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LANDSLIDING AND FLOODING EVENT TRIGGERED BY HEAVY RAINS IN THE TANARO BASIN (ITALY)

P. ALEOTTI, P. BALDELLI, G. POLLONI

Abstract

A study of the November 1994 rainstorm-triggered phenomena was carried out in a test area of the Tanaro basin (Piedmont, NW Italy), in particular with regard to the shallow slope failures. About 3000 soil slips/debris flows were inventoried and the water courses, together with the main bridges, were surveyed. The slope and river dynamics interaction has been examined and the influence of man-made structures (bridges) on solid transport process has been analyzed. Considerations on hazard and risk assessement, together with a susceptibility map, are also presented.

Riassunto

L'articolo contiene i risultati di uno studio sulle frane superficiali connesse all'evento meteoreologico del Novembre 1994 in Piemonte. In dettaglio sono riportate le analisi relative a circa 3000 soil slip/debris flow censiti in 4 bacini campione a sud dell'abitato di Alba. Particolare attenzione è stata posta all'interazione tra dinamica di versante e dimanica torrentizia evidenziando l'interazione tra processi di trasporto solido e strutture antropiche presenti (ponti). Si presentano, infine, alcune considerazioni circa la valutazione della pericolosità e del rischio fornendo una carta di suscettibilità dell'area in oggetto.

1. Introduction

At the beginning of November 1994 an uncommon rainstorm, lasting three days, affected the Piedmont Region (NW Italy) and in particular the Tanaro basin. Such hydrologic event triggered many landslides and flooding over most of the basin area causing 70 fatalities (50 due to flooding, 20 to landslides) and extensive damages (TROPEANO, 1995). This severe hydrologic event was characterized by great sediment transport composed essentially of floating trees in the stream current. These trees obstructed bridge openings, in many cases causing their collapse or rise of hydrological level and consequent flooding. Sediment transport derived essentially from landslides that occurred along the valley flanks due to heavy rains and partially from streamflow erosion along the river bed and banks. In fact, after about one day of very heavy rain, a great number of shallow slope failures affected valley flanks and the transported material (coarse soil and vegetal cover) reached the valley floor. As the flood rushed from the upper section of the valley downstream, it carried all the slided material lying on its way, increasing thus its destructive power, particularly near the artificial narrowings, such as bridges. A very detailed analysis of morphological conditions, land-use, in particular vegetation cover, has been carried out in test areas (the Seno d'Elvio, Cherasca, Talloria and Rea basins). This study, together with the inventory of the soil slips and of the bridges affected by the flood, provided useful information to assess the hazard levels in the basins and to outline adequate protection maesures suggestions.

2. Physical setting

The study area is located in the Langhe Cuneesi (Piedmont Region), within the Tanaro catchment basin. The area is characterized by hills with maximum elevation of 700-750 m a.s.l. and asymmetric slopes. The asymmetry of the flanks causes an unhomogeneuos spatial distribution of both the soil and vegetation covers. From a geologic point of view the area belongs to the Piedmont Tertiary basin with miocenic sedimentary units, mainly sands, sandstones and marls. All units outcrop according to a constant inclination, with monoclinalic trend towards the Astigian syncline axis.

3. Meteoreological and hydrological event

A negative metereologic situation (low pressure area over Great Britain, high pressure area both over central Mediterranean Sea and NE Europe) caused an exceptionally severe rainstorm in the Tanaro basin with total precipitation amounting to 200-300 mm and more (in 3 days), especially in the central-southern part where the study area is located (Fig. 1).

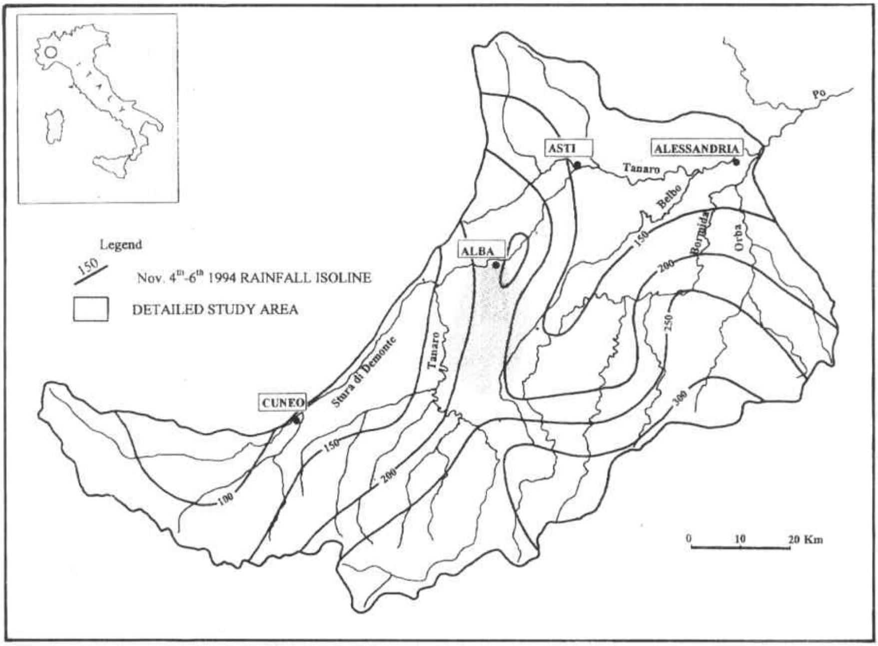


Fig. 1: Tanaro Basin Map (from POLLONI et al., 1996, modified)
Fig. 1: Carta del bacino del Tanaro

The rainfall, particularly intense on Nov. 5th when almost 90% of the rain fell, caused numerous landslides (rock block slide and soil slips) as well as heavy mass transport and flooding processes along the water courses.

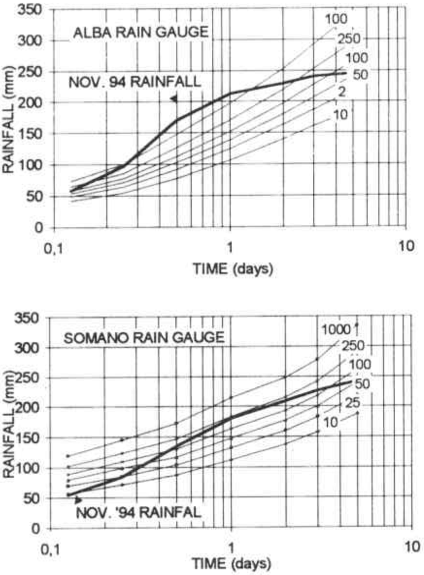
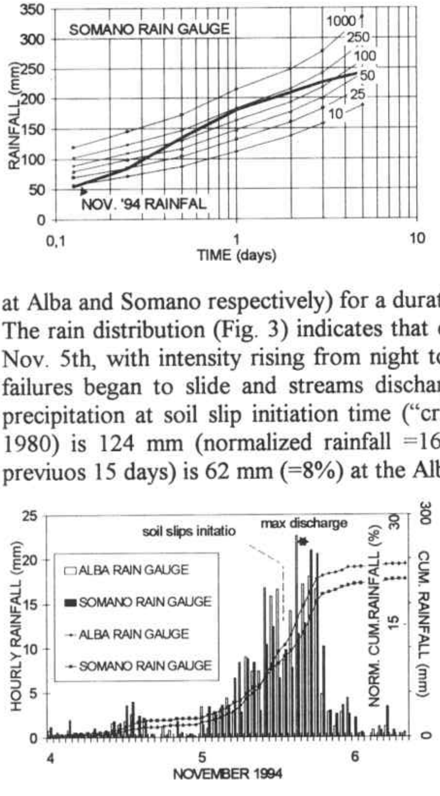


Fig. 2a, 2b: rainfall-duration frequency curves (Alba and Somano rain guage)
Fig. 2a, 2b: diagramma durata-altezza pioggia (Alba e Somano)

The Nov. '94 rainfall values, recorded in the study basins by the Alba and Somano rain-gauges, have been processed and compared with the probablistic data of maximum intensity and short duration using the Gumbel probabilistic distribution law. The diagram in Fig. 2a and 2b clearly shows that the hydrological event in Nov. '94 reached an exceptional intensity (return period R.T.= 1000 and 250 years at Alba and Somano respectively) for a duration in the order of 24 hours.
The rain distribution (Fig. 3) indicates that exceptional 24-hour values were reached on Nov. 5th, with intensity rising from night to late afternoon (up to 23 mm/h) when soil failures began to slide and streams discharges increased enormously. The cumulative precipitation at soil slip initiation time ("critical rainfall" after GOVI and SORZANA, 1980) is 124 mm (normalized rainfall =16%), while antecedent rain (referred to the previuos 15 days) is 62 mm (=8%) at the Alba rain gauge (Fig. 4).



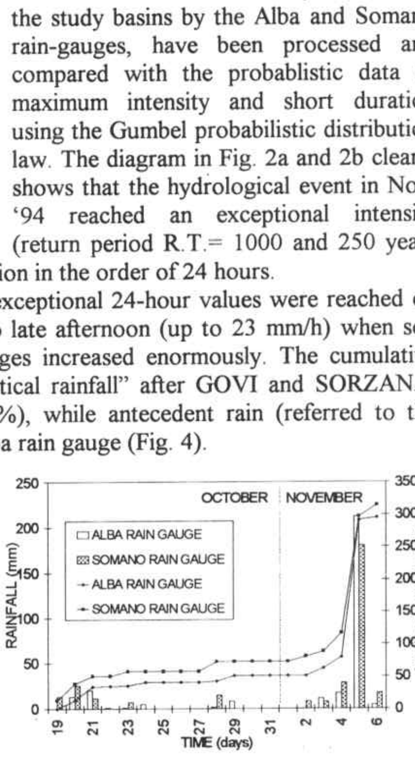


Fig. 3: Hourly rainfalls
Fig. 3: Piogge orarie

Fig. 4: Antecedent and critical rainfall
Fig. 4: Piogge antecedente e critica

4. Storm-triggered phenomena

The hydrological event caused a synergic negative effect on both slope and river dynamics, mainly in the upper part of the basins, almost contemporaneously over the whole area (Fig. 5).

The phenomena that affected not only the study area but also the whole Tanaro basin can be schematically described as follows:

- saturation, fluidification, sliding of cover soil; partial accumulation of slided debris and trunks on the narrow valley bottoms and loading up by the flood current;
- other typology landslides, mainly rock-block slides (total 109, many of large extent); temporary damming of the water courses and subsequent erosion of the accumulation and loading up by the current;
- lateral erosion by the flood current, undermining, sliding of slopes;
- obstruction of bridge openings by floating material, where their section and shape were inadequate and/or piers were present in the river bed;
- flooding and inundation of large areas of the valley floor due to rising of the water level in correspondence of the dammed bridges and, in some reaches, to the insufficient natural section of the water course.

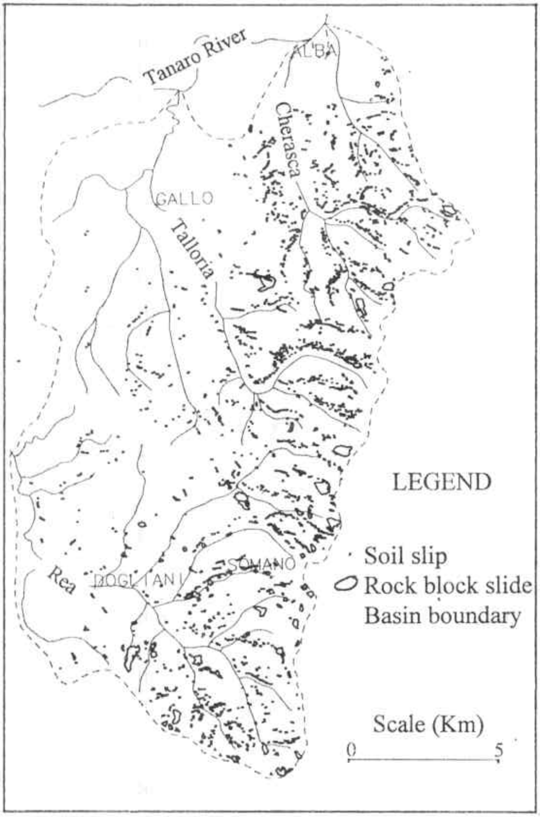


Fig. 5: Storm triggered phenomena

Fig. 5: Processi geomorfici indotti dall'evento idrologico

4.1 Bridge-flood interaction

The basins of the study area have similar characteristics with a well-developed subdendritic hydrografic net, narrow valleys, steep slopes in the upper parts and an alluvial plain with more gentle gradient in the middle-lower sections.

In the upper part of the basin erosional and mass transport processes of material (debris and vegetation) present along the stream bed prevailed; in the alluvial plain inundations, due to the insufficient both natural and bridge sections, took place causing severe damages to villages, industrial areas and roads along the flood plain.

In order to verify the influence of bridges on the river dynamics, an inventory of the bridges and their characteristics (location, typology, dimensions) was carried out as well as an hydrologic-hydraulic study of the Nov. '94 flood.

This study concerned the Cherasca, Talloria and Rea streams, near the main affected bridges (Tab. 1).

BASINS		CHARACTERISTICS					
		A (km^2)	L (km)	J (%)	T_c (h)	H_{tc} (mm)	Q_{94} (m^3/s)
CHERASCA	FINAL SECTION	36	13,8	4,0			
	BRIDGE n. 10 (Alba)	35	12,1	4,5	3,5	66	187
TALLORIA	FINAL SECTION	98	20,9	2,7			
	BRIDGE n. 7 (Gallo)	32	15,3	3,6	3,5	63	164
REA	FINAL SECTION	105	19,2	3,0			
	BRIDGE n. 2 (Dogliani)	66	11,6	4,4	3,7	63	310

LEGEND: A= basin surface; L= stream length, J= thalweg ave. gradient; T_c= corrivation time; H_{tc}= rain height in T_c; Q_{94}= Nov. '94 max. discharge

Tab. 1: Basins characteristics

Tab. 1: Caratteristiche bacini

The computation of the Nov. '94 liquid discharge (Q_{94}) was based on the rational method, according to the formula (1):

(1) $Q = c * I * A$

(with: c= yield coefficient, I= rain intensity, A= basin surface) and that of the discharge consistent with the bridge sections (Q_{Br}) on the Manning equation (2):

(2) $Q = M * A * i^{1/2} * R^{2/3}$

(with: M= roughness, A= basin surface, i= bed slope, R= hydraulic radius).

The results of the comparison between Q_{Br} and Q_{94} (Q_{Br}/Q_{94} <,=,>1) together with the bridges location and characteristics are indicated in Fig. 6.

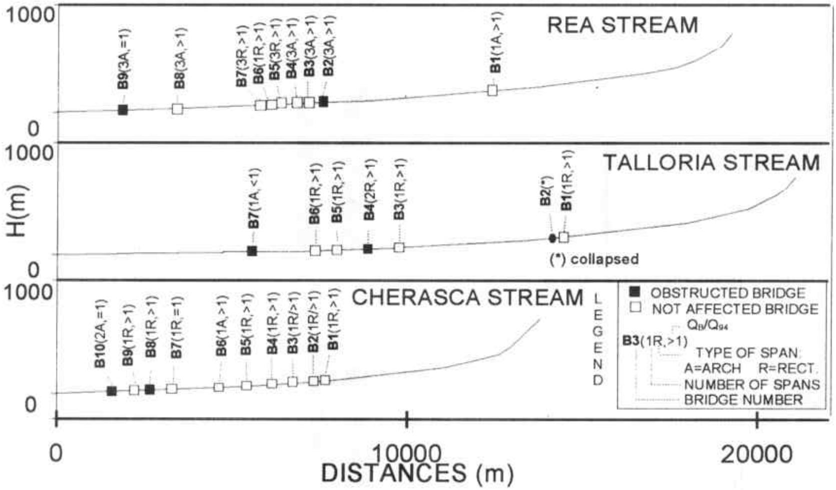


Fig. 6: Thalweg profiles

Fig. 6: Profili di fondo

It can be observed that:

(i) along the Rea stream, two bridges were seriously affected by the flood and obstructed by floating material: bridge n. 2, which caused damages in the town of Dogliani, and n. 9 responsible for casualties. It has to be noted that the other bridges with narrow spans in

the center of Dogliani were not obstructed probably due to the filtering effect generated by bridge n. 2 located just upstream;
(ii) along the Talloria, stream bridge n. 2 was destroyed, probably due to foundation undermining; bridges n. 4 and n. 7 were clogged up by transported vegetation and caused flooding in the countryside and the urban area of Gallo. All the bridge sections along the stream were adequate for water discharge, except n. 7;
(iii) along the Cherasca stream, all the bridges would have been adequate to support the Nov. '94 water discharge; nevertheless two of them (bridge n. 8, just upstream from sharp bend, and n. 10) have been obstructed by the trunks and overflooded, causing inundation in proximity of the town of Alba.
In general appears that the main problems were caused by obstructed bridges that retained floating vegetation (in particular long tree trunks torn away from the banks by the current or slided down from the valley flanks); the bridges with multiple narrow spans (typically < 10 m), arch form and piers in the river bed were the most critical. Almost all the bridges obstructed by the flood had sufficient sections to support water discharge, but the width of their openings, in particular of the upper part of the arches, did not allow the floating trunks to pass through.

4.2 Surficial slope failures

A complete inventory of the soil slips/debris flows was carried out by means of photointerpretation and field surveys: almost 3000 surficial failures were identified, whose spatial distribution is affected by the valley asymmetry tied to the monoclinalic attitude of the units.

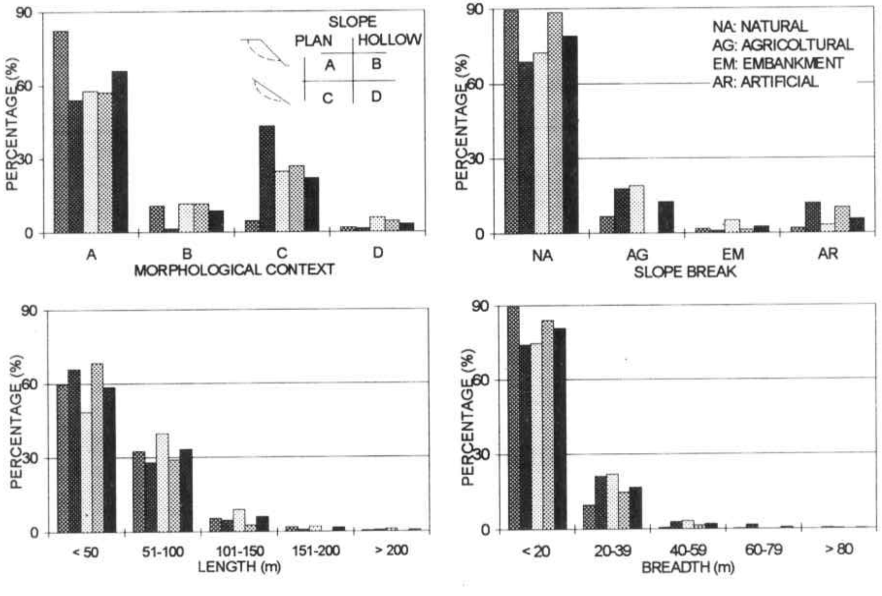


Fig. 7a: Main characteristics of the soil slips (column: Rea, Talloria, Seno d'Elvio; total)
Fig. 7a: Principali caratteristiche dei soil slips

The slips often originate in slightly concave slopes (zero order basins), frequently in correspondence with both natural and artificial breaks in slope; this particular location favours development and propagation of a wetting front resulting in faster saturation of soil covers. The frequency histograms (Fig. 7a, 7b) show most of the soil slips have length L < 50 m (58 %), breadth B < 20 m (80 %) and depth, generally corresponding to the impervious substratum limit, D=0.40-1.00 m (90 %). B/L ratio range is usually =0.1-0.5, only rarely <0.1 (10%) when soil slips evolve in channeled debris flow. The slopes affected by the slips are often (48 %) forest-covered (Pine, Maple, Oak, Robinia) and their steepness is mainly =30°-40°(68 %).

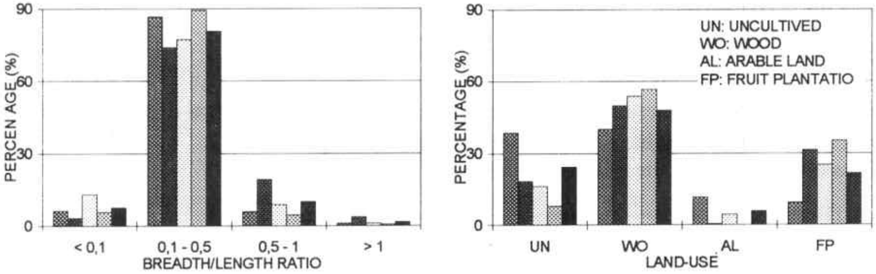


Fig. 7b: Main characteristics of the soil slips (column: Rea, Talloria, Seno d'Elvio; total)
Fig. 7b: Principali caratteristiche dei soil slips

5. Soil properties

Soils involved by the surficial failures are mainly of eluvial-colluvial origin. Their geotechnical properties were tested on 25 samples: they can be classified as clayey and sandy silts, with a low uniformity index (D60/D10>5) belonging to CL class, according to the U.S.C.S. classification.

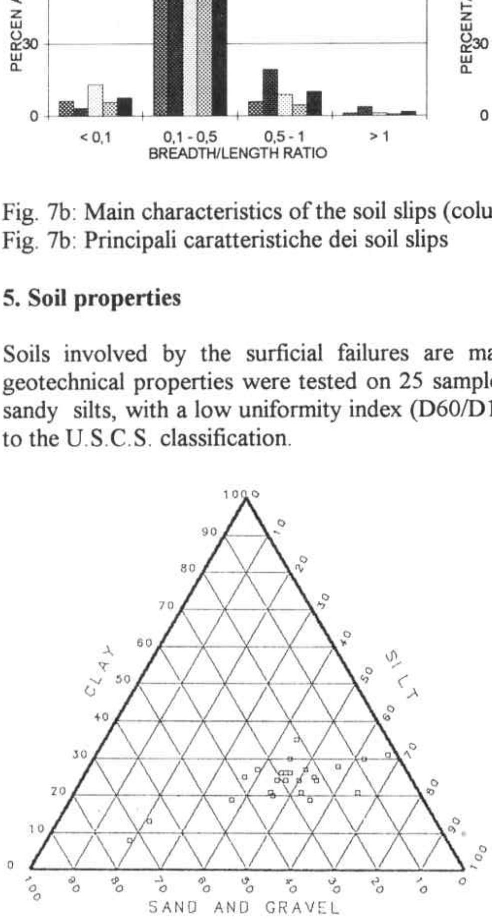


Fig. 8: Size analyses of soils
Fig. 8: Granulometrie

Clay fraction, CF, (Fig. 8) is 8-35 %, quite consistent with the values set in literature; in fact a CF in excess of 35% is sufficient to inhibit mobilization of soil slip during storm (ELLEN et al., 1988). The Approximate Mobility Index is about 1.Resistance parameters were estimated by means of torsional shear tests (POLLONI et al., 1996): ϕ'_r is 26°-31° and c' is 2-4 KN/m^2.

6. Stability analysis

In order to verify the dependence of soil slipping on the hydrological conditions of the November 1994 event, a set of parametric stability analyses of the slopes was carried out, based on the SKEMPTON and DE LORY model (1957). The model -infinite slope- is consistent with the soil slip geometry, typically a sliding surface parallel to topographic ground and D/L ratio <<1 (CANCELLI and NOVA, 1985; CROSTA and MARCHETTI, 1993). According to this model it has been verified that flow running parallel to the slope worsen the stabilty conditions, leading often to slope failure. In this case the safety factor (F) at a depth z_w is:

$$(3)\ F = \frac{c'+(\gamma_t-\gamma_w)z_w\cos^2\alpha\tan\phi'}{\gamma_t z_w\sin\alpha\cos\alpha}$$

with c' = effective cohesion, ϕ' = effective friction angle, z_w = vertical depth of saturated soil, γt= total unit weight, γ_w= water unit weight, α= slope angle.
Thus in back analysis the critical depth D = z_w is:

$$(4)\ D = \frac{c'}{\gamma t\cos^2\alpha\left[\tan\alpha-\tan\phi'\frac{(\gamma_t-\gamma_w)}{\gamma_t}\right]}$$

The diagram of Fig. 9 shows the D-α relation as function of the effective friction angle ϕ'. For α= 30°-40° and ϕ'= 25°-30° (values consistent with the slopes and soils involved by failures) the critical depth D is =0.5-1 m, that is in good agreement with on-site evidence.

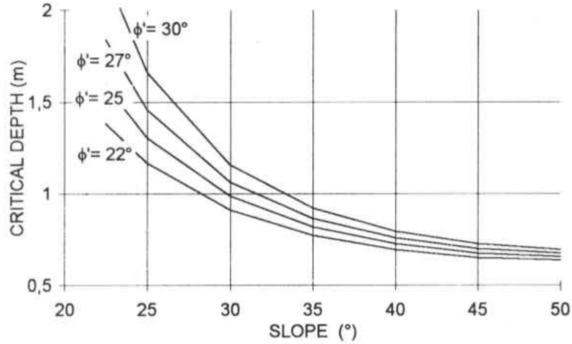


Fig.9: Relation between α, H_C and ϕ'.
Fig. 9: Relazione tra α, H_C and ϕ'.

It has also been noted that the soil slips involving less steep slopes are generally deeper than the ones on steeper slopes (Fig. 10).
Before seepage parallel to the slope face can take place, the soil must be completely saturated. This may be caused by a long period of heavy rainfall which should be sufficiently intense to develop both a ponding situation and a wetting front (minimum intensity I_{min}> infiltration rate), long enough to saturate the slope at depth z_w ($T_w > T_{min}$). The presence of impervious bedrock facilitates the clearing of the suction and complete saturation of the cover soil. In order to analyze this process (PRADEL and RAAD, 1993; CROSTA, 1994; DE LUCA et al., 1996) the GREEN and AMPT (1911) model can be adopted, according to which the time required to saturate the soil to depth z_w and the relative rain intensity are as follows:

$$(5)\ T_w = \frac{\vartheta_w - \vartheta_i}{K_w}\left[z_w - S\ln\left(\frac{S+z_w}{S}\right)\right]$$

$$(6)\ I_{min} = \frac{\theta_w - \theta_i}{T_{min}}\left[z_w - S\ln\left(\frac{S+z_w}{S}\right)\right]\left(\frac{z_w+S}{z_w}\right)$$

where θ_w-θ_i is the difference between the volumetric water content before and after wetting, S= suction, K_w= coefficient of permeability in the wetted zone.

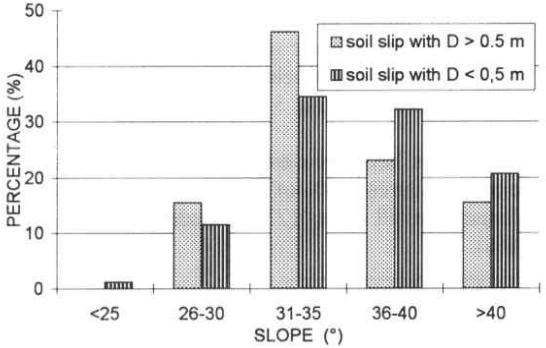


Fig. 10: Relationship between observed α and observed D
Fig. 10: Relazione tra valori misurati di α e valori misurati di D

In the computation the following values, consistent with field observation and laboratory tests results, were used: soil depth D= 40-80 cm, wettable porosity n= 20%, suction S= 80 cm. By comparing the resultig curves with the maximum rainfall intensity for different return periods (Fig. 11), we can estimate the minimum rainfall intensity/duration values capable of saturating soil at different depths.

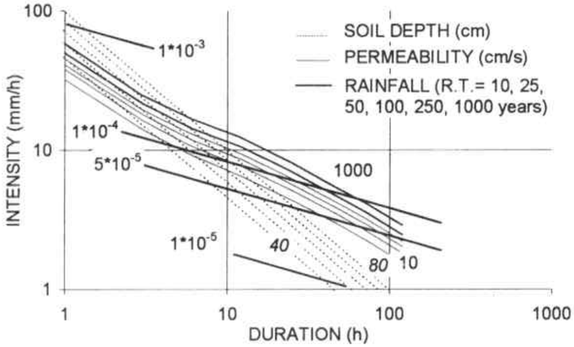


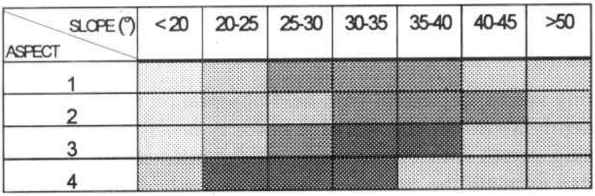
Fig. 11: Rainfall intensity (for differen return periods) vs. duration
Fig. 11: Diagramma intensità-durata

It is also possible to obtain the permeability threshold values as function of precipitations with different return times. It can be noted that for depth D= 40-70 cm the permeability threshold range is $K=10^{-3}$ -10^{-4} cm/s. The major drawback of this model is that it doesn't take into account runoff and evapotranspiration: thus the estimated rain intensity can be less than that actually required to achieve saturation. Moreover a rainfall prior to the critical event can reduce T_{min} by changing the initial soil moisture conditions.

6. Hazard assessment

Despite the low soil volume involved by each slip, the surficial slope failures must be considered as both direct and indirect extremely dangerous. In fact they have high density (10 slides per km^2 with max. values of 40 per km^2 in the upper section of the basins) and very high kinetic energy. Among the 3000 inventoried failures in the study area, 27% caused damages to man activities, of which 71% to agriculture, 27% to roads, 2% to buildings. The indirect danger is due to soil slip interaction with the drainage network: it has been seen that 48 % of soil slips (of which 70% in forest-covered areas) reached the valley bottoms with an estimated accumulation volume of $6*10^5$ m^3 (debris and vegetation). Field surveys and measurements performed along the streams pointed out that about 40% of this material (with approximately 7000 trees trunks of significant length compared to the bridge spans) was loaded up by the flood flow. Therefore, although the bridge spans were sufficiently wide to support water discharge (included the flood which occurred in Nov. '94), they were nevertheless obstructed by the high number of tree trunks. It can be significantly observed that 5 of the 6 obstructed bridges, had an arch or a multiple span section.

The soil-slip prone conditions of many slopes have been endangered by man activities, which represent a contributory cause of the failures in 8% of the recorded cases: they are due particularly to road cuts/embankments on hill slopes (73%), inadequate drainage of surface waters (18%), overloading (9%).



SLOPE (°) / ASPECT	<20	20-25	25-30	30-35	35-40	40-45	>50
1	░	▒	▓	▓	▓	▒	▒
2	░	▒	░	▓	▓	▓	▒
3	░	▒	▓	█	█	▒	▒
4	▒	█	█	█	░	▒	▒

Tab. 2: Susceptibility matrix

Tab. 2: Matrice di suscettibilità

In areas so prone to negative geomorphic processes, a precise risk assessment and a correct land planning are needed; this implies formerly the landslide susceptibility evaluation. A tentative approach to such an evaluation (Tab. 2, Fig. 12) has been tested using a matrix (BALDELLI et. al.,1996) based on slope steepness and aspect characteristics: the former represents the main cause of soil instability and the latter is a significant parameter due to the influence of the structural pattern on slope morphology. Lythology was not considered because of its homogeneity all over the area.

The matrix represents different classes of susceptibility (graphically indicated with different tones of gray) dependent on the number of slides relevant to each cell. The boundary values of the susceptibility classes have been based on the mean (M) and standard deviation (δs) values of each cell, as follows:

a) Low= $x < (M-\delta s)$; b) Low-Medium= $(M-\delta s) < x < M$;

c) Low-High= $M < x < (M+\delta s)$; d) High= $x > (M+\delta s)$.

7. Conclusions

The Nov. '94 rainstorm pointed out the high vulnerability of the area as regards both slope surficial stability and mass transport-floods along the river courses. Sliding and maximum discharge took place almost contemporaneously and their interaction intensified their negative effect. Vegetation transported by the flood played a fundamental role causing obstruction of bridges, rise of water levels and flooding. Although the bridge spans were sufficiently wide to water discharge, they were inadequate to support such a heavy floating load.

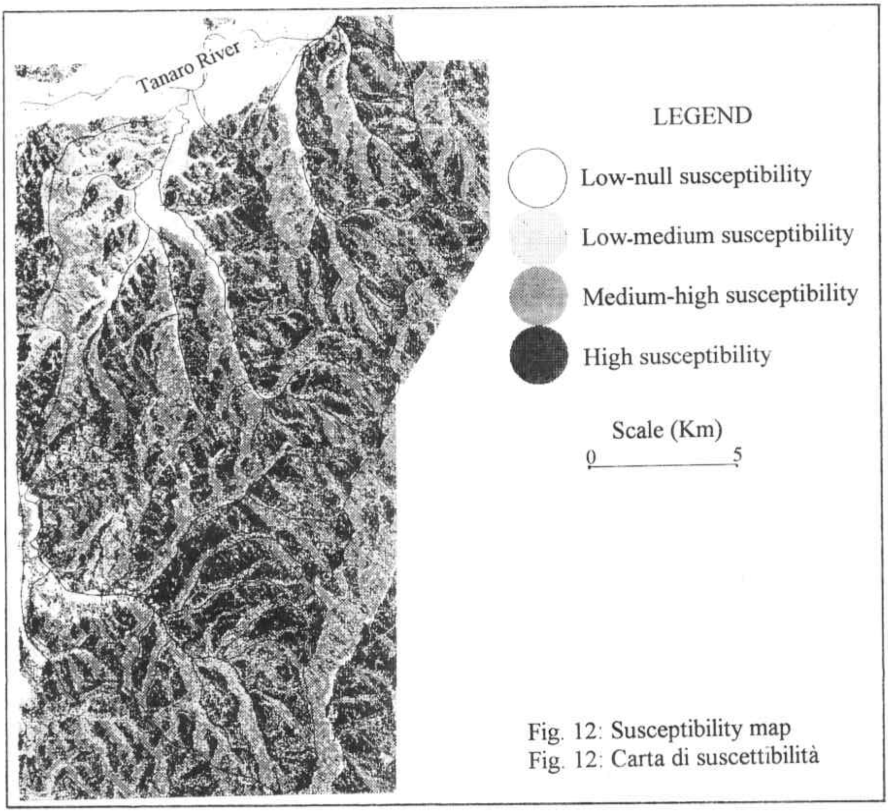


Fig. 12: Susceptibility map
Fig. 12: Carta di suscettibilità

The surficial landslide susceptibility map, derived from thematic maps at scale 1:10000, represents a methodological example, useful for two main objectivies:
(i) as regards the direct consequences of the failures, the map indicates the areas particularly prone to soil slips, in which local Authorities should carry out more detailed studies to define adequate mitigation measures and land-planning policies;
(ii) as regards the indirect effect of slips on river dynamics, the susceptibility map, compared with the forest map, provides useful information on the extent of the wooded cover that could be involved by sliding and thus increase the floating load. Depending on the forest characteristics, river morphology, presence and geometry of crossings-structures, adequate measures must be taken in order to reduce the risk of flooding. They can be as follows: a) restrain the floating material by means of check dams; b) (re)construct bridges with adequate openings; c) adopt-wherever possible- a forestry policy aimed to replace high coppice trees with shrub plantation.

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AUTHORS ADDRESS

Pietro Aleotti, Pieramelio Baldelli, Giovanni Polloni
Aquater
Via Miralbello 53
61047 SAN LORENZO IN CAMPO (PS), ITALY