Some considerations on the application of the FLO-2D model for debris flow hazard assessment

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Abstract

The two-dimensional flood routing model FLO-2D, with the capabilities of simulating non-Newtonian sediment flows, is becoming more widely used to route debris flows over alluvial fans of alpine torrents and to delineate hazard areas of inundation.

Nevertheless the different applications described in the literature are not comparable, because they are based on different assumptions related to the numerous parameters governing the debris flow simulation. This paper reports the applications of the FLO-2D computer model and discusses the assumptions made for the replication of two well documented debris flow events at Fiames (Belluno) and Rio Dona (Trento) in the Eastern Dolomites.

The simulation results are consistent with the field observations in terms of maximum flow depths and the extent of the inundated areas in the two study sites. These two applications have enhanced the experience for the requirements of model input data in small alpine catchments, in particular the assessment of the main rheological parameters of flows, that are crucial in the design of debris flow countermeasures; leading to a proposed simplification in choosing the FLO-2D rheological parameters; and facilitating the results comparison and their interpretation among different FLO-2D simulations.
Keywords: Alps, debris flow, hazard mapping, 2D model.

1   Introduction

Laboratory and field researches are available in the literature on the debris flow reology. The main aim of such investigations is the capability to model

propagation of water-sediment mixtures for a range volumetric concentration (C_v) from 10% to 55-65%. The use of these results is not yet mature, in the sense that the kind of numerical model and the adopted rheogramm affect the choice of viscosity (μ, Pa s) and critical shear strenght (τ_c) (yield stress).

Widespread debris flow models are the depth-averaged models. They assume debris flow as a homogenoeous fluid, whose velocity is well represented by the mean value along the flow depth. Depending on the kind of mixture, several constitutive rheogramms have been proposed to describe debris flow (Ancey [1]):

(i) Lahar-like mixtures behaviour may be described using a Newtonian constitutive law as a first approximation:

$$\tau = \mu \left(du / dy \right) \tag{1}$$

being τ the total shear stress (Pa) and du/dy the shear rate (s^{-1}) related to a local u velocity. Viscosity depends on C_v and is usually very high (10^3 Pa s) (Wan and Wang [2]), and several order of magnitude higher than that of the clear water (1.0×10^{-3} - 1.5×10^{-3} Pa s for temperatures from 20 to 5 °C).

(ii) Muddy debris flows are often represented by means of a Bingham or Herschel-Bulkley model; the last one has the form:

$$\tau = \tau_c + \nu \left(du / dy \right)^n \tag{2}$$

where ν is the Bingham or Herschel-Bulkley viscosity and n a positive parameter (n=1 corresponds to the Bingham model). It has been shown that τ_c increases exponentially with C_v and can be successfully applied to fluxes having a fine friction (>40 μm) percentage higher than (10%) (Coussot and Piau [3]). In the Alps, bulk yield stress values (τ) range from 500 to 15000 Pa and the ratio τ_c / ν falls usually in the field 3-10 (Coussot [4]). Coussot et al. [5] tested different suspensions (maximum diameter 0.4 mm) derived from the Moscardo torrent debris flow (Northeastern Italy). Authors used a rheometer equipped with parallel plates and obtained a satisfactory fitting of eq.(2) with n=0.33. Interpolation of ν and τ_c values published by Coussot et al. [5] is represented in Figure 1.

Same Authors integrated data of laboratory rheometer, inclined plane test, large scale rheometer and field test and proposed a rheology for the complete material constituting the debris flow: n=0.33, τ_c=2935 Pa and ν=2190 Pa $s^{1/3}$, giving an example of a low τ_c / ν ratio (1.3) for the whole mixture.

(iii) Granular debris flow behaviour is expected to be frictional and collisional; different models have been proposed for its interpretation (Takahashi [6]) for taking into account the turbolent-dispersive stresses and collisions between corser sediment particles. These mechanisms can induce a magnitude of shear stress not easy to eastimate both in laboratoty, both in the field.

A comprehensive model for debris mixtures have been proposed by O'Brien and Julien [7], by assuming the following constitutive equation (quadratic model):
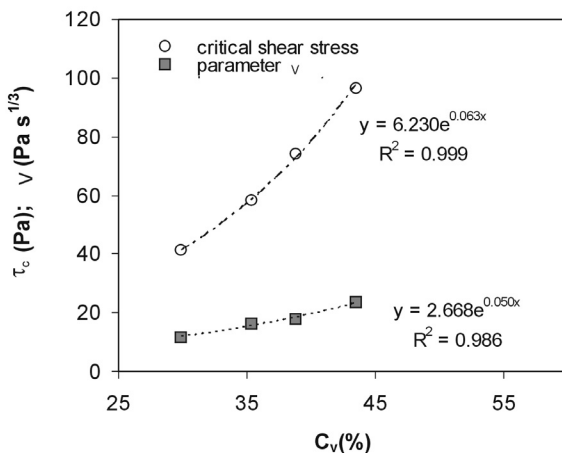
Figure 1:   Fitting of experimental data of Coussot et al. [5] for eq. (2) and n=0.33.

$$\tau = \tau_c + \mu(du/dy) + C(du/dy)^2 \qquad (3)$$

where C is the inertial stress coefficient. Rewriting eq.(3) in terms of depth-integrated dissipative friction slope (S_f) it follows (O'Brien et al. [8]):

$$S_f = \frac{\tau_c}{\gamma_m \, h} + \frac{K \mu V}{8 \gamma_m \, h^2} + \frac{n_d^2 \, V^2}{h^{4/3}} \qquad (4)$$

being γ_m the specific debris flow weight; h the flow depth, V the mean velocity, K the resistence parameter for laminar flow, n_d the turbolent dispersive n of Manning value ($n_d = 0.054 \, n \, e^{6.09 C_v}$; FLO2-D [9]). The parameter K equals 24 for smooth wide rectangular channels but increases significantly with roughness. A value of K=2285 is suitable to simulate mud-debris flows (O'Brien [9]). Viscosity and critical shear stress of eq.(4) are supported by laboratory measurements (O'Brien and Julien [10]), correlating these variables to C_v. The equations have the form:

$$\mu = \alpha_1 \, e^{\beta_1 \, C_v} \qquad (5)$$

$$\tau_c = \alpha_2 \, e^{\beta_2 \, C_v} \qquad (6)$$

Coefficients α_1, β_1, and α_2, β_2, were calibrated for different mixtures (O'Brien and Julien [10]) and by different Authors (see references in O'Brien and Julien [10]); the range of variation for viscosity μ (Pa s) covers approximately the range: [α_1=0.004; β_1=8.3] (Kang and Zhang [11]) - [α_1=0.004; β_1=22.1]; for τ_c (Pa) the field of variation is: [α_2=0.0005; β_2=22.2] - [α_2=0.017; β_2=25.6] (Fei [12]; in

O'Brien and Julien [10]) (Fig.2). The other two parameters K and n_d are not supported by measurements focused on debris flow motion.
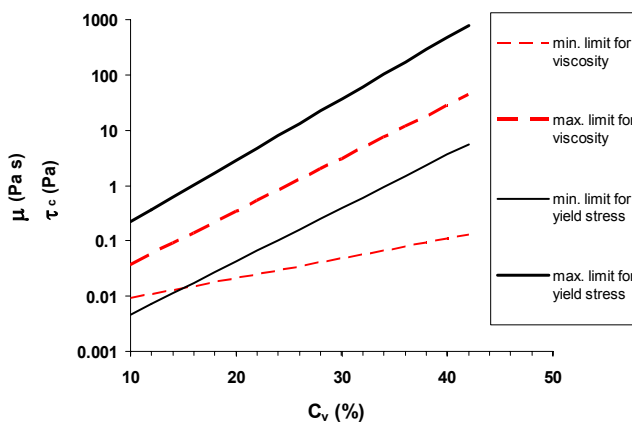

Figure 2: Region of existence for the rheological parameters: viscosity μ, eq. (5), and yield stress τ_c, eq. (6).

Calibration of eq.(4) presents many uncertainties and demands the selection of six rheological or quasi-rheological coefficients (α_1, β_1, α_2, β_2 n_d, K). Spite of this, FLO-2D model (O'Brien [9]), where the energy dissipation is founded on eq.(4), gives credit of numerous applications (O'Brien [13], Aleotti and Polloni [14], Bertolo and Wieczorek [15]), for which the simulated floodings (inundated areas, maximum flow depths and velocities) are consisting with the observed ones. In such simulations the combination of the above mentioned coefficients is not always in agreement with their phisics significance, even if they give, on the whole, satisfactory results.

The aim of this paper is to address a suitable calibration of the main rheological parameters of the FLO-2D model through the back analysis of two well documented events in the Dolomites, Fiames and Rio Dona. After calibration, the performance of the FLO-2D code is tested in terms of consistency of the results with the observed data, using different values of K, and empirical coefficients α_i e β_i for the calculation of the viscosity μ and the yield stress τ_c.

2 Locations of the study area and description of the events

Rio Dona and Fiames sites are both located in the Dolomites (North-Eastern Italy).

The two sites have been chosen because for both at least a well documented event exists, with field data on the extent of the flooded area, runout distance,

volume of the debris flow deposits, flow depths and flow velocity estimated using the superelevation method (Johnson and Rodine [16]).
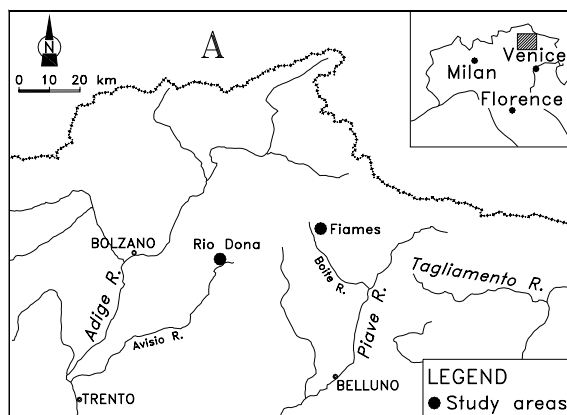

Figure 3:   Location of the two debris flow sites.

2.1 Rio Dona

Rio Dona catchment, with an area closed to the fan apex of 2.87 km^2, and ranging from 1360 to 2064 m a.s.l, is located on the right side of the Avisio River Valley. The headwaters consist of intrusive, effusive and piroclastic volcanic formations, and carbonates. Middle and lower slopes, formed of marly-arenaceous formations, are covered by talus, including scree, alluvium, morainic deposits and old debris flow deposits, that is the main debris source for floe events. The channel, with a mean slope of 8.5°, has a total length of 3.85 km and bankfull widths from 3 m to 6.5 m.; a wide alluvial fan, developed from 1440 to 1360 m a.s.l, has a mean slope of 7.8°. The debris flow of July 9, 1989, occurred after a severe thunderstorm of about one hour. A small failure, located in the talus at about 1750 m a.s.l., occurred and liquefied into a viscous debris flow, progressively enriching the flowing mass with debris erosion from channel banks and bed. The debris flow spread a volume of 15000 m^3 directly into the settled area on the apex, with maximum deposited depths of 4.5 m at the fan apex. This channelised debris flow transports gravely-sandy poorly sorted material, ranging in size from silt and clay to big boulders (up to 3-4 m in diameter); the fines content (silt and clay) is approximately 65% of the total sediment volume.

2.2 Fiames

Fiames is a hill-slope debris flow, located on the left side of the Boite River Valley. The upper rock basin, closed to the onset of the main flow path at 1845 m a.s.l., has a maximum elevation of 2450 m a.s.l., with an area of 0.16 km^2. It is formed of dolomite and limestone cliffs, that are the source of coarse debris and boulders. A thick talus, consisting of poorly sorted debris containing boulders up to 3-4 m in diameter and including heterogeneous scree, alluvium and old debris

flow deposits, covers the slope up to the valley bottom 1265 m a.s.l. The initiation area of the debris flow is located in the talus deposits between 2178 and 1732 m a.s.l.; the main channel with a mean slope of 20°, has a length of 1500 m, with depths ranging from 3 m to 6 m and widths from 10 m to 22 m. The debris flow of September 5, 1997 was triggered by an intense long rainstorm. The flow initiated at the onset of the main channel, about 1780 m a.s.l. from the liquefaction of a small debris failure into a flow with progressive entraining of debris from the channel banks erosion and bed scour. At an elevation of 1480 m, where the slope angle decreases to 20°−23°, the main channel branches off in several paths, spreading sediments on the slope and leaving lateral deposits further downslope, where the slope angle decreases to 12°÷14°. The total deposited volume was 25000 m^3. About 52% of the total volume deposited on the slope below 1480 m a.s.l. with depths of 0.8-1.1 m, whilst the remainder flowed further downslope to the Boite River, damaging some buildings for residential and industrial use. The debris flow transports gravely-sandy poorly sorted material, ranging in size from silt and clay to big boulders (up to 1-2 m in diameter); the fines content does not exceed 15%.

3   Calibration of the models

The calibration of the models is successfully when it produces simulation results consistent with the observed flow behaviour in terms of extent of the flooded area, runout distance, estimate of the deposited sediment volume and flow depth, as well as when the volume conservation is maintained. The rheological parameters yield stress and viscosity of debris flow are key factors for numerical modelling. Since rheological analyses of materials were not available, as it happens in most modeling problems, the choice of the rheological parameters is based on several simulations to back calculate the best combination of μ and τ_c, with the subsequent adjustment of other input parameters like K and n of Manning. Appropriate values α_i and β_i were selected from O'Brien [9], taking into account the grain size of the two debris flow deposits. Rio Dona parameters have been tried in the range of viscous flows, considering a quite large fines component of debris, whilst Fiames parameters have been selected in the range of flows with low viscosity and medium yield stress, due to its smaller percentage of fines in sediments. The reliable determination of the event hydrographs is another important factor for a good quality of the simulation.

3.1 Rio Dona debris flow

A volume of 15000 m^3 of debris flow material spread on the alluvial fan. It was documented that the event lasted 1 hour, moving down the channel in subsequent viscous waves. The sediment concentration by volume was assumed linearly increasing and decreasing according to the rising and falling limbs of a triangular shaped hydrograph (fig. 4). The peak concentration resulted of 69%, such that the bulked volume routed down the channel was 30000 m^3.

   The Manning's n-value was 0.04, both for the floodplain and the channel; the specific weight of the mixture γ_m and the resistance parameter for laminar flow

K, were assumed equals to 26.5 kN/m^3 and 24 respectively. The best fit with the field observations was obtained by the α_i and β_i values listed in Table 1.

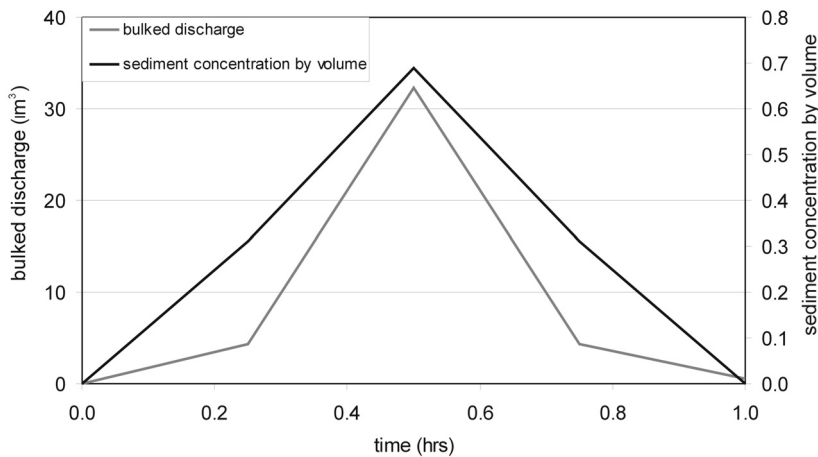The selected grid element size was 10 m which resulted in 2340 elements.

Figure 4:   Rio Dona hydrograph.

Table 1:   Empirical coefficients and related yield stress and viscosity used for the simulations.

	α_1 (poises)	β_1	viscosity (Pa s) (C_v=0.5)	α_2 (dyn/cm^2)	β_2	yield stress (Pa) (C_v=0.5)
Rio Dona	0.0015	22.00	9.0	0.050	22.00	299
Fiames	0.0075	14.39	1.0	0.152	18.70	175

3.2 Fiames debris flow

A total volume of 25000 m^3 was released over the slope, from the actual debris flow initiation zone, at an elevation of 1732 m a.s.l.

The selected grid element size was 5 m which resulted in 34396 elements. The water hydrograph used to replicate the debris flow of September 5, 1997 has been obtained applying the hydrologic model CLEM (Cazorzi [17]) to the rainfall recorded on the same date in the nearby meteo station of Faloria (BL). A sediment concentration by volume was assigned to the hydrograph, ranging between not less than 30% along the rising and falling limbs of the hydrograph, and a maximum of 60% corresponding to the mature debris flow. The water peak discharge was assigned a sediment concentration slightly less than the frontal wave to account for water dilution (fig. 5).

The Manning's n-value was 0.1, typical for open ground with debris; the specific weight of the mixture γ_m and the resistance parameter for laminar flow K, were assumed equals to 26.5 kN/m^3 and 2285 respectively. The best fit with the field observations were obtained by the α_i and β_i values listed in Table 1.
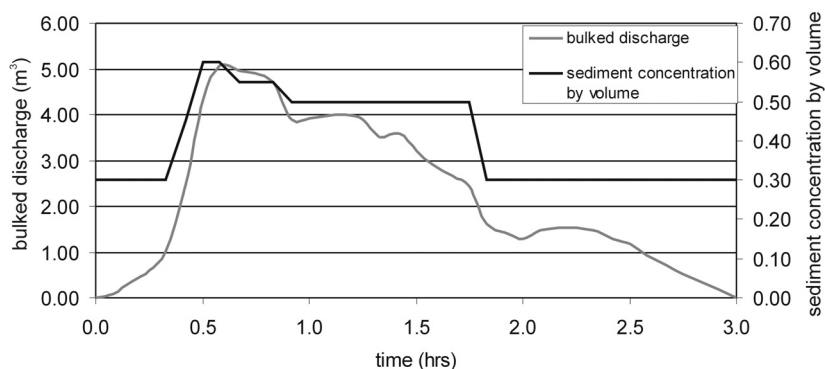
Figure 5: Fiames hydrograph.

4 Sensitivity analyses

In order to evaluate the influence of K and of the rheological parameters on the simulation results, a parametric study has been undertaken. Assuming as initial conditions the calibrated simulations that provided the best fit with field observation, six simulation tests in all were performed for three different values of K (24, 1000, 2285) and for the two selected rheological parameter sets, each one applied to both Rio Dona and Fiames (table 1). On both the floodplains we monitored three control points: at the fan apex (A), at the toe of the fan (C), and at an intermediate position (B) between the points A and C. The simulations have been analysed in terms of maximum depths and velocities, flooded area and runout distances. This last parameter was computed for the Dona torrent in relation to the overflow occurred on the left, near the fan apex and for Fiames by considering the propagation from point A to the Boite River.

In a first step, for both basins, we compared the influence of K variation when the correct rheology is selected. Fig. 6 reports the Dona torrent maximum depth variations in percentage at the three control points (appropriate K value is 24).

The graph shows an increasing deviation according to K increasing, with maximum overestimated depth values close to 20-30% (points A, B) and 40% (point C), when K is 2285. The companion analysis for Fiames (calibrated K value equal to 2285) gives maximum overestimation errors for K=24 of about 3% and 17% at points A and B respectively.

In the second sensitivity analysis we applied the Fiames rheology to the Dona torrent and vice versa. In such comparison the depth variations do not refer to the correct K value, but, supposing correct a given K, the influence of assuming a mistaken rheology is evaluated. Fiames simulations (fig. 7) point out how the depth errors are in general larger in comparison to the previous analysis, resulting around 100% at point B (K=1000 and 2285), and not lower than 35% at points A (overestimation) and C (underestimation), even for the correct K (2285). When K=24, it occurs a compensation between the too viscous rheology and the low resistance K parameter (fig. 7).
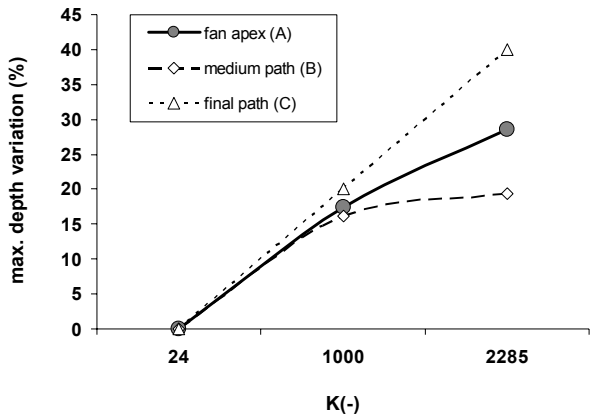
Figure 6:   Dona torrent: maximum depths variation with K (calibrated K =24).
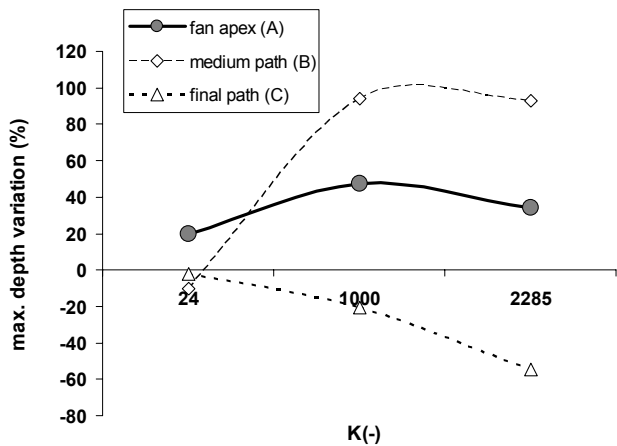

Figure 7:   Fiames: maximum depths variation with K when Dona torrent rheology is applied (calibrated K =2285).

In the Dona torrent analysis, the maximum errors (depth underestimation) are equal to 50% and about 25% for points A and B respectively, independently of K values. At point C there is a depth overestimation of 20% for K=24, and maximum error of 60% (depth underestimation) for K=2285. Also for the Dona torrent the error weight – in terms of maximum depth variation – in assuming a wrong rheology is higher respect to the assumption of a wrong K and a right rheology (fig. 6).

The specular analysis in terms of maximum velocity variation gives errors similar to the depth analysis for the Dona torrent; errors are of the same order both for wrong K or wrong rheology. For Fiames, the error in K assumption affects, in general, velocity variation (points A and B) more than it occurs when assuming a wrong rheology.

Further remarks descend on the spatial distribution of the flooded area and runout distance. Fig. 8 shows the inundated areas of the Dona torrent, using the appropriate rheology and different K. The lowest K (K=24) causes a more fragmentary and braided debris flow propagation. Increasing K values (1000, 2285) induce a progressive concentration all around the main propagation route.

Although the inundated areas increase with rising K values, the evaluation of the calibrated simulation (K=24), which displays the smaller flooded area, is also important in terms of hazard assessment. In fact, it evidences a zone affected by the flow, at the left side of the channel, close to the fan apex that is neglected by the others K simulations. Runout distance at the left side of the fan apex (fig. 8), reduces along with K values, up to 40% for K=2285.
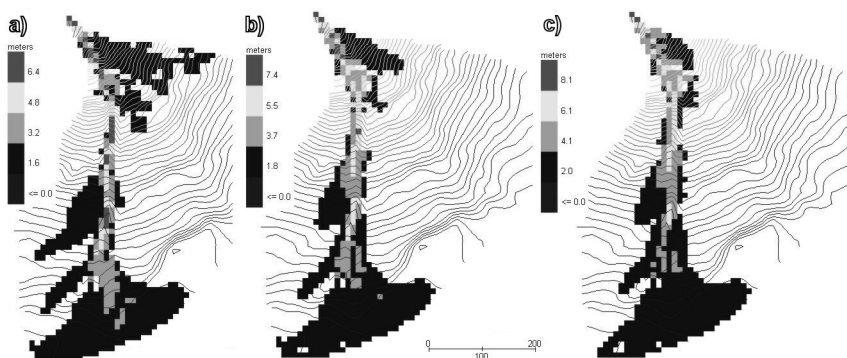

Figure 8:   Dona torrent. Maps of maximum flow depths (appropriate rheology): calibrated simulation K=24 (a), simulations K=1000 (b) and K= 2285 (c).

When the appropriate rheology is applied to Fiames, simulation for K=1000 and K=2285 give similar distribution of the flooded area. When a K=24 is applied, the simulation produces braided flow propagation in comparison to the K=2285 simulation (fig. 9). Results show a stronger influence of K parameter on the extent of the inundated area, whilst the runout distance appears to be under the principal influence of the rheology. In fact, with the most reliable viscosity and yield stress parameters, the flow always reaches the Boite River valley.

5   Final remarks

Debris flow modeling can be an important tool for hazard assessment as long as reliable input data required by the code (DEM, hydrological data and rheological

parameters), are available. Results of modeling of two debris flows in the Dolomites, using FLO-2D, increase experience for the requirements of model input for debris flow simulation. The parametric analysis revealed that mostly rheological parameters and K values influence final deposits distribution, runout and thickness, and outlines the following main points:

(1) As rheological investigations are not so common, a reliable calibration of the model must be undertaken on the basis of well documented debris flow events; field data should include, at least, extent of flooded area, runout distance and deposits depth.

(2) The selection of trial rheological parameters should address in a range of viscosity and yield stress values that take into account the grain size of debris flow material, as it brings out the viscous character of the flow.

(3) For both Dona torrent and Fiames, it is evident that error in assuming a wrong rheology weights, in terms of maximum depth, more than if a wrong K is assumed. Rheology and K have the same influence on velocity estimates for Dona torrent; for Fiames simulation, K has, on velocity values, an influence stronger than rheology.

(4) K controls in both debris flows the extent of flooded area: the higher is K, the larger is the deposition area. Runout of the main flow path depends mainly from rheology, and this is evident in particular for Fiames.

(5) The most convenient way to lead a simulation is to start from a medium value of K (1000) and then back calculate the rheological parameters that produce the best fit with field observations.

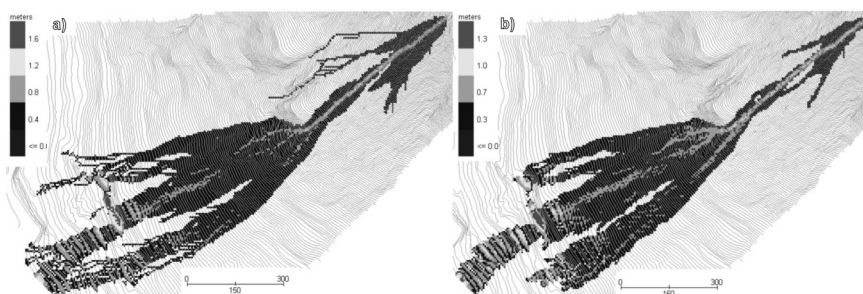(6) When a good consistency with field data has been reached, velocities can be adjusted, varying the K parameter.

Figure 9:   Fiames. Maps of maximum flow depths (appropriate rheology): simulation K=24 (a), and calibrated simulation K=2285 (b).

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