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Proposal of a model for simulation of debris flow on basin level with different rheology approaches and flow directions algorithms

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INTRODUCTION

Debris flows are natural phenomena that act in the transformation of landscape, but when occurring directly over or near anthropogenic areas, could result in great disasters. Preventive actions are, therefore, necessary for risk management and mitigation of resulting impacts. Identifying susceptible areas is essential, but there is no definitive and standardized methodology for mapping debris flows transport and deposition areas.

Among the applicable methods, the use of computational models stands out due to the possibility of representing the dynamics of debris transport over the slopes. However, most of the available models depend on data that are difficult to obtain, such as the debris flow hydrograph, solids concentration and material granulometry (*e.g.* PITMAN et al., 2003), making the analysis unreliable in regions with data scarcity. On the other hand, models that require less information, usually empirical (*e.g.* PROCHASKA et al., 2008; HORTON et al., 2013), seek to predict debris flow susceptible areas through statistical relationships. Empirical models do not aim to represent the physical processes associated to the phenomena, being unable to reliably generate important information for disaster risk management, such as flow velocity, propagation time, flow height and its deposition. There is, then, a need to consolidate models of simpler application, which require fewer input parameters, but that remain sufficiently capable of predicting debris flow susceptible areas.

Chiang et al. (2012) proposed a model for representing mass movements, coupled with a debris flow module which requires simpler data to be implemented. The module seeks to simulate debris flow transport and deposition by the application of equations based on a Newtonian fluid approach, coupled to a flow direction algorithm based on topography. The approach proved to be promising, providing information regarding the affected area, deposition depth and reached velocities with little input data required. With these considerations, the present research seeks to answer the following questions: could different flow direction algorithms improve the representation of debris flow? And what is the impact of different rheology approaches on these simulations? For this purpose, a grid-based model was developed, inspired by the proposal by Chiang et al. (2012), adding different methodologies for determining flow direction. To perform the analysis, debris flows occurring in the Mascarada River Basin, Brazil, in January 2017 were simulated and compared to field and remote sensed data.

METHODS

The grid-based model utilized in this study is based on Chiang et al. (2012) debris flow routing method. The model utilizes a pre-processed DEM to determine the flow path and calculates the volume flowing outwards of a cell based on flow height. The simulation ends when the difference of height between time steps in all cells are inferior to a predetermined value. The model was developed in Python 3.7. To test the effects of flow direction algorithms on the simulation routes and effects of rheological approaches on the velocity's calculations, two different sets of simulations were performed. A flowchart summarizing the methodology is shown in Figure 1.

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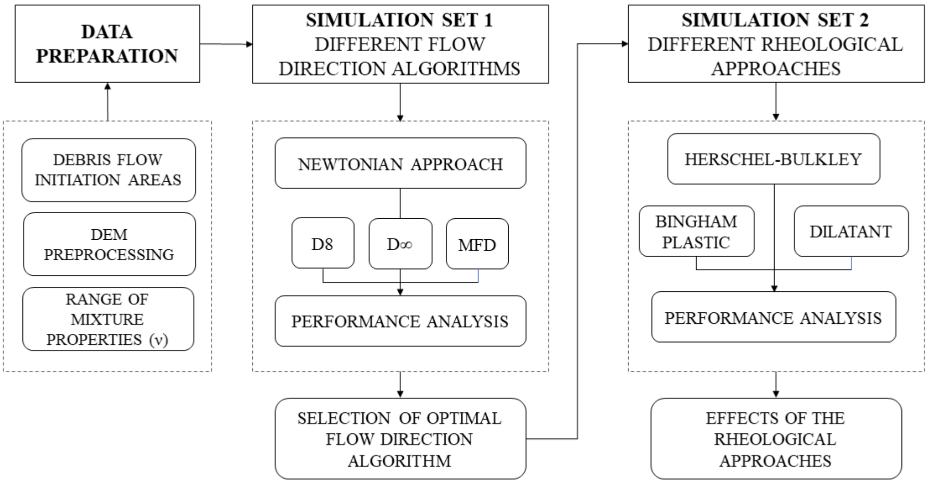

Figure 1. Study's methodology flowchart

Flow velocity for Newtonian, generalized Herschel-Bulkley and dilatant rheology are based on 1D laminar flow solution (HUNT,1994; JAN; SHEN, 1997). A generalized equation for the mean flow is given by:

$$U=\left(\frac{m}{m+1}\right)\left(\frac{g\cdot(h-z')^{m+1}\cdot\sin\theta}{\nu_m}\right)^{\frac{1}{m}}\left(1-\frac{m}{2m+1}\frac{h-z'}{h}\right) \qquad (1)$$

U is the mean velocity [m/s]; $\nu_m=\mu/\rho$ is the mixture kinematic viscosity [m²/s]; g is the gravity acceleration [m/s²]; h is the flow height [m]; θ is the slope angle [°]; z' represents fluid's yield stress as a plug height [m], therefore flow depths equal or below z' result in $U = 0$; m is the flow index (=1 for Bingham and Newtonian, >1 for dilatant; >0 and ≠ 1 for Herschel-Bulkley). The unitary flow ($q=U\cdot h$) is transported to the next cell based on the routes determined by the flow direction algorithm. This study utilized three different flow direction methods: Deterministic eight – D8 (O'Callaghan and Mark, 1984), D∞ (Tarboton, 1997) and Freeman's (1991) Multiple Flow Direction. To evaluate flow depth changes for each time step, the following mass balance equation is utilized:

$$\frac{\partial h}{\partial t}+\nabla q=0 \qquad (2)$$

Equation 3 expresses a balance of inflows and outflows of a cell linked to the eight surrounding cells:

$$h(t)=h(t-1)+\frac{\Delta t}{b}\left(\sum_{i=1}^{8} q_{in}-\sum_{i=1}^{8} q_{out}\right) \qquad (3)$$

b is the cell size [m]; q_{in} is the inflow [m²/s]; q_{out} [m²/s] the outflow, t the time step [s]. We utilized Heidke's score (Hs) – based on de Frattini et al. (2010) – to analyze the model performance. A perfect simulation has a H_S of 1. The utilized DEM has a pixel resolution of 1 m. Since the model cannot estimate flow velocities without slope values and may accumulate unrealistic volumes in pits due to flow convergences, DEM pits were removed. To test the resolution effects on the model, the DEM was downscaled to 2.5 m, 5 m, and 10 m resolution using bilinear interpolation. Based on the amplitude of measured rheological parameters of debris flow from Phillips and Davies (1991) study, the kinematic viscosity values ranged from 1×10^{-5} to 1 m^2/s.

RESULTS

D∞ and MFD performed better than D8, as indicated by the H_S. In terms of DEM resolutions, D∞ performed better with a 2.5 m DEM (H_S up to 0.63), whereas MFD performed better with the original 1 m DEM (H_S up to 0.63). Figure 2 shows the simulations that performed better with a 1 m DEM for each flow direction method: D8 resulted in the same H_S regardless of the kinematic viscosity since it reached the DEM edge; D∞ performance proportionally increased with kinematic viscosity, with the highest H_S at 1 m^2/s; MFD performed better with kinematic viscosity of 0.5 m^2/s. Final depths for D8 (982 m) were unrealistically higher in the simulations displayed in Figure 2, because it converged almost all initiation volume into a single cell at the DEM edge. The final depths of D∞ and MFD, on the other hand, were less than 0.52 m and 1.90 m, respectively.

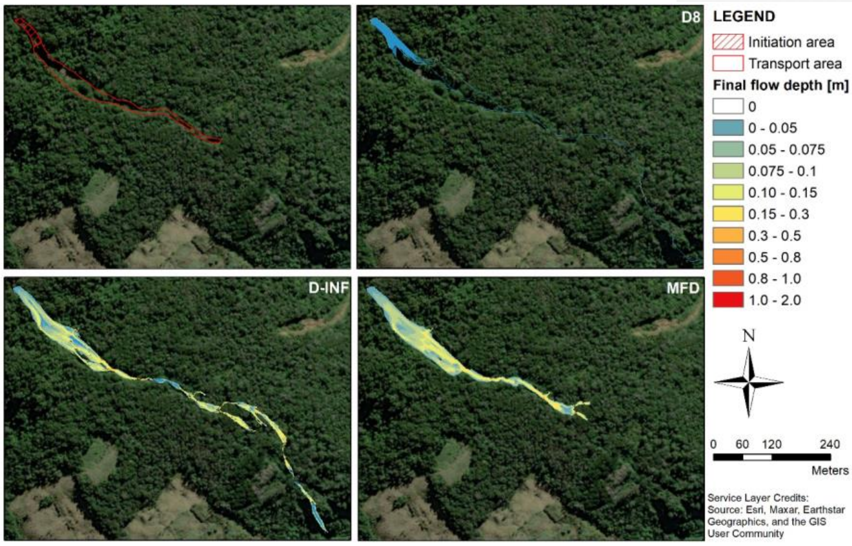

Figure 2. Simulations with best performance for each flow direction method.

Figure 3 shows plots with simulations performance for different rheological approaches. MFD was used as the flow direction algorithm because it performed better when applied to the original DEM. The upper plot show H_S values for dilatant and Bingham simulations, while the lower plot displays H_S for Herschel-Bulkley approach. Dilatant approach simulations resulted in H_S values up to 0.65. The simulation performances were higher for n of 1.2. For Bingham plastic, H_S values are clustered together for the same z', indicating little influence of this parameter over the simulation. For Herschel-Bulkley approach, H_S values tended to decrease with m lower than 1 as the ν_{HB} increased. Conversely, $m > 1$ simulations had an increase for ν_m up to 0.1 m^2/s, followed by a decrease as ν_m increased.

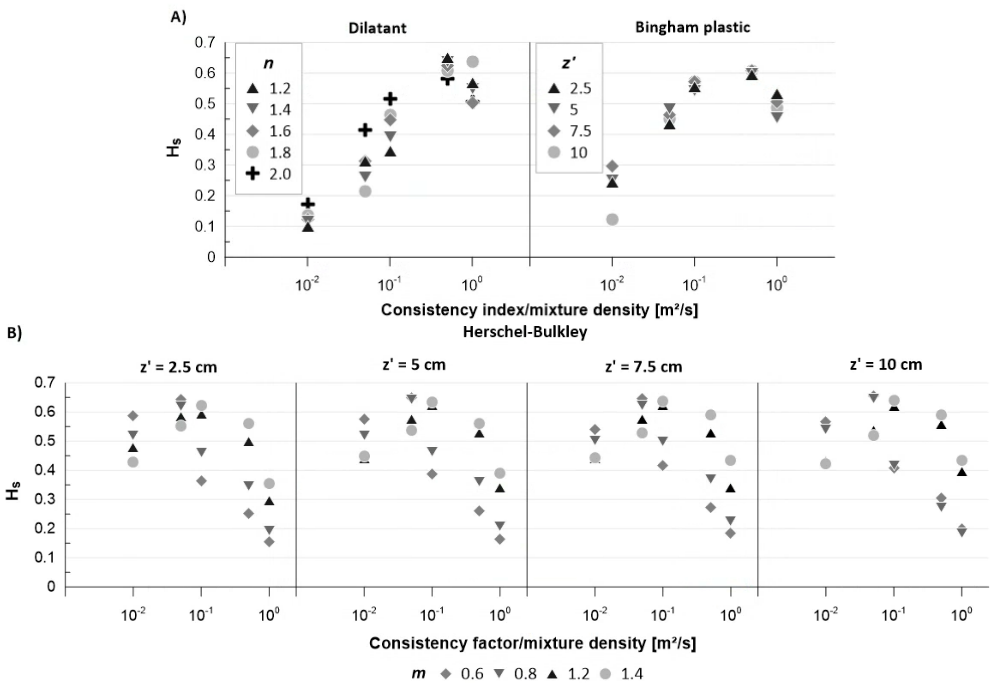

Figure 3. Performance for different rheological approaches to debris flow velocity calculations

CONCLUSIONS

This study evaluated effects of different rheological approaches and flow direction algorithms on a simplified model that requires few parameters to be utilized. In terms of flow direction algorithms, the MFD presented better performance for the original DEM resolution of 1 m. The MFD is capable to spread the flow to any surrounding pixel, therefore, reproduces more realistically the behavior of debris flow on flatter slopes. However, in low resolutions the flow spreading of MFD becomes a limitation. Furthermore, on steeper slopes, especially on the initiation zone, there is an overestimation due to excessive flow spreading. D_{∞} performance change is mixed: 2.5 m has the best performance, but as the pixel size increases the performance decreases.

Regarding rheology, the best results were obtained by dilatant with n of 1.2 and Herschel-Bulkley with m of 0.6 and plug of 10 cm, both considering a kinematic viscosity of 0.5 m^2/s. These two rheological approaches have very different behaviors, but rocky debris evidence from field surveys suggests that the flows in the region may behave as dilatant. The model is simple to calibrate since it requires few parameter inputs. It stays between a physically based model and a topographic descriptor, allowing for quick assessment of debris flow in areas with limited data and information. The model results can be used to verify areas prone to debris flow by providing information on volume distribution and flow velocities. However, deposition heights and flow velocities are calculated using simplified mathematical approaches and should be interpreted accordingly.

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