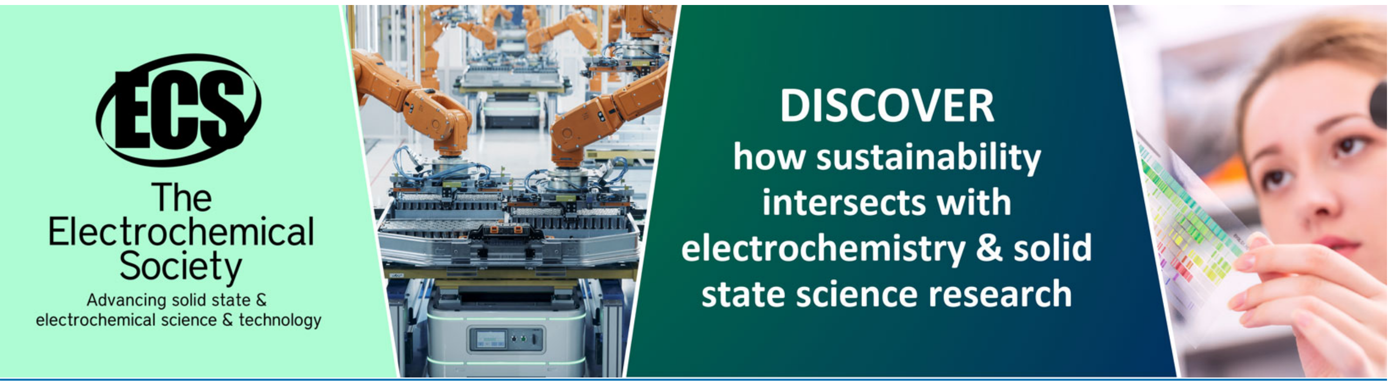
Parametric Study of an Alpine Wet Debris Flow Event (Novalesa, Torino, Italy) Applying The Finite Volume Method (FVM). Comparison with Available Experimental Data



Parametric Study of an Alpine Wet Debris Flow Event (Novalesa, Torino, Italy) Applying The Finite Volume Method (FVM). Comparison with Available Experimental Data

Antonio Pasculli [1], Jacopo Cinosi [1], Laura Turconi [2], Nicola Sciarra [1]

[1] Department of Engineering and Geology, University of G. D'Annunzio, Chieti-Pescara Via dei Vestini, 31, 66100 Chieti (Italy)
[2] CNR-IRPI Strada delle Cacce, 73 Torino (Italy)

a.pasculli@unich.it

Abstract. The Marderello torrent, located at an altitude ranging from 3538m to 900 m above sea level (Novalesa, Cenischia Valley, in Province of Turin) is known for its peculiar capability to generate, with relative frequency, important mud flows and debris (muddy debris flow). Accordingly, the CNR-IRPI (National Research Council) of Turin, since more than twenty years ago, selected this site in order to carry out field observations and measurements campaign. In this paper the muddy-debris flow event, occurred and monitored on July 22, 2016, was considered. The simulation of debris flow phenomena was performed by a 2D Finite Volume Method, solving PDE (Partial Differential Equation) based on the shallow-water approach, through a commercial numerical software. The mathematical-numerical model, beside hydrodynamic model, may also include solid transport and movable river bottom, not explored yet at this stage of the research. First of all, a morphological vectorial model of the basin under study was created and implemented as inputs. The inflow boundary conditions, deriving from the hydrogram consisting of values measured at the monitoring gauge were considered. Several parametric analyses were performed in order to individuate the best values fitting the experimental data concerning the estimated height of the front over time. To this purpose, different available rheological options such as Turbulent-Coulomb, Turbulent-Yield, Turbulent-Coloumb-Yield, and Full Bingham were selected and tested. The comparison with the values collected by the monitored event allowed to define the best values of the parameters to be used. The selected approach and the related model construction can be considered useful and suitable tools in order to study and to simulate this kind of phenomena.

1. Introduction

Monitoring data and survey to debris flows is important for applied research focused to prevention. In the Alps, debris flows occur with a frequency high enough to create serious hazards to human settlements. In 1994 a small creek located in the NW Italian Alps that presented a very high debris flows occurrence was thus selected by the CNR-IRPI of Turin, for the installation of a debris flow monitoring system consisting in a hydro-meteorological network based on 7 rain gauges in different portion of the

IOP Conf. Series: Earth and Environmental Science 221 (2019) 012160 doi:10.1088/1755-1315/221/1/012160

basin [1]. The monitoring equipment was recently extended along an alluvial fan with one ultrasonic water level sensor, two video-cameras, and four vertical geophones. Several debris flow events have occurred so far, with important result about their triggering rainfalls [2]. In particular, the Marderello Torrent basin was monitored by an ultrasonic water level sensor. In order to study this kind of phenomena, the use of simple models, usually, can solve just only few aspects of some problems. On the other hand, the category known as 'complex conceptual models' assumed that most of their parameters could be defined from the physiographic characteristics of the basins. In this field, advanced utilized approaches are based on the balance equations of physics, pursued by the *Computational Fluid Dynamic* (CFD). Nearly, all CFD rely on solving Navier-Stokes flow equations [3], supplemented by experimental laws that define the parameters related to the mass transport of material, the rate of erosion (for instance: [4]), etc. Besides the most common 'grid based methods', another category of approaches was proposed: the mesh-less solution of the differential equation. Among others, *Smoothed Particle Hydrodynamics* (SPH) appears to be promising ([5], [6], among many others). On the other hand, the *Reduced Complexity Models* (RCM), to which, for example, *Cellular Automata* (CA) approach belongs [7], represents an important alternative to the CFD, in particular in order to predict morphological changes, within large area and over relevant time scale (climate evolution as well), both at reach ([8]; [9]) and at catchment scale ([10]). On the other hand, for the study of the phenomena selected in this paper, involving small scale time, a right compromise could be find in approaches capable to simplify CFD technique, like the '*Shallow Water*' approach, implemented into the selected computer code RiverFlow2D [11]. Moreover, the testing of robust simplified CFD approach, including, however, features which allow the study of phenomena like debris flow, production and transport of sediments (*Sediment Transport Module*), erosion of river-bed and river-banks, would be very useful within the framework of the water management, landslides susceptibility maps construction and in the study of morphology variations of a territory. Another important features, also implemented in RiverFlow2D, is the possibility to include frequent wetting and drying phenomena, induced also by rainfall variability, which may lower soil mechanical strength (for example, for pyroclastic soil: [12], [13]), triggering possible landslides occurrences and accordingly, morphological variation of the territory. On the other hand, important phenomena affecting local erosion, like turbulence [14], [15], are missed into the present version of the code.

2. Geographical and geological setting of the site under study (Marderello test case)

The Marderello is a left tributary of the Cenischia valley (near Novalesa, Piedmont region, NW Italian Alps); the small basin (6.61 km^2) has elevations range between 3,538 m (Mt. Rocciamelone peak) and 900 m a.s.l. (fan apex), with a total drop of about 2,000 m in 4 km. A North-south oriented fault system has resulted in a complex network of rock joints and cracks [2], Figure 1. The catchment incide carbonatic, massive Mesozoic rocks (calcschists and greenstones). The bedrock of the Cenischia valley belongs to the Tectono-metamorphic units of Rocciamelone and Puys–Venaus (Deep Oceanic Units; Servizio Geologico d'Italia, 1999). The Rocciamelone unit caps the highest area above 2600 meters; it is made of a succession of calcschist and silicate marble. Ophiolites are tectonically interposed in the basal part of silicate marblewhich is found near Cà d'Asti Refuge (2854 m). Clayey-arenitic schists widely overlain by deep-seated slope collapse deposits and colluvium. The catchment incide carbonatic, massive Mesozoic rocks (calcschists and greenstones). The bedrock of the Cenischia valley belongs to the Tectono-metamorphic units of Rocciamelone and Puys–Venaus (Deep Oceanic Units; Servizio Geologico d'Italia, 1999). The Rocciamelone unit caps the highest area above 2600 meters; it is made of a succession of calcschist and silicate marble. Ophiolites are tectonically interposed in the basal part of silicate marblewhich is found near Cà d'Asti Refuge (2854 m). Clayey-arenitic schists widely overlain by deep-seated slope collapse deposits and colluvium.

2.1. Experimental measurement devices

At this first step of the research, just only one rainfall gauge was considered, even if some considerations about a different rainfall distribution within the Marderello basin's area were performed. Figure 1 shows the localization of the Pluviometric Station (Pian Marderello) and the Ultrasonic transducer gauges utilized to measure, respectively, the rainfall intensity and the water level related to the event under study. The resolution of the installed tipping bucket rain gauge is about 0.2 mm for each commutation of the bucket when the rainfall intensity reaches the value of 100 mm/h. The hydrometer was collocated under a small bridge. The instrument's measuring capability of the distance from the water surface ranges from a minimum of 0.8 m up to 16 m with a sensibility of 0.5 cm and an accuracy of ± 1 cm. The instrument takes also into account the variation of the sound velocity due to the air temperature variation.

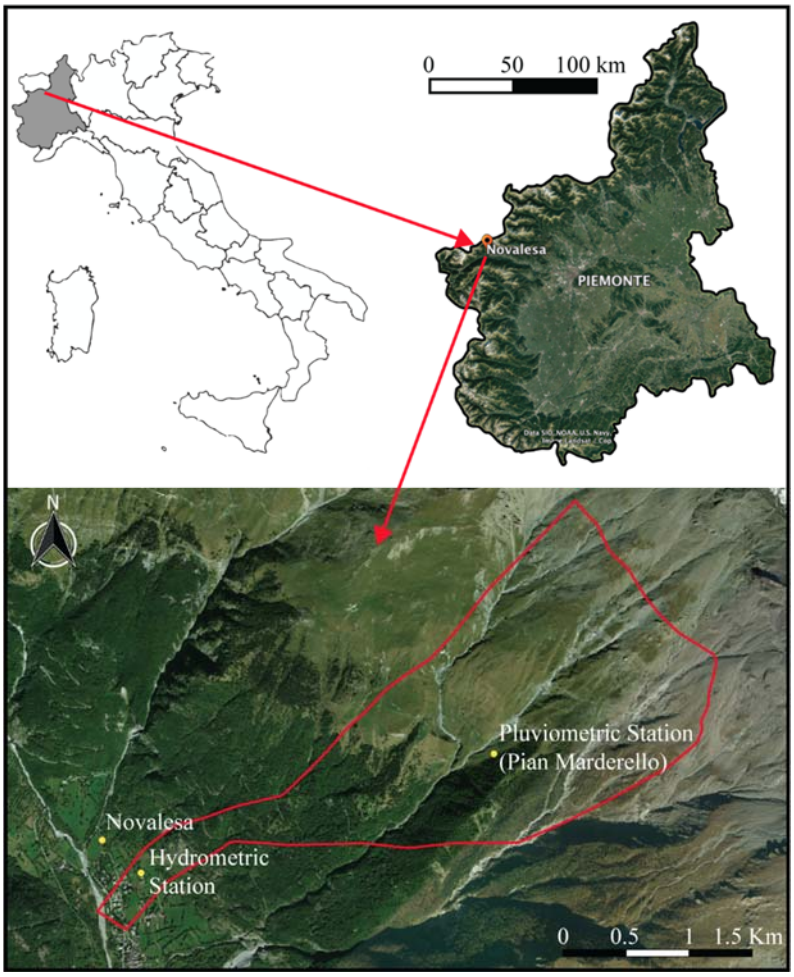


Figure 1. Map of the Marderello site; Pluviometric and Hydrometric Stations location

2.2. Experimental data

The available experimental data covered the rainfall and the hydrometry of the Marderello torrent, in particular from 21/07/2016 (16:00) to 22/07/2016 (23:59) with a cadence of one minute. However from the inspection of the complete plot (not reported), the rainfall event at 19:40 of 21/07/2016, characterized by a rainfall intensity spike of about 30 mm/hr, with a total 6 mm rainfall cumulate did not induce any relevant variation of the hydrometry. By consequence, the starting point for the numerical simulation was selected at 5:40 of 22/07/2016, Figure 2. Essentially three rainfall spikes occurred within the selected time interval. However, it appears that only two of these rain events, occurred within 30-60 minutes after the start point, produced a sensible variation of the Marderello hydrometry. Accordingly, it could be inferred that, for this system, a rainfall intensity threshold greater than 30 mm/hr may generate a wet debris flow at the selected hydrometric station site. From the Figure 2, seems that the Marderello hydrometric level experienced a constant value around 0.38 m. Actually, in situ inspection revealed that the bed bottom, used for the ultrasonic instrumentation calibration, was covered by accumulated brushwood. Moreover, after the last wet-debris flow spike, occurred around the 93nd minutes, the level decreased, probably due to partial removal of the brushwood. In any case, for the comparison between numerical and experimental level data, we assumed the zero level as the reference level. This assumption is partially justified observing that the accumulated brushwood was reasonably completely soaked from the water.

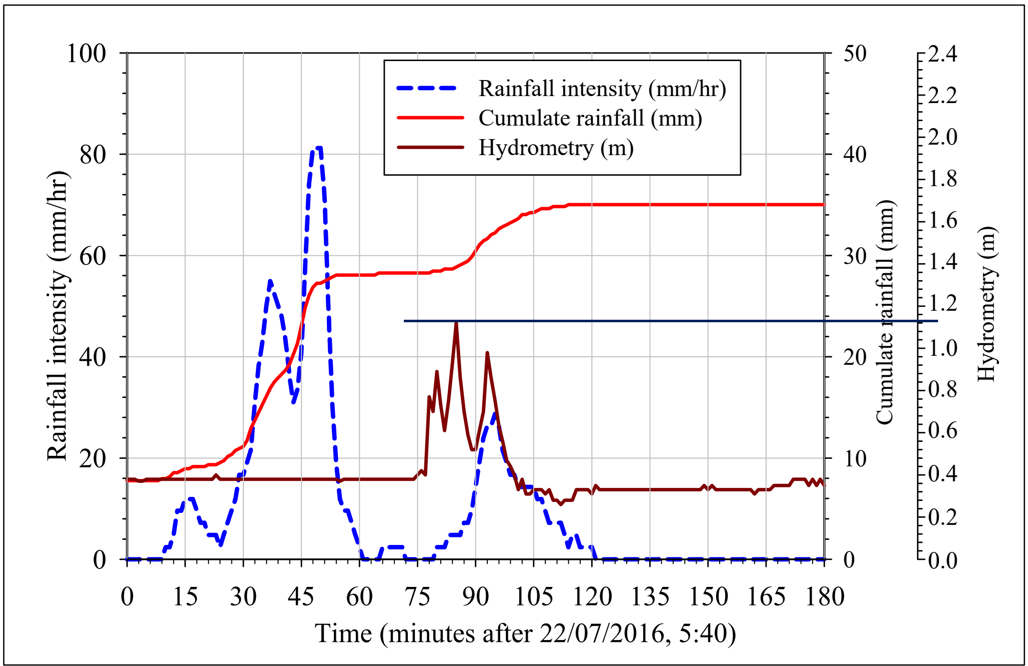


Figure 2. Measured data: Rainfall intensity (mm/hr); Cumulative rainfall (mm); Hydrometry (m) at Marderello station

3. Selected numerical approach

In order to study the impact of the selected rainfall event on the territory, we exploited the commercial computer code RiverFlow2D based on the Finite Volume Method (F.V.M.) [11]. The most physically realistic approach would had been the 3D modelling. However the relative computational time's cost, for the spatial and temporal scale regarding this study, would had been very high. Accordingly, the 'Depth Averaged 2D, shallow water approach' [16], adopted by the selected software, based on the assumption that the vertical depth of the flow is negligible compared to the other flow's dimensions, was the right compromise. In order to consider also bed level jumps (considered as source terms in the related differential equations), due to the geomorphology of real complex landform, the software includes the 'Augmented approximate Riemann solvers' approach [17]. To perform the content of the paper, among the other available software's options, the Hydrodynamic and the Mud-Debris flow models were selected. In the following sub-chapters a summarized description of the utilized mathematical approaches, freely adapted from [11] in which more details are reported, is briefly discussed.

3.1. Hydrodynamic models

The following is the resulting system of the coupled partial differential equations, based on the water volume conservation, solute volume conservation (if any), water momentum conservation and shallow water assumption:

$$\frac{\partial \boldsymbol{F}(\boldsymbol{U})}{\partial t}+\frac{\partial \boldsymbol{F}(\boldsymbol{U})}{\partial x}+\frac{\partial G(\boldsymbol{U})}{\partial y}=\boldsymbol{S}(\boldsymbol{U},x,y) \tag{1}$$

$$\boldsymbol{U}=\left(h,\ q_x,\ q_y\right)^T;\ \boldsymbol{F}=\left(q_x,\ \frac{q_x^2}{h}+\frac{1}{2}gh^2,\ \frac{q_xq_y}{h}\right)^T\ \boldsymbol{G}=\left(q_y,\ \frac{q_xq_y}{h},\ \frac{q_y^2}{h}+\frac{1}{2}gh^2\right)^T \tag{2}$$

$$\boldsymbol{S}=\left(0,gh\left(S_{0x}-S_{fx}\right),gh\left(S_{0y}-S_{fy}\right)\right)^T;\ S_{fx}=\frac{n^2u\sqrt{u^2+v^2}}{h^{4/3}};\qquad S_{fy}=\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}} \tag{3}$$

where: h is the water depth; $q_x=hu$ and $q_y=hv$ the unit discharges, resulting from the 'Shallow Water' approach; (u,v) the depth averaged components of the velocity vector $\boldsymbol{u}$ along x and y coodinates; g is the gravity acceleration; $\frac{1}{2}gh^2$ the flux obtained after assuming a hydrostatic pressure distribution in every water column, as common practice in shallow water models. The source term $\boldsymbol{S}(\boldsymbol{U},x,y)$ incorporates the effect of pressure force over the bed and the tangential forces generated by the bed stress, where $S_{0x}=-\partial z_b/\partial x$ and $S_{0y}=-\partial z_b/\partial y$ are the bed slopes of the bottom level z_b. The bed stress is modelled by means of the Manning friction law: S_{fx} S_{fy} parameters, where 'n' is the important roughness coefficient, whose value should be selected by the user.

3.2 Mud and Debris Flow Model (RiverFlow2D MD module)

The adopted mud-debris fluids models (based on Murillo &Garcia [18]), typically non Newtonian, are considered as a hyperconcentrated water and sediment mixture affected by stop and go mechanisms and regard bed and internal friction for free-surface flows, ranging from clear water to hyper-concentrated mixtures of sediments. The model involves the following assumption: a) the flow is confined to a layer which is thin compared to the horizontal scale of interest; the water and sediments mixture, assumed to be an homogeneous single phase with constant properties, e.g. density, yield stress etc., is described by continuum approach and is governed by equation (1), (2) and (3); the liquid and the solid phase velocities are assumed to be the same; the river bed does not erode; the fluid is assumed to be a homogeneous single-phase mix of water and sediment and has constant properties: e.g. density, yield stress, etc. The single-phase rheological formulation in RiverFlow2D MD MD accounts for different tangential forces friction terms, included in a same mathematical expression, that represent a variety of hyper-concentrated non-Newtonian fluids. Moreover the following are the available flow resistance terms options: Turbulent, Full Bingham, Simplified Bingham, Turbulent and Coulomb Turbulent and Yield, Turbulent, Coulomb and Yield, Quadratic, Granular. In particular a Bingham fluid will not flow until a certain threshold value of the the yield stress is reached. Once flowing, the movement is characterized by a plastic viscosity of the mixture.

4. Conceptual model and selected inputs

The implemented topographic data was based on a 5x5 m grid resolution Digital Terrain Model (DTM) and on a 1:10000 scale Regional Technical Chart, both available at on-line Geo-site of the Piemonte Region (Italy)[19]. WGS84, UTM Zone32N, was the used projection. In order to use the data obtained from the topographic map, the isoipse, the points quoted and those derived from the isoipse, in vector format, were converted using GIS software into an ASCII file containing the values of abscissa, ordinata and altitude regarding each point. The boundary of the geometric domain was traced considering the extension of the water catchment area of the Marderello torrent up to the hydrometer placed downstream of the waterfall. Free Inflow and Free-Outflow conditions were imposed respectively at upstream and downstream border of the water catchment area. The geometric domain of the conceptual model embedded the whole contours of the river basin. Moreover, no water sources was assumed in particular along the lateral borders. Accordingly, no lateral boundary flow was assumed. The beginning of the numeric transient (22/07/2016, 5:40, Figure 2) was set long after the previous rainy event, which in any case did not generate any flooding phenomenon, as from plots not reported. Therefore, the terrain under study was assumed in initial dry conditions.

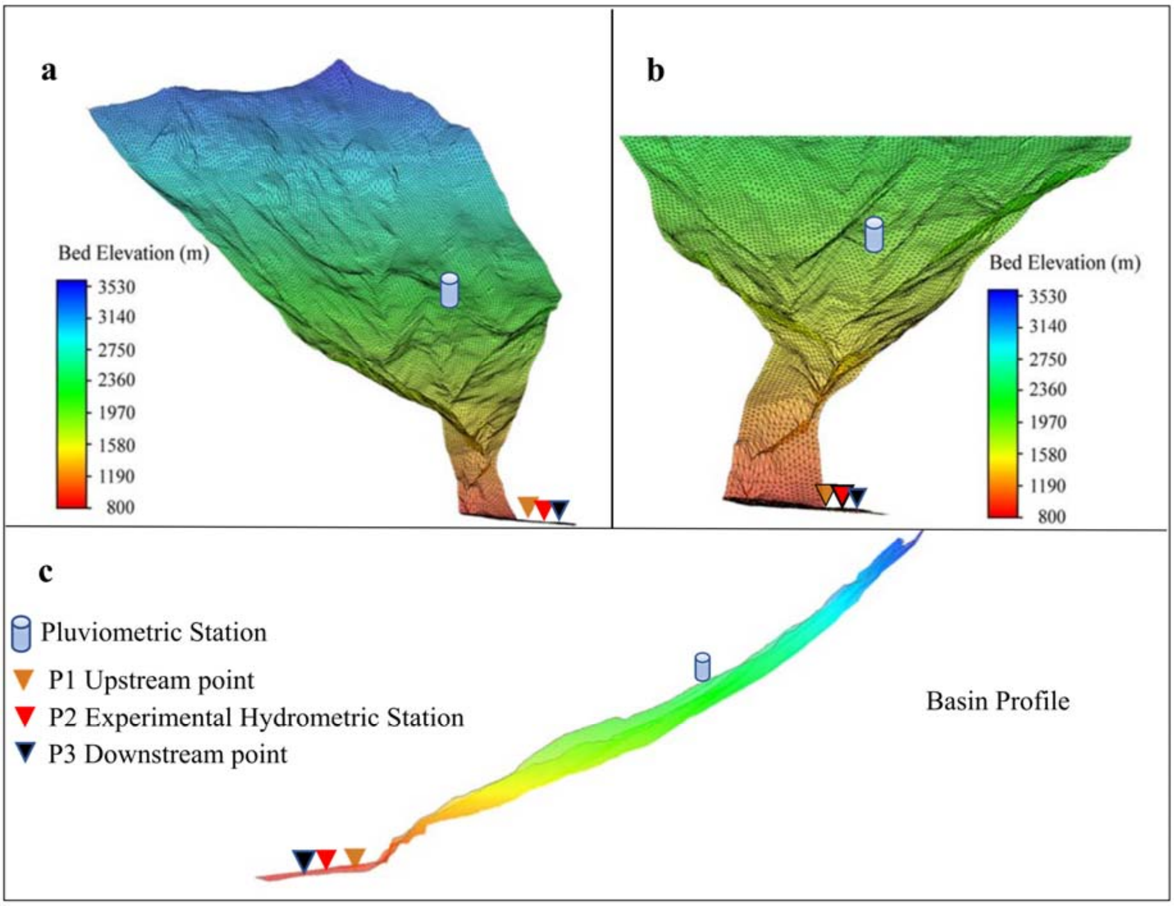


Figure 3. Conceptual model and measurement gauges allocation

4.1. Geometric discretization of the domain

The discretization of the geometric domain was performed through unstructured mesh approach, with linear triangular elements, Figure 3. Simulations based on different mesh width were performed in order to calibrate the model; in particular, meshes with spacing at 10, 5 and 2.5 meters were tested.

The 10 m meshes highlighted the presence of small, rather deep sinks in the mid-valley downstream of the Marderello Torrent which hinder the natural flow of water. By a meshes refinement, lowering their average width from 5 to 2.5 m, the depth of these numerical sinks decreased, suggesting that the presence of these small depressions has been emphasized by a discretization not sufficiently accurate to correctly reproduce the topography of the area. Accordingly, as further detailed in the 'Discussion' paragraph, in order to perform parametric study with a reasonable number of meshes, four different zones were identified (Figure 4): an upstream area (circle 1), characterized by a rather homogeneous surface, with 10 m spacing; a central area(circle 2), characterized by a homogeneous surface, but with deeper incisions than the previous one, with a 5m spacing; a downstream area (circle 3), characterized by strong roughness, with 2.5m spacing and, within the area 3, a further subdivision delimiting the riverbed of the Marderello torrent, characterized by a mesh spacing of 2m (circle 4).

4.2. Manning coefficient

The Manning's '*n*' coefficient in Eq.3 usually accounts for the effects of bed roughness, internal friction and variations in shape and size of the channel cross section, obstructions, river meandering. However the selected 2D numerical approach do not account for lateral friction. For these reasons, this kind of coefficient is used as a tune parameter in the calibration process in order to adjust the numerical results to measured data. The initial guessed values, employed in this paper, was based on the tables reported in Chow' book [20].

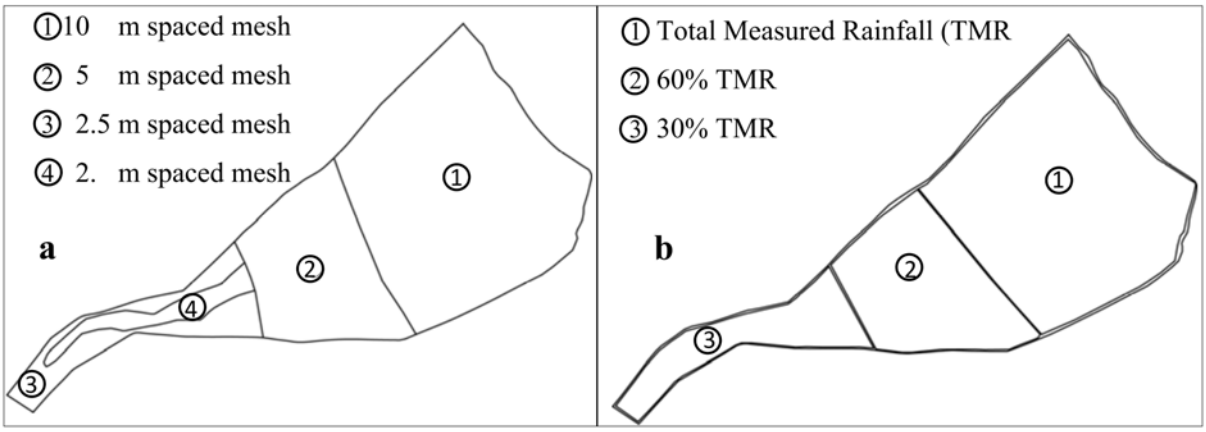


Figure 4. a) Basin area subdivisions based on variable average mesh width; **b)** Different rainfall intensity areas

5. Discussion

In order to compare the hydrometric values over time of the Marderello torrent, resulting from the numerical simulations to the measured data, three points belonging to the numerical model very close to each other were taken as references: P1 upstream point, P2 experimental measurement point, P3 downstream point (Figure 3). In Table 1 a summary of the performed simulations are reported. By first, we did not consider the Mud-Debris module. Accordingly, simple clear water, uniform mesh width and uniform rainfall distribution were simulated. Then, we checked how the mesh width affected the total mass flowing out the Marderello's basin through the boundary. At this aim we performed parametric analyses, varying the number of the triangular elements. By inspection of the resulting plot (not reported), based on the first simulation, it appeared that the asymptotic value of the maximum height of the water level was almost reached employing about more than 2 million of elements. Thus a uniform 2.5 m width mesh was selected as the last mesh refinement. From Figure 5a to c, it emerged that the refinement of the mesh width implied an increase of the water level resulting from the numerical simulations. This occurrence may be due to an increase of the total cumulative rainfall inventory or to an increase of the easiness with which water could flow through a topography rich in incisions, wells and sinks that can virtually trap numerically the water if the meshing is not adequate, This circumstance was observed also on the phase of the calibration of the number of meshes, as observed above. Anyway, this issue needs to be further analyzed. From the same figure, it appears clearly that the calculated arrivals of the flood wave and of the maximum peak of the water level anticipated, respectively, about 30 and 25 minutes the values actually measured, respectively at 78 th and 79 th minute, being about 30 minutes the time advance of the last peak of rain. Notwithstanding we used the *Graphic Unit Processing* (GPU) parallel approach option of the code, the computer time was too high in order to perform parametric analyses in a reasonable time. By consequence, we selected four areas in which different number of meshes were imposed, as already detailed above (Figure 4). Further, after a first simulation considering uniform rainfall distribution, the occurrence of a different distribution of rainfall over the entire basin area was explored. Accordingly, tests were performed in which the pluviometric inputs were assumed to be different within three different areas selected on the basis of the quotas (Figure 4): an upstream area with pluviometric input equal to the experimental data, a central area with an assumed lower rainfall intensity input equal to a reference value of 60% of the experimental data and a downstream area with a reference value of 30%. Then other different distributions were explored.

Table 1. Summary description of the main numerical parametric simulations; F.B.: Full Bingham; C.T.Y. Coulomb Turbulent Yield

Simul. (Figure)	Uniform Rainfall distribution	Debris (MD module)	Mesh width (m)	Manning (n)	Density (kg/m^3)	Yield stress (Pa)	Viscosity (Pa·s)	Angle (°)	Time step (s)
5a	Uniform	no	Unif. 10	0.04	1000	/	/	/	36.
5b	Uniform	no	Unif. 5	0.04	1000	/	/	/	36.
5c	Uniform	no	Unif. 2.5	0.04	1000	/	/	/	36.
6a	Variable	no	Variable	0.05	1000	/	/	/	6.
6b	Variable	F.B.	Variable	0.055	1100	0.075	0.01	/	6.
6c	Variable	C. T. Y.	Variable	0.055	1100	0.075	0.01	3	6.
6d	Variable	C. T. Y.	Variable	0.055	1100	0.075	0.01	3	3.

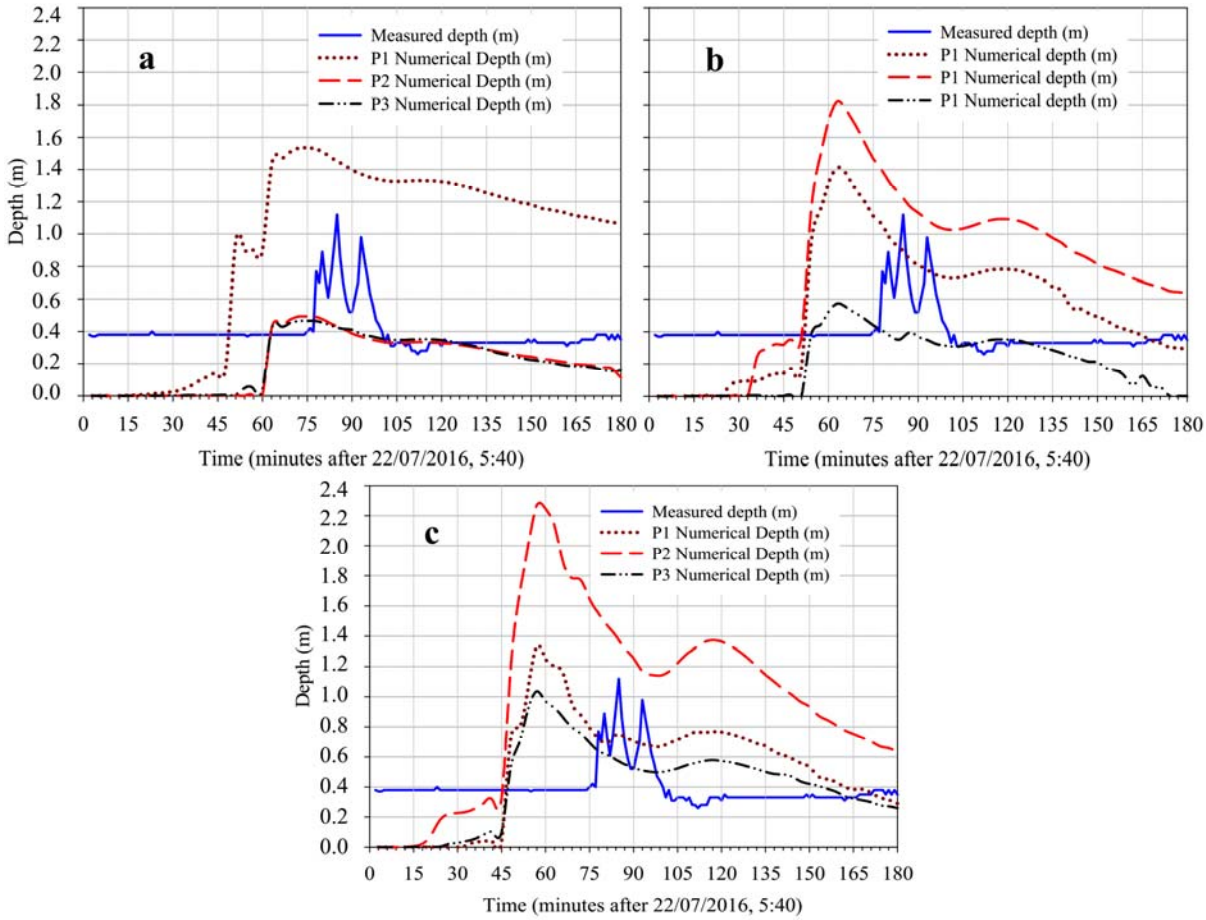


Figure 5. Clear water: uniform mesh and rainfall distributions; Manning coefficient=0.04
a) average mesh length (a.m.l.) = 10 m; **b)** a.m.l. = 5 m; **c)** a.m.l. = 2.5 m

Given the high rainfall rate, high air humidity and relatively low temperatures, for this case study, the phenomena of evaporation was estimated negligible. On the other hand, the infiltration was not considered, for the sake of simplicity and for this first parametric approach. The results are reported in Figure 6a. It is worth noting that the arrivals in advance have been reduced, moreover the calculated values of the peak of the water level fitted quite well the measured values. Finally, it was explored coefficient, the Yield stress, the density and the internal viscosity assigned values, in this phase of the study, are calibration parameters in order to fit the measured data. The particular behavior of the resulting numerical water level reported in Figure 6b (Full Bingham model) was due to that the flow of this type of material is subject to the constrain of overcoming a threshold of the Yield stress.

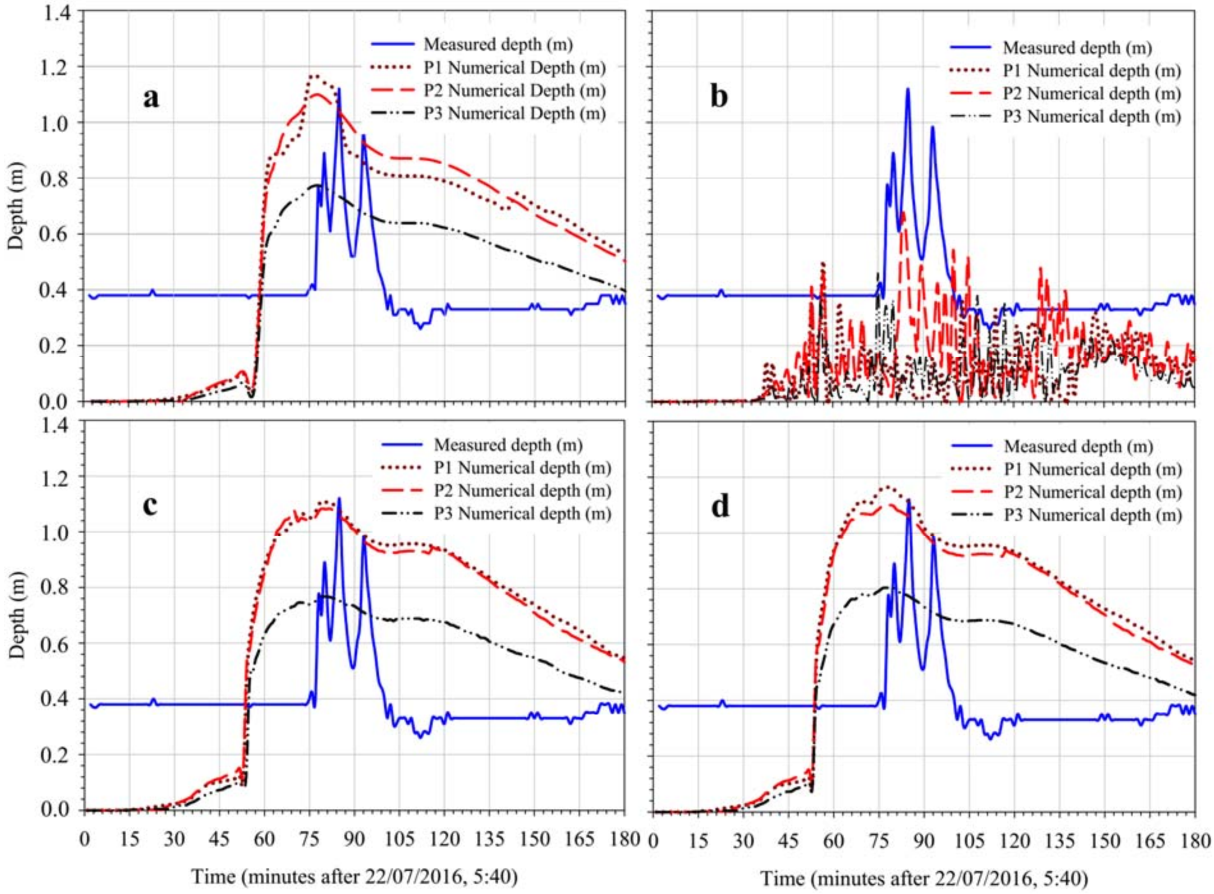


Figure 6. a) - d)

a) Clear water; variable mesh 2-2.5-5-10 m; variable rainfall distribution 100-60-30; Manning coefficient=0.05.
b) Wet debris; variable mesh 2-2.5-5-10 m; variable rainfall distribution 100-80-62; Manning coefficient=0.055; Full Bingham: Yield tension 0.075 (Pa); viscosity= 0.01 (Pa·s); time step= 0.1 minute.
c) Wet debris; variable mesh 2-2.5-5-10 m; variable rainfall distribution 100-80-64; Manning coefficient=0.055; Coulomb Turbulent Yield: Yield tension 0.075 (Pa); viscosity= 0.01 (Pa·s); Angle= 3°; time step= 0.1 minute.
d) Wet debris; variable mesh 2-2.5-5-10 m; variable rainfall distribution 100-80-65; Manning coefficient=0.055; Coulomb Turbulent Yield: Yield tension 0.075 (Pa); viscosity= 0.01 (Pa·s); Angle= 3°; time step= 0.05 minute.

6. Conclusion

Notwithstanding the complexities of the geomorphology of the system and of the physics of the studied phenomena, also by a mathematical and numerical point of view, the selected numerical approach demonstrated to be suitable for studying debris flow phenomena that may occur within basin like Marderello's site. However, the numerical outcomes are strongly affected by a correct knowledge of the local morphologies also at small scale. Moreover, a correct rainfall distribution knowledge is also requested. This requirement would be easily satisfied through a correct design of monitoring pluviometric stations network, that could be an important outcome deriving from this kind of study. An important issue emerged in order to better calibrate the arrival time of the first flood, even if, in this study, the arrival time and the peak value of the calculated water level fitted well the experimental data. A further issue was the correct use of some physical parameters that, however, were used as numerical parameters to fit the experimental data. Finally very important was the utilization of the GPU approach also in order to set early warning system of debris phenomena occurrence, specific of the selected site.

References

[1] V. Coviello, M. Arattano, L. Turconi, ‘Detecting torrential processes from a distance with a seismic monitoring network’, *Natural Hazards Journal of the International Society for the Prevention and Mitigation of Natural Hazards*, vol. 78. 3, 2055-2080; DOI: 10.1007/s11069-015-1819-2, 2015.

[2] L. Turconi, K. SUNIL DE, D. Tropeano, G. SAVIO, G., ‘Slope failure and related processes in the Mt. Rocciamelone area (Cenischia valley, Western Italian Alps), *Geomorphology* 114, 115-128, 2010.

[3] A. Pasculli, A., ‘CFD-FEM 2D Modelling of a local water flow. Some numerical results’, *Alpine and Mediterranean Quaternary,* SCOPUS: 2-s2.0-84983037047, 21(B), (1), 215-228, 2008.

[4] A. Pasculli, N. Sciarra, ‘A probabilistic approach to determine the local erosion of a watery debris flow’, *XI IAEG International Congress*; Liege, Belgium, 3-8 September. SCOPUS id: 2-s2.0-84902449614., Paper S08-08, 2006.

[5] A. Pasculli, L. Minatti, ‘Dam break Smoothed Particle Hydrodynamic modeling based on Riemann solvers’. *Advances in Fluid Mechanics VIII, WIT Transactions on Engineering Sciences, WIT Press*, SCOPUS id: 2-s2.0-78449235684, (6) 9, pp. 145-156, 2010.

[6] A. Pasculli, L. Minatti, N. Sciarra, ‘Insights on the application of some current SPH approaches for the study of muddy debris flow: Numerical and experimental comparison’. *Wit Transaction 10th International Conference on Advances in Fluid Mechanics, AFM 2014*; A Coruna; Spain, SCOPUS id: 2-s2.0-84907611231, 82, 3–14, 2014.

[7] A. Pasculli, A., C. Audisio, ‘Cellular Automata Modelling of Fluvial Evolution: Real and Parametric Numerical Results Comparison Along River Pellice (NW Italy)’, *Environmental Modeling and Assessment*;. SCOPUS id: 2-s2.0-84940588890, 20, (5), pp. 425-441, 2015.

[8] C. Audisio, A. Pasculli, N. Sciarra, ‘ Conceptual and numerical models applied on the river pellice (North western italy)’, *Engineering Geology for Society and Territory Volume 3,* SCOPUS id: 2-s2.0-84944586202, pp. 327-330, 2015.

[9] A. Pasculli, C. Audisio, G. Lollino, G., ‘Application of cellular automaton model for river morphological studies: CAESAR and the Pellice River (Piedmont, Italy)’. *Rendiconti Online Società Geologica Italiana*, SCOPUS id: 2-s2.0-84863090597, 11, (1) pp. 118-119, 2010.

[10] A. Pasculli, C. Audisio, N. Sciarra, ‘Water and sediment output evaluation using cellular automata on alpine catchment: Soana, Italy - Test case’, *IOP Conference Series: Earth and Environmental Science.* SCOPUS id=2-s2.0-85044335598, 95, pp. 1-8, 2017.

[11] Hydronia LLC, ‘RiverFlow2D, Two-Dimensional Flood and River Dynamics Model, Reference Manual’, www.hydronia.com, December 2017.

[12] L. Esposito,A. W. Esposito, A. Pasculli, N. Sciarra, N. ‘Particular features of the physical and mechanical characteristics of certain Phlegraean pyroclastic soils’. *CATENA*, SCOPUS id: 2-s2.0-84873130083, 104, pp. 186-194, 2013.

[13] A. Pasculli, N. Sciarra, L. Esposito, A.W. Esposito, ‘Effects of wetting and drying cycles on mechanical properties of pyroclastic soils’, *CATENA,* SCOPUS id=2-s2.0-85017109027, 156, 113-123, 2017.

[14] C. Di nucci & A, Russo Spena, ‘On the steady two-dimensional open channel flow’, *Journal of Interdisciplinary Mathematics*, 21 (3), 579–594, 2018.

[15] C. Di nucci & A, Russo Spena, ‘Mean velocity profiles of fully-developed turbulent flows’, *Comptes Rendus Mecanique*, 340, 629-640, 2012.

[16] J. Murillo & P. Garcia-Navarro, ‘Weak solutions for partial differential equations with source

terms: application to the shallow water equations', *Journal of Computational Physics* 229 (11), 4327-4368, 2010.
[17] E. Toro, 'Shock-Capturing Methods for free-Surface Shallow Flows', Wiley, New York, 2001.
[18] J. Murillo, P. Garcia-Navarro, J. Burguete, 'Wave Riemann description of friction terms in unsteady shallow flows: Application to water and mud/debris floods', *Journal of Computational Physics* 231, 1963-2001, 2012.
[19] Servizio Geologico d'Italia, Carta Geologica F° 154 SUSA., 1999.
[20] V. T. Chow, '*Open-channel hydraulics*' New York, McGraw-Hill Book Company, 680 p., 1959.