Comparative numerical modelling of a debris-flow fan in the Eastern Italian Alps

ANDREA M. DEGANUTTI[1]*, PIA R. TECCA[1] & GIUSEPPE NIGRO[2]

[1]*Research Institute for Hydrological and Geological Hazard Prevention-CNR, Cso Stati Uniti 4, 35127, Padova, Italy*

[2]*Department of Geosciences, University of Padova, Via Gradenigo 6, 35131 Padova, Italy*

**Correspondence: andrea.maria.deganutti@irpi.cnr.it*

Abstract: Knowledge of rheology can reduce damage caused by debris flows, providing a means to delineate hazard-prone areas and to estimate the dangerous effects of these phenomena. The application of numerical models of debris-flow propagation and deposition for hazard prediction requires detailed topographical, hydrological and rheological data, which are not always available. The large Rivoli Bianchi Fan on the Eastern Italian Alps is mainly built from sediment transported by debris flows along the Citate Torrent and its tributaries. We compared the results of numerical simulations performed with two different single-phase, non-Newtonian, two-dimensional models, FLO-2D and IDRA2D-DF, to test their reliability in simulating the behaviour of debris flows on alluvial fans. Data from field topographic surveys and from rain gauges were used as input for the boundary conditions, referring to the Rivoli Bianchi Fan as an example location. The commercial FLO-2D model creates a more accurate representation of the hazard-prone zone in terms of flooded area, but the results in terms of runout distances and deposit thickness are similar to those obtained through the open-source IDRA2D-DF. Parameters obtained through back analysis with both models can be cautiously applied to predict hazard in areas of similar geology, morphology and climate.

The aim of this study is the calibration of numerical debris-flow models to test their applicability in predicting the dynamic and depositional characteristics of a debris flow in the Eastern Italian Alps. Debris flows are dense mixtures of soil, rock and water flowing over relatively steep slopes under direct action of gravity, behaving as non-Newtonian fluids with a plastic yield strength, a high bulk density (up to twice that of water) and a much greater viscosity than water (Genevois *et al.* 2000). These geomorphic processes, with a behaviour that can be considered intermediate between landslides and water floods (Johnson 1970), represent a severe natural hazard in mountainous regions given their high velocity, the large volumes of debris often involved and the frequent recurrence (Deganutti & Tecca 2013).

Because of the potential destructiveness of these processes and the increasing human occupancy of alpine regions, the yearly economic cost of such disasters is severe: debris flows have been responsible for the destruction of roadways, bridges and real estate, and have repeatedly caused casualties (Marchi *et al.* 1999). Adequate procedures are required to recognize hazard-prone areas and the degree of risk in order to design effective protective countermeasures or to prescribe land-use restrictions (Tecca *et al.* 2006).

Alluvial fans affected by debris-flow activity can be easily identified through field surveys of the fan surface, whereas topographic surveys highlight the evidence of deposits left by debris-flow events (Morton & Campbell 1974; Govi 1975; Pierson 1980; Costa 1984; Eisbacher & Clague 1984; Johnson 1984; Peiry 1990; Whipple & Dunne 1992; Deganutti & Tecca 2013). Moreover, unequivocal field evidence of debris-flow occurrence consists of typical geomorphic markers (fan gradients between 3° and 10°, levees and terminal lobes comprising coarse debris, boulder berms), sedimentological features (muddy matrix surrounding larger particles, inversely graded deposits) and vegetation damage (Aulitzky 1982; Costa 1984; Pasuto & Tecca 2000). Several studies on debris-flow sites based on field evidence of past events have been carried out worldwide as well as in the Eastern Italian Alps, among others at Cancia (Deganutti & Tecca 2013) and Acquabona (Tecca & Genevois 2009).

Field surveys for the estimation of morphometric features of alluvial fans and streams include techniques such as total topographic station measurements, 3D laser scanning and terrestrial stereo-photogrammetric surveying (Tecca & Genevois 2009).

Reliable prediction of the extent of the debris-flow-inundated areas, flow velocities and sediment

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depths can reduce damage and casualties by providing a means to delineate hazard areas and implementing both zoning restrictions and parameters for the design of protective measures (Genevois & Tecca 2014). Several methods have been developed for mapping debris-flow hazard – historical–geomorphological (Aulitzky 1994), empirical and semiempirical (Hungr *et al.* 1987; Ikeya 1989) – but in recent years debris-flow prevention has also been supported by numerical modelling.

Several numerical codes simulating single-phase flows (the entire mass being considered a homogeneous fluid which follows a proposed rheological law) or two-phase flows (models which take into account the dynamic interactions between solid and liquid phases of the flowing mass such as friction, buoyancy, contact stresses, etc.) have been developed so far to estimate the propagation and deposition of debris flows in terms of runout, flow depth and velocity, in response to different scenarios of event magnitude.

Simplified single-phase models, considering a constant-density fluid and following the concept of an ‘equivalent fluid’ (Hungr 1995), are often used because the number of model parameters, which are usually difficult to determine, remains restricted. In this assumption, the debris flow stops only if the adopted rheological model foresees the presence of a plastic yield strength for the flowing mixture. Some models assume a rigid bed, such as DAMBRK (Boss Corporation 1989), FLO-2D (FLO-2D Software Inc. 2006) and MassMov2D (Beguería *et al.* 2009), while others include sediment-erosion/entrainment processes such as TRENT-2D (Armanini *et al.* 2009), DAN3D (Hungr & McDougall 2009), IDRA2D DF (2013) and RAMMS (Bartelt *et al.* 2013). Some of these models have been implemented in GIS environments (MassMov2D, IDRA 2D). All models require detailed topographic and hydrological input data as well as values for rheological parameters that are rarely available, so they have to be calibrated by means of post-event analysis based on actual field data in order to predict the critical motion characteristics of debris flows.

In this study we examine the applicability of two single-phase, two-dimensional, non-Newtonian numerical codes, IDRA2D DF and FLO-2D, evaluating and comparing their performances in simulating the routing and deposition of debris flows on an alluvial fan.

The two models are applied to the debris-flow fan of Rivoli Bianchi, located on the Eastern Italian Alps. This large alluvial fan is a complex system of coalescing alluvial fans, mostly built by a single stream (Rio Citate) fed by a small basin (Table 1), and with minor contributions from five even smaller watersheds. The highly fractured rocky slopes of these watersheds supply material prone to being mobilized as debris flows following intense rainfall events. The activity of debris flows on this very dynamic fan was continuous over several decades of the last century, with a peak period of activity following the 1976 earthquake (Govi & Sorzana 1977), when the material transported several times invaded the National Road 52 that runs close to the fan toe, near the city of Tolmezzo.

Data from topographical surveys and rain gauges are used as boundary conditions in running the numerical simulations (Armento *et al.* 2008). As a first step, we calibrate the unknown rheological parameters of the two models through the retro-analysis of documented events in similar geomorphological conditions, using a trial-and-error procedure. In a second step, we apply the calculated values to new simulations in order to evaluate the predictive potential of both models for debris-flow behaviour under specific boundary conditions.

Study site

The alluvial fan of Rivoli Bianchi is located on the left side of the Upper Tagliamento River Valley, on the Eastern Italian Alps, near the city of Tolmezzo (Fig. 1). The fan has been built by various ephemeral streams; the Rio Citate, draining an area of 1.02 km^2 on the western slope of Mt Amariana (1906 m a.s.l.), and whose narrow gorge follows a sub-vertical fault, is by far the largest contributor to the fan formation.

The fan has a volume of 0.2×10^9 m^3, disproportionate to the minimal extension of the basin; indeed the Rivoli Bianchi Fan is among the largest active alluvial fans in Europe. Its sediments originate from erosion of Mt Amariana, formed by highly

Table 1. General features of the study site

Yearly average rainfall (mm) Lithology	2022 Calcareous–dolomitic debris
Fan	
Area (km^2)	2.44
Max elevation (m a.s.l.)	573
Min elevation (m a.s.l.)	300
Mean slope (deg)	6.6
Rio Citate basin and channel	
Area (km^2)	1.02
Max elevation (m a.s.l.)	1825
Mean basin slope (deg)	50
Mean channel slope (deg)	7.4
Control works on the alluvial fan	
Diversion dike (300 m long, 5 m high) built in 1990	
Debris basin built in 1990	

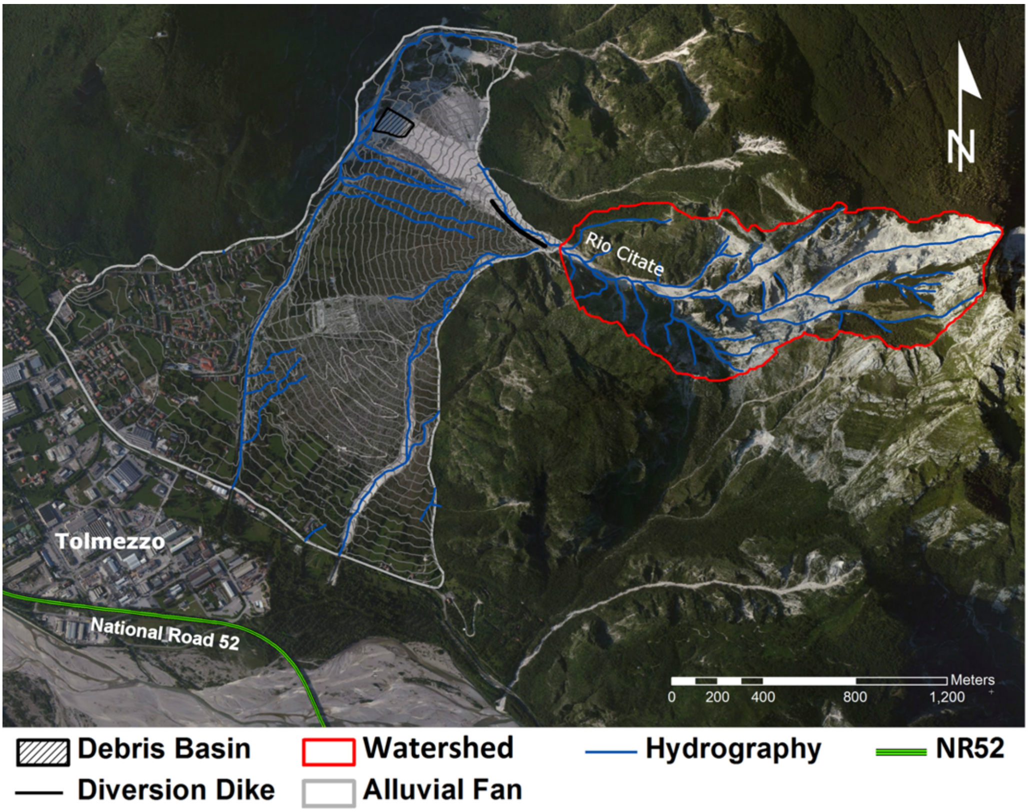

Fig. 1. Aerial view of the Rivoli Bianchi alluvial fan with geomorphological elements (satellite photo from Google Earth).

fractured Upper Triassic dolostones and limestones of the Dolomia Principale Formation (Carulli 2006). The area is affected by a severe seismicity: in 1976, a series of seismic shocks (magnitude 5.8–6.4 on the Richter scale) triggered large rockslides and rockfalls, also in the Rio Citate basin (Govi & Sorzana 1977). The intense weathering of the fractured bedrock and the severe seismicity favour high sediment yield rates and contribute to the thick scree deposits that cover the rocky slopes down to the valley floor, consisting of poorly sorted debris containing boulders up to 3–4 m in diameter and including colluvial, alluvial and old debris-flow deposits. The supply of large volumes of loose debris to the steep channel of the Rio Citate feeds the Rivoli Bianchi Fan and has favoured its progradation since the end of the Würmian glaciation.

Precipitation in the area is elevated and well distributed all over the year (Deganutti *et al.* 2000); mean annual value as recorded in the closest rain gauge is 2022 mm, rather higher than the average yearly rainfall of northern Italy, which is *c.* 500 mm (Fig. 2).

Debris flows usually occur in summer and early autumn and are associated with intense, localized rainfall events, usually related to brief thunderstorms. A typical debris-flow-triggering rainstorm in the area reaches an intensity of 30–40 mm in 1 h. In 1990, in order to protect the national road and the buildings close to the fan toe, a 5 m-high stone-deflecting wall and a basin for debris containment were constructed on the left bank of the Rio Citate near the fan apex and on the distal part of the fan, respectively (Fig. 3), in order to divert debris flows northwestward. The general features of the study site are shown in Table 1.

Numerical simulations

In this study we compare the results of the two debris-flow simulation codes, FLO-2D and IDRA2D DF, to test their ability to simulate the behaviour of debris flows on the Rivoli Bianchi fan. Simulations also consider the effectiveness of a debris-flow-deflecting wall built in 1990 as a

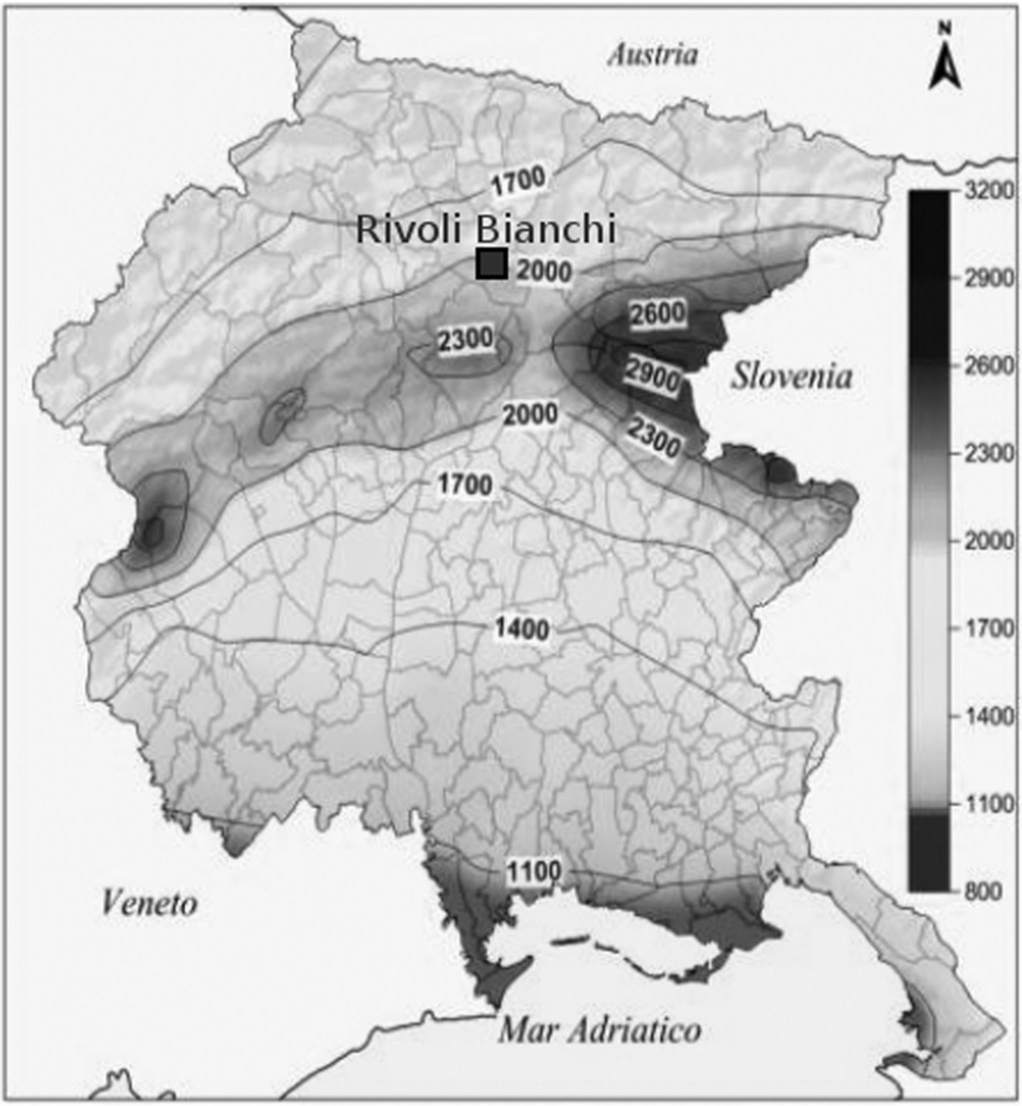

Fig. 2. Mean annual isohyetal lines for NE Italy.

measure to mitigate hazard from flow propagation and deposition.

FLO-2D

FLO-2D is a commercial model widely adopted in different countries for the assessment of debris-flow hazard since 1993 (O'Brien *et al.* 1993; Garcia *et al.* 2004; Bertolo & Wieczorek 2005; Rickenmann *et al.* 2006; Tecca *et al.* 2007), and has proved to be useful in various field conditions (especially when the mixture involved is granular). The model is based on a finite difference numerical algorithm, designed for the simulation of debris and mud flow. It is able to simulate the routing of waterflows and non-Newtonian flows on alluvial fans, with both channel and unconfined overland flow modules. The surface topography is discretized into square-grid elements and elevation and roughness factors are assigned to each of them. The resolution and accuracy of a simulation are obviously related to the grid size: the smaller the grid element, the higher the accuracy. Eight possible flow directions are assumed for every grid element; a rigid flow bed is also assumed (no erosion or sediment entrainment in the flow). When routing hyperconcentrated

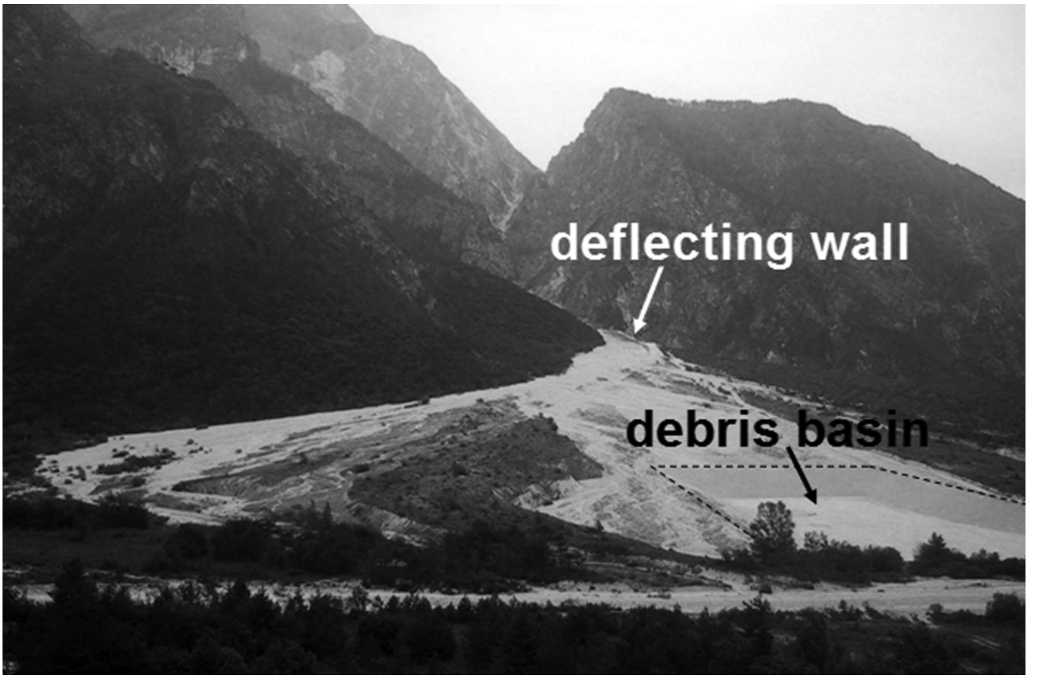

Fig. 3. Deflecting wall and debris basin in the Rio Citate.

flows (mud or debris flows), as a fluid continuum, the solved model momentum equation includes the viscous and yield stresses. The viscosity η and the yield stress τ_y of the mixture are assumed to vary principally with volumetric sediment concentration C_v and are defined by the following empirical relationships:

$$\eta = \alpha_1 e^{\beta_1 C_v} \quad (1)$$

and

$$\tau_y = \alpha_2 e^{\beta_2 C_v} \quad (2)$$

in which α_i and β_i are empirical coefficients defined by laboratory tests (O'Brien & Julien 1988). The general motion resistance is expressed by a quadratic rheological law through the slope of the energy line S_f as:

$$S_f = \frac{\tau_y}{\rho h g} + \frac{K_1 \eta v}{8 \rho h^2 g} + \frac{n^2 v^2}{h^{4/3}} \quad (3)$$

where τ_y and η are respectively the Bingham yield stress and viscosity functions of sediment concentration, ρ is the flow density, g is gravitational acceleration, v is the mean flow velocity, K_1 is a laminar flow resistance coefficient and n is the pseudo-Manning's resistance coefficient accounting for collisional and turbulent frictional losses. The model can predict the area of inundation, flow velocity and depth, and simulates flow cessation, maintaining mass conservation for both the water and sediment volumes (O'Brien *et al.* 1993; FLO-2D Software Inc. 2006).

IDRA2D DF

IDRA2D DF is an open-source code based on the GIS platform AdB Toolbox distributed by the Italian Ministry of Environment for modelling monophasic debris flows; it has been applied in the Italian Alps (Gregoretti *et al.* 2011, 2016). IDRA2D DF is an erodible-bed code and includes a choice of friction relations to account for energy dissipation.

IDRA2D DF has been designed for the simulation of debris-flow routing from triggering to deposition. The code, which includes a hydrological module, is based on the Cellular Automata method (Deangeli & Segre 1995): the flow pattern is discretized into square cells; the model considers eight flow directions as in FLO-2D; and flow is represented as a continuum equivalent fluid in terms of runout, deposit thickness and mean velocity. Erosion and deposition are modelled through the Egashira equation (Egashira & Ashida 1987;

Egashira *et al.* 2001) adjusted for monophasic continuum:

$$r = K_f u \tan(\theta_f - \theta_e) \quad (4)$$

where r is the erosion-deposition velocity, θ_f is the bed slope, θ_e is the bed equilibrium slope, K_f is a calibration parameter and u is the flow velocity.

The embedded hydrological model allows the creation of the liquid hydrograph, by which it is possible to calculate the solid–liquid hydrograph of the debris flow, representing the main input of the model for the simulation of the routing and depositional phases of a debris flow on a fan. The rheology of the mixture is determined by the mean sediment concentration c, and its velocity is controlled by the conductance coefficient C, having values in the range 2–3 on the basis of field measurements of velocity and flow depth (Gregoretti 2000).

Methodology

With the aim of evaluating and comparing the responses of the two models and their predictive potential, a characteristic debris flow with the imposed conditions of rock debris availability and of rainfall (see below) has been calculated and replicated, using FLO-2D and IDRA2D DF. This kind of simulation is normally done by engineers for the design of debris-flow-mitigation structures, channels, etc. The analyses were carried out with a medium-viscosity and a high-viscosity rheology (see below for details) in natural conditions (data from recorded debris-flow events in the field by monitoring systems in a close-by debris-flow-prone basin; Marchi *et al.* 2002) and considering the presence of the deflecting wall.

The preliminary steps consisted of identifying the potential debris sources (such as areas of loose debris, bank and channel-bed erosion and landslides) by means of field surveys and digital mapping from aerial photos, and subsequently estimating the volume of debris potentially subject to mobilization.

The inflow liquid hydrograph for the FLO-2D simulations was obtained by applying the hydrological model Hec-HMS to the maximum 5 min annual rainfall recorded 3 km from the study area (rainfall data from the closest rain gauge at 348 m a.s.l. near Tolmezzo), and the hydrological model calculated the hydrograph for a total rainfall duration of 45 min with a return period of 100 years, the resulting 45 min cumulative precipitation being 64.0 mm.

Hec-HMS loss parameters were calibrated, generating a peak water discharge of of 9.4 $m^3 s^{-1}$ and a total volume of the water hydrograph as much as 12 100 m^3. The debris-flow hydrograph was built by assigning a sediment concentration by volume ranging from 0.2 to a maximum of 0.6, the solid–liquid discharge having a peak value of 22 $m^3 s^{-1}$. These values and the shape of the solid–liquid hydrograph were chosen to take into account the input requirements of the two codes (there are code constraints on input hydrographs to ensure numerical stability; FLO-2D Software Inc. 2006) and data from debris-flow field monitoring systems (Marchi *et al.* 2002; Tecca *et al.* 2003). The duration of the solid–liquid hydrograph was fixed at 1.5 h as an average value from documented debris-flow events in the Eastern Italian Alps, involving calcareous–dolomitic sediments in similar geomorphological settings, generally show a duration from 1 to 3 h, moving down the channel in subsequent viscous waves (Berti *et al.* 1999; D'Agostino & Tecca 2006; Tecca *et al.* 2007). Figure 4 shows the water hydrograph, the solid hydrograph and the assigned sediment concentrations by volume.

For both models, the input digital elevation model (DEM) has a grid size of 5 m, obtained from topographic vectorial data of the Friuli Venezia–Giulia Region at scale 1:10 000.

FLO-2D

In addition to the DEM, the input data requirements include values for channel and floodplain roughness, inflow hydrographs and rheological properties of the sediment–water mixture. The inflow point of the sediment hydrograph is located at the fan apex, at an elevation of *c.* 573 m a.s.l. A basal roughness coefficient of 0.18 was assumed, typical for open ground with debris (FLO-2D Software Inc. 2006). The specific weight of the mixture γ_m and the resistance parameter for laminar flow K were assumed equal to 20.5 kN m^{-3} and 2285, respectively, values generally suggested for debris flows (Tecca *et al.* 2003; FLO-2D Software Inc. 2006).

As specific rheological analyses of the *in-situ* material were not available, appropriate values of the coefficients α_i and β_i were selected from O'Brien & Julien (1988) to compute viscous and yield stresses in equations (1) and (2), so as to obtain two simulations with different values for viscosity. These rheologies provided realistic results in terms of flooded areas and deposit thickness for similar flows involving carbonate debris (Tecca *et al.* 2003; D'Agostino & Tecca 2006). The resulting rheological parameters, calculated for a solid concentration by volume of 0.6, are listed in Table 2.

IDRA2D DF

The DEM and the inflow point of the sediment hydrograph are the same as those used in the FLO2D application. As for Flo2D, the duration of

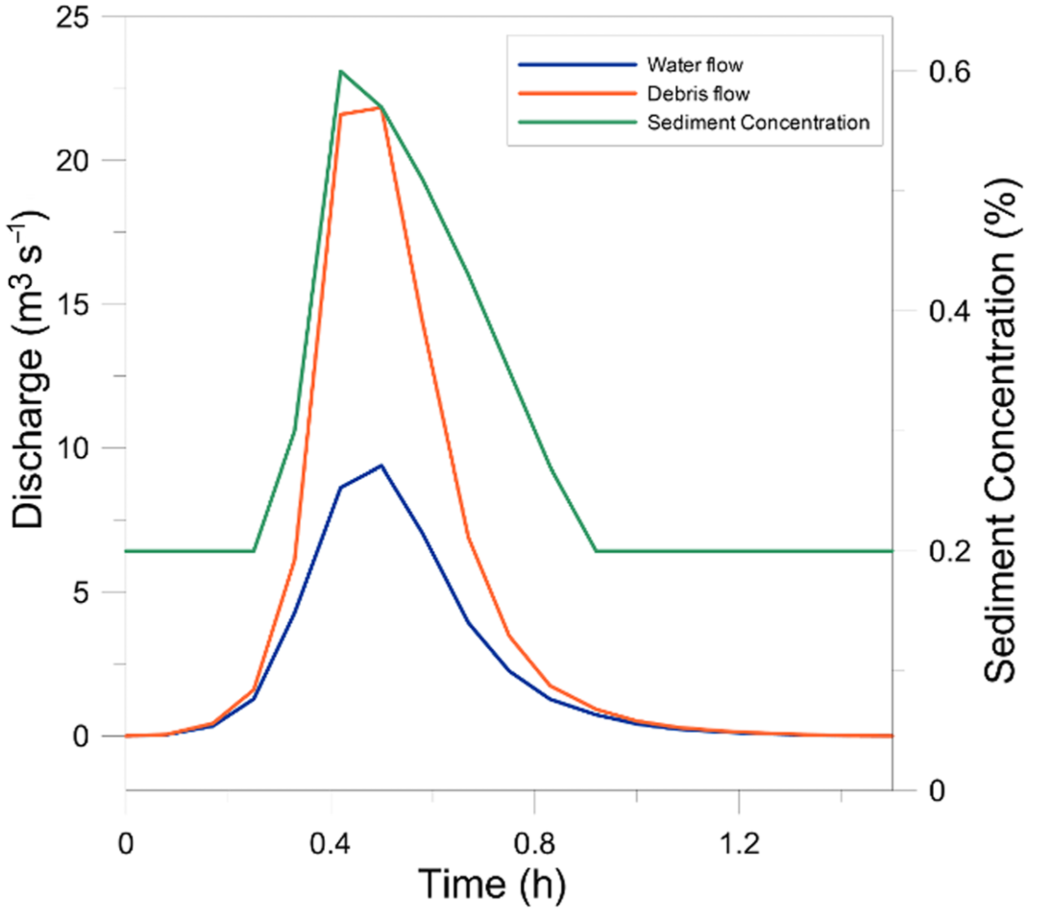

Fig. 4. Water hydrograph, solid hydrograph and assigned sediment concentrations by volume.

the simulation is assumed to be equal to 1.5 h (for comparability of Flo2D simulations), the minimum flow stage is 0.01 m and the calculation time-step is 5 min – values chosen to ensure calculation stability (Gregoretti *et al.* 2016).

Results

Table 3 displays the flow depth and velocity values computed by the two models at two representative locations A and B (Fig. 5), at the fan apex and a site downslope, respectively. Figure 5 shows the comparison between the flooded area maps obtained with IDRA2D DF and FLO 2D, in natural conditions and in the presence of the deflecting wall, to test the effectiveness of the artificial structures for flow containment.

For the high-viscosity flow, the two models generate similar results in terms of extension of the flooded area (even if the shape of the depositional area is rather different) and volume of deposits, both in natural conditions (Fig. 5a, b) and in the presence of the deflecting wall (Fig. 5c, d), as displayed in Table 3. IDRA2D DF simulations show velocities and flow depths at the two chosen locations of the fan apex, A and B, generally higher (and much higher for the velocity) than those provided by FLO 2D, in both configurations.

Likewise, for the low-viscosity flow the two models give generally comparable results in terms

Table 2. *Calculated yield stress and viscosity for $C_v = 0.6$*

Rheology type	Viscosity η (Pa s)	Yield stress τ_y (Pa)
1	32	139
2	0.6	19

Table 3. *Computed values by the two numerical models*

		IDRA2D DF						FLO 2D					
		Flooded area, m^2	V, m^3	dA, m	dB, m	vA, m s^{-1}	vB, m s^{-1}	Flooded area, m^2	V, m^3	dA, m	dB, m	vA, m s^{-1}	vB, m s^{-1}
Natural conditions	Hη	58 200	21 800	2.4	2.5	4.1	4.2	69 800	23 500	2.4	1.25	0.50	0.14
	Lη	73 100	17 700	2.8	3.9	4.2	1.0	146 400	23 500	1.1	0.6	0.51	0.69
Deflecting wall	Hη	61 300	21 900	4.4	5.4	5.2	2.9	58 400	23 500	2.7	2.2	0.44	0.42
	Lη	128 100	18 300	2.6	7.2	5.6	3.9	132 700	23 500	1.51	2.06	0.39	0.68

Abbreviations: Hη, High viscosity; Lη, low viscosity; V, event volume; dA, flow depth at fan apex; dB, flow depth downslope fan apex; vA, flow velocity at fan apex; vB, flow velocity downslope fan apex.

of extension of the flooded area and volume (Fig. 5e, f), although in natural conditions FLO 2D generates wider flooded areas (Fig. 5f) than the simulation in the presence of the deflecting wall (Fig. 5g, 5h). Again, velocity and flow depth values calculated by IDRA2D DF are higher than FLO2D values.

Discussion

The availability of powerful computing techniques in recent years has prompted the development of numerical models for the study of geological phenomena, given the impossibility of predicting their evolution in deterministic terms owing to the inherent high complexity. Even relying on modern fast processors and sophisticated numerical models, simplifications need to be applied when attempting to model and predict various geological and natural phenomena in order to 'downgrade' natural complexity and to make processes 'solvable' in mathematical terms. Debris-flow modelling has evolved mostly with the purpose of evaluating and managing the risk related to these phenomena. The choice of different approaches to simulate processes in terms of equations, also relying on heavy simplifications, characterizes the different models and codes proposed for debris flows. In particular, different relations have been proposed for the description of flow resistance.

As previous work showed (e.g. Hungr 1995; Ayotte & Hungr 2000; Rickenmann *et al.* 2006), not only in the case of debris-flow simulation but in the broader field of numerical modelling of geological phenomena, the choice of boundary conditions and inherent parameters is critical for the balance between model results and field evidence. As mentioned above, in our work on debris-flow modelling we consider previous studies in order to select adequate models for comparative application to the Rivoli Bianchi Fan.

Armento *et al.* (2008) compared the results of simulations of two well-documented debris-flow events in the Dolomites area (Italy) obtained with two single-phase, non-Newtonian models, the two-dimensional FLO-2D model (O'Brien *et al.* 1993) and the one-dimensional Dynamic Analysis (DAN-W) developed by Hungr (1995). The aim was to verify whether debris-flow dynamics could be modelled relying on a limited number of input parameters. Compared with DAN-W, the FLO-2D model requires more detailed input on substrate topography and a more strict specification of rheological and hydrological data; both codes implement a variety of rheologies. Armento *et al.* (2008) found that DAN-W model results more accurately represent documented events in terms of runout distances using the Voellmy rheology, while underestimating

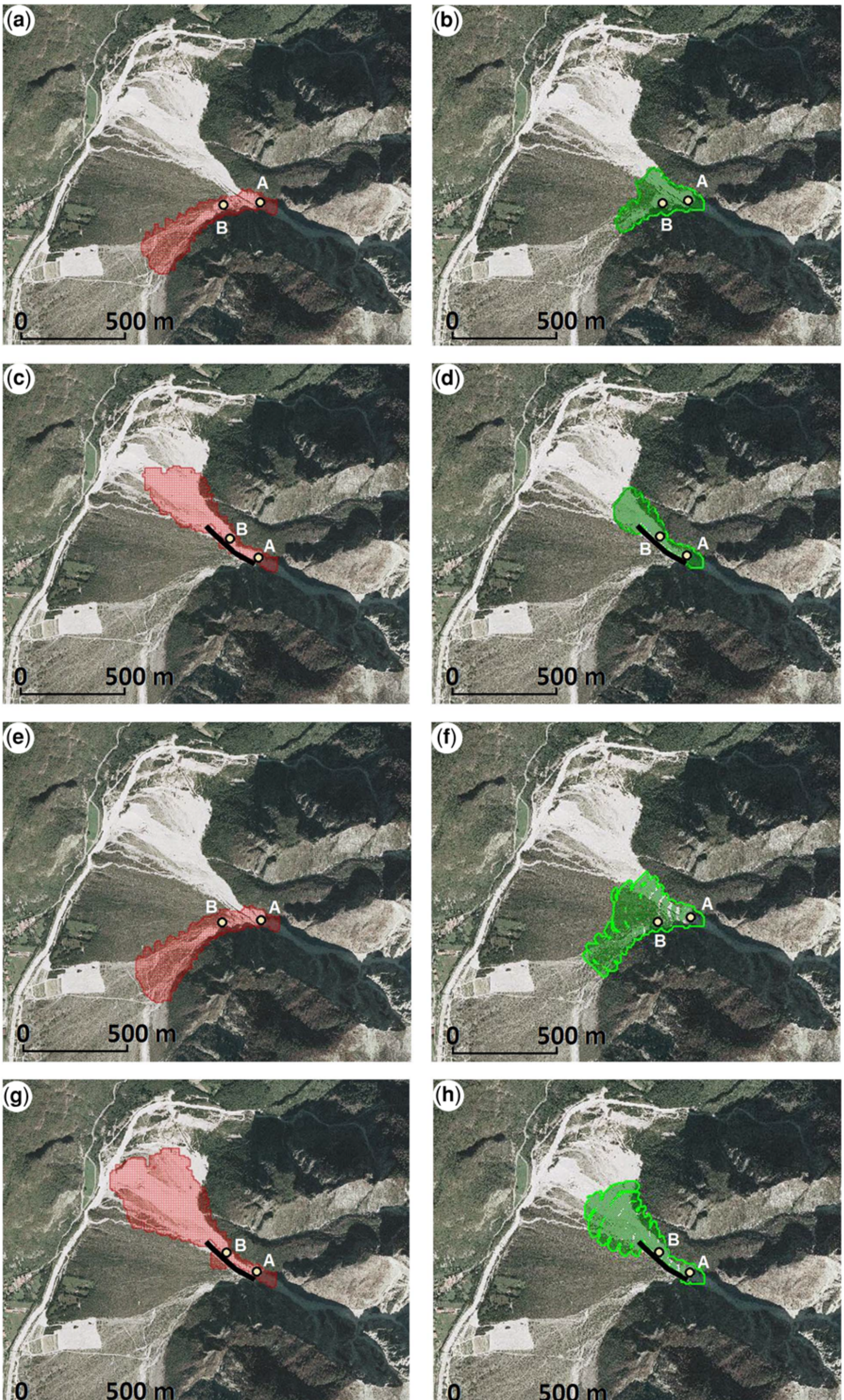

Fig. 5. Maps of flooded areas processed by IDRA 2D DF (red) and FLO2D (green). A, Fan apex; point B, downslope fan apex; black line, deflecting wall. (**a**, **b**) Natural condition – high viscosity; (**c**, **d**) deflecting wall – high viscosity; (**e**, **f**) natural condition – low viscosity; (**g**, **h**) deflecting wall – low viscosity.

the predicted depth of resultant deposits. The FLO-2D algorhithm provides a more accurate hazard representation in terms of flooded area, while estimates of flow-runout distances are similar to those of the DAN-W model. The authors concluded that when detailed topographical, rheological and hydrological data are not available, DAN-W is a valuable tool for the prediction of debris-flow hazard to a first approximation, since it requires less detailed boundary parameters.

In a different geographical context (Yosemite Valley, California, USA), Bertolo & Wieczorek (2005), using again the one-dimensional DAN-W and the two-dimensional FLO-2D models, attempted to predict and compare the velocities and runout distances of debris flows. Although the outputs of both models appeared strongly influenced by topographical boundary conditions, the results were similar to the field observations, and good agreement between the models was found for calculated flow velocities; obviously, the authors found a rather good set of calibration parameters through a large number of simulations.

Three different, two-dimensional debris-flow models were applied to two field cases in the Swiss Alps (Rickenmann *et al.* 2006): the DFEM model (Debris flow Finite Element Model), developed by the Swiss Federal Research Institute WSL; the 2D-HB model, developed by Cemagref in Grenoble (Laigle 1997); and the FLO-2D described here. The first one is a model based on the numerical solving of finite elements and includes various friction/rheological relations; the second one adopts a Herschel–Bulkley rheology. The authors, as usual after a careful calibration with historical data, found that the runout and the final depths of deposits were reasonably reproduced, concluding optimistically that, given such levels of agreement between model output and field data, the simulated velocities during the final flow stages should not have differed significantly from real values. It is surprising that the authors obtained similar results for the debris-flow depositional features from three fundamentally different codes; this probably demonstrates that 'good' results can be derived from any numerical model by means of a sufficiently accurate calibration. Ten years later, Rickenmann (2016) applied the same models to the Millibach Fan (Switzerland) and ascertained the considerable output variability among the three debris-flow models, even though all models were calibrated upon the same depositional data based on a past event.

The numerical models adopted for this study are both single-phase and two-dimensional: the FLO-2D model is the one most used worldwide for the design of debris-flow countermeasures, while the relatively open-source IDRA2D code can take into account substrate erosion and entrainment. The aim here was to evaluate and compare model performances by simulating debris-flow routing and deposition on an large alluvial fan. In particular, we aimed to test how different approaches and mathematical assumptions related to the governing equations would influence model outputs such as flow velocity, inundated area and final deposit thickness.

After calibration through field-based data from past events, the performance of both codes was tested in terms of consistency of the results with the observed data: while the calculated extent of the flooded area was acceptably consistent, values for flow velocities were in complete disagreement, a problematic outcome since higher flow velocities in the field would result in larger areas of debris inundation. As for the models discussed above, the problem lies probably in the different approaches and in the introduced assumptions. In principle, this ambiguity in the results could be thought to hinder the applicability of debris-flow modelling for planning and hazard reduction in mountainous areas subject to debris-flow activity (such as alluvial fans). In fact, it should be considered that debris-flow numerical modelling has practical use only with the awareness that model results need to be accompanied by estimates of uncertainty when applied to risk reduction.

Consequently, the present study does not offer great support to numerical models of debris flows: how could it be possible to constrain a highly complex natural process that is even too difficult to study in the field, owing to its sporadic occurrence, impulsive character and high variability in all the involved parameters? A growing availability of field data about debris-flow events, along with a strict collaboration between numerical modellers and geologists, should contribute to the building of increasingly robust models in the future.

Conclusions

The objective of this study was to compare two numerical codes characterized by a different debris-flow simulation approach, applying them to the case of a well-documented debris-flow fan in the Eastern Italian Alps. Since the natural processes involved in debris-flow activity from triggering to actual flow propagation deposition are very complex, various simplifications need to be applied to a numerical modelling approach in order to make the phenomenon mathematically solvable. Moreover, several boundary conditions necessary to perform a simulation (e.g. volume of available debris in the watershed and rheological parameters of the flowing mass, such as viscosity, size and concentration of sediment in the mixture etc.) are not easily measured in the field and may vary even during a single surge.

Modellers must always resort to back-analysis in order to ensure realistic simulations; however, the resulting model can hardly be considered a predictive tool under different boundary/initial conditions, even in the same field test area, given that all of the involved parameters normally differ from event to event (Oreskes *et al.* 1994). The comparison we made in the present study provides a clear example in case: a well-known geological setting, a large debris-flow fan, is modelled through a 5 m DEM grid and a debris-flow flood is simulated by means of two 2D codes starting from the same DEM and input hydrograph in two different physical and rheological settings. After many simulations, changing some of the uncertain parameters, especially the pseudo-Manning coefficient (accounting for the general flow resistance), the results of the two models are realistic and compatible with the natural evolution of the Rivoli Bianchi Fan, but while the values for the extent of the flooded area are comparable, the calculated flow velocities differ substantially. The inconsistency in flow velocity between the two codes is most likely due to the different assumptions introduced by modellers to render the natural process numerically treatable, and to in-built differences in the approach to the debris-flow phenomenon. For instance, Flo2D considers a fixed bed for the flow, while Idra2D DF takes into consideration an erodible bed; the numerical algorithms of the inherent differential equations differ as well.

The study thus shows the importance of understanding the conceptual foundations of numerical modelling for the simulation and prediction of natural geological phenomena, such as debris flows. Model results are certainly useful for hazard mapping or for the design of debris-flow countermeasures, but given the inherent uncertainties, one has to bear in mind an unavoidable lack of trustworthiness of numerical simulations, and the fact that a general knowledge and field surveys of active processes in the interested areas are still indispensable for a correct approach to risk reduction. In general, numerical simulations have to be considered as a qualitative support rather than a quantitative design instrument for the study of geological hazard and the design of countermeasures.

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