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Flow behaviour and runout modelling of a complex debris flow in a clay-shale basin

Alexandre Remaître,[1]* Jean-Philippe Malet,[1†] Olivier Maquaire,[1] Christophe Ancey[2‡] and Jacques Locat[3]
[1] *Institut de Physique du Globe, UMR 7516 CNRS-ULP, 5, rue René Descartes, F-67084 Strasbourg Cedex, France*
[2] *Cemagref, Division Erosion Torrentielle, Neige et Avalanche, B.P. 76, Domaine Universitaire, F-38402 St-Martin-d'Hères, France*
[3] *Département de Géologie et de Génie Géologique, Université Laval, Sainte-Foy, G1K7P4, Québec, Canada*

**Correspondence to: A. Remaître, Institut de Physique du Globe, UMR 7516 CNRS-ULP, 5, rue René Descartes, F-67084 Strasbourg Cedex, France.
E-mail: alexandre.remaitre@eost.u-strasbg.fr
†Present address: Faculty of Geosciences, University of Utrecht, PO Box 80.115, 3508 TC Utrecht, The Netherlands.
‡Present address: École Polytechnique Fédérale de Lausanne, ENAC, Laboratoire d'hydraulique environnementale, Ecublens, CH-1015 Lausanne, Switzerland*

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Abstract

Identification of debris-flow hazard areas necessitates the knowledge of the flow thickness and the runout distance. Both have been investigated using a numerical runout model. On the Faucon stream (South French Alps), representative of clay-shale basins, results of various rheological tests and numerical experiments are presented and discussed. The calibration of the model was undertaken using the results of both geomorphological surveys and sedimentological analyses. Rheological tests using either a parallel-plate rheometer, a coaxial rheometer, slump tests, and an inclined plane were carried out on several samples. Results have shown that the flow behaviour could be described by an Herschel-Bulkley constitutive equation. The rheological responses of several natural suspensions collected from surficial deposits (sandstones, moraines, weathered black marls) were also investigated. In order to model the runout of the flow, the model *BING* was used. The model describes well the influence of each type of sediment on the behaviour (runout distance, deposit thickness) of the flow, although the velocities were significantly overestimated. Different risk scenarios are tested and discussed.

Keywords: muddy debris-flow; clay-shale basins; rheology; Herschel-Bulkley; numerical modelling

Introduction

Modelling of debris-flow runouts has received considerable attention from researchers over the last decade (Hungr, 2000; Laigle and Marchi, 2000; Massimo, 2000; Ghilardi *et al*., 2001). Two approaches are possible. On one hand, the flow is considered as a one-phase constant-density fluid (Johnson and Rodine, 1984). On the other hand, the flow is considered as a two-phase variable-density mixture composed of a granular material immersed in an interstitial fluid (Takahashi, 1991; Iverson, 2003). The one-phase fluid approach is usually used for the modelling of muddy debris flows (Laigle and Coussot, 1997; Locat *et al*., 2004) whereas the two-phase mixture approach is used for the modelling of granular or clay-poor debris flows (Iverson, 1997; Iverson and Vallance, 2001). In clay-shale basins, the debris-flow matrix is characterized by a high fines content. For this reason, this paper uses a one-dimensional model of a viscoplastic mud including a yield stress due to the colloidal fraction.

The purpose of this paper is to characterize the flow behaviour and to calibrate the runout model *BING* on a torrential stream representative of clay-shale basins. The Faucon torrent, in the Barcelonnette basin, was selected as an experimental site because an important debris flow occurred in 1996 (Remaître *et al*., 2003a) and because the geomorphological and hydrological conditions of the area are quite typical of other torrents evolving in clay-shale outcrops.

A study has been carried out to:

- define the rheological characteristics of the 1996 debris flow and of each of the main surficial formations located in the Faucon watershed;
- simulate the runout of the debris flow by calibrating the *BING* model on the observed event (morphology and rheology);
- test several modelling scenarios regarding torrential hazard assessment (source area volume and sediment properties).

Model Characteristics

Numerical scheme

The one-dimensional runout model *BING*, developed by Imran *et al*. (2001) for the study of the downslope spreading of finite-source debris flows, has been selected for this study. The code has been developed and validated either for the study of submarine fast slope movements (Marr *et al*., 2002; Locat *et al*., 2004) or for subaerial debris flows (Remaître *et al*., 2003b; Malet *et al*., 2004). The model is based on the numerical scheme of Jiang and LeBlond (1993). The numerical model solves conservation of mass and momentum equations that are integrated over the viscous and the plug layer thickness. These are solved using an explicit time-marching finite difference scheme in a Lagrangian framework. The solution procedure is similar to the one described by Savage and Hutter (1991) and Pratson *et al*. (2001). If x denotes an arc length streamwise coordinate imbedded into the boundary over which the debris flow is to run, y denotes the direction upward normal to the bed, and u and v denote the corresponding flow velocities. Equations of mass and momentum conservation take the following forms (e.g. Imran *et al*., 2001):

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

and

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\left(1 - \frac{\rho_a}{\rho_d}\right) g \frac{\partial D}{\partial x} + \left(1 - \frac{\rho_a}{\rho_d}\right) gS + \frac{1}{\rho_d} - \frac{\partial \tau}{\partial y} \tag{2}$$

where D is the flow thickness, ρ_d and ρ_a are the density of the debris slurry and the ambient fluid respectively, S denotes the slope gradient, g is the acceleration due to gravity and τ is the shorthand for the component τ_{xy} of the stress tensor.

Starting from an initial parabolic shape the debris mass is allowed to stretch until the front velocity decelerates to a negligible value at which point the calculation is terminated. The model enforces a no-slip bed condition. Erosion, deposition, and entrainment of water and sediment are neglected (Marr *et al*., 2002; Imran *et al*., 2001). The debris mass of viscoplastic mud is allowed to collapse and propagate on a given rigid impermeable slope. The number of grid cells remains the same throughout the calculation. Each grid node is allowed to move at the local depth-averaged velocity after each time step. As a result neighbouring nodes can move closer to or away from each other (Imran *et al*., 2001).

The model incorporates various rheological models (Bingham, Herschel-Bulkley, bilinear (Locat, 1997)) of viscoplastic fluid (Figure 1).

In both the Bingham and Herschel-Bulkley rheologies, the fluid is considered to consist of a distinct shear layer and a plug layer. The shear stress at the interface of these two layers is the yield stress. The material can deform only if the

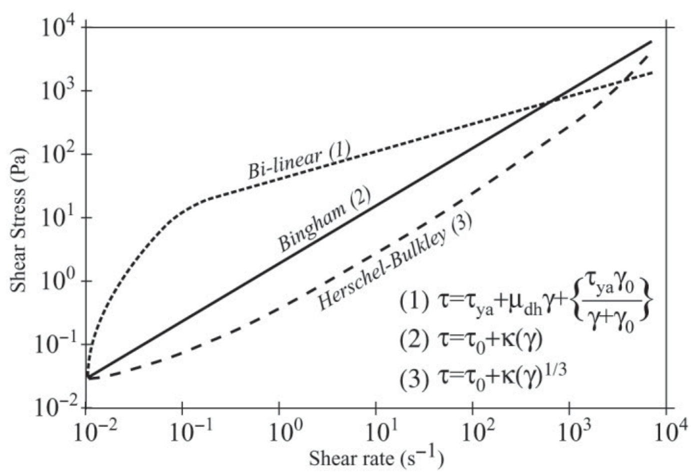

Figure 1. Typical flow curves of the three rheological models implemented in *BING*.

applied stress exceeds the yield strength (e.g. Imran *et al*., 2001). The Herschel-Bulkley equation is preferred to the power law or Bingham relationships because it results in more accurate models of rheological behaviour when adequate experimental data are available. Both are written as follows:

$$\tau = \tau_0 + \kappa(\gamma)^n \tag{3}$$

where τ is the shear stress, τ_0 is the yield stress, κ is the consistency, γ is the shear rate and n the power law exponent. The behaviour is of Bingham type when $n = 1$ and of the Herschel-Bulkley type when $n = 1/3$.

The bilinear model (Locat, 1997) uses an apparent yield strength to distinguish between behaviour at low and high shear stress. The material is allowed to behave like a Bingham fluid at high shear stress, and as a much more viscous Newtonian fluid at very low shear stress, with a smooth transition between the two near an 'apparent' yield stress (e.g. Imran *et al*., 2001). The formulation of the bilinear rheology is written as follow (e.g. Locat, 1997):

$$\tau = \tau_{ya} + \mu_{dh}\gamma + \left\{\frac{\tau_{ya}\gamma_0}{\gamma + \gamma_0}\right\} \tag{4}$$

where τ is the shear stress, τ_{ya} is the yield strength, μ_{dh} is the viscosity, γ is the shear rate and γ_0 is the shear rate at the transition from a Newtonian to a Bingham behaviour.

Input parameters

The model needs several input parameters: the longitudinal profile, the failure volume and geometry and the sediment properties. Determination of input parameters for the model are made from previous work on the study area (Malet *et al*., 2003; Remaître *et al*., 2003a). Morphological and sedimentological characteristics are exposed and discussed in Remaître *et al*. (2005). Longitudinal path profiles obtained from a GPS survey and careful morphological mapping are used in model simulations. It is important to notice that check dams have been included in the path profile. The slope of the Faucon stream ranges from 80° in the headwater basin to 4° on the fan.

In order to use the estimates in the one-dimensional *BING* model, lobe volumes (m^3) are converted to volume per unit width, v (m^2) by dividing the volume of the source area by the failure area width. The *BING* code approximates the failure geometry as a parabola. The model requires the length (L) and the thickness (H) of the failed sediment. As a consequence of working in one dimension, the initial magnitude of L and H must therefore be larger than is realistic, in order to run the simulation with a correct volume. The function of L and H defined by Marr *et al*. (2002) was used to obtain the correct volume.

Sediment properties reflecting the sediment rheology are the most important parameters of the model and the most difficult to determine (Ancey, 2001; Rickenmann and Koch, 1997). The required parameters are sediment bulk density, yield strength and dynamic viscosity. Rheological properties of the sediments were gathered using several methods.

Rheological Analysis

In order to investigate the rheological characteristics, five samples (identified as LTF in Figure 5) of the 1996 debris flow were analysed (Remaître *et al*., 2005). The three main surficial deposits, weathered black marls (MAR), morainic deposits (MOR) and sandstones slope deposits (SAN), were considered as the source material. They were also investigated for comparison.

The direct determination of the behaviour of debris-flow material using classical rheometric methods is faced with the problem that they generally contain particles of various sizes including big boulders (Coussot and Meunier, 1996). Numerous studies have shown that the behaviour of fine-grained debris flows is mainly guided by the muddy matrix rather than the blocks carried (O'Brien and Julien, 1988; Major and Pierson, 1992; Coussot and Meunier, 1996). In the case of coarse-grained debris flows (Iverson, 1997; Iverson and Vallance, 2001), simple constitutive relations (Bingham, Herschel-Bulkley) are not able to capture the complex grain–grain and water–grain interactions controlling these flows (Hungr, 2000). Grain-size distribution analyses (Remaître *et al*., 2005) of the debris-flow deposits demonstrate the muddy character of the flow (more than 20 per cent of clay and silt). Moreover, in clay-shale basins, during the debris-flow runout, the coarse particles may be crushed. Hence the fraction of fine elements may increase during the runout. In such a case the presence of colloidal fractions may introduce yield stress (Major and Pierson, 1992). For these reasons, some specific rheological analyses were carried out, using either a parallel-plate rheometer and a coaxial

Table I. Rheological characteristics of the 1996 debris-flow and the three main surficial deposits for a total solid fraction $\phi = 0{\cdot}50$

	Rheometry (*)			Inclined plane yield stress, τ_c (Pa)	Slump tests yield stress, τ_c (Pa)
	Yield stress, τ_c (Pa)	Consistency, κ Pa s^{-1}	Herschel-Bulkley exponent, n		
LTF	85–95	50–72	0·35	170	95–115
MAR	170–230	85–190	0·34	210	190–240
MOR	115–130	75–90	0·36	145	105–130
SAN	35–45	8–25	0·27	65	45–75

* τ_c, κ and n are the Herschel-Bulkley parameters

rheometer on the <400 µm fraction, slump tests and an inclined channel for the <20 mm fraction. The complete methodology is explained in Malet *et al.* (2003).

The behaviour of debris flow is usually described using empirical models. The three models explained above were tested for all the material and for several total solid fractions. Validity of the results has been discussed in Malet *et al.* (2003). Best-fit parameters were obtained with the Herschel-Bulkley model (Table I). Rheological parameters obtained with the two rheometers (parallel-plate, cone plate) gave estimates of the yield stress that were in close agreement. The estimation of the yield stress by slump tests and inclined channel tests gave more dispersed results. This is mainly due to the widening of the grain size distribution of the tested samples. The relative error varied between −15 per cent and +15 per cent. These values are within the margin of error specified by Coussot and Ancey (1999) who indicated that differences in yield stress estimates using various methods are between 10 and 25 per cent.

In a first step, rheological tests were conducted on the debris-flow deposits (LTF). The yield stress of debris flow ranges from 1 to 170 Pa for a total solid fraction by volume between 0·35 and 0·50. The consistency factor κ ranges from 1 to 72 Pa s^{-1} (Figure 2).

Rheological characteristics of the three surficial deposits have to be put in relation with their grain-size distribution. SAN provides the weakest yield stress (2–30 Pa) while MAR provides the highest (14−800 Pa) for a total solid fraction by volume between 0·35 and 0·50. Hence, we can suppose that the yield stress of the 1996 debris flow has increased during the runout due to the incorporation of moraines and marly sediments. Figure 2 shows rheological characteristics of the 1996 debris-flow deposit and of the three surficial deposits gathered with the three methods. A more precise description of the different samples is given in Remaître *et al.* (2005).

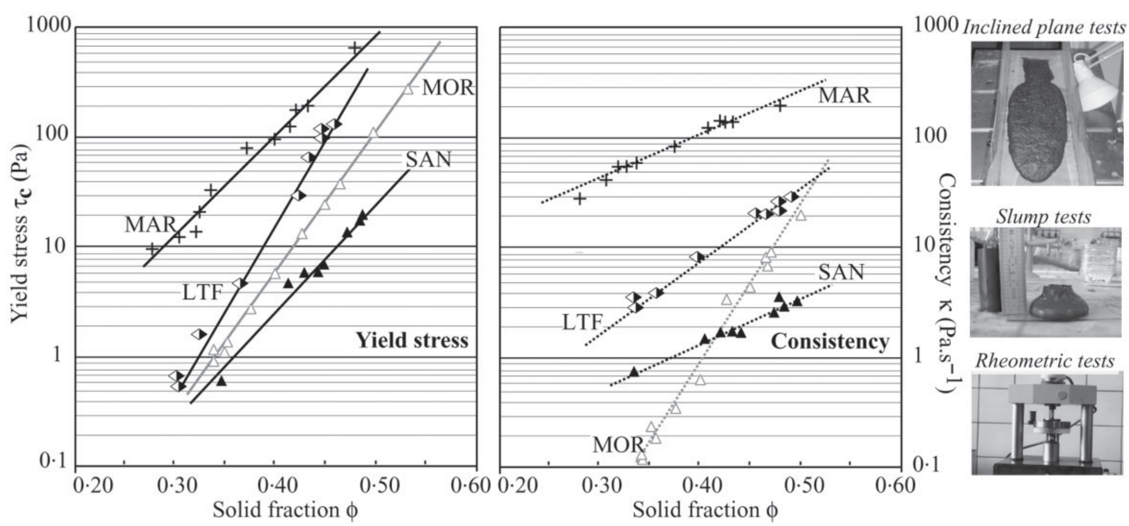

Figure 2. Herschel-Bulkley rheological model characteristics (yield stress and consistency) of the debris-flow deposit (LTF1) and for the three main surficial deposits as a function of the total solid fraction (ϕ).

Numerical Modelling

Objectives

Objectives of the numerical modelling study are: (1) to calibrate the model by comparing output results and field observations; (2) to evaluate the influence of each parameter (volume of the source area, yield stress, density, number of nodes) on the modelling results; (3) to define the minimal volume necessary to reach the apex and the confluence with the Ubaye River.

Calibration of the code and sensitivity analysis

The first step consists of checking the validity of the model. We need to evaluate if the Herschel-Bulkley rheology and the *BING* code are able to replicate field observations (deposit thickness, velocities). In order to calibrate the model, we compare observed thickness deposits to the model output. Runout distance at stoppage could not be used. Indeed, the 1996 debris flow did not stop in the channel and reached the the Ubaye River. Input parameters are given in Table II.

The influence of the number of nodes was evaluated by performing several numerical simulations. In this case the best-fit rheological parameters from the 1996 debris-flow mobility analysis was used by changing the number of nodes (simulations performed for 5, 10, 20, 25, 40, 50, 60, 80 and 100 nodes). For at least 20 nodes, the variation of the deposit depth and the runout distance (Figure 3a) becomes negligible (0·5 to 1 per cent). Hence, 20 nodes were used to reduce the computation time.

In order to evaluate the influence of each input parameter on the simulated deposit thickness a parametric study has been undertaken. Assuming the same initial conditions, different tests have been performed for various input parameters (volume of source area and bulk density). Results show a strong relation between the volume of the source area and the deposit thickness (Figure 3c).

Figure 4 shows the deposit thickness as a function of variable yield stress and consistency from several *BING* simulations. The thinnest deposit is obtained for the lowest yield stress.

It was stated in Remaître *et al*. (2005) that the initial volume coming from the source area was about 5000 m^3 and that the debris-flow slurry volume increases during the runout until reaching a value of 100 000 m^3. It is not possible to impose a scour per metre value at the boundaries of the *BING* model. The source volumes used for these simulations is in agreement with the deposit volumes given in Remaître *et al*. (2005), but not the source volume given in the same paper. The potential energy of the flow is therefore highly overestimated by assuming that all the deposited mass was initiated at source.

A careful geomorphologic survey and field observations have shown that the debris flow maximum flow depth, with a thickness of about 4·5 m, occurred immediately upstream of the bridges located on the alluvial fan (Figure 5b). In this case, the *BING* simulations matched the observed deposit thickness fairly well (Figure 5a). The best-fit simulated deposit thickness is obtained for yield stress and source area volumes ranging respectively from 110 to 150 Pa and 110 000 to 125 000 m^3. These results seem to show that the Herschel-Bulkley constitutive equation and the *BING* code are able to replicate field observations for various total solid fractions and rheology.

The only problem consists in the high overestimation of the debris-flow velocity by the *BING* code. In our case, computed velocities for the best-fit simulation are about 80 m s^{-1}. This value is much greater than the calculated velocities, which were approximately 5 m s^{-1}. (Remaître *et al*., 2002). For example, a flow velocity of 5 m s^{-1} is given by *BING* for a yield stress of 7500 Pa and a consistency of 250 Pa s^{-1}. Indeed as shown by Malet *et al*. (2003) velocities are three orders of magnitude higher than that measured in the field. In fact, the overestimation of the velocities is mainly due to: (1) the potential energy of the flow is highly overestimated by assuming all the deposited mass was initiated at source; (2) the underestimation of the real viscosity mobilized during shearing, which must be three orders of magnitude more.

Table II. Input parameters used in *BING* simulations

	Material parameters			Initial geometry	
Model specificity, number of nodes	**Bulk density (kg/m^3)**	**Yield stress (Pa)**	**Consistency (Pa s^{-1})**	**Length of deposit (km)**	**Thickness of deposit (m)**
5–100	1600–2000	30–1000	5–100	0·01–0·5	10–200

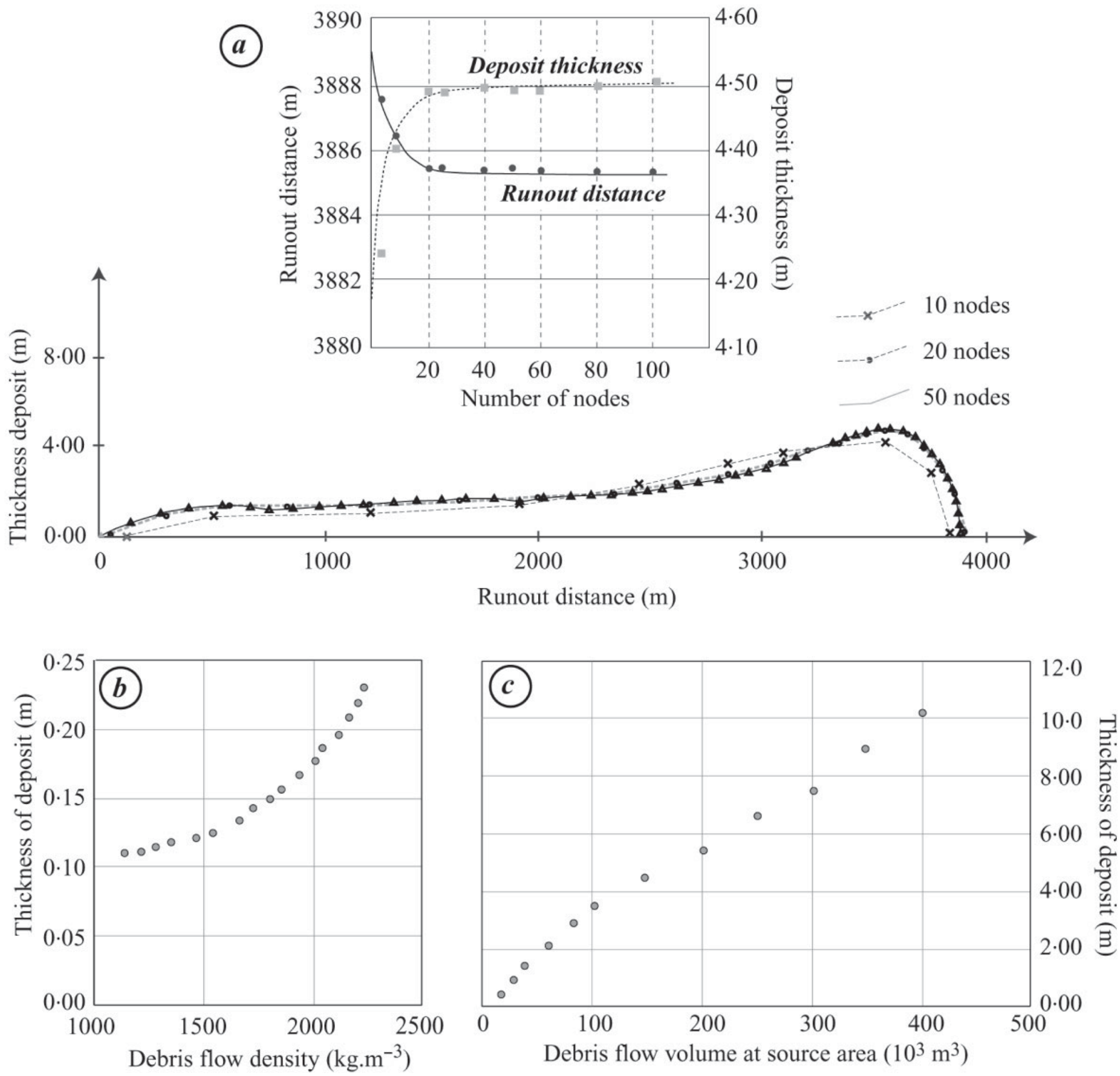

Figure 3. Parametric study with the *BING* code: sensitivity of output results according to the number of nodes (a), deposit thickness vs debris-flow density (b) and volume of the source material (c).

Runout Modelling Scenario

Assessment of debris-flow hazards on alluvial fans is essential for risk management. This is particularly true for the Ubaye valley (Flageollet *et al*., 1999; Malet *et al*., 2002; Remaître *et al*., 2002; Maquaire *et al*., 2003). To reduce debris-flow hazard, it is common to combine structural and non-structural protections, such as zoning of the risk-prone areas. Protection plans require the definition of scenarios that can be assessed by means of simulations with numerical models. A first step in torrential hazard assessment is presented here, by the way of runout modelling scenarios. In our case, we estimate the potential volume of debris to reach the apex and/or the confluence with the Ubaye River.

Several numerical simulations were performed, using the best-fit parameters from the debris-flow mobility analysis by changing the volume of released debris for various yield stress (we used yield stress obtained on MAR, SAN, MOR and LTF).

Results show a strong relation between the runout distance and the volume of the source area. Indeed the runout distance increases with the volume. Figure 6 shows that the debris-flow volume must be at least more than 12 000 m^3 to reach the apex and around 15 000 m^3 to reach the confluence with the Ubaye River. We can notice that in 1996 the

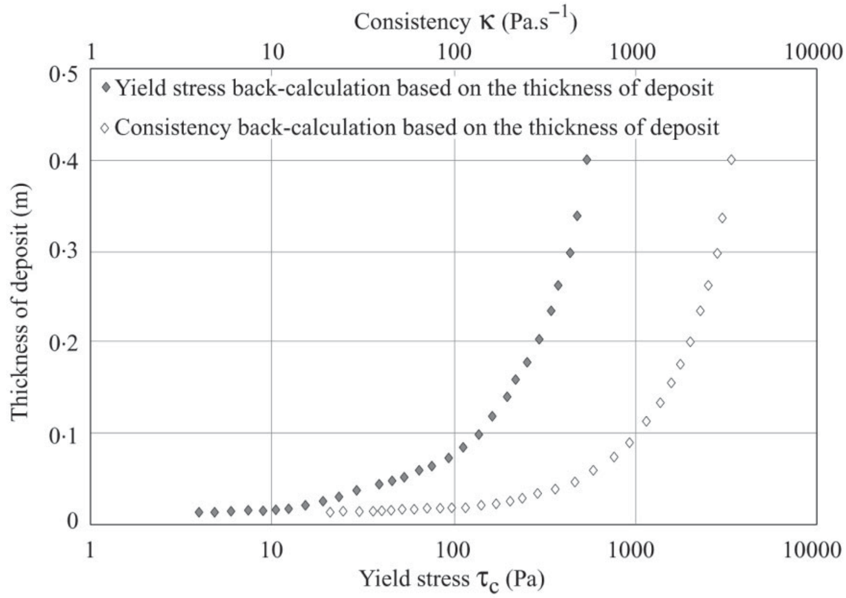

Figure 4. Data plots showing debris thickness as a function of material yield stress and consistency.

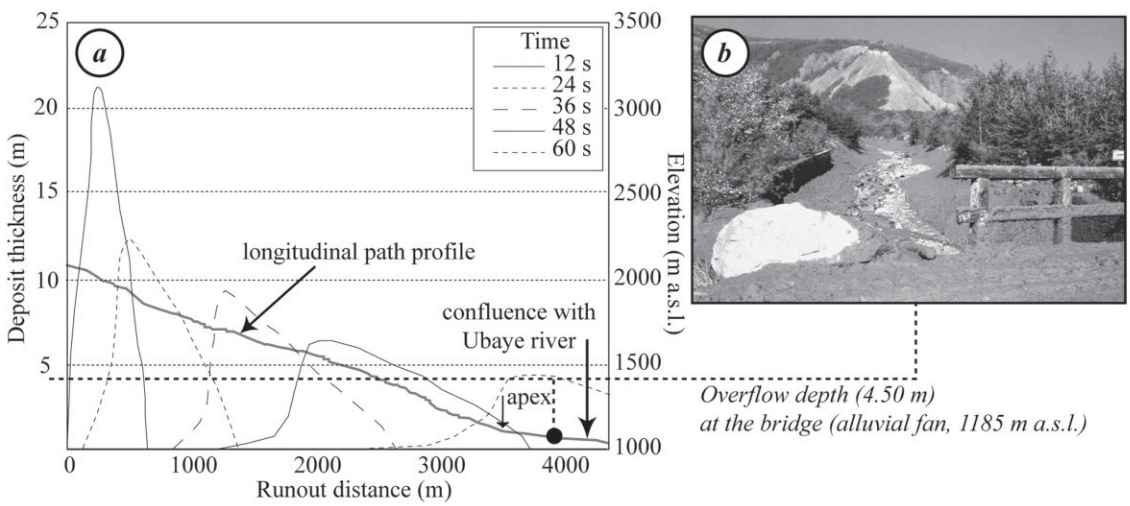

Figure 5. Computed debris-flow geometry overflowing at the apex (a) and photograph of the 1996 debris flow overflowing at the bridge (b).

debris source volume was approximately 5000 m^3, so if any scouring phenomena have occurred, the debris flow would not have reached the confluence with the Ubaye River. We can suppose that small failed volumes required an additional mechanism to generate long runout distances.

Runout distance differences between the four types of material (Figure 7) must be put in relation to their rheological characteristics. The material with the weakest yield stress (in our case SAN) presents the highest runout distance, but not the thickest deposit. So increases in yield stress (by addition of a surficial deposit in the mixture by scouring) result in shorter runout distances and thicker final deposits. Additional data must be obtained for the artificial mixture of the three main surficial deposit to find the mixture which presents the most favourable characteristics for flowing.

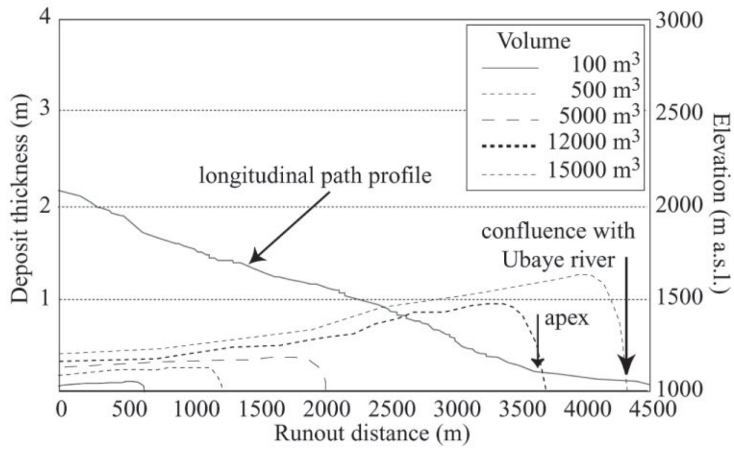

Figure 6. Estimation of the debris volume necessary to reach the apex of the torrent and the Ubaye River confluence for LTF1 (for $\phi = 0{\cdot}45$).

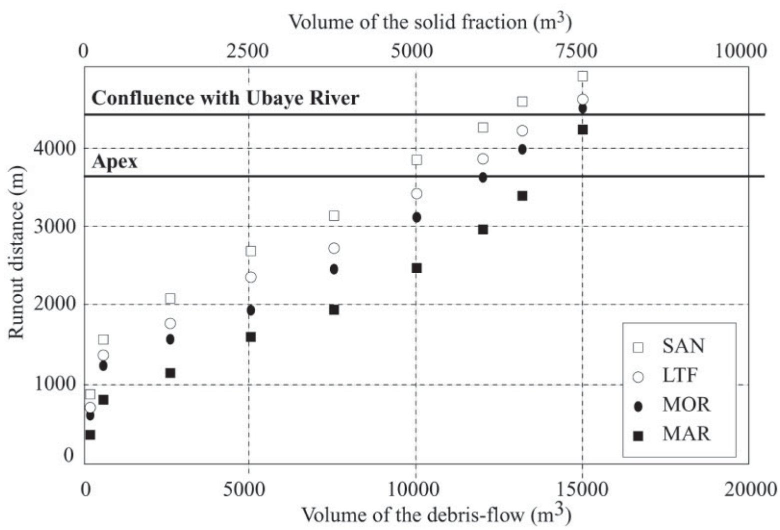

Figure 7. Relationship between the debris-flow volume and the runout distance for the three main surficial deposits and the 1996 debris-flow material.

Discussion

When coupled to a careful geomorphological survey and a rheological investigation, debris-flow runout modelling can be an important tool for hazard assessment. In such a case the calibration of the model must be undertaken on the basis of well documented debris-flow events. Results of modelling show that the *BING* code is able to replicate field observations for various total solid fractions and behaviour. Nevertheless, some aspects need further investigation especially concerning the overestimation of the debris-flow velocities and the entrainment of loose sediment during the flow (bulking by scouring phenomena for example). This last point can lead to an underestimation of the debris-flow volume and by extension, of runout distances and deposits thicknesses.

The parametric study outlines the importance of the debris source volume and the rheological characteritics of the source material(s) on the deposit thickness and the runout distance. Additional modelling focusing on the influence of the slope configuration (longitudinal path profile) will give information on this topic.

Conclusion

A combination of several analyses (geomorphology, sedimentology, rheology, and numerical modelling) provides valuable data to understand the 1996 debris-flow event. Comparison of debris-flow deposits with the three main surficial deposits may help in understanding triggering conditions and scouring phenomena during this event. Grain-size distributions and petrographic analysis of the debris-flow deposit bring out the granular character of the flow during the first hectometer and its cohesive character beyond that point and as far as the debris fan. Geomorphic observations and laboratory tests show the existence of two source areas: a triggering area and several contributing areas. These contributing areas, characterized by the presence of black marl outcrops and a morainic cover, seem to have supplied the bulk of the flow material. Field observations and laboratory tests were introduced in the *BING* code in order to model the runout of the 1996 debris flow. In order to check the validity of the code, comparisons of *BING* computation output data and runout characteristics measured in the field have been carried out. Results show that the Herschel-Bulkley constitutive equation and the *BING* code are able to replicate, for various total solid fractions and rheology, the field observation. Parametric study with the *BING* code revealed that several parameters influence final deposit runout and thickness, especially debris source volume and rheometrical characteristics (yield stress). Additional computation with several types of source material showed that the debris-flow volume must be at least more than 13 500 m^3 for reaching the confluence with the Ubaye River. The rheological parameters of the sediment of the source area seem to influence debris-flow runout distances and deposit thickness. Nevertheless, the development of tools incorporating the entrainment of loose particles during the runout, and able to account for evolving rheology, is required to build reliable scenarios for watersheds characterized by high scour potential and slope/bank instabilities.

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