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Debris-flow hazard investigation with Kanako-2D in a rural basin, Alto Feliz municipality (Brazil)

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Abstract

Mountainous regions of Brazil, especially where rural families live, need to be assessed for debris flow. Though debris flows rarely occur in this country, they have caused serious damages including human losses. Computational modeling of debris flows is an important tool to develop hazard maps and to improve the understanding of debris-flow mechanisms, since observed occurrences are rare. Therefore, the objective of the present study was to evaluate the potential for debris flows in a small rural basin (0.712 km^2), in the municipality of Alto Feliz, Rio Grande do Sul state (Brazil), by using the Kanako-2D model which was calibrated with another debris flow in the same region. We simulated three scenarios by altering the debris volume and consequently the hydrograph (peak flow and peak time). All the scenarios show that debris flows would impact an existing rural house, even with the smallest potential debris volume. The modeled erosion and deposition areas along the debris flow are similar, with the magnitudes (depths) of erosion and deposition being different among the scenarios. In general, in each transversal section, the most pronounced point of erosion or deposition is almost always at the thalweg location. Along the stream channel, deposition was greatest upstream of an abrupt reduction in slope. The formation of a natural dam is observed at the channel junctions where erosion and deposition alternatively took place. Because of the investigation of the potential of debris flows, the simulation results were not compared with the actual occurrence in the present study. However, the present study could show that computational modeling of debris flow is very important for localities where debris flow occurs and that the debris-flow hazard map is useful for land-use planning.

Keywords: Debris flows; Kanako-2D; Southern Brazil.

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1. Introduction

In Brazil, ecotourism, construction of small hydropower plants, and establishment of water supply systems in headwater areas, have caused increased infrastructure development in mountainous regions. Increased occupation of mountain regions without adequate management has caused an increase in the frequency and magnitude of debris-flow disasters, especially in the last decade (Kobiyama et al., 2019). Under these circumstances, preventive measures based on scientific investigations are necessary to reduce the disasters. Numerical modeling is a useful tool for investigating the mechanism of debris flow and measures, such as hazard mapping and alert system implementation that can improve safety (Jacob and Hungr, 2005; Takahashi, 2007).

Debris flows usually occur in mountains regions and are rarely observed. Since they occur suddenly, it is very difficult to monitor and record them. After the scientific observation with continuous photos reported by Okuda et al. (1977), many photos and videos of debris flows have been captured around the world. However, the number of these materials that demonstrate debris flows in Brazil is small.

Hence the investigation of debris flow with numerical models should be carried out in Brazil. Among various computational models in the world, the Kanako-2D (Nakatani et al., 2008) has been applied to several areas and situations. The Kanako-2D was initially developed to evaluate the check-dams´ influences on debris flow

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propagation. However, it has been increasingly used for mapping areas susceptible to these events. Its good performance was confirmed by Michel and Kobiyama (2016), Paixão and Kobiyama (2017) and Kobiyama et al. (2018) that constructed hazard maps and visually compared with real occurrence of debris flows. Therefore, the objective of the present study was to investigate the potential of debris flows in a rural area of the Alto Feliz municipality, Rio Grande do Sul state, Brazil, by using this model calibrated by Kobiyama et al. (2018) that investigated a large debris flow which occurred in this region in December 2000. Note that at that time the debris flow caused the deaths of four peoples. In this municipality there are many places susceptible to debris flows, which has increased the worries of local inhabitants about the debris flows. Thus, it is thought that the investigation of the potential of debris flow by using the calibrated numerical model is useful for understanding the future disasters.

2. Materials and methods

2.1. Study area

The study basin (0.712 km²) is located within the Jaguar basin which is a rural area of Alto Feliz municipality, southern Brazil (Fig. 1). Elevation ranges from 290 m to 670 m. The Alto Feliz region has historically suffered from hydrological disasters, including flash flood and mass movement. In 2000 the Jaguar basin was damaged by an extreme rainfall event, which triggered several landslides that became debris flows (Michel, 2015).

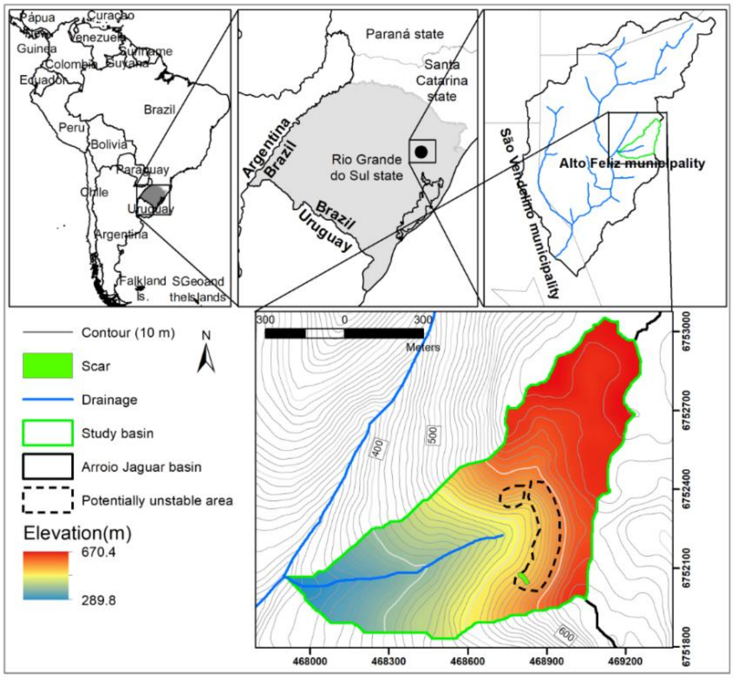

Fig. 1. Location of the study area

The study area is characterized by a mountainous landscape with steep hillslopes and vegetation consisting of native forest and eucalypt reforestation. Geologically it is located on the escarpment of the Serra Geral formation (basalt) (Viero and Silva, 2010). The predominant soils on hillslopes and near river networks are entisols and ultisols, respectively (Flores et al., 2007).

2.2. Kanako-2D

Kanako-2D (Nakatani et al., 2008) is a physically-based computational model and has a graphical interface, which allows the graphical modification of input parameters. The basic equations of the model are based on the theory established by Takahashi and Nakagawa (1991) and are shown below:

- Continuation equation for the total volume of debris flow:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=i \tag{1}$$

- Continuation equation for determining the debris flow of the k-th grade of particle i:

$$\frac{\partial C_k h}{\partial t}+\frac{\partial C_k uh}{\partial x}+\frac{\partial C_k vh}{\partial y}=i_k C_* \tag{2}$$

- Equation of momentum in x and y-axis:

$$\frac{\partial (u,v)}{\partial t}+u\frac{\partial (u,v)}{\partial x}+v\frac{\partial (u,v)}{\partial y}=g\ \sin\theta_{(wx,wy)}-\frac{\tau_{(x,y)}}{\rho h} \tag{3}$$

- Equation to determining change in bed surface elevation:

$$\frac{\partial z}{\partial t}+i=0 \tag{4}$$

where h is the flow depth; u and v are the velocities in the x and y-axis, respectively; C_k is the k-th sediment concentration by volume; z is the bed elevation; t is the time; i is the erosion/deposition velocity; i_k is the k-th erosion/deposition velocity; g is the gravitational acceleration; ρ is the interstitial fluid density; θ_{wx} and θ_{wy} are the flow surface gradient (in x and y-axis respectively); C_* is the sediment concentration in movable bed layer; τ_x and τ_y are the riverbed shearing stresses in the x and y-axis, respectively.

2.3. Input data

The present study considered three different scenarios for a debris flow simulation. There is a landslide scar mapped by the CPRM in the study area and this scar's area was used to construct Scenario 1. Scenario 2 adopted the mean area between Scenarios 1 and 3, for comparison. Scenario 3 considered that all areas determined as unstable in the basin by Michel (2015) collapse at the same time. Thus, it can be said that Scenario 3 is the largest possible event for the basin. According to Michel (2015) which carried out the field survey, the mean soil depth in this basin is 2 m. Then, this value was adopted and considered constant for all scenarios. Table 1 shows the values of the input parameters common to all scenarios. These values are similar to those used by Kobiyama et al. (2018) that calibrated this model to one debris flow whose locality is very near to the present study area.

Table 1. Kanako-2D input parameters common to all simulations

Parameter	Unity	Value
Mass density of bed surface	kg/m³	2650
Mass density of fluid phase	kg/m³	1000
Concentration of movable bed	m³/ m³	0.65
Manning's roughness coefficient	$s/m^{1/3}$	0.03
Coefficient of erosion rate	-	0.0007
Coefficient of deposition rate	-	0.05
Diameter of material	m	0.45
Internal friction angle	°	37
Minimum flow depth	m	0.01
Minimum depth at the front of debris flow	m	0.01
Concentration of material	m³/ m³	0.5

The debris flow propagation input is a hydrograph which is set at the upper part of channel (1D system). This hydrograph was constructed by following the triangle hydrograph theory of Whipple (1991), where the ascension duration is 1/3 of the total time. The hydrograph peak discharge was calculated using the formula proposed by Rickenmann (1999). The values of input parameters in each scenario are shown in Table 2. Scenario 1 supposed that the smaller unstable area (930 m^2) marked in Fig 1 suffers from shallow landslide and causes debris flow. Scenario 3 considered that the total unstable area (44062 m^2) marked in Fig. 1 generates landslide. Then Scenario 2 treated half of volume of Scenario 3. Therefore, three scenarios have the same hydrograph-form but the different magnitudes.

Table 2. Parameters variation in each case

Parameter	Unity	Value		
		Scenario 1	Scenario 2	Scenario 3
Sediment volume	m^3	1860.01	44,062.05	88,124.1
Peak discharge	m^3/s	52.9	738.7	1,316.02
Peak time	s	23.3	39.8	44.7

One of the main bases for the debris flow propagation in the model is topographic data, which were extracted from a digital elevation model (DEM) with a spatial resolution of 2.5 m, obtained from the Brazilian Geological Survey (CPRM). Since the present study treated the potential of debris flow, the year of the DEM construction is out of question.

2.4. Model application

According to Nakatani (2008), Kanako-2D simulates debris flow in the channel with one-dimensional equations (1D) and propagation and deposition with two-dimensional equations (2D). The outputs of simulations were: flow depth, material concentration, velocity in the two dimensions, bed surface altitude and deposition thickness, in each configured time interval. The present study focused on changes in deposit thickness with time.

The simulation result is limited, because the limit of the matrix size that can be used as the elevation model is restricted to 500 x 500 pixels. In the present study, the time interval for calculation was 0.01 s and the simulation time was one hour, in order to ensure that at the end of the simulations there would be no further changes on the bed of the modeled area.

In the study basin, the possible propagation channel was not observed on field. It implies the possibility to have various courses. Hence, the propagation area in one-dimension was minimized (only two pixels with 5m x 5m) and the two-dimension calculation area was maximized, because of the restricted pixels.

3. Results and discussion

Fig. 2 shows the results of three simulated scenarios, which allows the comparison between the flow propagation in each case. The whiter color presents the larger thickness of the deposition layer, meanwhile, the blacker the more erosion in all the scenarios. Due to the model spatial limitation, the flows propagated to exceed the maximum simulation area. However, it did not cause the difficulty to analyze the phenomena, because the very small volume reached the final pixel of simulations.

Scenario 1 represents propagation of the smallest volume, which results in a smaller deposit extent and also a smaller difference between the maximum erosion and maximum deposition (Fig. 2a). In Scenario 3, which has a volume of material that is 47 times than Scenario 1, the difference between the maximum erosion and the maximum deposition is approximately 10 m (Fig. 2c). All the scenarios indicate that an existing house inside the study basin would be affected by a debris flow, regardless of the propagated volume. It is noted that the largest depth of erosion was 2 m due to the fact that this was the maximum depth of soil configured in the model.

Fig. 2d shows the locations at which the cross sections were made along the longitudinal profile of the debris flow travel path. Fig. 3 shows the longitudinal profile along the river thalweg before and after the debris flow occurrence in Scenario 3. In the upstream portion the largest change in the riverbed was a deposition of 7.98 m. This large deposition resulted from the entrance of debris in the channel in the upper part of the thalweg and also from the abrupt change of slope of the thalweg that is present approximately at the altitude of 400 m (Fig. 3).

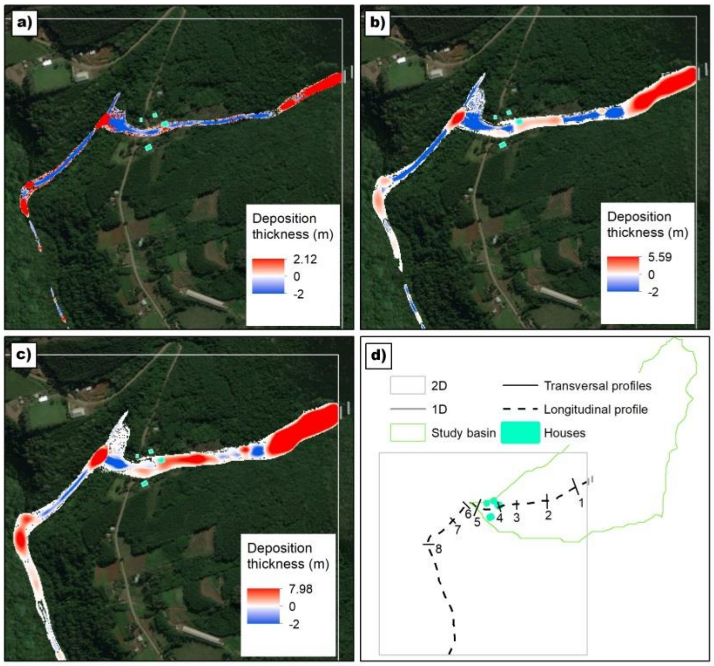

Fig. 2. Results of simulations: a) Scenario 1; b) Scenario 2; c) Scenario 3; and d) cross-sections localities.

It is apparent along the longitudinal profile that there is a semi-regular occurrence of erosion and deposition of debris, which are presented in agreement with the abrupt or smooth variations of channel slope, respectively. The portions of the flow with higher deposition are in the intervals with lower slope along the channel.

Other accumulation points of material are in sections 6 and 8. These two sections are located in a neatly embedded channel and there is accumulation of material, even with the propagation of a low volume in the debris flow. Precisely for this reason, these places possess the potential for natural dams to form.

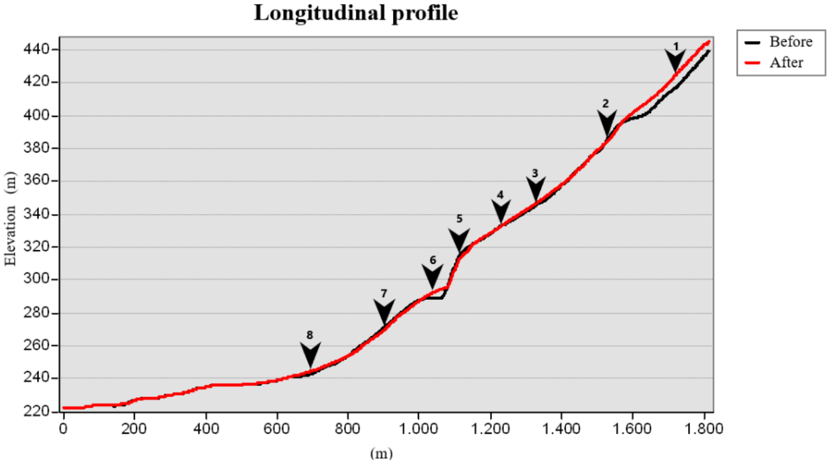

Fig. 3. Debris flow longitudinal profile. After and before Scenario 3.

Fig. 4 shows changes in profiles at 8 cross- sections, whose locations are indicated in Fig. 3, before and after debris-flow occurrence of Scenario 3. The profiles are distributed along the river, perpendicular to the thalweg. Note that the profile is viewed in the upstream direction. Deposition occurred at cross-sections 1, 3, 4, 6 and 8, while erosion occurred at cross-sections 2, 5 and 7 (Fig. 4). At cross-section 4 the arrow indicates the location of a residence near the channel, demonstrating that the residence is susceptible to debris flow impacts in the future.

The deposition forms a normal pattern, with higher deposition rates upstream, and lower rates further downstream. Besides, the deposition surface is approximately parallel to the horizontal line. The surfaces formed by erosion present a “V” shape.

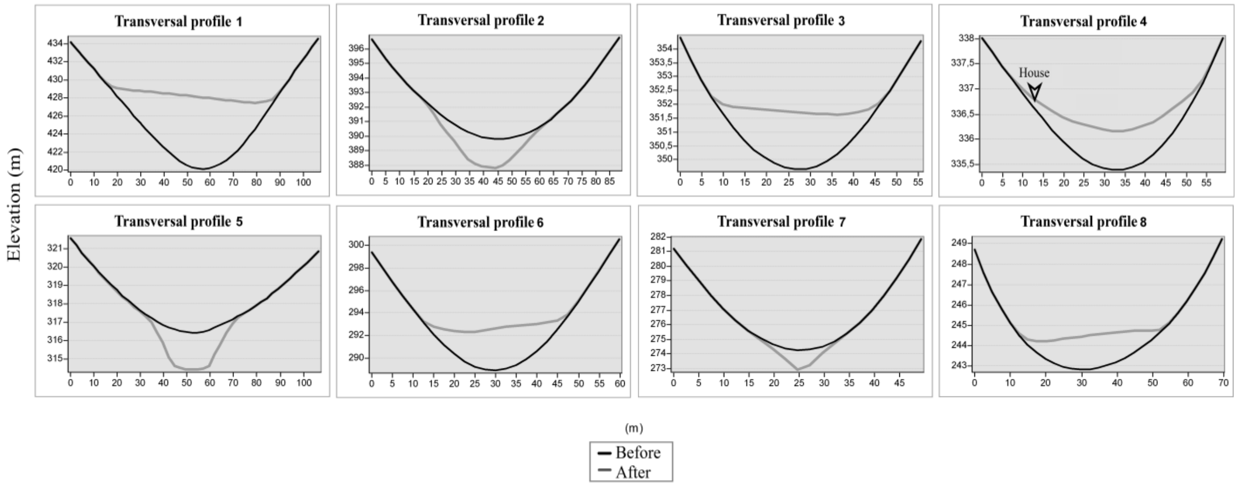

Fig. 4. Transversal sections to debris flow. After and before at the Scenario 3.

Near cross-section 6 there is a confluence (Fig. 2). Fig. 5 demonstrates the erosion and deposition dynamics at the confluence during different time steps. Just after the confluence point, the deposition process is more predominant meanwhile just before the confluence erosion dominates. After reaching the confluence point, the debris flow propagation generated a backwater processes in the direction of the affluent upstream. At the time step 1800 s, the influence area along the affluent stream reached about 100 m. As the debris flow dynamics is very complex at the confluence, more detailed analyses should be numerically done in a future study. Though the simulation results are nor confirmed on field, the local inhabitant should recognize the possibility that at the confluence point a part of debris flow go upstream.

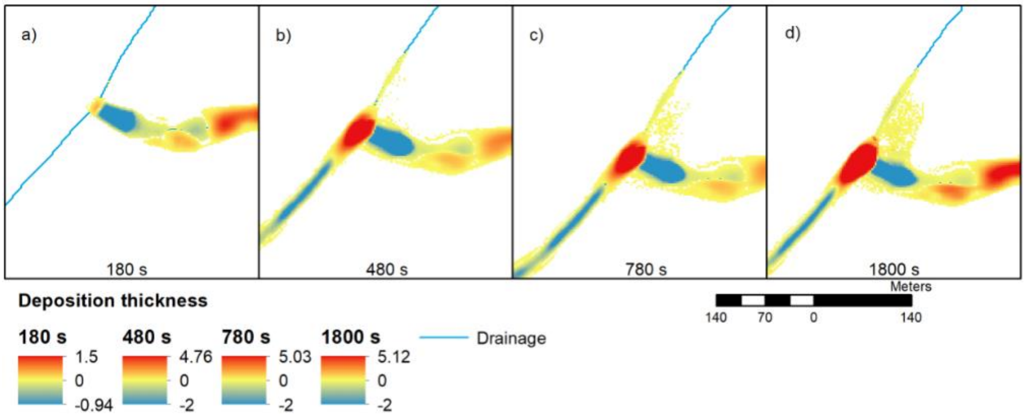

Fig. 5. Detailed results of simulation at the confluence: a) 180 s; b) 480 s; c) 780 s; and d) 1800 s.

In case of the context of the alert system, it is very important to know the speed of the debris flow. In order to observe this speed, the flow propagation features at the different time-steps are demonstrated in Fig. 6. By using each runout map in Fig. 6, the mean speeds of the debris flow through its evolution on time were estimated (Table

3). Though the speed is slightly reduced along the downstream displacement, the reduction rate is not exactly linear to the time or to displacement.

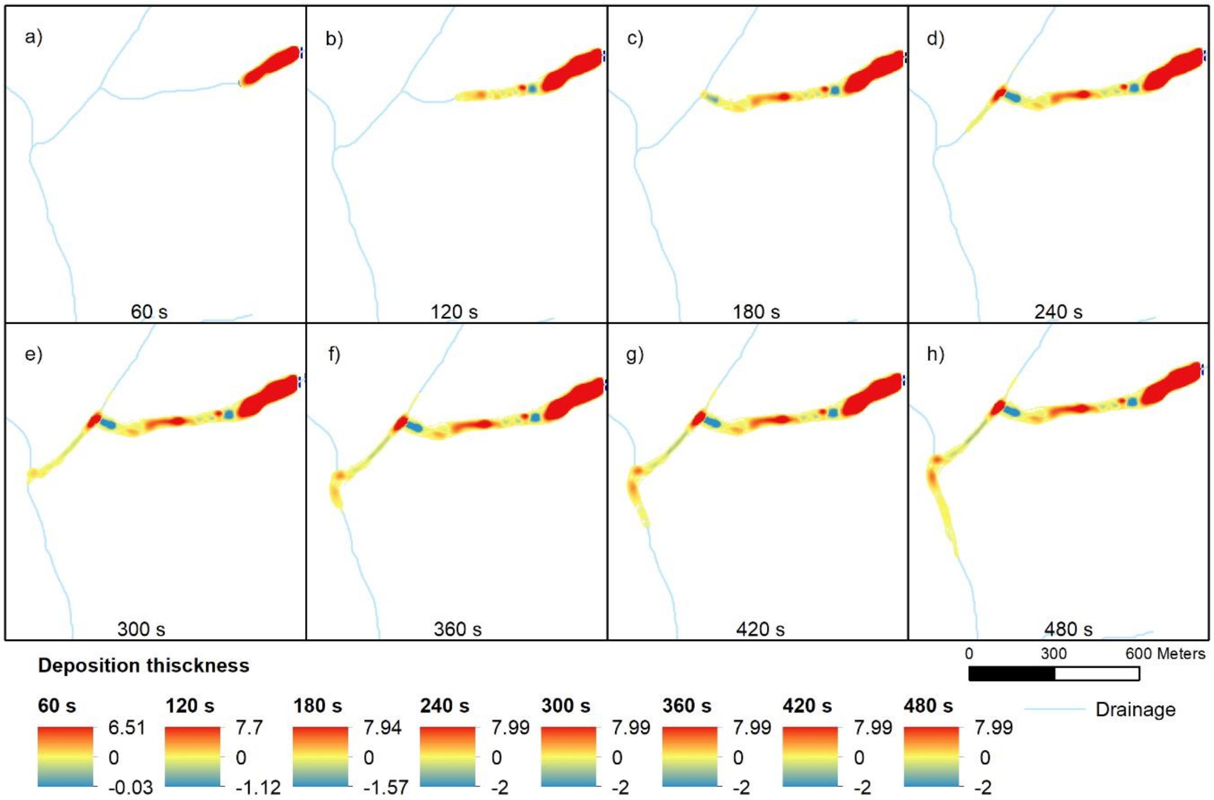

Fig. 6. Temporal evolution of the debris flow: a) 0 s to 60 s; b) 60 s to 120 s; c) 120 s to 180 s; d) 180 s to 240 s; e) 240 s to 300 s; f) 300 s to 360 s; g) 360 s to 420 s; and h) 420 s to 480 s.

Table 3. Displacement and speed variations of the debris flow over the time.

Time interval (s)	L (m) (horizontal variation)	ΔS (m) (vertical variation)	Displacement (m)	Mean spead (m/s)
0 - 60	242.69	42.91	246.45	4.11
60 - 120	306.92	59.29	312.59	5.21
120 - 180	198.36	47.32	203.93	3.40
180 - 240	190.4	24.25	191.94	3.20
240 - 300	151.03	20.16	152.37	2.54
300 - 360	91.87	4.44	91.98	1.53
360 - 420	79.85	3.13	79.91	1.33
420 - 480	144.27	2.39	144.29	2.40

4. Conclusions

Computational modeling of the debris flows is an important tool to make hazard maps of this phenomenon and also to comprehend its occurrence mechanism. This importance should be emphasized in countries which have rare occurrence of debris flow and suffer from large damages due to this phenomenon. Therefore, the present study applied the Kanako-2D model to a small basin, the majority of which is covered by forest and characterized by the mountains environment in the municipality of Alto Feliz, southern Brazil.

By changing the debris volume and consequently the hydrograph (peak discharge and peak time), three scenarios were simulated. Regardless of the scenarios, the hazard maps generated with all scenarios show that the debris flow would destroy an existing rural house. Though the localities of erosion and deposition in the stretch of the debris flow are similar among the scenarios, their magnitudes (depths) of erosion and deposition were different among them. In general, at each cross-section, the most pronounced local of erosion or deposition is almost always the thalweg location.

Numerical modeling research allowed the recognition of debris flow dynamics at confluence as well as flow speed. Though the comparison between numerical simulation results and field observation of actual occurrences is essential for debris-flows studies, only computational investigation also has its own importance because the phenomenon is comparative rare. In this sense, the Kanako-2D model remains very useful especially in Brazil.

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