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DEVELOPMENT OF PRELIMINARY ASSESSMENT TOOLS TO EVALUATE DEBRIS FLOW HAZARD

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ABSTRACT

With the objective of providing guidance for an early detection of phenomena potentially giving raise to Debris Flow, one of the main topics is the preliminary identification of areas at risk. In case of early warning a coarser identification of areas at risk should be sufficient. In this perspective, the hazard of phenomena, as component of risk, can be estimated in a simplified way. In the framework of the IMPRINTS European Research Project (FP7), a toolbox for fast assessment of debris flow hazard has been developed. The aim of this toolbox is to implement different existing models inside a common package useful for a fast evaluation of potential hazard. The identification of hazard is performed by different levels of accuracy, depending on the availability of input data. As an example, the result could be achieved by a rough handling of topographical data but could be improved in quality by adding geological and hydrological data. Both the initiation and propagation of the debris flow are modelled. For this study, the methodology has been applied in a catchment located in the North East of Spain.

Key words: debris flow, hazard assessment, run out, shallow landslide

INTRODUCTION

Concerning the hazard, usually two types of assessments can be distinguished: studies at regional scale and studies at local scale. Debris flow hazard assessments at regional scale generally imply a Geographic Information System (GIS), in combination with statistical analysis (e.g., Mark *et alii*, 1995) simple physical based and dynamic approaches (e.g., Iverson *et alii*., 1998; Guzzetti *et alii*, 1999). Detailed studies require numerical models and comprehensive field work to determine the hazard in the debris flow deposition areas.

Focusing on hazard assessment at regional scale the identification of prone areas is substantially different from the mapping that is usually performed by the basin authority in order to give guidance for the plans of urban development and, in general, for the management of the territories. Actually, in case of early warning, a comparatively coarser identification of the areas at risk can be sufficient. In this perspective the hazard, as a component of risk, may be estimated in a simplified way and it will be the topic of the present study.

The hazard is defined as a combination of event intensity and its probability of occurrence. Therefore, in order to construct a hazard map it is necessary to estimate, for each elementary portion of the area examined, the intensity of possible events and the corresponding event probability.

The intensity of a debris flow is defined as its ability to cause damage and is generally estimated through the impact energy of the flow against an obstacle, which depends on the characteristics of flow depth and velocity (Rickenmann, 2005).

This document proposes a preliminary methodology to evaluate the hazard due to debris flow triggered by shallow landslides and his propagation through the paths

Different methodologies are selected in order to define a "multilevel approach" to the problem, depending on the data input availability and on the detail required by the analysis.

The methodologies selected are applied on the upper part of the basin of Llobregat River in the North East and some preliminary results are presented. The validation of the models is still a work in progress..

DEBRIS FLOW HAZARD ASSESSMENT METHODOLOGIES

As the hazard assessment at regional scale is concerning a wide area it is necessary to find a general and common methodology able to describe the phenomenon in a wide range of cases. A flow chart of methodology is described in Fig. 1.

As said before, the hazard is given by the combination of intensity and probability of occurrence. For the debris flows triggered by rainfall of particular intensity and duration, the probability of occurrence of an event may be related to the return period of the triggering rainfall. The connection between the rainfall and its effects can be reconstructed by the simulation of the different processes, which take place during the spatial and temporal evolution of the flow from its mobilization to its stop. In this sense we can distinguish two distinct phases: the first aims to estimate the volume potentially mobilized by a given precipitation, with an assigned return period, (initiation models), the second has the objective to estimate the area of invasion and the resulting intensity (propagation models)

It is of crucial importance to extract the areas in which potential debris flow triggering is expected in order to perform the simulations only in those areas and save computational time. Past studies have investigated the occurrence of debris flows and reported the area of the catchments affected by various debris flows events (Stock & Dietrich, 2003; Marchi & D'Agostino, 2004). From those studies seem to emerge a threshold value for the area of catchments known to have experienced debris flows. Scheidl (2009) proposed a threshold value of 25 km^2. In his geomorphologic study of Spanish debris flows, Chevalier *et alii* (2010) report that many of the Strahler's second-order catchments, where debris flows occurred, has a similar maximum value.

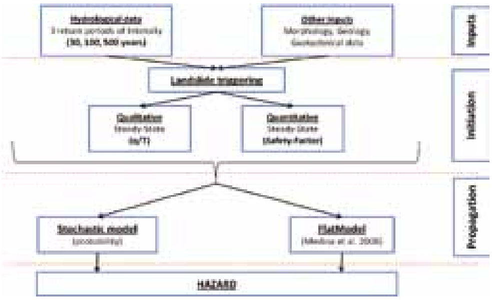


Fig. 1 - debris flow hazard assessment methodology's flow chart

An important pre-process is the application of the typical "fillsinks" algorithm to the DEM in order to fill the natural depressions that could influence seriously the execution of the subsequent steps. Because of that lakes and dams are removed from the DEM, making those areas as "no data". It means that in case of the presence of dams the method is not valid. A "fillsinks" algorithm is included in the methodology implemented..

INITIATION MODELS

The initiation of debris flow is possible by means of various mechanisms (Coussot *et alii*, 1996; Hungr *et alii,* 2001) but the mobilization from rainfall-triggered landslides (Iverson *et alii,* 1997) seems to be the most common process.

Starting from that, it has been decided to include in that framework a model that describes this common behaviour of debris flow initiation.

These movements are triggered during intense rainfall when high pore pressure is produced inside a loose sediment layer, thus reducing the factor of safety. This behaviour is described by the typical Coulomb failure approach in the infinite slope stability model (Iverson *et alii,* 1997)

The water pore pressure may be estimated, in a simplified way, by assuming that steady-state conditions are reached after a rainfall having constant intensity and indefinite duration (Dietrich *et alii*, 1995). If the assumption of complete saturated material (water table coincident with the free surface) is also made, a very simple relation between rainfall and soil transmissivity may be derived (Dietrich *et alii*, 1995) for each cell of the DEM:

$$\frac{q}{T}=\frac{\sin\alpha}{(a/b)}\left(\left(\frac{c'}{\rho_w gz\cos^2\alpha\tan\varphi}\right)+\left(\frac{\rho_s}{\rho_w}\right)\left(1-\frac{\tan\alpha}{\tan\varphi}\right)\right) \tag{1}$$

where q is the rainfall intensity, T is the soil transmissivity,)α is the slope, a/b is the cumulated area per width of flow, p_w is the density of water, z is the thickness of soil, c' is the soil cohesion,φ is the soil internal friction angle and p_s is the saturated bulk density of the soil.

In this extremely simple approach the output of the model will assess only the most prone areas of ruptures and it is not possible to compute the total unstable debris volume. For these reasons this approach is here called "*qualitative-steady state*".

Removing the assumption of complete saturated layer, the ratio between the water table depth *h* and the thickness of the soil layer *z,* may be derived by equation [2] (DIETRICH *et alii*, 1995).

$$\frac{h}{z}=\frac{q(t)}{T}\frac{a}{b}\frac{1}{\sin\alpha} \tag{2}$$

The safety factor F_s may be then computed as follows:

$$F_s=\frac{c'+z\gamma_w\cos^2\alpha-\tan\varphi}{z\gamma_s\sin\alpha\cos\alpha}-\frac{\gamma_w}{\gamma_s}\frac{\tan\varphi}{\tan\alpha}\left(\frac{h}{z}\right) \tag{3}$$

where γ_s is the specific weight of saturated soil, 1w is the specific weight of water.

Such equation is valid in the hypothesis of constant intensity and indefinite duration rainfall. Consequently the corresponding return period is not defined. To overcome this difficulty, the duration of the rainfall event is fixed equal to the time necessary for the soil to reach to steady state condition. A simple relation to evaluate such interval time is proposed in equation [4] (PAPA *et alii*, 2010):

$$\tau_s=\frac{1}{n}\sum_{i=1}^{n}\frac{a_i}{b_i}\frac{\theta_{s_i}}{K_i\cos\alpha_i\sin\alpha_i} \tag{4}$$

where n is the basin cells number, τ_s is the time to saturation, τ_s is the water content at saturation.

In that case prone areas and volume will be assessed and the model proposed is named "*quantitative-steady state*".

Once the duration time of rainfall (τ_s) is assessed, the rainfall intensity for the different return periods is derived by the Intensity- Duration-Frequency curves (IDF). An example of those curves is given in Figure 2.

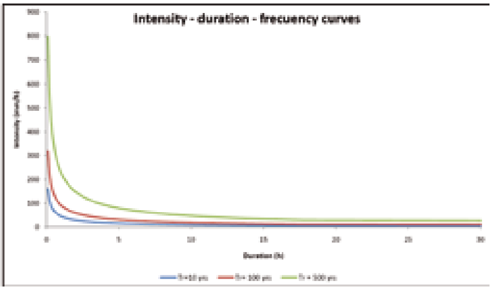


Fig 2 - IDF curves in the Upper Llobregat Basin in Catalonia, Spain

PROPAGATION MODELS

A stochastic model and a 2D model of propagation are implemented.

The stochastic model consists in a flow routing algorithm incorporated into a random walk to generate trajectories of debris flow. GAMMA (1999) & HÜRLIMANN *et alii* (2008) combined a D8 flow routing algorithm (O'CALLAGHAN & MARK, 1984) with Montecarlo and random walk theory. The method was successfully applied in the European Alps and the Spanish Pyrenees catchments. The model used here is a modification of the previous one with the incorporation of local flow velocity computation and a stopping mechanism

Starting from initiation points evaluated with methods previously described, that procedure permits to obtain a flow path of propagation for each point, and subsequently n_{iter} flow trajectories were calculated. Finally the probability P_{xy}, was computed for each cell of the DEM using the following equation.

$$P_{xy}=\frac{n_{afect}}{n_{iter}} \tag{5}$$

where n_{afect} is the number of debris-flow trajectories that invaded a cell. The output of this method is a map containing information on the probability of each cell of the DEM to be affected by a future debris flow. The result depends strongly on the DEM resolution and on the number of iterations, which is recommended to be set to 10^4 (HÜRLIMANN *et alii*, 2008)

. Computation of flow velocity is achieved applying the Voellmy Fluid Flow Rheology for Granular Debris Flow (1955):

$$\frac{1}{2}\frac{dv^2}{ds} = g(\sin\alpha - \mu_m \cos\alpha) - \frac{v^2}{k} \tag{6}$$

where v is velocity of the mixture, s is the flow path line, μ_m is the sliding friction coefficient, k is the "turbulence coefficient, also called "mass to drag ratio". μ_m and k should be defined by backanalysis, but typical values can be settled.

The stopping mechanism of the routing is assessed by the following relationship between the reach angle and the total debris flow volume (Corominas, 1996):

$$\tan\beta = H/L_{\max} = 0.97V^{-0.105} \tag{7}$$

where β is the reach angle, H is the gradient between centre of mass of landslide and fan, *Lmax* is the travel distance and V is the volume in m^3 of total amount of mobilized sediment.

This volume may be is estimated trough the initiation model introduced above. In Figure 3 the variables involved in equation 7 are described

That method is extremely simple and has a very short computing time, but the result is not deterministic and does not includes the depth of deposit. However the velocity, useful for hazard assessment, is estimated.

It is important to note that this methodology is valid only in a natural environment, where the anthropogenic modification of land is considered low

The 2D model proposed here is the FLATModel (Medina *et alii*, 2008). FLATModel is a two-dimensional finite volume code that has been validated with analytical, experimental and real test cases. It is a complete model that include basal entrainment of sediments, stop and go phenomenon, dynamical correction of the evolution of fan slope and different fluid models including laminar rheologies (Bingham, Herschel-Bulkley), granular flows (Coulomb, Voellmy) and turbulent ones (Manning, Chezy). The model is based on the shallow flow hypothesis and is depth integrated. A bi-dimensional approach is used for momentum conservation..

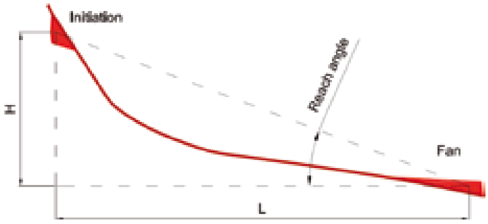


Fig. 3 - scheme of a debris flow reach angle and variables involved

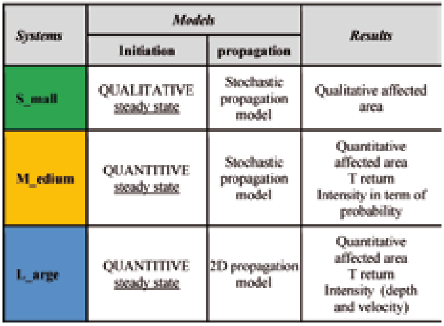
The main characteristics of the model are:

- monophasic flow is considered
- constant density flow is considered
- no pore pressure effect is considered
- Terrain curvatures are neglected
- Steep slopes are considered
- Multiple rheologies are implemented

Apart from rheological parameters (from backanalysis), the necessary input data are two raster data sets including a DEM and a raster defining the initial extension and volume of the debris flow. The accuracy of calibration of the rheological parameters and the computational time requirement represent the major drawback of this technique, but the outputs can be directly used to generate intensity maps, since velocity and flow depth are simulated within the entire study area. The computational cost also increases considerably with the number of initiation points..

MULTILEVEL APPROACH

Three levels of models system characterize the multilevel approach: S_mall, M_edium, L_arge (see Tab. 1). Obviously the quality of output depends on the system applied: detailed input data allow for the use of more complex models and give better results. The three systems proposed (S_mall, M_edium and L_arge) are composed by two models, an initiation model and a propagation model.



Systems	*Models*		*Results*
	Initiation	**propagation**	
S_mall	QUALITATIVE steady state	Stochastic propagation model	Qualitative affected area
M_edium	QUANTITIVE steady state	Stochastic propagation model	Quantitative affected area T return Intensity in term of probability
L_arge	QUANTITIVE steady state	2D propagation model	Quantitative affected area T return Intensity (depth and velocity)

Tab. 1 - Multilevel approach at debris flow hazard assessment.

The S_mall system is suitable for preliminary risk analysis or when the advanced systems cannot be applied, for the width of study area and for the lack of input data. The compilation of input data files and the running of the system are very fast. The assessment of possible unstable areas is performed by the infinite slope stability model in which the water pore pressure is estimated, in a simplified way, by assuming steady-state groundwater flow (Dietrich *et alii*, 1995) and complete saturation of the soil. In this extremely simplified approach only the morphological description of the basin is needed and the result does not depend on rainfall data. As a consequence it is not possible to define a return period for the event. The given result is simply a qualitative map of the area most prone to debris flow initiation

The propagation model is performed by the stochastic approach. The result of the S_mall system is a map with qualitative assessment of classes of debris flow intensity corresponding to hypothetical scenarios.

The complexity increases in the M_edium system in which the water pressures are computed depending on a given rainfall in the hypothesis of steady-state groundwater flow (Dietrich *et alii*, 1995). With the proposed method for the estimation of rainfall duration it is possible to obtain a map of instable area with given return period..

As the S_mall system, the M_edium implements a stochastic propagation model. The result of the M_edium system is a map with qualitative assessment of classes of debris flow intensity corresponding to fixed return periods.

The L_arge system is the most complex computational level. The initiation model is the same as in the M_edium system while the propagation model is a two-dimensional shallow water flow model (FLAT-Model). In order to run such model it is necessary to estimate the rheological properties of solid-liquid mixture in motion. The results of the computation are the flow depth and velocity for each numerical cell of the affected area. The result of the L_arge system is a map with quantitative assessment of classes of debris flow intensity corresponding to fixed return periods.

The parameters required for each proposed system are shown in the Tab. 2.

DEM	*S*	*M*	*L*
ϕ, *c'* homogeneous	*S*		
ϕ,*c'*,*K* non homogeneous		*M*	*L*
z homogeneus	*S*		
z non homogeneous		*M*	*L*
Rheology			*L*
q constant, *Dt* infinite	*S*		
q constant, *Dt* finite		*M*	*L*

Tab. 2 - Data input required by the different proposed methods. DEM, Digital Elevation Model; „ internal friction angle; c', cohesion; K, hydraulic conductivity; z, soil thickness; q, rainfall intensity; D, rainfall duration

HAZARD ASSESSMENT

In that case hazard is assessed by the probability that a debris flow can invade a certain area. The probability is given by the combination of the initiation and the propagation models. Depending on the model adopted, the hazard is defined as below.

HAZARD IN THE S_MALL MODEL

A qualitative steady state stability model is adopted as in equations 1 in which the ratio q/T is defined. Taking in account the works of Dietrich (1995), Guzzetti (1999) and Carrara (2008), three thresholds, in term of logarithm, are defined as in Tab. 3. It has to be remarked that values of Log(q/T)= 1 are possible due to particular local values and truncation errors. Such value has to be neglected.

After the definition of the three zones of landslides initiation, the propagation is carried out for each zone and the invaded areas are assigned the same level of hazard defined in Tab. 3.

HAZARD IN THE M_EDIUM MODEL

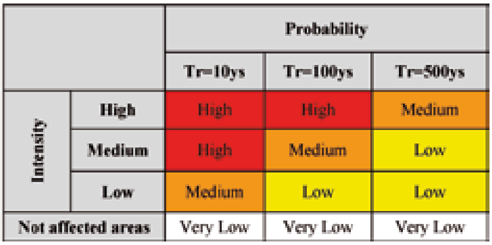
The quantitative steady state stability model is adopted as in equations 3, where the safety factor Fs is

Hazard	*Log(q/T)*
High	< -3.4
Medium	$< -2.9; \geq -3.4$
Low	$< -2.0; \geq -2.9$

Tab. 3 - Definition of hazard in the S_mal model

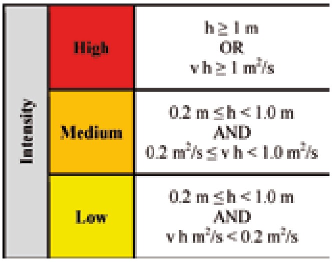
Hazard	*Tr(years)*	*Fs*
High	10	<1
Medium	100	<1
Low	500	<1

Tab. 4 - Definition of hazard in the M_edium model



		Probability		
		Tr=10ys	Tr=100ys	Tr=500ys
Intensity	High	High	High	Medium
	Medium	High	Medium	Low
	Low	Medium	Low	Low
Not affected areas		Very Low	Very Low	Very Low

Tab. 5. - Definition of hazard in the L_arge model



Intensity	High	$h \geq 1$ m OR $v\,h \geq 1$ m^2/s
	Medium	0.2 m $\leq h < 1.0$ m AND 0.2 m^2/s $\leq v\,h < 1.0$ m^2/s
	Low	0.2 m $\leq h < 1.0$ m AND $v\,h$ m^2/s < 0.2 m^2/s

Tab. 6 - Definition of inensity in the L_arge model (Garcia et alii, 2005)

computed for each return period.

When Fs<1, the instability is recognized. In Tab. 4 the hazard is defined depending on the return period.

HAZARD IN THE L_ARGE MODEL

In the large model the classical definition of hazard could be done and is explained in Tab. 5. The definition of the intensity is done in Tab. 6 following Garcia *et alii* (2005).

IMPLEMENTATION OF ALGORITMS

The proposed methodologies and algorithms are implemented using the Java language, and declared as GNU/GPL open source code. Most of the algorithms require basic common Geographic Information System (GIS) tools (i.e. slope, curvature, aspect). These tools are provided through the SEXTANTE GIS library (Gimenez & Olaya, 2008). Other new libraries are implemented by GITS team to carry out the presented job. Algorithms themselves are included inside SEXTANTE to be available to extern applications. Notice that SEXTANTE is not a GIS but a library that could be accessed from different open source as well as commercial GIS. A command line application to use SEXTANTE library without GIS is developed in that study. The data exchange formats of information are ESRI ASCII for raster and ESRI shapefile for vectorial.

Fig. 4 - Upper Llobregat basin location

APPLICATION OF METHODOLOGIES

The methodologies are applied in the Upper part of Llobregat River Basin in the region of Cataluña (Spain). The outlet is located immediately upstream of the Baells Reservoir in the municipality of Berga. The catchment considered has an area of about 350 km

A digital elevation model (DEM) of 30x30 meters of resolution is used as the best DEM that covers all the world is a 30x30 meters, coming from the database of ASTER_GDEM (2008).

S_MALL MODEL APPLICATION

Here a unique value of cohesion, thickness and internal friction angle is chosen:

- c' = 770 Pa
- z = 1 m
- Z = φ.48 rad

The saturated bulk density chosen for the calculation is [= 1700 kg/m^3.

It must be emphasized that the model could work even without any value of cohesion and thickness, but only with the internal friction angle. In that case the internal friction angle should be increased till 450 to counteract the absence of cohesion (Dietrich *at alii*, 1994).

In Figure 5.a, it is showed the result after the qualitative steady state model simulation for the slope stability. It is a common result that that technique is overestimating zones of failure (as also reported in previous studies as Carrara *et alii*, 2008). In Figure 5.b, it is shown the result after running the

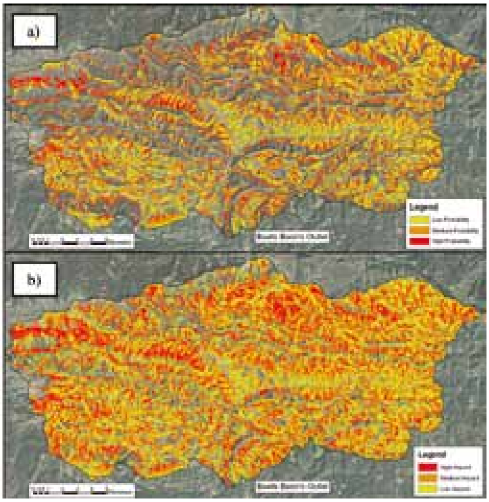


Fig. 5 - S_mall model application. a) Result of the qualitative steady state initiation model; b) hazard after the propagation with the stochastic model

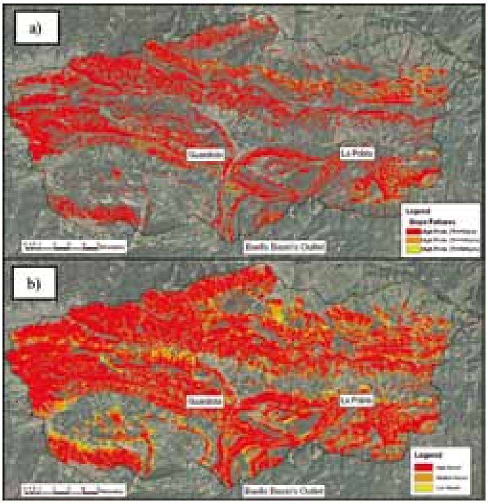


Fig. 6 - M_edium model application. a) Result of the quantitative steady state initiation model; b) hazard after propagation with the stochastic model

stochastic model of propagation. The result is given qualitatively and not in term of return period..

M_EDIUM MODEL APPLICATION

In that case spatial distributed values of cohesion, thickness, permeability and internal friction angle are estimated from geological maps. In that region no soil map is available and a reclassification of a geological map has been done. The use of geotechnical parameters coming from geology maps is not appropriate for the methodologies presented (Van Westen, 2008). In that case, the use of such maps shows to influence the results.

The saturated bulk density chosen for the calculation is $\rho = 2200$ kg/m^3.

Figure 6.a illustrates the result after the qualitative steady state model simulation for the slope stability. In Figure 6.b it is shown the result after running the stochastic model of propagation. In that case the result is given in term of return period.

A validation of the model is in progress, but since the results are too much depending on the geotechnical parameters, it would be more interesting to move in a basin where those parameters are well known

L_ARGE MODEL APPLICATION

For that application is decided to work on the catchment of Ensija Creak, a small sub-catchment of Llobregat that is suffering debris flow activity. In that spot the Technical University of Catalonia, thanks to the National Research Project DEBRISCATCH, has installed a monitoring system to study the mass movement and the local weather condition (Hürlimann *et alii*, 2010). In the framework of the same project, also a rather good number of field studies have been done, including the reconnaissance of initiation points, total volume involved and depositional area through standard studies as well as dendrochronology studies on affected trees. The event of 2006 is taken in account for the present simulation (Fig. 7)

Starting from de initiation model, the initiation points are selected consistently with field studies..

The propagation is performed with the FLAT-Model that gives as outputs the velocity and the water depth of the flow..

In particular here are reported the maximum velocity (Fig. 8) and depth (Fig. 9) over the simulation. The volume of initiation is estimated to be 2000 m3. The Voellmy rheology for granular flow is used and the rheological parameters are estimated by back analysis and settled as below:

- dry friction coefficient: $\mu = 0.25$
- turbulent friction term: $C = 10$ m$^{0.5}$/s.

The analysis of intensity of a single return period is reported asan example in Figure 10.

The model's agreement with the depositional area witnessed on the field is satisfactory, even if a bifurcation of flow at the end of the fan is registered. That trend seems to be possible in the future, due to the reconnaissance of a new flooded path emphasized by recent events.

Fig. 7 - Initiation and depositional areas of debris flow for the event of 2006 in the Ensija's Catchment

Fig. 8 - FLATModel simulation result in the Ensija's Catchment. Maximum velocity recorded during the simulation

Fig. 9 - FLATModel simulation result in the Ensija's Catchment. Maximum depth recorded during the simulation

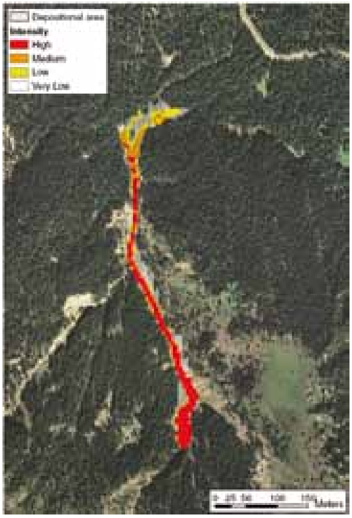


Fig. 10 - Result of the intensity analysis using the output of FLATModel

DISCUSSION AND CONCLUDING REMARKS

Different methodologies have been proposed for the evaluation and determination of risk areas for debris flow and flash floods. Methodologies of different level of accuracy have been developed, requiring different level of elaboration, manual work and data accuracy. The project has shown that hazard assessment delineation is a large computational process seasoned with an important manual effort for the user. The approaches proposed in this study allow the users to choose the most appropriate method according to their data and needs. A toolbox has been developed to facilitate users in the application of the methodologies for their test beds.

Through the project, a stepwise prescription for obtaining hazard maps for debris flow has been provided: The first step of the process is the assessment of event intensity and consequent hazard; it requires mathematical and numerical modelling of the debris flow.

A multilevel approach is defined with increasing complexity, data request and computational effort.

Obviously the quality of the output depends on data input availability.

Resuming, the three levels of system are, in order of increasing complexity:

- The S_mall system
- The M_edium system
- The L_arge system

The choice of the proper system may be done depending on the requested result quality, the size of the study area and the computational effort; the simple models (S_mall and M_edium) well meet requirements of early warning system, while the complex models, like the L_arge, are more useful for the compilation of detailed hazard maps to be used for territorial planning

As the validation of the methodologies used is in progress, the results here shown are only preliminary. The S_mall model is known from previous similar studies, which is overestimating the zone of failure (Carrara *et alii*., 2008) due to the low accuracy of the initiation model; while for the M_edium model, an accurate study has to be done to validate the methodology. The main issue, in that case, is the lack of data in the current basin. As discussed before, the results are too much depending on the geotechnical parameters and it would be more interesting to move in a basin where those parameters are known.

Concerning the L_arge model, some studies and validation cases are available (i.e. Medina *et alii*, 2008, Hürlimann *et alii*, 2008) and the case of studies presented, as reported below, show a good agreement between the model and the field studies.

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