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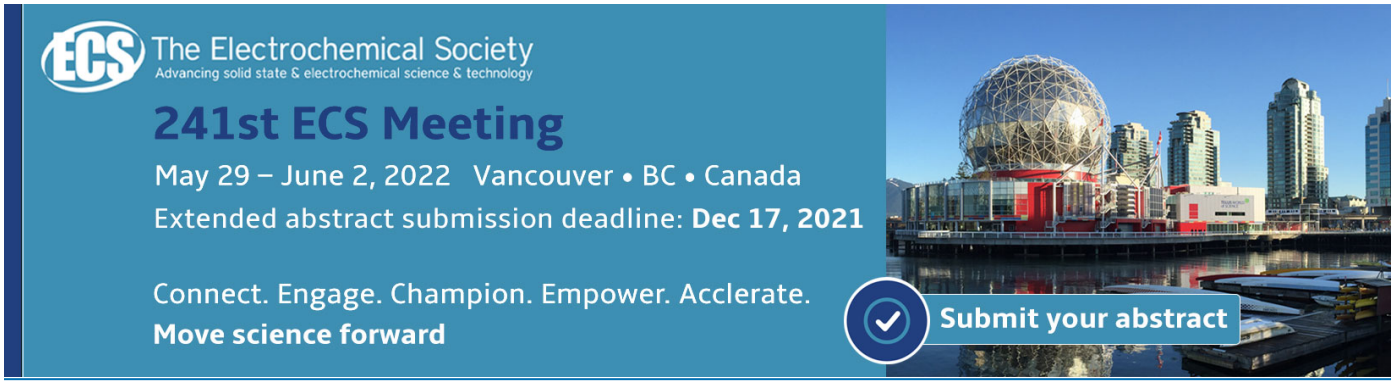

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Rainfall-triggered debris flows: triggering-propagation modelling and application to an event in Southern Italy

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Abstract. Debris flows are high-speed and unpredictable phenomena, considered among the main sources of hazard worldwide, since they can affect structures, the economy, and human lives. Rainfall typically triggers these events, causing the flowing of the unconsolidated soil downslope. This work focuses on debris-flow events characterized by multiple triggering areas, which are extremely complex since they involve a spatial sequence of numerous triggers in a relatively small portion of the slope. Numerical modelling of this type of phenomenon can contribute to hazard and risk assessment, which is key to designing effective mitigation structures. In this article, two different models are applied for triggering and propagation, respectively. The former computes the transient pore-pressure changes and the consequent factor of safety variation caused by rainfall infiltration, inducing the triggering of the event. The latter is a depth-averaged numerical model that simulates the event runout, and whose parameters are calibrated through back-analysis. The applicability of the two combined approaches is tested through modelling of an historical event in Southern Italy, which was characterized by large mass releases from multiple triggering zones. Residential areas were hit, suffering serious consequences. Two rheologies are compared to individuate the most suitable propagation model for the study case and obtained results are commented.

1. Introduction

Debris flows [1] are dangerous events characterized by high kinetic energy, often causing casualties and serious damage to the economy. They consist of three main phases: triggering, propagation and deposition. The most common triggering cause is rainfall. Water infiltrates inside the susceptible soil, thus increasing the pore water pressure, and reducing the shear strength. As a consequence, the soil can slide downstream [2]. In this context, the numerical modeling of the phenomenon can help in risk assessment, and in designing more effective protective structures.

The article describes the triggering and runout phases through numerical modelling. The former is approached through a program for the grid-based slope stability determination, by calculating the changing pore water pressure and consequent factor of safety variation caused by rainfall (TRIGRS [3]). The latter is carried out with a depth-averaged model, based on a continuum mechanics approach (Rash3D [4]). The mass behavior is simulated comparing two rheologies, whose parameters are calibrated through back-analysis. This modelling approach is tested on an event happened in 2009 in Southern Italy [5]. The phenomenon was characterized by multiple triggering areas on the slope, and the involved mass was large. A settlement was hit, causing extensive damages and numerous causalities.

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The article briefly describes the used methods for triggering and propagation modelling, TRIGRS [3] and Rash3D [4], respectively. Afterwards, the study case is introduced. Finally, the results are described, along with a critical discussion on the capabilities and limits of the approach.

2. Methods

2.1. Triggering: A grid-based slope-stability model for rainfall-induced shallow landslides

TRIGRS (Transient Rainfall Infiltration and Grid-based Regional Slope-Stability model) [3] is a program for the instability analysis and modelling of the triggering phase of rainfall-induced shallow landslides. It calculates the pore-pressure changes caused by rainfall infiltration, and the consequent variation in factor of safety of the slope. As inputs, it requires the Digital Terrain Model (DTM), the rainfall data, starting saturation condition, spatial sediment distribution and characteristics. As output, it yields the distribution of the unstable mass.

2.2. Runout: A depth-average model

Rash3D [4] is a program that models the runout of debris flows, based on a continuum mechanics approach. The runout phase includes both propagation and deposition. The mass is treated as an equivalent fluid, whose rheological properties simulate the behaviour of the real mixture. It requires as input the DTM, the depth of the unstable soil layer, and the rheological parameters.

Two rheologies were selected for the case study: Voellmy and Bingham. The key difference in the two approaches is the nature of the yield stress. The Voellmy rheology combines two terms into the formulation of the basal shear resistance τ_z: a Coulomb frictional term, and a turbulent one. The latter considers all velocity-dependent energy dissipations. The constitutive equation is the following:

$$\tau_z = -\left(\gamma h \tan\varphi + \frac{\rho g v^2}{\xi}\right), \tag{1}$$

with γ the bulk specific weight, h the flow depth, φ the dynamic friction angle, v the depth-averaged flow velocity, and ξ the turbulence coefficient [6].

The Bingham rheology consists of a viscous dissipation term and a constant yield stress τ_0. The fluid shows a rigid behaviour below the yield strength, and a viscous behaviour above it. The basal shear resistance τ_z is obtained in Rash3D seeking the zeros of a polynomial:

$$\tau_z^3 + 3\left(\frac{\tau_0}{2} + \frac{\nu_B v}{h}\right)\tau_z^2 - \frac{\tau_0^3}{2} = 0\,, \tag{2}$$

where ν_B is the post-yield dynamic viscosity [6].

3. Description of the benchmark event

Giampilieri is a small village in the Nord-East side of Sicily (Messina province). Figure 1(a) illustrates its location. The area is characterized by slopes with high inclination, from 30 to 60° [7]. The studied slope contains three main creeks (Loco, Sopra Urno and Puntale), and the village is crossed by the Giampilieri river (Figure 1b).

On the 1st of October 2009, the city was hit by a massive debris-flow event which caused a large number of casualties and extensive damage to the structures [5]. In Figure 1 (c, d) the flow path can be observed. During those days, exceptional levels of rainfall were registered by the nearby rain gauge stations. In figure 2, the rainfall records at the four closest stations to the hit area are showed: at *Santo Stefano di Briga* station, the one considered for the analysis, 250 mm of rainfall were measured in eight hours.

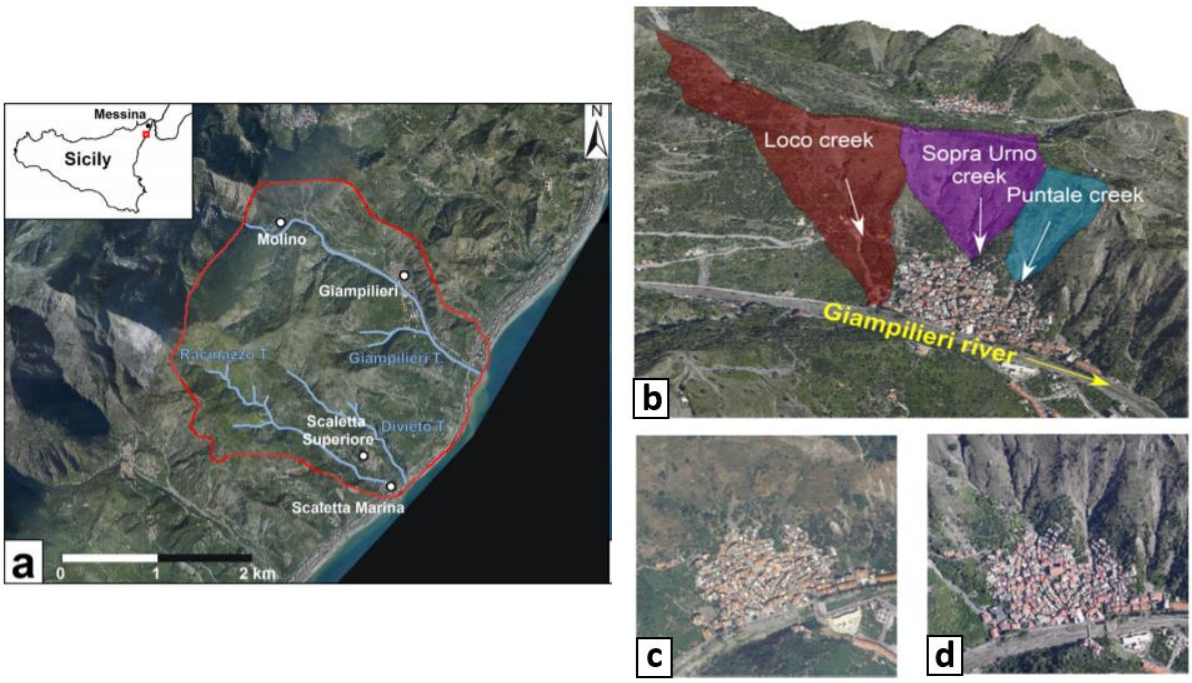

Figure 1. (a) The inset shows the position of the event area within Sicily. In the main figure, the red line highlights the focus area. In blue, the hydrography is represented [8]; (b) Illustration of the event area: Loco, Sopra Urno and Puntale creeks and Giampilieri river; (c) Giampilieri Superiore village before the event; (d) Post-event picture of the settlement, with observable debris-flow scars [7].

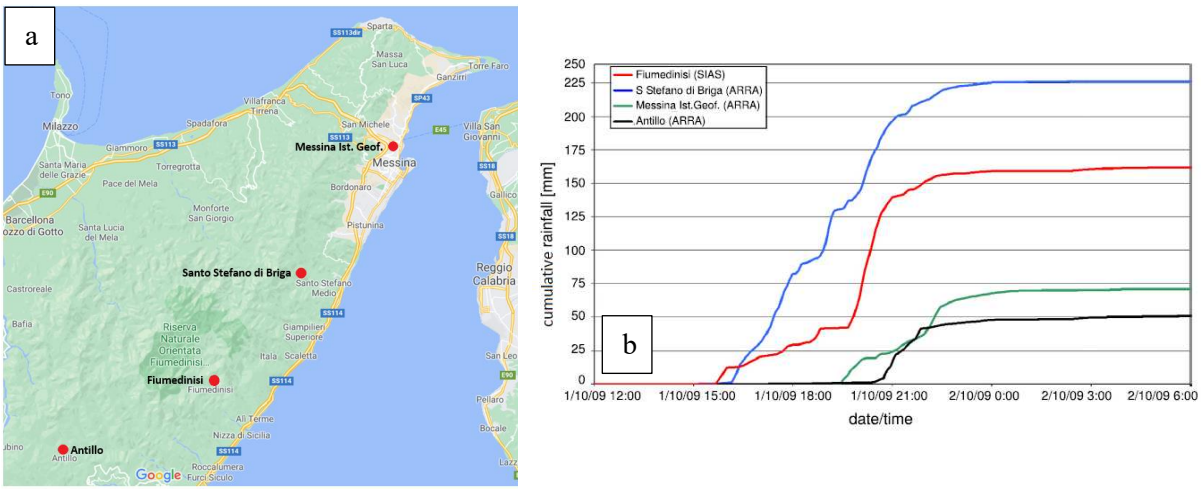

Figure 2. (a) Position of the four closest rainfall recording stations to the hit area (source: Google Maps), and (b) rainfall data recorded at those stations, before and during the Giampilieri event [5].

4. Triggering model

The adopted Digital Terrain Model is a 2x2 m cell system (Figure 3). The buildings are modeled by raising the terrain elevation by a constant height. The adopted parameters for the TRIGRS analysis are reported in Table 1 [9]. The soil depth was calculated through the equation $d_{LZ} = 32\, e^{-0.07\delta}$, with δ the slope [9]. This was applied to slope inclinations between 35° and 45°. For slopes steeper than 45°, bedrock outcropping was assumed, while for slopes lower than 35°, the value of soil depth corresponding to 35° was imposed.

The triggering model after the eight hours of strongest rainfall is shown in Figure 4. Herein, a comparison with the literature [5] is displayed: the two results are extremely similar. This validates the employed parameters and therefore the model was adopted for analyzing the runout phase.

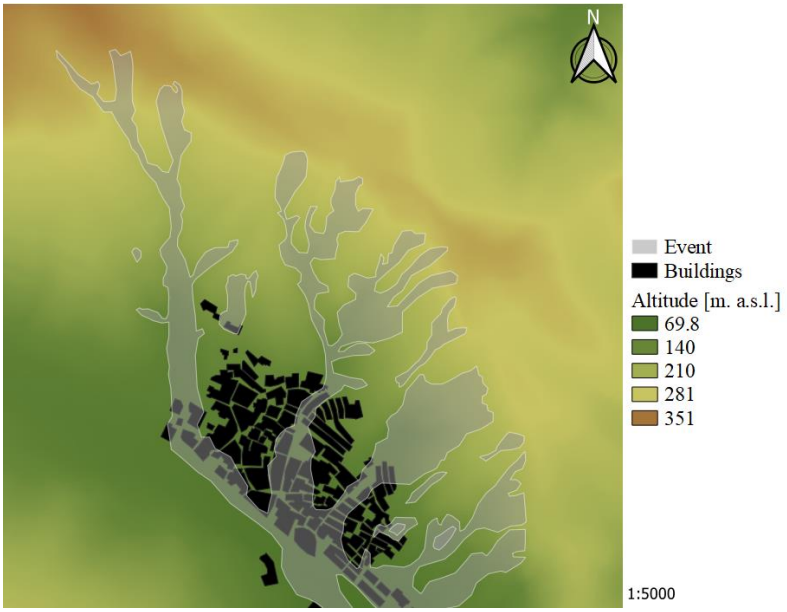

Figure 3. Digital terrain model for TRIGRS. Buildings of Giampilieri Superiore village, and contour of the October 2009 event are showed.

Table 1. Terrain parameters for the TRIGRS model of the study case. [9]

$\phi'[°]$	$c'[\mathrm{kPa}]$	$\gamma_s[\mathrm{N/m^3}]$	$\theta_s[-]$	$K_s[\mathrm{m/s}]$	$\theta_r[-]$	$\alpha[m^{-1}]$	$D_0[\mathrm{m^2/s}]$
39	4	19000	0.35	$2 \times 10 - 5$	0.045	3.5	5×10^{-5}

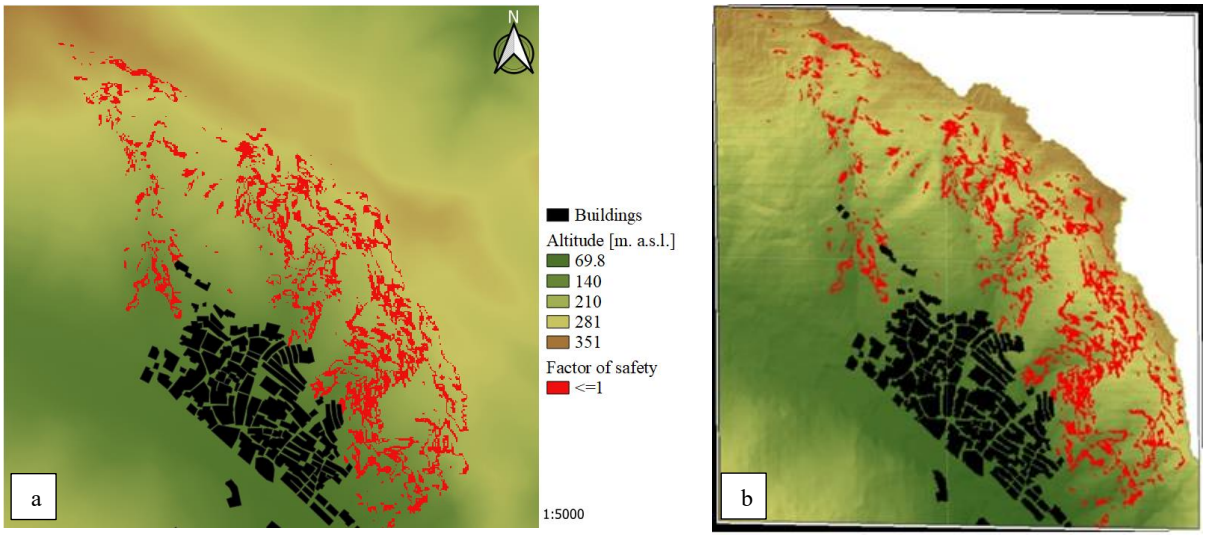

Figure 4. TRIGRS analysis: cells with a factor of safety lower than 1: (a) Results of this study; (b) result obtained by Stancanelli *et al*. (2017) [5]. No substantial differences are noticeable.

5. Propagation model

The Voellmy and Bingham rheologies were tested for the case study, calibrating the parameters through back-analysis. At this stage, the surveyed path during the event of 2009 was adopted as a first factor of comparison to numerically reproduce the event. In this article, two significative examples are shown, to highlights the most appropriate rheology law for the analyzed debris-flow event. Maximum flow heights and velocities were monitored in the simulations to evaluate the performance of the model. Future works will aim at obtaining a direct comparison between observed and simulated values.

5.1. Runout simulations

The calibration parameters of the Voellmy law are the bulk friction angle φ and the turbulence coefficient ξ. The turbulence coefficient was tested between values of 200 and 2000 m/s^2 (with steps of 100 m/s^2), an established range from other modelled events in the literature, see Ref. [10]. Changes in the velocities were observed: larger values of ξ lead to higher velocities. The bulk friction angle should be lower than the terrain slope, to allow sliding. Taking into account the proclivity of the slopes in Giampilieri, and aiming at reproducing the followed real path during the event, a range of φ between 0° and 10° (with steps of 0.5°) was chosen for the calibration. It was observed that low values of φ (lower than 1°), so considering a minimal friction between flow and terrain, are required in order for the flow to follow the surveyed path without halting inside the settlement. This motivated the use of the Bingham rheology, a model based on a constant yield stress τ_0 and a post-failure dynamic viscosity ν_B. It was observed that the yield stress has a crucial influence on the flow path. On the other hand, increasing the dynamic viscosity, a significative reduction of velocity is appreciable. Once again, starting from used values in the literature (e.g. in [10]), a combination between the two parameters was studied to reach the best agreement with the real measurements of the event. The yield stress was varied between 0.5 and 5 kPa (with ten equally-spaced intermediate values), while the dynamic viscosity was tested in a range between 1 and 50 Pa s (with steps of 10 Pa s). In Figure 5, two representative examples of the tested rheologies at different runout instants are reported. Herein, the Giampilieri runout simulation with a Voellmy rheology characterized by $\varphi = 10°$ and $\xi = 500\ \mathrm{m/s^2}$ is shown. Furthermore, the simulation with the Bingham rheology is characterized by $\tau_0 = 0.5$ kPa and $\nu_B = 50\ \mathrm{Pa \cdot s}$. These two simulations were chosen to show the previously highlighted characteristics of the adopted rheological laws.

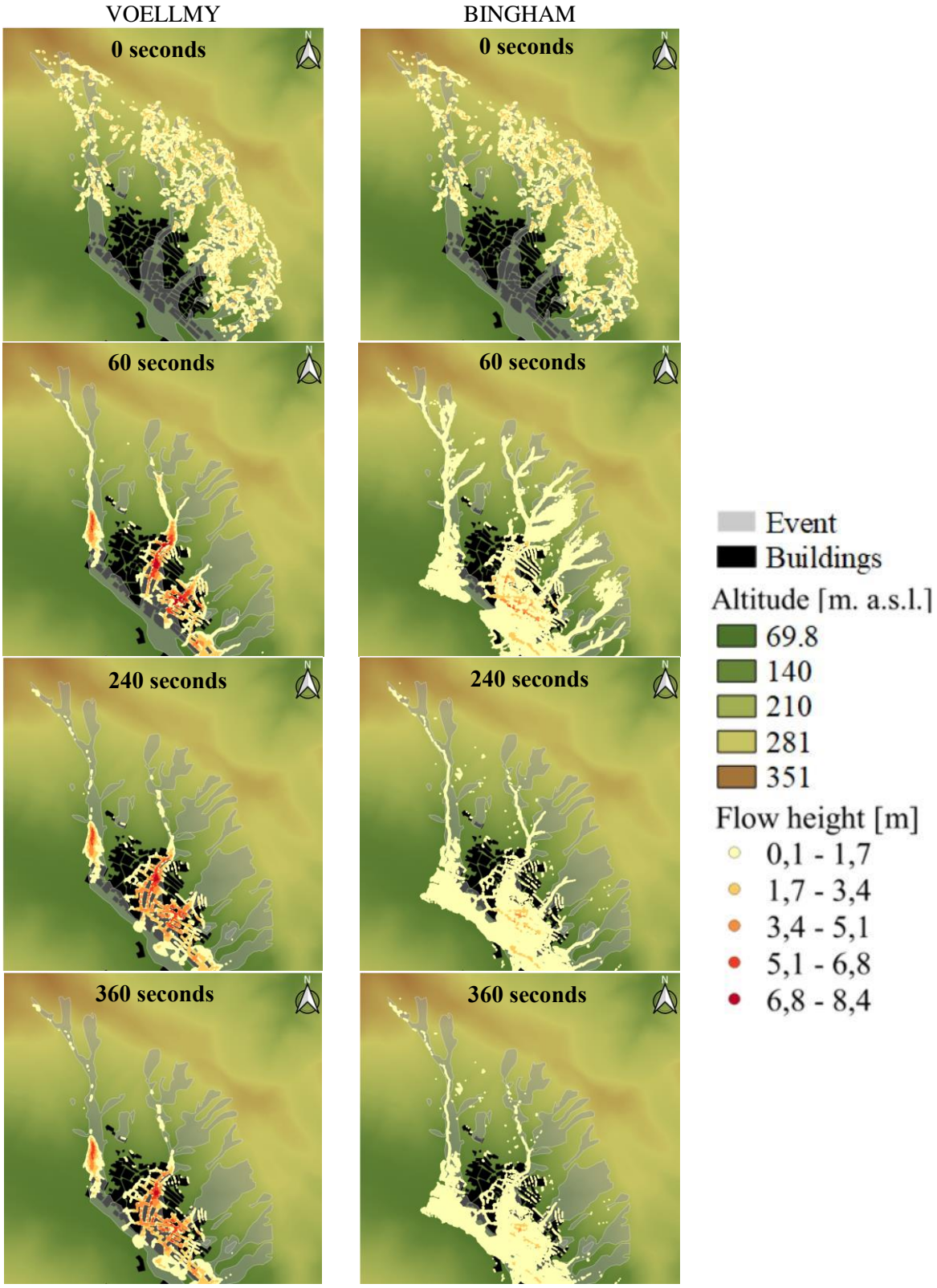

Figure 5. Rash3D simulation of the Giampilieri event: Voellmy and Bingham rheologies in comparison. Pictures at different runout instants.

As observable from the sequence, the flow with a Voellmy rheology behaves correctly on the slope: the path follows the surveyed one (grey layer in the pictures). Unfortunately, inside the settlement, the mass stops when the slope becomes too low, as already observed. Additionally, the flow height in the village is locally extremely high (until values of around 8 meters), with respect to the observed values during the event [5]. The Bingham law exhibits a behaviour which seems closer to the real event, especially with respect to the Voellmy simulation. The path follows the Giampilieri river bed. The simulated flow height in the village is more realistic and the mass has a longer runout, crossing the village and proceeding towards the sea. Unfortunately, the simulation still shows an overestimation of the flooded area and of the number of hit buildings.

6. Discussion and conclusion

This article describes the modelling of debris flows triggering and runout. The chosen methods were applied to a case study in Giampilieri (Southern Italy), which was hit by a large event in 2009.
The triggering was modelled through TRIGRS, which carries out a grid-based slope stability analysis of rainfall induced events. The results agree with those shown in the literature with a similar procedure.
The propagation was simulated through Rash3D, which models the flow as an equivalent homogeneous mass, whose rheological behaviour corresponds to the real mixture. The work focused on determining the most suitable rheology for describing the propagation of the distributed rainfall-induced debris-flow event of Giampilieri. Two rheologies were analysed, mainly focusing on the comparison with the observed real event path, at this stage. Firstly, the Voellmy constitutive law was used, being characterized by a frictional and a turbulent component. The law produces results that are not suitable for the study case, as it causes the flow to halt when reaching gentler slopes. Additionally, the simulated maximum flow height in the village greatly exceeds that observed during the event. Alternatively, the Bingham rheology was considered. It consists of a viscous component and a constant yield stress. This constitutive behaviour seems more appropriate for the considered case, making the mass follow the observed path during the event. Nevertheless, the simulated flooded area is overestimated.

The modelling of multiple triggering debris-flow events is a complex topic. In this study case, the simultaneous convergence of the whole unstable mass in the village causes an accumulation of mass larger than the one observed in site, and an overestimation of the number of hit buildings. However, it seems unrealistic that all the instable zones triggered in the same instant. In this context, future research will focus on studying a combined time- and space distribution approach to describe these particular events. This could help in obtaining more realistic values of flow heights from simulations.

Acknowledgements

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