Davide Tiranti · Sabrina Bonetto · Giuseppe Mandrone

Quantitative basin characterisation to refine debris-flow triggering criteria and processes: an example from the Italian Western Alps

Abstract This paper investigates rapid channelized debris flow related to rainfalls in small alpine basins. Its goal is to evaluate and correlate different geological and technical aspects with predisposing and triggering factors that can control these phenomena. The study area is the upper part of the Susa Valley where 12 small basins were selected. For each of them, lithological, geomorphological, climatic and technical information were mapped and analysed. Debris-flow triggering conditions, flow and depositional processes were related to physical characteristics of the basin that can be easily measured and quantified. At least three different groups of basins were found: G1) basins with one event each 4–6 years, characterised by massive or blocky calcareous rocks, G2) basins with more than one event per year that show an abundance of layered or sheared fine-grained rocks and G3) basins with recurrence levels exceeding 10 years, activated only by heavy and prolonged rainfalls, marked by massive or blocky coarse-grained igneous rocks. Furthermore, important morphometric differences were found. These considerations are useful in terms of hazard zonation and risk mitigation.

Keywords Morphology · Engineering geology · Rainfall · Western Alps · Italy

Introduction

Many authors have proposed different ways of forecasting triggering of and evolution of debris flow and soil slip using easily observable parameters. These are especially useful for civil protection alert purposes. Most authors agree that these techniques are valid in a specific geological-geomorphological-climate context and cannot be applied directly to other situations. Most reports place the triggering factor as short, intense rainfall (Wieczorek and Glade 2005) often associated with a certain quantity of rainfalls before the event (the first in this area of Italy was Govi and Sorzana 1980). Based on the type of weather forecast, correlations allow users to issue warnings or even evacuation bulletins for high-risk weather conditions.

Working in the Italian context and especially in the North-Western Alps, many limits to this approach become clear. Most of the phenomena are triggered because of extremely concentrated rainfall, which is controlled basically from orography. Meteorologic data (from classic raingauges on the ground to those calculated by fixed weather radar) can hardly provide specific assessment on this type of event, so any correlations are very approximate.

This study concentrates on other parameters which act as predisposing factors or indexes of certain phenomena both in terms of magnitude and recurrence interval. Other authors have tried to associate phenomena types or recurrence intervals with:

– Bedrock characteristics (Lin et al. 2000)
– Geotechnical characteristics of deposits in the source areas (Bonnet-Staub 1998)

– Basin morphometry, topography of source area and debris-flow accumulations (Bardou et al. 2003; Fioraso and Chiarle 1996; Wieczorek et al. 1997; Wilford et al. 2004)

In this paper, the influence that specific parameters (geological, sedimentologic, geomechanical, geomorphological and hydrological) can have on frequency, type and intensity of debris-flow events is studied.

The basins chosen for this study differ considerably in their geological-structural and geomorphological aspect in order to represent the variability of these typical alpine environments. Twelve basins in the High Susa Valley were examined. Debris flows have been recorded in these areas in recent years. These phenomena differed in intensity, frequency and the type of physical processes influencing their development. A good amount of historical information could be retrieved about these areas, both concerning the number of events and the rainfall records. Unfortunately, despite the considerable amount of data, information is not always complete and does not always show what triggered the event, the type of debris flow and relative magnitude.

Study area

The study area (Fig. 1) is in the upper Susa Valley, 80 km west of the city of Torino (Western Alps-Italy) where the river Dora Riparia flows; it is one of the most important valley systems in the area and seat of the Torino 2006 Olympic Winter Games. The Alps are a segment of the orogenic Alpine–Himalayan system made up of a fold and thrust belt split into four main structural domains: Helvetic, Penninic, Austroalpine and Southern Alps.

The units outcropping in the upper Susa Valley belong to the Penninic Domain. In particular, they are part of the Piemonte Nappe System and show the presence of (Polino et al. 2002; Barféty et al. 1996; Alberto et al. 2007):

– Continental margin units—a crystalline, pre-Triassic basement and autochthonous series of Mesozoic meta-sediment covers (calcschists, marbles and quartzites)—and a group of carbonate Mesozoic rocks with calcschists subordinates
– Ophiolithic and oceanic units mainly made up of calcschists and, to a lesser degree, marbles, quartzites and "green stone"

The study area shows both ductile deformation, due to four alpine events, and fragile deformation from three primarily distensive sub-vertical systems. We also had indication of morphotectonic factors and surface-deforming elements (trenches, faults) involving the pre-quaternary bedrock and surface formations. Traces of glaciation are recognisable by the presence of well-preserved shapes and deposits along the entire valley axis. The post-glacial phase was characterised by gravitational instability linked to tensional release from melting glaciers and to the structural setting. Landslides of

Fig. 1 Geographic and geologic location of the study area (Susa Valley, Western Alps, NW Italy). *1* Alluvial deposits; *2* calcschist; *3* gneiss and micascist; *4* limestone and dolostone; *5* serpentinite; *6* green stone, anfibolite, gabbro and basalt; *7* quartzite
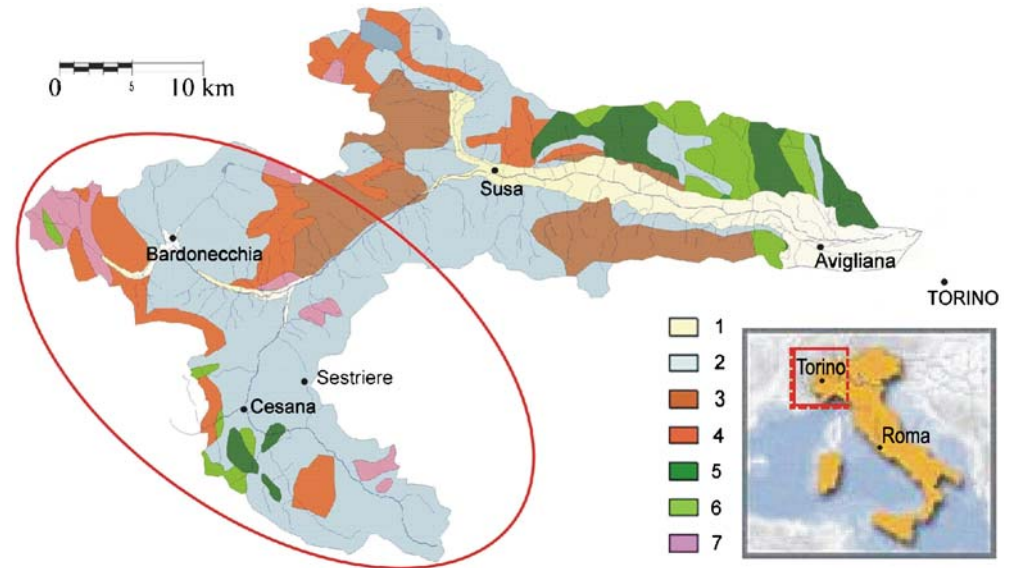
different types (mainly rockfalls, slides and deep-seated gravitational phenomena), age and size are widespread in this area too.

Annual rainfall distribution in Piedmont is of the bimodal type with two peaks in spring and in autumn and two minimum in winter and summer (Cagnazzi and Marchisio 1998). The Susa Valley is characterised by a sub-coastal regime, which means that autumn rainfall values are lower than alpine average, while there are higher levels in summer (Fratianni and Motta 2002). Average annual rainfall is less than 900 mm; normally, events are of low intensity (below 20 mm/day).

Materials and methods

Each basin was analysed from a geological, engineering geological, geomorphological and climate point of view to find specific aspects useful in assessing the susceptibility to landslide (Fig. 2). Parameters chosen are those that control the factors that usually determine the triggering and evolution of debris flows (Turner 1996). In particular:

– To verify the availability of mobilizing material: land use, sedimentology and geotechnical properties for the covers and the bedrock
– To find the slope able to cause the triggering and the transport: DEM and slope map
– To evaluate the quantity of water necessary to failure: critical rainfall and temperature

First, each of these factors was handled using qualitative parameters. Then, we passed to a quantitive description to make data observations as objective as possible and usable statistically.

Basins were characterised with the help of a Digital Elevation Model with 10×10 m cells, a map of vegetation and soil use and geological map in vectorial format (scale 1:10,000). By processing vectorial coverage in a geographic information system environment, the areas of the basins and their slope maps were obtained.

Rainfalls

The rainfall analysis was based on processing hourly and subhourly rainfall recorded during events and rain accumulated over days preceding the triggering of phenomena.
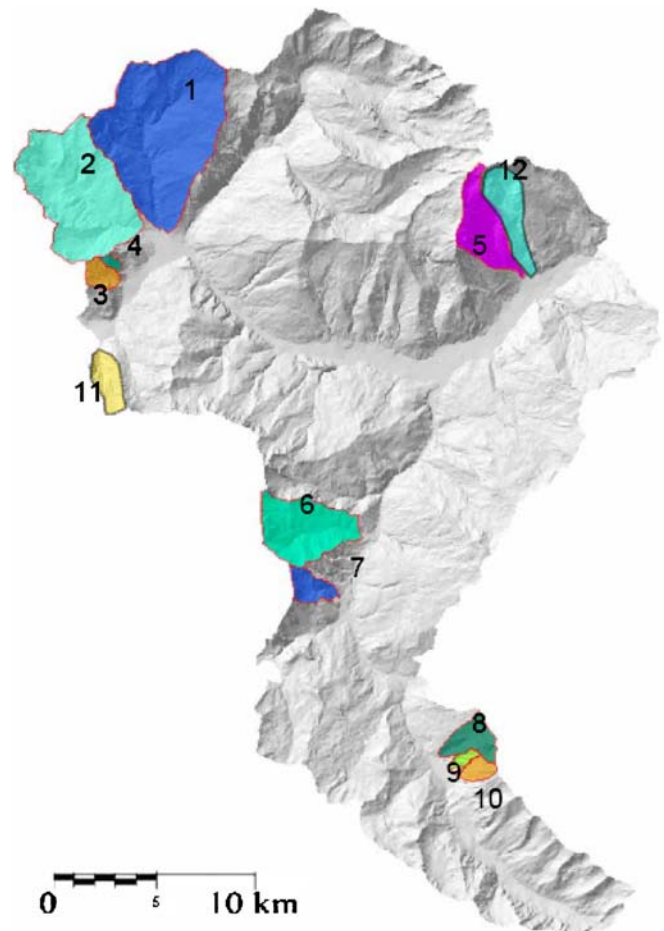
Fig. 2 Digital Elevation Model of the upper Susa Valley and the location of the studied basins. In the brackets of the municipalities: *1* Rio Frejus (Bardonecchia); *2* Vallone della Rho (Bardonecchia); *3* Rio Fosse (Bardonecchia); *4* Rio Sagne (Bardonecchia); *5* Rio Secco (Salbertrand); *6* Rio Fenils (Cesana); *7* Grand Vallon (Cesana); *8* Rio Saint (Cesana); *9* Rio Leità (Cesana); *10* Comba Crosa (Cesana); *11* Comba della Gorgia (Cesana); *12* Rio Gronde (Salbertrand)

Rainfall data used were recorded by the 16 raingauge stations (active since 1986) and by weather radar system (active since 1999) of the ARPA (Regional Agency for Environmental Protection) Piemonte Automatic Monitoring Network. For historical events, data recorded by the ten mechanical raingauges belonging to the former River Po Hydrographic Office (active from 1913 to 1986) were used.

The ARPA Piemonte raingauges are automatic stations for remote multi-sensor measurement, equipped with automatic raingauges with a minimum recording resolution of 1 min (mm/1 min). They are scattered over an area of 400 km² at elevations from 1,010 to 2,200 m a.s.l., and the range of distances from the respective basins is between 0 and 7 km. The weather radar equipment is installed at an elevation of 736 m a.s.l. on the Torino Hill, 80 km eastward of the area studied. It is a C-band radar with a range of 125 km (primary scan)–250 km (secondary scan) and a range resolution of 300 m with acquisition cycles of 10 min (Bechini and Cremonini 2002). The mechanical raingauges of the former Hydrographic Office of the Po are equipped with traditional pluviographs or manual pluviometers. The characteristics of their distribution are similar to those of the automatic stations.

For each rainfall event during which debris flows were triggered, the method used to assess the critical precipitation expects:

– Finding the raingauges in that basin or the one nearest to it
– Identifying, by analysing rainfall data and radar maps (if available), date and time of the start of the rainfall event
– Determining the critical interval between the start of rainfall and the debris flow triggering
– Evaluating the possible role played by previous rainfalls

– Identifying critical rainfall values, consisting in the quantity of rain to have fallen in the previously defined interval

Rainfall is expressed in pluviometric dimensions (rain with an assigned recurrence interval, maximum rainfall, cumulated rainfall, average hourly intensity) for appropriate periods of time (sub-hourly, hourly, daily and monthly).

Rock masses characterisation

Each basin was characterised with an initial distinction between areas in which bedrock outcrops directly and those covered by loose materials.

For bedrock, a distinction was made between the main rock types outcropping. Each geological formation and, if possible, each lithology was classified according to the structural characteristics and the degree of rock mass alteration. It is important to point out that weak rocks can change from rock-like behaviour to loose material behaviour when at low depth from the surface and with high water content: in these cases, they suffer weathering and produce large quantity of debris. The Geological Strength Index of Hoek and Brown (1997), also in the Marinos and Hoek (2001) version for heterogeneous or structurally complex rock masses, was used for the rock mass classification. The various outcropping lithologies were divided into six classes (I1–I6) based on the tectonic and/or fracturing disturbance and on the different surface discontinuity conditions (Fig. 3). The introduction of class I4* should be pointed out—used to describe weak rock masses like gypsum or travertine which, despite their massive aspect, are characterised by limited uniaxial compressive strenght values.

Each class is associated with an average Geological Strength Index (GSI) value, so a characteristic GSI value was calculated for

Fig. 3 Ranges of GSI for various qualities of rock masses in the study area, after Hoek and Brown (1997), modified
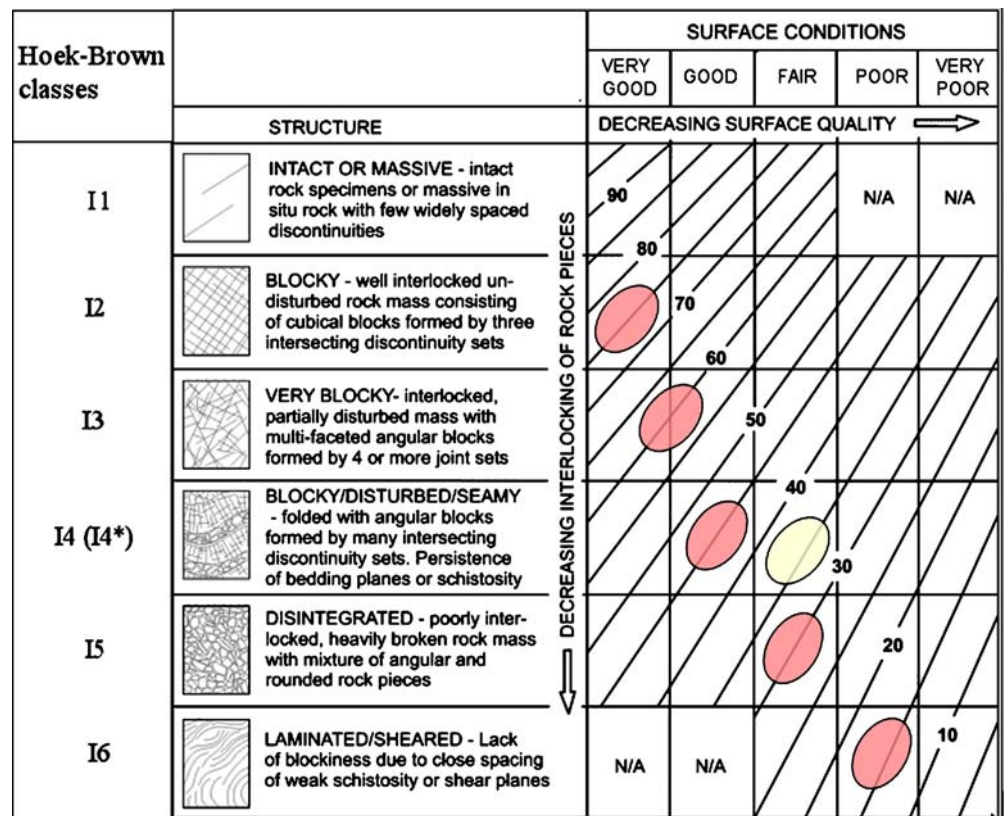
the whole basin, considering the different percentage of out-cropping for each recognised class. All data was standardised for the different basin areas to make them directly comparable.

Sedimentological description

The spatial distribution of deposits and sketches of stratigraphic relationships were mapped along the entire length of each drainage, from the divide to the toe of the respective alluvial fan. To identify different types of basins, the size, shape, roundness, lithology and direction of the larger clast were measured. To quantify the finer fraction, samples of the matrix of deposits with a good state of preservation were collected, and then particle-sizing laboratory analysis was carried out. Deposit structure, texture, shape, morphology and direction were so assessed.

Superficial deposits were classified using three different depositional styles identified and suggested by Moscariello et al. (2002) in a study of Italian Alps alluvial fans (Fig. 4).

The three depositional styles called Rudavoi type, Grand Vallon type and Inferno type, from the names of the reference basins, are characterised by three catchment lithology groups:

– Group 1 (G1): basins made of massive carbonate rock masses
– Group 2 (G2): basins made of fine grain and/or tightly foliated metamorphic rock masses
– Group 3 (G3): basins made of igneous, or coarse grain metamorphic, rock masses

The three types consist in two facies correlated to cohesive sediment gravity flow phenomena and a third correlated to non-
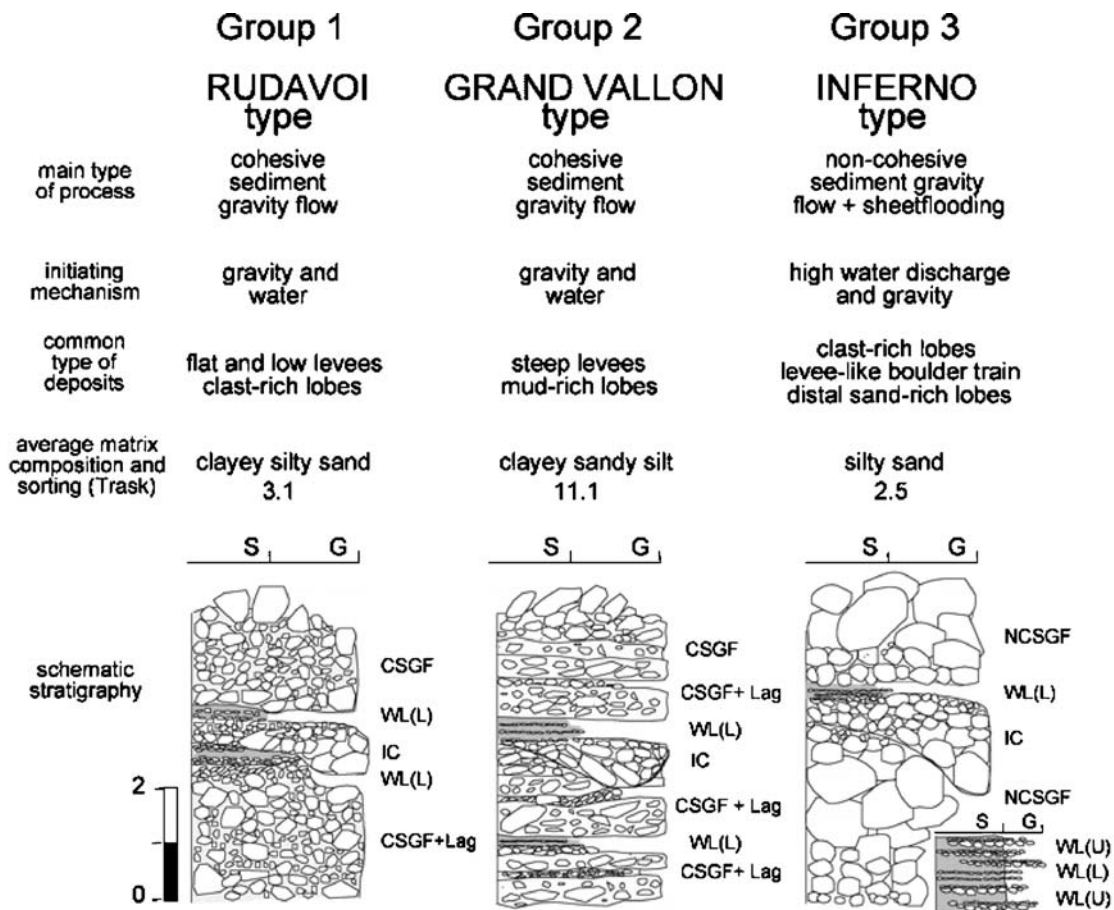
CSGF: cohesive sediment gravity flow
NCSGF: non-cohesive sediment gravity flow
Lag: matrix-free gravels produced by winnowing of debris flow by recessional and/or secondary overland water flows
IC: incised channel facies: massively matrix-poor or -free coarse gravel formed as a result of successive winnowing and erosion of sediment gravity flow deposits by high energy, channelised water flows
WL(U): waterlaid deposits formed under supercritical flow conditions by sheetflooding.
WL(L): waterlaid deposits formed under subcritical flow conditions (planar stratification) during the waning stage of the flood or secondary overland water flows

Prevailing grain-size: S: sand and sillt; G: gravel with matrix

Fig. 4 Sedimentological-stratigraphical classification of debris flow deposits (from Moscariello et al. 2002)

Table 1 Summary of the most important data on debris flows collected for the studied basins

Basin	Area (km²)	Soil-like deposits (%)	Mean bedrock GSI	Alluvial fan area (% of the basin)	Mean slope angle (°)	Basin type	Mean recurrence interval (year)	Mean daily triggering rainfall (mm/day)	Season of occurrence
R. C. Crosa	0.91	24.5	57	20.6	42.54	G1	4	38.4	Late spring–summer
R. Fenils	8.54	77.1	45	1.9	29.89	G2	3	10.6	Summer
R. Fosse	1.40	49.9	48	28.6	37.34	G1	5	20.4	Late spring–summer
R. Frejus	22.32	80.4	43	2.8	28.1	G2	3	17.7	Summer
R. Geronda	3.83	70.5	80	4.3	34.18	G3	11	76.8	Autumn
R. C. Gorgia	2.33	65.2	57	22.4	34.06	G1	5	31.4	Late spring–summer
R. Grand Vallon	2.68	27.6	51	7.0	39.95	G2	2	28.6	Summer
R. Leita	0.44	4.5	40	44.1	38.5	G1	6	41.4	Late spring–summer
R. V. della Rho	15.88	73.2	46	3.2	31.54	G2	3	15.7	Late spring–summer
R. C. Sagne	0.71	11.2	50	17.9	40.03	G1	9	31.6	Summer
R. Saint	2.24	64.2	40	2.7	29.31	G2	4	31.2	Summer
R. Secco	4.85	42.6	75	5.6	36.74	G3	16	70.4	Autumn

cohesive phenomena (Blair and McPherson 1994). The terms "cohesive" and "non-cohesive" refer to the quantity of silt and clay present in the deposit: high levels of fine fraction cause cohesive debris flows with visco-plastic behaviour, while low levels produce collisional-frictional debris flow.

Soil characterisation

Area distribution values were calculated for soils for each basin, standardised for the basin area. The different deposit types (talus, landslide deposits, glacial deposits, fluvial and/or lacustrine deposit, etc.) were divided into three main groups based on grain-size distribution:

– D1—fine deposits (earth): >50% in weight less than 0.06 mm (silt + clay)
– D2—poorly sorted soils: mixture of rock fragments and fine-grained materials

– D3—coarse deposits (debris): >50% above 0.06 mm (sand + gravel + cobble + block)

The first group (D1) behaves cohesively and can change its physical state based on water content. The third group (D3) behaves as a frictional material: in this case, the degree of compaction and texture are important as they can modify the way water flows in the deposit. The same problem, even more important and frequent statistically, occurs for the D2 type.

Debris-flow accumulation areas were characterised by taking samples, at different elevations, both along channels and, in alluvial fans, of levees and lobes deposits. The knowledge of the complete grain-size distribution (from silt to boulders) of a debris-flow deposit is fundamental for accurate description, classification and forecasting. This data is important to understand the forces that drive initial failure, the transportation of large blocks within the flows and, finally, the travel distance and deposition of the displaced

Fig. 5 Example of geological-geomorphological map referring to the basin of the Fosse T. *1* Tectonic breccias; *2* limestones; *3* calcschists; *4* talus; *5* dolostones; *6* black shales; *7* landslides; *8* gypsum; *9* carbonate schists; *10* foliated carbonate sequence; *11* alluvial fan
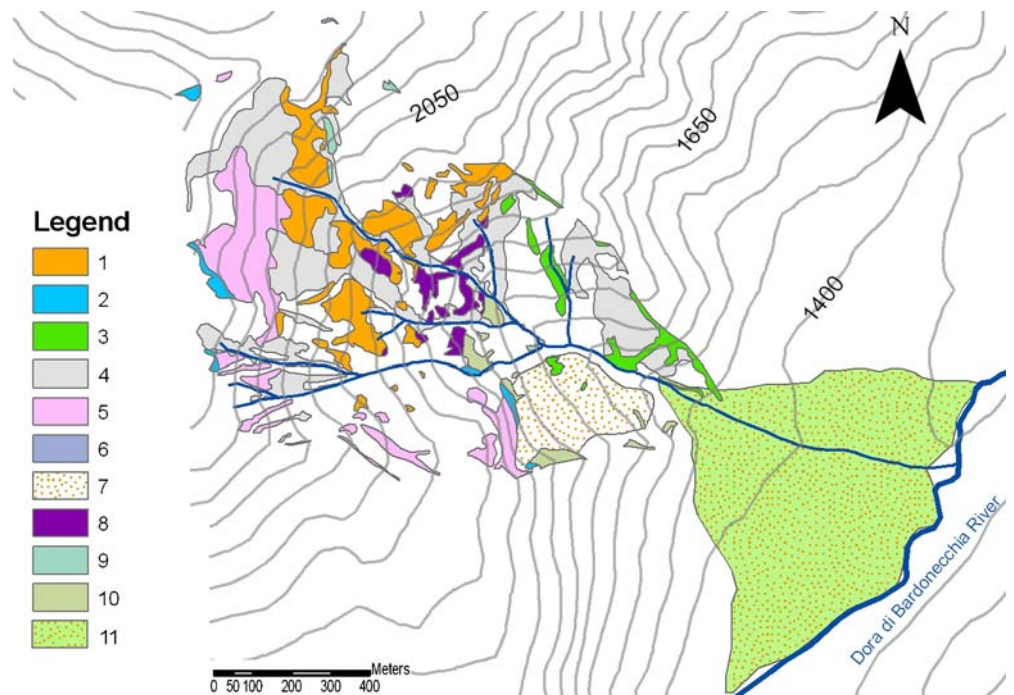
Fig. 6 Example of debris-flow deposit in G1 type basin (R. C. Gorgia): the *white tape* is 1 m long

material. The studied materials are highly heterogeneous in size. So, it is not possible to carry out grain-size analysis using only standard sampling and sieving procedure. It is possible to alleviate this problem using image analysis of undisturbed outcrops which, when images are properly scaled and measured, allows an estimate of the proportions of the grain-size classes visible in the image. In these cases, suitably scaled photos were taken of the sampling points in

Fig. 7 Example of debris-flow deposit in G2 type basin (R. Frejus)

Fig. 8 Example of a train boulder in a debris flow along the T. Secco (G3 type): the *white tape* is 1 m long

order to carry out image analysis of the whole deposit. About 5–10 kg of material of each sample was analysed in laboratory. Data obtained with the two methods were finally compared and integrated.

Historical events and validation
The study of historic data relative to basin activity was carried out using different sources, for example, from the ARPA Piemonte Geological Information System (SIGeo), publications of the CNR IRPI-Turin section (Tropeano et al. 1999; Tropeano and Turconi 2002), from municipal archives or press reviews and from inter-
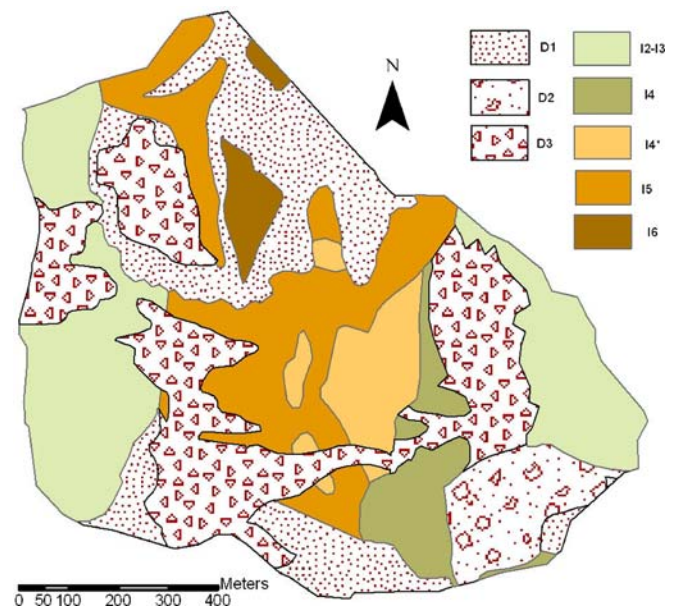

Fig. 9 Example of litotechnical map referred to the basin of the Fosse T. *D1* Fine-grained deposits (earth); *D2* poorly sorted soils; *D3* coarse-grained deposits (debris); *I2–I3* undisturbed or partially disturbed rock masses with blocky to very blocky structure; *I4* disturbed heterogeneous rock masses with blocky and seamy structure; *I4** disturbed heterogeneous weak rock masses (gypsum and travertine); *I5* heavily broken and poorly-interlocked rock masses; *I6* laminated and sheared rock masses
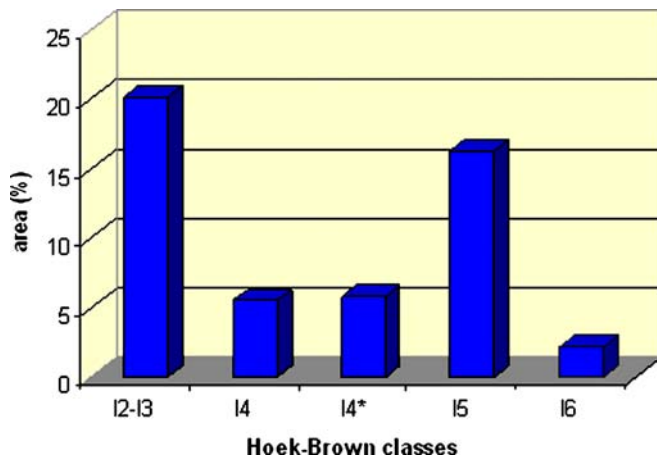
Fig. 10 Areal distribution of the different rock masses referring to the basin of the Fosse T

Fig. 12 Example of distribution of slope angle classes (step of 2°) referring to the basin of the Fosse T

views with local witnesses. Some of the more recent events (from 2003 to 2006) were directly observed by the authors. On the basis of the available data, it was possible to identify a total of 165 debris-flow events from 1728 to 2006, although significant information gaps are present. The data collected is not always exhaustive; for example, some events (especially among the older ones) lack specific information as regards the date of the onset or the date of the event. Sometimes, data is not readily comprehensible because it was expressed in unconventional and arbitrary terms. However, efforts made to reduce the uncertainty by making a cross-referenced analysis from different sources (after verifying their reliability) have reduced to a minimum the loss of information.

Field and laboratory results

The studied debris flows were triggered in different ways but usually by reactivation in the stream bed of loose deposits, already carried there by fast-moving water, and soil slips or minor landslides that almost instantly become rapid flows. Some coalescent phenomena were observed, producing slope and/or channelled debris flows that do not necessarily run the entire stream to the fan.
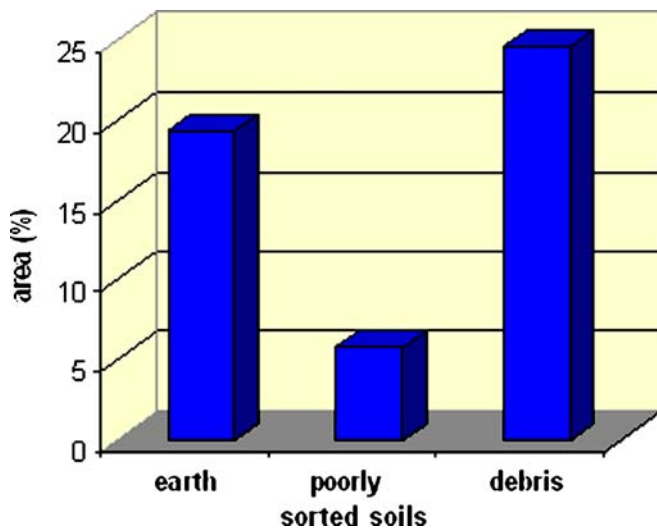
Each basin was characterised in quantitative terms, and Table 1 lists the main results obtained.

Geological and geomorphological maps (scale 1:10,000) show main lithological outcrops, the zones of instability (along the streams or on the slopes), the main shapes and the types of deposits. An example of this product is illustrated in Fig. 5.

They also allowed to distinguish prevailing catchment lithology, assigning each basin to one of three sedimentological groups (G1–G3). Moreover, sizes of the fans were quantified, indicating the fan area in normalised percentage terms with respect to the basin area. The differences between the three types of basins, not affected by tectonics or external morphogenetic processes, can be distinguished through an observation of the alluvial fans with respect to their morphology and their dimension, compared with the total area of the basin from which they originate. Photographs of each type of basin are shown in the following pages.

Type G1 (Fig. 6) shows a broad fan with a gentle slope and a high ratio of fan/basin area. A prevalence of lobes can be noted in the central and distal fan sections, while levees are concentrated in the apical zone. The passage between the zone with a prevalence of levees to that with a prevalence of lobes is characterised by a low gradient of the slope.
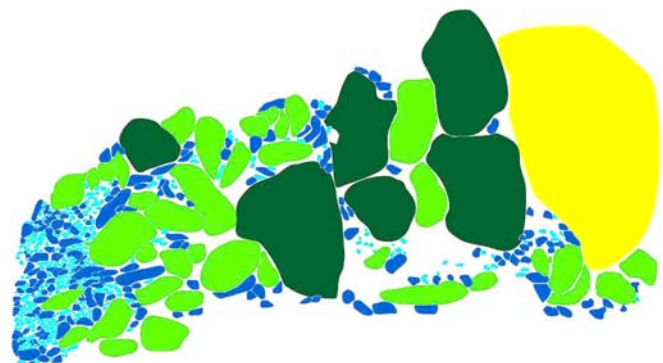

Fig. 11 Areal distribution of the different loose materials referring to the basin of the Fosse T

Fig. 13 Example image analysis of a train boulder along the T. Secco (the same in Fig. 8): results of the grain-size distribution made by bi-dimensional image analysis based on the minor axis length of the visible grains. *Yellow* >60 cm; *dark green* 20–60 cm; *light green* 6–20 cm; *blue* 2–6 cm; *cyan* <2 cm

Table 2 Grain-size classes based on the minor axis length obtained by bi-dimensional image analysis of the deposit shown in Fig. 13

Minor axis range (cm)	Description	Count	Mean value	Standard deviation
0.6÷2.00	Medium gravel	354	1.2	0.4
2.00÷6.00	Coarse gravel	175	3.17	0.95
6.00÷20.00	Cobbles	37	10.29	3.58
20.00÷60.00	Small boulders	6	30.85	8.3
>60.00	Medium boulders	1	60.14	0

Type G2 (Fig. 7) shows a reduced fan with a moderate slope and a low ratio of fan/basin area. A prevalence of levees will be noted on the fan surface, uniformly distributed between the apical zone and the toe, while the lobed deposits are also present. The passage from the apical zone to the central body to the toe is not emphasised by a noticeable change in the fan gradient.

Type G3 (Fig. 8) shows a reduced fan with a steep slope, especially in the apical zone, and with a high ratio of fan/basin area compared to the two groups described above. A clear division in the dimensions of the clasts can be noted between the apical zone and the rest of the fan. Effectively, the largest boulders are concentrated in the apical zone, and it is possible to observe, in correspondence to less abrupt gradient changes, a gradual decrease in the number of boulders and a more heterogeneous grain-size distribution. The toe of the fans shows a prevalence of gravel-sandy facies degrading to sand and silt. The predominant deposits consist of lobed forms with subordinate boulder-trains.

The rock mass characterisation enabled us to produce a litotechnical map (Fig. 9). The respective percentages of outcropping have been calculated (Fig. 10) and, on the basis of these values, an average GSI value has been assigned to the entire basin. In the same maps, the spatial distribution of the soils is also illustrated, grouped in the three fundamental types, on the basis of which the percentage of extent of loose materials was calculated for every basin studied (Fig. 11).

Slope maps, reconstructing the distribution of the declivity by classes of 2°, were also created using the Digital Elevation Model (Fig. 12): the results usually indicate a Gaussian type of distribution so mean values, and standard deviation could be identified for each basin.

The grain-size analyses, done both in laboratory and using image analysis, highlight the peculiar sedimentologic and stratigraphic features of the deposits (dimensions, shape, orientation of clasts and deposit style). They were used to confirm the sedimentological considerations on the type of basin. Figure 13 illustrates an example from a train boulder deposit in the basin of the Secco T (the same in Fig. 8). Grains larger than approximately 1 cm are distinguished using the minor axis length, and the results are shown in Table 2. The finer part of the same deposit was analysed using laboratory sieves (Fig. 14). In the studied cases, gravels prevail (about 70%), while silt and clay make up less than 15%.

The results of the grain-size characterisation of the deposits did not lead to equally clear and univocal results due to two main problems that affect image analysis methods: the concealment effect and the calculation of the third dimension of a grain (Baroni et al. 2003). The first problem is that a clast of large dimensions can be partially hidden and may be assigned to a smaller class than the one it actually belongs to. Since the contrary cannot happen, an under-estimation of the percentage of the largest classes can result. The second problem arises from the fact that a photo is two-dimensional. Transposition from two to three dimensions can introduce error. Despite this, data were compared and qualitative information collected.

Quantification of rainfalls triggering debris flow

The intense rainfall patterns that characterise the western Alps are within the two extremes: (1) brief localised storms and (2) prolonged rainfalls over a large area. The former are represented by thunderstorms resulting in downpours that are configured as small cells of instability, characterised by high speed and the ability to discharge

Fig. 14 Grain-size laboratory analysis of two samples of the "fine-grained" portion of the deposit shown in Fig. 8
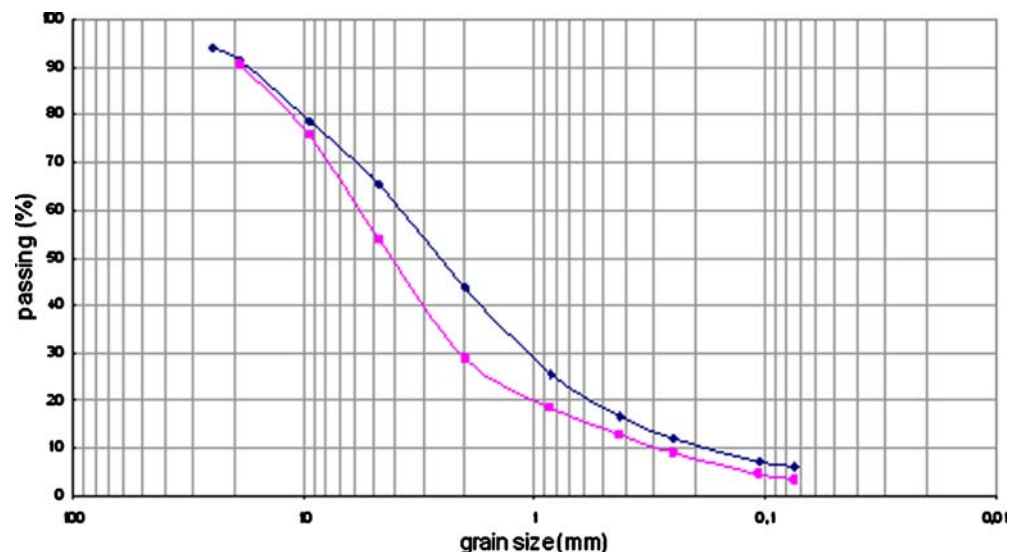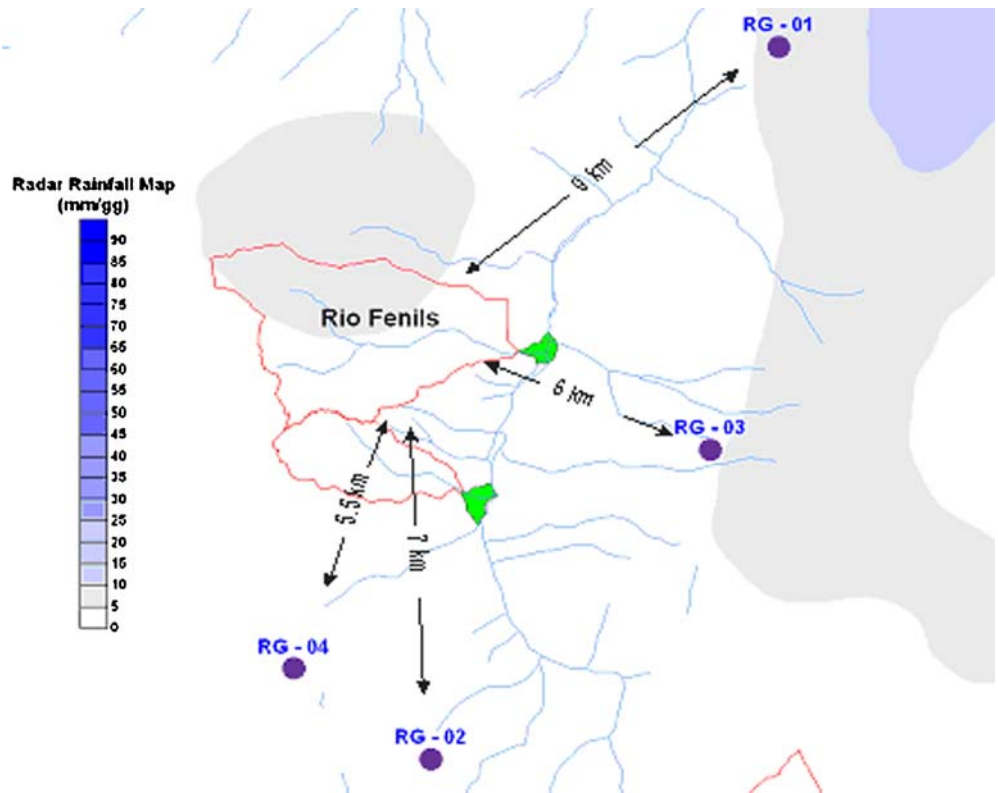
Fig. 15 Example of brief and localised storm (06 August 2004) that triggered debris flows in the basin of the Fenils T. measured by weather radar and by raingauges, the *blue dots* (*arrows* show their distance from basin centroid): none of raingauges was seriously affected by the storm cell nor gives meaningful data to characterise that event

large quantities of water in a few minutes. The latter are characterised by weather fronts of long persistence, up to several days, in which the cumulative rainfall can be very high. Moreover, an extended weather front can cover a vast area. In addition to these two extremes, there are intermediate types of rainfall events that, like the others, are controlled by seasonal factors.

Comparing recorded rainfall on the local raingauges, at comparable distances from the basin, it is possible to note a wide range

Fig. 16 Example of prolonged rainfalls over a vast area measured by weather radar. *Blue dots* show raingauges that, in this case, provide useful realistic results
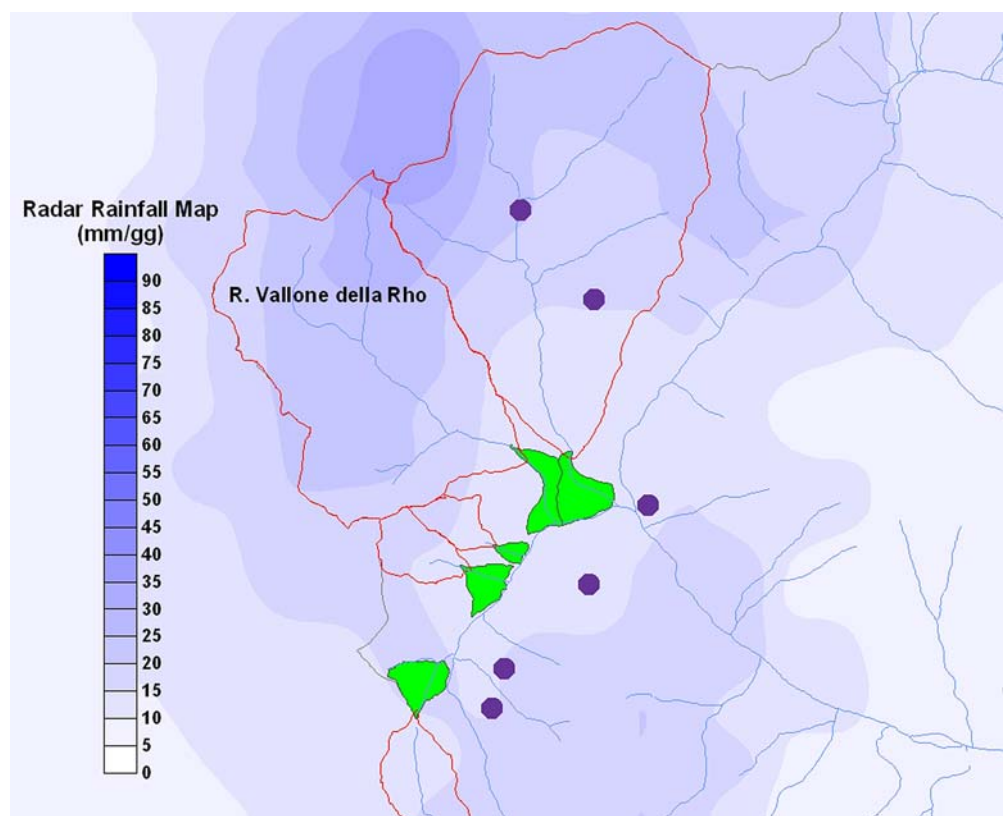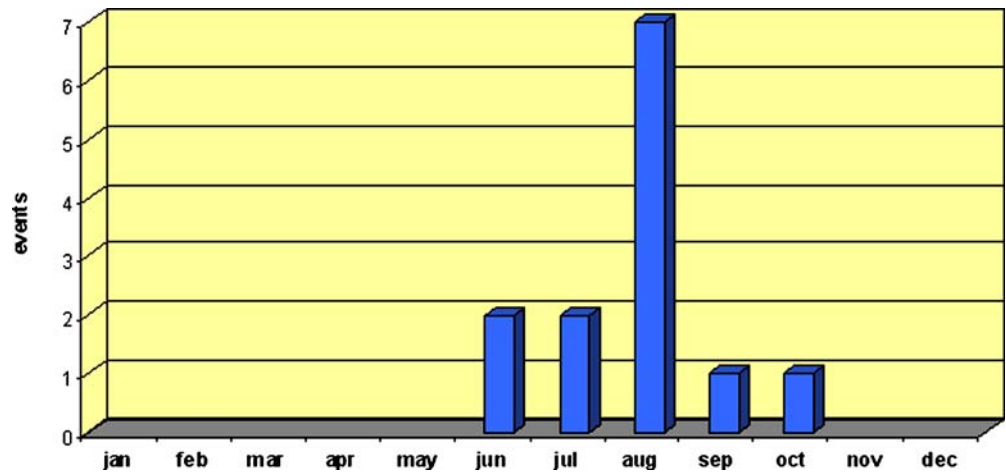
Fig. 17 Example of the annual distribution of historic debris-flow events in the basin of Fosse T

of variability in rainfall at the scale of each event. In fact, spatial distribution of high intensity rainfall is extremely variable, and it is not possible to assign a critical value based on raingauge measurements (Fig. 15). Attempts to distribute the values by using various methods of interpolation (i.e. kriging) were unsuccessful in providing reliable results if compared with the maps of real distribution provided by the weather radar. Indeed, the weather radar, in spite of the problems of reliability of estimating the intensity of rainfall linked to the distance of the radar from the area studied and the orographic interference of the mountain chains, permits a more correct assessment of the rainfall distribution (Wieczorek et al. 2001). The obvious consequence, taking raingauge data as the reference, is that the rains that are effectively responsible for triggering debris flows can be underestimated.

The situation is different if widespread rainfall is considered (Fig. 16), where the data recorded by the raingauges is more uniform and the radar maps do not highlight major discrepancies between the distribution of the fields of rainfalls and the position of the raingauges.

Finally, the annual distribution of the debris-flow events, based on the historic data set considered, was calculated (Fig. 17) to identify the seasonal aspect of events for each basin.

Discussion

The most common causes triggering debris flows in the western Alps are linked to rainfall. However, for the three types of basin (G1, G2 and G3), rainfalls have to be considered in different ways. A simple analysis of the frequency of failures triggered by rainfall (Fig. 18) shows that the three types of basins are distinctive in their reactivations, especially G3 types (one debris-flow event each 10–15 years) as compared to G1 and G2 (characterised by shorter recurrence periods).

The seasonal aspect of the events differs substantially among the different basins (Fig. 19): group G1 shows a high frequency of events especially during spring season, while group G2 is recurrent in the summer; group G3 is charaterised by events that occur more frequently in the autumn. Seasonality influences, in some way, the quantity of rainfall before the event, the water content of the surficial deposits and, of course, the presence of a water table on the slope and its level.

The three types of basins also differ clearly in the following two ternary diagrams: the first (Fig. 20) illustrates the ratio between the fan area and the engineering-geological features of the basin (GSI and % of loose materials), while the second (Fig. 21) shows how the three groups differ depending on the fan area, the average slope

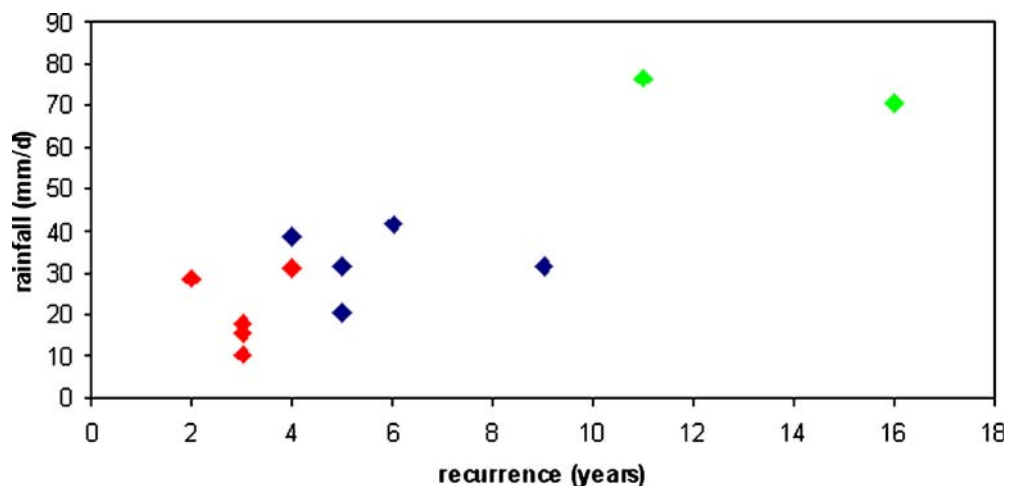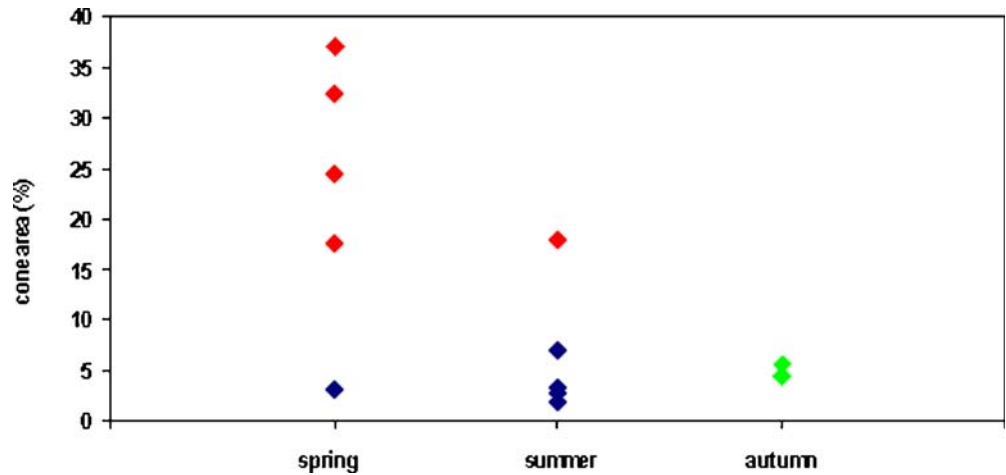**Fig. 18** Mean reoccurrence interval versus triggering rainfalls

Fig. 19 Seasonality of debris flows in the different basin types

angle of the basin and the recurrence of events. Both diagrams are successful in differentiate the three types of basin and highlight especially the differences in the normalised fan areas between the basin type G1 (about 25%) and the others (no more than 10% for G1 and G2).

It must be noted that the assignment of a geomechanical class to certain formations is not always unambiguous. A detailed analysis of the characteristics of the calcschists, for example, demonstrated the presence of carbonate masses with subordinate and rare phyllitic interbedded layers, and another lithofacies with a predominance of the phyllosilicatic fraction and a higher production of debris with a high percentage of clay minerals.

Finally, the study points out how difficult is to find out reliable thresholds of critical precipitation for triggering debris flow. Spatial variability of rainfall prevents correct evaluation of critical rainfall values, since a raingauge is unlikely to be placed in the midst of the downpour of a local storm or at the centre of the maximum rainfall for a moderately larger weather front. The raingauge network is more useful for estimating the amount of critical rain in case widely distributed rainfalls prolonged in time. Weather radar is therefore indispensable to identify the distribution of localised rainstorms that normally slip through the gaps in the raingauge

network on the ground. Weather radar, in orographic contexts characterised by good visibility, is capable of quantifying the exact amount of rainfall necessary to trigger debris flows even for a local or moderately distributed rainstorm. Without the aid of this technology, it is only possible to provide a qualitative estimate of the amount of critical rainfall necessary to trigger debris flows. Of course, this technique is available only in recent years, so for previous events, the quantity and the uncertainty must be seriously evaluated.

Conclusions

The study carried out on 12 basins in the upper Susa Valley leads us to identify three basic groups of basins with substantially different features (Table 3), based on sedimentological classification improved by adding much more technical and morphological information.

Type G1 includes basins in which soils occupy about one third of the total area and where rock masses show a blocky aspect (average GSI about 50). The fans are unusually large (on average, one fourth of the area of the basin), and the basins show the steepest slope gradients (38.5°). Here we observe events about every 5–6 years with a higher occurrence in the late spring, a season characterised by intermediate styles of rainfall (averaging about 32 mm/day).
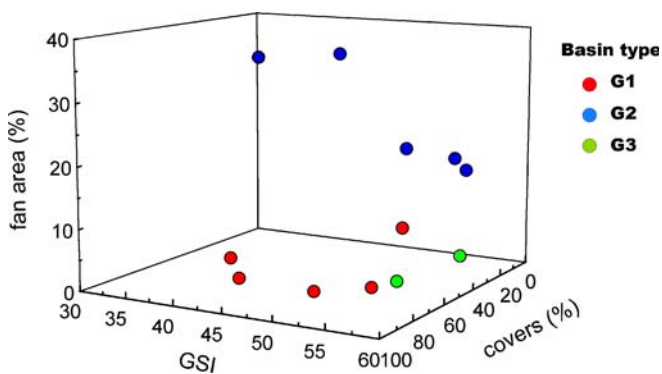

Fig. 20 Ternary diagram showing the relationship between loose material areal distribution (covers), the average GSI of the basin and the area of the fan (in percentage referred to the area of the basin)
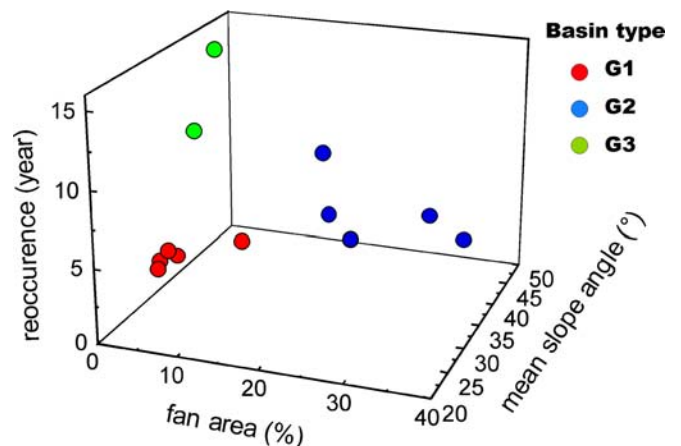

Fig. 21 Ternary diagram showing the relationship between fan areas, average slope angle of the basin and re-occurrence interval of debris flow in year

Table 3 Main characteristics of the three types of basin affected by debris flow

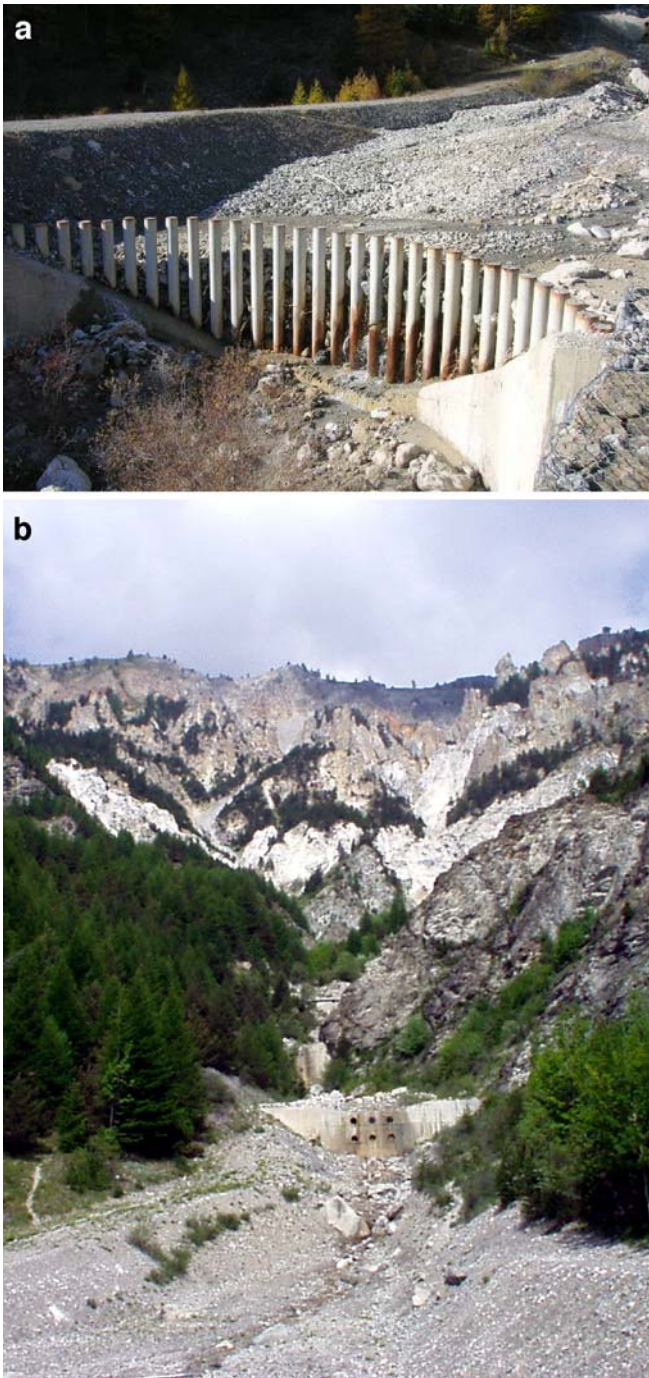| Basin type	Soil-like surficial deposits (%)	Average bedrock GSI	Alluvial fan area (% of the basin)	Average slope angle (°)	Recurrence interval (year)	Triggering rainfall (mm/day)	Season of activation
G1	31.06	49.40	25.80	38.49	5.80	32.64	Late spring–summer
G2	64.50	47.60	3.66	31.76	3.00	20.76	Summer
G3	56.55	58.00	4.95	35.46	13.50	73.60	Autumn

Fig. 22 Two photographs of the basin of Fosse T. It is possible to observe: (*on the left*) a recent debris flow in a trap created by artificial levees and an open check dam, (*on the right*) the general view of the basin and two older check dams

G2 type basins are associated with more abundant superficial deposits. Outcrops consist of rock masses ranging from very blocky to disturbed (GSI slightly below 50). They have very small fans and relatively low slope angles. Events are relatively frequent (averaging one every 3 years) and are triggered by rainfalls of all kinds, as average daily rainfall slightly exceeds 20 mm. Debris flows occur more frequently in the summer and late spring.

Type G3 basins have percentages of loose materials slightly lower than those of type G2. The GSI is the highest (about 60, from very blocky to blocky behaviour). Events are much more widely spaced, usually over 10 years, and occur almost exclusively in the autumn, characterised by prolonged and extended intense rainfall (over 70 mm/day as mean value, about 10% of the average annual rainfall in the area).

The study highlights that these three types of basins react in different ways to rainfalls and that any assessment of debris-flow events for a given basin cannot be categorised in a uniform, generic way. It is not possible, however, to speak of a scale of increasing danger, as the frequency of events may not be as significant as their magnitude. Many of these basins interact substantially with anthropic activities that occupy the fan areas and main valley of the Dora Riparia. This valley is the most direct route for communication between Italy and France and is also the site of many towns and well-known ski resorts. It is crossed by an international railway, a highway and many local and regional roads. It is thus an area where works have been carried out in the past to mitigate the risk, both by local (Fig. 22) and regional action plans, and many studies have dealt with risks related to this zone. The Piemonte regional administration has also installed warning systems to alert local authorities and civil protection in case of potentially damaging meteorological events. However, these warning systems are rather generic in geographic location, including several valleys and a large number of basins that differ in geology, geomorphology, exposure and rainfall patterns.

The proposed methodology, if systematically extended throughout the alpine territory, would make it possible to operate in a more systematic way, taking account of the peculiarities of the individual basins. The goal of the study was to identify a number of easily observable and indicative parameters about the types of events that could be triggered depending on the features of basin and rainfall pattern. First results are promising and indicate that this method is certainly a good approach to achieve targeted structural countermeasures (trap or check dams, stabilisation of the loose materials, etc.) as well as non-structural actions (warning systems, territorial planning).

This approach can open the way for future developments. First of all, a systematic study should be extended to larger areas to define the most significant discriminating hazard parameters. A great deal remains to be done on the technical characterisation of the source areas, zones of accumulation and deposits, in both geo-hydrological and geotechnical terms.

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D. Tiranti
Area previsione e monitoraggio ambientale, ARPA Piemonte,
Via Pio VII, 9-10100 Torino,
Turin, Italy

S. Bonetto · G. Mandrone (✉)
Dip. di Scienze della Terra, Università di Torino,
Via Valperga Caluso 35-10125,
Turin, Italy
e-mail: giuseppe.mandrone@unito.it