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Geo-hydrological risk management for civil protection purposes in the urban area of Genoa (Liguria, NW Italy)

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Abstract. Over the past century the municipal area of Genoa has been affected by recurring flood events and several landslides that have caused severe damage to urbanized areas on both the coastal-fluvial plains and surrounding slopes, sometimes involving human casualties. The analysis of past events' annual distribution indicates that these phenomena have occurred with rising frequency in the last seventy years, following the main land use change due to the development of harbour, industrial, and residential areas, which has strongly impacted geomorphological processes. Consequently, in Genoa, civil protection activities are taking on an increasing importance for geo-hydrological risk mitigation. The current legislative framework assigns a key role in disaster prevention to municipalities, emergency plan development, as well as response action coordination in disaster situations. In view of the geomorphological and environmental complexity of the study area and referring to environmental laws, geo-hydrological risk mitigation strategies adopted by local administrators for civil protection purposes are presented as examples of current land/urban management related to geo-hydrological hazards. Adopted measures have proven to be effective on several levels (planning, management, structure, understanding, and publication) in different cases. Nevertheless, the last flooding event (4 November 2011) has shown that communication and public information concerning the perception of geo-hydrological hazard can be improved.

1 Introduction

The enormous potential for disaster resulting from natural hazards has been well known in Europe since the final decade of the 20th century. These issues were highlighted, particularly for urban areas, by the European Union conference which took place in October 1993 exploring the development of cohesive civil protection policies as part of the United Nations International Decade of Natural Disaster Reduction (Horlick-Jones et al., 1995). Horlick-Jones (1995) has stressed the need for better dialogue between researchers and practitioners of civil protection issues, a field that involves several different scientific, socio-economic, psychological, cultural and practical factors. Increasing population density and numbers of settlements in hazardous areas make disasters more frequent, severe and expensive (Petak, 1985; Drabek, 2004; Barredo, 2007; Castaldini and Ghinoi, 2009; Alberto et al., 2010), and as a result, the role of communication becomes more and more important (Horlick-Jones, 1995, Pearce, 2003; Arattano et al., 2010). With particular relevance to geo-hydrological risks, integrated meteo-hydrological systems for real-time flood forecasting have been developed since the 1990's (Fattorelli et al., 1995; Glade, 2000; Luino, 2005) and linked to technological advancement in weather forecasting. Prevention of and subsequent rescue after landslide events requires an understanding of their evolution, which is generally gained by the installation of often sophisticated and expensive monitoring systems by national or regional governments (Flageollet, 1995; Giardino et al., 2012). In Britain, land management strategy in urban areas involves the coordination of community response by improving public awareness through explaining both the nature of landslides and the policies to be

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implemented, using public meetings, information booklets, planning, codes of practice, meetings with professionals and educational activities (Sayers et al., 2002). Another possible approach is to establish rainfall thresholds for landslide triggering (Ferreira and Corominas, 1995; Guzzetti et al., 2008).

Around the world, civil protection activities are organized on different levels, from national governments to local administrations. The role of municipalities is similar in different countries and involves disaster prevention, emergency plan development, as well as response action coordination that requires the help of external organizations in disaster situations. Preventative measures, cooperation, information, planning and rescue services are also obligations for municipalities (Organisation de la Sécurité Civile du Quebec, 2002; Arattano et al., 2010; Swedish Civil Contingencies Agency, 2010).

The city of Genoa, currently home to around 650 000 people, represents an Italian national case-study of the issue of geo-hydrological risk. In fact, during the last century the municipality of Genoa has been affected by recurring flood events and landslides that have caused heavy damage and casualties (Brandolini and Ramella, 1994; Nosengo, 2008).

In 2001, the geo-hydrological critical condition of the Bisagno catchment was defined by the Italian Civil Protection Agency as a "national emergency". The Bisagno Stream flows through the most urbanized part of Genoa, with around 100 000 inhabitants as well as associated economic and industrial activity. Geo-hydrological risk mitigation in the Bisagno catchment area is therefore currently one of the most important civil protection objectives in Italy (Agenzia di Protezione Civile, 2001).

The occurrence of very short hydrological runoff times makes accurate weather forecasts vital, with the time window during which potential intervention could take place in an emergency being very narrow.

It is also worth highlighting that during the last century, the Genoese coast has been affected by significant changes in land-use management with the development of harbour, industrial and residential areas. Due to inadequate planning, the exploitation of almost all plain and slope areas has also led to the widespread abandonment of traditional agricultural practices on the terraced slopes surrounding the metropolitan area. This environmental imbalance, together with the overbuilding, rectification and restriction of the lower stretches of local streams in recent decades, has increased erosion and instability of slopes and flooding of the alluvial plains (Nosengo, 1987; Brandolini and Terranova, 1994; Maifredi, 1995; Brandolini and Sbardella, 2001).

After a brief overview on the current Italian national and regional legislative framework for civil protection, this study explores the complex environmental setting, the most important land-use changes and historical flooding events affecting the urban area of Genoa, as well as then, as an example of current land/urban management related to geo-hydrological hazards, outlining geo-hydrological risk mitigation strategies adopted at a municipal scale. Referring to the emergencies faced in the last decade, the effectiveness of these strategies is reported in the final remarks.

Following the recurrent natural disasters that have affected different Italian regions in the recent past, civil protection has assumed an increasingly important role in the national and local legislative framework. Consequently, local administrations are now required to develop activities and devote resources to the planning, programming and management of operations in case of emergency.

In Italy, law 24/02/1992 n. 225 gave rise to the National Civil Protection Service, identifying the mayor as the local authority for civil protection. Subsequently, legislative decree 31/03/1998 n. 112 delegated to regional administrations the responsibility for "prediction and prevention programs" and assigned to municipalities the preparation of "Municipal Emergency Plans"; these regulatory requirements were also outlined in Regional Law 17/02/2000 n. 9 ("Delegating to the municipalities the preparation and updating of the Municipal Emergency Plans"). Italian law therefore provides that a collaboration involving the Prefect, the provincial and the regional administrations is responsible for coordinating activities, including providing post-emergency assistance for the population, as well as carrying out preventative and predictive measures in order to protect people, the environment, and property.

With regard to geo-hydrological risks, the abovementioned civil protection laws interface with other laws related to soil defence, such as National Law 183/1989 and Regional Law 9/1993. These laws led to the introduction of the Basin Master Plan, a planning and management tool defining risk zones at a basin scale for both landslide and flood risks, and also providing regulations for land use. Legislative Decree 180/1998, published immediately after the Sarno landslide disaster in Southern Italy, forces local administrations to identify higher risk areas within their administrative districts.

For areas assigned the highest risk level ("R4 – very high risk area"), interventions aimed to risk reduction are scheduled. These areas have priority as regards the allocation of available state economic resources.

Following the Directive of the President of the Council of Ministers of 27/02/2004 ("Guidelines for the organizational and functional management of national and regional warning systems for hydraulic and hydro-geological risks for Civil Protection purposes"), the administrative body of Liguria published the "Map of criticism for Civil Protection use" (D.G.R. 746 of 09/07/2007), in which areas with different degrees of hazard in terms of floods and landslides are mapped. For areas with a high degree of landslide hazard, the Liguria Region has established that, in cases of a meteorological and hydrological "state of alert" being issued, local authorities are expected to hold territorial responsibility.

Fig. 1. Location of the study area (relief image derived from 25 m DTMs – Regione Liguria – using ArcGIS®).

2 Study area

The city of Genoa lies along a narrow WNW–ESE – oriented coastal zone about 32 km in length in the central part of Liguria (north-western Italy) (Fig. 1). Covering a total area of 243 km^2, the municipality is morphologically very complex, with ten main catchments characterized by very steep slopes and a small fluvial-coastal plain. Development occurring in the last century has resulted in urbanized areas occupying the entire coastline, all flood plains, the surrounding slopes and in particular the terminal sectors of the Bisagno and Polcevera valleys. The current population density of the city exceeds 6/7000 inhabitants per km^2 in the altitudinal range between 100 and 200 m (Brandolini and Spotorno, 1997).

2.1 Geological and geomorphological setting

The study area has a very complex geology and is considered a transition zone between the Alps and the Apennines (Chiesa et al., 1975; Cortesogno and Haccard, 1984; Capponi et al., 1994; Crispini and Capponi, 2001; APAT, 2008). Proceeding from W to E, a number of different tectonic units are recognized (Fig. 2):

- oceanic crust and mantle units (Jurassic-Cretaceous): Voltri Unit and Palmaro-Caffarella Unit, both part of the "Voltri Group"; Cravasco-Voltaggio Unit and Figogna Unit, both belonging to the so-called "Sestri-Voltaggio Zone" which is considered by many authors to be the limit between the Alps and Apennines;

- continental margin units (Triassic-Jurassic): Gazzo-Isoverde Unit, included in the "Sestri-Voltaggio Zone";

- units consisting of flysch succession (Upper Cretaceous): Mignanego Unit, Montanesi Unit, Ronco Unit and Antola Unit;

- late- and post-orogenic deposits, largely of Pliocene age.

The region's current complex structural setting is the result of different tectonic phases (APAT, 2008). An initial subduction phase involving mantle, oceanic crust and continental margin units was followed by exhumation and stacking unit phases ("Alpine"). These were then succeeded by a convergence phase ("Appenninic") associated with the counter-clockwise drifting of the Sardinian-Corsican block. Finally, a post-orogenic phase of brittle tectonics led to the formation of the largely N-S-oriented fault systems observed today.

The variety of landforms and deposits derived from the interaction of the above-mentioned complex geology and morphogenetic processes (mainly via the action of running water, gravity, marine action and karst landscape processes) make the study area extremely geomorphologically heterogeneous.

The region is entirely located on the southern side ("Ligurian side") of the Tyrrhenian-Adriatic watershed, whose evolution was strongly influenced by the genesis and dynamics of the Ligurian Sea and adjacent continental shelf (Fanucci and Nicolich, 1986). In general, this side of the watershed is characterized by high relief, regressive erosive landforms and a poor hierarchical drainage pattern (Piccazzo and Firpo, 2008). The steepness of the slopes is largely due to the proximity of the Apennine watershed to the coastline, with altitudes reaching 1000–1200 m in the area behind Voltri and 800–900 m behind Sturla and Nervi (Fig. 3). For the same reason, the extent of local catchments is generally small and, under high intensity rainfall conditions, their response time is limited to a few hours. The most extensive catchments are those of the Polcevera (138 km^2; 37 km^2 in the municipal district) and Bisagno streams (93 km^2; 53 km^2 in the municipal district); the remaining basins have areas under 30 km^2.

The drainage pattern is profoundly influenced by the phase of post-orogenic brittle tectonics, with the main fault lines oriented N–S, NW–SE, NNE–SSW and E–W (Marini, 1984; Spagnolo, 2008).

The hydrogeological characteristics of the territory are linked to the extreme variability of its geological and structural features. The degree of fracture of rock masses, predominantly intense, has in many cases allowed the establishment of deep water circuits. Conversely, localized clays and schists have low permeability or are altogether impermeable. Karst phenomena are present on both the Mesozoic calcareous-dolomitic rock formations which outcrop along the "Sestri-Voltaggio Zone" and the area of M. Antola flysch. The larger aquifers correspond to the alluvial deposits of the Bisagno and Polcevera streams, with estimated volumes of 55 million m^3 and 30 million m^3, respectively (Nosengo, 2008).

Different kinds of gravitational phenomena, as well as the risks arising from them, have been recognized within the Genoese municipal area. A number of "palaeo-landslides", Deep Seated Gravitational Slope Deformations (DSGSD) and other landslides with different kinematics conditioned by the structural features of discontinuities may be found in the central-high sectors of catchments (Brancucci et al., 1982, 1985; Comune di Genova, 1996; Bonfante et al., 1997;

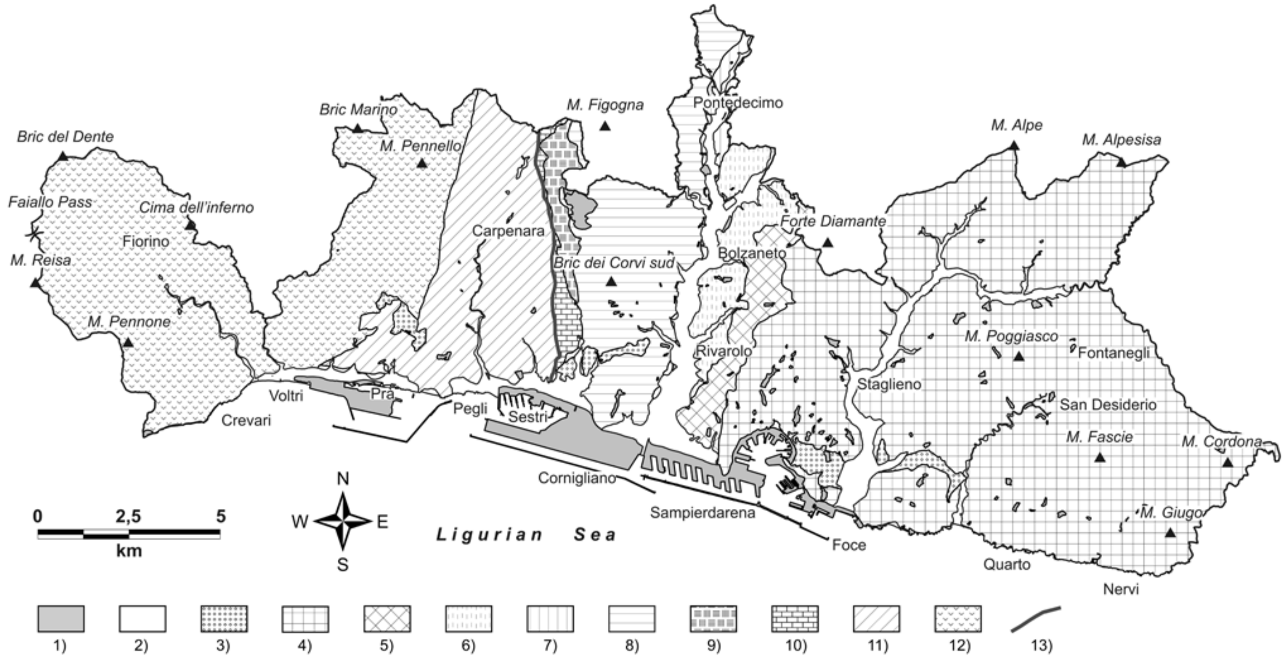

Fig. 2. Geologic sketch map of the Genoa Municipality area. Legend: (1) embankments; (2) alluvial and beach deposits; (3) Late- and post-orogenic deposits; (4) Antola Unit; (5) Ronco Unit; (6) Montanesi Unit; (7) Mignanego Unit; (8) Figogna Unit; (9) Cravasco-Voltaggio Unit; (10) Gazzo-Isoverde Unit; (11) Palmaro-Caffarella Unit; (12) Voltri Unit; (13) Sestri – Voltaggio fault (modified from APAT, 2008).

Fig. 3. Morphological map of the study area. Base image from TerraExplorer® (2011). Legend: (1) Genoa Municipality boundaries; (2) catchments boundaries; (3) sub-catchments boundaries; (4) main water courses; (5) catchments: Cerusa (a); Leiro (b); Branega (c); San Pietro (d); Varenna (e); Chiaravagna (f); Polcevera (g); Bisagno (h); Sturla (k); Nervi (j).

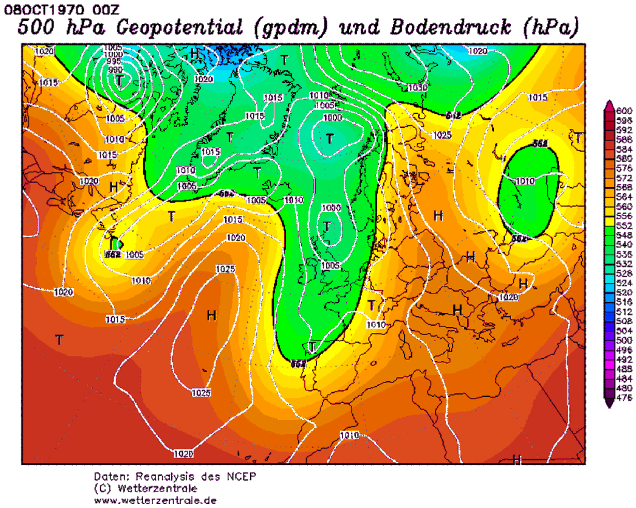

Fig. 4. The weather map on 8 October 1970, 00:00 UTC shows the typical configuration of sea-level pressure (white contour lines) and the geopotential height at 500 hPa (colored scale) favoring heavy rainfall and flooding in the Genoese area (from www.wetterzentrale.de).

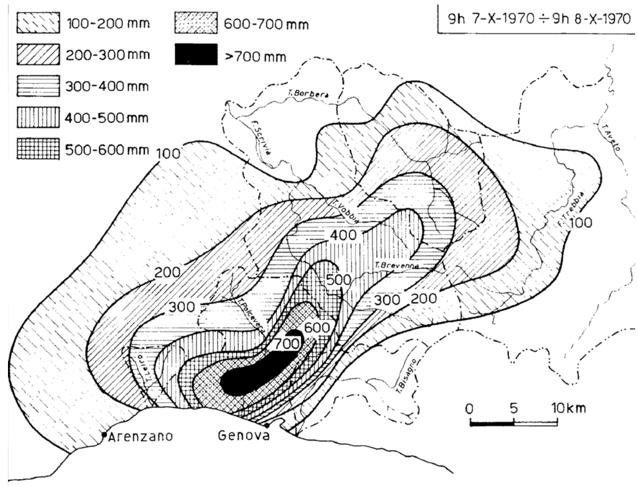

Fig. 5. Isohyets map of 7–8 October 1970 in the Genoa area (from Cati, 1970).

Regione Liguria, 2002). As a consequence of the rainfall regime and morphological features peculiar to this area, shallow landslides such as *debris flows* and *soil slips* are also very common (Brandolini and Ramella, 1994; Cevasco et al., 2008, 2010).

2.2 Pluviometric regime

The rainfall regime of the municipal area of Genoa is strongly affected by the proximity of both the Mediterranean and the Alpine-Appenninic mountain chain; indeed, Atlantic disturbances are frequently diverted to the Gulf of Genoa because of the barrier effect of these mountains (Bossolasco, 1948). In autumn and winter, cold northern currents are often surmounted by warmer and moister southern currents. Together with the constant dichotomy of land and sea, the contrasting natures of these two types of air mass can result in large amounts of precipitation that make Liguria, especially its central-eastern sector, one of the most rainy regions in Italy (Bossolasco et al., 1969).

Previous studies (Bossolasco et al., 1971; Dagnino et al., 1978) have highlighted that this typical weather configuration favouring high intensity rainfall events is characterized by a powerful blocking action due to the presence of a warm eastern anti-cyclonic air mass on whose western edge flows cold air associated with a wide Atlantic depression (Fig. 4).

Between the end of summer and the start of autumn, when the heat contrast between both air masses and land/sea are at a maximum, rainfall events exceeding 200 mm d^{-1} can frequently occur. An exceptionally heavy and persistent event characterized by values up to 948 mm d^{-1} was recorded at the Genoa-Bolzaneto weather station, 10 km from the city centre, on 7–8 October 1970 (Cati, 1970; Bossolasco et al., 1971; Fig. 5)

Some peculiar aspects of the Genoese rainfall regime can be recognized by analyzing the rainfall data set obtained by the historic Genoa University weather station, which has been recording since 1833 (Flocchini et al., 1981). Interesting patterns include:

- the strong dispersion of values for total precipitation and number of rainy days, on both a monthly and annual basis. Annual precipitation varies from a minimum of 543.5 mm to a maximum of 2764.5 mm, with the number of rainy days recorded between 67 and 157 dd yr^{-1}. Monthly precipitation levels can reach 780 mm, with up to 24 rainy dd m^{-1} recorded. Daily precipitation values reach a maximum of 456 mm;

- intra-annual variation in precipitation levels show an absolute maximum occurring in autumn and a relatively lower peak in the winter-spring period (Mediterranean transition climate), with the two separated by an absolute minimum in summer. Mean annual precipitation levels are around 1300 mm.

An analysis of historical precipitation trends for 1833–2008 reveals that despite a stationary trend in annual precipitation values (Flocchini et al., 1981) being observed, a significant decreasing trend is also apparent in terms of the number of rainy days, and thus the overall precipitation rate can be said to have increased steadily since the start of the recording period (Pasquale et al., 1994; Russo et al., 2000; Fig. 6).

Another peculiarity of the study area's rainfall regime is the significantly uneven geographical distribution of rainfall, in terms of both annual precipitation (Ministero Lavori Pubblici, 1957) and individual rainy events (Federici et al., 2004). For instance, annual precipitation values increase

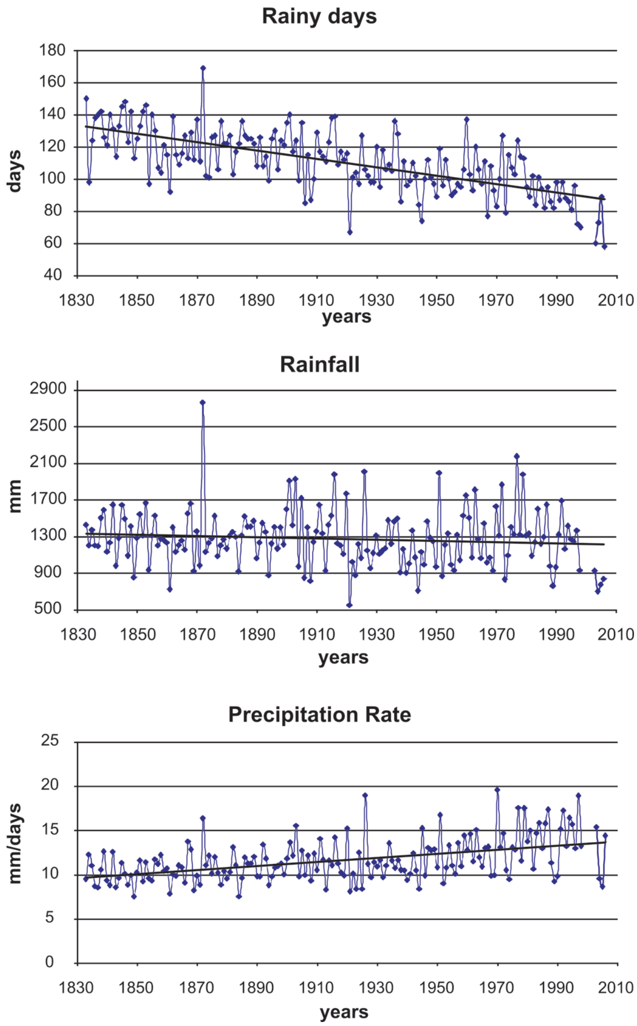

Fig. 6. Rainy days, rainfall and precipitation rate historical trend recorded at Genoa University station in the 1833–2006 period.

from west to east (and from the sea to the mountains) (Flocchini et al., 1992), while significant variation in precipitation levels over an area of a few kilometres, as well as large variations in highest hourly and daily precipitation rates are also observed. Coastal stations are characterized by maxima in events lasting 1–3 h, with the heaviest events lasting for 6, 12 and 24 h observed at inland stations.

2.3 Land-use change

Constrained by its geological and geomorphological setting, the initial expansion of the metropolitan area of Genoa during the last century took place along the narrow littoral and flood plains. Later, land reclaimed from the sea and surrounding slopes was progressively occupied by new settlements.

By comparing land-use maps of 1878–2000, it is clear how coastal, fluvial and slope landforms and processes have been heavily modified by intense urbanization (Brandolini et al., 1996). Due to a lack of available space for the development of port and industrial activities, since the beginning of the 20th century a progressive expansion toward the sea has taken place. Large embankment areas and coastal defences have been created between Voltri and the mouth of the Bisagno Stream, completely transforming the littoral landscape. In front of the former beaches at Pra, Pegli, Cornigliano and Sampierdarena, large embankments have been built along the shoreline (about 16 km in length) via the displacement of millions of cubic metres of debris, creating a new landmass at sea at a depth of 15–20 m with an area of about 8 km^2 (Fig. 7). As a consequence, the coastline has subsequently prograded 700–1000 m (Brandolini et al., 1994b).

Such changes have ultimately led to the complete disappearance of local beaches, whose area has been reduced from 790 000 m^2 at the end of the 19th century to their current extent of less than 200 000 m^2. Only the coastal zone between Crevari and Voltri is still home to a 1.5 km beach – although even this one is currently undergoing progradation as a consequence of the interaction between eastward coastal drift and the new container port of Pra-Voltri (Brandolini et al., 2000).

Moreover, human activities following urbanization have strongly modified local drainage patterns. Within the municipal limits of Genoa, the drainage pattern has expanded by 915 km, comprised of embanked stretches (70 km), covered tracts (115 km), as well as artificial (28 km) and natural channels (702 km) (Brandolini and Sbardella, 2001). The above-mentioned modifications have particularly affected the lower stretches and mouths of local streams, forcing them into new artificially-restricted run-off sections. The most emblematic example of this is the complete canalization and coverage of the lower stretch of the Bisagno River from Brignole to Foce (about 1.4 km long), built in the late 1920's.

The total consumption of space in coastal and flood plain areas was followed by intense urbanization of slopes and the widespread abandonment of surrounding terraced areas, used in the past for agricultural purposes. This additional environmental imbalance, together with the above-mentioned factors, has certainly favoured the increase in slope instabilities and frequency of flood events which has affected the municipal area of Genoa during the last few decades (Brandolini and Ramella, 1995; Brandolini and Sturla, 2003).

3 Previous flooding and related events

The causes of floods in the Genoese urban area are various, but it is well-known that both natural and anthropogenic processes play an important role in their genesis. The occurrence of high intensity and/or heavy rainfall events is favoured by peculiar meteorological and orographic conditions, such as the proximity of the Apennine's main watershed to the Ligurian Sea. Other causes are again linked to natural factors,

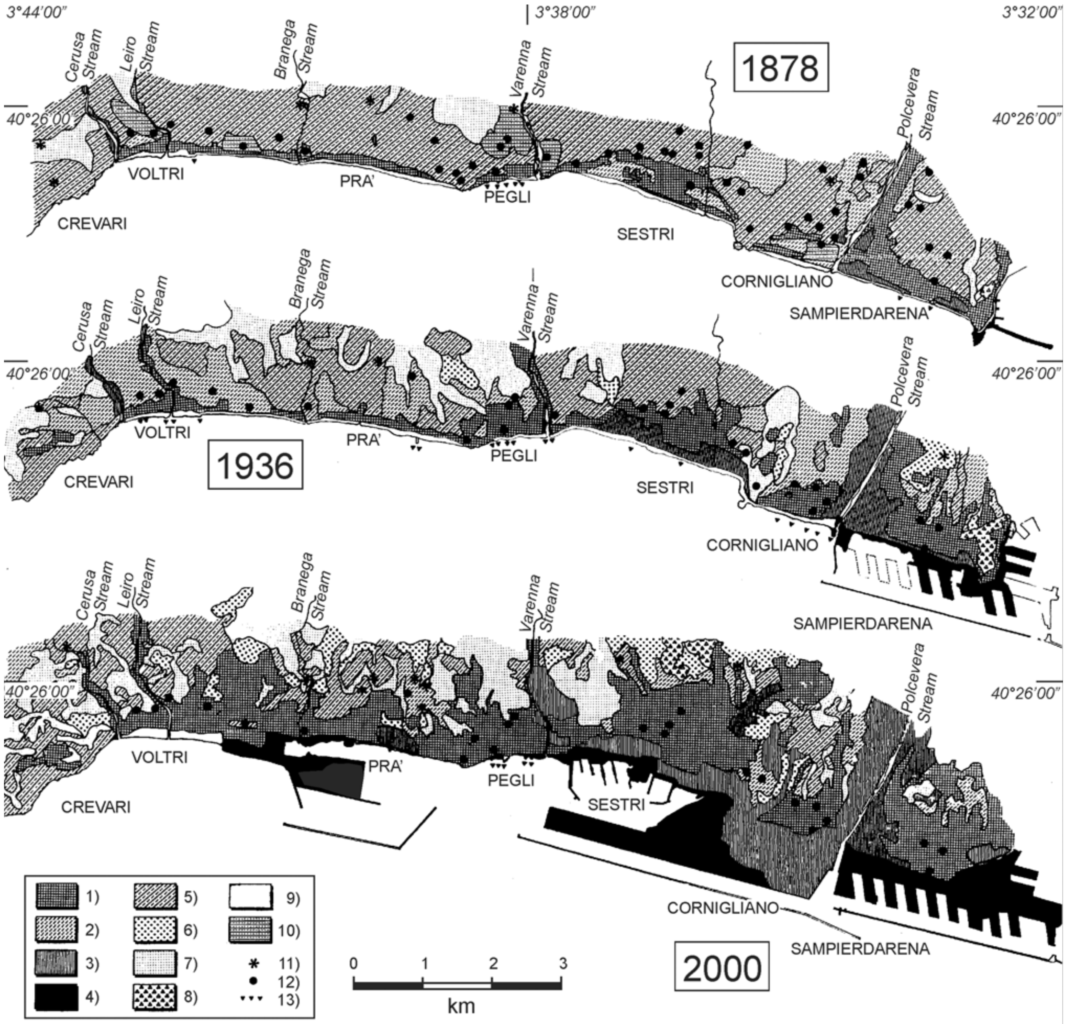

Fig. 7. Land use changes in the middle-western sector of the Genoa Municipality, affected by major morphological modifications in the 1878–2000 period: (1) urban settlements; (2) sparse settlements in cultivated areas; (3) industrial settlements; (4) harbour and airport settlements; (5) cultivated areas; (6) abandoned cultivated areas; (7) wooded areas; (8) quarry areas; (9) beaches; (10) urban gardens (only in 1878 map); (11) isolated residential areas; (12) villas and/or villas with garden; (13) coastal defences (modified from Brandolini et al., 1996).

such as the small area of local catchments and the steepness of their slopes which together result in very short hydrological run-off times, in some cases less than one hour. Flash floods have hit Liguria more frequently in recent years than in the past (Russo and Sacchini, 1994; Frontero et al., 1995, Russo et al., 2000), while precipitation rates are increasing (Pasquale et al., 1994) according to the forecasts of the Intergovernmental Panel on Climate Change (IPCC, 2007).

Since the 19th century, the Genoese municipal area has been affected by recurring flood events and several landslides. Rising in frequency in recent decades, these events have periodically caused severe damage, sometimes involving human casualties, to a number of urbanized areas on the coastal-fluvial plains and surrounding slopes. The following section will include a brief description of these events and the resultant damage.

Few historical data are available regarding the extreme rainfall event which occurred on 25–26 October 1822, although an estimated 812 mm/24 h of rainfall is thought to have caused significant flooding in the centre of the town, leading to the collapse of arches of the S. Agata bridge and the partial collapse of the old Pila bridge (Provincia di Genova, 2005; Nosengo, 2008).

Exceptional precipitation levels were recorded on 6 October 1892 and 24–25 October 1907 at the Meteorological Observatory of Genoa University, with cumulative rainfall totals of 181 and 246 mm, respectively. Both events were followed by inundation and severe damage, which particularly affected the lower parts of the Bisagno and Polcevera plains (Russo and Sacchini, 1994).

More detailed data are available for the extreme rainfall events of 1926, 1945 and 1951 that especially affected the Polcevera catchment (Cati, 1970):

- on 2 November 1926, the Bolzaneto rain gauge recorded a cumulative rainfall total of 206 mm, with a peak flow of 1050 $m^3 s^{-1}$ estimated for the lower reach of the Polcevera Stream;

- on 29 October 1945, the Passo dei Giovi rain gauge (located in the Tyrrhenian/Adriatic watershed 10 km north of Pontedecimo) recorded rainfall levels of 510 mm/24 h, with an accompanying peak flow of 1432 $m^3 s^{-1}$ calculated for the mouth of the Polcevera. All industrial settlements located in the alluvial plain suffered damage, with the collapse of a small dam in the Lagaccio valley, located on the eastern border of the Polcevera valley, resulting in a number of human casualties;

- on 8–9 November 1951, the Bolzaneto rain gauge recorded precipitation levels of 367 and 107 mm (338 and 146 mm at the Madonna della Guardia rain gauge), with a peak flow of 1091 $m^3 s^{-1}$ calculated for the mouth of the Polcevera Stream.

Although the Bisagno Stream was also affected by the abovementioned heavy rainfall events of 1945 and 1951, the surrounding urban areas suffered most damage after the floods occurring in 1953 and 1970 (Cati, 1970):

- on 19–20 September 1953, a cumulative total rainfall level of 330 mm was recorded by the Molassana rain gauge, with a peak flow of 755 $m^3 s^{-1}$ calculated for the Bisagno Stream at Staglieno, around 4 km from the river mouth. This event was preceded the previous week by rainfall, that although less intense, saturated soils and therefore favoured the flooding that ensued. The rainfall event of 19–29 September 1953 particularly affected the middle portion of the western Bisagno catchment and the eastern half of the Polcevera catchment (the Secca, Verde and Riccò creeks), resulting in the destruction of two bridges crossing the Geirato and Torbido streams near Molassana and a number of walkways crossing the Bisagno Stream and the inundation of the city centre (Fig. 8). Other floods and shallow landslides also affected the Secca valley (within the Polcevera catchment), destroying a bridge across the Genoa-Milan railway line and interrupting the flow of the municipal aqueduct;

- on 7–8 October 1970, the most intense rainfall event ever to hit the Genoa area occurred. Exceptional precipitation levels were recorded, with rainfall intensity peaks of 130 mm/1 h, 700 mm/12 h and 900 mm/24 h. All catchments within the municipality, from Cerusa to Nervi, suffered damage, with the most severe observed in the town of Voltri in the West, and the central and southern sectors of the Bisagno catchment between Molassana and the mouth of the Bisagno Stream (Fig. 8). The peak flow of the Bisagno was calculated to be around 1400 $m^3 s^{-1}$ at Brignole (Nosengo, 2008). This value far exceeded the 500 $m^3 s^{-1}$ used for the design and construction of the canalization and coverage of the river's final stretch, whose runoff section was drastically reduced in extent (Fantoli et al., 1909). This exceptional peak flow significantly increased pressure on the Bisagno stream coverage, resulting in catastrophic floods which affected 3.5 $km^2$of the city centre, claiming 10 lives and causing over 10 billion lira of damage;

Also triggered by rainfall, although not of an exceptional level, was the landslide that occurred on 21 March 1968, in Via Digione (Fig. 9). 16 000 m^3 of rock fell from the slopes of an abandoned quarry located within the urban area, resulting in the collapse of an entire building and causing 19 fatalities and numerous other injuries (Peretti, 1969). A key role was also played by an earlier rainfall event in February of the same year, with levels reaching 333 mm at the Genoa University weather station (the closest weather station to the site of the landslide).

On 6–8 October 1977, a rainfall event similar to that of 1951 occurred, characterized by precipitation levels of 370 mm/48 h recorded at the Meteorological Observatory of Genoa University.

The accompanying peak flow of the Bisagno Stream is unknown, but a number of areas within its catchment were affected by flooding. Other catchments to the west of Genoa (Cerusa, Leiro and Polcevera) experienced the most damage, with widespread flooding taking place along their lower reaches, as well as numerous shallow landslides in the central-upper parts of the catchments. Total damage amounted to over 16 billion liras.

On 27 September 1992, a cumulative total rainfall of 435 mm was recorded by the Molassana rain gauge, with a peak flow of the Bisagno Stream of 700 $m^3 s^{-1}$ measured at its mouth. Severe damage occurred both in the eastern urban area of Genoa, which was affected by the flooding of the Bisagno, and in the surrounding hills, affected by numerous shallow landslides. The Sturla Stream also overflowed, resulting in two casualties, other injuries and general devastation in the surrounding urban areas (Conti et al., 1993; Brandolini and Terranova, 1994).

On 23 September 1993, the Fiorino and Bolzaneto rain gauges recorded rainfall levels of 300 and 397 mm, respectively, in less than 24 h, with intensity peaks of 108 $mm h^{-1}$ and of 211 mm/3 h (recorded by the Madonna della Guardia rain gauge). This exceptional event largely affected an area of around 50 km^2 in the west of Genoa (the Leiro, Varenna and Verde catchments), although several floods also occurred in the historic centre of the town. As a result of this heavy rainfall event, several shallow landslides were triggered within a short timeframe. A large amount of detritic material was mobilized along the drainage network, reducing runoff sections and compounding the effects of flooding. At

Fig. 8. The map shows: historical flooded areas with return time of 50 yr (1) and 200 yr (2); high risk landslides identified for Civil Protection purposes (3); shallow landslides based on data inventory 1991–2011 period (4); location of most weather stations in Genoa Municipalitiy cited in the text (5) (modified from Comune di Genova, 2008).

Fig. 9. Via Digione landslide (from Peretti, 1969).

the mouth of the Varenna Stream, 20 000 m^3 of detritic material was deposited in a few hours (Brandolini and Ramella, 1994).

On 26 November 2002, heavy rainfall affected the Nervi, Sturla and Bisagno catchments, with levels of more than 200 mm/12 h recorded by the Genoa University rain gauge. The lower reach of the Bisagno Stream rose very close to flooding. On 27 November a shallow landslide occurred on the right-hand side of the Bisagno valley, resulting in the blockage of the municipal aqueduct.

On 4 October 2010, heavy rainfall affected the Sestri Ponente area, with a total cumulative precipitation level of approximately 400 mm/6 h accompanied by intensity peaks of more than 120 mm h^{-1} and 18 mm/5 min. This event caused the lower reach of the Chiaravagna Stream to flood, while the upper part of the Molinassi catchment was also affected by a large number of shallow landslides, debris flows and instances of gully erosion. The lower parts of these catchments, the urbanized fluvial-coastal plains, were almost completely flooded, with a total surface area of 0.7 km^2 covered by an average water level height of 0.5 m.

On 4 November 2011, heavy rainfall affected a small area in the easternmost part of the municipality. The Quezzi rain gauge (LIMET network, http://www.centrometeoligure.it) recorded a cumulative rainfall of 546,8 mm in less than 24 h, with peak intensity of 17 mm/5 min and 163 mm h^{-1}. A flash flood occurred in the Fereggiano catchment (within

Fig. 10. Brignole area inundation on 4 November 2011.

Bisagno valley), causing 6 casualties and the inundation of the Brignole area (Fig. 10).

Finally, it is worth highlighting the great importance of shallow landslides triggered by high intensity rainfall with respect to their impact on civil protection. Indeed, analysis of an inventory comprising reports carried out by public offices, companies and citizens on behalf of the Civil Protection Office of the Municipality of Genoa reveals that around 150 *debris flows* and *soil slips* occurred during the period 1991–2011 (Fig. 8).

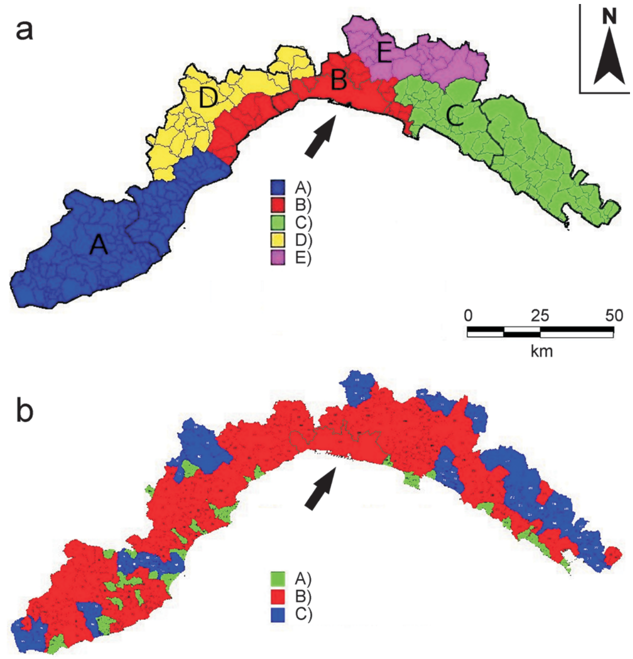

Fig. 11. **(a)** Meteo-hydrological alert zones map in Liguria: (A) Tyrrhenian catchments of western Liguria; (B) Tyrrhenian catchments of central Liguria; (C) Tyrrhenian catchments of eastern Liguria; (D) Adriatic catchments of western Liguria; (E) Adriatic catchments of eastern Liguria. **(b)** Municipal hydrological map in Liguria: (A) Ist category municipalities; (B) IInd category municipalities; (C) IIIrd category municipalities (modified from Regione Liguria, 2008).

4 Risk mitigation strategies

With reference to the national and regional legislative framework, since 2001 the Municipality of Genoa has adopted its own "Municipal Emergency Plan". Modular and continuously-updated in order to combat the various types of civil protection emergencies which may occur in the Municipal area, the plan consists of a "general report", which contains the guiding principles governing the municipal roles in case of emergency, as well as several "operational schemes" outlining the specific procedures to be adopted for the management of various kinds of emergency, such as floods, heavy snowfall, bushfires and earthquakes (Comune di Genova, 2010).

The Administration of the Municipality of Genoa has developed an independent operational structure for civil protection, both in terms of carrying out planning/programming activities and the management of emergency operations. In the occurrence of a natural disaster, staff and equipment belonging to the Municipal Administration, service companies operating in the municipal area, a municipal group of civil protection volunteers and affiliated volunteer organizations are all made available to work under the coordination of the Municipal Civil Protection Committee, which consists of both technical experts and political staff.

4.1 Geo-hydrological risk mitigation

As flooding in the study area can potentially develop within a very short timeframe (hence the term "flash floods"), such events can only be tackled properly if advance action is taken, with a low degree of space-time indeterminacy.

In this regard, the Administration of Liguria uses its own weather forecasting system for the issuing of states of alert, both in terms of hazardous weather and hydrological conditions (Civil Protection Meteo-Hydrological Functional Centre). This system is known to be highly reliable, despite operating within a framework of possible or partial indeterminacy derived from the peculiarity of the region's meteo-hydrological behaviour.

The Administration of Liguria divides its territory into different "Alert Zones", the boundaries of which coincide not with provincial administrative limits but, more appropriately, take into account morphological and physiographical criteria (Fig. 11a). These "Alert Zone" boundaries therefore respect both territorial (basins) and meteorological criteria, identifying meteorologically similar basin areas in terms of the dominant type of rainfall.

The meteo-hydrological critical scenarios described by the Meteo-hydrological Functional Centre for Civil Protection of Liguria are graded on an increasing scale of three levels: ordinary, moderate, and high. These levels correspond to the rainfall thresholds forecasted by the ARPAL Agency (Agenzia Regionale di Protezione dell'Ambiente Ligure) and/or instrumentally observed hydrometric thresholds provided for each of the five areas of early warning.

For the management of flood risk, a model is applied which, using both predicted and measured data, is able to simulate the hydrological behaviour of catchments.

This model is based on basin morphological features, identifying critical situations for each class of catchment based on the probability that certain flow thresholds are exceeded.

Three hydrological scenarios have been identified, with different levels of alert state outlined by the Prefecture (Table 1).

Each municipality is assigned a "hydrological category" according the size of local catchments: Category I, basin areas less than 10 km^2; Category II, basin areas of between 10 and 150 km^2 (the Municipality of Genoa falls within this category); Category III, basin areas greater than 150 km^2 (Fig. 11b).

Using this legislation and on the basis of the different predicted scenarios, the Administration of Liguria can therefore issue a suitable hydrological warning for each municipality.

In compliance with the regional warning system described above, the Municipality of Genoa has prepared an "Operational Scheme" for the management of geo-hydrological emergencies. The latter are graded according to the various levels of alert, with an increasing number of preventive measures taken with rising risk level. The plan is articulated into a series of actions aimed at mitigating potential damage, safeguarding both property and lives.

These actions are themselves divided into "internal actions" – those involving the public administrative bodies (including technical staff and volunteers) responsible for the handling of the expected (emergency) event – and "outside actions", which include the public release of alert messages and the restriction of activities in areas of highest risk. Other planned activities have to be carried out irrespective of the state of alert. Actions to be taken in the case of the most critical scenario (Alert 2) and "general activities" are listed in Table 2.

Regarding "general activities", a collaboration between public administration and the university has been carried out. In particular, a flood wave propagation model for the Bisagno Stream was developed in 2002 by Municipal Civil Protection Office and Inter-University Research Centre for Environmental Monitoring (CIMA).

4.2 Landslide risk mitigation

Although landslide risk is dealt with alongside that of flooding in the Municipal Emergency Plan, landslide risk mitigation has its own associated issues that the Municipality Administration has acted upon, with the aim of preparing in a short time a specific operational plan for the purpose.

With more than 250 areas in the Municipality of Genoa having been identified as landslide-prone (albeit with varying degrees of hazard) (D.G.R. 877/2004), it was therefore deemed necessary to define criteria that would allow municipal activities only in landslide areas of major interest for the purposes of civil protection. To this end, a screening operation comprised of several phases was carried out. This process included: (a) the comparison of hazard maps prepared by the regional government of Liguria, as well as maps of at-risk elements derived from basin master plans; this action enabled the identification of areas with the highest degree of landslide risk; (b) examination of the type of assets at risk in these areas. In this regard, only those areas characterized by the presence of residential and/or commercial buildings or areas within which, for the purposes of civil protection, conditions were most critical, were considered.

This operational plan resulted in the number of areas to be monitored in case of meteo-hydrological alert being reduced to 35 (Fig. 8), a number which included the five areas considered to have a high degree of landslide risk ("R4" class) by Legislative Decree 180/98.

For the 35 selected areas, geological and geomorphological surveys were conducted in collaboration between municipal geologist and university researchers that enabled the subsequent construction of detailed maps (1:3000 and 1:4000 scale). Furthermore, all available information within the Municipal Administration archive was collected and a file system created for each of them. This file system is able to be updated on the basis of results obtained from periodic surveys carried out by municipal technicians. In addition, a detailed study has also been carried out which aimed to identify, in each area, the number of buildings and citizens (residents and non-residents) exposed to landslide risk, potential escape and evacuation routes, as well as possible contacts (administrators or owners of buildings) in case of imminent danger.

With regard to landslide risk management during a state of meteo-hydrological alert, each of the 35 landslide areas are overseen and directly controlled in order to verify any signs of movement.

At-risk areas are also monitored regularly in the absence of a state of alert. In particular, areas classified as "R4" are allocated funds with which to carry out geotechnical investigations and to install control systems (e.g. piezometers, inclinometers). In the remaining areas affected by very slow slope movement (few $mm\,yr^{-1}$), a structural stability monitoring system (of e.g. retaining walls, sidewalks, walls of houses) has been established via the installation of crackmeters.

With respect to shallow landslides (*soil slips*, *debris flows*), Genoa Municipality has recently implemented, in collaboration with the University of Genoa, a computerized monitoring system (Acrotech, 2008) based on the coupling

Table 1. Scenarios and alert states defined on the basis of a range of potential critical conditions (from Regione Liguria, 2008).

Scenario	Critical condition	State of alert
0	Localized flooding of creeks and/or regurgitation of rainfall drainage systems, potentially affecting the lowest-lying urban areas. There may also occur: flooding and damage of underground locations; temporary interruption of traffic; water runoff in urban and suburban roadways; possible triggering of shallow landslides; occasional hazard for people and property.	None
1	In addition to the effects predicted in "scenario 0", the following may also occur: widespread flooding due to stagnation of water; sewer systems inability to drain; water runoff in peri-fluvial urban and suburban roadways; river water levels rising potentially causing localized flooding in surrounding areas, as well as triggering shallow landslides in surrounding slopes; moderate hazard for people and property.	1
2	Significant increase in channel water levels potentially leading to: flooding; river bank erosion; rupture of embankments; walkways and bridges overtopped; flooding of surrounding urban areas. Likely to trigger widespread and extensive slope instabilities, with high hazard for people and property.	2

Table 2. "Internal and outside"actions to be undertaken in the case of the most critical alert scenario and "general activities" (from Comune di Genova, 2010).

"Internal actions" (state of alert 2)	"Outside actions" (state of alert 2)	"General activities" (irrespectively of state of alert)
– The Municipal Civil Protection Committee assumes command of event operations and mana-gement; – Alert and activation of on-call employees; – Acquisition of onsite information regarding meteo-hydrological conditions through communication with local branches of the Municipal Police; – Online monitoring of hydrological gauges and nowcasting; – Communicating with institutional contacts for any information and/or updates of the ongoing meteo-hydrological situation; – Organization of volunteers for the monitoring of rivers, high- and very high-risk flood-and landslide-prone areas, as well as other necessary actions such as assisting the public; – Monitoring the status of rivers and suspension of river-based activities, including the evacuation of worksites and other possible obstacles to stream runoff; – Verification and subsequent suspension of any current or planned public events involving concentrations of the population in at-risk areas.	– Toll-free information made available to citizens; – SMS information for all citizens enrolled in the service (free); – Information provided for all citizens regarding the state of the alert/risk scenario via signs displayed along roadsides and at bus stops; – Press releases via radio/tv/internet/newspaper.	– Creation of river monitoring stations; – Disaster simulation exercises; – GIS-supported creation of a database and thematic maps examining the hazards necessitating civil protection and their management (flood-prone areas, areas of landslide hazard, residents at risk inventory, banning of traffic in case of flood, alternative routes, shelter sites for the population); – Modelling of flood propagation in urban areas; – Construction projects in areas at risk of flooding are obliged to adopt specific measures to mitigate flood risks, with the go-ahead of the Municipality; – Design and acquisition of environmental monitoring systems; – Production of targeted information campaigns (advertising) to spread public awareness of the risks posed by natural hazards and to teach effective self-protection behaviours; – Creation of educational workshops regarding hydro-geological risk, directed specifically at the school-age population; – Installation of roadside information panels indicating the location of flood and landslide risk areas; – Issue of Mayoral ordinances aimed at informing individual landowners/re-sidents in areas at risk of landslide and flood.

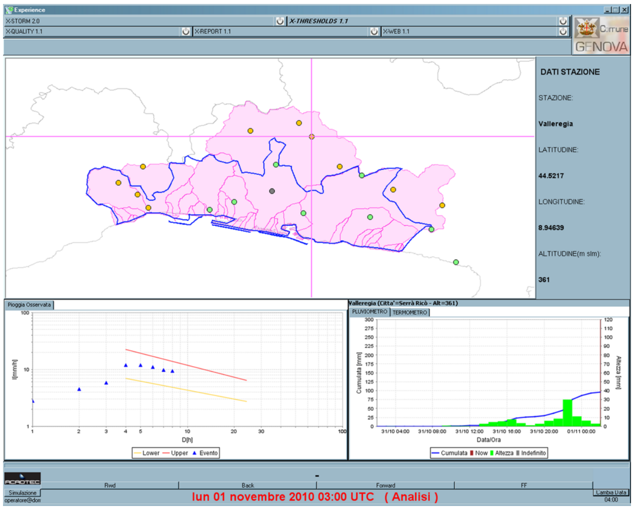

Fig. 12. Genoa Municipality web page (under construction) showing the pluviometric thresholds model utilized by the Civil Protection Office (Acrotech, 2008). Top: Genoa Municipality boundaries (blue line); catchments (pink line); rain gauges (colored dots). Bottom left: intensity/duration diagram (logarithmic scale on both axes), referred to the selected rain gauge (dot marked by crossed lines), showing rainfall thresholds (yellow and red lines) for triggering shallow landslides (from Cevasco et al., 2010). Bottom, right: rainfall amount (blue line) and hourly rainfall amount (green histogram). As different threshold values are exceeded, the weather station on synoptic (at the top) takes on a different color (dark green).

Fig. 13. Genoa Municipality web page (under construction) showing the weather station network of the Municipality administration: daily rainfall amounts (mm) are shown real-time in correspondence of the different rain gauges. The color of small boxes varies in relation to the rainfall amount. The system also provides all the other usual weather parameters in real-time (e.g.: instantaneous, min. and max. temperature, relative humidity, dewpoint, wind direction and intensity) as well as graphs and tables based on historic data.

of real-time rainfall data with rainfall thresholds obtained from previous studies of the Bisagno catchment (Cevasco et al., 2010). Understanding whether the characteristics of measured rainfall are able to trigger (or reactivate) shallow landslides allows civil protection teams to act where they are most needed (Fig. 12). For effective application in the geo-hydrologically complex area that is the Municipality of Genoa, the system described above requires several rain gauges able to provide real-time data. To this end, in 2010 the Municipality set up a network of 24 rain gauges placed in sites of particular relevance to Civil Protection to complement the existing regional rain gauge network (Fig. 13). The reliability of this system can be verified by the occurrence of new heavy rainfall events.

5 Final remarks

Following National Law 24/02/1992 n. 225, the Municipality of Genoa has adopted a number of different measures for geo-hydrological risk mitigation. These measures are structured on different levels: planning, management, structure, understanding, and publication.

The process of documentation and establishment of procedure for the planning and management of emergencies has been continuously updated according to new technical and/or legislative requirements. Current geo-hydrological emergency procedures being set-up include those for both floods and landslides. Considering the growing importance of landslide risk in the Genoa municipal area, a specific operative plan is set to be adopted by the Municipal Administration. In any case, existing plans have been heavily tested as a result of the numerous emergencies faced by the Municipality in recent years (e.g. during the 2002 heavy rainfall event in the Nervi, Sturla and Bisagno valleys and the 2010 flooding in Sestri Ponente). Adopted measures have proven to be effective in several cases, but the 2011 flooding event has shown the need to make improvements in their application.

The peculiarities of the Genoese geo-hydrological environment have necessitated the development of risk mitigation procedures by means of forecasts rather than observation. Alert levels derived from weather forecasts have shown acceptable levels of reliability, especially in the last years, with the ensuing municipal procedures proven to be efficient in the adoption of emergency operations in risk zones, such as traffic (e.g. blocking of roads and bridges along the Bisagno Stream in 2002) or crowd management (e.g. the cancellation of a national football match in 2000). The rescue or evacuation of citizens during emergencies, although less frequent, has also been carried out successfully (e.g. Carpenara landslide in 2000 and Sturla stream flooding in 1999 and 2002). Exceptional measures in hazardous areas resulted in the demolition of buildings (e.g. in the Fontanelle Creek, near Voltri (1998), where a wide debris flow occurred). As regards communication, roadside poster campaigns have also been carried out and information panels are placed at strategic points of the city when alert states are issued. Nevertheless, the flooding that occurred on 4 November 2011 showed that aspects relating to traffic management and communication/public information concerning the perception of geo-hydrological hazard have to be improved. Another issue is that the resolution of the current forecasting systems makes it impossible to know where the heaviest rainfall will occur. That causes many problems in activating emergency interventions, as well as activations of personnel and civil protection volunteers and alarms on the catchment effectively hit by the precipitation.

However, significant mitigation of the effects of natural disasters in the Genoa area could only be achieved by physical construction work, at all scales. Since a century of urbanization has widely modified the drainage network and reduced the runoff sections of almost all watercourses, structural engineering may be the only way to reduce the risk of flooding at a local scale as provided by the Basin Master Plan. A large amount of significant work has been carried out in the last few years, including the restoration of covered channel sections (e.g. the Bisagno Stream between Brignole and Foce), the adjustment of flow sections through levée (e.g. the Polcevera Stream between Bolzaneto and Cornigliano; the lower stretch of the Sturla Stream), channel modification by means of tunnels (e.g. Nervi Stream), as well as the demolition and relocation of buildings adjacent to channels (e.g. in the Fontanelle creek in 1998, in the Varenna Stream in 2000 and in the Fereggiano Stream in 2009). Nevertheless, physical construction works of fundamental importance to reduce flood risk, such as the underground floodway for the Bisagno Stream, already designed since the nineties, have still not been executed. On a smaller scale, although just as important, are the projects associated with the areas most at-risk of landslides, with five of these (classified as "R4" or maximum risk by the regional government of Liguria) already financed. The most note-worthy of the low-cost immediate interventions made by the Municipality of Genoa to reduce geo-hydrological risk is the recent installation of automatic gate blockers for many city underpasses.

From a planning perspective, it should be necessary to rethink the whole process of urban development, which in the last century indiscriminately expanded on both steep hill sides and on narrow fluvial and coastal plains. However, solutions will certainly not be easy to find, especially for politicians and public administrators, since in most cases entire residential buildings or manufacturing facilities will likely have to be demolished and relocated.

Stating that the public dissemination of knowledge is an essential component of risk mitigation and may also help to form a more responsible generation of citizens, new initiatives have to be undertaken in order to increase the awareness of citizens and the effectiveness of communication during geo-hydrological emergencies. One such project soon to be implemented includes a pilot-study in the flood-risk area of the Chiaravagna and Fereggiano Streams, involving the sounding of an alert siren and sending of text messages when channel water levels exceed a certain limit. Moreover, a detailed and pervasive informative campaign specifically addressed to the resident population of risk areas is going to be carried out.

Finally, we emphasize the need for enhancing the link between Genoa Municipality and the Genoa University changed to plural to improve the effectiveness of both interventions and geo-hydrological risk mitigation strategies adopted for civil protection purposes.

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