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ANALYSIS OF THE DEBRIS-FLOW HAZARD ON THE RIOULONG TORRENT (HAUTES-PYRÉNÉES, FRANCE) ALLUVIAL FAN USING A SCENARIO-BASED APPROACH

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ABSTRACT

A method of debris-flow hazard analysis, using the Cemagref LAVE2D model, within a scenario-based approach, is applied to a torrent of the French Pyrenees. A preliminary analysis of the catchment shows that some risk of debris-flow occurrence is present and that scenarios should be constructed accordingly. Numerical simulations are carried out on the basis of these scenarios. They produce maps of maximum extension of debris flows in relation to qualitative levels of probability of occurrence. Simulations also provide information that is useful for the design of a protection structure. Finally, the maximum extension of debris flows resulting from the presence of the protection structure is analyzed.

Key words: *debris-flow, mudflow, erosion processes, hazard assessment, numerical simulation, protection structures*

INTRODUCTION

Mudflows and debris flows, like many other natural phenomena, vary greatly in their occurrence conditions. This variability originates, of course, in the occurrence of triggering rainfall conditions, but also in the nature and availability of solid material present in the debris-flow-prone catchment. These two factors, once combined, will determine not only the volume of each individual event, but also the mechanical properties, and more generally speaking, all flow conditions. For people in charge of protection strategies, it is necessary to evaluate the intensity (flow depth, velocity and potential damage) and probability of occurrence (once every 10 years, 100 years, 1000 years?) of events likely to affect a given point in the area (a house, for instance). It is therefore crucial to take this variability into account. In this context, the scenario-based approach exemplified here can be considered a practical method of hazard assessment. It consists first in a diagnosis of debris-flow triggering processes at work in the catchment considered. Then the ranges of variation of all the inputs of a debris-flow simulation model are deduced from the diagnosis. Each of the input values is then assigned a probability of occurrence, mostly qualitative (frequent, rare, exceptional, etc.). Numerical simulations, covering these predefined ranges of variation of input data are then carried out. Each simulation result can subsequently be assigned a probability of occurrence, once again mostly qualitative.

This method is here exemplified on the Rioulong torrent (Loudenvielle, Hautes-Pyrénées, France) alluvial fan, with a few houses, a camp site and a local road within the hazard zone. First, the catchment is diagnosed considering erosion processes at work in the catchment. This diagnosis means that the probability of debris-flow triggering cannot be ruled out. It also provides an evaluation of the magnitude of debris flows likely to affect the alluvial fan. In the second part of this article, a scenario-based analysis, using a numerical model dedicated to the computation of debris-flow spreading on alluvial fans, is carried out in order to assess the debris-flow hazard. In practice, we use the Cemagref LAVE2D model (Laigle *et alii*, 2003), but other models are able to compute the spreading of debris flows as well, for instance, FLO2D (O'Brien *et alii*, 1993) could similarly be employed.

Scenarios are constructed based on the diagnosis outcomes. In the third part, the effect of a protection levee is also analyzed within the scenario-based approach. This analysis provides useful elements for the design of the protection structure. Finally, the consequences of the presence of the protection levee on the flow downstream, and thus on the hazard on the alluvial fan, are also analyzed.

PRELIMINARY ANALYSIS OF THE RIOULONG CATCHMENT

MAIN FEATURES OF THE CATCHMENT

The Rioulong torrent is a tributary of the Neste du Louron, a valley river located in the Hautes-Pyrénées district in France (Fig. 1). This torrent catchment covers 1.72 km² and ranges from 1920 m to 960 m a.s.l. The catchment is for the most part well covered by vegetation and partly subjected to anthropogenic effects. Six per cent of the catchment area is impervious because of the presence of the Val Louron ski resort in its upper part. The channel in the medium reach is rather steep, with mean slopes ranging from 0.3 m/m to 0.5 m/m (Figure 1). In this area, the stream cuts into ancient morainic deposits. Covering about one-quarter of the catchment, this sector resembles a large hanging humid zone with more or less active instabilities. It is also the confluence point of several gullies of the upper catchment hydrographic network (Figure 2). Given the small size of the basin, the steepness of slopes, gullies and stream bed, the large number of gullies, and the presence of humid or impervious zones, the catchment is likely to respond very quickly to any rainfall event.

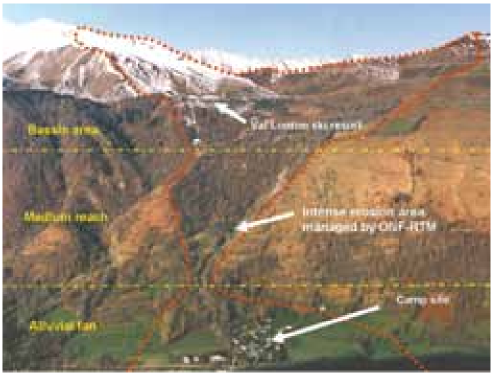

Fig. 1 - General overview of the Rioulong catchment (photo: ONF - RTM 65-64)

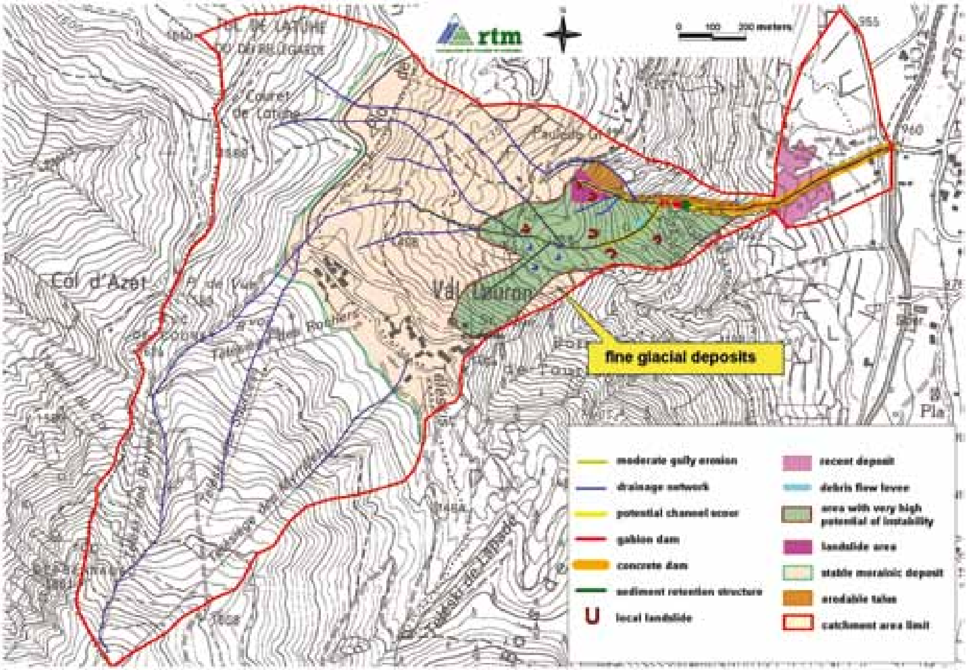

Fig. 2 - Limits of the catchment and map of sediment production areas

Historically, several floods triggered by intense rainfalls have been recorded (1875, 1885, 1891, 1909, 1929, 1936, and 1987, according to the unpublished archives of the ONF-RTM department who is in charge of the torrent control). The consequences were severe for human activities in the vicinity of the stream. Characterized by huge sediment transport with gravels, blocs, and mud of glacial origin, some of these floods probably included debris flows. This is confirmed by the typical shape of ancient deposits still present on the alluvial fan.

A preliminary protection strategy, mainly based on small check-dams and revegetation, was defined as early as the late 19th century and reinforced in 1945. More recently, a camp site has been established on the alluvial fan, thus increasing the vulnerability already present in this area (several houses and a local road). A drainage network and check dams were built during the 1990s (unpublished archives of the ONF-RTM department who is in charge of the torrent control).

EROSION AND DEBRIS-FLOW MAGNITUDE

Erosion processes

In the catchment's present state, the extension of erosion processes is rather limited. The most active phenomenon is a landslide in morainic terrains, drained by the Paulède gully, a small tributary of the Rioulong torrent. Consequently, sediment transport in the channel remains very limited for common discharge values, occurring once a year on average. Nevertheless, for intense flooding, bed destabilization is likely to occur in the steep channel between the upper basin and the alluvial fan, involving at least 700 m of channel where the bed grain size distribution appears very small compared to the stream steepness. Only one-third of this channel has been protected by check dams.

Also in this intermediate zone, an automatic analysis using GIS, based upon instability criteria defined by Zimmermann *et alii* (1997) and completed by detailed field surveys, showed that landslides are likely to be triggered under long and intense rainfall conditions.

These observations led us to map the most erosion-sensitive areas (Fig. 2) and carry out a quantitative evaluation of the mobile material potential (Tab. 1). These assessments show very large uncertainties but given the present state of the catchment, they can be considered realistic.

Possible magnitude of debris flows

Even though the observed erosion activity is limited, the field surveys carried out in the catchment and the analysis of the lengthwise profile of the stream show that the risk of debris-flow triggering cannot be neglected.

Huge quantities of weathered and wet material, with features that are similar to viscous debris-flow deposits, are present in the vicinity of the channel and gullies and are likely to mobilize. Furthermore, the steep longitudinal slope of the channel and gullies in this area are compatible with the triggering and propagation of mudflows down to the alluvial fan.

When comparing the results of the application of several evaluation methods of the volume of material potentially mobilized, it appears pertinent to consider at least three debris-flow scenarios associated with a probability of occurrence qualified as follows: infrequent, rather rare and rare. The absence of recent events, however, gives substantial uncertainty to the estimations. We therefore considered the possible occurrence of an exceptionally rare event. Table 2 gives the debris-flow volume values associated with these qualitative terms and an order of magnitude of the annual probability of occurrence of these volumes.

Three assumptions of peak discharge values were considered and their probability of occurrence described. These values were established based on the catchment hydrology and the empirical relationship between peak discharge and volume of a debris-flow event proposed by Rickenmann (1999). These values

	Erosion processes	
Sediment production rate	Channel scouring	Landslides
Low	4 000 m^3	5 000 m^3
High	14 000 m^3	10 000 m^3

Tab. 1 - Assessment of potential mobilized volume of material considering erosion processes at work

Occurrence of event	Infrequent	Rather rare	Rare	Exceptionally rare
Volume of debris-flow	5 000 m^3	10 000 m^3	15 000 m^3	25 000 m^3
Annual probability of occurrence	5.10^{-2} to 2.10^{-2}	2.10^{-2} to 1.10^{-2}	1.10^{-2} to 3.10^{-3}	$< 3.10^{-3}$

Tab. 2 - Reference scenarios considered: qualitative probability of occurrence, volume and tentative value of the annual probability of occurrence are: 30 m^3/s (infrequent occurrence), 100 m^3/s (rare occurrence) and 180 m^3/s (exceptionally rare occurrence).

Given the channel's low capacity on the alluvial fan, the risk of some overflow for any debris-flow occurrence (including events with a low discharge value) is quite high. Some spreading of the flow towards human settlements on the alluvial fan is therefore likely to occur.

MODEL PRESENTATION

LAVE2D (Laigle *et alii*, 2003) is a numerical model dedicated to the computation of the unconfined free-surface spreading of materials with complex rheology. It is based upon the 2D steep-slope-shallow-water-equations which are solved by using a finite volume technique. It takes into account viscous dissipation inside the flowing material, assumed homogeneous, by the use of the wall shear stress expression. This expression from Coussot (1994) is based upon the assumption of a visco-plastic behavior which can be represented by a Herschel-Bulkley model mainly applying to mudflows or so-called viscous debris flows. Apart from values of the rheological parameters, model inputs are: boundary conditions (imposed discharge versus time at the point where the flow enters the zone of spreading), a computation mesh combined with a digital elevation model of the alluvial fan and a set of numerical parameters (i.e. stability criterion of the numerical scheme, simulation duration). For more details about this model and its evaluation by comparison to laboratory experiments or records of real events, we invite the reader to refer to Laigle (1997), Laigle *et alii* (2003) and Rickenmann *et alii* (2006).

CONSTRUCTING THE SCENARIOS

Since the topography of the alluvial fan is known based on a precise survey (up to 1 elevation value per square meter), using the LAVE2D model (Laigle *et alii,* 2006) required two additional input data: the debris-flow hydrograph at the alluvial fan apex and the rheological parameters of the flowing material.

INPUT HYDROGRAPH

The input hydrograph imposes the debris-flow discharge versus time at the alluvial fan apex. With no data on the shape of this hydrograph, we assume a linear evolution of the discharge between its peak value at time $t = 0$ to a zero value at time t_1. This time t_1 is easily computed from the peak discharge and the volume of the event. The scenarios studied hereafter have been inferred from the diagnosis presented previously. The hydrograph is "injected" into the computation domain (Fig. 3) in the channel located at the apex of the alluvial fan.

RHEOLOGICAL PARAMETERS

We assume that Rioulong debris flows are of the viscous type, which is consistent with field observations (shape of ancient deposits, grain size distribution of soils present on the slopes and in the gullies).

Fig. 3 - Maximum simulated flow depth for a debris-flow volume of 10 000 m^3, a peak discharge of 100 m^3/s and a τ_c/ρ = 0.5 m^2/s^2 ratio

Following Coussot (1994), we consider that their rheological properties are properly described by a Herschel-Bulkley model. These material properties are determined by two parameter values: the yield-stress to density ratio, τ_c/ρ (m^2/s^2), and the consistency to yield-stress ratio, K/τ_c (s$^{1/3}$). With no means to evaluate these parameter values for the Rioulong torrent, we made the following assumptions. The value of parameter K/τ_c is taken equal to 0.3 s$^{1/3}$, following Coussot (1996) who proposes this value as a first approximation. The value of parameter τ_c/ρ is considered parametrically and three values were considered for the simulations:

- An average value τ_c/ρ = 1.0 m^2/s^2, considering, based on our experience, that a value on this order of magnitude is frequently observed on many torrents. Its probability of occurrence is considered high. Furthermore, the observation of the ancient deposits on the Rioulong alluvial fan tends to confirm this assumption.
- A high τ_c/ρ = 2.0 m^2/s^2 value, with a low probability of occurrence, but which is useful to consider in the parametric approach because it gives high flow and deposit thickness values (considered here as the highest thickness likely to be observed for a given set of discharge and volume values).
- A low τ_c/ρ = 0.5 m^2/s^2 value, with a low probability of occurrence, but which is useful to consider in a parametric approach because it gives high flow velocities and extensions (considered here as the highest velocity and extension likely to be observed for a given set of discharge and volume values).

SYNTHETIC PRESENTATION OF SCENARIOS CONSIDERED

The simulations presented below are the results of scenarios based upon the assumptions summarized in Table 3. They do not cover all possible cases, for practical purposes unlimited in number. For each of the cases considered, perturbing phenomena are likely to modify the result substantially. As an example of

Debris-flow volume (m^3)	Peak discharge (m^3/s)	τ_c/ρ (m^2/s^2)	K/τ_c (s$^{1/3}$)	Goal of the simulation
10 000	100	0,5	0,3	Sensitivity analysis on the material yield-stress (Figures 3 and 4)
10 000	100	1	0,3	
10 000	100	2	0,3	
10 000	30	1	0,3	Sensitivity analysis on the peak discharge
10 000	100	1	0,3	
10 000	180	1	0,3	
5 000	100	1	0,3	Sensitivity analysis on the volume and basic results of hazard mapping (Figures 4 and 5)
10 000	100	1	0,3	
15 000	100	1	0,3	
25 000	100	1	0,3	
10 000	100	0,5	0,3	Identical to the previous case considering fluid material (Figure 6)
15 000	100	0,5	0,3	
25 000	100	0,5	0,3	
10 000	100	1	0,3	Analysis of an example of a log jam, 9 m wide (Figure 7)
25 000	100	1	0,3	
10 000	100	1	0,3	Analysis of the influence of a protection levee with a 45° orientation angle (Figure 8)
10 000	100	1	0,3	Analysis of the influence of a protection levee with a 15°–20° orientation angle
10 000	180	0,5	0,3	Identical to the previous case with all parameters chosen to maximize flow velocity (Figure 9)
10 000	180	2	0,3	Identical to the previous case with all parameters chosen to maximize flow depth (Figure 10)
25 000	180	1	0,3	Impact of the presence of the protection levee on inhabited areas downstream, considering an exceptionally rare event (Figure 11)
25 000	180	0,5	0,3	Identical to the previous case considering fluid material

Tab. 3 - Synthetic presentation of all scenarios considered in the study. Not all of them are illustrated in the present paper these perturbing phenomena, we considered one assumption of log jamming occurring in the channel at the apex of the alluvial fan. Two protection levee assumptions are also considered.

HAZARD ASSESSMENT: ANALYSIS OF MAXIMUM EXTENSION OF DEBRIS FLOWS

Since debris flows are likely to generate major damage at any point of their spreading area, we considered their maximum extent as the most pertinent criterion for the hazard analysis on the Rioulong alluvial fan. These extensions are mapped for each of the scenarios considered. However, rather than considering only the extensions it is more interesting to consider their variation related to any variation of the model's input parameters. This is why the results are presented as a sensitivity analysis.

INFLUENCE OF THE YIELD-STRESS VALUE

The goal of the following simulations is to evaluate the influence of rheological properties of the flowing material. We consider a given volume of 10 000 m^3 and a given peak discharge of 100 m^3/s. Three assumptions on the material properties are considered: fluid (τ_c/ρ = 0.5 m^2/s^2) (Figure 3), average (τ_c/ρ = 1.0 m^2/s^2) (Figure 4) or viscous (τ_c/ρ = 2.0 m^2/s^2).

These simulations show the substantial influence of the material viscosity on the final deposit extension. This is consistent with previous results established on other torrents (Rickenmann *et alii*, 2006). However, one can see an important trend on Rioulong: the lateral overflow at the alluvial fan apex of all the material coming from upstream with a distribution between the right and the left bank. This trend is confirmed by simulations presented below.

INFLUENCE OF THE PEAK DISCHARGE

The goal of the following simulations is to evaluate the influence of the peak discharge. These simulations are carried out considering a given volume of 10 000 m^3 and rheological characteristics corresponding to a mean viscosity (τ_c/ρ = 1.0 m^2/s^2). Three peak discharge assumptions were considered: 30 m^3/s, 100 m^3/s and 180 m^3/s. These simulations show that a variation in the peak discharge moderately influences the maximum extension of the flow. The peak discharge value essentially influences the flow velocities and to a lesser extent the flow depth, mainly in the channelized area at the apex of the alluvial fan.

INFLUENCE OF THE VOLUME

The goal of following simulations is to evaluate the influence of the debris-flow volume. These simulations were carried out considering a peak discharge of 100 m^3/s and an average viscosity material (τ_c/ρ = 1.0 m^2/s^2). The volume assumptions considered are: 5

Fig. 4 - Maximum simulated flow depth for a debris-flow volume of 10 000 m^3, a peak discharge of 100 m^3/s and a τ_c/ρ = 1.0 m^2/s^2 ratio

Fig. 5 - Maximum simulated flow depth for a debris-flow volume of 25 000 m^3, a peak discharge of 100 m^3/s and a $\tau_c/\rho = 1.0$ m^2/s^2 ratio

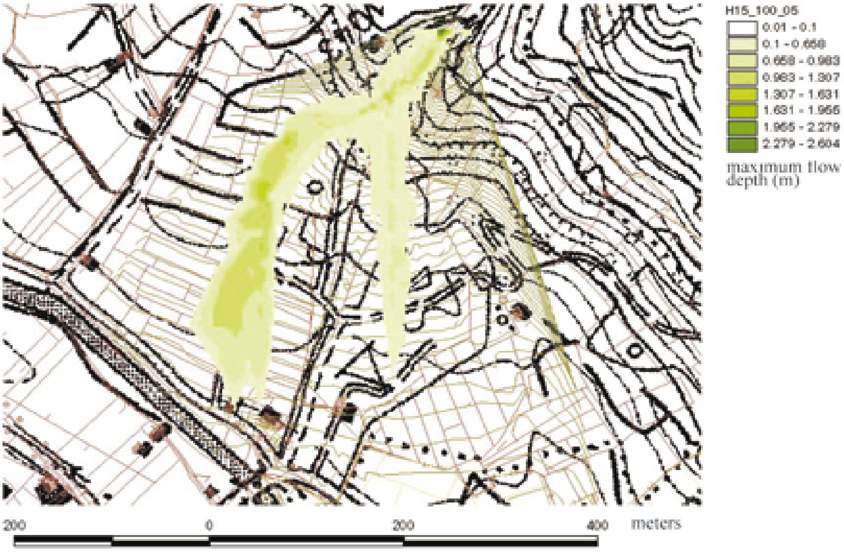

Fig. 6 - Maximum simulated flow depth for a debris-flow volume of 15 000 m^3, a peak discharge of 100 m^3/s and a $\tau_c/\rho = 0.5$ m^2/s^2 ratio

000 m^3, 10 000 m^3 (Fig. 4), 15 000 m^3 and 25 000 m^3 (Fig. 5). The simulations show that the assumed volume has a substantial influence on the flow extension. This result is coherent with previous results obtained on other torrents (Rickenmann *et alii*, 2006).

ANALYSIS OF THE MAXIMUM EXTENSION OF A FLUID MATERIAL

The goal of the following simulations is to evaluate the maximum flow extension for the unlikely occurrence of a fluid material ($\tau_c/\rho = 0.5$ m^2/s^2), which tends to spread more easily but whose deposits are less thick. The simulations are carried out considering a peak discharge of 100 m^3/s. The volume assumptions considered are 10 000 m^3 (Fig. 3), 15 000 m^3 (Fig. 6) and 25 000 m^3.

The simulations show that beyond a debris-flow volume ranging from about 15 000 to 20 000 m^3 and under the assumption of a fluid material, the houses (represented as black rectangles in the figures) located on the right bank of the channel, downstream of the alluvial fan, are likely to be reached by debris flows. Additionally, as for the previous simulations, the risk is high on the left bank of the channel (notably the camp site area).

EXAMPLE OF THE INFLUENCE OF LOG JAMMING

Given that the catchment is covered by timber and the channel is narrow, it is pertinent to consider the assumption of log jamming. It is unrealistic to consider all possible assumptions of log jamming, since this phenomenon is likely to occur almost anywhere in the channel and the resulting plug dimensions can vary greatly. Consequently, we illustrate this phenomenon using an example. The assumption is that the log jamming occurs at the alluvial fan apex, where previous simulations show that the flow tends to spread laterally. Simulations are based on a peak discharge of 100 m^3/s and an average viscosity. Two volume assumptions are considered: 10 000 m^3 (Fig. 7) and 25 000 m^3. The log jamming is numerically represented as a wall, 9 m wide, indefinitely high, clogging the channel at the alluvial fan apex.

When compared to previous simulations carried out under the same assumptions, the presence of the log jamming tends to increase the overflow towards the left bank of the channel. The location of this overflow is not fundamentally modified. Consequently, this plausible phenomenon tends to increase the volume of material driven to the left part of the alluvial fan and increase the risk in this sector, notably in the camp site area. This phenomenon can explain the numerous old flow traces still visible in this area.

A PROTECTION LEVEE AGAINST OVERFLOW: DESIGN ELEMENTS

COMPARING TWO POSSIBLE ORIENTATIONS OF THE PROTECTION LEVEE

The most vulnerable area (the camp site) is located on the left part of the alluvial fan. Consequently, the RTM service, in charge of controlling the torrent, considered of building a protection levee within a more general protection strategy. The objective of the levee, located at the apex of the alluvial fan where the flow tends to diverge, is to eliminate the overflow risk towards the left bank. We examine two orientations of the levee. The first orientation (type A levee in Figure 8) presents a 45° angle with the upstream channel and a second one (type B levee in Fig. 8) presents a 15-20° angle with the upstream channel. The following assumptions are considered for the comparison of these orientations: an average viscosity ($\tau_c/\rho = 1.0$ $m^2/$

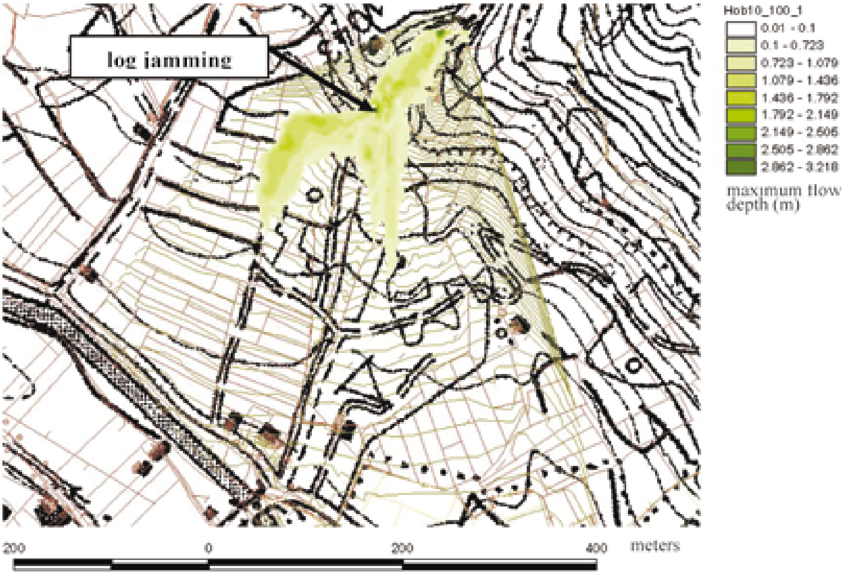

Fig. 7 - Maximum simulated flow depth for a debris-flow volume of 10 000 m^3, a peak discharge of 100 m^3/s and a $\tau_c/\rho = 1.0$ m^2/s^2 ratio assuming log jamming of the stream at the apex of the alluvial fan

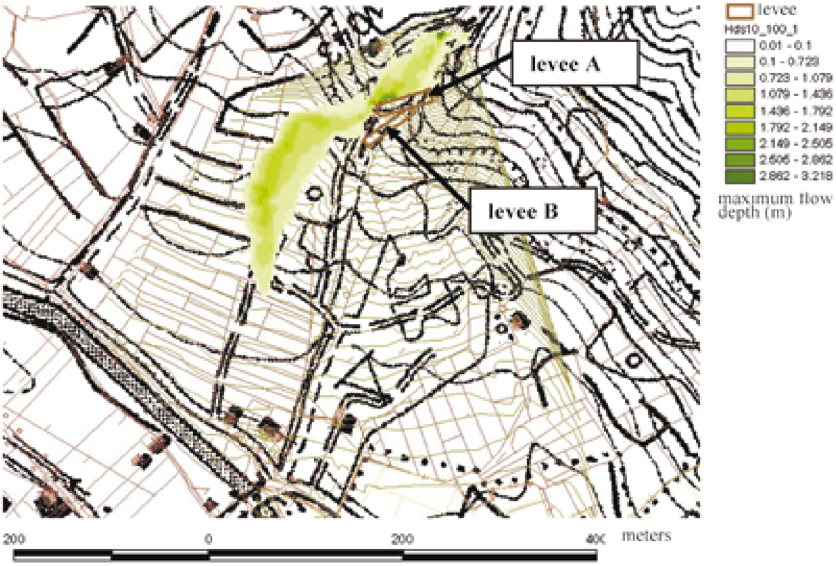

Fig. 8 - Maximum simulated flow depth for a debris-flow volume of 10 000 m^3, a peak discharge of 100 m^3/s and a τ_c/ρ = 1.0 m^2/s^2 ratio assuming the presence of a protection levee showing a 45° angle with the channel axis

s^2), a volume of 10 000 m^3 and a peak discharge of 100 m^3/s. The aim of this comparison is to establish which of these orientations is best in terms of efficiency and then in terms of the required dimensions. Levees are numerically considered to be cells impervious to any flow.

Simulations show that the hydraulic behavior of the type B levee is better than the type A. In terms of flow extension, both types of have similar effects. However, flow depths and velocities in the vicinity of the type B levee are lower than for the type A levee (maximum flow depth: 2.8 m and maximum velocity: 5.6 m/s for type A and maximum flow depth: 1.5 m and maximum velocity: 1.0 m/s for type B). This presents two advantages in favor of type B: for similar efficiency, the type B levee can be lower and the risk of impact and erosion is also lower because of a lower velocity. Furthermore, the type A levee creates a bottle-neck for the channel flows immediately downstream of the levee, producing local acceleration of the flows (maximum local velocity under the assumptions considered: 8.2 m/s). The type B levee does not generate this bottle-neck effect and thus no local acceleration of the flow (maximum local velocity under considered assumptions: 5.3 m/s). A type B levee is therefore preferred.

ANALYSIS OF FLOW SIMULATIONS IN THE VICINITY OF THE LEVEE

Only a type B protection levee is considered here: the simulations have two objectives:

- analyze the flow in the vicinity of the levee in order to determine the maximum flow depth and velocity under several assumptions.
- analyze the consequences of the presence of the levee in terms of risks on the alluvial fan.

To do this, we consider:

- one scenario based upon the assumption of a fluid material and a high discharge value. Simulations carried out under this assumption will provide information on maximum flow velocities likely to occur in the vicinity of the levee.
- one scenario based upon the assumption of a viscous material and a high discharge value. Simulations carried out under this assumption will provide information on maximum flow depths likely to occur in the vicinity of the levee (as well as elements for the future design of the levee).
- two scenarios based upon the assumption of an exceptionally rare volume and a high discharge value. Simulations carried out under these assumptions will provide information on the maximum flow extension in presence of the levee.

The volume has a very limited influence on the flow features in the vicinity of the levee. The assumption leading to the maximum velocity (peak discharge

Fig. 9 - Maximum simulated flow velocity for a debris-flow volume of 10 000 m^3, a peak discharge of 180 m^3/s and a $\tau_c/\rho = 0.5$ m^2/s^2 ratio assuming the presence of a protection levee showing a 15° angle with the channel axis

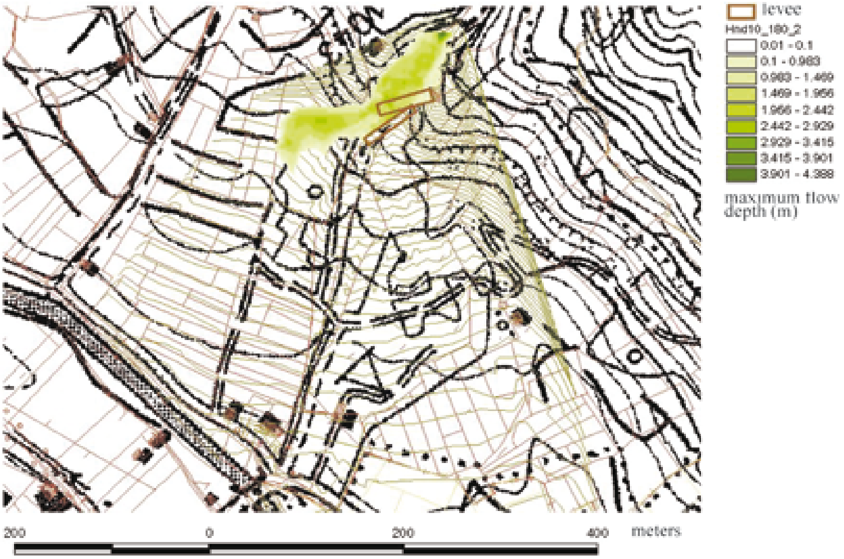

Fig. 10 - Maximum simulated flow depth for a debris-flow volume of 10 000 m^3, a peak discharge of 180 m^3/s and a $\tau_c/\rho = 2.0$ m^2/s^2 ratio assuming the presence of a protection levee showing a 15° angle with the channel axis

of 180 m^3/s and a fluid material with $\tau_c/\rho = 0.5$ m^2/s^2) gives simulated velocities on the order of 10 m/s and very locally 13 m/s in the vicinity of the downstream edge of the levee (Fig. 9). The assumption leading to the maximum flow depth (peak discharge of 180 m^3/s and a fluid material with $\tau_c/\rho = 2.0$ m^2/s^2) gives simulated flow depths on the order of 2.5 m in the vicinity of the levee (Fig. 10). Even though these figures should be considered with caution, they can contribute to the future design of the levee.

CONSEQUENCES OF THE PRESENCE OF THE LEVEE

The levee, driving all the flow volume towards the right bank of the channel, intensifies the flows and subsequent extensions on this part of the al-

Fig. 11 - Maximum simulated flow depth for a debris-flow volume of 25 000 m^3, a peak discharge of 180 m^3/s and a τ_c/ρ = 1.0 m^2/s^2 ratio assuming the presence of a protection levee showing a 15° angle with the channel axis

luvial fan (Fig. 11), notably on the road and two houses located downstream. However, the houses are potentially hit in only one of the two scenarios considered with a volume of 25 000 m^3 and a τ_c/ρ = 0.5 m^2/s^2 ratio. This scenario has a very low probability of occurrence.

CONCLUSION

In this study of debris-flow hazards on the Rioulong torrent alluvial fan, we first present a susceptibility analysis of the torrent catchment for producing debris flows. This analysis was a necessary step prior to the numerical modeling for the scenario-based analysis employed in the second phase of this study. This analysis made it possible to define flow volume and discharge scenarios and to assign a qualitative probability of occurrence. In conjunction with the assumptions of flow rheology, a complete set of flood scenarios was developed.

Flow simulation in this scenario-based approach is of particular interest, as the alluvial-fan area affected by debris-flow hazards can be predicted. It also provides practical information on the design of a protection levee, including guidelines on the levee's orientation and dimensions based on modeled maximum flow depths and velocity and on evaluation of the potential changes to the debris-flow hazard area on the alluvial fan due to the presence of the levee.

This scenario-based approach, as applied to the Rioulong torrent, provides a simple method to assess the variability of debris-flow hazards on an alluvial fan without the costs of more rigorous approaches. Such rigorous approaches do exist, however they all require the assessment of statistical properties for model input parameters which is difficult to achieve in practice.

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