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Possibilities and limitations for the back analysis of an event in mountain areas on the coast of São Paulo State, Brazil using RAMMS numerical simulation

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Abstract

Debris flows are mass movements that develop along drainage networks and involve generally dense fluids, compose of materials of different grain sizes, as well as woods and variable amounts of water, identified as natural processes that constitute the dynamics and the modeling of the landscape. The areas most susceptible to the occurrence of these processes in Brazil are in the foothills of the Serra do Mar, Serra da Mantiqueira and the Serra Geral, and on the north coast of São Paulo State. In 03/18/1967 there was an important landslide and debris-flows which affected the region of Caraguatatuba and São Sebastião. In this area, there is a pipeline network associated with Petrobras Treatment Units, other enterprises, structures and a large urban area in growth. The aim of this work is to show the results of the back-analysis of the debris-flow events that occurred in 1967 in a mountain area in the Serra do Mar in Caraguatatuba region (São Paulo State, Brazil) with RAMMS numerical simulation, using calibrated input parameters. The inputs were viscosity, DEM, landslide scars as release areas, the density of the debris-flow material, duration of debris-flow process and orthophoto. The modeling results were compared with the deposit area mapped in aerials photos, which was established zones of iso-thickness of the materials. The results showed a good correlation between the area and thickness of deposition modeled and observed. Moreover, the fieldwork and the retro-analysis studies revealed that the Serra do Mar debris flows have a predominantly granular rheological flow and the modeling results showed that the deposition zones are given preferably in regions with slope less than 5º.

Keywords: Numerical simulation; RAMMS model; Serra do Mar; Brazil

1. Introduction

Debris flows are rapid downslope, gravity-driven movements of materials behaving as, highly viscous, dense and concentrated to hyperconcentrated fluids. Debris-flow processes can comprise large volumes of soils, blocks of rocks, wood and other plant materials, man-made structures, and varying amounts of water. Often initiated by heavy rainfall and/or landslides, debris-flows process commonly develop along steep thalwegs and deposit in flat areas (Selby, 1993; Hutter et al., 1994; Takahashi, 2014; Kang and Lee, 2018). They are characterized by the long range, high speed, high peak flow, high erosion capacity, impact force and for this they constitute an important risk factor for the population (Begueria et al., 2009; Kang and Lee, 2018).

Mathematically, debris flows can be described as a one-phase fluid composed by an interstitial liquid and by a granular fluid that constitutes the solid phase and has proper rheological properties (Iverson, 1997; Rosatti and Begnudelli, 2013; Liu et al., 2017). This represents a simplification of a debris-flow process where the main components are water and solid material consisting of a wide range of grain sizes (Rickenmann et al., 2006). Thus,

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several numerical models have been elaborated in the last years, to measure, identify, predict and monitor debris-flow processes with more accuracy, as FLO-2D, KANAKO 2D and MassMov2D (Pudasaini, 2005; Wu et al., 2012). One of these models is RAMMS (Rapid Mass Movement Simulation), which uses a single-phase model, that doesn't distinguish between fluid and solid phases and the material is modeled as a bulk flow. This model describes the frictional behavior of debris-flows movement using the Voellmy relation (Christen et al., 2010).

The most susceptible areas to debris-flow processes in Brazil are located in the southeastern in the SW-NE oriented foothills of Serra do Mar, Serra da Mantiqueira and Serra Geral. In the city of Caraguatatuba (São Paulo State), one of the most expressive brazilian mass movements event occurred in 1967, triggered by heavy rains. It is estimated that a huge volume of earth material and over 30,000 trees descended the Serra do Mar slopes of the and reached the city, totally or partially destroying 400 houses, and killing 120 people (Gomes et al., 2008a).

Studies involving modeling of debris flows both, retro- and forward analysis are still very rare in Brazil. The pioneering work of Alvarado (2006) used of the Discrete Element Method (DEM) to simulate debris-flow process and in the last years Lopes and Riedel (2007), Gomes et al. (2008b), Polanco (2010), Bueno et al. (2013), Gomes et al. (2013), Sakai et al. (2013), Silva et al. (2013), Conterato (2014), Pelizoni (2014), Rocha et al. (2014), Sancho (2016), and Silva-Filho (2016) also included in their scope studies of brazilian debris-flow cases involving mathematical modeling.

Thus, the aim of this work is to show the results of modeling of a debris-flow process occurred in 1967 in a mountain area in the Serra do Mar in Caraguatatuba region (São Paulo State, Brazil) with RAMMS numerical simulation, using parameters calibrated as input, obtained by retro-analysis of the event. In the last years, there has been an increase in the occurrence of these phenomena in Brazil, which demands a better understanding of their conceptual model. In the Serra do Mar region there is a pipeline network associated with Petrobras Treatment Units, roads, industries and a large urban area in growth, which increases the risk factor for debris-flow movements.

1.1. Study area

The study area is the Santo Antônio river basin (Fig 1), inserted in the Serra do Mar mountain range, an escarpment area on the eastern margin of the Brazilian highlands, which has been known to be the most landslide and debris flows prone location in Brazil, due to the local hot and humid climate and its long slopes (Cruz, 1974; Lacerda and Silveira, 1992; Cruz, 2000; Cerri et al., 2018). The region has as a humid tropical climate with dry season. Rainfall is concentrated during summer, which amounts for 70% of the annual total, while winter months (June to August) are characterized as the dry season, with monthly precipitation around 100 mm. The annual precipitation ranges from 1,784 to 2,000 mm and the annual average temperature is 27°C (Cruz, 1974; Seluchi et al., 2011).

The Santo Antônio river basin, which has an area of 37.5 km^2, extending from the Serra do Mar escarpments to alluvial and coastal plains, the Caraguatatuba urban area. The most upstream portions of the catchment are characterized by particularly steep slopes, while the downstream areas are very flat area (Fig 2), where urbanization is still expanding (Sakai, 2014).

The geology encompasses neoproterozoic rocks, such as to gneisses, migmatites, migmatitic gneisses, granites, schists and quartzites, with a predominant NE-SW structural orientation (Almeida, 1964; Chieregati et al., 1982; Cerri et al., 2018). The lower section of the Santo Antônio Basin is composed of unconsolidated sediments such as sands, silts, clays and fluvial gravels, as well as colluvial sediments and beach, marine and fluvial-marine deposition sands (Chieregati et al., 1982).

1.2. The 03.18.1967 event

The occurrence of the 1967 event in Caraguatatuba is related to the incidence of high rainfall rates that affected the region in March of the same year. So, about 945.9 mm were recorded in this month, from that, 260 mm and 325 mm were recorded on 17th and 18th, respectively. In the day of the event, 585 mm accumulated in 48 hours (IPT, 1988).

Landslides began on the morning of March 18th and were gradually occurring until the afternoon, a period that registered its most critical phase, in a generalized and simultaneous manner, particularly on slopes steeper than 22º (Cruz, 1990; Gramani, 2001) (Fig 3).

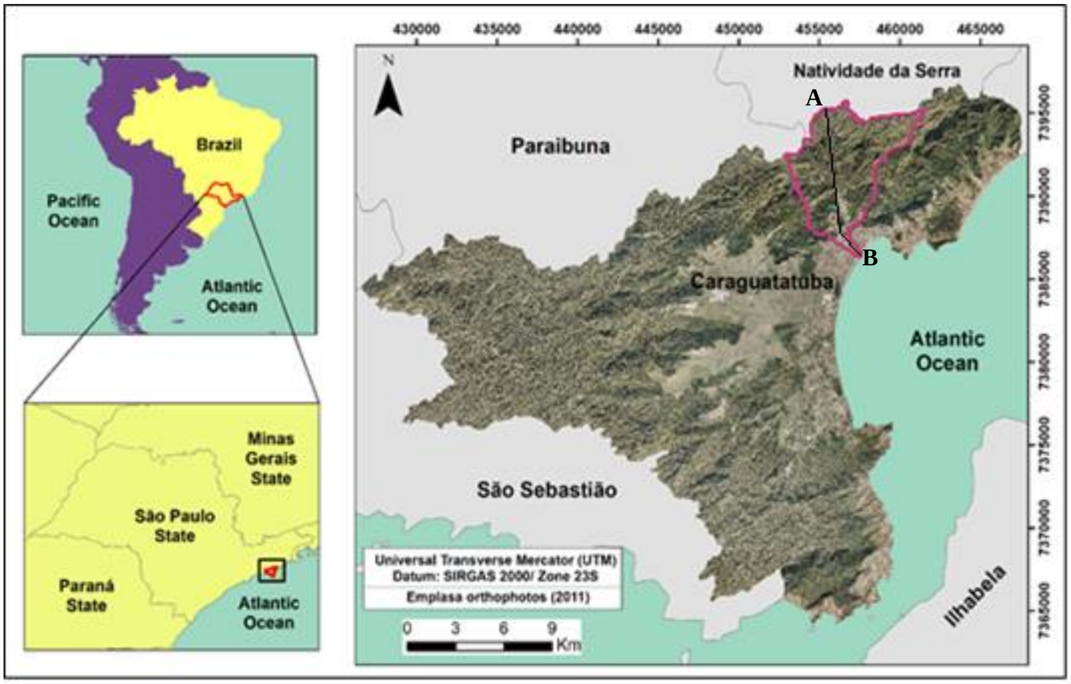

Fig. 1. Location map of the study area. The Santo Antônio basin is marked on pink. The A-B section represents the profile path (Fig 2).

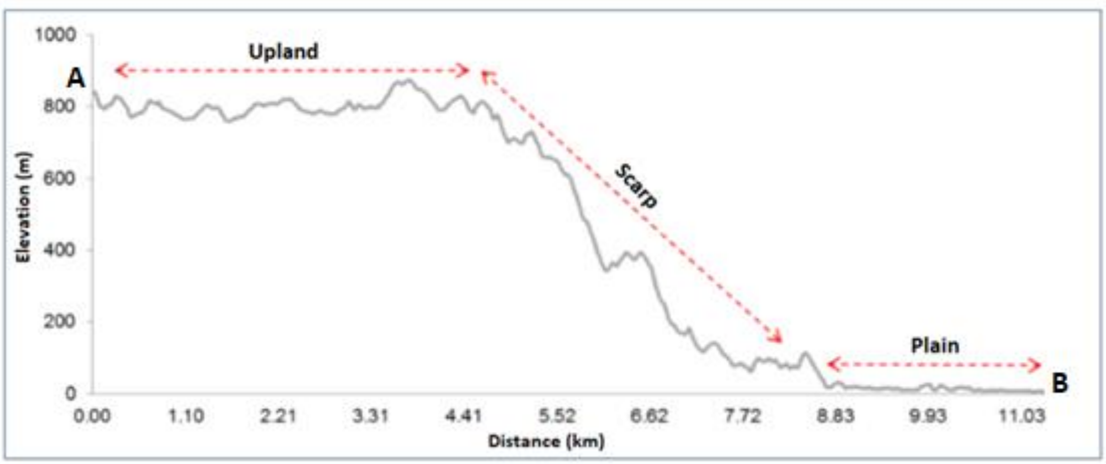

Fig. 2. Topographic profile of Santo Antônio Basin. The relief in the catchment is compartmentalized in upland, escarpment, and plain, whose associated features are mamelonized hills, predominantly retilinized slopes, and flat areas, respectively (Cruz, 1974). Adapted from Nery (2016).

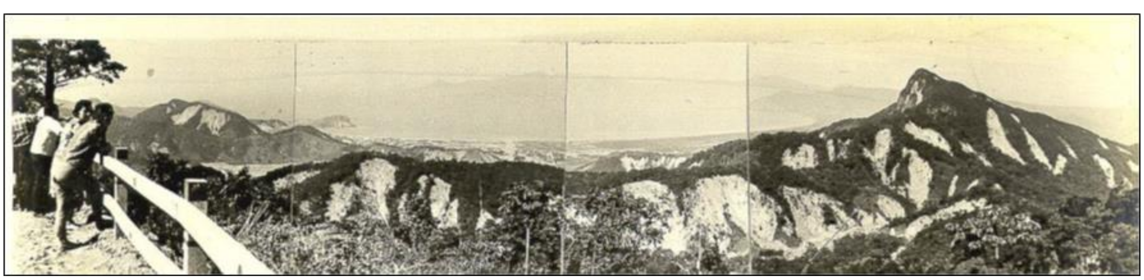

Fig. 3. Landslide scars on the Serra do Mar slopes in the Santo Antônio basin. The photo was taken from a belvedere on the Tamoios Highway, main access road of the plateau to the coast, one month after the occurrence of the events of 03/18/1967. Landslide scars are mainly distributed on slopes with slopes greater than 22º. Photograph by Cruz (1974).

Around 4:15 pm, after the material mobilized by the landslides converged almost simultaneously to the main drainages of the mountainous region and were channeled, causing debris-flow process, that transported a great amount of earth and biomass. After 5 pm, in the final section of the river, next to the coast, the processes of mud flow and mud flood began, so that the material mobilized by these processes accumulated in a bridge of the Santo Antônio River and caused its disruption, which promoted a flood in the whole plain of the river with lots of mud and logs, reaching the urban area and the beach, where drainage flows into the sea (Cruz, 1974) (Fig 4). In the fieldwork

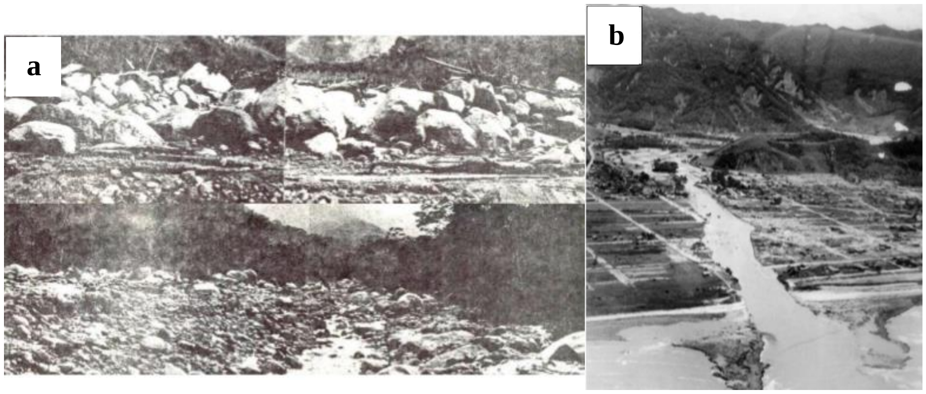

Fig. 4. Mud flow, mud flood and debris flows of 03/18/1967 in the Santo Antônio basin in Caraguatatuba. (a) Blocks mobilized during the process, near the landslides, in the tributary channels and in the middle section of the main river of the Santo Antônio basin. In the fieldworks, the block deposits also were observed in the middle section of the main channel. (b) Aerial view of the escarpments with the landslide scars and the plain with mud flow and mud flood processes. Photographs by Cruz (1974) and municipal archives of Caraguatatuba.

1.3. The RAMMS model

RAMMS (Rapid Mass Movement Simulation) is a numerical 2D simulation model developed by the WSL Institute for Snow and Avalanche Research SLF and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL. The physical model of RAMMS uses the Voellmy-Salm continuous flow model (Salm et al., 1990; Salm, 1993) based on Voellmy friction law (1955) and describes debris-flow processes as a continuous model of medium depth. This model divides the frictional resistance into two parts: a dry-Coulomb type friction (coefficient μ) that scales with the normal stress and a velocity-squared drag or viscous-turbulent friction (coefficient ξ). Thus, the friction resistance S (Pa) is defined as

$$S = \mu\rho Hg cos(\emptyset) + \frac{\rho g U^2}{\xi} \qquad (1)$$

where ρ is the density, g the gravitational acceleration, $\emptyset$ the slope angle, H the flow height and U the flow velocity. The normal stress on the running surface, $\rho Hg cos(\emptyset)$, can be summarized in a single parameter N. RAMMS uses a single-phase model, so we cannot distinguish between fluid and solid phases and the material is modeled as a bulk flow. Regarding the entrainment of bed materials, the version v1.5 does not consider the erosion effect, so it is not possible to predict the increase in volume of the debris-flow material as it travels along the channel.

The input parameters of RAMMS are the total volume of the debris flow and the resistance parameters μ and Ɛ. As output data, the program provides values (for each grid cell) of flow height, flow velocity, flow pressure, impact forces, as well as profiles of height, velocity and flow pressure at certain locations for projecting structures (Bartelt et al., 2013).

2. Materials and methods

2.1. Back-analysis studies of the 03/18/1967 debris flows

The back-analysis studies included the historical retrieval of the variables that involved the debris-flow processes in the Santo Antônio basin in March 1967, the extraction of the landslide scars and the mapping of the deposits and their respective thicknesses (Gregoretti et al., 2016). The main causes of occurrence of the event were investigated through bibliographical research on reference works, including photographic and cartographic registration.

For the landslides scars extraction aerial photos in 1: 25,000 scale with 1.5 x 1.5 m spatial resolution of the VASP (São Paulo Airway) aerial photogrammetric survey were selected for the respective procedures. The extraction was performed using photointerpretation techniques in a GIS environment so that the size, the vegetation, the texture and shape were the criteria considered to the identification (Loch, 1984; Marchetti and Garcia, 1986; Barlow et al., 2003; Guzzetti et al., 2012). The mapping of the debris-flow deposits and their respective thicknesses was also carried out in the GIS environment using photointerpretation techniques (Vandine, 1985; Van Steijn, 1996), complemented information from bibliographical data and fieldwork.

2.2. Debris-flow modeling RAMMS

Prior to numerical modeling in RAMMS, the program input parameters were listed and modified according to the model needs. Thus, the topographic data from the DEM was converted to ASCII format. Moreover, the calculation domain and the release area were transformed to the shapefile format and the release height was inserted in the program/ imported of the shapefile attribute table of the release areas. The information about debris flow duration, the material density and μ/ ξ parameters were obtained from bibliographical data (Table 1).

The modeling step in the RAMMS version 1.5 program was performed through the establishment of a simulation routine, based on different release heights, material density, and viscosity (ξ).

3. Results and Discussion

Before the modelling in the RAMMS program, the input parameters were adjusted according to the its requirements (Table 1).

Table 1. Input parameter, data source and numerical parameter required in the RAMMS model

Input	Source	Numerical parameter
Topographic data	DEM in 1:10,000 scale, from 1979	Grid of 8 m
Release area	Landslide scars from aerial photos (1973)	-----------
Release height	Back-analysis (Fúlfaro et al. 1976; Massad et al., 1997; Massad, 2002) and fieldwork observations	1.0 m 1.3 m
Calculation domain	Santo Antônio basin with 600 meters buffer	------------
Debris flow duration	Back-analysis (Gramani, 2001)	45 min (2,700 s)
Material density	Back-analysis (Fúlfaro et al., 1976; Listo and Vieira, 2015)	Fúlfaro et al. (1976) – 1.8 ton/m^3 (1,800 kg/m^3) Listo and Vieira (2015) – 1,800 kg/m^3, 1,900 kg/m^3 e 2,000 kg/m^3
μ (dry-Coulomb type friction coefficient)	Back-analysis / tan(α) (α is the slope angle in the deposition zone)	0,05 [-] (slope angle in the deposition zone (2.9^0) was obtained by photointerpretation analysis in the debris flow deposit)
ξ (viscous-turbulent friction coefficient)	Back-analysis (flow characteristics described by Cruz (1974), Fúlfaro et al. (1976) and Gramani (2001)) and empirical tests	100, 130, 160, 190 and 200 m/s^2

From the presented inputs, the simulations routine conducted in the program was based on the different thicknesses of the landslide scars, material density, and viscosity (Table 2).

Table 2. Simulation routines in the RAMMS model

		Release height 1 meter					Release height 1.3 meters				
ξ (m/s²)		100	130	160	190	200	100	130	160	190	200
Material density (kg/m³)	1,800	S-1	S-2	S-3	S-4	S-5	S-16	S-17	S-18	S-19	S-20
	1,900	S-6	S-7	S-8	S-9	S-10	S-21	S-22	S-23	S-24	S-25
	2,000	S-11	S-12	S-13	S-14	S-15	S-26	S-27	S-28	S-29	S-30

In general, the simulations of the different scenarios showed that the materials mobilized by the landslides in the escarpments of the tributaries of the Santo Antônio river were channeled in the thalwegs and advanced downstream, where slopes lower than 5º prevail (Fig. 5). The mud flow and mud flood processes, which occurred after the debris flow and caused the rupture of a bridge in the Santo Antônio River, were not simulated.

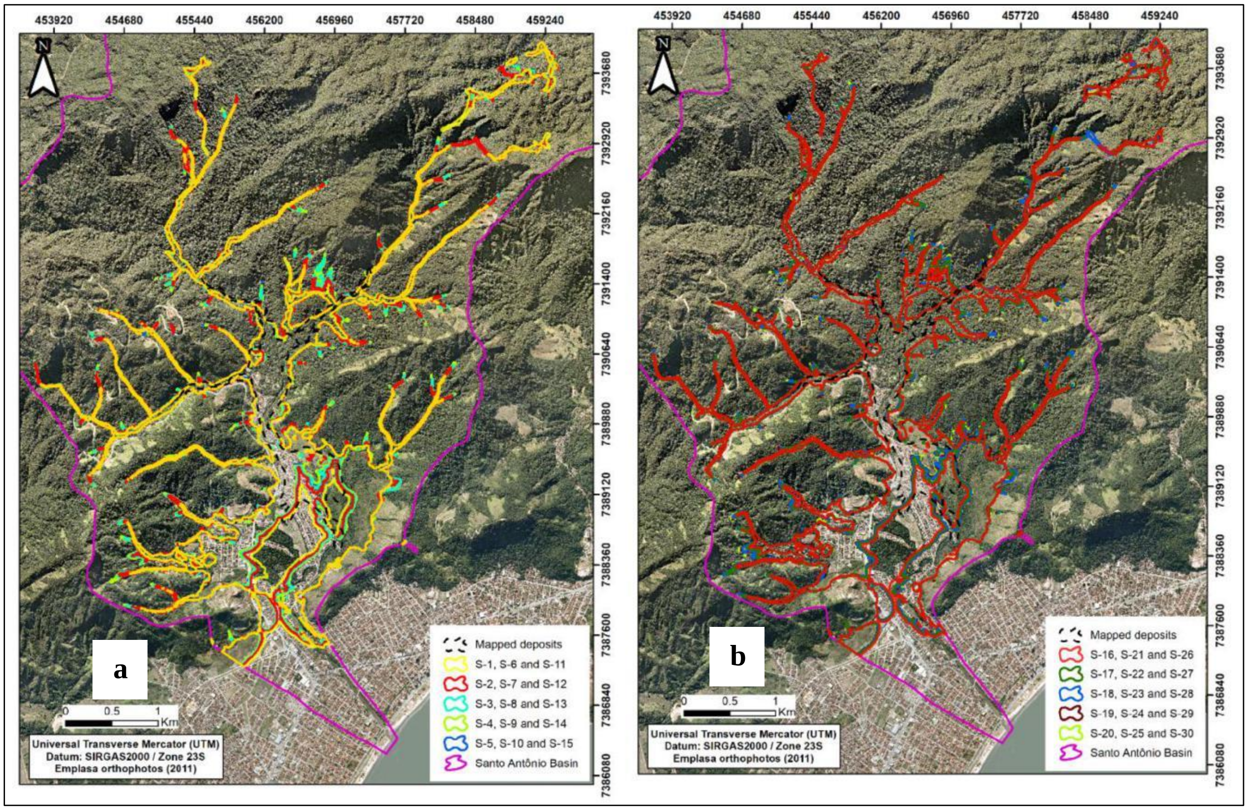

Fig. 5. (a) Spatial distribution of the debris-flow deposits produced by the RAMMS model from release height of 1.0 meter vs. deposits mapped on 1973 aerial photographs in the retro-analysis step and (b) debris-flow deposits resulting from RAMMS model for release height of 1.3 meters.

The debris-flow fan could not be represented by the simulations due to the Digital Elevation Model used, dating from 1979 (IGC, 1979), 12 years after the event. Consequently, the DEM does not represent the conditions of relief before the debris flow. Thus, noticeable differences are observed in the Santo Antônio river thalweg, which was originally meandering, and after the event, whose date is not precise, underwent a process of channelization. The limitation of DEM is because there are no older topographical bases for the place, since the first aerophotogrammetric surveys in the region date back to 1974 and correspond to the 1:50,000 scale. It was decided not to use them because the elaboration of a DEM from these data would hinder and reduce the quality of the simulations in the model.

Although the mapped deposit considered aerial photographs of 1973, 6 years after the event, it is notorious that the debris-flow deposit area that the limitation of the DEM (based on 1979 topographic data) influenced the result calculated by the model, especially in relation to the river Santo Antonio in plain area, which was channeled some years after the 1967 event. Hussin et al. (2012), when performing debris-flow modeling in the French Alps in 2003, also verified that changes in channel morphology directly influence the results produced in the simulations in the RAMMS.

4. Conclusions

Even though the simulations have not been able to adequately reproduce the geometry of the debris-flow deposits related to the 1967 event in the Santo Antônio basin, they suggest that future debris-flow events are unlikely to form debris cones due to the channeling of the Santo Antônio river. Results of the retro-analysis and modeling showed that the areas of deposition of the debris-flow process to the place are preferably in regions of low slope (<5º).

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