The Assessment Of Mudflow Peak Discharge Through A Monte Carlo Simulation Method

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ABSTRACT

The present study introduces a probabilistic approach able to estimate the mudflow peak discharge through the use of a Monte Carlo simulation method. In a classical deterministic approach, for a specific catchment, the parameters involved in estimation of the peak flow (topographical, hydrological parameters) are assumed to be known. As a result, in such approaches, the only source of uncertainty in evaluation of the peak discharge is due to rainfall intensity and frequency estimation. In this work, the standard Monte Carlo simulation is used in order to propagate also the unceratinties in various parameters related to hydrographic basin modelling and to obtain a probability distribution for the peak-discharge flow for a given return period. As a test case, the peak discharge of a mudflow in the basin of the Mandrizzo River, located in the town of Cava dei Tirreni in Southern Italy, is evaluated.

INTRODUCTION

Due to its geological and morphological configuration, almost the entire Italian territory is exposed to hydrogeological risk. This situation is further aggravated by human activities who are responsible for continuous changes to the territory. These changes, on one hand increase the likelihood of occurring hydrogeologic phenomena, and, on the other hand, increase the exposure to risk by concentrating assets and people in susceptible areas. The catastrophic disasters that have happened recently in Italy, unfortunately confirme the high level of hydrogeological risk in this country.

A census made by the GNDCI (National Defence Group from Hydrological Disasters) of the National Research Council (CNR) shows that 59.5% of 8102 Italian towns (about 75% of the national territory) have gone through at least once a landslide, 55.1% (71% of the territory) at least one flood, and 79.9% (91% of the territory) have gone through a landslide or a flooding event (CNR-GNDCI, 1998).

The mudslides, may be considered as intermediate phenomena between landslides and floods. Like landslides, mudflows have high speed, no visible warning signs, while, like floods, may also cover distances of several miles. Sadly documented by the news reports, the mudflows of 5 and 6 May 1998 affected the towns of Sarno and Quindici with very heavy consequences, (178 destroyed houses, 170 damaged houses, 452 victims). Over the last decades, the River Basin Authorities (in Italy) mapped, almost in a complete manner, the areas suscepitible to flooding and mudslide through the Hydrogeological Plan (PAI). This makes Italy the only country in the world with a national cartography of the delineation of prone areas to hydrogeological risk. With the goal of developing a mitigation plan for the risks arising by mudslides, a fundamental step is to evaluate the peak flow discharge. Methods for the estimation of the discharge of mudflows have been studied in the literature by many authors like Takahashi (1978), Kang (1985), Wang and Chang (1985). However, the proposed methods are based on deterministic concepts and only average values of physical parameters involved in the phenomenon are taken into account.

In fact, the evaluation of the parameters involved in the calculation of the peak discharge for a mudslide, is affected by a certain degree of uncertainty. In this study, using a Monte Carlo simulation method (MCSM), the uncertainties in the variables involved in the phenomenon, are propagated in order to evaluate their influence on the estimation of the peak flow discharge. Finally, the results obtained by applying (MCSM) are compared with those derived by using the deterministic methods.

MUDFLOW PEAK DISCHARGE WITH A MONTE CARLO SIMULATION METHOD (MCSM)

The volumetric sediments concentration in the flow C_v is defined as the ratio between the sediment flow Q_s and the total flow of sediment-water mixture Q_t ($Q_t = Q_s + Q_w$). According to the indications of the National Research Council Committee on Methodologies for Predicting Mud Flows (NRC, 1982), a mudslide occurs when $0.20 < C_v < 0.55$.

The ratio of the peak flow of the mudslide and the peak flow of only the liquid phase can be estimated through the relationship (de Wrachien et al. 2011):

$$\frac{Q_t}{Q_w} = \frac{c_*}{c_* - \left\{S_b + \left(1 - S_b\right) \cdot c_*\right\} \cdot C_v} \tag{1}$$

where c_* is the packing concentration of the solid phase (usually equal to 0.65), C_v is the debris flow concentration and S_b the degree of saturation of the river bed before the debris flow passage. Assuming $S_b = 1$, the expected debris flow discharge could be 6 times the liquid discharge.

The flood peak discharge, Q_w, can be evaluated through the rational formula written in its simplest form:

$$Q_w = \frac{1}{360} \cdot C \cdot I_{dT} \cdot A_m \tag{2}$$

where:

- A_m is the area of the basin (*ha*);
- C is the runoff coefficient, which depends on the properties of the ground, slope, vegetation, etc.
- I_{dT} is the average rainfall intensity (*mm/h*) in the (time) length d and the return period T.

Referring to the project guidelines VAPI Campania (Rossi and Villani 1994):

$$I_{dT} = K_T \cdot I_d \tag{3}$$

where K_T is the variable growth factor as a function of the return period T; I_d is the intensity of precipitation on the length d (the basin critical duration), and that, in accordance with the indications of VAPI, can be determined through:

$$K_T = K_1 + K_2 \cdot \ln T \tag{4}$$

$$I_d = \frac{\mu(I_0)}{\left(1 + \frac{d}{d_c}\right)^{\beta}} \tag{5}$$

with

$$\beta = C_1 - D \cdot z \tag{6}$$

In (4, 5 and 6) K_1 and K_2 are constant within the entire regional territory, respectively equal to 0.456 and 0.11; $\mu(I_0)$, d_c, C_1 and D are constant within individual rainfall homogeneous areas and z is the average height of basin expressed in meters.

In relation (5) the critical duration of the precipitation d was set equal to the time to concentration time t_c (h) of the basin, which is measured as:

$$t_c = \frac{l}{v} + \frac{1}{72} \cdot \frac{L^{1.6}}{H^{0.6}} \tag{7}$$

where:

- l (*km*) is the length of the path that the drop of water must travel to reach the canal (surface flow);
- v (*km/h*) is the speed with which makes this route. In literature the v value is placed in the range 1.08-2.26 *km/h* (Chen et al., 2004);
- L (*km*) is the channel length;
- H (*km*) is the difference of height between the ends of the canal.

Hence, substituting Eqs. (2) to (7) into Eq. (1) :

$$Q_t = \frac{1}{360} \cdot \frac{c_* \cdot C \cdot A_m \cdot (K_1 + K_2 \ln T)}{c_* - \left\{ s_b + (1 - s_b) \cdot c_* \right\} \cdot c_v} \cdot \frac{\mu(I_0)}{\left(1 + \dfrac{\dfrac{l}{v} + \dfrac{1}{72} \cdot \dfrac{L^{1.6}}{H^{0.6}}}{d_c} \right)^{\beta}} \qquad (8)$$

Eq. (8) provides a closed-form relationship for calculating the peak flow of a mudslide related to a given return period *T*. The parameters involved in the calculation of the mudslide discharge in the above equation are generally affected by various sources uncertainity. These uncertainties stem from various sources:

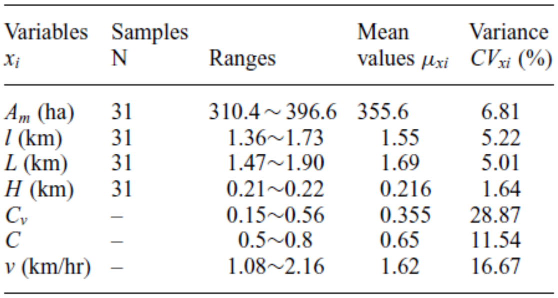
(1) The topographical nature of the parameters involved, (A_m, *l*, *L* and *H)*, that have to be measured from a topographic map of watershed;

(2) The soil properties vary in space and are non-homogeneous over the territory. This contributes to the spatial variability of the overland flow velocity *v* and the runoff coefficient *C*;

(3) There is a high level of uncertainty associated with the estimation of the sediment concentration C_v of debris-mud flow. This is due to fact that C_v depends on the geometrical and mechanical properties of the sediment, its slope and the proportion of sediment versus water in the mudflow.

The uncertainties in the above-mentioned parameters can be represented through Normal (or Lognormal) probability distributions whose first two moments (e.g., mean and standard deviation) are matched with statistical data. For instance, Chen et al. (2004) (table I) report the statistical results of the evaluation of topographical parameters (A_m, *l*, *L* and *H*) at Fushing village in Taiwan, basing on the measured data, independently acquired by 31 graduate students using the same map of watershed. It can be observed that the variance in the parameters *Am*, *l* and *L* are larger than 5%. On the other hand, the variance in *H* is 1.64%. The first two statiscal moments for other parameters, C_v, *C* and *v*, are estimated from the range of possible values owing to the absence of field data.

Table I . Statistical properties of seven parameters at Fushing village (Chen et al. 2004).



Variables x_i	Samples N	Ranges	Mean values μ_{xi}	Variance CV_{xi} (%)
A_m (ha)	31	310.4～396.6	355.6	6.81
l (km)	31	1.36~1.73	1.55	5.22
L (km)	31	1.47~1.90	1.69	5.01
H (km)	31	0.21~0.22	0.216	1.64
C_v	–	0.15~0.56	0.355	28.87
C	–	0.5~0.8	0.65	11.54
v (km/hr)	–	1.08~2.16	1.62	16.67

Monte Carlo simulation is a widely applied method for propagating uceratinties in the components to the system performance level. The MCSM procedure used herein is shown schematically in Figure 1.

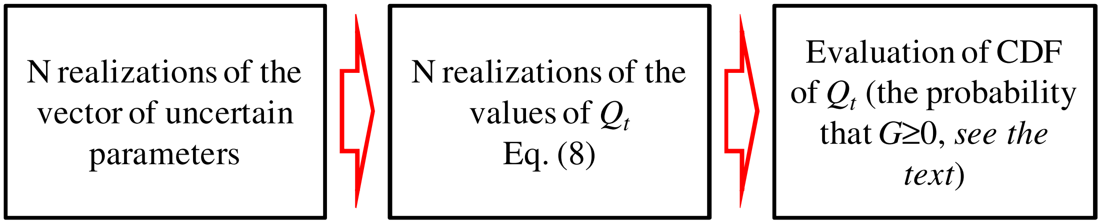


Figure 1. Flow chart of Monte Carlo simulation method.

With the aim of obtaining a probabilistic description of the debris-mud-flow discharge, the following steps were followed:

1. N=1000 random realizations of the vector of uncertain parameters $\mathbf{\Theta}=[C, C_v, A_m, l, v, L, H]$ are obtained based on the marginal property distributions per each parameter, assuming that the uncertain parameters are independent.
2. Per each realization of the vector $\mathbf{\Theta}$, the debris-flow discharge Q_t was calculated from Eq. (8). This process was repeated for all the N Monte Carlo realizations of the vector of unceratin parameters.
3. Given a certain value of Q_d (i.e., a debris-flow design discharge) the probability that the state function G≥0 ($G = Q_d - Q_t$), was calculated based on the N generated values of Q_t. This leads to a Cumulative Distribution Function (CDF) for Q_t.

THE CASE OF STUDY: MANDRIZZO TORRENT CATCHMENT AREA

Geological and geomorphological remarks

The basin of the Mandrizzo torrent covers about 46 hectares across the eastern slopes of the Lattari Mountains, in the municipality of Cava de' Tirreni (SA) (Fig. 2). It is characterized by its high relief (from 830 to 170 m a.s.l.) and steep slopes (up to 45°) in stratified dolomites-carbonates bedrock (Fig. 3B).

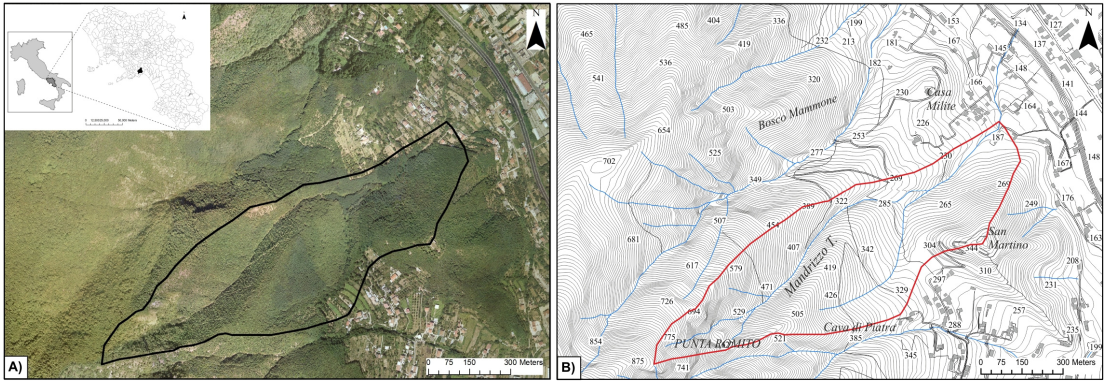


Figure 2. Boundary of the basin in the case-study on ortophotos (A) and on topographic map (B).

The sector is located within the axial and proximal radious of the fall of volcanic ash from the 79 AD Vesuvius eruption. Therefore, the pyroclastic cover (weathered and unweathered ash and pumices) is the result of only one principal eruption. The pyroclastic covers which lie on carbonatic slope may reach thicknesses in the range of 2 m (see Fig. 3B).

The geological and geomophological characteristics of the catchment are very similar to those affected by flow-type landslides (Hungr et al. 2001). Actually the geological context of Peninsula Sorrentina has been frequently affected by flow-type landslides that caused many victims and several damages (Di Crescenzo & Santo, 1999). The mudslide events of Sarno (Sarno, Quindici and Bracigliano) provide a sad testimony of this fact.

Recent studies on flow-type landslides in pyroclastic deposits have been performed in order to identify the potential source areas, magnitude and the main deposition mechanisms for these phenomena.

In order to estimate the the landslide volume, first a (triggering) susceptibility map is drawn by using one of the various methods existing in the literature (heuristic, deterministic and statistical methods). The susceptibility map highlights and delineates the areas most susceptible to flow-type landslide activation (Pareschi et al. 1998, 2002; Aleotti et al. 2000; Calcaterra et al. 2004; Di Crescenzo et al. 2008; Andriola et al. 2009).

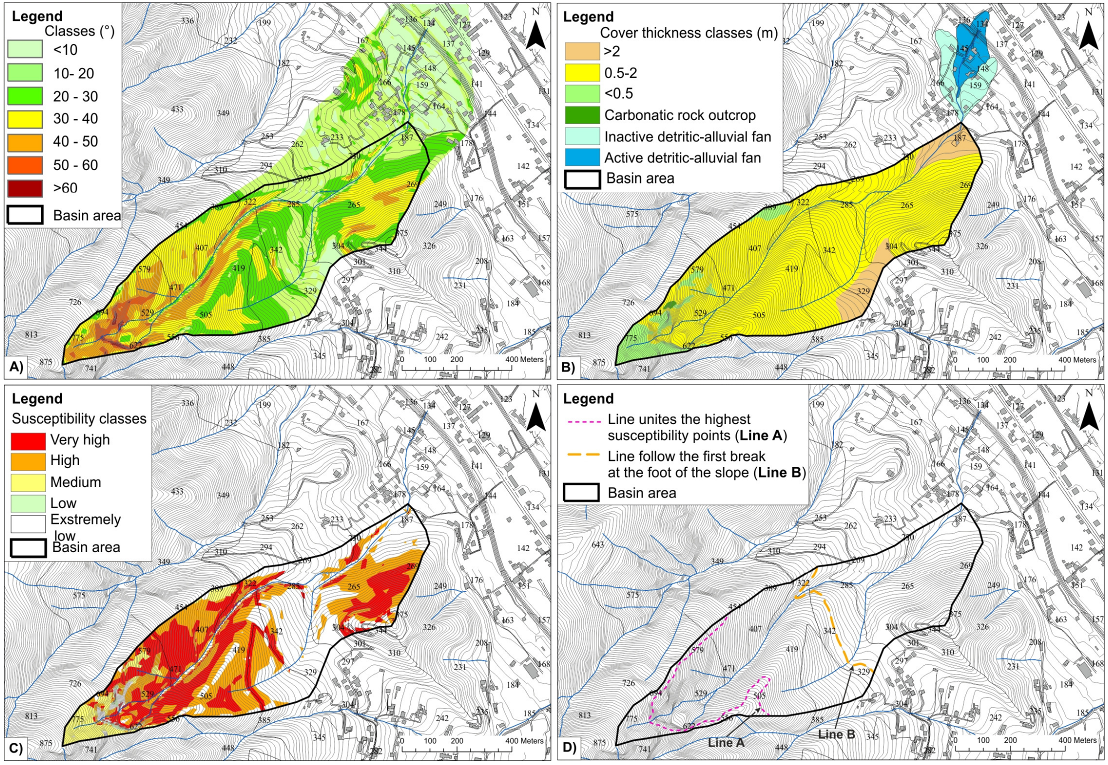


Figure 3. Acclivity map (A); Pyroclastic cover map (B); Triggering susceptibility map (C); Map with the morphometric parameters used to calculate maximum and minimum volume in the Table III (D).

In this work, the triggering susceptibility is evaluated by means of a semiquantitative method (Di Crescenzo et al. 2008; Andriola et al. 2009). This method takes into account some predisposing factors (e.g., slope angle, pyroclastic cover thickness, historical landslides, springs, rocky cliffs, tracks and man-made cuts) weighted by using a statistical approach. The final result is obtained by overlaying various thematic maps by means of a GIS-based application (Fig. 3C).

Once the areas with highest susceptibility values during the trigger phase have been identified, the volume can be estimated. This is done by exploiting the definition of certain morphometric parameters (De Falco et al. 2012).

Estimation of the height H constitutes the first step in this procedure. The height is evaluated as the difference in level between the point on the slope with highest susceptibility (line A in fig. 2D) and the first break at the foot of the slope (line B of fig. 2D). Using a statistical correlation between H and the area of the detachment and erosion-trasport zone (Af), calculated for historical landslides, we can evaluate the area of a potential landslide on a slope. For the hierarchized drainage basins of the carbonates context (such as that slope of interest) this relation is:

$$A_f = (H/10.707)^{1/0.3326} \tag{9}$$

Finally, the potential volumes are estimated by multiplying the area A_f by the minimum MT_m and maximum MT_M thickness of the pyroclastic cover (Table II).

Table II. Evaluation of the minimum and maximum volume values for the slope of the case-study

Altitude of the very high triggering susceptibility (Line A) (m a.s.l.)	Altitude of the first break of slope at the foot of the slope (Line B) (m a.s.l.)	Height of the detachment an erosion-transport zone H (m)	Area of the detachment an erosion-transport zone A (m^2)	Cover thickness min Mt_m (m)	Cover thickness min MT_m (m)	Volume Min (m^3)	Volume Max (m^3)
700	300	400	53000	0.5	1.5	**27000**	**80000**

Probabilistic evaluation of the peak discharge through Monte Carlo simulation

The basin analyzed in the present study, referring to VAPI regionalization, is located in the homogeneous area nr.1 and is characterized by a small average height. As a result, the product $D \cdot Z$ in Eq. (6) can be assumed negligible and β will be (approximately) equal to C. The run-off velocity v is determined in compliance with WSCTC (Water and Soil Conservation Technique Criteria) (Chen et al. 2004). It is assumed that the runoff coefficient varies in the range 0.15-0.30. Note that this range includes the mean values for a basin with woody hedging.

Sediment volume concentration Cv has been estimated considering the deploying potential volume range, computed in the previous section, assuming saturated soil characterized by porosity values between 0.55 and 0.75 (Olivares & Picarelli, 2003; Papa et al., 2008; Cascini et al., 2010). These values are based on the results of analyses conducted in the area of interest and confirmed by the extracted assays in situ.

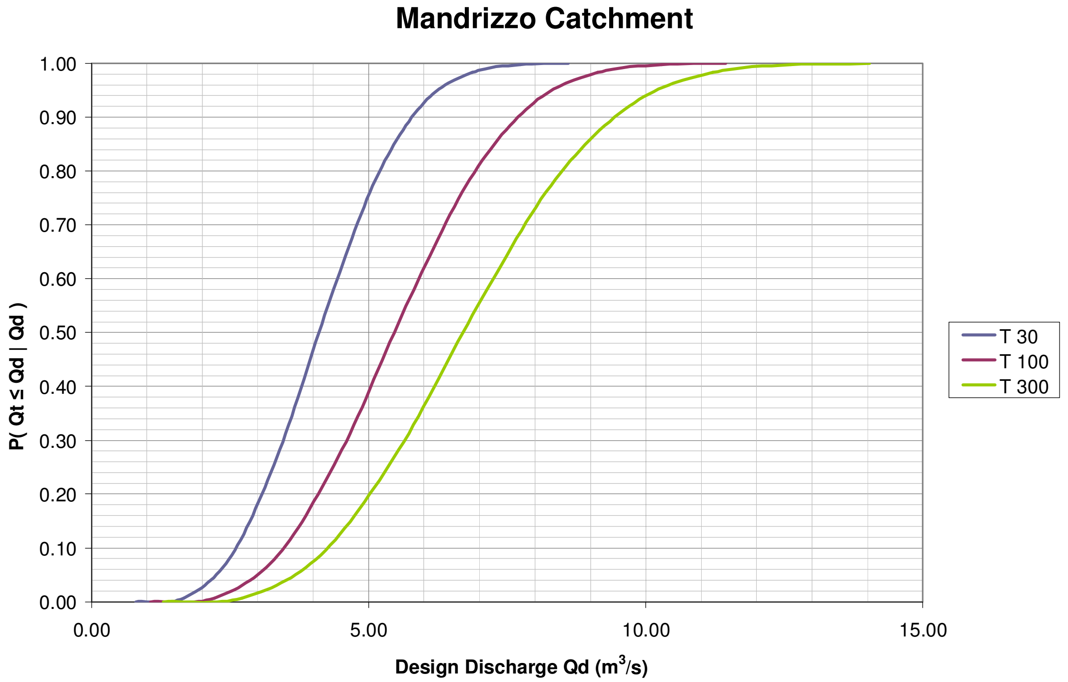
In this specific case, the geometrical parameters *Am*, *l*, *L* and *H* as assumed to be deterministic. This is because they have been estimated using automatic procedures with ArcGis software, considering a digital elevation model (DEM) with 2 m vertical resolutions (map scale 1:2000).

Table III below summarizes the peak discharge model parameters. It should be noted that, apart from the return period, only *Cv*, *C* and *v* have been considered as random variables.

Table III. The peak discharge model parameters

x_i	*N*	*RANGES*	μ_{xi}	CV_{xi}	σ_{xi}	k_1	0.110
C_v	-	0.23-0.44	0.33	0.21	0.07	k_2	0.456
C	-	0.15-0.30	0.22	0.28	0.06	$\mu(I_0)$	77.08
v (*km/h*)	-	1.08-2.16	1.62	0.17	0.27	d_c	0.37
A_m (*ha*)	-	46.30	46.3	-	-	β	0.7995
L (*km*)	-	0.21	0.21	-	-	*T* (*years*)	30; 100; 300
L (*km*)	-	1.48	1.48	-	-	*d* (*h*)	0.16
H (*km*)	-	0.58	0.58	-	-		

The Monte Carlo simulation procedure described in Figure 1 is used to obtain the probability distribution for the peak discharge Q_t related to a given retun period. The resulting cumulative probability distributions are plotted in Figure 4 versus Q_d (the design discharge) for three return periods.



Figure(4). The cumulative distribution function for peak flow discharge, Q_d vs. $P(Q_t \leq Q_d)$ Graph for T = 30, 100, 300 years

CONCLUSIVE REMARKS

This study employs a Monte Carlo simulation-based probabilistic approach in order to estimate the mudflow peak discharge (Chen et al 2004). This probabilistic approach provides a probability distribution for the peak flow discharge as a function of the uncertainties for the model parameters. This method was used to estimate the probability distribution for the peak mudflow for the Mandrizzo Catchment, located in the town of Cava dei Tirreni in Southern Italy. It can be observed that possible values (i.e. with P=0.90) for the peak dishcharge could be more than doubled if compared with those obtained by a classical deterministic approach (P=0.50).

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