resulting in about 900 mm in only 24 h in some locations in the Polcevera valley (catchment "I" in Fig. 1). Most of streams and creek in the Municipality flooded large urbanized areas in a very short time. The most affected area was Genoa center and its western neighborhoods. Serious damage also occurred in the other 20 municipalities in the Genoa province, among which the most affected localities in the hinterland were between the valley of Polcevera and Bisagno streams and Stura and Scrivia Valleys. The fatalities were 44 and the evacuees were over 2000 individuals. More recently, significant damaging hydro-geologic events in Genoa city took place in 2010, 2011 and 2014 (October and November) causing several victims and heavy socio-economic damages.

In this study, the authors examine the circumstances that led to an increased geo-hydrological risk in Genoa city and in its immediate surroundings. By studying historic

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urban development it is noteworthy that population and infrastructures are more and more concentrated around areas exposed to risk. This development took place and continues with a locally unique combination of meteorological, climatic and geographical factors favoring geo-hydrological hazard events. The combination of the increasing climate hazard and growing vulnerable urban conditions have made Genoa emblematic of the recent increase in flooding risk around the Mediterranean area.

2 Geographical settings of Genoa

Since Middle Age, Genoa was a very important maritime republic trading all over the world between the Atlantic Ocean and China. Today, Genoa is home to one of the most important harbors in both Italy and Europe due to its strategic position for trade between Northern Europe and the Mediterranean Sea. It serves as a transit point between the Ligurian Sea and important areas of the Po Valley. Consequently, Genoa is one of the ten metropolitan cities of Italy with an urban area of over 500 km^2 in which 600 000 inhabitants live (from Voltri to Nervi) within the more extensive metropolitan area covering a total amount of 4000 km^2 and hosting a population of 1,5 million of inhabitants distributed in the central sector of the Ligurian coastal arch (CityRailways, 2011).

The area of Genoa is characterized by a complex morphology determined by the Alpine–Apennine system which hosts relief extending from peaks between 1000 and 2000 m, rapidly descending towards the Ligurian Sea. The resulting hydrographic network consists of numerous steep and short watercourses that during floods can attain a concentration time of less than an hour. Ten catchments have an area of more than 4 km^2; moving From W to E, they are Cerusa, Leiro, Branega, S. Pietro, Varenna, Chiaravagna, Polcevera, Bisagno, Sturla and Nervi (Fig. 1). Nine other stream catchments range in area from 1 to 4 km^2. From W to E, they are San Michele, Sant'Antonio, Molinassi, Cantarena, San Pietro, Priaruggia, Castagna, Bagnara and Murcarolo. Finally, there are about 10 other catchment with less than 1 km^2 areas that flow directly

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into the old port which underlies the original historic amphitheater of Genoa. These small streams define floodplains only within the terminal sector near the estuary area. Of these catchments, the two most important are: (1) the Polcevera Stream which is the largest and the most populous basin (140 km^2) located West of the historic amphitheater, and (2) Bisagno Stream (95 km^2) flowing immediately on the East. Important urban areas are also located in the plain coastal basins of Leiro Stream at Voltri (27 km^2) of Varenna Stream at Pegli (22 km^2) and Chiaravagna Stream at Sestri Ponente (11 km^2).

Following a practice widespread in in Liguria, many of these Genoan river beds are culverted sometimes for long stretches, especially towards the mouth. On these new narrow spaces roads have been developed, parking areas and in some cases even homes have been realized.

The coastal climate is characterized by short and temperate winters (average January 8 °C), temperate summers (average July 24 °C) and widespread rainfall in all seasons with the maximum occurring in autumn (150–200 mm in October) and an annual average ranging from 1100 to 1300 mm (Table 3) and an annual average temperature around 16 °C (Cortemiglia, 2006). Overall, it is a humid temperate climate with limited dry season restricted to one or two summer months.

From the meteorological point of view, the Genoa Gulf is characterized by a typical circulation referred to as the Genoa Low which is also known as a Ligurian Depression ("Genua Tief" for Central Alps). It is a cyclone that forms or intensifies from a pre-existing cyclone to the south of the Alps over the Gulf of Genoa, Ligurian Sea which then moves over the Po Valley (Sáez de Cámara et al., 2011). A secondary depression linked to the arrival of the Atlantic perturbations behind the Alps is formed on the 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 cold air masses over the Po Plain and behind the mountainous Ligurian arc are redirected by the Genoa Low toward the center of the Gulf, where they arrive through the

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mountain passes included the ones between Savona and Genoa, reaching modest altitudes, between 450 and 600 m a.s.l. (Fig. 2). This typical circulation is responsible for the large amounts of rainfalls distributed over the region surrounding the Ligurian Sea (Sacchini et al., 2012). Similar air masses contrasts are responsible for triggering of thunderstorm supercells between the end of summer and autumn.

The morphology of the Ligurian Gulf and the orographic barrier also contribute to rainy events which may be very intense especially at the end of the summer or autumn when Atlantic perturbations may be blocked by the European continental anticyclone (Bossolasco et al., 1971; Caredio et al., 1998; Cevasco et al., 2010).

Of particular importance during times when hot humid flows coming from Mediterranean Sea are associated with pre-frontal situations preceding the arrival of Atlantic perturbations, are the great contrasts between the air mass stationed over the warm Mediterranean basin and the air masses moving from the Po basin. The convergence of these air masses triggers the development of storm supercells (Silvestro et al., 2012). These supercells have recently affected different locations over the Ligurian Gulf (Faccini et al., 2012) causing flash floods arising from rainfall intensities of over 500 mm 6 h^{-1} or 180 mm h^{-1}. The most recent of these events occurred on November 2014 in Genoa. These phenomena have been recurring and particularly violent in recent years, especially the last two events that took place in Varazze and Genoa-Sestri Ponente in 2010 (Faccini et al., 2014), Cinqueterre (Buzzi et al., 2013) and Genoa-Bisagno Valley in 2011 (Brandolini et al., 2012) and 2014.

3 Previous research in the study area and methodological approach

Flood risk being the result of two factors, hazard and vulnerability, we analyzed them both considering: (i) floods from the point of view of the increase of such events in the territory on the basis of observed climatic variations and (ii) the land vulnerability from the point of view of the territory modifications, above all increasing urbanization assessed by historical comparison of ancient and recent maps. The present study de-

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pends greatly on historical documents; the authors incorporated research on past geo-hydrological events from both published and unpublished reports pertaining to the local area and undertook analysis of historic maps and urban studies to assess interaction with urban changes.

A number of authors have studied geo-hydrological hazard and its recent increase by analyzing meteorological and climate factors and their interaction with the complex orography of Genoa and surrounding localities (Pasquale et al., 1994; Russo and Sacchini, 1994; Russo et al., 2000; Cevasco et al., 2010; Sacchini et al., 2012; Brandolini et al., 2012; Faccini et al., 2014). Meteorological factors were studied by analyzing the atmospheric circulation generating heavy rainfalls and more recently initiating flash floods through many coastal localities. Climate factors were studied by analyzing data from a dataset composed of over 180 years of raingauge station measurements at University of Genoa. The data were used to compile the annual amount of precipitation and annual total of rainy days (Cortemiglia, 2002). These data let us analyze the trend of daily precipitation rate (mm days^{-1}) and, particularly, the changes in precipitation during recent years.

The time evolution of the parameters was analyzed using the Standardized Anomaly Index (SAI), which expresses the anomaly of the parameter examined compared to the mean value of the reference period (Coles, 2001). The index was calculated on annual basis by averaging the standardized anomalies for all parameters analyzed: precipitation, temperature, rainy days and rainfall rate.

The annual average temperature shows a clear growth according to recent climate variations (Fig. 3). The total annual rainfall shows a slight decrease. A slight negative trend for the number of rainy days per year has also been observed. They have decreased from almost 90 per year at the beginning of 1800s to the current nearly 80 per year. Analyzing the historical trend (almost 200 years) of the precipitation rate (annual rainfall/number of rainy days) it is possible to notice a significant increasing trend according to the study by Pasquale et al. (1994) and Russo et al. (2000). The months of October and November, when flood events most frequently occur, showing an increasing trend in the monthly rainfall amount. It is noteworthy that when important autumnal floods occur, it is associated with a rainfall total over a few hours greater than the sum of the monthly rainfall that commonly falls in the autumn months. In very recent years, in opposition to the trend of the last century, it has been observed a slight increase of the rainy days number and consequently a decrease in the annual precipitation rate: in the year it is often raining with moderate intensity but rarely there are very intense thunderstorms. This seems related to a recent decrease in the number of Genoa Low on the city's gulf (Anagnostopoulou et al., 2006).

This study utilizes maps produced after the annexation of the Republic of Genoa to the Kingdom of Savoy (1815). During the period 1815–1830 they it was in use a so-called map "Gran Carta degli Stati Sardi di Terraferma" at 1 : 50 000 scale, surveyed and produced by Military Corps. For all the areas analyzed, this historic map has been compared with maps produced afterwards by the Italian Military Geographic Institute IGMI (after Italian unification, 1861): in particular the maps of 1878, 1907, 1923, 1934 and 1939 were used. Finally the recent Regional Technical Cartography (CTR by Regione Liguria Administration) mapped in 1980, 1994 and 2007 obtained by aerial snapshots and the Google Earth satellite have permitted the comparisons of recent development.

Similarly, historical sources constituted important documents in the reconstruction of the areas exposed to the risks due to either the frequency or magnitude of hydrogeological events (Glade et al., 2001; Luino et al., 2002; Tropeano and Turconi, 2004; Llasat et al., 2005; Porfido et al., 2009). Studies about past geo-hydrological events in Italy carried out by Consiglio Nazionale delle Ricerche (CNR, National Research Council) and by Servizio Idrografico e Mareografico Nazionale (SIMN, National Hydrographic and Seagraphic Service) (Cati, 1970; Cipolla et al., 1993, 1999; Tropeano et al., 1995) have been used to gather the most relevant information for the study area.

4 Genoan geo-hydrological disasters from 1970 to present

As mentioned earlier, Liguria in general and Genoa in particular have been subjected to flood events due to the predisposing conditions of climate and urban morphology. Considering only Genoa city, in the last forty-five years, ten important events took place: six of them caused very severe damage and casualties (Table 4). Five of the six disastrous events resulted from similar meteorological circumstances. The weather conditions were characterized by a blocking anticyclone to east and a deep trough to west (Bossolasco et al., 1971; Cati, 1970) producing pre-frontal storms on the warm branch of the perturbation.

The 1970 event in Genoa City was also one of the most dramatic. On 7 October, pre-frontal storms struck the western side of the city, then the center and the hinterland the day after. The storms affected Voltri and Genoa before the arrival of the cold front. The heavy rainfall lasted more than 24 h with highs in Polcevera Valley. At Bolzaneto rain-gauge over 950 mm of rainfall in 24 h was measured. Over the city center and the Bisagno Valley, 400 mm in 24 h was recorded. Cerusa, Leira, Varenna, Chiaravagna and Bisagno stream channels overflowed submerging the city center. In absence of discharge gauge stations, the maximum flow rate of the Bisagno Stream was estimated by Cati (1971), near the railway station of Genova Brignole, as 950 $m^3 s^{-1}$ (12 $m^3 s^{-1} km^{-2}$). The flow rate ensured by the Bisagno coverage was approximately 700 $m^3 s^{-1}$. The maximum flow rate of the Polcevera Stream, which barely remained within its banks, was estimated at 1656 $m^3 s^{-1}$ (12 $m^3 s^{-1} km^{-2}$).

On 27 September 1992, under meteorological circumstances like those of the 1970 event resulted in rainfall for 14 h with a cumulated rainfall of about 400 mm. Sturla and Bisagno streams overflowed. The maximum estimated discharge of the Bisagno Stream in 1992 (Conti et al., 1994) was about 700 $m^3 s^{-1}$ at Castelfidardo bridge, located just upstream of the culverted stretch near the railway (7.5 $m^3 s^{-1} km^{-2}$). The Bisagno overflowed upstream the coverage under the Genoa Brignole railway station flooding the historic district of Borgo Incrociati, the center city around the neighbor-

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hood of the Genoa Brignole railway station and the district called Foce (means steam "mouth"). Fortunately, as soon as the stream overflowed, the rain stopped and damage was limited. Additionally, there were some fatalities near the mouth of the smaller adjacent Sturla Creek that overflowed a few hours before (Fig. 1, catchment "o").

In 1993 on 23 September, with similar weather conditions a new flood event occurred with values up to 350 mm in 5 h near Pegli (in Genoa over 300 mm of rain in 15 h were recorded) which provoked the overflowing of Leira Stream in Voltri, Varenna Stream in Pegli, S. Pietro Stream in Genova-Prà and tributaries of the Polcevera Stream. Some criticalities affected the center of Genoa, in the historic amphitheater, where several streams, totally or partially culverted, overflowed with a lot of damage, in particular the underpass under construction in Piazza Caricamento Square (near the Old Port and the current waterfront drawn by the famous architect Renzo Piano, who is from Genoa). The rainfall event regarded some basins not provided by hydrometric rain-gauge stations: so it is not possible to comment on the hydrological response of the watercourses.

During the severe event occurred on 4 October in 2010, the Mt. Gazzo rain-gauge station (Genoa-Sestri Ponente) measured a hourly peak that exceeded 120 mm and the cumulative rainfall was more than 400 mm over 6 h: the Chiaravagna Stream overflowed and severely damaged the area near its mouth (Fig. 1 catchment "k"). Also the small adjacent Cantarena Creek flooded the western part of Sestri Ponente town.

During the event of 4 November, in 2011, under the same meteorological configuration, the Vicomorasso rain-gauge station (North Genoa) measured a rainy peak of nearly 180 mm $1\,h^{-1}$ and over 500 mm in 6 h. This event struck in particular the Bisagno Valley and the catchment of Fereggiano creek, one of its small left tributaries: more than 500 mm $6\,h^{-1}$ of water fell in such basin, with a peak of about 160 mm $1\,h^{-1}$. The creek violently overflowed together with other small creeks just upstream the Molassana area. The Bisagno Stream, on the contrary, overflowed upstream the beginning of the artificial cover, flooding the center of Genoa. The peak discharge was estimated of about 800 $m^3\,s^{-1}$ (8.7 $m^3\,s^{-1}\,km^{-2}$).

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The most recent disastrous flood event of Genoa occurred on 9–10 October 2014, with a rainfall mechanism linked to the repeated "self-regenerating" thunderstorms, stationing for several hours over the city, which started up in the warm pre-frontal sector of the perturbation. Between 6.00 a.m. on 9 October and 12.00 a.m. on 10 October on the basin of the river Bisagno were recorded some peaks of rain up to almost 140 mm h^{-1} and heaps of more than 550 mm 24 h^{-1}, which resulted in a rapid increase in the level of all streams and subsequent flooding in the final stretch of the Bisagno stream. The maximum discharge estimated by flood markers was more than 800 $m^3 s^{-1}$. In Genoa city also Sturla, Fereggiano, Noce and Torbella Creeks overflowed: so neighborhoods of West-center and East-center were inundated.

Other geo-hydrological events occurred in Genoa since 1977 as well as the most significant in the Genoan metropolitan area are shown in Table 5.

Comparing the storm events of 1970, 1992, 1993, 2010, 2011 and 2014 that hit Genoa city with extensive flooding damage and casualties in the city, it could be assumed that rainfall is becoming more concentrated in time (few hours). From the meteorological point of view these events are all related to a block action and a prefrontal flow in the warm sector, but with the trigger of very narrow supercells storm that determined extremely intense and localized raining able to generate flash floods (Fig. 2). Figure 4 shows the rainfall intensity (mm h^{-1}) in time (hours) of the events that have struck Genoa in 1970, 1992, 1993, 2010, and 2011 and 2014 and the statistics of the rainfall peaks through 1, 3, 6, 12, 24 h directly in the Bisagno basin (Pontecarrega-Gavette raingauges). It is possible to note that rainfall intensity is higher in the events of the Third Millennium, while the same rainfall amount was attained in a shorter time. The same consideration can be deduced from the trend of the annual maximum rainfall depth values in the station of Pontecarrega, located in the central sector of the Bisagno Valley: the cumulative rainfall during 1, 3 and 6 h is higher in the event of 2011 and 2014 (an exceptional event with return period greater than 200 years) than the 1970 flood, which was more severe (return period about 50 years) over a span of 12 h.

During these severe past events, 400 mm was recorded or exceeded in shorter time periods. More than 400 mm w.e.re recorded in 24 h, during October 1970, approximately the same value, but in 15 h in September 1992, up to more than 500 mm in only 8 h in October 2011 and 2014.

Figure 5 shows the trends of hyetograph and hydrograph related to events from 1970 to 2011 where we can observe the rapid response between the impulse rainfall and the flood (3 h for Bisagno Stream, 4 h for Polcevera Stream).

The high intensity within periods of long duration rainfall caused many problems for the basins larger than 10 km^2. In the Bisagno and Polcevera basins a rather complicated response on the ground of the hydrographic network was observed, characterized by multiple bursts distributed in different temporal periods, presumably with different temporal influence on the sub-basins.

The high intensity of precipitations of short duration and the sewage system created problems especially in the basins with areas lesser than 10 km^2 (e.g. Fereggiano Creek, and neighboring Noce and Rovare creeks), causing flash-flood phenomena with practically instantaneous time of response.

5 Genoan urban development

Analyzing many maps of the Republican Age (from 10th century to 1815) we can observe that Genoan urban development was limited to the hills surrounding the ancient natural harbor which is the actual historical center. Connecting valleys and areas further inland were populated only by small villages and narrow trade routes while the city, surrounded by walls for military defense, was open only to the sea. A number of small channeled streams flow towards the harbor and there is historical information indicating some hydrological problems (during the years of 1222 and 1407 in particular). Since the annexation of the Republic of Genoa to the Kingdom of Savoy (1815) new roads were built triggering urbanization of surrounding valleys where the majority of citizens live nowadays.

As examples valid for the whole Ligurian context, the urban growths of Genoa-Bisagno Valley, Genoa-Polcevera Valley and of Genoa Sestri Ponente (2010 flood) are shown in Figs. 6–8. Using old maps it is possible to observe the gradual occupation of the fluvial plain, which started in the 19th century and which was completed after the World War II. The building numbers have increased from 65 000 in 1861 to 305 000 today, while the population in the area of the present Genoa Municipality rose from about 240 000 inhabitants (1861) to a maximum of 850 000 in the early 1970s (Fig. 9). The urbanization of the hills still continued in the 1980s and 1990s after the full urbanization of the floodplain.

The geo-hydrological problems related to the Genoa urban development can be grouped into four main geomorphological-environmental issues:

1. modifications in land-use changed from predominantly agricultural to urbanized (Fig. 9), particularly with the complete urbanization of the plain and the covering of the watercourses (Disse and Engel, 2001; Nirupama and Simonovic, 2007; Luino et al., 2012; Luino, 2014);

2. variations in the flood channel width of the streams with narrowing of the effective discharge section (Corominas and Alonso, 1990; Baioni, 2011; Faccini et al., 2014);

3. progradation of the coastal plain towards the sea with new embankments and urbanization (Petrucci et al., 2012; Kellens et al., 2013);

4. total diversion of the natural riverbed and concentration of surface runoff in new more restricted areas.

In order to exemplify the anthropic changes related to these four issues (see Fig. 1 for location), the maps of the Gran Carta degli Stati Sardi di Terraferma (1816–1830) have been used comparing them with the current state shown by the maps of Google Earth for: (1) the end stretch of the Bisagno Stream, (2) the town of Sestri Ponente on the Chiaravagna Stream, (3) the final stretch of the Polcevera Stream and (4) its valley stretch near Bolzaneto. These lands were autonomous municipalities in the past and then they were incorporated in the Genoa municipality starting from 1873 (end stretch of the Bisagno stream) and in 1926 (Polcevera Valley, Sestri Ponente and the rest of the present municipality) under the fascist dictatorship.

5.1 Variations about the land-use

The Bisagno basin can be considered as a "key-watershed" for the analysis of changes in land use. Figure 6 shows the areas on the Bisagno stream valley floors but similar patterns of change could be made for all the coastal plains of the municipality of Genoa, from Voltri to Nervi, and also for all the major coastal towns of Liguria. The whole final stretch of Bisagno Stream is culverted downstream parallel to the railway (Fig. 10); the length of the main watercourse in the plain area is about 12 km (24 km in total), of which 0.3 km totally culverted just on the flank of the Genoa football stadium and 1.4 km of final coverage between the railway and the mouth. While the land-use in the basin shows a relevant decrease of the wooden areas in the last two centuries and a progressive increase of the urbanized surfaces, particularly near the mouth (Fig. 9); the growth of the Genoan population occurred when the urban pressure began in the plans of streams: just the Bisagno plain, unfortunately, is probably one of the worst examples at a Mediterranean level.

The Polcevera Valley (Fig. 8) and particularly its final stretch and the district of Sestri Ponente (Fig. 7) have suffered the gradual and complete urbanization of the valley floors; first in the middle of the nineteenth century, when such strategic areas located near the sea were the subject of the first industrial settlements that allowed the Italian industrial development; then the further extension pursued with residential building, public housing, facilities and road infrastructures. Among the Polcevera Valley and Sestri Ponente (Fig. 8 westward Polcevera stream) it is possible to observe an area still occupied by a steelworks built in the 50's over a large beach area and, now, partially abandoned and demolished.

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5.2 Modifications in the width of riverbed

The Bisagno riverbed has undergone a significant constriction in channel width in the last two hundred years. Comparing a 1830 map and a recent aerial photograph, it is possible to note that the St. Agata medieval bridge, built along the ancient Roman road, changed approximately from 280 m wide to the actual 70 m (Fig. 6). The bridge was repeatedly damaged and almost destroyed during the floods of 1970 and 1992. Near the present city center, the so-called Pila bridge crossed a 120 m wide channel at the beginning of the nineteenth century is now constricted by the complete covering of the Bisagno stream which took place in the 1930s with an actual width of about 50 m, while at the mouth called Foce the width was reduced from about 200 (early nineteenth century) to the present 50 m. Similarly in the Polcevera Valley, the bridge of Cornigliano, on the Via Aurelia di Ponente, passed over a channel of about 150 m in width at the beginning of the nineteenth century but has been reduced at present to a width of 75 m (Fig. 8).

5.3 The progradation of the coastal line to the sea

In Fig. 8 at the mouth of the Polcevera, we can observe the progradation of the coastal line to the sea, totally due to the filling of the seaside to create flat surfaces for industrial activities. It is possible to notice the total banking of the stream, the new roads on the banks built in the 1990s and the commercial center of the Fiumara, close the stream's mouth, built in the 2000's in place of abandoned steel and engineering industries. On the left bank, moreover, the works related to the Genoa Sampierdarena container harbour, the piers and the breakwater dam.

With respect to Sestri Ponente (Fig. 7), around 11th century the sea flew in the Chiaravagna valley through the little San Lorenzo Gulf and a little harbour lay at the base of the hills. In 1238 the sea reached the root of the present marine terrace, while in the 17th century the sea touched the main Church of the "Assunta", whose portal is, in effect, facing upstream. The church was built on the seaside and it is 1 km far from the

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sea nowadays. These notes show that the area was interested by progradation of the alluvial plain since historical times. In addition to this natural trend anthropogenic factors contributed to the enlargement of the plan. In the second half of the 19th century, a seashore railway was built which facilitated the plane becoming completely urbanized in the 20th century. Additionally, the shipyards which were developed mainly in the 1930's and the Genoa airport "Cristoforo Colombo" constructed in the 1960's resulted in the final separation of the town from the sea by cyclopic embankments and the curving of the streams. Consequently, historical floods occurred mainly in the 20th century with the historical analysis identifying some major floods linked to strong meteorological events at Sestri Ponente in 1900, 1906, 1911, 1929, 1945, 1951, 1970, 1977, 1993 and 2010.

5.4 The riverbed diversion

Urbanization in this area included riverbed diversion. Inland at Bolzaneto, the passage of the railroad Genoa-Turin (1854) entailed the cutting of a Polcevera's meander (Fig. 11).

A new riverbed was excavated and displaced about 300 m towards the west with a narrower discharge section about 60 m less than the original situation. The abandoned meander has been filled in with digging debris of the railway tunnels: such a filled riverbed has been used as a preferential settlement for Bolzaneto district expansion (once an autonomous municipality).

In Sestri Ponente (Fig. 7) we can observe the Ruscarolo Stream diversion. It does not flow naturally into its urbanized beach anymore, but is displaced 400 m parallel to the seashore. This was accomplished by artificially diverting the Ruscarolo into the Chiaravagna Stream without channel adjustment to accommodate the new discharge.

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6 Discussion and conclusion

Considering the historical analysis it appears that the frequency of significant damaging events has become intensified with more recent times. In Genoa city, Their recurrence has passed from two events per fifty years, during the span 1800–1950, to six events between 1951–2000, to four events during the first 14 years of the 21st Century (Fig. 12).

The increase of precipitation rate with the average temperatures are confirmed by data of other worldwide recording stations which demonstrate the global warming of the planet (IPCC, 2013). The recent slowdown in the growth of an upward trend in the precipitation rate (Fig. 3d) appears due to the decrease in annual rainfall (Fig. 3a), but not in the number of rainy days (Fig. 3b). This change may be a consequence of more recent climatic variations, in particular the decrease of the number of Genoa Low events due to the tropical air expansion towards north, which causes less annual rainfall, but not a decrease in the rainy days (Anagnostopoulou et al., 2006).

The rainfall amount of the flash floods generated by local supercells are unrivaled in the Mediterranean area: 948 mm 24 h^{-1} in Genoa-Bolzaneto in the Polcevera valley, north-westward the center nell' alluvione del 7–8 October 1970, and 181 mm 1 h^{-1} at Vicomorasso raingauge, in the Genoa inland nell'alluvione del 4 novembre 2011 (Fig. 13).

In the Liguria central sector, there are special weather-orographic conditions that accentuate the effects of global warming, so that the same effects on the ground occur in ever shorter time, as a response to the climate change. An evident reduction in time necessary to reach the same precipitation values and the same effects on the ground which pass from 24 h in 1970 to 14 h in 1992, to 5–6 h in the last storm events; suggests there can be more flash floods with continued climatic warming (Table 5, Fig. 4).

Damages for those flash floods, evaluated starting from the 1953 event just considering Genoa city, have been increasing from 50 million liras (Tropeano et al., 1993) to over 250 millions euros of the most recent floods. These are very high figures taking

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in account that those events, because of their meteorological and orographical conditions, usually hit with maximum intensity only a very narrow strip of land involving some tens of square kilometers.

The increased risk posed by the greater frequency of intense rainfall events may be evaluated not only in terms of casualties, but also in terms of goods potentially exposed to the floods. Using the historical maps of the last two centuries it is possible to note a remarkable increase in urbanization in the alluvial plains along the riverbeds, a general narrowing of the watercourses flow section, some examples of original riverbeds subsequently artificially diverted, and a general progradation towards the seaside of the coastal plain due to human embankments for further urbanization. In many places these situations create very high vulnerability compared to historic conditions. Additionally, the progressive urbanization of floodplains and hills, accompanied by a marked increase in population and infrastructures leading to the reduction of flow sections, results in a prominent reduction also in the times of concentration together with the greater vulnerability.

Consequently, the geo-hydrological risks, determined by the result of hazard and vulnerability, are progressively raised because of climatic change influencing an existing high level of hazard and continuing urban development creating greater vulnerability. The resulting increase in damage costs and the number of deaths can hardly be considered an acceptable level of risk (Nielsen et al., 1994). As documented by this paper, Genoa City and surrounding communities have experienced significant geo-hydrological events over a long period of time. The meteorological, climatic, and geographical conditions responsible for these events will continue for the foreseeable future and may even become more severe. This means we can define the hazard potential but can do little to change this risk component. Vulnerability as represented by the urban development potentially at risk from a future event is the only means for avoiding a continuing upward spiral of disastrous impacts. This is similar to the situation present in New Orleans, Louisiana (USA) after Hurricane Katrina where governmental actions had resulted in promoting development in potentially hazardous areas and paying too little attention to the planning in order to limit local vulnerabilities (Burbey, 2006).

Reducing risk posed by future geo-hydrological events requires both the knowledge of the hazard but also taking actions to use that knowledge (De Graff et al., 2015). Future development needs to incorporate actions that maintain the natural river channel, limit further coastline progradation, avoid constricting the width of the river channel, and counter the effect of more impervious urban surfaces. The intent would be to reduce vulnerability by increasing the community resilience to future hazardous events. Resilience being- *the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse effects* (Committee on Increasing National Resilience to Hazards and Disasters, 2012). In this framework, future development could both limit adding to existing vulnerability and, potentially, reduce it as developmental opportunities provide for replacement and modification of urban features contributing to existing vulnerability. This is obviously a long-term effort involving both governmental and private institutions who will be depending on the knowledge gained from the study of past geo-hydrologic events to properly design, site, and alter urban development in Genoa City. Increasing resilience will result in decreasing vulnerability, and in turn, reduce risk from future geo-hydrological events.

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Table 1. Italian severe geo-hydrological processes in the last 20 years.

Day(s) Month Year	Region/Area	Geo-Hydrological process	Damage	Fatalities (> 5)
5–6 Nov 1994	Piedmont/Tanaro basin and Langhe Hills	Large floods of Tanaro River and some tributaries: thousand of landslides on the slopes	More than 100 urban areas flooded. 2000 homeless, over 10 billion US $ of damage in all	69
13 Mar 1995	Eastern Sicily/Area of Acireale and Giarre towns	Flash flood	Flood of some torrents: highway, roads and railways interrupted	6
19 Jun 1996	Tuscany/Versilia	Flash flood	Intense rainfall: 478 mm 13 h^{-1} with a peak of 157 mm 1 h^{-1} (Caredio et al., 1998). Over 450 soil slips on the slopes. Violent flash flood hit some villages: mud and debris up to 4–5 m. 1500 homeless	14
14 Oct 1996	Calabria/Crotone	Flash flood	Flood of the Crotone town. Thousands of homeless: 358 firms damaged for 65 millions of euro	6
5 May 1998	Campania/towns of Sarno, Bracigliano, Quindici, Episcopio, Siano	Mudflows hit some little towns	Heavy rainfalls (about 140 mm 72 h^{-1}) triggered over three billion tons of such pyroclastic material slid on urbanized areas. 1550 homeless, 200 houses destroyed only on Sarno town. Damage for more than 500 millions of euro	159
9–10 Sep 2000	Calabria/Soverato	Flash flood	441 mm of rain caused a rapid discharge increasing of a little creek called "Fiumara Beltrame". A camping was inundated with victims	14
15–16 Oct 2000	Piedmont and Aosta Valley	Debris flows and large floods	Some days of rainfalls (more than 700 mm): floods along main watercourses and debris flows on the alluvial fans: severe damage to structures and infrastructures with victims and 40.000 evacuated	34
6 Nov 2000 and 23	Liguria/Imperia and Savona provinces	Floods	Flood and overflowing of some streams	7
1 Oct 2009	Eastern Sicily/Messina province	Soil slips and mudflows hit urbanized areas	Heavy rainfall (52 mm 30 min^{-1}, 145 mm 6 h^{-1}) created instability processes: many victims into the houses and cars	36
3 Mar 2011	Mare/Sant'Elpidio a mare and Ascoli Piceno; Romagna/Cervia	Flash floods of some streams	Intense rainfall and quick growth of some streams: four people drowned in their car	5
25 Oct 2011	Liguria/Spezia-Cinque Terre	Soil slips and flash flood involved small villages on the coast	520 mm in less than 6 h: fast discharge increasing of many streams and little creeks	12
4 Nov 2011	Liguria/Genoa	Flash flood in urbanized areas	500 mm in 5 h provoked flash floods of all watercourses narrowed into the buildings and often covered	6
12 Nov 2012	Tuscany/Maremma	Floods	Some streams flood urbanized areas	6
18 Nov 2013	Sardinia/Olbia	Flash flood in urbanized areas	Intense rainfall (175,2 mm) caused a rapid increase of the water levels in the channels: large areas inundated till the second floor of the houses	18

Table 2. Main geo-hydrological events involving Genoa city and neighboring areas from the 19th century to 1970.

Day(s) Month Year	Area/town	Geo-Hydrological process	Damage	Source
26 Oct 1822		Regular flood	15 h of violent rainfall with more than 760 mm of cumulated rainfall. Flood of many streams: destroyed two bridges on the Bisagno Stream. Mud and water up to the second floor of the houses. According to sources 812 mm of cumulated rainfall.	Gazzetta Piemontese, 2 Nov 1822; Gazzetta di Genova, 26 Oct 1822; Pagani (1822); Cati (1971)
1825	Passo Cento Croci/Vara Valley	?	Floods and landslides.	Almagià (1907)
27 Aug 1842	Genova	Flash flood	Violent rainfall (247 mm in less than 10 hs) hit the slopes behind the city: flood of some streams. Mud and water up to the second floor of the houses.	Cati (1971)
13 Oct 1853	Sestri Levante Cinqueterre	?	Gromolo Creek, Vara and Magra Streams	Gazzetta del Popolo, 15 Oct 1853
1869	Lemeglio	?	Floods and landslides in the Eastern Riviera	Almagià (1907)
17 Oct 1872	Western Riviera, then Bisagno and Scrivia Valley	Regular flood	Floods and landslides. Overflowings of the Bisagno and Scrivia Streams	Almagià (1907); Tropeano (1993)
1878	Scrivia Valley	Regular flood	Floods and landslides	Almagià (1907)
1885	Deiva M.	?	Floods and landslides	Almagià (1907)
8 Oct 1892	Genoa, Bisagno Valley	Flash flood	Bisagno Streams floods at Molassana and Foce. The only measure is 181.3 mm 24 h^{-1} at Genoa University, in the center city, westward Bisagno Valley. Probably the event involved a very narrow area.	Cati (1971); Russo and Sacchini (1994); Tropeano et al. (1995)
1905	Scrivia Valley	Regular flood	Floods and landslides at Vobbia and Isola del Cantone	Almagià (1907)
1907	Genoa	Regular flood	Bisagno Streams floods at Molassana and Foce. 246 mm/24 hs measured at Genoa University	Cati (1971); Russo and Sacchini (1994)
18 Jul 1908	Genoa	Flash flood	Bisagno Streams flooded Foce district. 238,6 mm at Viganego raingauge (upper Bisagno Valley) in 9 h were recorded, with highest concentration in the span 4:00–6:30 ST of 18 Jul. The Bisagno estimated discharge was about 420–450 $m^3 s^{-1}$.	Inglese et al. (1909); Cati (1971); Tropeano et al. (1995); Cipolla et al. (1999)
2 Nov 1926	Genoa, Polcevera Valley	Regular flood	206 mm 24 h^{-1} at Bolzaneto; Polcevera maximum discharge about 1050 m^3/s	Cati (1971); Cipolla et al. (1999); National Hydrografic Service, 2/1927
29–30 Oct 1945	Genoa, Polcevera Valley, Bisagno Valley	Regular flood	510 mm 24 h^{-1} at Passo dei Giovi but the Polcevera flood removed the measuring discharge instrument in Bolzaneto. The Polcevera was flooded with damage and deaths. Breaking of the Lagaccio dam. The Bisagno stream overflowed upstream the cover: there was also the Fereggiano flood and Molassana was flooded. 276 mm/24 hs at Genoa University were recorded.	Cati (1971); Cipolla et al. (1993); Russo and Sacchini (1994); Tropeano et al. (1995)
8–9 Nov 1951	Genoa, Polcevera Valley; Bisagno Valley	Regular flood	368 mm 24 h^{-1} at Bolzaneto, 475 mm/48 h 396 mm 24 h^{-1} at Genoa University. Polcevera flood; Fereggiano and Geirato creeks overflowed at Molassana district.	Cati (1971); Cipolla et al. (1993); Russo and Sacchini (1994)
19 Sep 1953	Genoa Bisagno Valley, Polcevera Valley	Flash flood	Intense rainfall: 205 mm/4hs at Genoa University (219 24 h^{-1}) and 330 mm in the whole event at Molassana district. Flooding of Bisagno Stream, floods and shallow landslides in the hinterland; damage at railways (Genoa-Milan) in the Polcevera Valley and at the aqueduct. Damage estimation equal to 50 billion liras (more than 25 millions of euro)	Cati (1971); Cipolla et al. (1993); Russo and Sacchini (1994)
14 Aug 1963	Genoa Voltri	Flash flood	Floods and damage at Voltri district	Cati (1971)
1 Nov 1968		Regular flood	Violent rainfall and consequent floods: Albisola and Savona towns were inundated. Some bridges were destroyed.	Cipolla et al. (1999)

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Table 3. Monthly average rainfall and yearly total in the Genoan area.

Raingauge Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	TOTAL
Genoa Università	111	99	108	99	84	64	37	65	122	197	176	124	1286
Genoa Sestri Ponente	106	95	106	85	76	53	27	81	99	153	111	81	1073
Genoa Sant'Ilario	144	104	113	95	91	60	36	61	109	166	169	136	1284

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Table 4. Impacts from the main geo-hydrological events in Genoa city from 1970.

Major Storm Event Date	Storm-related Deaths	Damage Losses	Other damages
7 Oct 1970	44 fatalities (25 within Genoa City)	1.1 billion Euros*	1000 people homeless; 50 000 people without jobs
27 Sep 1992	2 fatalities in Genoa City	75 million Euros*	250 people homeless
23 Sep 1993	7 fatalities	500 million Euros*	100 people homeless; Impacts to historic structures and significant construction project
4 Oct 2010	1 fatality	90 million Euros	20 people homeless
4 Nov 2011	6 fatalities	150 million Euros	150 people homeless
9–10 Oct 2014	1 fatality	250 million Euros	250 people homeless

* Original cost in Lira; adjusted to 1970 Euro equivalent.

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Table 5. Other geo-hydrological processes in Genoa city and main events in Genoa metropolitan area from 1977.

Year, Month, day(s)	Locality	Peak ($mm\,1\,h^{-1}$)	Rainfall event ($mm\,h^{-1}$)	Notes of the geo-hydrological event
1977, 6–8 Oct	Genoa city and hinterland (Stura Valley)	109	405/240	Geirato Stream overflowed, Middle Bisagno Valley (Dagnino et al., 1978)
1992, 22 Sep	Western Metropolitan area and Savona town	92	523/24	Damages for over 100 billions of liras (more than 50 millions of euros) (Cipolla et al., 1993; Tropeano et al., 1993)
1993, 23–25 Sep	Genoa center city and Western Metropolitan area	95	393/24	Western basins (Varenna Valley), 2 victims, 5 casualties in the inland areas (Tropeano et al., 1993)
1994, 4 Nov	Western Metropolitan area	87	211/24	Western basins of Genoa (Varenna valley)
1995, 5–6 Oct	Eastern Metropolitan area	70	215/24	Boate and San Siro streams overflowed (Rapallo and S. Margherita Ligure cities)
2000, 6–23 Nov	Genoa city and Eastern Genoan Metropolitan area	60	115/3	Lavagna Valley (Faccini et al., 2005)
2002, 24–26 Nov	Genoa city and Eastern Metropolitan area	93	200/12	Entella stream catchment (Faccini et al., 2005), 1 casuality. Some minor torrents overflowed in the Bisagno and Polcevera Valleys
2007, 1 Jun	Eastern metropolitan area	146	228/3	Recco stream catchments (Faccini et al., 2012)
2010, 4 Oct	Western metropolitan area and Varazze town	96	308/5	Teiro Stream catchment in Varazze, Chiaravagna stream and all minor catchments in Sestri Ponente (Sacchini et al., 2011)
2011, 25 Oct	Eastern Riviera	143	468/6	Vara Valley catchment, Monterosso and Vernazza cities (Cinque Terre)
2013, 21 Oct	Eastern Metropolitan area	87	187/3	Entella stream catchment, collapse of the Carasco bridge, 2 casualities
2014, 18–19 Jan	Eastern Metropolitan area	34	176/24	Eastern Genoan basins and Poggio stream catchment in Bogliasco, 1 casuality
2014, 10–11 Nov	Eastern Metropolitan area	58	162/24	Entella stream catchment, 2 casualities
2014, 15 Nov	Genoa city Western Metropolitan area and inland	52	290/12	Upper Polcevera valley, 1 casuality

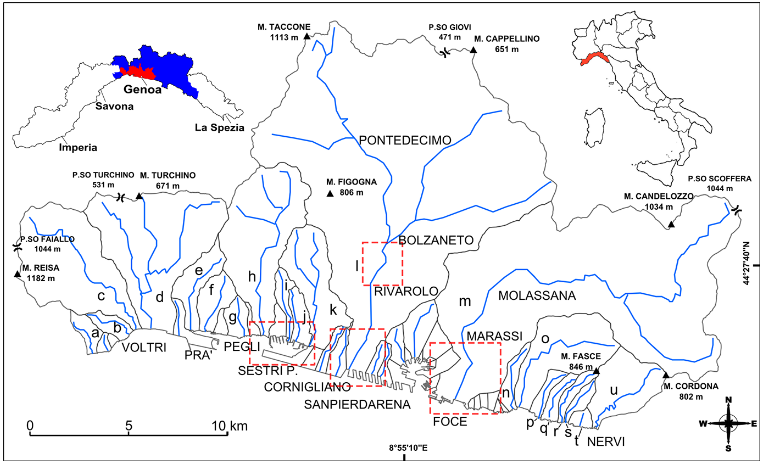

Figure 1. Main catchments and relative streams crossing Genoa City in the stretch between the districts of Voltri (W) and Nervi (E): (a) Vesima; (b) Fontanelle; (c) Cerusa; (d) Leira; (e) S. Pietro; (f) S. Michele; (g) S. Antonio; (h) Varenna; (i) Molinassi; (j) Cantarena; (k) Chiaravagna; (l) Polcevera; (m) Bisagno; (n) Vernazzola; (o) Sturla; (p) Priaruggia; (q) Castagna; (r) Bagnara; (s) S.Pietro; (t) Murcarolo; (u) Nervi. In the boxes (red dashed lines), from W to E: Sestri Ponente and the mouth of Chiaravagna Stream, Cornigliano and the mouth of Polcevera Stream, Foce and the mouth of Bisagno Stream. At the center of the figure, the inset shows Polcevera Stream near Bolzaneto.
The red area indicates the city of Genoa, the blue area indicates the Genoan metropolitan area.

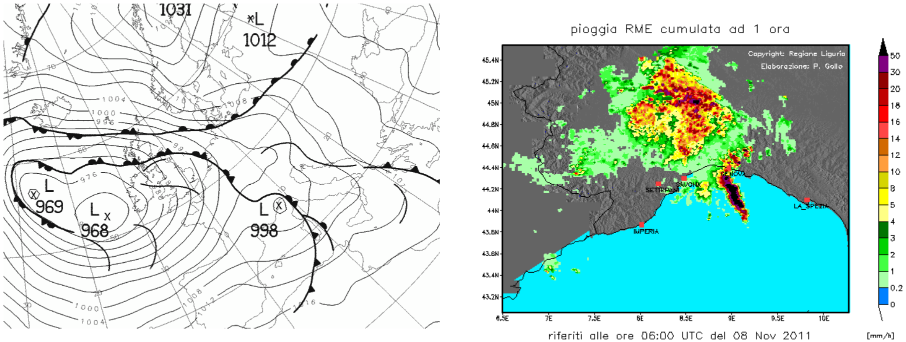

Figure 2. Isobars and fronts on the ground during Genoa Low (left). The convergence of currents coming from northerly and southerly sectors can create the formation of a thundery supercell characterized by intense rainfall able to trigger flash floods (right).

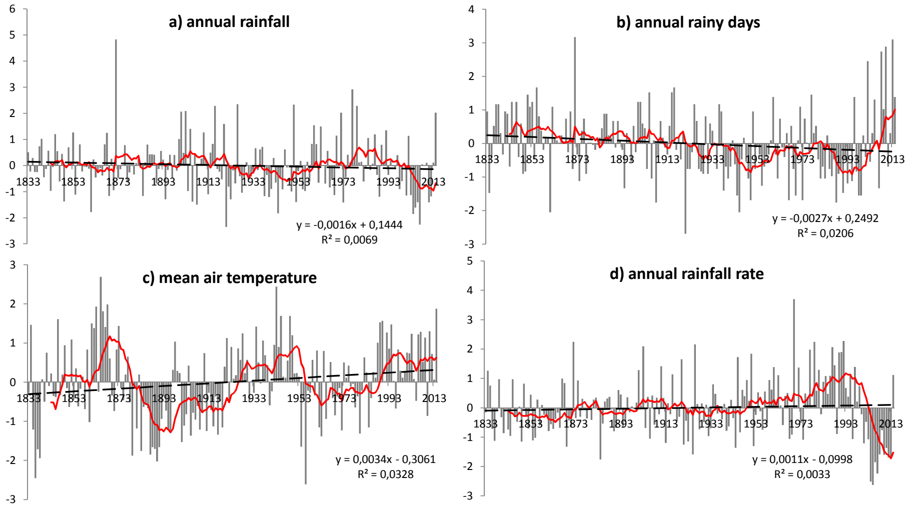

Figure 3. Climate trends in Genoa from 1833 to 2014 using the Standardized Anomaly Index: **(a)** annual rainfalls, **(b)** annual rainy days, **(c)** mean annual temperature, and **(d)** annual precipitation rate.

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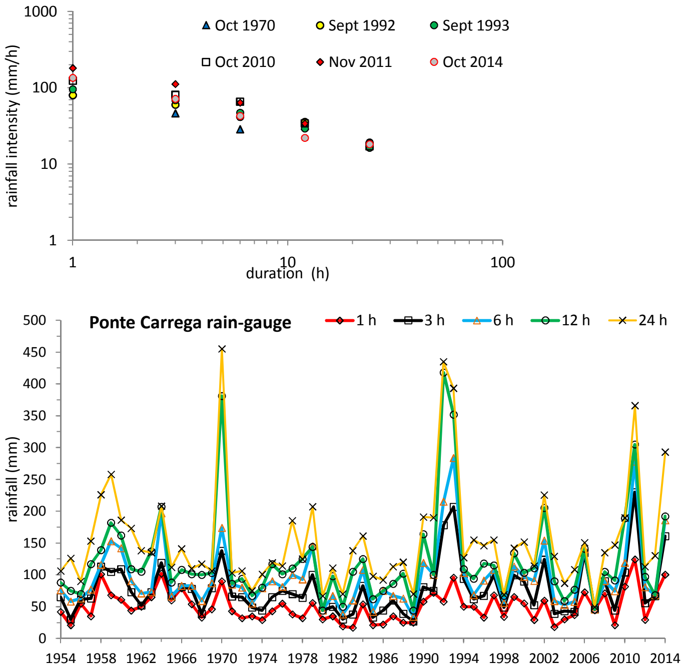

Figure 4. Rainfall intensity ($mm\,h^{-1}$) vs. time (hours) for the events occurred on 1970, 1992, 1993, 2010, 2011 and 2014 at Genoa University (Genoa historical center, between Polcevera and Bisagno valleys), and maximum annual rainfall depth for 1, 3, 6, 12 and 24 h at Pontecarrega-Gavette raingauges (Bisagno Valley, between Marassi and Molassana).

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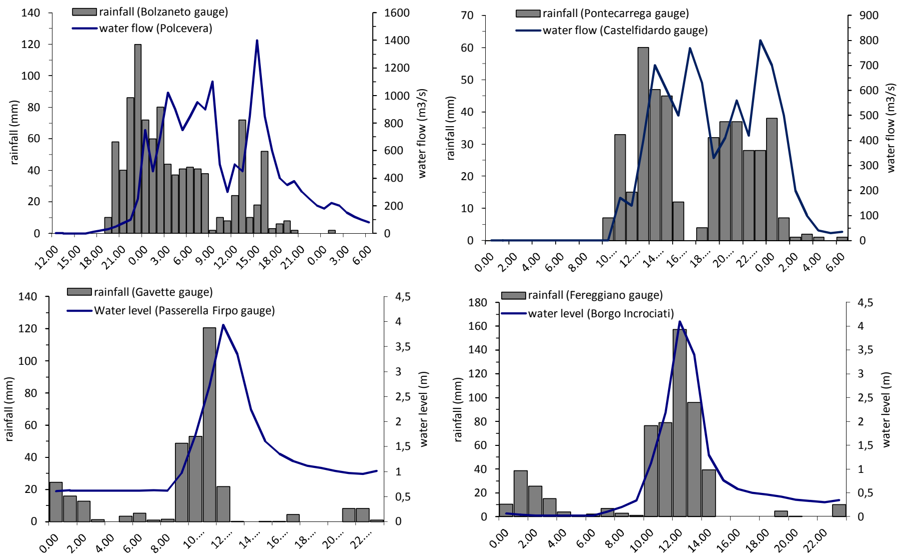

Figure 5. Rainfall vs. water level for the events of 1970, 1992 and 2011: **(a)** Bolzaneto in 1970, **(b)** Bisagno in 1970, **(c)** Bisagno in 1992, **(d)** Bisagno in 2011.

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Figure 6. Final stretch of the Bisagno Stream at the beginning of the 19th century (left) and to present day (right). Note the complete urbanization, the progradation to the sea in the Piazzale Kennedy area and Fiera del Mare (4) and the narrowing of the flow section near the S. Agata bridge (1) and of Pila bridge (S. Zita) (3). Number 2 shows the Sant'Agata Cloister, where the left shoulder of the bridge rose (280 m length). Note that the stream is completely culverted downstream the railway since "30"s (red dashed line). In orange dashed line we can see the Bisagno Stream banks at the beginning of 1800; in yellow dashed line the shoreline at the beginning of 19th century.

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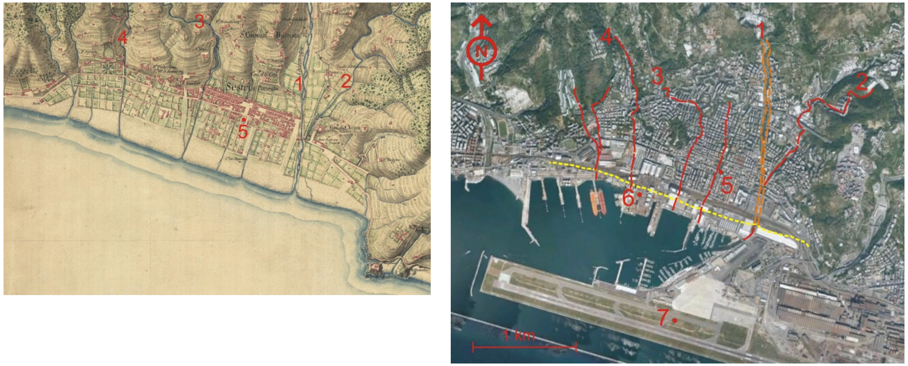

Figure 7. Comparison of the final stretch of the Chiaravagna Stream 1821 and now. Note the urbanization of the plain, shipyards (6), the little harbor and the airport (7) and the railway. It is possible to observe the strong progradation to the sea, the covering of the Chiaravagna Stream (1), the banks of which are indicated by dashed orange, and the Rio Ruscarolo Creek (2), its deviation that has entailed its flow into the Chiaravagna Stream and not on the beach. Numbers 3 and 4 indicate the Molinassi and Cantanera Streams (dotted red), number 5 is the Church of N.S. dell'Assunta in the historic center of Sestri Ponente. Dashed yellow indicates the shoreline at the beginning of the 19th century.

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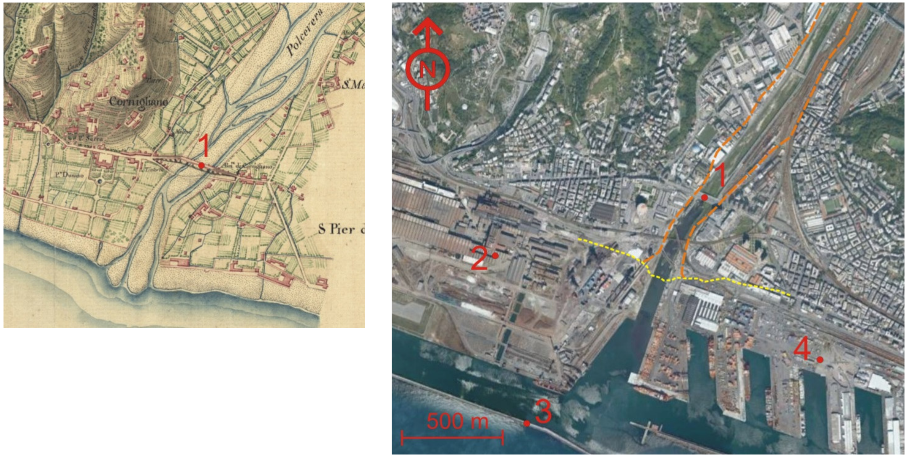

Figure 8. Final stretch of the Polcevera Stream: 1821 (left) and now (right). It is possible to note the change in land-use on the coast, its strong narrowing of the useful flow section, the narrowing of the Cornigliano bridge (1), the urbanization of the plain, the steelworks (2), the Sampierdarena harbour (4), the barrier in the sea (3) and the impressive progradation towards the sea. It is also important to observe that the water course with braided facies has been reduced to a channel. Orange dashed indicates the slope of the Polcevera Stream at the beginning of the 19th century; yellow dotted marks the shoreline in the same period.

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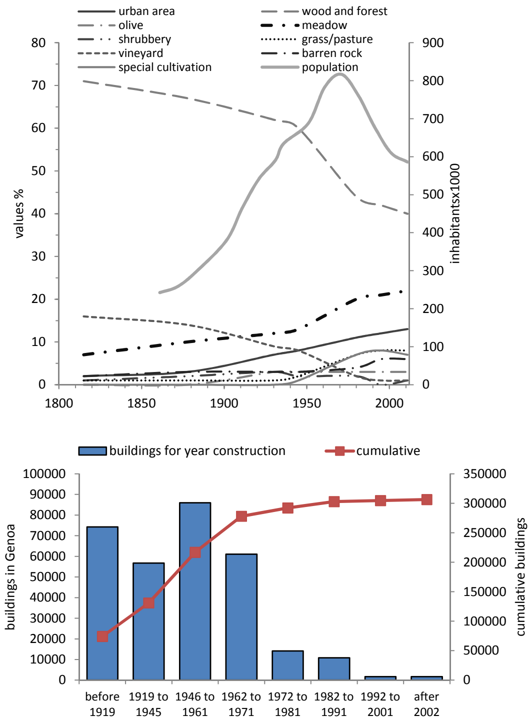

Figure 9. Land-use trend in the Bisagno Stream basin (area of about 93 km^2) from 1800 to the present day, and Genoa's population proceeding since the birth of the Italian Republic to date (above); number of buildings in Genoa from the end of the First World War to date, from ISTAT, 2001 (below).

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Figure 10. The Bisagno stream culvert during its construction (1930) and nowadays.

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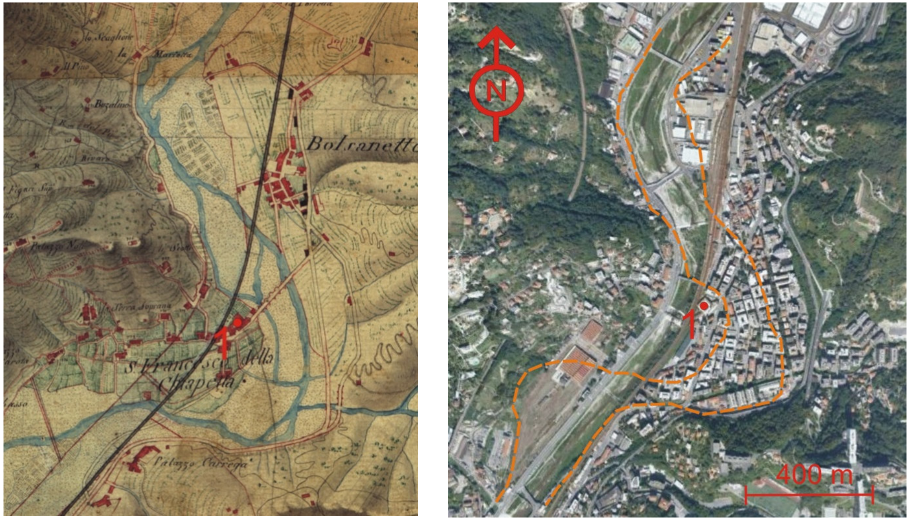

Figure 11. Bolzaneto urban area in the medium stretch of Polcevera Stream: (left) at the beginning of the 19th century, (right) today. With number 1 is evidenced the San Francesco Friary: till the half of 19th century the church was located on the right bank, inside a large bend. When the Genoa–Turin railway was realized (black line) the Polcevera riverbed was straightened and embanked, removing its bend. A new riverbed was digged for 500 m, cutting the foot of the Murta Hill: so the San Francesco Friary moved from the right to the left bank. It is evident the narrowing of the useful section of the flowstream, which banks are indicate with orange dotted in the present aerial photograph. The largest part of the abandoned meander is occupied by the populated center of Bolzaneto.

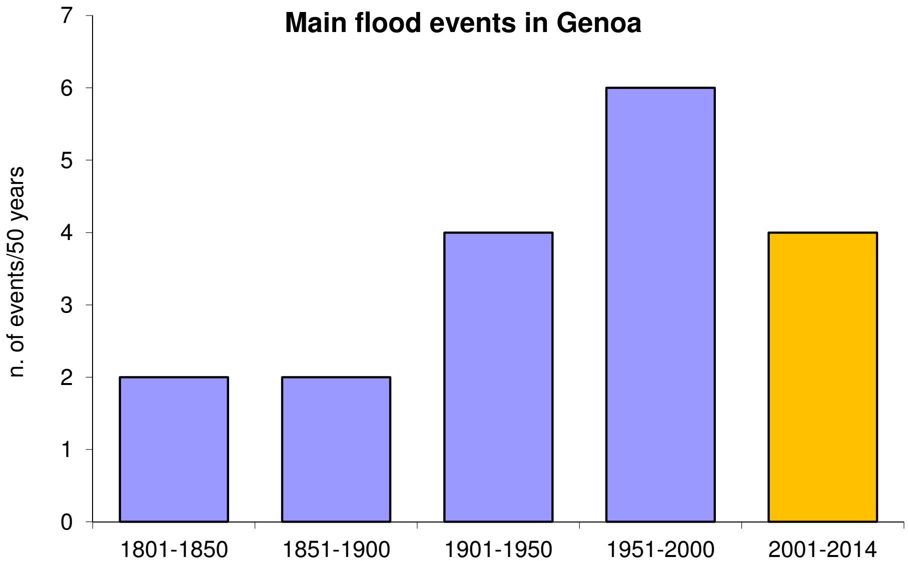

Figure 12. Semicentennial distribution of the most important flood events in Genoa city since 1801. In the present Millennium four events have been occurred in only 14 years.

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Figure 13. Inundations in Genoa city: some dramatic photographs of different flood events. **(a)** October 1970: Bisagno overflowing in the zone downstream the covering near the Genova Brignole railway station; **(b)** September 1992: the swollen waters of the Bisagno have destroyed some arches of the Sant'Agata bridge, already damaged in 1970; **(c)** October 2010: Chiaravagna's inundation in Sestri Ponente; **(d)** November 2011: Genova Brignole railway station inundated again (compare **a**).

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