Tierz, P., Woodhouse, M., Phillips, J., Sandri, L., Selva, J., Marzocchi, W., & Odbert, H. (2017). A Framework for Probabilistic Multi-Hazard Assessment of Rain-Triggered Lahars Using Bayesian Belief Networks. *Frontiers in Earth Science*, *5*, [73]. https://doi.org/10.3389/feart.2017.00073

Supplementary material: Multihaz and LaharFlow parameterization at Somma-Vesuvius (Italy)

A framework for probabilistic multi-hazard assessment of rain-triggered lahars using Bayesian Belief Networks

Pablo Tierz[1*], Mark J. Woodhouse[2], Jeremy C. Phillips[2], Laura Sandri[1], Jacopo Selva[1], Warner Marzocchi[3], Henry M. Odbert[2, 4]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Bologna, Italy.

[2]School of Earth Sciences, University of Bristol, Bristol, United Kingdom.

[3]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Roma1, Roma, Italy.

[4]Met Office, Exeter, United Kingdom.

*** Correspondence:** Pablo Tierz: pablo.tierz@ingv.it

1 *Multihaz* parameterization

1.1 Definition of hydrological catchments

The triggering of lahars by rainfall typically requires (1) the availability of loose, readily mobilised pyroclastic material; (2) a rainfall event that is able to remobilise a significant amount of this pyroclastic deposit (through erosion or shallow landslides); and (3) steep slopes that favour such mass-wasting processes (Vallance, 2000; Pierson and Major, 2014; Mead et al., 2016). A slope inclination of 30° is often considered to be a threshold for gravitational stability of the deposit (Pareschi et al., 2000; Sulpizio et al., 2006) and it is this threshold which separates volcaniclastic erosion from deposition at other volcanoes (e.g. Chinen, 1986).

At Somma-Vesuvius, such steep slopes occur along the volcano edifice and over the topographic reliefs located towards the southeast, east and northeast from the volcano (Bisson et al., 2010, 2014). We deem all the catchments that have a substantial proportion of their upper area comprising slopes greater than 30° are potential sources of rain-triggered lahars (Figure 5 in the main text). Using a 20m-resolution Digital Elevation Model (DEM) as the base topography, we develop a procedure to identify and demarcate hydrological catchments that, in addition to containing steep slopes, share the following characteristics: (1) their areas are not smaller than about 0.08 km^2 (approximately 1/3 of the area of each grid point used to quantify the aleatory uncertainty in the pyroclastic volume, 0.25 km^2 as in Sandri et al., 2016); (2) they have at least one potential initiation point for lahars located on a slope greater than 5° (so the lahar simulations develop an inertial component at initiation); (3) their outlet points (i.e. the points where all the surficial runoff of the catchment should converge) are located further away than 1.5 km from the coastline (to give the lahar simulations some distance to propagate through).

The definition of both the hydrological catchments and the initiation points is done in a semi-automatic way by using an application of Quantum Geographical Information System (QGIS Development Team, 2016). Specifically, we carry out the following steps (e.g. Pistolesi et al., 2014): (a) we fill the sinks (i.e. local depressions) in the original DEM to obtain a realistic flow-direction raster; (b) we derive the flow-accumulation raster and the junctions of the channel network from the "filled" DEM; and (c) we calculate the watershed basins, that we refer to as catchments, from the channel network previously derived. Finally, we manually group the catchments and choose the initiation points (from the junctions automatically defined) in order to fulfil the requirements indicated above. We only overrule criterion (2) in the case of two catchments located on the Somma-Vesuvius edifice, simulation group 24 (see section 6.2 in the main text). We proceed in this way because, even though the exact DEM grid point where the lahar-initiation point is placed has a slope equal to or smaller than 5°, this initiation point is actually surrounded by a majority of DEM grid points with slopes greater than 5°.

In summary, we assume that all the catchments delimited will behave in a similar way when they experience a specific rainfall event and thus we use the general-purpose CPTs of the nodes WR, RD and RE for all the catchments.

1.2 Rainfall intensity at Somma-Vesuvius

The climate of the Campanian region can be classified as warm-temperate with dry and warm summers (Kottek et al., 2006). The area around Somma-Vesuvius receives average monthly precipitations from few tens of mm during summer up to few hundreds of mm during fall (e.g. Fiorillo and Wilson, 2004). In terms of rainfall intensity, average yearly maximum values can be in the order of 10-30 mm/h for rainfall events shorter than 6 hours but can be below 5 mm/h for rainfall events of 20 hours or longer (AdBCC, 2015).

Given that we separate rainfall intensity and duration in the structure of *Multihaz*, we build a PDF for RI alone. We separate rainfall intensity and duration because it is easier to obtain a probabilistic quantification of our variable of interest, RI. Nevertheless, we do model the widely-acknowledged inverse relationship between rainfall intensity and duration (e.g. Bernard, 1932; Houze, 1993) through the CPT of RD, whose parent node is RI. We use the Two-Component Extreme Value PDF described by Rossi et al. (1984), and used by AdBCC (2015), to model the (maximum yearly) rainfall intensity at each catchment over the study area. From such PDFs, we can calculate the prior probabilities for each state in the RI node. We choose two (general-purpose) thresholds: RI ≤ 1 mm/h for RI=low, RI > 10 mm/h for RI=high, and, 1 < RI ≤ 10 mm/h for RI=medium. We make sure that the thresholds are compatible with the parameterization of the WR node, given the infiltration capacity of the pyroclastic deposits (e.g. Favalli et al., 2006; Sulpizio et al., 2006). We note that our parameterization of the RI node is likely to be an overestimation of rainfall intensities, since we are using yearly maxima. However, the prior table of RI could be also specified by using real-time meteorological data, for instance.

2 ***LaharFlow* parameterization and boundary conditions**

LaharFlow is a dynamic physical model of lahars that is implemented on topography. *LaharFlow* includes empirical models for erosion and deposition, and a phenomenological model for the variation in the basal stress as a function of the composition of the flow.

LaharFlow models erosion by adopting a Shields criterion (e.g. Raudkivi, 1976), whereby material is entrained into the flow when the Shields stress (the non-dimensional shear stress acting on the base boundary of the flow) exceeds a threshold value that is dependent on the properties of the bed (specifically the grain size and density). When the critical Shields stress is exceeded, material is entrained from the bed into the flow at a rate that is a function of the excess of the Shields stress (Woodhouse et al., in prep).

In contrast to many hydraulic flows, the solids phase can constitute a very substantial proportion of lahars and significantly influence the flow dynamics. In *LaharFlow* we model the influence of the solids phase primarily through the basal frictional resistance to motion, referred to as the basal drag. Our model adopts a basal drag that varies as the concentration of solids (denoted by c) in the flow evolves. At low concentrations, we expect the solids to have relatively little dynamical influence, and so model the flow as a turbulent fluid with a basal drag that is velocity dependent; we take a Chézy drag formulation where the resistance takes the form $F_f = C_D|\boldsymbol{u}|^2$ where C_D is referred to as the Chézy drag coefficient and $\boldsymbol{u}$ is the depth-averaged flow velocity. If the solids concentration increases sufficiently, then the flow can transition to a (lubricated) dense granular flow. For granular flows, experiments suggest that a Coulomb basal drag is appropriate, where $F_g = \mu g h$ with μ referred to as the friction coefficient, g is the gravitational acceleration and h is the thickness of the flowing layer. Here we adopt a granular drag model proposed by Pouliquen (1999), calibrated using observations of lahars, that specifies a non-constant granular friction coefficient μ, allowing uniform flows to exist over a range of inclinations of the bed surface (as observed in experiments).

At intermediate concentrations, we expect both fluid-like velocity-dependent and granular-like depth-dependent basal drag forms to contribute to the bulk flow resistance. We model this transition between regimes by introducing a switching function, $f(c)$, so that the basal drag:

$$F = \left(1 - f\left(c\right)\right) \cdot F_f + f\left(c\right) F_g \qquad (1)$$

with $f(0) = 0$, $f(c_m) = 1$ and $f(c)$ monotone increasing for $0 < c < c_m$, where c_m is the maximum packing fraction of the grains. In this study we take $f(c) = \frac{1}{2}(1 + \tanh(\gamma\,(c - c_0)))$ with the parameters γ and c_0 calibrated against observations of lahars (Woodhouse et al., in prep).

The parameters in *LaharFlow* must be calibrated by comparison of the model predictions to laboratory or field observations. Given our primary aim of illustrating the coupling of *Multihaz* to *LaharFlow*, we use model parameters calibrated by Woodhouse et al. (in prep) for lahars at volcanoes other than Somma-Vesuvius. Moreover, we do not quantify the uncertainty present in the calibration process. Thus, the predictions of the lahar model must be considered as illustrative and highly uncertain. Nevertheless, they provide indications of the possible lahar dynamics and demonstrate the utility of coupling *Multihaz* to a deterministic flow simulator.

We initiate the model simulations with numerous sources distributed across the study region. At each source, we specify a simple time series to model the release of fluid from the catchment, with a volume flux $Q_j(t)$ for source j given by:

$$Q_j(t) = \begin{array}{c} Q_{mj}\, t/t_0 \text{ for } t<t_0, \\ Q_{mj}(t_1 - t)/(t_1 - t_0) \text{ for } t_0<t<t_1, \\ 0 \text{ for } t>t_1 \end{array} \qquad (2)$$

The total volume released at source j is then $V_j = Q_{mj}t_1/2$ which is specified through *Multihaz*. The specification of flux time series at the sources is preferred over instantaneous releases of a volume of material as a model of the source, but introduces additional parameters characterizing the release. In this demonstration of the *Multihaz* coupling to the lahar dynamical model we do not explore in detail the sensitivity of the predictions to the parameters in the source model, but take $t_0 = 150$ s and $t_1 = 300$ s for each source.

The confluence of channels is a point of interest in the flow dynamics as the combination of material can lead to overtopping of channels. Thus, the 273 catchments identified from the geospatial analysis of the region (see section 1.1) are partitioned into 24 simulation groups comprising sources that produce flows that have the potential to interact during their propagation. The flows from multiple sources in each group are simulated together. Without grouping the catchments in this way, the interactions of flows from different sources may not be correctly simulated. For simplicity, we model the sources as initiating simultaneously, but note that more sophisticated source initiation models could be adopted.

3 References

Autorità di Bacino Regionale della Campania Centrale (2015). *Piano Stralcio per l'Assetto Idrogeologico (P. S. A. I.): Relazione Idrologica (in Italian)*. Available online at: http://www.adbcampaniacentrale2.it/documenti/psai/relazioni/RelazioneIdrologica.pdf

Bernard, M. M. (1932). Formulas for rainfall intensities of long duration. *Trans. Am. Soc. Civ. Eng.* 96, 592–606.

Bisson, M., Spinetti, C., and Sulpizio, R. (2014). Volcaniclastic flow hazard zonation in the Sub-apennine vesuvian area using gis and remote sensing. *Geosphere* 10, 1419–1431.

Bisson, M., Sulpizio, R., Zanchetta, G., Demi, F., and Santacroce, R. (2010). Rapid terrain-based mapping of some volcaniclastic flow hazard using Gis-based automated methods: A case study from southern Campania, Italy. *Nat. Hazards* 55, 371–387.

Chinen, T. (1986). Surface erosion associated with tephra deposition on Mt. Usu and other volcanoes. *Environ. Sci. Hokkaido J. Grad. Sch. Environ. Sci.*, Hokkaido Univ. Sapporo 9, 137–149.

Favalli, M., Pareschi, M. T., and Zanchetta, G. (2006). Simulation of syn-eruptive floods in the circumvesuvian plain (southern Italy). *Bull. Volcanol.* 68, 349–362.

Fiorillo, F., and Wilson, R. C. (2004). Rainfall induced debris flows in pyroclastic deposits, Campania (southern Italy). *Eng. Geol.* 75, 263–289.

Houze, R. A. (1993). *Cloud dynamics*. Academic Press.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorol. Zeitschrift* 15, 259–263.

Mead, S., Magill, C., and Hilton, J. (2016). Rain-triggered lahar susceptibility using a shallow landslide and surface erosion model. *Geomorphology* 273, 168–177.

Pareschi, M. T., Favalli, M., Giannini, F., Sulpizio, R., Zanchetta, G., and Santacroce, R. (2000). May 5, 1998, debris flows in circum-Vesuvian areas (Southern Italy): Insights for hazard assessment. *Geology* 28, 639–642.

Pierson, T. C., and Major, J. J. (2014). Hydrogeomorphic Effects of Explosive Volcanic Eruptions on Drainage Basins. *Annu. Rev. Earth Planet. Sci.* 42, 469–507.

Pistolesi, M., Cioni, R., Rosi, M., and Aguilera, E. (2014). Lahar hazard assessment in the southern drainage system of Cotopaxi volcano, Ecuador: Results from multiscale lahar simulations. *Geomorphology* 207, 51–63.

Pouliquen, O. (1999). Scaling laws in granular flows down rough inclined planes. Phys. fluids 11, 542–548.

QGIS Development Team (2016). QGIS Geographic Information System. Available at: http://qgis.osgeo.org.

Raudkivi, A. J. (1976). Loose boundary hydraulics. Oxford: Pergamon Press.

Rossi, F., Fiorentino, M., and Versace, P. (1984). Two-Component Extreme Value Distribution for Flood Frequency Analysis. *Water Resour. Res.* 20, 847–856.

Sulpizio, R., Zanchetta, G., Demi, F., Di Vito, M. A., Pareschi, M. T., and Santacroce, R. (2006). The Holocene syneruptive volcaniclastic debris flows in the Vesuvian area: Geological data as a guide for hazard assessment. *Geol. Soc. Am. Spec. Pap.* 402, 217–235.

Vallance, J. W. (2000). Lahars. *Encyclopedia of Volcanoes*, Ed. by Sigurdsson, H, Houghton, BF, McNutt, SR, Rymer, H, Stix, J, 601-616.

Woodhouse, M. J., Hogg, A. J., and Phillips, J. C. (in prep). A dynamic model of lahars for hazard assessments.