Geogr. Fis. Dinam. Quat.
33 (2010), 205-213, 4 figg., 5 tabb.

GUIDO NIGRELLI (*) & CHIARA AUDISIO (*)

FLOODS IN ALPINE RIVER BASINS (ITALY): AN INTERDISCIPLINARY STUDY COMBINING HISTORICAL INFORMATION AND HYDROCLIMATIC DATA

ABSTRACT: NIGRELLI G. & AUDISIO C., *Floods in Alpine river basins (Italy): an interdisciplinary study combining historical information and hydroclimatic data*. (IT ISSN 0391-9838, 2010).

In the hydrographic basins of the Alps, well-defined meteorological configurations lasting several consecutive days give rise to extraordinary rain events. These events often impact on the catchments, with repercussions on the valley floors and along the main channels network. Floods are frequent with ever greater associated damage. The Research Institute for Geo-hydrological Protection of the National Research Council (IRPI-CNR) has developed an interdisciplinary procedure for flood study. In this procedure, hydropluviometric data and information acquired from historical documentary sources are combined. The method is specifically designed to identify areas exposed to flood danger. The procedure has been applied in the Orco river basin and this paper reports the results of this work.

KEY WORDS: Rain events, Floods, Historical data, GIS, European Alps.

RIASSUNTO: NIGRELLI G. & AUDISIO C., *Studio dei fenomeni alluvionali nei bacini alpini mediante l'utilizzo di informazioni storiche e dati idropluviometrici*. (IT ISSN 0391-9838, 2010).

Nei bacini idrografici alpini, gli eventi pluviometrici più importanti si originano da poche e ben definite configurazioni bariche e durano di norma alcuni giorni consecutivi. Questi eventi hanno spesso ripercussioni sul territorio ed i loro effetti si manifestano con maggior evidenza nei fondivalle e lungo la rete idrografica principale, dando origine in molti casi a fenomeni alluvionali. I danni alle attività antropiche sono spesso molto gravi. Per lo studio di queste problematiche, l'Istituto di Ricerca per la Protezione Idrogeologica del CNR, ha messo a punto una metodologia di analisi particolarmente indicata per l'individuazione delle aree esposte al pericolo di inondazione. Essa si basa sull'analisi integrata evento-fenomeno-danno. Le diverse tipologie di informazioni raccolte vengono inserite in un GIS, opportunamente modificato per poter gestire in forma integrata e secondo criteri oggettivi le notizie storiche e d'archivio relative ai tipi di fenomeno ed ai danni. In questo lavoro viene illustrato l'approccio metodologico seguito ed un caso di studio in cui questo è stato applicato.

TERMINI CHIAVE: Eventi pluviometrici, Alluvioni, Dati storici, GIS, Alpi.

INTRODUCTION

Over the past 25 years, the annual number of flood events and flood victims has increased alarmingly. Since 1990, 259 major river floods have been reported in Europe, of which 165 have been reported since 2000 (EEA, 2008). Within Europe, Italy ranks first in the variety of natural instability processes. According to historical research, 11 000 landslides and 5 400 flood events have occurred in the past 80 years, incurring billions of euros in damage. Since 1980, some 42.4 billion euros have been paid out by the Italian government (Luino, 2005). Climate change among other factors is likely to further increase the frequency of extreme flood and flash flood events, which carry the highest risk of fatality.

The climate of the Alpine region is characterized by a high degree of complexity due to the interactions between the mountain environment and the general circulation of the atmosphere (Beniston, 2005). Throughout the Alps, annual winter and summer temperature records indicate a gradual warming as compared to the colder conditions prevalent before 1900; 2003 holds the record as the warmest year since 1500 (Casty & *alii*, 2005). Since 1980, another 20-30% of the remaining ice has been lost. Since 1850, glaciers in the Alps have lost approximately two-thirds of their volume, with a clear acceleration since the 1980s. In the hot, dry summer of 2003 alone, 10% of the remaining glacier mass was lost (EEA, 2008). A gridded precipitation analysis of the European Alps (1901-1990)

(*) *CNR - Istituto di Ricerca per la Protezione Idrogeologica, UOS di Torino* (www.irpi.to.cnr.it).

We wish to thank ARPA Piemonte for providing data, the Società Meteorologica Italiana for information and data, and Dr. Tropeano (IRPI, UOS di Torino) for his useful suggestions during revision of the manuscript. Special thanks are due to anonymous reviewers for their helpful comments and suggestions.

has revealed a significant decrease of 20-40% in autumn precipitation in Northern Italy (Schmidli & *alii*, 2002). In the Western Alps and Western Po Plain, annual precipitation has decreased by about 5%, the greatest seasonal decline (-9%) occurring in spring with (Brunetti & *alii*, 2006; Buffoni & *alii*, 2003). A major cause for concern is the increase in rainfall intensity in the area, particularly in the highest class interval (Brunetti & *alii*, 2001; Brunetti & *alii*, 2002). In the Southern Alps, closed cyclonic fields with orographic control characterized by prolonged rainfall are generally responsible for extensive flooding in spring and autumn, as occurred in September 1993 and October 2000 (Weingartner & *alii*, 2003).

The discussion on the relationship between prolonged rainfall and extensive floods which can cause widespread damage needs to take in account two important considerations. First, the impact of climate change on the Alps does not appear to be solely responsible for the recent increase in flood events and economic losses. Inappropriate land planning and land-use should be considered a determinant factor for the rise in economic loss (Arnaud-Fassetta & *alii*, 2005). Second, prolonged rainfall does not always result in a flood event, as demonstrated by some alpine environment studies (Lollino & *alii*, 2005; Luino, 2005). In addition, regional law promulgated by the Piemonte Regional government has underlined the value of historical research as a starting point for delimiting the boundaries of human activities (Regione Piemonte, 1999b).

Historical flood records can be obtained from a wide variety of sources: town libraries, municipal and governmental archives, parish and newspaper archives (Tropeano & Turconi, 2004; Audisio & *alii*, 2009). The study of floods based on historical documentary sources in Europe began with large-scale data collection around the second half of the 19th century, but only recently has flood research been set within a modern climatic perspective (Llasat & *alii*, 2005). Some international examples of the use of historical records for estimating natural hazards are reported in Tropeano and Turconi (2004). Other recent studies include Govi and Turitto (1997), Plate (2002), Weingartner & *alii* (2003); Benito & *alii* (2004); and Loukas & *alii* (2004). However, few authors have correlated historical information describing flood phenomena and damage with instrumental hydropluviometric and meteorological data (Arnaud-Fassetta & *alii*, 2005; Llasat & *alii*, 2005).

The collection and analysis of historical records, the chronological reconstruction of rainfall events, the description of types of phenomena and related damage and the affected areas are the focal points of this research. The methodology uses GIS to analyze historical data and to delimit the areas that, over time, were more frequently affected by floods. The aim of this method is not to replace conventional procedures applied on national and regional scales but rather to provide a useful tool for identifying the areas where hazard is individuated by major damage in an Alpine river basin and to determine hydropluviometric reference values for identifying alert zones and for the purposes of civil protection engineering. In operation and application, the method is situated in an intermediate position between simple information that can obtained from a data acquisition network and complex warning systems.

The paper describes the methodology used in collecting and analyzing data and the results in a catchment of the Italian Western Alps (Orco River basin).

METHODOLOGY

Two levels of data entries combine in the integrated study approach applied in this research: hydropluviometric data and information acquired from historical documentary sources. The applied methodology, particularly the use of GIS and data entry, has been illustrated in Audisio & *alii* (2009).

Hydropluviometric data

In the method described here, we take the rain event as a defined meteorological and climatic entity. For flood studies, a rain event of several days duration is, in our opinion, one of the main phenomena that acts directly on modelling the Alpine landscape. Depending on total rainfall depth, peak rainfall amount, mode and season in which it occurs, the event can quickly trigger dangerous fluvial or slope phenomena. When possible, meteorological analysis of flood events identified in documentation sources is a valuable tool for understanding potential scenarios with strong rainfall variability (Llasat & *alii*, 2005). Construction of meteoclimatic scenarios that can generate a flood is done by integrating information from a synoptic analysis with data on rain events. By extrapolating the hydropluviometric values for various floods, a critical range can be obtained as a reference. For flood analysis in mountain areas, it is extremely useful to have a basin-scale critical range as reference to identify the so-called point and areal rainfall thresholds. Archiving, validation and processing of the climatic data were done using a dedicated database (Nigrelli & Marino, 2008). The hydropluviometric aspects can be characterized in six steps:

1. Selection of rain and river flow gauging stations. Greater representativeness based on number of years in operation, data quality and geographic position in the river basin are the advantages of the extended data.
2. Creation of a rain events database. In this method we considered: rain event (Re), i.e., one or more consecutive rainy days preceded and followed by a zero value; rainy day, i.e., the day with a rainfall depth ≥0.2 mm; peak day (Pd), i.e., the day the most rain fell.
3. Analysis of rain events. Based on total rainfall amount (Rtot) and rainfall amount on peak day (Rmax), the most common frequency patterns are determined for duration, peak day, and seasonal distribution.
4. Synoptic and mesoscale analysis. For rain events that caused floods and for extreme rain events (Re with a high level of Rtot and Rmax), the meteorological configuration responsible and their spatiotemporal evolution need to be identified.

5. Ordinary and catastrophic floods analysis. Identify the water levels and the peak flows. Where possible, when pluviometric and hydrometric data have been recorded at intervals shorter than hourly, it is extremely useful to determine the lag time (the measure of the catchment response time).
6. Detection of the hydropluviometric critical range. For every flood, data on the meteorological configuration that generated the rain event, the total point rainfall height, the point peak height and the flows responsible for the phenomenon can be extrapolated. Particular attention should be paid to interpreting the entire meteoclimatic situation and the lowest values. Then, after a comparative analysis of the examined floods, the critical range of values to be referred to similar areas are compared. For the purposes of this method, we think it is more correct to use point data instead of areal data. In this way, the rainfall heights recorded in various points across the basin can be directly compared for each event to obtain useful information for application purposes.

Historical data

Before the data can be coherently organized, various types of archives need to be found and explored from which documents can be selected and collected for analysis (Govi & Turitto, 1990).

The IRPI-CNR institute has exploited for this river basin a wide array of historical sources related to floods: for the analysed basin, about 100 legacy archive information, 50 original papers and studies, more than 60 scientific and technical publications, and a newspaper article collection dating back to the early 1800s. Most documents date from the early 19th century, but there are also records from the 17th and 18th centuries. Other sources incude about 400 aerial photographs taken from 1945 to the present, 800 survey data and several electronic databases.

GIS technology

Hydropluviometric and historical data were inserted in a GIS. The software (ESRI ArcView) has an application specifically developed for entering historical information. The application was created using the software extension «Dialog Designer» to set up a form and a series of customized scripts compiled with Avenue scripting language (Audisio & *alii*, 2009). The form constitutes the Graphic User Interface of the event-phenomenon-damage point theme. The point theme is the geographically-referenced database of the Sistema Informativo Territoriale Rischio Idraulico e Geologico, SIT-RIG (Lollino & *alii*, 2005). With this application, the point theme elements and the rainfall data can be associated with the type of phenomenon and the damage it caused. The records in the event-phenomenon-damage theme are compared and analyzed with the other layers stored in the SIT-RIG with the ESRI Spatial Analyst extension. A simple multi-layer analysis reveals the areas of major hazard and flood frequency in the river basin under study. The connection between hazard and risk is related to the extent of damage caused by natural processes to buildings and infrastructures. With this kind of approach, useful information can be obtained for multilevel land-use planning, where the issues concern the study area, environmental protection and estimation and mitigation of hydrologic and geologic hazard (Allegra & *alii*, 2003; Audisio & *alii*, 2009).

CASE STUDY: THE ORCO RIVER BASIN

The study area

The Orco River basin lies in the Graian Alps (Western Piedmont), bordering to the north with the Aosta Valley, taking part of the Gran Paradiso National Park; to the south with the Stura di Lanzo Valley, to the east with the Po Plain, and to the west with France and the Parc National de la Vanoise (fig. 1). The Orco basin ends at its confluence with the Po River. The hydrographic network displays a dendritic drainage pattern. The Orco's main morphometric and hydrologic parameters are shown in table 1. Geologically, the basin is part of an area dominated by Upper Pennidic Units of the Gran Paradiso massif composed of a crystalline basement in which augen gneiss predominate (Compagnoni & *alii*, 1974). The eastern border is marked by formations belonging to the Piedmontese Zone, composed of calcshists bearing green rocks (Ophiolite); externally there are units of the polycyclic basement of the Sesia-Lanzo Zone composed of micaschist and paragneiss (Venturini, 1995). Morphologically, the basin is characterized by a mountain sector and a plain sector. The first sector, stretching from the valley head to the town of Courgnè, is characterized by glacial morphogenesis. The valley floor morphology is primarily characterized by fluvial and stream dynamic processes. The main river is at a young stage of evolution, with steep gradients, marked erosion phenomena and many areas of flooding (Audisio, 2002). Intense summer storms may trigger soil slips. The soil slips can lead to stream debris flows with large amounts

TABLE 1 - Orco river basin: main morphometric and hydrologic parameters ([a] calculated by GIS techniques based on Regione Piemonte Official Cartography; [b] source Provincia di Torino, 2002)

Main morphometric parameters[a]		
Area	km^2	890
Perimeter	km	210
Highest elevation point (Punta il Roc)	m a.s.l.	4025
Lowest elev. point (Orco-Po confluence)	m a.s.l.	177
Mean slope angle	degrees	27.1
Mean exposure		E - NE
Main hydrologic variables[b]		
Mean annual rainfall	mm	1180
Mean annual runoff	mm	861
Mean annual flow	m^3/s	24.9
Orco river length	km	85.7
Mean river slope angle	degrees	1.4

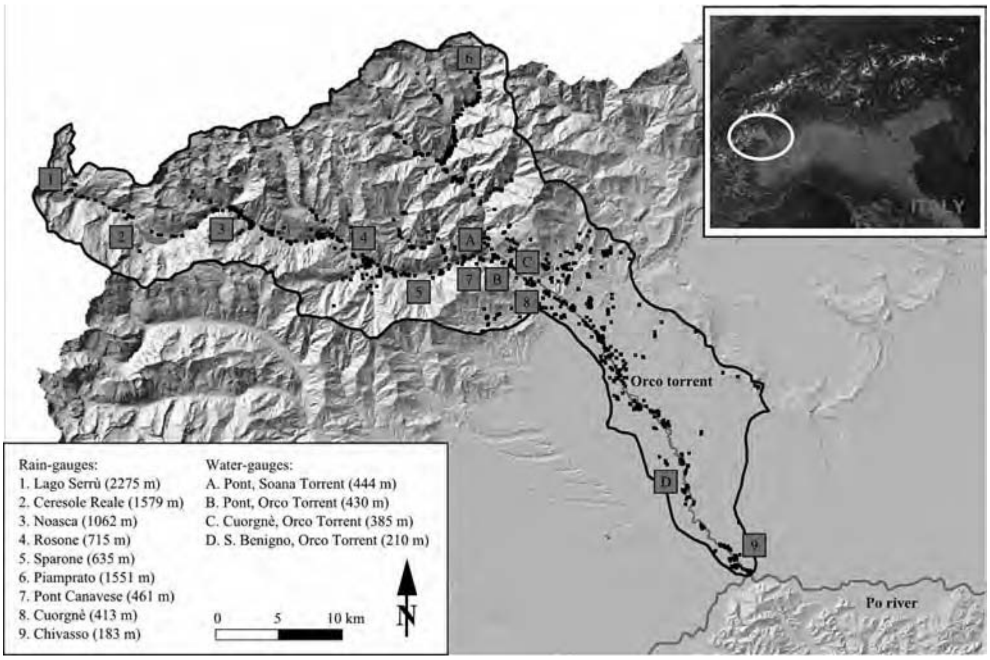

FIG. 1 - Orco river basin: location map, rain-gauges (m a.s.l.), water-gauges (the zero of the gauge, m a.s.l.) and event-phenomenon-damage GIS dataset (1053 solid points).

of solid deposition on alluvial fans often occupied by small towns. The second sector stretches from Cuorgnè to the Orco's confluence with the Po. It is characterized by erosion-deposition phenomena typical of river plains. Here, the river attains a state of equilibrium characterized by a multi-thread pattern but with a tendency to single-thread defined by its morphologic evolution rather than by the impact of human activity (Turitto & *alii*, 2008).

The climatic conditions differ markedly because of areas of highly different morphology (fig. 2). The average monthly temperatures show a typical bell-shaped curve distribution; substantial differences at higher elevations and geographic position are found in the mean and extreme values. The coldest and the warmest months are January and July, respectively. The average monthly rainfall has a bimodal distribution typical of Alpine climate environments. The main seasonal minimum is in winter and the main maximum and secondary maximum are found in spring and autumn, respectively. Recent studies have shown a significant increase in mean annual temperature in the basin (1980 to present). Rainfall intensity records show no significant trends (Mercalli & Cat Berro, 2005).

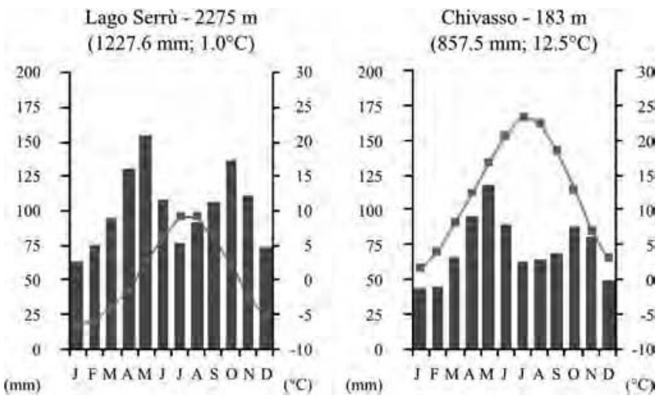

FIG. 2 - Orco river basin: Mean monthly rainfall (bars) and mean monthly temperature (boxes) at the Serrù Lake station (period 1955-2005) and Chivasso station (period 1875-1991). The elevation of the station is given next to the place name (m a.s.l.); total annual rainfall and mean annual temperature are shown in brackets (data from Mercalli & Cat Berro, 2005).

Floods

Over the past century, the Orco catchment has been repeatedly struck by major floods that have had a major impact on hillslopes and along the river network, causing damage to infrastructures and occasionally fatalities. After the September 1993 flood, a study by the Regione Piemonte Government stated that «The historical data in the geologic database indicate that the Alpine valleys of the Orco river are among those in Piemonte that have been heavily struck most often by floods… Generally, based on available data, the Orco valley appears to be affected by flood events of a certain importance with a recurrence of about 10 years». (Regione Piemonte, 1996a). Seven years later, the October 2000 flood struck the Orco valley once more. On May 2008, an extreme rain event in Piemonte also involved the Orco valley and triggered several flood processes (ARPA Piemonte, 2008d).

Studies by IRPI-CNR in this basin have shown that 140 flood events have been recorded over the past 400 years. A brief frequency analysis revealed that, on average, floods caused damage or destruction about every 3-8 years (Tropeano & Turconi, 2005). Between 1868 and 1978, landslides and stream floods in one place or simultaneously in several places occurred about every 3 years on average (Govi & Turitto, 1994). The documented floods were classified into three levels of criticality based on slope and stream dynamics, size of area involved and damage incurred (table 2). Other remarkable floods are those of July 1654, October 1845, October 1907 and August 1900.

TABLE 2 - Orco river basin: main historical floods of the last 250 years classified into three criticality levels (adapted from Govi & Turitto, 1994)

level 1	
2000/10/13	*Mountain sector*: widespread landslides, violent torrential
1957/06/12	floods and intense erosion with local damage to settle-
1947/09/25	ments and roads, serious in places.
1938/09/08	*Plain sector*: overflows and pulsatory modifications to river
1755/10/14	bed; floods and extensive flooding with road damage.
level 2	
1993/09/22	*Mountain sector*: landslides, local stream floods and in-
1948/09/04	tense erosion along the stream course with damage to set-
1866/09/26	tlements and roads.
1827/05/11	*Plain sector*: overflows with modifications to the bed; floods
1829/11/07	and extensive flooding with road damage.
level 3	
2008/05/24	*Mountain sector*: some landslides, floods and erosion par-
1962/11/05	ticularly along the stream course, with local damage to
1958/08/19	towns and roads.
1945/10/29	*Plain sector*: local flooding.
1920/09/24	
1852/08/20	

Some data in the SIT-RIG date back to 1600; a total of 1053 georeferenced records provide good continuity over a span of 200 years (1800-2000). Multidisciplinary analysis was performed on the two morphologically very different sectors that exhibit different types of phenomena: the mountain sector (from the valley head to Cuorgnè) and the plain sector (from Cuorgnè to the Orco's confluence with the Po). The increase in human activity along the valley floor, together with the lack of room for flood expansion, has forced people to occupy high hazard zones (alluvial fans, intravalley plains and river corridor). Damage is chiefly caused by the action of lateral tributaries that deposit large quantities of material, debris flows and mudflows and by intense stream action that causes large processes of overflow, bank erosion and flooding along the main stream. Possible reactivation of old phenomena of ever larger extent or triggering of soil slips contribute to a lesser degree to life lines damage.

Based on the SIT-RIG data processing, the areas with the highest flood frequency and magnitude, hence indicated as those at greatest danger (the reference numbers are reported in fig. 3):

I. The Noasca village and the left hydrographic slope downstream from the settled area. The greatest damage has been caused by debris flows along the Orco's left and right tributaries, which repeatedly involved weirs and defense works, also damaging roads in particularly extreme events (May 1949, June 1957, September 1993, October 2000). The damage caused by the floods along the Orco river involved the main road (State Highway 460) downstream from Noasca.

II. Rosone village (Locana). The major damage is attributable to a highly complex landslide (Luino & *alii*, 1993) belonging to an extensive deep-seated gravitational deformation that was reactivated following intense rainfall, leading to rock falls and soil slips which reached the highway, damaging it in several places. In addition, the Piantonetto stream (a left tributary of the Orco) deposits large amounts of debris on the alluvial fan, sometimes damaging the hydroelectric plant during extraordinary rainfalls associated with mass stream transport.

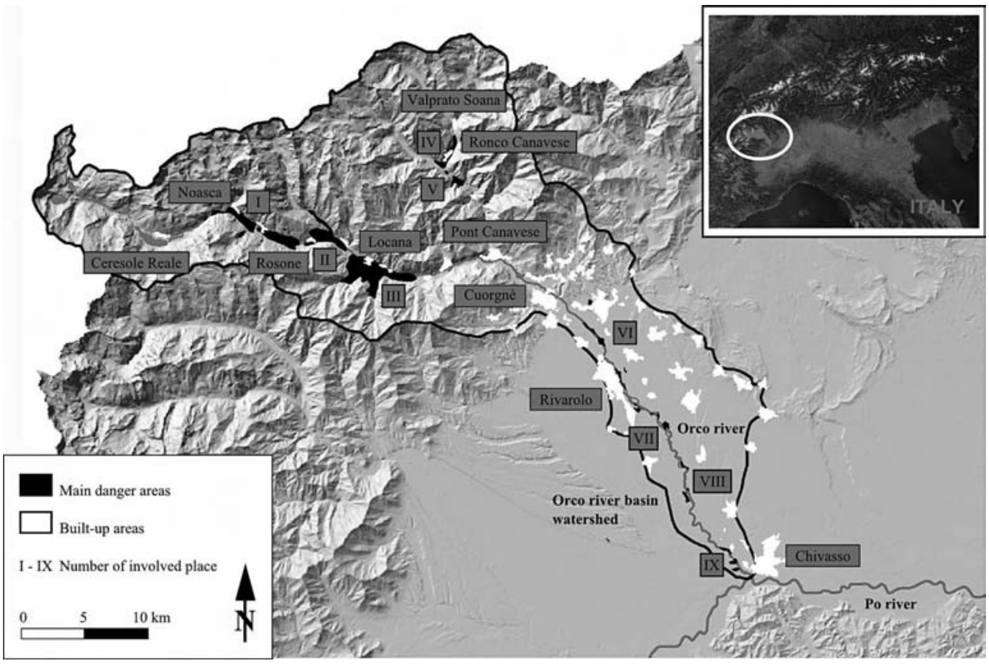

FIG. 3 - Orco river basin: main danger areas. Numbers indicate the involved place: explanation are in the text.

TABLE 3 - Chief meteorological configurations (MC) generating rainfall events and floods in NW Italy

Depression type	Low-pressure geographical centre	Symbol
Atlantic	British Isles	A1
	Gulf of Biscay	A2
	France	A3
	Portugal	A4
Mediterranean	Between Algeria and Tunisia	M1
	Between the Balearics and Spain	M2
	Between the Balearics and Sardinia	M3
	Gulf of Lyons	M4
	Corsica-Sardegna	M5
	Côte Azure	M6
	Ligurian Gulf	M7

III. The Locana municipality. Damage is commonly brought to bank revetments and levees. The September 1993 event caused greater damage than that of October 2000, particularly to roads and buildings, with widespread landslides and debris flows. The documents also report damage to the bridge connecting Locana with Nusiglie (September 1947, June 1957).

IV. Ronco Canavese village. Intense bank erosion on the right slope of the Soana torrent (the largest tributary of the Orco, in which it inflows near Pont Canavese) has repeatedly damaged the main road (Provincial Highway 47) in several places, along with defense works, paths and bridges. Severe damage was also caused to buildings and public works. Sometimes, primarily around the early 20th century, several tributaries of the Soana were involved by debris flows, causing severe damage to public works, roads and buildings (1900 and 1907 floods events).

V. Villanuova village (Ronco Canavese). Repeated stream erosion on the right bank by the Soana torrent damaged and in some cases washed out stretches of the main road (Provincial Highway 47), portions of bank revetments and buildings. Paroxysmal phenomena of hyperconcentrated flow in a right tributary of the Soana have repeatedly damaged the roadbed and nearby houses (1654, October 1755, 1805, 1845, 1908, September 1981, September 1993, October 2000).

In the plain sector (from Cuorgnè housings to the inflow of the Orco in the Po River), the most severe damage occurred to river crossings and roads, bank protections and buildings. The northern sector, between Cuorgnè and Rivarolo Canavese, has the highest point density. Farmlands extending over the flood plain were most severely and repeatedly damaged by erosion or flooding, as were those with vegetation cover (bushes and trees), which played an important role in containing and laminating the flood waters. The hardest hit areas were:

VI. the left hydrographic side, east of Salassa village: sometimes repeated major damage to levees; re-activation of secondary channels. During the October 2000 event, one bridge collapsed, claiming one victim;

VII. the area east of Feletto village: repeated damage to left bank protection works and the left bridge approach (damaged in October-November 1945, November 1951, May 1961); the bridge over the river collapsed (1852, 2000). On the hydrographic right side, widespread flooding caused damage to buildings and required evacuation (Cascina Bianco) in some areas, while tree farms (prevalently poplar stands) were damaged on the left side;

VIII. the left hydrographic area, near Frazione Cortereggio (San Giorgio Canavese): the village and the area to the north were affected by deep erosion in the left bank and flooding which destroyed buildings in some cases (1920). Much of the information derives from construction plans of defense works erected to protect the village but often damaged in later flood events;

IX. the left hydrographic area, west of Frazione Pratoregio (Chivasso): widespread flooding along river corridor areas used as farmland involved farmhouses, field roads and buildings (1835, September 1993, November 1994).

The area and numbers are reported in fig. 3.

Rainfall reference values

Rainfall reference values were determined from the data collected from various sources (ARPA Piemonte, 2008a, 2008b, 2008c; Mercalli & Cat Berro, 2005; Ufficio Idrografico e Mareografico di Parma, 1920-2005). The use of multisource data was necessary because, in compliance with the agreement between the State and the Regions of 24 May 2001, the Regions are mandated to super-

TABLE 4 - Orco river basin: floods 1913-2008, water-level values at peak flow time. Wl, water level; Pf, peak flow; Wg, water-gauge; Da, drainage area; MC, meteorological configuration; nd, no data available; a, similar data from indirect measurements; b, water-gauge on the Orco at Spineto, about 2 km downstream from Station C; c, the bridge carrying hydrometer D was destroyed in the Second World War and during the 1948 flood; it was rebuilt and widened but destroyed again in the 1993 flood; a modern water-gauge was later installed on a newly rebuilt bridge; d, uncertain data because the meter failed during a rainfall event. See figure 1 for location of stations, figure 4 for observation period related to single stations and table 3 for details on MC

Flood	Time	Wl (m)	Pf (m^3/s)	Wg	Da (km^2)
2008/05	2008/05/29 - 19:00	2.27	300	C	630
	2008/05/30 - 06:00	2.32	400	D	846
2000/10	2000/10/15 - 03:30	4.28	900	A	214
	2000/10/14 - 12:30	4.29	1650	C	630
	2000/10/14 - 15:30	4.11	nd	D	846
1993/09	1993/09/24 - 16:00	5.50a	1500	Cb	656
	1993/09/24 - 17:00	6.16a	1600a	D	846
1962/11	1962/11/08 - 07:00	5.44	1260	B	617
1958/08	1958/08/19 - 22:00	3.88	474	B	617
1957/06	1957/06/14 - 11:00	4.20	620	B	617
1948/09	1948/09/04 - 16:00	5.10	1070	B	617
1947/09	1947/09/26 - 07:00	5.74	1410	B	617
1945/10	1945/10/31 - 09:00	5.00d	1140d	B	617
1938/09	1938/09/10 - 06:00	4.90	970	B	617
1920/09	1920/09/24 - 13:30	3.00	1350	Dc	875

vise management of personnel and observation networks of the Servizio Idrografico e Mareografico Nazionale. Unfortunately, since the sources are several, the time scales of the available rainfall data are not uniform (fig. 4). In the analysis of the meteorological configurations, data come from the ECMWF data server (www.ecmwf.int) and the German Wetterzentrale internet site (www.wetterzentrale.de).

Analysis of the rain events revealed the predominant types of events and the meteorologic configurations that gave rise to them. The maximum rain event in the study area during 1-5 consecutive days was observed at Rosone and refers to the October 2000 flood event (413.8; 649.0; 816.2; 836.0 and 855.8 mm on days 1÷5, respectively). In the Orco valley (Rosone) and in the Simplon area (Ossola, northern Piemonte), the two nuclei of maximum rainfall related to this event were identified in reference to an area that covered Piemonte, Liguria, southern Switzerland and eastern France (ARPA Piemonte, 2003).

The most common rain event in the Orco valley lasts between 3 and 7 days on average (952 total events). In 50% of observed cases, rain events with rainfall height >100 mm peak on day 2 or day 3.

Extreme rain events (total rainfall depth >350 mm) last 9 days on average and peak is attained on day 3 (20 events, 34%) and generally occur in autumn (55%) and spring (40%). The most frequent meteorological configurations giving rise to such events are characterized by Mediterranean low pressure areas centred over the Gulf of Lyons and Corsica-Sardinia (24%) and the Balearic Islands and Spain (19%). In some cases, an anticyclone block over eastern Europe causes a low pressure area to persist over western Europe, generating considerable rainfall (October 2000 flood).

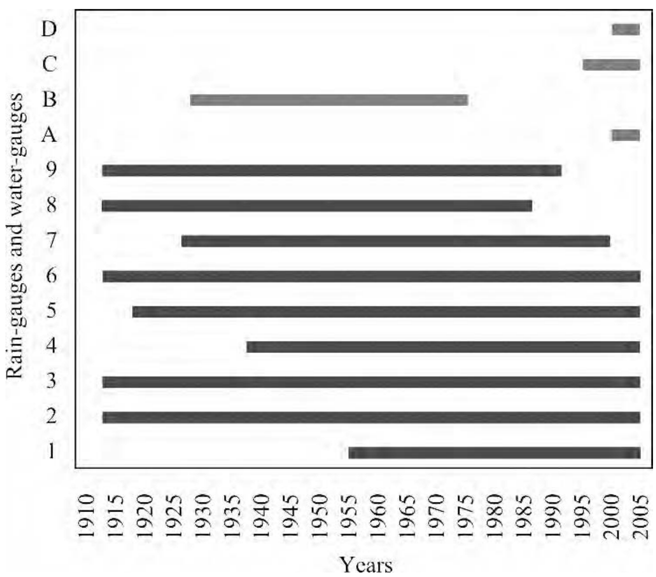

FIG. 4 - Orco river basin: observation period related to single stations. (see figure 1 for location of stations).

TABLE 5 - Orco river basin: extreme rainfall events (1913-2008). The asterisk denotes a flood event. Rtot, total rainfall; Rmax, total peak day rainfall; Re, duration of the rainfall event; Pd, peak day of the event; MC, meteorological configurations. See figure 1 for location of stations, figure 4 for observation period related to single stations and table 3 for details on MC

Data and station		**Rtot (mm)**	**Rmax (mm)**	**Re**	**Pd**	**MC**
2000/10/10 (*)	4	868.0	413.8	8	6th	M4
1993/09/22 (*)	6	583.4	187.8	5	3th	M4
1962/11/05 (*)	6	577.6	312.2	9	4th	M4
1981/03/29	4	518.4	218.0	5	4th	M5
1994/11/02	6	505.2	360.4	6	4th	M2
1977/04/28	7	482.4	129.8	11	3th	A1 - M2
1957/06/07 (*)	2	457.2	90.4	11	9th	M5
1945/10/29 (*)	4	450.0	150.0	6	2th	n.d.
2008/05/24	2	433.8	155.0	20	6th	M7
1986/04/13	1	427.6	75.0	17	12th	M5 - A1
1937/10/21	2	408.4	69.0	14	8th	M2
1941/09/28	5	405.0	134.0	9	7th	M5
1933/09/25	2	396.8	130.6	5	4th	A1
1949/04/30	4	393.4	112.0	8	3th	M2
1993/04/25	5	378.6	106.2	20	2th	A2
1953/10/13	6	371.0	88.0	18	7th	M5
1926/05/14	5	370.0	200.0	4	3th	M7
1920/09/22 (*)	5	365.8	170.0	6	3th	M4
1995/04/20	4	363.8	128.4	7	3th	A3
1976/10/24	6	360.0	120.0	6	3th	M3
1937/05/20	2	351.0	288.0	3	2th	M4

Comparing the data in table 5, one can note that the 22 September 1920 event originated from a Mediterranean depression centred over the Gulf of Lyons, like the first three events listed, and caused a flood even though the rainfall values were relatively modest compared to the other events marked with an asterisk (about 366 mm rainfall in 6 days). In contrast, the rain event of 29 March 1981 (fourth on the list), despite a total rainfall height of 518.4 mm, did not produce any floods. The August 1958 rainfall event (total depth 196.8 mm) generated a flood. The difficulty in correctly identifying rainfall thresholds for this type of natural phenomena lies largely in this paradox and in the role past rainfall events have played.

Based on these descriptions, the range of daily rainfall depths, which could be taken as reference, should be two-sided in relation to the two seasons with greater rainfall amounts (spring and autumn). There is a wider range in spring than in autumn (reference values 130-160 mm/day versus 100-130 mm/day, respectively). Autumnal rainfall events are more intense and more dangerous than those occurring in spring owing to the energy they draw from the warm Mediterranean waters. In addition, the catchment response to such events (i.e., the ability to retain rainwater and discharge runoff into the drainage network) appears lower than in spring events. Eight out of the 11 floods listed in table 4 occurred, in fact, in autumn. The estimated flow alert threshold for the Orco river is around

$600 \text{ m}^3/\text{s}$ in the segment downstream from its confluence with the Soana torrent. Use of these data should also take into account the fact that the study basin has a relatively short time lag (see table 1). Upstream from its confluence with the Soana, particularly in winter, some segments of the Orco stream bed are nearly dry. Water extraction for generating hydroelectric power and irrigation is the principal factor that modifies discharge in the stream bed. In some cases, for example during the October 2000 flood, artificial dammed lakes for hydroelectric plants at the basin head positively influenced the maximum flow discharge thanks to the meteoric waters.

DISCUSSION AND CONCLUSIONS

Several studies have investigated Orco river basin floods. However, this analysis is the first to evince that the flood-prone areas, and hence those with higher hazard and risk, within an Alpine basin are always the same. In most cases, the differences in the affected area will depend on the magnitude of the event.

The increased hazard and risk is largely due to human activity encroaching into these areas. In the last 50 years, the number of buildings, roads, bridges and related defence structures has progressively increased in the plain area. On the one hand, such artifacts have somewhat influenced the natural processes; on the other, these elements are to be considered vulnerable. The records from the last 60 years inserted in the SIT-RIG document damage to roads (28%), bridges (22%) and buildings (15%) in both the mountain and the plain sectors. Since the delimited areas lie close to the main hamlet, their detection can be very useful for research purposes. However, an intrinsic problem with historical data is that phenomena occurring far away from settlements are not likely to be noted. This influences the analysis, because the absence of hazard evidence might be mistaken for a real absence of hazard.

A interdisciplinary approach using historical and rainfall data may be better able to define territorial boundaries and rainfall range, and thus identify danger areas. This can be best achieved by taking into account the historical evolution of land use and the frequency of past events so as to improve our understanding of what occurred in the past. The reliability of the obtained result fairly approximates the quality and quantity of available data.

Compounding the complexity of these studies is climate change and its more easily perceivable manifestations: temperature and precipitation. The response of the Alpine environment to increased temperature is all too evident, particularly at higher elevations where glacial head retreat and ice mantle reduction continue year after year (Chiarle & *alii*, 2007; Chiarle & Mortara, 2008). Compared to past records, rainfall appears to have become more intense and so more dangerous. The fact remains that flood frequency in Alpine basins has increased alarmingly in recent years. In light of this scenario, whose evolution is still unclear, it is important to step up basin-scaled studies.

REFERENCES

ALLEGRA P., FADDA M., LOLLINO G., NIGRELLI G. & PORPIGLIA M. (2003) - *WebGIS application to an informatic territorial database for natural risk mitigation*. Proceedings of the 4th European Congress «Cartografia Geoscientifica Regionale e Sistemi Informativi, dati geoscientifici per la pianificazione territoriale», Bologna, Italy, June 17-20, 376-378.

ALLEGRA P., AUDISIO C., LOLLINO G. & NIGRELLI G. (2004) - *Land-use planning and risk management: a multi-temporal GIS analysis applied to hydrogeological instability phenomena*. Proceedings of the 32nd International Geological Congress, Florence, Italy, August 20-28, 115 pp. and poster presentation.

ARNAUD-FASSETTA G., COSSART E. & FORT M. (2005) - *Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queyras, Southern French Alps)*. Geomorphology, 66 (1-4), 41-67.

ARPA PIEMONTE, (2003) - *Eventi alluvionali in Piemonte. Evento alluvionale regionale del 13-16 ottobre 2000*. Settore Studi e Ricerche Geologiche, Sistema Informativo Prevenzione Rischi. Torino, Italy: AGES, Arti Grafiche, 327 pp.

ARPA PIEMONTE (2008a) - *Banca dati idrologica*. On line at http://www.arpa.piemonte.it/.

ARPA PIEMONTE (2008b) - *Banca dati meteorologica*. On line at http://www.arpa.piemonte.it/.

ARPA PIEMONTE (2008c) - *Banca dati meteo-idrologica in tempo reale*. Servizio ANTARES. On line at http://www.arpa.piemonte.it/.

ARPA PIEMONTE (2008d) - *Rapporto preliminare sull'evento alluvionale del 28-30 Maggio 2008. Analisi meteoidrologica ed analisi dei processi e degli effetti al suolo*. Torino, 4 Giugno, 85 pp.

AUDISIO C. (2002) - *Analisi geomorfologica dei conoidi di deiezione della Val Soana*. Università degli Studi di Torino, Graduation thesis, 240 pp. (Unpublished).

AUDISIO C., NIGRELLI G. & LOLLINO G. (2009) - *A GIS-based tool for historical instability processes data entry: an approach to hazard management in two Italian Alpine river basins*. Computers & Geosciences, 35, 1735-1747. Doi:10.1016/j.cageo.2009.01.012

BENISTON M. (2005) - *Mountains Climates and Climatic Change: An Overview of Processes Focusing on the European Alps*. Pure and Applied Geophysics, 162 (8), 1587-1606.

BENITO G., LANG M., BARRIENDOS M., LLASAT M.C., FRANCÉS F., OUARDA T., THORNDYCRAFT V.R., ENZEL Y., BARDOSSY A., COEUR D. & BOBÈE B. (2004) - *Use of systematic, paleoflood and historical data for the improvement of flood risk estimation. Review of scientific methods*. Natural Hazards, 31 (3), 623-643.

BRUNETTI M., COLACINO M., MAUGERI M. & NANNI T. (2001) - *Trends in the daily intensity of precipitation in Italy from 1951 to 1996*. International Journal of Climatology, 21 (3), 299-316.

BRUNETTI M., MAUGERI M., NANNI T. & NAVARRA A. (2002) - *Droughts and extreme events in regional daily italian precipitation series*. International Journal of Climatology, 22 (5), 543-558.

BRUNETTI M., MAUGERI M., MONTI F. & NANNI T. (2006) - *Temperature and precipitation variability in Italy in the last two centuries from homogenized instrumental time series*. International Journal of Climatology, 26 (3), 345-381.

BUFFONI L., BRUNETTI M., MANGIANTI F., MAUGERI M., MONTI F. & NANNI T. (2003) - *Ricostruzione del clima italiano negli ultimi 130 anni e scenari per il XXI secolo*. Acts of the Workshop «CLIMAGRI - Cambiamenti Climatici e Agricoltura», Cagliari, Italy, January, 16-17.

CASTY C., WANNER H., LUTERBACHER J., ESPER J. & BÖHM R. (2005) - *Temperature and precipitation variability in the European Alps since 1500*. International Journal of Climatology, 25 (14), 1855-1880.

CHIARLE M., IANNOTTI S., MORTARA G. & DELINE P. (2007) - *Recent debris flow occurrences associated with glaciers in the Alps*. Global and Planetary Change, Special Issue on «Climate Change Impacts on Mountain Glaciers and Permafrost», 56, 123-136.

CHIARLE M. & MORTARA G. (2008) - *Geomorphological impact of climate change on alpine glacial and periglacial areas. Examples of processes and description of research needs*. Interpraevent 2008, Dornbirn, 26-30 May 2008, II/111-122.

COMPAGNONI R., ELTER G. & LOMBARDO G. (1974) - *Eterogeneità stratigrafica del complesso degli «gneiss minuti» nel Massiccio cristallino del Gran Paradiso*. Supplemento Memorie della Società Geologica Italiana, 13 (1), 227-239.

EEA (2008) - *Impacts of Europe's changing climate*. European Environment Agency, Report 4, Copenhagen, Denmark. On line at: http://eea.europa.eu.

GOVI M., SERVA L. & TURITTO O. (1990) - *La conoscenza delle piene storiche nelle valutazioni di sicurezza e protezione del territorio*. Sicurezza e protezione, 23-24, 1-13.

GOVI M. & TURITTO O. (1994) - *Elementi per la valutazione della pericolosità idrogeologica nei bacini tributari del Fiume Po.* Autorità di Bacino del Fiume Po «Atlante dei rischi idrogeologici per il bacino del Fiume Po». CNR-IRPI, RT 94/12.

GOVI M. & TURITTO O. (1990) - *Recent and past floods in Northern Italy*. Workshop River Flood Disasters, ICSU SC/IDNDR, Koblenz, Germany, 13-32.

LLASAT M.C., BARRIENDOS M., BARRERA A. & RIGO T. (2005) - *Floods in Catalonia (NE Spain) since the 14th century. Climatological and meteorological aspects from historical documentary sources and old instrumental records*. Journal of Hydrology, 313 (1-2), 32-47.

LOLLINO G., NIGRELLI G. & AUDISIO C. (2005) - *Bacino idrografico del Torrente Orco: analisi integrata evento-fenomeno-danno*. Quaderni di Geologia Applicata, 12 (1), 49-62.

LOUKAS A., VASILIADES L. & DALEZIO N.R. (2004) - *Climate change implications on flood response of mountainous watershed*. Water, Air and Soil Pollution: Focus, 4 (4), 331-347.

LUINO F. (2005) - *Sequence of instability processes triggered by heavy rainfall in the northern Italy*. Geomorphology, 66 (1-4), 13-39.

LUINO F., RAMASCO M. & SUSELLA G. (1993) - *Atlante dei Centri Abitati Instabili Piemontesi*. L'Artistica Savigliano, Torino, 245 pp.

MERCALLI L. & CAT BERRO D. (2005) - *Climi, acque e ghiacciai tra Gran Paradiso e Canavese*. Società Meteorologica Subalpina, Torino, 755 pp.

NIGRELLI G. & MARINO A. (2008) - Dbclim, database per la gestione di dati climatici acquisiti da stazioni meteorologiche di supeficie. On line at http://www.irpi.to.cnr.it/

PLATE E.J. (2002) - *Flood risk and flood management.* Journal of Hydrology, 267 (1-2), 2-11.

PROVINCIA DI TORINO (2002) - *Risorse Idriche Superficiali dei Principali Bacini della Provincia di Torino*. Settore Risorse Idriche On line at: http:// www.provincia.torino.it.

REGIONE PIEMONTE (1996) - *Gli eventi alluvionali del settembre-ottobre 1993 in Piemonte.* A cura dell'Assessorato Ambiente, Cave e Torbiere, Energia, Pianificazione e Gestione delle Risorse Idriche, Lavori Pubblici e Tutela del Suolo - Settore per la Prevenzione del Rischio Geologico, Meteorologico e Sismico. Con la collaborazione del C.N.R. Istituto Italiano di Idrobiologia, dell'Istituto di Idraulica Agraria dell'Università degli Studi di Torino e delle Risorse Idriche S.p.A. Torino, 112 pp.

REGIONE PIEMONTE (1999b) - *Nota Tecnica Esplicativa alla Circolare P.G.R. 8 Maggio 1996 n 7/LAP.* Regione Piemonte, Direzione Regionale Servizi Tecnici di Prevenzione, Ordine Regionale dei Geologi del Piemonte, 122 pp.

SCHMIDLI J., SCHMUTZ C., FREI C., WANNER H. & SCHÄR C. (2002) - *Mesoscale precipitation variability in the region of the European Alps during the 20th Century*. International Journal of Climatology, 22 (9), 1049-1074.

TROPEANO D. & TURCONI L. (2004) - Using historical documents for landslides, debris flow and stream flow prevention. Application in Northern Italy. Natural Hazards, 31 (3), 663-679.

TROPEANO D. & TURCONI L. (2005) - *Le alluvioni*. In: Mercalli L. & Cat Berro D., «Climi, acque e ghiacciai tra Gran Paradiso e Canavese», Società Meteorologica Subalpina, Torino, 669-746.

TURITTO O., AUDISIO C. & AGANGI A. (2008) - Ruolo svolto da piene straordinarie nel rimodellare la geometria di un alveo fluviale. Il Quaternario, Italian Journal of Quaternary Sciences, 21 (1B), 303-316.

UFFICIO IDROGRAFICO E MAREOGRAFICO DI PARMA - Annali idrologici con Studi e ricerche. Roma, Istituto Poligrafico dello Stato.

VARNES D.J. (1984) - Landslide hazard zonation. A review of principles and practice. UNESCO, IAEG Commission on Landslides, Paris.

VENTURINI G. (1995) - *Geology, geochemistry and geochronology of the inner central Sesia zone (Western Alps - Italy)*. Mémoire de Géologie, 25, 148 pp.

WEINGARTNER R., BARBEN M. & SPREAFICO M. (2003) - *Floods in mountain areas, an overview based on examples from Switzerland*. Journal of Hydrology, 282 (1-4), 10-24.

(Ms. received 1 October 2009; accepted 15 May 2010)