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LANDFORM EVOLUTION IN MOUNTAIN AREAS

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SLOPE INSTABILITY AND FLOOD EVENTS IN THE SANGONE VALLEY, NORTHWEST ITALIAN ALPS

Abstract. Slope instability and streamflow processes in the mountainous part of the Sangone river basin have been investigated in conjunction with their influence on relief remodelling. Through historical records, the most critical sites during extreme rainfalls have been evidenced, concerned natural parameters and their effects (impact on man-made structures) reiterated over space and time. The key issue of the work is the simulation of a volume of detrital materials, which might be set in motion by a debris flow. Two modelling approaches have been tested and obtained results have been evaluated using *Debris*© (GEOSOFT s.a.s.) software. Simulation of debris flow in a small sub-catchment (Tauneri stream) was carried out and the thickness of sediment "package" that could be removed was calculated in order to assess the debris flow hazard. The Turconi & Tropeano formula (2000) was applied to all the partitions of the Sangone basin in order to predict the whole sediment volume which might be delivered to the main stream during an extreme event and the result being 117 m^3/hectare.

Key words: landslip, torrential flood, debris flow, predictive model

INTRODUCTION

The Alpine valleys, throughout centuries, are in search of an equilibrium between anthropogenic activity and natural processes; interventions due to ameliorating productivity, accommodation and safety conditions for Man and environment often were done overlapping or contrasting the slowly-operating exogenous agents. Sometimes the man-made structures resulted to increased damaging effects of natural events, such as slope failure and torrential flooding.

The Sangone valley is situated along the western border of the Torino plain and possesses patches of intensely built-up areas. The valley has frequently been affected by flood hazard, even today (November 1994; October 2000). The Sangone river and its tributaries as well as shallow slides brought damage to roads and threatened several housings.

This paper examines processes of geomorphological instability characterising the upper Sangone valley. Attention is focused on some aspects conditioning the landscape evolution, as well as on critical conditions of natural processes. Physical, geological, geomorphological and hydrological features of sub-catchments were analyzed in the following four steps.

1) Historical data concerning flood events those have affected the territory over the centuries were collected from CNR/IRPI archives. Information of recent flood events were gathered through direct witnesses, on-site surveys, aerial photo-interpretation, integrated with data supplied by town plans (Giaveno and Coazze communes), by the 'Hydrogeological System Plan' (River Po Basin Authority), and other studies.

2) The historical analysis was synthesized in tables and thematic maps in order to detect intensely affected areas by such flood events mainly due to extreme rainfall.

3) "Debris potential" in the mountain basin was empirically assessed through several models aiming at estimating the total debris amount that could be delivered to the main stream during such an extreme event involving all the head slopes.

4) The Rio Tauneri debris flow, that occurred in 1929, was analyzed by the software *Debris*© (GEOSOFT s.a.s.). In-channel sediment depth was estimated in three channel segments in order to assess the stream hazard in case of paroxysmal, massive sediment transport.

GEOLOGICAL SETTING

The Western Alpine region includes the Sangone valley and belongs to different structural units. The upper mountain basin is W-E oriented, flanked by the Lower Dora Riparia and Chisone valleys and crowned by the Orsiera-Rocciavré Massif. Pre-quaternary bedrock belongs to the main lithologic units outcropping in this region of the Cottian Alps: the *Dora-Maira* unit and the oceanic units *Rocciavré*, *Lanzo*, *Orsiera* (Sheet No. 154-Susa, Geological Map of Italy, 1 : 50,000 scale; Carraro et al. 1999).

The rocks prevailing in the former unit are various kinds of *gneiss*, usually coarse-grained, *metagranite* and *mica-schist* outcropping on the slopes of numerous tributaries. The latter units refer to a part of the Sangone valley, i.e. the Balma-Mirolette and Ricciavré sub-catchments, and part of the Sangonetto valley; they comprise especially ophiolites (*meta-gabbro*, *prasinite*, *serpentine*) with *rodingite* layers (Bortolami and Dal Piaz, 1970; Petrucci, 1970; Pognante, 1979, 1980). Other lithologies are: *calcschist* with scarce marble interbeds in the high Sangonetto valley and granate-bearing and graphitic *mica-schist* in the land strip Pian del Secco-Prafieul-Maddalena. The Quaternary cover in the mountain zone is represented by glacial and glacio-fluvial deposits as well by widely-extended coarse-grained detritus mainly arising from rockfall. The valley bottom, where the main built-up sites are located (Giaveno and Coazze), is mostly formed by glacio-fluvial (west of Giaveno) and Holocene overflow deposits; in particular, the widely flattened surface southeast of Giaveno corresponds to young fluvial deposits. The hilly land strip, being a belt zone between the Sangone and lower Susa valleys, is formed by Pleistocene glacial and glacio-fluvial deposits genetically linked to the former Susa glacier.

CHARACTERISTICS OF THE SANGONE VALLEY AND GEOMORPHOLOGICAL INSTABILITY PROCESSES

The upper Sangone mountain basin (sectioned at the "Sangonetto" locality, Fig. 1) and the sub-catchments of Sangonetto sub-basin (Balma-Mirolette, Ricciavré, Fronteglio, Tauneri and Romarolo) form part of the typical mountain zone, incised by streams of torrential regime. All sub-catchments and their sub-partitions were considered for analysing main geomorphological characteristics connected to instability processes they involve (Table 1). From the analysis of combined physical and geomorphological characteristics of sub-catchments and

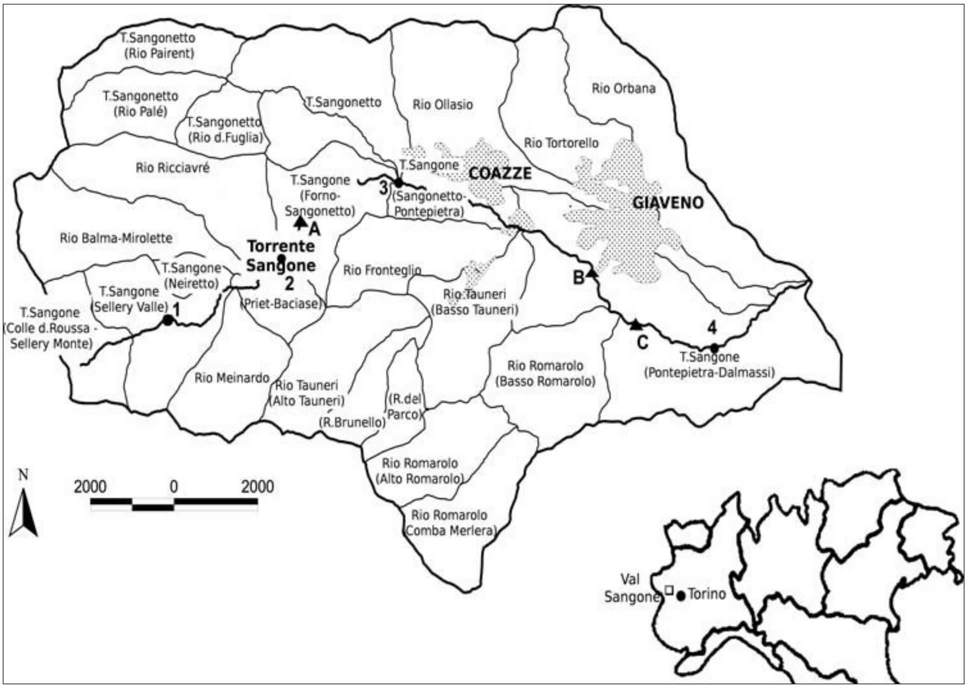


Fig. 1. Sketchmap of the Sangone valley (study area) along with the sub-catchment divisions and cited localities. A, B and C refer to main localities more than once damaged by flood (Forno di Coazze road; "Ruata Sangone" bridge; "Cumiana" bridge, respectively)

Table 1

Synthesis of the physical, geological and geomorphological characteristics of the Sangone mountain sub-catchments. Values in Italic Bold are classified as very critical ($Ia > 15°$; $Iv > 34°$; $Dr > 3.5$ km/km^2; $Sd > 25\%$), those in Bold are critical ($Ia > 10°$; $Iv > 32°$; $Dr > 3.2$ km/km^2; $14\% > Sd > 25\%$) inasmuch as threshold values for triggering natural instability processes; in *italic* channel gradient values ($Ia < 5.5°$) by which sedimentary process and overflow hazard prevail

Sub-catchment		*S* [km^2]	Lithology and morphological elements	*Ia* [°]	*Iv* [°]	*Dr* [km/km^2]	Sd [%]	Slope instability processes	Channel feature
Torrente Sangonetto	Rio Pairent	3.7	DM: gneiss, calcschist (rare); SU: serpentine. *Palé* moraine deposit	**11.0**	28.4	3.0	12.5	A, S, T	C
	Rio Palé	4.1	SU-RO: serpentine, metagabbro, prasinite, calcschist. *Palé* moraine deposit	**10.3**	***36.2***	***3.8***	12.8	K, A, S, R	C
	Rio Fuglia	2.5	DM: gneiss; SU-RO: serpentine, metagabbro.	***19.0***	**32.6**	***3.6***	11.0	K, A, T, R, D	C
	T.Sangonetto	9.3	DM: gneiss, metagranite, micaschist	*5.3*	**32.3**	2.3	2.2	K, A, T, R	E, Z, C
	Rio Ricciavré	7.3	RO: metagranite, serpentine DM: micaschist, metagranite Intensely fractured rock masses *Ricciavré* moraine deposit	**12.6**	***34.8***	***4.2***	***28.6***	K, A, S, T, V, R, D	E
	Rio Balma-Mirolette	7.1	RO: metagabbro Intensely fractured rock masses/*Balma-Mirolette* moraine deposit	**10.6**	31.6	2.4	***34.2***	K, A, S, T, V	C
Torrente Sangone	Colle della Roussa Sellery monte	3.4	RO: metagabbro and serpentine DM: micaschist, metagranite, calcschist (rare) and gneiss	***16.1***	***34.6***	2.8	8.0	K, A, S, D, T, V	
	Sellery valle	6.2	RO: metagabbro and serpentine DM: micaschist and metagranite *Sangone* moraine deposit	6.5	***36.0***	**3.3**	**18.3**	K, A, T, V, S	E, P
	Neiretto	1.1	RO: metagabbro and serpentine DM: micaschist and meta granite	***14.9***	31.5	***3.7***	**15.5**	T	

Table 1 cont.

Sub-catchment		S [km²]	Lithology and morphological elements	*Ia* [°]	*Iv* [°]	*Dr* [km/km²]	Sd [%]	Slope instability processes	Channel feature
Torrente Sangone	Priet-Baciase	2.4	DM: meta granite and micaschist *Sangone* moraine deposit	*5.5*	**32.6**	**3.4**	**16.6**	K, S	E
	Forno – Sangonetto	5.4	DM: meta granite and micaschist	*3.3*	**32.9**	2.5	0.7	K, L, R	E, P
	Sangonetto - Pontepietra	2.9	DM: metagranite	n.d.	n.d.	n.d.	n.d.	K	E, P
	Pontepietra - Dalmassi	19.3	DM: metagranite, micaschist, gneiss SU: serpentine and prasinite	n.d.	n.d.	n.d.	n.d.	K	E, P, Z
	Rio Meinardo	4.9	DM: metagranite and micaschist Intensely fractured rock masses *Meinardo* moraine deposit	**13.6**	***35.3***	2.3	***25.2***	K, R	
	Rio Fronteglio	5.3	DM: micaschist and meta granite	*4.8*	26.5	1.8	0.4	R, S	
Rio Tauneri	Alto Tauneri	5.4	DM: metagranite/Intensely fractured rock masses	**11.7**	***37.9***	2.4	**14.3**	K, T, R, S, A	
	R.Brunello	2.3		**11.6**	**33.3**	**3.2**	**14.4**		
	R.del Parco	1.9		**10.8**	31.6	2.0	6.1		
	Basso Tauneri	5.8	DM: metagranite and micaschist	*3.9*	22.1	2.1	1.4	T, R	E, P, Z
Rio Romarolo	Alto Romarolo	5.0	DM: meta granite and micaschist	6.1	***34.0***	**3.2**	**16.1**	T, R, S	
	Comba Merlera	4.5		9.5	***36.7***	2.7	0.5		
	Basso Romarolo	6.2		*2.9*	26.2	***3.7***	0.8		E, P, Z

LEGEND
S – sub-catchment area, *Ia* – average gradient of the main stream, *Iv* – average slope gradient, *Dr* – drainage density, *Sd* – surface of detrital cover.
Lithology: *DM – Dora-Maira* unit, *SU – Bassa Val di Susa-Valli di Lanzo* and *Monte Orsiera* units, *RO – Rocciavré* unit, n.d. – undetermined.
Slope instability processes: *A* – heterogeneous or coarse deposits, *S* – soil slip and shallow slides, *K* – rockfall, *T* – mass transport processes, *V* – snow avalanches, *R* – rapid mud flow and/or debris flow, *L* – slow mud flow, *D* – Deep-seated gravitational slope deformations
Channel instability feature: *E* – erosion processes along streams or ravine incisions, *P* – in-channel sediment deposit, *Z* – overflow, *C* – alluvial fan

their propensity to raise torrential and/or slope instability phenomena, it is observed that those sub-catchments are vulnerable where slope instability-related processes are active with reference to one or more of the factors below:
– average longitudinal gradient of the main channel;
– average gradient of the slopes;
– drainage density;
– per cent surface bearing detrital cover.

The upper Sangone Valley is characterised by a widespread mantle of detritus on the slopes, mainly originated by moraine deposits and intensely fractured bedrock (calcschist, mica-schist and serpentine). It must be noticed that the catchments having the average slope gradient greater than 30° are mostly affected by frequent rockfall processes or covered by gravity-originated coarse-block deposits. Such landforms, as well deep-seated landslides and earth flow processes, are a proof of diffuse slope instability conditions, particularly at the head of the main valley and in the Rio Ricciavré and Torrente Sangonetto sub-valleys.

During extreme rainfall events, the initiation of mass transport phenomena is easier in these sub-catchments where debris availability and slope steepness are combined with the scarcity or absence in vegetal cover; densely-distributed drainage network (above $3.2\ km \cdot km^{-2}$) and/or average main channel gradient considerably steep (above 10°). Such conditions occur in the upper Sangone basin and in the sub-basins of T. Sangonetto and Rio Ricciavré, Rio Meinardo and Rio Tauneri (Fig. 1). The lower portions of the catchments are also characterized by high-gradient slopes, for which rockfalls or mudslides occur even along ravines or minor streams. At the same time the slope inclination is dramatically reduced along the lower valley stretches, where the channel gradient ranges between 2.9° and 5.5°. Rainfall events trigger huge stream discharges combined with intense bed-load motion, in the upper stretches huge sediment deposit occurs in stead of bank erosion and flooding on adjoining stripes of land.

Resuming the observations drawn from Table 1, some small catchments are found to be unfavoured in terms of the occurrence of various types of slope instability, such as Rio della Fuglia, Rio Ricciavré, Rio Balma-Mirolette, Alto Sangone (Sellery) and Rio Tauneri. Catchments in which stream channel activity is a dominant process are located in the lower portion of the valley; particularly hazardous is the course of T. Sangone downstream of the Sangonetto village.

The critical sites for conditions triggering slope instability lie generally above 1000 m a.s.l., on grass- and pastureland and surrounding hamlets frequented especially in summer; the Rio Tauneri catchment is an exception developing at lower elevation. Areas vulnerable to streamflood usually correspond to rural settlements, infra-structures and farm or touristic activities.

METHODS OF ASSESSING PAST EVENTS

Assessment of different hazard situations are derived from the analysis of physical and geomorphological characteristics of the territory. They are further reinforced by the historical documents concerning past damages of Giaveno and Coazze communes by landslide and flood events. Many unpublished reports and files have been consulted, mostly from the Municipal Archives and other administrative Bodies, such as:

— Technical bureaus of the Giaveno and Coazze communes;
— Archive of the Fire Brigade Volunteers, Giaveno;
— Land protection Survey of the Torino Province;
— Historical Archive (documents, aerial photographs, etc.) of the IRPI/CNR, Torino;
— Hydrogeological System Plan;
— IFFI Project documents (Inventory of the Italian Landslides).

Based on the analysis of documents kept in the historical archives of Giaveno and Coazze communes, a chronology of the past damaging events is prepared (Tabs. 2a and 2b). Recent flood events are also recorded from the inhabitants of the Sangone Valley, who witnessed such events. Since early 18th century most of the problems were generated from stream activity and damage mainly footpaths and roads, but during last few decades most of the damages are caused due to landsliding.

Tables 2a, 2b

A synthesis of flood events that affected all Sangone sub-catchments from 1725 to 2000. Information is given about: number of events evidenced by documents found in the Archives of the Giaveno and Coazze communes, dates of flood occurrence, important reported damages

Name of torrent / Date event	Torrente Sangone	Rio Tauneri	Rio Romarolo	Rio Ollasio	Rio Tortorello	Rio Orbana	Rio Fronteglio	Torrente Sangonetto
1725								
1757								
26–27/06/1763								
1767								
06/1824								
31/07–01/08/1834								
16–17/05/1846								
10/1857								
27/06/1867								
10/1872								
08/06/1891								
19/09/1900								
10/1901								
10/09/1907								

Tables 2a, 2b cont.

Name of torrent / Date event	Torrente Sangone	Rio Tauneri	Rio Romarolo	Rio Ollasio	Rio Tortorello	Rio Orbana	Rio Fronteglio	Torrente Sangonetto
Springtime 1908								
06/1920								
04/1925								
14–16/1926								
28–29/04/1928								
16/06/1929								
10/1945								
3–4/05/1947								
25–26/09/1947								
2–4/05/1949								
24/09/1949								
19/12/1960								
7–8/11/1962								
Springtime 1968								
03/11/1968								
19/02/1972								
19–21/06/1973								
18/02/1974								
18–21/05/1977								
5–6/11/1994								
14–15/10/2000								
Total	25	16	14	13	7	7	7	6

Name of torrent	No. Events	Effects and damages reported
Torrente Sangone	25	Damages to the bridges to Borgata Brandol locality and road to Cumiana, and to bank protections; bank erosion along the road Sangonetto-Forno and at Pontepietra locality, overflow in the inflow area of the Rio Romarolo stream and in B.ta Dalmassi village. Landslides in Forno di Coazze locality.
Rio Tauneri	16	Landslides in the catchment head, bank erosion processes, damages to roads and bridges.
Rio Romarolo	14	Landslides and damages to roads and bridges.
Rio Ollasio	13	Damages to bridges and roads in the centre of Giaveno, bank erosion processes, landslides in the upper catchment.
Rio Tortorello		Damages to bridges and roads in the cetre of Giaveno, bank erosion processes, landlised in the upper catchment.
Rio Orbana	7	Damages to bridges and roads in Sala di Giaveno locality, bank erosion processes.
Rio Fronteglio	7	Landlides and damages to roads. Damages to roads in the centre of Giaveno and in the surrounding villages.
Torrente Sangonetto	6	Landslides in the upper catchment and in Indiritto di Coazze locality, damages to bridges and bank protections, flood processes.

PRESENT-DAY PROCESSES AND HISTORIC ANALYSIS

Sangone torrent. In the upper Sangone valley some slopes are incised by ravines and generate mass transport processes or snow avalanches, affecting the cart road to "Sellery" pasture land (Fig. 1). Towards the downslope of Loja Scura locality (1250 m) channel gradient decreases significantly and thereby increases the deposition of solid materials. Due to further lowering of the channel stretch between the Forno di Coazze and Sangonetto villages more sedimentation takes place and forms multi-channel flow (a braided-like pattern) through wide valley bottom. During peak flow period, more solid material is carried down by the stream, causes huge amount of bank erosion due to high-energy flow, in several cases disruption of the provincial road (Fig. 1 A, Figs. 2a, 2b) and villages due to rockfall and debris flow events.

Between Sangonetto and Pontepietra villages the Sangone stream channel bears a monocursal route without any critical flow condition. Between Pontepietra and Dalmassi villages the river crosses the floodplain south of the Giaveno settled area. The channel gradient lowers progressively, by which the Sangone loses its own torrential character, assumes a typical braided pattern and a downward tendency to meandering. The land crossed by the torrent is devoted to

Fig. 2a. The road stretch (A in Fig. 1) between Coazze and Forno localities was almost damaged twice by channel overflow (T. Sangone) in September 1947 and October 2000 (Courtesy Fire Brigade Volunteers, Giaveno)

Fig. 2b. The road stretch (A in Fig. 1) between Coazze and Forno localities was almost damaged twice by channel overflow (T. Sangone) in September 1947 and October 2000 (Courtesy Fire Brigade Volunteers, Giaveno)

agriculture along with some sparsely distributed hamlets, sometimes few ten metres away from the river bank. During floods such farmland area become prone to erosion, overflow and sedimentary processes; often damages the bridges, like "Ruata Sangone" and "Cumiana" (Fig. 1, B and C respectively), roads and embankments. The left abutment of the "Cumiana" bridge has found vulnerable due to recurrent bank erosion during flood (Fig. 3). Evidence of such damages is noted from different historical documents in the Giaveno commune archives (Tab. 3). The embankments along the channel stretch between the said bridges were often reinforced during the last few decades. Overflowing flood water sometimes invaded fields and roads, destroyed some houses specially in November 1962 and June 1973, when bank-protecting gabions were swept away over 150 m and floodwaters spread off. During the flood in May 1977, embankments were damaged in the vicinity of "Ruata Sangone" bridge, while downstream at the junction of Rio Romarolo a considerable amount of sediment accumulation resulted in a overfilled channel stretch and farmland was flooded.

The embankments along the stream stretch above were severely failed once more during November 1994 flood, when both the banks were subjected to downcutting and erosion (sometimes few ten metres deep). Flood water was also inundated the neighbourhoods of the Dalmassi village and forced the inhabitants to leave their houses. Similar problems occurred during the flood of Octo-

Fig. 3. The “Cumiana” bridge on the Sangone torrent, along the provincial road No. 193, was re-built after the old one collapsed during the October 2000 flood. From the end of the 19th century onward, such artifact was damaged and reconstructed at least three times: in the 1890s in concrete blocks, in the 1950s through reinforced concrete and recently (2002–2005) in a cable stay structure. The recently-built artifact is more than 15 m long; piers are found along the right bank

Table 3

Short chronology of major damages to roads and bridges along the Sangone torrent

	Locality	Witnessed occurrences	Years
A	Road Forno di Coazze-Sangonetto	Bank erosion and road damaging	1947–1994–2000
B	Bridge “Ruata Sangone” and bank protections	Damages in general	1824–1834–1846–1857–1901 – 1974–1977–2000
C	Bridge so-called “di Cumiana”, bank protections, road in vicinity	Damages in general Restoring works Reconstruction	1725–1834–1846–1857–1872–1891–1900–1901–1926–1928–1945– 5/1947–9/1947–5/1949–1994–2000 1761–1767–1809–1811 end XIX century–1950 ca.–2005

ber 2000, when the protecting dam above the bridge “Cumiana” was destroyed and the bridge itself collapsed due to lateral erosion and failure of the left abutment (Fig. 3).

Sangonetto Torrent. In the north-west of the Coazze village of Sangonetto valley there is the Indiritto di Coazze village, one of the most densely populated and settled areas in the high Sangone basin. Deep-seated slides, earthflows and rockfalls are widely distributed within the area with multi-sized debris flows along minor watercourses (Figs. 4 and 5). Small shallow slides usually occur

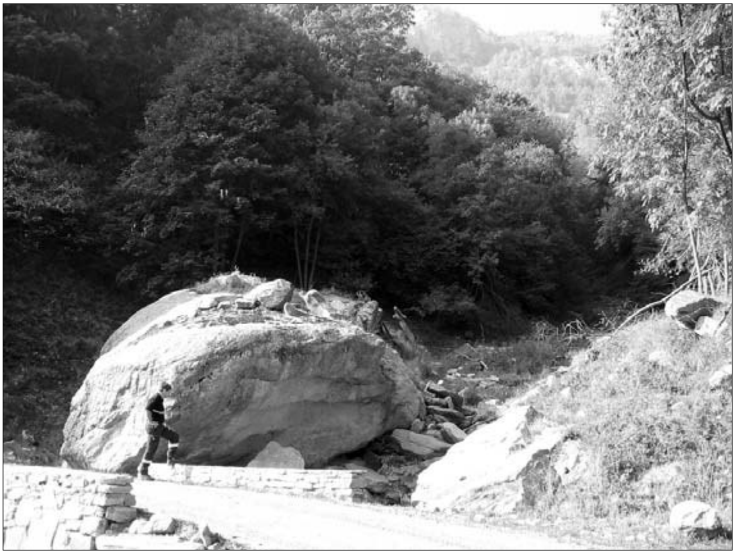


Fig. 4. The Canalera stream (Sangonetto Valley): a large boulder carried downward by the May 1947 debris flow

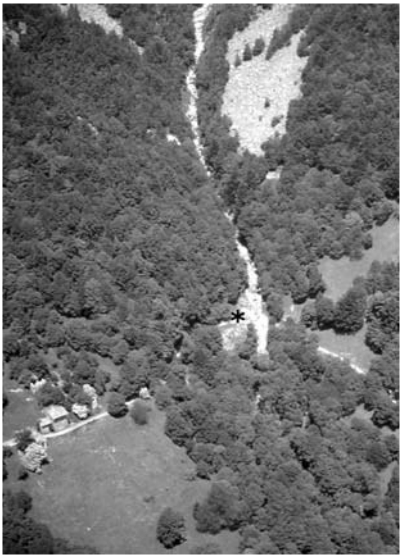


Fig. 5. The Canalera stream seen from helicopter after the October 2000 flood. Asterisk marks location of the boulder depicted in Fig. 4 (Courtesy Fire Brigade Volunteers, Giaveno)

during extreme rainfall events and often disconnect transport links. In the lower portion of the valley some edifices are built-up on potentially active alluvial fans; the road connecting Indiritto with Borgata Sangonetto localities may be affected both by rockfall and flood as happened in 1947 and 2000. In the 20^{th} century, the heaviest flood took place on 3–4 May 1947, due to the occurrence of several soil slips/debris flows in the basin head; stream-flood swept away four bridges and almost entire road to the valley bottom. Due to collapse of the Sangonetto bridge, the link to the Forno di Coazze village was cut-off; some edifices were severely damaged, pasture land and woodland were flooded or deeply eroded over tens of hectares.

Rio Ollasio and Rio Tortorello. The entire Rio Ollasio catchment is densely populated, the upper portion of it possesses several hamlets (especially inhabited during Summer) while the lower part passes through the main settlement, i.e. the city of Giaveno. On many occasions, small slides in the catchment head (which interrupted the road network) and debris flows along minor watercourses were recorded; the four bridges across Rio Ollasio, in the city area, were damaged several times between 1763 and 1949 (Figs. 6, 7). Although in the early 50s urban flood risk was sensibly reduced due to channelization, further flood and bank erosion occurred in the downstream part of the Rio Tortorello inflow in November 1968, February 1972, May 1977, November 1994 and October 2000 and severely damaged the embankments.

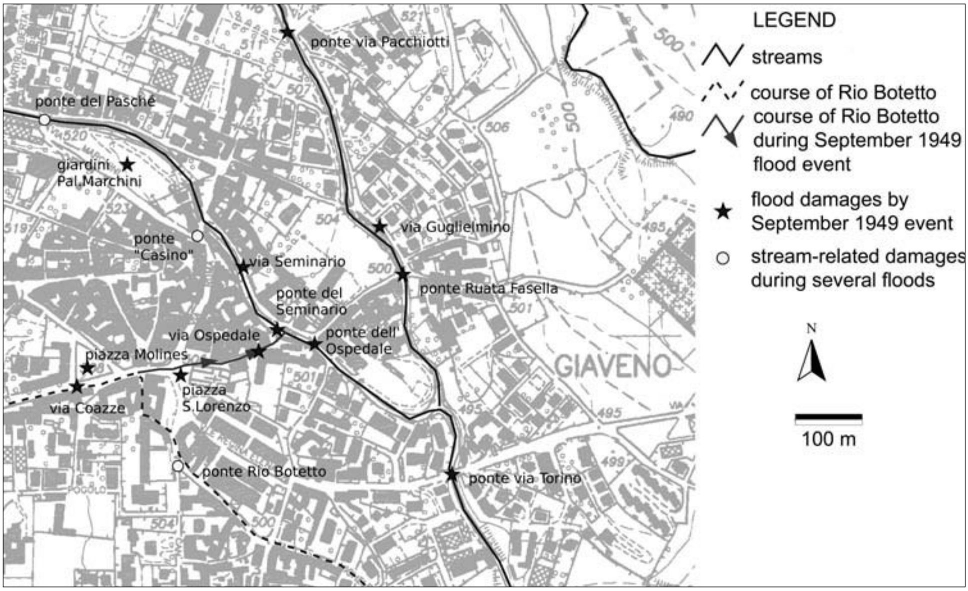


Fig. 6. Historical centre of Giaveno, crossed by the Ollasio, Tortorello and Botetto streams. Symbols refer to different objects concerning the September 1949 flood

Fig. 7. “Seminario” street in Giaveno, eroded by the Ollasio stream during the September 1949 flood (Courtesy Lions Club Giaveno)

Fig. 8. The presently-called “Piazza Molines” (Giaveno), flooded by muddy debris rushed out the Rio Botetto culvert underlying a closely-driving street on September 1949 (Courtesy Lions Club Giaveno)

In the 20th century major damages in the centre of Giaveno were brought on September 24, 1949 by the Rio Ollasio and its tributary Rio Botetto, a small stream presently canalized underground. Flood water carried huge amount of muddy debris over the roads and squares of the city (Figs. 6, 8). The Rio Ollasio damaged three bridges; Rio Tortorello eroded few stretches of road embankments. Similar kind of effects occurred again with lesser consequences on November 3, 1968.

Rio Tauneri, Rio Romarolo, Rio Fronteglio. The first two are the largest tributaries into the main stream (T. Sangonetto apart).

In 20th century several roads were interrupted in April 1925; during May 14–16, 1926, Rio Tauneri swept away bridges connecting the parish church of Maddalena with surrounding villages. Some bridges were again damaged during April 28–29, 1928. On 12 June 1929 a landslide took place at the head of the Rio Brunello catchment- a tributary of Tauneri, triggering in turn a huge debris flow along the main channel, which severely damaged the intake artefacts of the Giaveno aqueduct and some bridges (A, Fig. 9). The rainfall events of September 1947 and May 1949 induced new shallow slides and older slides began to move; slope failure processes of various sizes were recorded in December 1960, No-

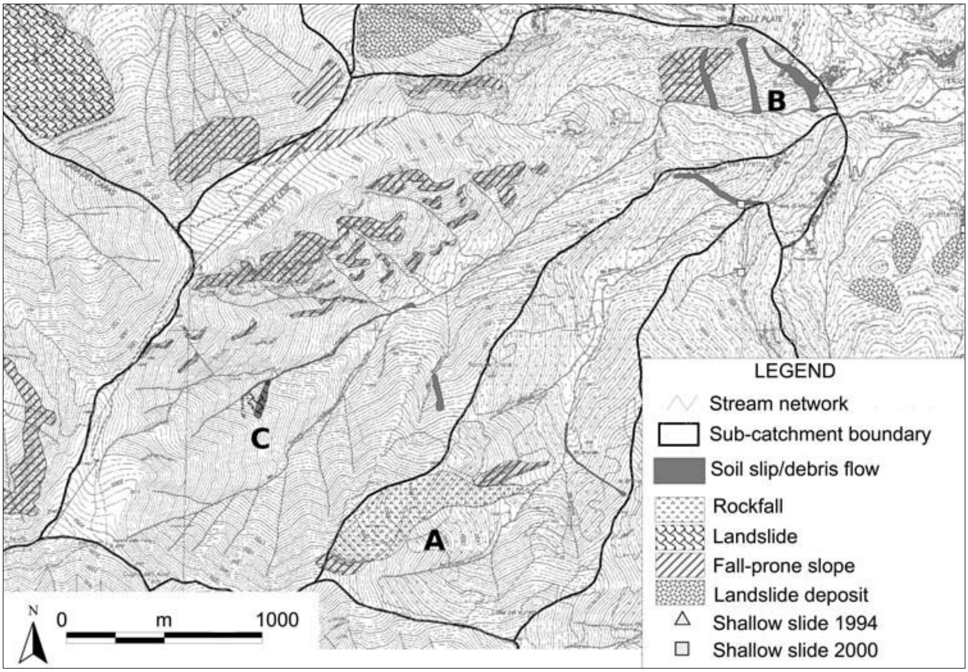


Fig. 9. Shallow slides in the upper catchment zone of the Rio Tauneri and its tributary Rio Brunello. Capital letters refer to: rockfall-delivered detritus (A) and related debris flow on 12th June 1929 along the Brunello stream, soil slips/muddy debris flows (B) triggered in the November 1994 event above the housings of Borgata Balangero-Bert, landslide-induced debris flow occurred on September 2006 (C)

vember 1962, Springtime 1968, November 1972 and February 1974 and May 1977. In several cases roads and houses were hit by such slides.

In November 1994 the catchments of Rio Tauneri, Rio Romarolo and to a lesser extent of Rio Fronteglio experienced several landslide events those ultimately created rapid earth-flow or debris flow events in the lower part of the Sangone Valley affecting several roads and buildings. Amongst numerous instability processes developed on 5th and 6th November, 1994, the largest one was a landslip that destroyed four houses in the Bert-Balangero village invaded the valley bottom i.e. the channel of Rio Tauneri (Figs. 10, 9 site B).

During the October 2000 flood, shallow slides affected roads and buildings in the catchments, broke off the links and caused damages for hundreds thousand Euros. In addition to that small debris flow events occured locally (e.g. Fig. 11). Streamfloods carried down huge amount of detritus damaging embankments and crossing structures. During September 14–16, 2006 two slides were triggered in the heading of Rio Tauneri, later turned into debris flow (Figs. 12, 13; C in Fig. 9) providing a replay of the June 1929 event to a lesser extent. In the Rio Tauneri catchment, slopes above 800 m height are unstable especially due to deeply weathered and intensely fractured bedrock, which is largely covered by rockfall detritus. This explains the relative tendency for soil slip/debris flows in such area.

Fig. 10. Main deposition zone of the "Bert-Balangero" soil slip (Giaveno), occurred on 6th November 1994 (Courtesy Fire Brigade Volunteers, Giaveno)

Fig. 11. Double-levee debris flow deposit in the Brunello sub-catchment, likely due to the October 2000 downpours (photograph Summer 2004)

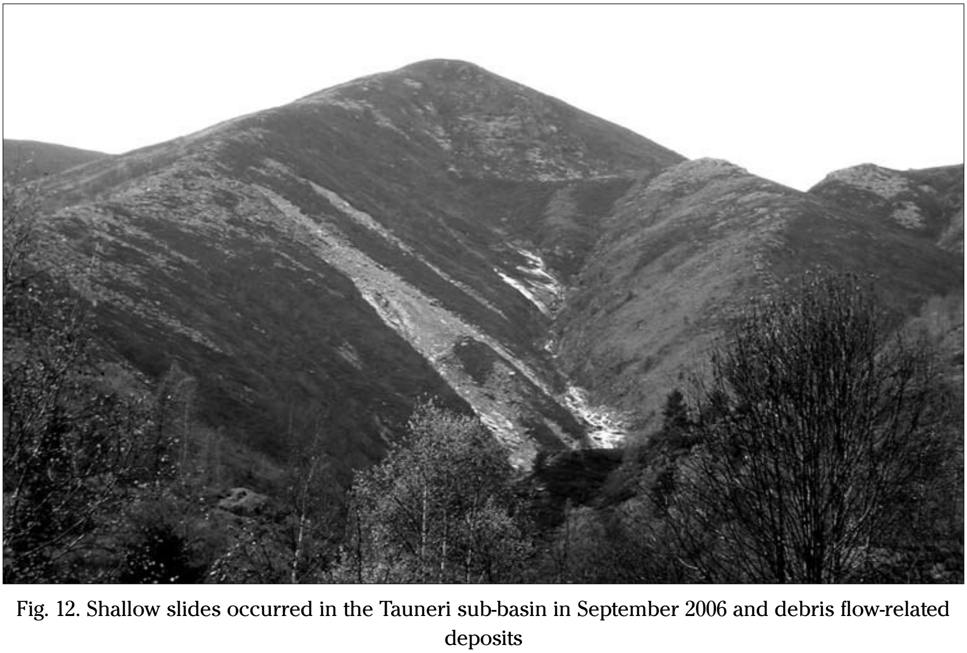


Fig. 12. Shallow slides occurred in the Tauneri sub-basin in September 2006 and debris flow-related deposits

Fig. 13. Shallow slides occurred in the Tauneri sub-basin in September 2006 and debris flow-related deposits

ly fractured rock outcrops and frequently occurred rockfalls are forming a thick debris mantle in these catchments and supply materials to the streams as bed-load. In particular, the slopes in the Ricciavré and in the Balma catchments are ravine-shaped and sparsely vegetated; snow avalanches or debris flows are quite common processes. These three sub-valleys are poorly frequented today, except for rambling paths.

INSTABILITY PROCESSES IN THE SANGONE VALLEY

From the historical record and direct evidences a list of 290 slope instability phenomena have been prepared; among which 29.5% cannot be classified properly with respect to the involved process due to gaps in the data sources. The majority of information, however, may be arranged according to cluster process typologies from which it is seen that bedrock failures or unstable coarse debris may lead to rockfall in majority of cases (42%), soil slip/debris flows occur on 17% of cases while other kinds of process are less frequent (12% in total). About one fifth of the landslides occur in the Rio Tauneri catchment, the same quantity in the uppermost Sangone valley but it is less in other catchments

(Sangonetto-Ollasio-Romarolo and others). The highest landslide density (Tab. 4) exists in the Rio Tauneri catchment (3.8 km^{-2}) while it ranges between 3.2 km^{-2} and 0.1 km^{-2} in other area.

It is noticed that the instability phenomena are often concentrated in densely settled areas having a dense network of pathways and roads.

Table 4

Sangone sub-catchments: No. of signalled landslides in relation to catchment areas

Sub-catchment	Area [km^2]	Landslides [number]	% total [%]	Landslides density [No./km^2]
Tauneri	15.4	58	19.9	3.8
Ollasio	11.3	36	12.3	3.2
Fronteglio	5.3	17	5.8	3.2
Ricciavré	7.3	22	7.5	3.0
Sangonetto	19.6	49	16.8	2.5
Balma-Mirolette	7.1	17	5.8	2.4
Romarolo	15.7	28	9.6	1.8
Sangone	40.6	55	18.8	1.4
Tortorello	6.5	7	2.4	1.1
Meinardo	4.9	2	0.7	0.4
Orbana	9.7	1	0.3	0.1
Total	143.3	292	100.0	

ASSESSMENT OF THE SEDIMENT DELIVERY IN THE MOUNTAIN BASIN

Several analytical methods are available in order to assess debris flow magnitude empirically. Most of them are based on morphometric parameters of the catchment, stream network and alluvial fan, through which the maximum probable debris flow volume can be assessed quantitatively. The results considerably differ from one method to another in the same catchment; thus it is very much necessary to compare and integrate such values with experimental values along with the feeding debris volumes in the source area as well as the instability processes potentially active in the catchment.

In the present study an estimation of debris volume has been made (magnitude) during an extreme (paroxysmal) event, which is able to trigger massive sediment transport in the mountain sector, in order to hypothesize the whole debris amount that is carried down the main stream (Sangone) during such event. The following formulae have been applied for such estimation:

$M = 8.96 \cdot A^{0.765}$ Eqn. 1 Bianco-Franzi (2000)
$M = 13.6 \cdot A^{0.61}$ Eqn. 2 Takei (1984)
$M = 21.24 \cdot A^{0.28}$ Eqn. 3 Bottino-Crivellari (1998)

where, the estimated magnitude (M) is a function of the catchment area (A) and the coefficients are determined on the basis of case-events in a homogeneous area. The above formulae were applied both considering the whole area of every sub-catchment and inserting the land surface covered by detritus instead of the parameter A, which is the sum of Adet 1 + Adet2 (Tab. 5).

In addition to that the authors applied the formula proposed by Turconi and Tropeano (2000) that takes into account not only relevant morphometric parameters of the catchment, but also data gained through historical analysis, field mapping and photo-interpretation. The sub-catchments have been sub-divided into areas of <10 km^2, in the sight of best fit the method. The general expression is:

$$M = (AE \cdot tgs \cdot r \cdot h \cdot (1 + n) \cdot e^{f})/1000 \qquad \text{Eqn. 4}$$

where:
AE – actual catchment area [m^2], computed as $A/cos(I_v)$;
tgs – average slope gradient (I_v) [%];
r – proportionality coefficient (between 0 and 1), that is the ratio between 'surface extent of the loose materials directly liable to be carried downstream' and 'actual catchment area';
h – average thickness of the debris 'package' which could be delivered into stream network;
n – coefficient comprised between 0 and 10, expressing the 'potential debris availability in case of an exceptional event (e.g. slope failure)'/'actual catchment area';
f – frequency factor, expressing the number of events occurred in a standard time lapse = 100 years.

In order to define the physical characteristics of all sub-catchments morphometric parameters have been computed first. From historical records information about the number of debris flow events witnessed for each sub-catchment has been collected to draw the frequency factor f. Through geomorphological interpretation of aerial photographs and intensive field investigation, the areal extent of the debris/soil mantle and its thickness have been carried out (factor h) in order to define r, h and n coefficients. The approach illustrated above concerns about the determination of both the actual sub-catchment area and the surface occupied either by 'active' debris/sediment deposits and/or sediments in temporary equilibrium.

Following the methods of Bianco-Franzi (Eqn. 1), Takei (Eqn. 2) and Bottino-Crivellari (Eqn. 3), the total volumes liable to be set in motion obtained by considering the whole area of sub-catchments, vary between 570,000 m^3 and 680,000 m^3 approximately (Tab. 5); when the area occupied by debris is consid-

Table 5

Estimation of the debris volume which by occurrence of an extreme event could be entrained into flood (magnitude) in every sub-catchment of the Sangone valley, according to prediction models proposed by Franzi and Bianco (2000; M_{F-B}), Takei (1984; M_{TAK}), Bottino and Crivellari (1998; M_{B-C}) and Tropeano and Turconi (1999; M_{T-T}), and value of some parameters employed

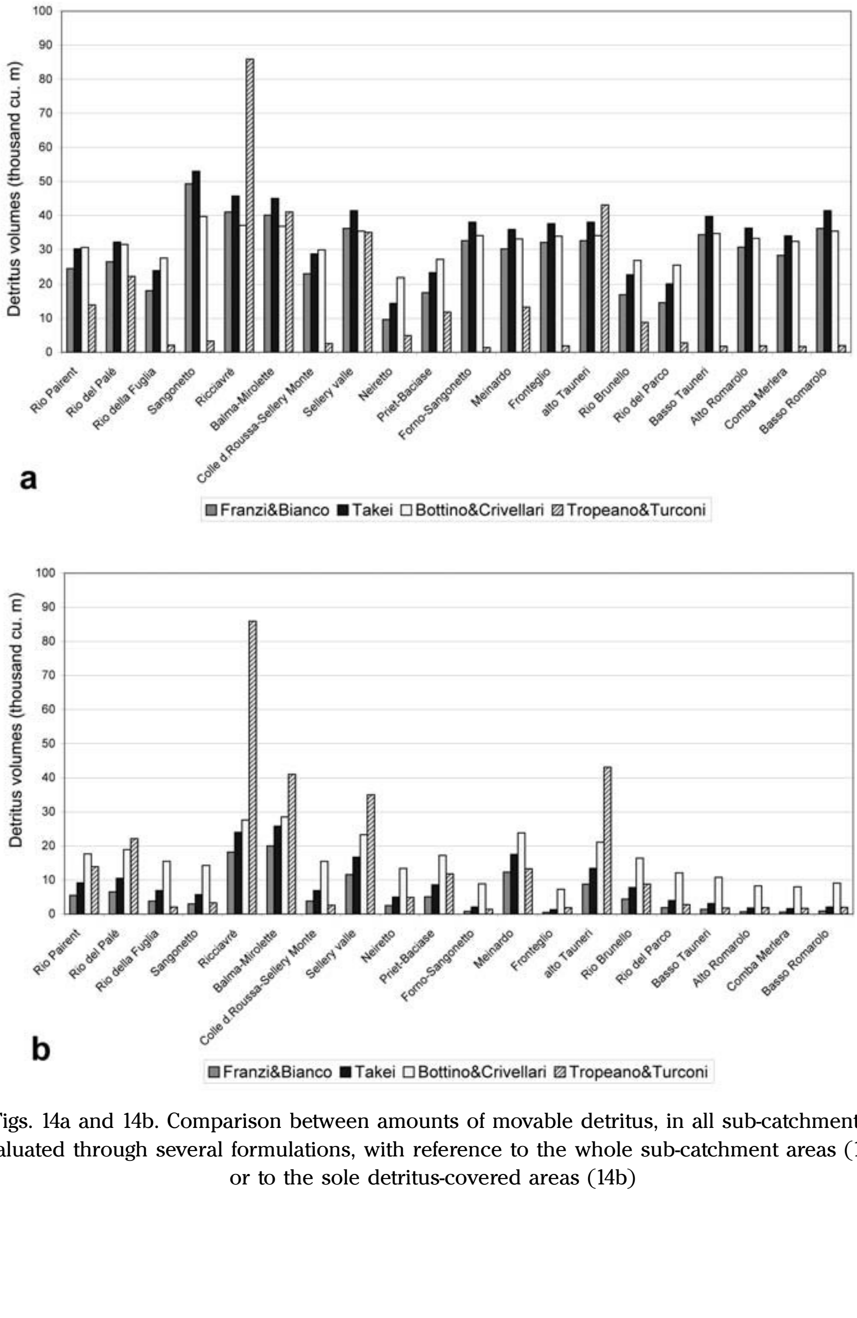
Sub-catchment		S [km²]	Adet 1 [km²]	Adet 2 [km²]	h [m]	N	f	M_{F-B} S 10³m³	M_{F-B} $A_{det\ 1+2}$ 10³m³	M_{TAK} S 10³m³	M_{TAK} $A_{det\ 1+2}$ 10³m³	M_{B-C} S 10³m³	M_{B-C} $A_{det\ 1+2}$ 10³m³	M_{T-T} 10³m³
Torrente Sangonet	Rio Pairent	3.7	0.101	0.423	0.60	1	0.830	24.4	5.5	30.2	9.2	30.6	17.7	13.9
	Rio del Palé	4.1	0.125	0.532	0.60	1	0.830	26.4	6.5	32.2	10.5	31.5	18.9	22.1
	Rio della Fuglia	2.5	0.015	0.311	0.80	2	0.415	18.1	3.8	23.8	6.9	27.5	15.5	2.1
	Sangonetto	9.3	0.056	0.186	0.60	2	0.415	49.3	3.0	53.0	5.7	39.7	14.3	3.3
	Ricciavré	7.3	0.336	2.197	0.80	2	0.415	41.0	18.2	45.7	24.0	37.1	27.6	85.9
	Balma-Mirolette	7.1	0.079	2.775	0.80	–	1.000	40.1	20.0	45.0	25.8	36.8	28.5	41.0
Torrente Sangone	Colle d.Roussa-Sellery monte	3.4	0.015	0.313	0.60	–	1.000	22.9	3.8	28.7	6.9	29.9	15.5	2.6
	Sellery valle	6.2	0.129	1.267	0.60	–	1.000	36.2	11.6	41.4	16.7	35.4	23.3	35.0
	Neiretto	1.1	0.017	0.174	0.80	–	1.000	9.6	2.5	14.4	5.0	21.8	13.4	4.9
	Priet-Baciase	2.4	0.051	0.423	0.60	–	1.000	17.5	5.1	23.2	8.6	27.1	17.2	11.8
	Forno-Sangonetto	5.4	0.045	0.000	0.40	3	0.277	32.6	0.8	38.0	2.1	34.1	8.9	1.4
	Meinardo	4.9	0.029	1.480	0.80	–	1.000	30.2	12.3	35.9	17.5	33.1	23.8	13.3
	Fronteglio	5.3	0.022	0.000	0.80	1	0.830	32.1	0.5	37.6	1.3	33.9	7.3	1.9
Rio Tauneri	Alto Tauneri	5.4	0.313	0.666	0.80	3	0.277	32.6	8.8	38.0	13.4	34.1	21.1	43.1
	Rio Brunello	2.3	0.056	0.343	0.80	2	0.415	16.9	4.4	22.6	7.8	26.8	16.4	8.8
	Rio del Parco	1.9	0.028	0.108	0.80	2	0.415	14.6	1.9	20.1	4.0	25.4	12.1	2.8

Table 5 cont.

Sub-catchment		S [km^2]	Adet 1 [km^2]	Adet 2 [km^2]	h [m]	N	f	M_{F-B} S 10^3m^3	M_{F-B} $A_{det\ 1+2}$ 10^3m^3	M_{TAK} S 10^3m^3	M_{TAK} $A_{det\ 1+2}$ 10^3m^3	M_{B-C} S 10^3m^3	M_{B-C} $A_{det\ 1+2}$ 10^3m^3	M_{T-T} 10^3m^3
Rio Tauneri	Basso Tauneri	5.8	0.090	0.000	0.40	3	0.277	34.4	1,4	39.7	3.1	34.7	10.8	1.8
Rio Romarolo	Alto Romarolo	5.0	0.035	0.000	0.60	2	0.415	30.7	0.7	36.3	1.8	33.3	8.3	1.9
	Comba Merlera	4.5	0.030	0.000	0.60	2	0.415	28.3	0.6	34.0	1.6	32.4	8.0	1.7
	Basso Romarolo	6.2	0.048	0.000	0.60	2	0.415	36.2	0.9	41.4	2.1	35.4	9.1	2.0
	Total		1.619	11.198				574.0	112.4	681.3	173.9	640.6	317.8	301.3

S – sub-catchment area; Adet 1 – areal extent of detritus and/or in-channel sediments prone to be eroded; Adet 2 – areal extent of detritus and/or in-channel sediments in temporary equilibrium; h – estimated mean thickness of deposits; N – Number of debris flow events recorded between 1921 and 2004; f – "frequency factor" i.e. number of debris flow events adjusted to a standard interval of 100 years.

ered solely the resulting values comprise between 110,000 m^3 and 310,000 m^3. The value derived by the Turconi and Tropeano formula corresponds to an intermediate position and expresses a transfer of detritus roughly equals to 21 m^3/h. When the whole surface area for all sub-catchments is considered (Fig. 14a), the largest magnitude pertains to the T. Sangonetto followed by Rio Ricciavré and Rio Balma-Mirolette. On the contrary, taking into account the surface area occupied by only detritus (Fig. 14b), the most potentially hazardous sub-catchment becomes Rio



Figs. 14a and 14b. Comparison between amounts of movable detritus, in all sub-catchments, evaluated through several formulations, with reference to the whole sub-catchment areas (14a) or to the sole detritus-covered areas (14b)

Balma-Mirolette followed by Rio Ricciavré and Rio Meinardo sub-catchments. In both of the cases, the Ricciavré catchment receives high magnitude of debris according to the Turconi and Tropeano formula and it is more than double in comparison with the maximum value drawn by other methods, the corresponding value (transfer of detritus) per unit surface is estimated to 117 m^3/h, that is surely a very high but realistic value for the Alpine area.

SIMULATION OF THE 12 JUNE 1929 EVENT (RIO BRUNELLO)

The Rio Brunello (Tauneri) debris flow has been chosen for a case study, which occurred in Rio Tauneri on June 12, 1929.

From unpublished records it is found that on June 12, 1929 "a heavy downpour affected all the valley attaining maximum intensity around 11:00, two hours later it appeared in the upper Rio Brunello catchment and something worse was happened. In fact above the Ca Verda spring a tremendous landslide was choking the narrow stream channel of the Rio Brunello and temporararily damming the flow. Due to overpressure created by such water and huge landslide deposit, a sudden dam break occurred and all previously accumulated water mass rushed down-valley destroying meadows, fields and riparian woods up to the Case Arietti village; small bridges to the houses of Pomeri, Mollar Cordola, Ughettera, Prese Viretto an Riboda were swept away..." (Land Surveyor of the Commune to the Prefecture Commissioner, 13/6/1929; Communal Historical Archive, Giaveno).

Another report (Report of the State Forestry Corp, June 1929, historical archive IRPI Torino) minutely mentions that "during the heavy thunderstorm of 12 June current year, landslides occurred on the northern slopes of Monte Brunello, Rocca Bianca and Colle del Muretto, on the eastern flank of the Giallonasso ridge and at the head of the Rio Brunello, which infilled into the valley bottom giving rise to an ephemeral lake. Dam break occurred and a debris flow travelled for about 4500 m, leaving deep furrows and ravaging all cultivated fields along the Brunello and Tauneri streams".

The major slide originated around 1600 m a.s.l. and widened downslope over 300 m length.

Eighty years later it is a hard task to find direct witness of the event for modelling purposes, thus many input data have been estimated or hypothesized. A part of the landslide mass products and debris flow deposit can be discerned still now (Fig. 15). The deposit is mainly composed of blocks and for (intermediate) b-axis, average length of 30–40 cm may be assumed; thickness of deposit can reasonably be assessed as 1.5–2.0 m. A masonry artefact (water intake for irrigation) which was damaged in 1929 still bears traces of repair of about 1.5 m high, thus giving proof of the debris flow wavefront depth in this site, i.e. perhaps above 2 m.

Fig. 15. The channel bed of the Rio Tauneri stream near Borgata Balangero locality: one may notice detritus deposit that may be ascribed to the 1929 debris flow

A few ten metres downstream, between 1160 and 1040 m, the Rio Brunello valley considerably widens and the stream channel gradient ranges between 8° and 10°. It is likely that in such stream stretch, about 600 m long debris flow materials were partly deposited during the 1929 event. It is also demonstrated by the historical documents and evidenced by the morphology of valley bottom that is widely covered by coarse blocks.

At the adjoining tributary "Rio Spinola" the channel gradient approaches to 15°; part of the debris flow velocity possibly increased in this valley stretch, then materials were gradually released in the lower Rio Brunello course. It may be noticed that the Rio Tauneri stream corresponding to the Rio Brunello inflow is forced to make a bend due to a huge (about 2 m thick) boulder deposit in this flat area extended over several ten metres with total volume of 15,000 m^3. The probable year in which such sediments were formed is likely 1929, because subsequent events do not bear any mark of carrying such huge amount of debris in this site.

SIMULATED DEBRIS FLOW PROCESSES ACCORDING TO DIFFERENT HYPOTHESIS

Takahashi's theory and Kinematic Wave method have been applied in simulating the 12 June 1929 event using of the *software Debris*© produced by GEOSOFT s.a.s. The basic input data has been drawn from the observations reported above.

HOURLY RAINFALL INTENSITY

One of the input parameters required for simulation is the maximum rainfall depth, having a similar duration of the average basin lag time; such value is automatically computed by the program once inserted the morphometric parameters of the catchment. It is thus necessary to know the hourly rainfall intensity for the event in study. Rain-gauge data at Forno di Coazze account for 144 mm rain in a day, so for a rainfall lasting for 12 hrs average hourly intensity should be equal to 12 mm/h. By considering the stormy character of the event, one could admit a shorter duration than the standard value of 24 hrs, thus various duration (D) and average intensity (*Iav*) hypothesis have been put forward, that is:

$$D = 12 \text{ hrs} \rightarrow Iav = 12 \text{ mm/h}$$
$$D = 9 \text{ hrs} \rightarrow Iav = 16 \text{ mm/h}$$
$$D = 7.2 \text{ hrs} \rightarrow Iav = 20 \text{ mm/h}$$
$$D = 6 \text{ hrs} \rightarrow Iav = 24 \text{ mm/h}$$
$$D = 5 \text{ hrs} \rightarrow Iav = 28 \text{ mm/h}$$

It is noticed that an average rainfall value has been assumed as maximum hourly value, while the program requires as input value the maximum rainfall depth for a duration equal to basin lag time, which in the present case is shorter than 1 hour: in case of downpours, shower(s) may occur with much higher intensity than the average value of the whole event.

Comparing the hypothesized values with the rainfall depth values (Tab. 6), estimated on the basis of the IDF (Intensity-Duration-Frequency) curve of equal rainfall for the Rio Brunello catchment, it is clearly noticed that a rainfall event equal to 144 mm in a time-span between 6 and 24 hrs is to be expected with return period equal to or lower than 200 yrs. Such eventuality is confirmed by some events occurred in the last decades, for which more than 120 mm rain in 6 hrs have been recorded.

Table 6

Rainfall depth units for the Rio Brunello sub-catchment, drawn from rainfall rating curve

Equalled rainfall for the Rio Brunello sub-catchment Rainfall recorder: Forno di Coazze					
T [yrs]	1 hr	3 hrs	6 hrs	12 hrs	24 hrs
20	40.63	71.91	103.09	147.78	211.85
50	47.18	83.63	120.01	172.22	247.14
100	52.08	92.41	132.69	190.53	273.57
200	56.97	101.16	145.32	208.77	299.91
500	63.41	112.70	161.99	232.83	334.66

Thickness of the material liable to be eroded in the starting zone

In the model it was assumed that the debris flow could have initiated corresponding to the lower limit of the landslide deposit, at 1300 m a.s.l., thickness of material was hypothesized in the region of between 2 and 4 metres.

Mean diameter (d_{50}) of the blocks liable to be removed

The mean diameter of the grain/clast materials liable to be eroded is a parameter bearing major incertitude in its definition. Based on careful field survey, the value has been assessed between 300 and 450 mm.

Planned mean diameter (d_{50}) of the materials involved in the flow

As mean diameter of the coarse deposits lying in the channel bottom or on the banks, suitable for to debris flow-feeding, a 300 mm-value has been considered.

Amplitude of the flow path

As assessed by several field surveys carried out along the Rio Brunello stream channel, the hypothesized flow section in various stretches has been estimated between 3 and 8 m. The simulation has been made according to the two following hypotheses:

1. continuous flow between 1300 m and 780 m heights;
2. pulsatory flow (two main waves): a first debris flow has travelled along the upstream stretch of the hanging plain between 1160 m and 1040 m, a second debris flow pulse has attained the confluence zone in the Rio Tauneri.

CASE 1

The following data entry were considered as the most reliable solutions:
– *hTc* (rain) = 12 mm,
– *H* (wavefront depth)=1.8 m;
– d_{50} mat *er* (outside-channel deposit) = variable between 300 mm and 450 mm
– d_{50} mat *alv* (in-channel deposit) = 300 mm

Results obtained through 300 mm and 450 mm as input data expressing the mean diameter of solid material are reported and commented below.

By varying mean diameter values in the range considered, the solutions provided by software do not change significantly. The results obtained according to the theories of Takahashi and the kinematic wave (Fig. 16) proved dissimilar; for example, corresponding to the top 4 of the pathflow (near the intake edifice at Ca' Verde) at 1180 m a.s.l., the wavefront depth according the two simulations equals to about 3.5 m and 1.6 m respectively. Along the same path the wavefront depth computed according to Takahashi theory is rather high. More precisely the results are over-dimensioned in the initial stretch where it should attain about 20 m depth. The values drawn from the kinematics wave theory

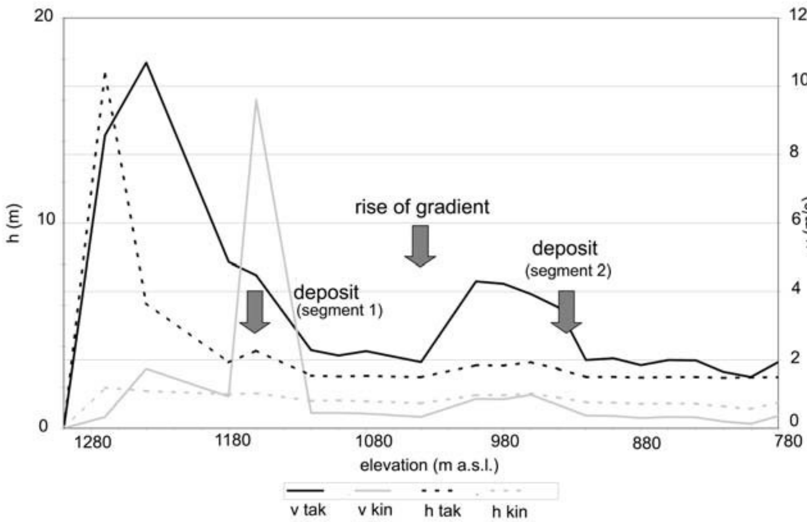


Fig. 16. Case 1: flow velocity (v) and wavefront depth (h) values, computed by considering D1 = 300 mm (hypothesized d_{50} of the material prone to erosion) and D2 = 300 mm (hypothesized d_{50} of debris flow materials), according Takahashi's method and kinematic wave theory

prove more realistic being comprised between 1 and 2 m, thus damage of the Ca' Verde intake (above reported) is justified.

According to the said two theories flow mixture deposition begins since top point 5 (1160 m) in accordance with the hypothesis above. On the contrary, according to the simulations the materials did not accumulate on the hanging plain entirely, but a part of materials have travelled down to the confluence zone with "Rio Spinola", where the channel gradient increases. Similarly, a newly-increased debris flow velocity could make the mass transport easier down to the inflow of the Rio Tauneri, where the thickness of deposits have attained more than 1 m in accordance with the depth of materials (boulders and blocks) and it is still visible in such valley stretch.

Concerning the wavefront depth and the extent of deposit, the values suggested by the kinematic wave theory appear consistent. As regards to the flow velocity, the values obtained from both the theories behave similarly, but those obtained by the kinematic wave theory are generally lower. In both cases two apexes are visible corresponding to the tops of 3, 4 (or 5, following the case) and 12. The flowpath stretches are more inclined towards the end and thereby lessening of velocity in the following stretches, where the valley bottom gradients suggest a tendency for deposition. The first peak of velocity comprises between 9 m/s (kinematic wave) and 11 m/s (Takahashi), while the second peak value considerably changes depending upon the grain size of the feeding material and the method considered (it lessens when applying the kinematic wave method).

CASE 2

Case 2 concerns the hypothesis that the whole flow have been travelled through two pulsatory waves; in practice, such simulation has taken into account for the formation of two debris flows, along two channel stretches in which the Rio Brunello has been subdivided.

As a first track the Rio Brunello has been considered between 1300 m and 1040 m; the second track firstly develops with a gradient of about 15° that justifies the starting point conditions for a debris flow and then ending at the Rio Tauneri inflow (770 m a.s.l.). For the first track the input data are the same as applied to the Case 1. By increasing the average size of the feeding material, wavefront depth and velocity may vary easily in comparison with the former case:

– According to the Takahashi's theory, wavefront depth varies between 3.6 m and 4.9 m near the Ca'Verde locality (1180 m), whereas the value is 1.8 m according to the Kinematic Wave method;
– In all simulations the deposit begins at 1160 m and do not exhaust before 1040 m a.s.l.;
– Behaviour of the velocity values obtained from the Takahashi method is characterized by a peak corresponding to the end of the stretch of higher gradient; such peak value however appears exceptionally high, particularly when the average size of feeding material is considered as >350 mm.

The solutions derived from the said simulations as well as from the on-site observations considering a mean size of the coarse material ranges between 300–400 mm (b-axis).

In order to explain the formation of a debris flow in the second channel stretch, it is assumed that the flow starts from the readily available material from the upper stream stretch. Thus the following entries may be considered in analyzing such genesis:

– hTc = 12 mm;
– H = 1.2 m (wavefront depth at the end of track 1, according to kinematic wave's theory);
– d_{50} mat er = 300 mm;
– d_{50} mat alv = 200 mm.

Results drawn from this simulation (Fig. 17) seems to be satisfactory, although not the best for in-situ observations, by considering the simulation according Takahashi, because:

– The wavefront velocity displays the highest value in the most inclined channel stretch, with a peak of above 11 m/s; diminishes dramatically with the initiation of sedimentation, lowering to 1.85 m/s near 1040 m a.s.l.; again increases correspondingly towards the upper end of stretch 2 and further diminishes down to the Rio Tauneri inflow;

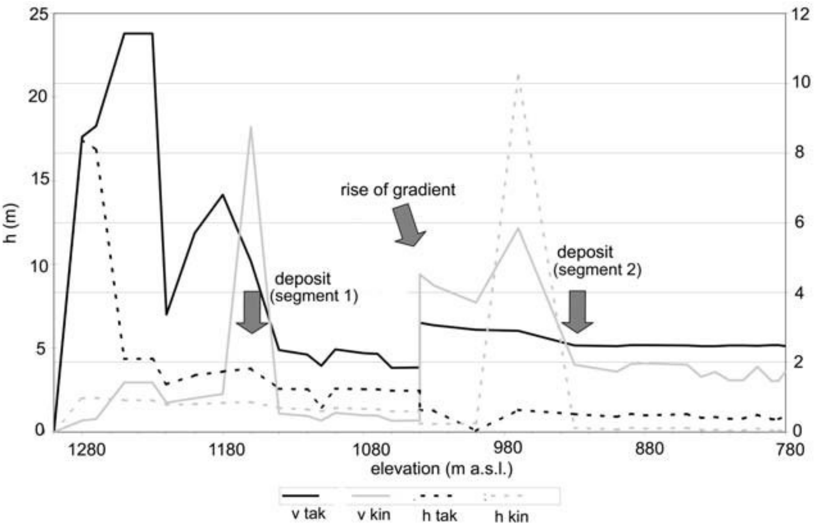


Fig. 17. Case 2: wavefront depth and flow velocity values, computed according Takahashi's method and kinematic wave theory

– The wavefront depth appears over-estimated, particularly in the first two stretches, then attains considerably high values corresponding to the first channel stretch, while they appear underestimated in the following lower track.

Lastly, considering the intrinsic biasness of a monodimensional model for which several input data have been estimated, the simulation's result ameliorates the application of Kinematic wave theory considering the formation of a sole debris flow, with mean size of the coarse materials (both supplied by the channel and adjoining banks under erosion) equal to 300 mm.

ESTIMATING CONDITIONS FOR DEBRIS FLOW OCCURRENCE IN THE RIO TAUNERI STREAM

The occurrence of debris flows in the heading zone of the Rio Tauneri catchment may trigger hazardous situations if huge amount of incoming debris material be spread over into stream incisions down to the settled areas, as happened in 1929.

Based on the model proposed by Takahashi (1978, 1991) concerning debris flow trigger conditions due to the occurrence (or increase) of a surficial in-channel water flow, the Ministry for Public Works in Japan has proposed a table (based on the ground gradient) for classifying the torrential streams with respect to their liability in debris flows (Tab. 7).

Table 7

Relationship between ground gradient and debris flow behaviour, proposed by the Ministry for Public Works in Japan

Gradient (α)	Flow behaviour
$\alpha < 3°$	Deposition
$3° < \alpha < 10°$	Stopped or lessened wavefront velocity
$10° < \alpha < 15°$	Lessening or movement
$15° < \alpha < 20°$	Formation or movement
$\alpha > 20°$	Formation

Suggested values are exactly matching with the process occurred on June 12, 1929, which was originated on a slope dipping above 20° (locally 15°–20°) and ended on the alluvial fan or corresponding low-dip channel stretches (<10°).

Most of the debris mass was deposited in the channel of Rio Tauneri, downstream of the Rio Brunello inflow having valley slope of less than 5° and very high width of the channel. The whole channel stretch comprised between the Rio Brunello inflow and the so-called Praverdino bridge bears a noteworthy amount of deposits, which spreads over the valley bottom outside the present channel bed, even during non-extreme events.

Following the Takahashi's model the thickness of debris has been evaluated and found that the stream is able to carry such mass through all its three different stretches of the Rio Tauneri, imposing the changes of head-flow between 0.2 m and 3 m.

In order to make easy a comparison between simulated results and real conditions, discharge corresponding to every assigned value of the headflow h has been considered (being known channel width) and the flow velocity value has been estimated on the basis of the Strickler formula (Eqn. 5):

$$v = K_s \cdot R_h^{2/3} \cdot \sqrt{i} \qquad \text{Eqn. 5}$$

where:

K_S – $26/(d_{90})^{1/6}$ = rugosity coefficient (Müller 1943) [$m^{1/3}/s$];
R_h – hydraulic radius, i.e. wetted area/wetted perimeter product [m];
i – channel gradient.

The representative diameter of the channel deposit (d_{90}) has been estimated on the basis of the indirect method suggested by Mancini et al. (1987) by which the grain size distribution of coarse sediments can be evaluated from the on-site photographs in stead of non-feasible laboratory tests.

Percentage values of the effective grain-size classes of the study area have been obtained through the said method. Distribution coefficients attenuated the bias in classifying large-sized clasts, which may be partly hidden, thus improperly assigned to a wrong class. Numerical percentages have been converted in volumes and then weights, supposing the same specific weight to all clasts. From the clast-size curve representing cumulative per cent classes 90% passing was drawn (290 mm) that has been considered in computing Müller rugosity coefficient and then utilized in the Strickler formula for estimating the flow velocity.

THICKNESS OF IN-CHANNEL DEPOSIT RIO TAUNERI

Two channel segments between 900 m and 780 m a.s.l., towards upstream from the deposition zone as mentioned before and a third one in the deposition zone itself have been considered for estimating the thickness of in-channel deposits; such channel segments are characterized by different width and average channel gradient between 5.5° and 7.4°; thickness has been estimated of the in-channel deposit liable to be removed by changing water head (i.e. draught water) that implies discharge. In such segments the gradient values are usually noted <10° those are not typical for triggering debris flow. In fact, the value of the discriminative relation has been computed on the basis of the following formula and the result obtained for <0.15:

$$\frac{\sin\alpha}{\left(\frac{\rho_s}{\rho_w}-1\right)}$$

According to Takahashi, in such cases an immature flow is expected first, followed by a partially dispersed hybrid flow and then muddy flow, but no typical debris flow.

Anyway, the analysis illustrated above for the three channel segments has been done on the basis of the Takahashi's formula, allows to draw the thickness value (a_L) of the material liable to set in motion when equilibrium is attained between the two tangential stresses "destabilizing" (τ_d) and "resisting" (τ_r):

$$a_L = \frac{\rho_w \tan\alpha - C \cdot (\rho_s - \rho_w)\cdot(\tan\varphi - \tan\alpha)}{C' \cdot (\rho_s - \rho_w)\cdot(\tan\varphi - \tan\alpha) - \rho_w \cdot \tan\alpha} \cdot h$$

where: α is the slope angle of the deposit; the values of ρ_s (2,65 g/cm^3), ρ_w (1 g/cm^3), φ (36°), C' (0,6) parameters have been considered as constants; h_0, the flow head, is changing in nature and a_L is the corresponding thickness value liable to be set in motion, obtained from the aforesaid constant and changing variables.

For Rio Tauneri, maximum discharge values for recurrence intervals of 500 yrs have been computed through several rational methods (U.S. Soil Conservation Service, 1986; Giandotti and Visentini 1938) and obtained the results between 60 and 80 m^3/s, whereas values obtained from empirical methods (e.g. Mantica 2005) are almost double in comparison with the previous methods.

In case of discharges of about 70 m^3/s the thickness of material liable to move, it is found that amount varies between 5 and 16 cm (Fig. 18) depending

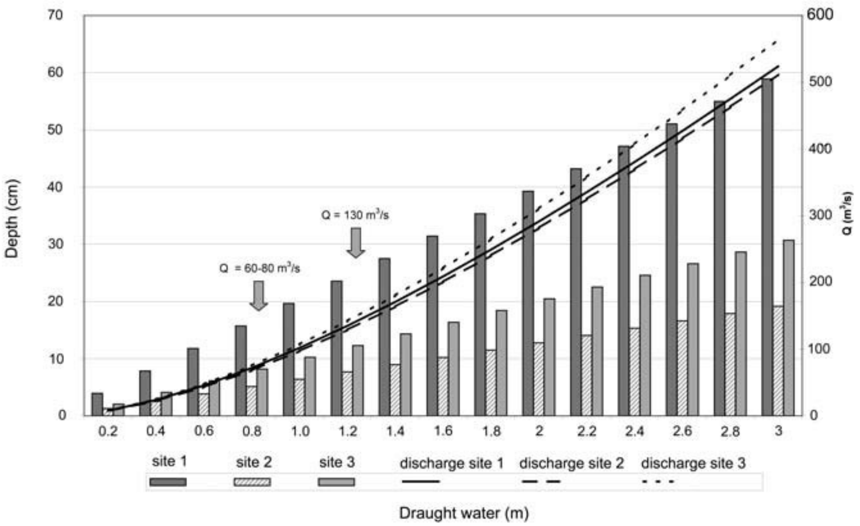


Fig. 18. Depth of erosion-prone detritus deposit in three channel segments (sites 1, 2 and 3) of the Rio Tauneri stream, as a function of different water head and discharge values according to Takahashi's theory

upon the nature of the channel segment. Such values are much lower than d_{90} computed above. Thus it is unlikely to generate any debris flow in this zone rather bedload transport processes. The volume of material involved in motion in the region is about 180–1150 m^3 and the three channel segments altogether deliver about 2000 m^3 of sediments.

However a discharge value state above, in the channel stretch having an average gradient of 7.4° can remove 60% of the in-channel material of aforesaid clast-size distribution. In addition to that a sediment depth between 24 and 27 cm can be displaced with a discharge range of 135–170 m^3/s. The values are comparable to the values obtained from the empirical methods and seems overestimated for the stream under consideration.

Channel segments with lower gradient in the downstream of the Rio Brunello and Rio del Parco (near the confluence with Rio Tauneri) possesses the total discharge (the sum of peak discharges of such three watercourses computed with rational methods) of about 130 m^3/s and can remove 8–12 cm thick layer of sediments. In case of the channel segments 1 and 2–3, the amount of discharge is equal to $60 \div 80$ m^3/s and 130 m^3/s respectively (Fig. 18) and the total amount of displaced material is about 2650 m^3.

CONCLUSIVE REMARKS

Some limitations of the above analysis can be evidenced:

- characterizing d_{90} of in-channel deposit upon a gravel-bed sample of restricted size;

- the prediction of an extreme discharge value of the Rio Tauneri could be expressed only arbitrarily (owing to lack of water-level records) based on the computing models issuing a rather wide range of values;
- in applying the Takahashi's theory for predicting debris flow triggered by removal of a sediment layer of given thickness, only liquid discharge value was considered in spite of increasing specific weight of the flowing mass during an extreme event, thus making in-channel sediment motion easier.

From the present study it is evidenced that the Sangone valley in the last three centuries has severely been affected by flood events those have caused heavy damage to infrastructures, housings and local activities. At least 35 rainfall events have occurred and sometimes affected the same localities at few-years intervals. Concerning the effects of natural events in such territory, attention should be paid not so much to catastrophic events rather to critical and recurring hazard-prone areas. It may be useful to assess the nature and extent of interaction between the Sangone river-system and the infra-structural layout in urban areas, as well as the nature of critical conditions both in the centre of major settlement (Giaveno) and in the catchments of Torrente Sangonetto and Rio Tauneri with a view to prevent the consequences of possible events of similar magnitude occurred in the past centuries. It is not by chance that in some localities hydraulic restoration works and newly-planned channel cross structures have set in place after the last heavy flood of October 2000.

Since few years back, the anthropogenic presence has steadily been increasing both in valley bottom and in sparsely-distributed villages in the Sangone valley due to the expansion of both residential population and tourists. In this context, properly-planned and shared land use choices should lead to a civil protection system more effective in order to ameliorating safety conditions for citizens and providing socio-economic benefits.

The present study area can be considered as a test-area for experimental investigation on the relationship between rainfall (triggering factor) and landsliding and for process-response analysis (e.g. geo-morphological impact of the physical changes, especially due to extreme hydrological events). The shape and dimensions of the Sangone basin and its sub-catchments can be treated as the representative of both geographical and anthropogenic characters of most of the Alpine valleys in the Western Italy.

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