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RISK ANALYSIS OF DEVELOPED AREAS ON ALLUVIAL FANS

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ABSTRACT

Damages to developed areas caused by flooding and sedimentation processes are recurrent on alluvial fans in mountainous regions. Risk analysis is a crucial problem for the mitigation of such damages and the regulation of new settlements.
A scheme of analysis and feasible tools for evaluation of processes is proposed with reference to the case of debris-flow generation. The purpose is the assessment of the degree of hazard.
In the proposed scheme, rainfall of assigned probability of occurrence is assumed at the headwater of the watershed. Runoff is estimated, by rainfall-runoff modeling (WMS). The transformation of water discharge into debris-flow is discussed on the basis of available relationships. The debris-flow downstream movement along the generally incised channel is simulated by means of a 1-D unsteady model. Deposition processes are investigated by means of a 2-D model. The accuracy of results is strongly dependent on topographical information and local phenomena.
A few real world cases occurred in North Western Alps are cited and referred for comparison.

Key words: Design hydrograph, numerical modeling, alluvial fan.

FOREWORD

The major floods occurred in the last decades in the Northwestern region of Italy induced local administrations to revise the current procedures of approving development plans (Regione Piemonte, 1996; 2002). The concept of risk (vulnerability x hazard) has been introduced and used to control land use and development. People have worked for centuries to mitigate the effects of floods locally with structural works, but flood risk prevention must be understood as a management tool at the catchment scale. The River Po Authority accelerated its activity to approve tools able to promote integrated management (Autorità di Bacino del Fiume Po, 2001). The European Commission (DG XII) and INTERREG supported studies that were specifically devoted to the investigation of flood risk and to devise operational procedures.

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At the scale of local communities, the evaluation of risk, both to permit new developments and to devise protection needs of existing homes, is one of the preliminary steps in the planning process.

In the mountainous areas of the Northwest of Italy, flash floods in small catchments and debris flows on alluvial fans are of major concern. The evaluation of risk must face a number of serious constraints such as lack of data on local rainfall-runoff processes and poor topographical information.

This study proposes an operational scheme, at basin scale, to assess the debris flow hazard on alluvial fan. The procedure is based on reasonable assumptions about hydrological and rheological parameters and it makes use of numerical tools widely diffused. There are several mechanisms of initiation, but this approach will study only the mobilization of solid material in the riverbed. A water flow, induced by rainfall on a steep slope, first saturates the debris layer and then mobilizes it by overland flow, spreading solid material all over the current depth with the formation of a debris flow (Armanini and Gregoretti, 2000).

There are many difficulties in defining a standard predictive method, because of the high variability in debris flow occurrence, initiation and behavior. Then it seems suitable to propose a schematized approach to numerical models (Laigle and Marchi, 2000), taking into account different critical scenarios resulting from the simultaneous occurrence of volumes, discharge values and material characteristics.

A FEASIBLE PROCEDURE

Generally, alpine catchments may be divided in three zones (Surell, 1841; Mougin, 1910): (a) the headwater, where rainfall is collected and conveyed through the stream network into a unique branch; (b) the main stream stem, incised between steep slopes somewhere supplying debris, along which the flood is conveyed and is likely to be transformed into debris-flow; (c) the alluvial fan, with ancient villages and recently developed areas.

Evaluating the hazard and defining the extent of the flood prone areas are at the beginning of the procedure and the cited constraints must be overcome.

Three steps are necessary: (1) to derive the design flood hydrograph at the headwater of the catchment, (2) to assess the debris-flow discharge at the apex of the cone, (3) to evaluate the extent of the flooding. Professionals as well as local administration staff need reliable tools to be found among commercial products.

Each step requires input data and produces output ones. The procedure is schematized in Fig. 1.

The evaluation of the flood hydrograph is easily performed by Hec-1 in the frame of Boss-WMS®. After the transformation of water hydrograph into debris flow hydrograph, this is routed through the main stream until the fan apex using a 1-D numerical model (DAMBRK). Downstream the fan apex, the debris flow spreading on alluvial fan is simulated by means of a 2-D model (FLO-2D).

The procedure was applied to two alpine basins in Susa Valley (Piemonte), located west of Torino, to solve real problems: in the first basin (Rhô Torrent) the procedure was applied to evaluate the debris flow discharge; in the second basin (Ronelle Torrent) to estimate the affected area on the fan, where detailed topography was available.

The Rhô Torrent is a tributary of the Dora of Bardonecchia and it has an area of 16.3 km^2. The highest elevation of the watershed is 3200 m a.s.l., the lowest is 1430 m a.s.l. and the mean elevation is 2178 m a.s.l.. The main stream has a length of 6.7 km^2, with a main slope of 16 %; the mean slope of the basin is 68%.

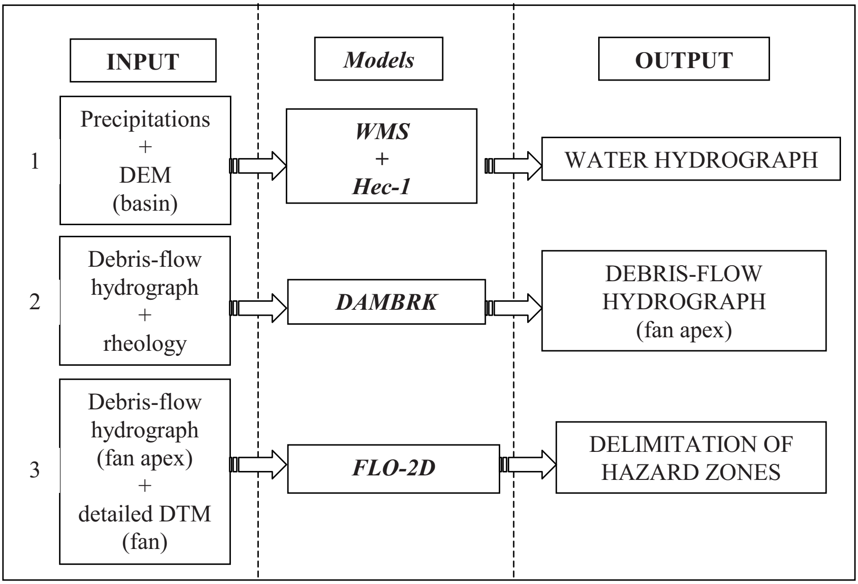

Fig1: Schematization of proposed procedure.

The left side is mainly formed by calcareous schist, on the right side there are carbonatic rocks in the upper part and deposital detritus in the lower part. A study conducted by CNR-IRPI of Torino (Tropeano and Turconi, 1999) recognized two kinds of sediment sources: the “active sediment”, which is immediately available to the mobilization, and the “sediment in temporary equilibrium”, which is not immediately available but could be mobilized in some condition. In the Rhô basin an analysis of aerial photograph determined a total surface of 0.39 km^2 covered by the first type of sediment and 3.20 km^2 covered by the second type (Tropeano and Turconi, 1999). Written sources recording debris flow events in the basin can be found since 1728 (Tropeano and Turconi, 1999), but no records of volumes and discharges are available.

The Ronelle Torrent has a small basin (less than 1 km^2) and it is a tributary of Cenischia Torrent in the lower part of the Susa Valley. In 1986 it was affected by a debris flow that almost reached the Villaretto village: the extent of the debris flow on alluvial fan was surveyed and it is used here to evaluate the accuracy of the 2-D simulation.

Definition of clear water hydrograph

The Watershed Management System (WMS) is based on the availability of a DEM whose accuracy is at the origin of the stream network automatic derivation. The hydrological model of the catchment was built using Hec-1 and the precipitation losses simulated according to the SCS (Soil Conservation Service) method. In lack of rainfall-runoff information, SCS method looks of practical importance. The SCS Runoff method relates accumulated rainfall with an empirical parameter CN (Curve Number). The CN is assumed in dependence of land use, soil hydrologic characters and antecedent runoff conditions (Hoggan, 1989). Ranzi and Rosso (1994) proposed a set of CN values.

Input data for WMS are (1) the DEM of the basin, (2) land use and/or land coverage, (3) hydrological soil type, (4) precipitation data.

The DEM of the basin was derived from the Digital Terrain Model (DTM) of Regione Piemonte, which has one elevation point per 50x50 m.

Regione Piemonte distributes land use maps as Arcinfo files. Hydrological soil type, in lack of soil type maps, was inferred by crossing information of geological, lithological, pedological maps and local investigations at different scales. For our alpine basins the prevailing soil types were A and B (soils having high and moderate infiltration rates).

Precipitation data derive from a probabilistic analysis of short duration rainfall conducted by the Po River Basin Authority, which gives the parameters *a* and *n* of the rainfall intensity-duration curve:

$$h_{Tr} = a \cdot \left(\frac{t}{24}\right)^{n} \qquad (1)$$

where h_{Tr} is the rainfall corresponding to a given return period (mm) and t is the rainfall duration (hours). This criterion was used awaiting the Regione Piemonte choice of TCEV distribution. Nowadays a more detailed analysis of rainfall is available at the Po River Basin Authority.

The hyetograph was defined as follows:

a) the rainfall *h* was computed for different duration to find the maximum discharge value, which resulted for 2-hour rainfalls and high soil saturation. A return period of 200 years was chosen, according to the guidelines of the Po River Basin Authority for these studies.

b) the precipitation was distributed assuming that the intensity increases in the last quarter of the event. The assumption originates from an investigation of more than 16000 hyetographs (Ferrari, 1994). In that way the maximum rainfall intensity is reached several hours after the beginning of the event (it depends on rainfall duration): this condition seems to be suitable to simulate debris flow occurrence and, on the same terms, it represents the worst scenario.

Fig. 2 schematizes the WMS method to produce hydrograph at the basin outlet. Starting from a DEM of the basin, the WMS computes flow direction and flow accumulation (with TOPAZ); once the watershed outlet and interior sub-basin outlets are identified, it defines basins and computes basin geometric data (such as area, slopes, runoff distances, etc.). With geometric data, land use and soil type coverage, WMS computes CN for each sub-basin by taking an area-weighted average of the different CN for the different regions (soil type and land use combination) within a basin (Boss Intl., 2000). CN is used to compute the Lag Time, a parameter defined as the difference in time between the center of mass of net rainfall and peak rate of flow (Gupta, 1989). The Lag Time (hours) is computed with the relation due to Mockus:

$$TL = 0.342 \cdot Y^{-0.5} \cdot L^{0.8} \cdot (1000/CN - 9)^{0.7} \qquad (2)$$

where Y is the watershed slope (%) and L is the hydraulic length of watershed (km).

CN values are the weakness of the procedure. Improvements may derive from calibrating parameters using rainfall-discharge records in analogous catchments. Gauging stations in watersheds of interest have been set up in the last decade by the regional administration of Piemonte and stage-discharge relationships are being derived. In a few years, available data will be of primary importance.

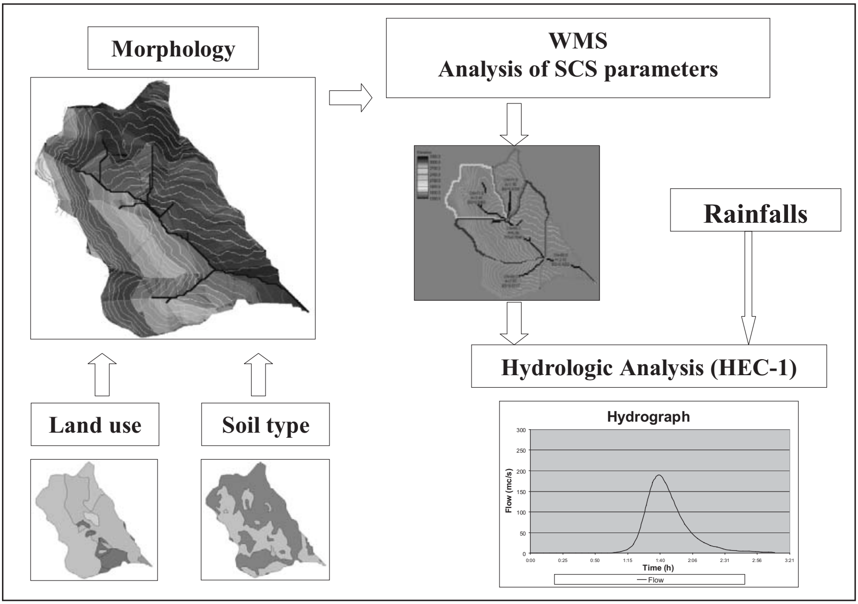

Fig2: WMS method for hydrograph computation.

The water hydrograph obtained has a peak flow of 49 m^3/s for the Rhô Torrent: this value represents the worst hypothetic condition in terms of rainfall duration and antecedent moisture condition.

Estimation of debris-flow hydrograph and its routing through the channel

The flood hydrograph must be transformed into debris-flow. It is important to point out that the return period assumed to define the water hydrograph shouldn't be associated to the debris flow hydrograph. In fact, the initiation and the behavior of a debris flow depend not only on precipitation, but also on material characteristics.

In lack of measured discharges, the debris flow hydrograph can be obtained starting from the following relationship (Armanini, 1999):

$$U_f h = U_0 h_0 \frac{C^*}{C^* - C + \frac{h_0}{a} C \left(1 - \frac{U_0}{U_f} \right)} \tag{3}$$

where U_f is the debris front velocity (m/s), h is the front depth (m), U_0 is the approaching water flow velocity (m/s), h_0 is the water depth (m), C is the volume concentration, C^* is the maximum concentration of loose materials, and a is a coefficient (0.042 according to Bagnold or 0.35, according to Takahashi, for debris flows over erodible bed).

Supposing that $U_f = U_0$ the relationship leads to (Armanini, 1999):

$$Q_{df} = Q_0 \frac{C^*}{C^* - C} \tag{4}$$

which allows to assess the debris-flow discharge. Regarding concentration values, we can assume $C^* = 0.7$ (Armanini, 1999; Johnson & Rodine, 1984; Costa, 1984), for non-cohesive materials. Volume concentration C can be derived multiplying C^* by 0.8. At the end:

$$Q_{df} = 5Q_0 \tag{5}$$

applied to the whole hydrograph may be a rough estimation for practical purposes. In this way, the peak flow of 49 m^3/s (clear water) becomes 245 m^3/s (debris flow) for Rhô Torrent (Fig. 3) and the peak flow of 15 m^3/s becomes 75 m^3/s for Ronelle Torrent (Fig. 4). This is, of course, an overestimation of the total volume mobilized during the event, but it allows a precautionary evaluation.

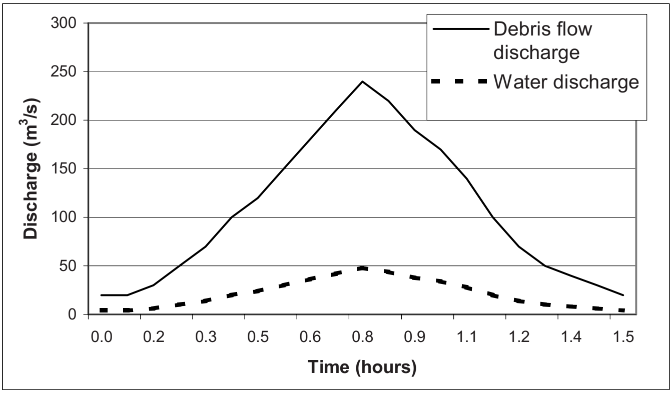

Fig3: Water discharge and debris flow discharge for the Rhô Torrent.

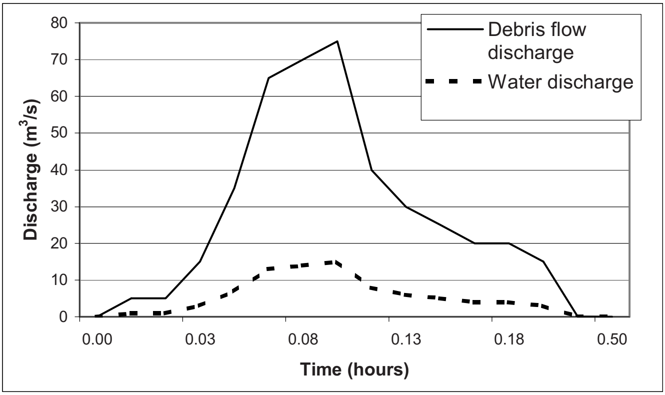

Fig4: Water discharge and debris flow discharge for the Ronelle Torrent.

The conveyance of the debris-flow along the stream main stem was investigated by means of the most recent version of Boss-Dambrk® able to simulate the unsteady flow of a viscous fluid. The simulation starts from where the debris flow is supposed to initiate and ends at the fan apex.

Required data are (1) the stream longitudinal profile and very schematic cross sections, (2) debris flow roughness (n, $\mathrm{m}^{-1/3}\mathrm{s}$), (3) debris-flow viscosity (μ, $\mathrm{Ns/m^2}$), and (4) initial shear stress (K, $\mathrm{N/m^2}$).

The roughness was evaluated according to the following equation that relates the mean velocity to the slope (Takahashi, 1981; Armanini, 1999):

$$U = \frac{2}{5}\frac{h}{\lambda d}\sqrt{\frac{\rho}{\rho_s}\frac{(C\Delta + 1)}{sin\phi a}ghsin\alpha} = \chi_{df}\sqrt{hsin\alpha} \tag{6}$$

where d is the mean material size, ρ is the water density, ρ_s the density of the material, ϕ the angle of internal friction, g the gravity acceleration, α the slope, $\Delta = (\rho_s-\rho)/\rho$ the relative density and λ the linear concentration expressed as:

$$\lambda = \frac{C^{1/3}}{(C^*)^{1/3} - C^{1/3}} \tag{7}$$

If we set $a = 0.035$; $\lambda = 12.95$; $d = 0.078$ m; $\Delta = 1.65$; $C = 0.56$; $C^* = 0.70$; $\phi = 35°$, we obtain a n value ranging between 0.04 and 1.14 $\mathrm{m}^{-1/3}$ s for a debris flow front depth ranging respectively between 2 and 4 m: then we defined a mean n value of 0.08 $\mathrm{m}^{-1/3}$ s.

In a few cases of investigation, μ and K values were derived from literature (Johnson & Rodine, 1984; Costa, 1984), investigating a range of the order of 50 ÷ 2000 $\mathrm{Ns/m^2}$ for viscosity and 5 ÷ 40 $\mathrm{N/m^2}$ for shear stress.

Fig. 5 shows the results of debris flow routing in Rhô channel from the point of initiation to the fan apex: the second hydrograph is used as input in the following 2-D simulation on alluvial fan.

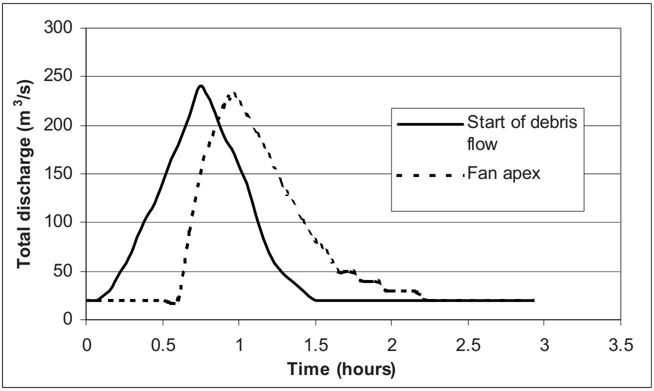

Fig5: DAMBRK flow routing in the Rhô channel.

Debris-flow spreading on alluvial fan

The prediction of volumes that a debris flow can deposit on alluvial fan is very important for the choice of suitable countermeasures. In case of debris flow overflowing by the fan apex, the deposition area can be simulated with the 2-D numerical model FLO-2D. FLO-2D is a two-dimensional flood routing model used to delineate flood and debris flow hazards; it routes a flood hydrograph conserving volume while predicting the area of inundation (O' Brien, 2001). FLO-2D is on FEMA's list of approved hydraulic models for this kind of studies.

Required data are (1) the input hydrograph, (2) detailed topographic data of fan surface and (3) rheological characteristics of the debris flow.

The input hydrograph can be determined as shown before and it is routed over a square grid system derived from topographic data.

Rheological characteristics are the same assigned in the DAMBRK simulation, but FLO-2D allows assigning a dynamic viscosity variable in time. The viscosity η is defined as follows:

$$\eta = \alpha e^{\beta C_v} \tag{8}$$

where C_v is the sediment concentration and α and β are coefficients.

The FLO-2D was routed for the Ronelle Torrent to simulate the spreading of the debris flow described previously, taking into account different scenarios, with debris flow volumes ranging between 5000 and 25000 m^3. The fan was schematized with a grid of 2240 square cells: the grid size was 25x25 m, according to the accuracy of available topography.

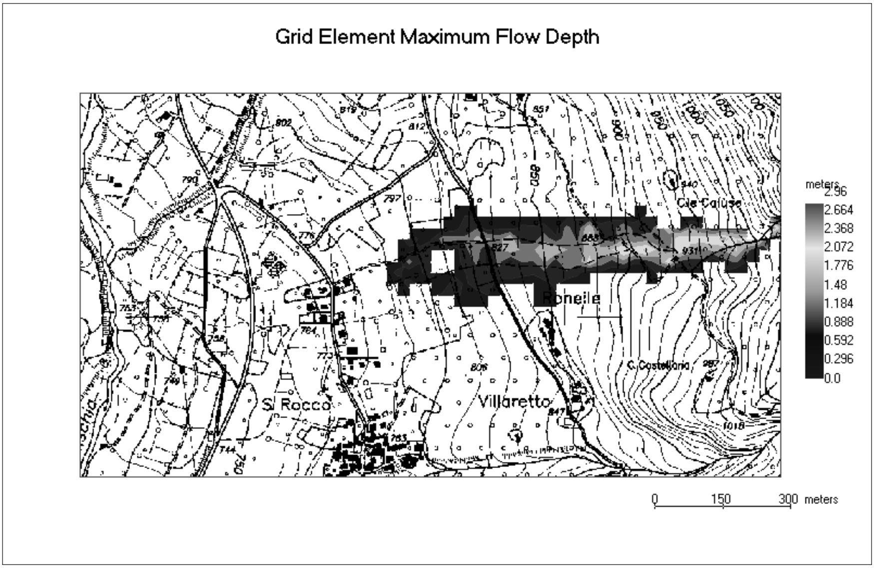

Fig6: Maximum flow depth for a the debris flow simulated on the small tributary of the Cenischia torrent (flow from the right to the left of the figure).

The more satisfying results, compared with the real event occurred in 1986, were found with a debris flow volume of 25000 m^3 (Fig. 6). The sediment concentration varied in time, studying

three possible cases: high (0.20-0.65), medium (0.20-0.55) and low (0.20-0.45) sediment concentration. The sediment concentration rapidly increases in the rising limb of the hydrograph and then it decreases in the falling limb of the hydrograph, which corresponds to the real situation found during debris flow events.
FLO-2D result fits well with the depositional area surveyed after 1986 debris flow event.

CONCLUSIONS

The procedure presented herein can be of help in the process of revision of development plans. The reliability of results depends on the availability of the required inputs (with particular regard to detailed topography) and on further improvements of the relationship water-debris hydrograph.

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