

Correlation between rainfall and landslides in Nova Friburgo, Rio de Janeiro—Brazil: a case study

Nathalia Silva de Oliveira¹ · Otto Correia Rotunno Filho² · Edilson Marton³ · Corbiniano Silva⁴ 

Received: 6 March 2016 / Accepted: 6 October 2016 / Published online: 15 October 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract Rainfall is recognized as one of the main factors that influence the triggering of landslides in mountainous regions. The city of Nova Friburgo, which is located in the elevated regions of Rio de Janeiro—Brazil, suffers constantly from landslides usually associated with extreme rainfall events. Under this framework, an empirical study was conducted to analyze records from the rain gauge Ypu jointly with landslides dataset in order to define accumulated precipitation thresholds associated to the occurrence of mass movements in the referred municipality. In addition, we examined the relationship between the Ypu rainfall dataset and the rainfall estimated by Tropical Rainfall Measuring Mission (TRMM) satellite for the pixel in which the rain gauge Ypu is located to assess the representativeness of both

types of measurements in our case study due to the rugged features of the relief. The TRMM data revealed a similar behavior to the Ypu in situ data surface, highlighting a correlation of 0.5 ($R^2 = 0.25$). The study showed that the integrated analyses between the rainfall and landslides provided important information to contribute to decision making in the city of Nova Friburgo—RJ, especially with regard to the issuance of warnings and alerts to the responsible agencies and population.

Keywords Landslides · Rainfall thresholds · Mountainous regions · Nova Friburgo—RJ · TRMM · GIS

Introduction

The mountainous region of Rio de Janeiro (Região Serrana do Rio de Janeiro—RSRJ), located in the mountain ridge named Serra do Mar, suffers constantly with problems of landslides and floods, which are almost always associated with intense rainfall events and sometimes with long-term rainfall. The beginning of the year 2011, for example, was marked by multiple landslides in this area, which, due to its magnitude and incalculable human losses, shook the entire country. Nova Friburgo was one of the most affected municipalities, and this event became known as “Mega Disaster” with international repercussions, and the United Nations Organization (UN) classified it as the 8th worst slide in world history, also considered the greatest weather disaster in Brazil’s history. Thousands of slides (close to 3000 slides) were identified in Nova Friburgo between January 11 and 12, 2011, using geoprocessing, satellite images and visual mapping (SMADUS 2013).

Problems related to landslides occur in cities across the world. Dowling and Sant (2013) addressed the global

✉ Corbiniano Silva
corbiniano@gmail.com

Nathalia Silva de Oliveira
nathalia.meteoro@gmail.com

Otto Correia Rotunno Filho
otto@coc.ufrj.br

Edilson Marton
edilson.marton@ufrj.br

¹ Civil Engineering Program (PEC), Alberto Luiz Coimbra Institute of Post Graduate Studies and Research (COPPE), Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

² Laboratory of Water Resources and Environment, Civil Engineering Program, Alberto Luiz Coimbra Institute of Post Graduate Studies and Research, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

³ Department of Meteorology, Institute of Geosciences, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil

⁴ Faculty of Geology, Center for Technology and Sciences, State University of Rio de Janeiro, Rio de Janeiro, Brazil

impacts of debris flows in the period 1950–2011, providing evidence that higher numbers of deaths tend to occur in developing countries. The analysis also indicated that the most common trigger for fatal events is the extreme precipitation, due to atmospheric phenomena events such as cyclones and monsoon storms; however, more rare events not directly related to rainfall such as earthquakes are the ones that tend to create streams debris with the greatest total of deaths. Seluchi and Chou (2009) conducted a study for the mountainous region of Serra do Mar—southeastern Brazil, where he identified that the sliding events were mainly related to the presence of the South Atlantic Convergence Zone (SACZ) or to the passage of cold fronts. Furthermore, we identified synoptic patterns associated with these weather events, noting that these systems differ from the climatologic studies, showing more intense features for frontal systems and a movement setting locked configuration for SACZ affected events. The study aims to help predict weather conditions that cause landslides in the Serra do Mar, since such patterns can be identified between 72 and 48 h in advance.

Different studies have been conducted with the aim of contributing to the solution of problems related to landslides, seeking to minimize losses and material and human damage. Most of these research works focuses on establishing a rainfall threshold, hereafter simply called threshold, based on correlation between rainfall and landslides as a support to warning systems emphasizing the worth of such relationships as recognized in the literature (Tatizana et al. 1987a, b; Lumb 1975; Costa Nunes 1982; Soares 2006), among others. Usually these studies, though physically based, are empirical, since the peculiarities of each region might influence considerably the results.

There are many factors that influence the outbreak of landslides beyond the precipitation itself (e.g., climatic conditions, soil type, vegetation cover, slope and among others). Therefore, detailed studies are needed to recover aspects of geological and geomorphological of the considered region, among other features, which are not, unfortunately, readily available to allow obtaining rainfall rates that could serve in principle as a better and reliable guideline for warning of slipping on slopes, taking into account mainly physical–mathematical models. On the other side, it is possible to make a correlation between landslides and rainfall records, making the process much more streamlined in the absence of detailed information. Thus, this type of study is in a certain sense more tailored for operational purposes as it also provides reliable and straightforward results whenever critical thresholds of rain can be established (Keefer et al. 1987; D’orsi 2011). Sengupta et al. (2010) reported the success of such alternative approach in which the study identified a landslide threshold if the 15-days normalized cumulative rainfall exceeded

250 mm. However, it is worthwhile to mention that it is not always possible to obtain precipitation thresholds by a certain mathematical expression, such as the exponential relationship between accumulated rainfall and duration of rain, which is the most used.

Indeed, the thresholds are important elements in warning systems, which, in turn, must be composed of several other basic components such as rainfall forecasting, nowcasting, monitoring real-time rainfall with the support of weather radar, satellites and rain gauge network, as mentioned by Aleotti (2004), whose work reinforces that this type of correlation is highly dependent on the quality of the database used and highlights the importance of determining accurately the time of onset of the critical precipitation and time of the collapse. In addition, Glade et al. (2000) showed regional differences in susceptibility of certain areas under the same condition trigger due to in a study developed for northern New Zealand, in which the authors calculated thresholds using an empirical model of daily rainfall that combines the antecedent precipitation and precipitation on the day of the event. These differences relate both to the database sliding as to the variation of the existing physical conditions between regions. Wasowski (1998) stated that there are several problems when attempting to establish specific correlations between rainfall and landslides, including the effect of anthropogenic changes, the variability in precipitation patterns and the physical difference between landslides differing for time periods. Guzzetti et al. (2008) established new global thresholds of intensity-duration rainfall based on a Bayesian statistical approach. The limits obtained were lower than the overall thresholds previously established, indicating that shallow landslides and debris flows could be triggered by rainfall conditions less severe than known hitherto.

A good knowledge of the area to be studied is fundamental for the analysis of both rainfall and landslides. In this sense, the use of GIS (Geographic Information System) and remotely sensed images can contribute to a better understanding of the geology and geomorphology of the region of interest. It is evident that, for the study of natural disasters, an interdisciplinary approach would be recommended because currently there is a major limitation in explaining the nature of certain phenomena. On the other hand, due to this restriction, many studies focus on quantification of these accidents based only on rainfall datasets (Lifen et al. 2013). This work addresses the relationship between rainfall and landslides by conducting a physical-based empirical study with the objective to establish rainfall thresholds from the occurrence of mass movements in Nova Friburgo, Rio de Janeiro. The thresholds obtained from rain gauge data of just 3 years long were then faced with rainfall satellite measurements acquired by TRMM (Huffman et al. 2007).

Materials and methods

Study area

The study area is the municipality of Nova Friburgo, located in the mountainous region of the state of Rio de Janeiro, Brazil (Fig. 1). The municipality has a total population of 173,321 inhabitants and covers an area of 938.5 km², whose coordinates are latitude 22°16'55''S and longitude 42°31'52''W, with an average altitude of 846 m. Its main economic activities are tourism, horticulture, goat farming and industry (SMADUS 2013). The climate is quite humid and mild, predominantly associated with the Atlantic Forest biome (IBGE 2007), currently in advanced stages of deforestation, with replacement by pasture and agriculture. The soils are slightly thick and subject to the process of leachate with high vulnerability for occurrence of mass movements. The relief is very heterogeneous and uneven, with the presence of mountains and valleys in almost its entire length (Dantas et al. 2001).

The slope is an important factor for the occurrence of landslides. Figure 2 shows predominant high slopes

throughout Nova Friburgo, which are striking features of RSRJ.

Dantas et al. (2001) suggests that these extensive mountainous areas (cliffs, mountains and hills) should be intended primarily for the preservation and restoration of the Atlantic Forest, associated with the implementation of agro-forestry and forestry systems and a low density or ecotourism, and not for urban occupation. Considering the fact that the urbanization is a trigger to landslides, Fig. 3 shows the use and soil occupation of the region, which includes the large urban area, the main place where there are landslide occurrences in the city. These aspects corroborate with Nunes (2015) that considered the landslides have as many human actions contributing to change the unstable balance of the slopes, where rampant occupation that alters these local low thresholds of stability, especially in the humid tropical environment, strong contributor to the advent these events, which are related to the disorderly occupation of risk areas and various human actions (releases and concentration of rainwater leaks in the water network, excessive slopes in cuts, landfills run improperly and removal of vegetation) and as with the rainfall, the

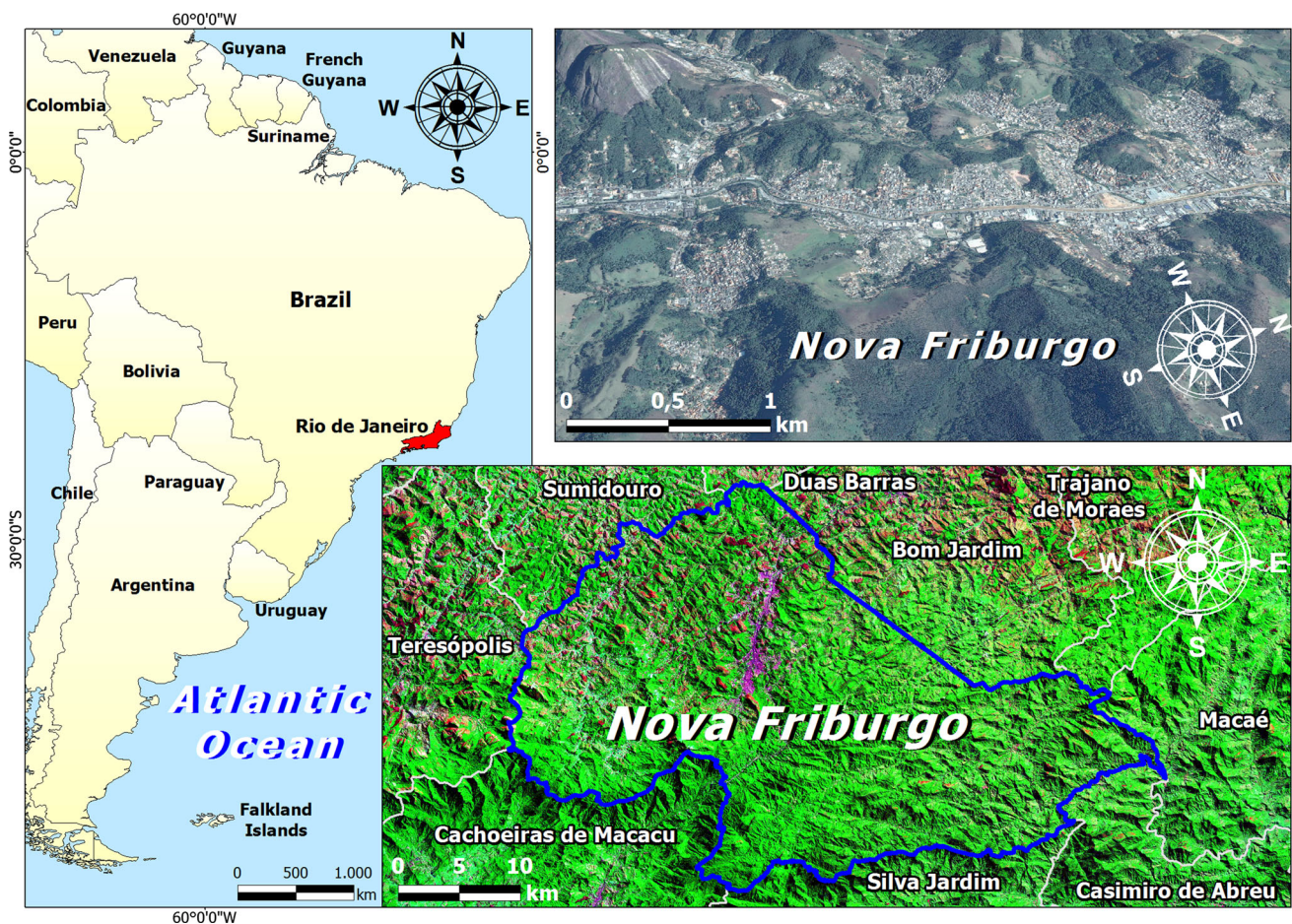


Fig. 1 Location map of the study area—Nova Friburgo, RJ

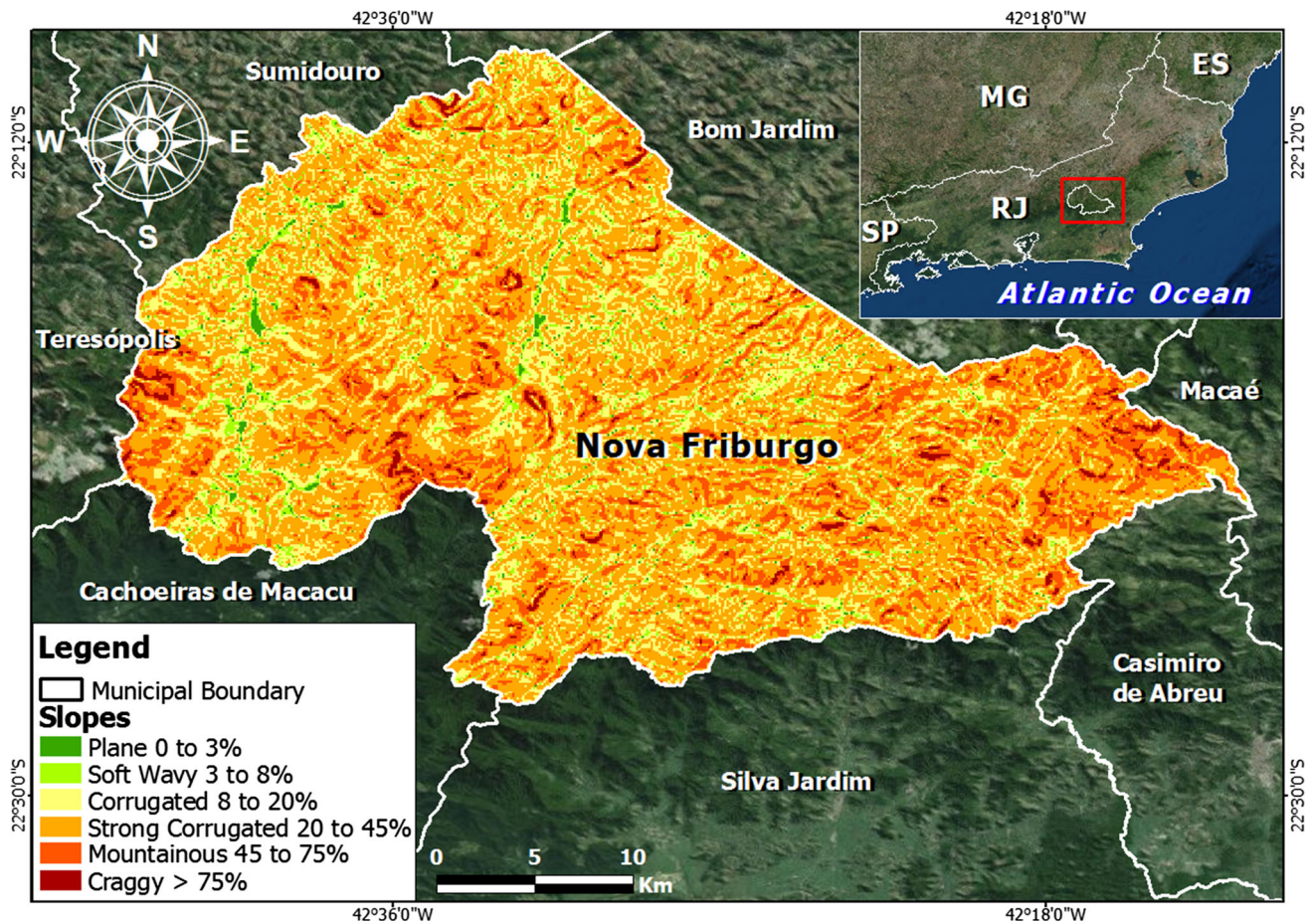


Fig. 2 Map of slopes

triggering element of such occurrences. According to Cascini et al. (2005), several situations may occur with respect to landslide hazard in which urban areas are concerned, which highlights large landslide zones that are generally affected by slow movements that may be permanent or occasional; old villages or new urban areas may extend onto these unstable areas. First, because an active landslide zone generally presents a gentler slope than adjacent stable zones and thus is assessed as more favorable for settlements; then because the fast development of the suburbs of a city located in a valley may induce inhabitants to occupy unstable slopes in the vicinity of the city center, where stable areas are not available. Some examples highlight that the major risks in urban areas derive from the unplanned development during centuries as well as from the growth of marginal housing in landslide-prone areas which imply cut and fill in slopes without appropriate design, construction of leaking sewage and water pipes and a concentration of flow in creeks during rainfall events that accelerate the erosion process and destabilize the slopes along their banks.

Data collection

The following datasets were used for this research work:

- Rain gauge—record derived from a weather station from environmental agency of the state of Rio de Janeiro (INEA—Instituto Estadual do Ambiente), which presents daily rainfall for the area of study covering the time period from November 2008 to December 2011; the study examined the data of rain gauge Ypu with latitude $22^{\circ}17'45''\text{S}$ and longitude $42^{\circ}31'35''\text{W}$;
- Landslides—information provided by the Civil Defense of the municipality of Nova Friburgo/RJ, with the number of landslides between January 2008 and December 2011;
- TRMM rainfall—dataset provided by algorithm 3B42 V7 (Huffman et al. 2007), with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ and temporal resolution of 24 h for the 3-year period from November 2008 to December 2011, covering latitudes between 22.25°S and 22.50°S and longitudes between 42.50°W and 42.75°W , corresponding to the pixel containing Ypu rain gauge.

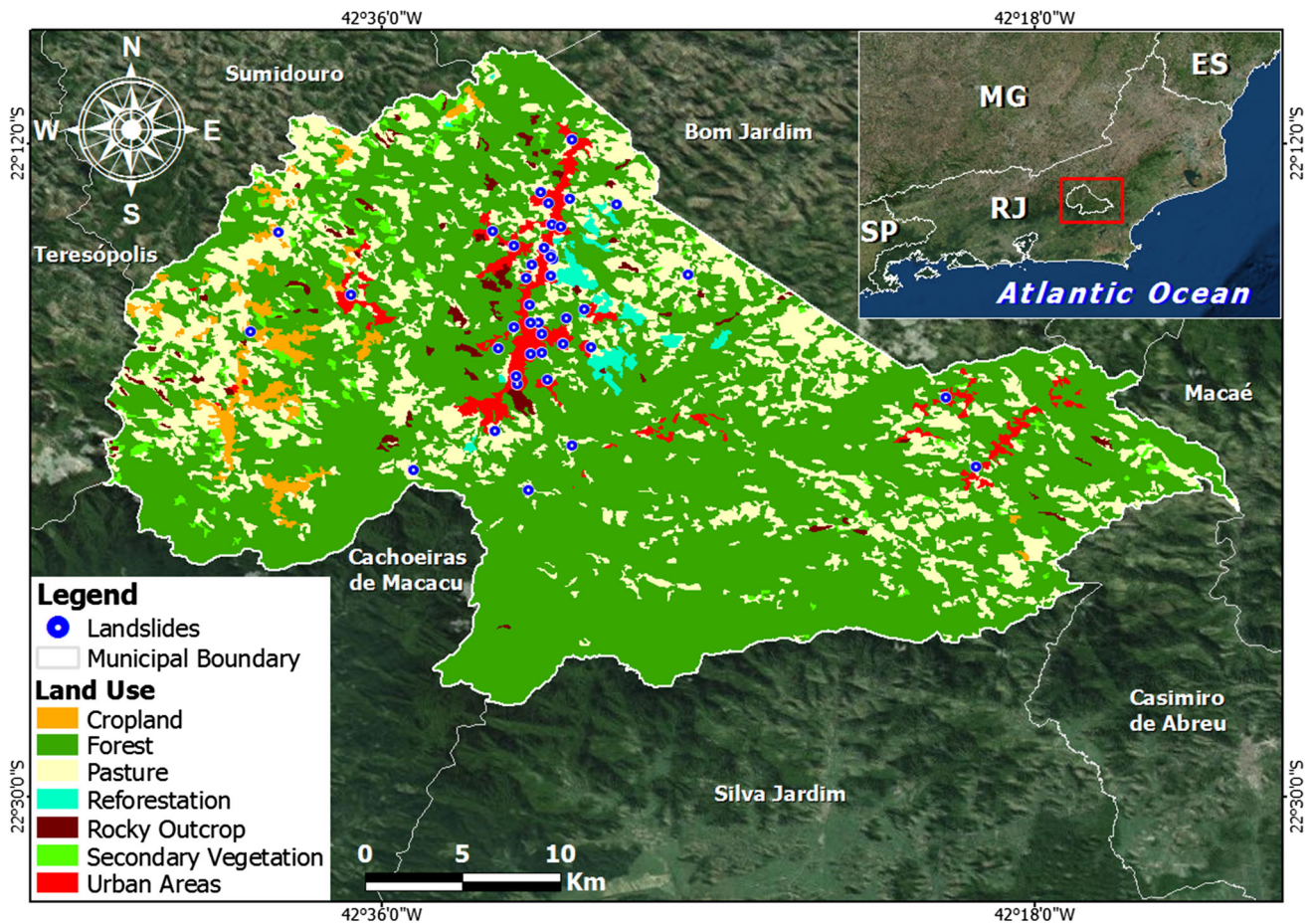


Fig. 3 Land use and land cover, highlighted urban areas and landslides

Methodology

Initially, we sought to identify the location with the highest concentration of slip events based on latitude and longitude of the neighborhoods. A review of four rainfall stations available with minimum time series of 3 years was proceeded. Rainfall correlation matrix of these posts/stations highlighted the Ypu station as representative of the rainfall in the region affected by landslides. Then, an evaluation of the precipitation measured at Ypu station was performed for the period of study in contrast to the dataset obtained from the climatological precipitation of Nova Friburgo (1961–1990), which was developed based on a weather station of the Brazilian National Institute of Meteorology (INMET—Instituto Nacional de Meteorologia), as shown in Fig. 4.

The next step required to set the rainfall thresholds involved the separation of the records of landslides associated and non-associated with rainfall that took place in Nova Friburgo once landslides can occur due to other reasons. For this separation, criteria defined by Soares (2006) (A, B and C) and by Tatizana et al. (1987a, b) (T) were used. These criteria are, in fact, the minimum volume

of accumulated precipitation that needs to be achieved before registering the landslide associated with rainfall, and they are entirely empirical. Tatizana et al. (1987a) developed the T criterion to differentiate the sliding cases associated and non-associated with rain in Cubatão—São Paulo based on an exponential curve

$$I(AC) = K \cdot (AC4d)^{-0.933},$$

where $I(AC)$, hourly intensity; AC4d, amount of accumulated rain referring to 4 days before the event; K , conditioning parameter to the geotechnical conditions of the slope, the intensity of landslides and breaking model.

Thus, only the records of landslides plotted above the curve were associated with rain. Soares (2006) established similar criteria A, B and C, but more appropriated to Angra dos Reis—Rio de Janeiro. In the present study to Nova Friburgo, we use all the criteria mentioned in the definition of landslide events that may be associated with rain. Table 1 shows the criteria A, B, C and T computed for 24, 48 and 72 h in advance of the landslide. In order to confirm that a criterion is met, it is necessary that the accumulated volume of precipitation reaches the minimum threshold set

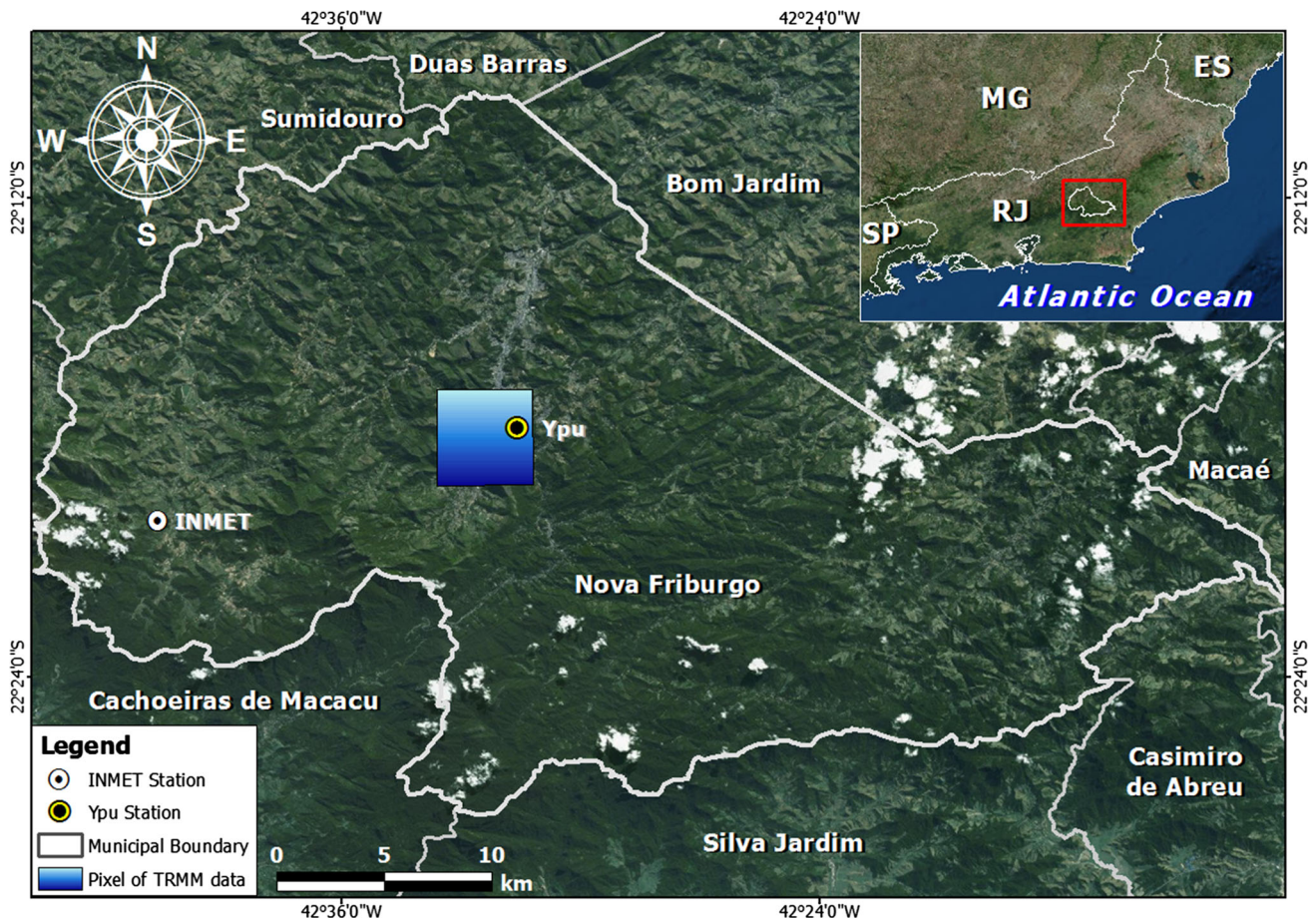


Fig. 4 Ypu station and pixel of TRMM data

Table 1 Criteria A, B, C and T computed for 24, 48 and 72 h in advance

Criterion	Accumulated rain		
	24 h	48 h	72 h
A	50 mm	60 mm	100 mm
B	50 mm	75 mm	120 mm
C	75 mm	120 mm	150 mm
T	100 mm	150 mm	200 mm

to 24 or 48 or 72 h. It is worthwhile to note that criterion A is less rigid, while the T criterion is the most rigorous in considering the landslide as a consequence of a meteorological cause. Once keeping in mind this framework of analysis for classifying slip events, time series of cumulative rainfall for 24, 48, 72 and 96 h are created for each of the criteria. The threshold is then set based on the straight line that allows the number of landslides plotted under this baseline be equal or close to the number of cases without slip events situated above the referred crosscut.

It was observed that several dates related to precipitation events that met the less rigorous criterion A were not

included in the database of slip events of the Civil Defense of Nova Friburgo basically due to two situations:

- The landslide registered in the database occurs a few days after soil waterlogging due to significant accumulated volume of precipitation before the date of the slip event;
- Significant accumulated volume of rain after the landslide (48, 72 and 96 h) due to the accumulated rainfall that had already caused the slip event in previous days.

In this context, these dates were also considered as associated with landslides, although there is no slip event effectively registered in the database of the Civil Defense of Nova Friburgo in those days, but up to 2 days before or after the slip events. It is noteworthy that there is a difficulty when working with databases of landslides, because the registration is done after the event itself, conditioned to the time in which the citizen takes to communicate the municipal civil defense.

The comparison between the estimated TRMM rainfall and the observed precipitation at Ypu station was evaluated through statistical measures for the entire data period of analysis. Since TRMM data are provided on standard time (UTC), while the data of the meteorological station are in local time, the times of both datasets were synchronized. In

addition, there was the need to make corrections taking into account the commonly called summer time in Brazil. The following statistical indicators were used:

- Sample mean value (SMV)

$$\frac{1}{n} \sum_{i=1}^n X_i$$

where x_i , data value of the variable of interest; n , total number of data.

- Bias (systematic error)

$$\frac{1}{n} \sum_{i=1}^n (E_i - O_i)$$

where E_i , rainfall measured by TRMM; O_i , rainfall measured by rain gauge; n , total number of data.

- RMSE (root mean square error)

$$\sqrt{\frac{1}{n} \sum_{i=1}^n (E_i - O_i)^2}$$

where E_i , rainfall measured by TRMM; O_i , rainfall measured by rain gauge; n , total number of data.

- Coefficient of variation of the RMSE (CV-RMSE)

$$CV = \frac{RMSE}{\bar{O}}$$

where RMSE, root mean square error; \bar{O} , average value of the rainfall measured by rain gauge.

- Linear correlation coefficient (CORR)

$$\frac{\sum_{i=1}^n (E_i - \bar{E}_l)(O_i - \bar{O}_l)}{\sqrt{\sum_{i=1}^n (E_i - \bar{E}_l)^2} \sqrt{\sum_{i=1}^n (O_i - \bar{O}_l)^2}}$$

where E_i , rainfall measured by TRMM; \bar{E}_l , average value of the rainfall measured by TRMM; O_i , rainfall measured by the rain gauge; \bar{O}_l , average value of the rainfall measured by rain gauge; n , total number of data.

Results and discussion

The cumulative amount of rainfall per month in rain gauge Ypu (columns), monthly climatological rainfall (continuous curved line), average rainfall at Ypu (continuous straight line) and climatological average rainfall (dotted straight line) between the months of November 2008 and December 2011 are shown in Fig. 5. Note that rainfall at Ypu station has accumulated above the monthly climatological rainfall along for at least 1 month of the summer quarter (December–February), while the accumulated rainfall of Ypu station remained very close to the monthly climatological rainfall in the winter quarter (June to August). Observe also that the monthly rainfall for December 2010 and January 2011 was the highest recorded in the Ypu station within the study period, both with values >420 mm in those months reaching almost twice the climatological value. The average precipitation in the Ypu station was 132 mm, while the average climatological rainfall was 112 mm for the same time

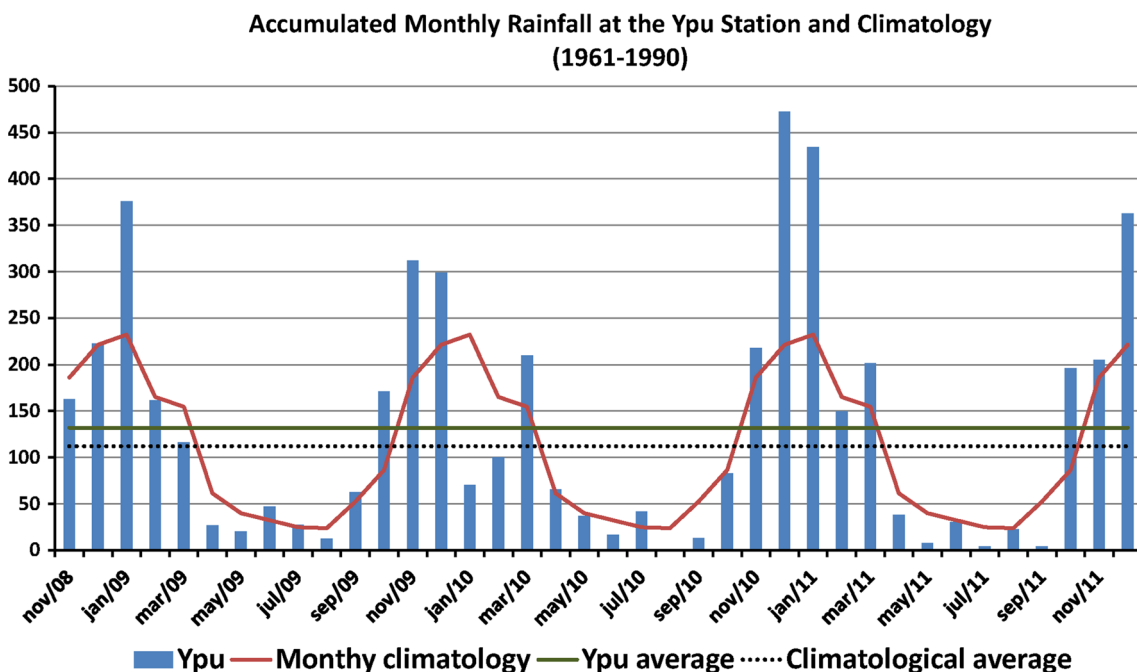
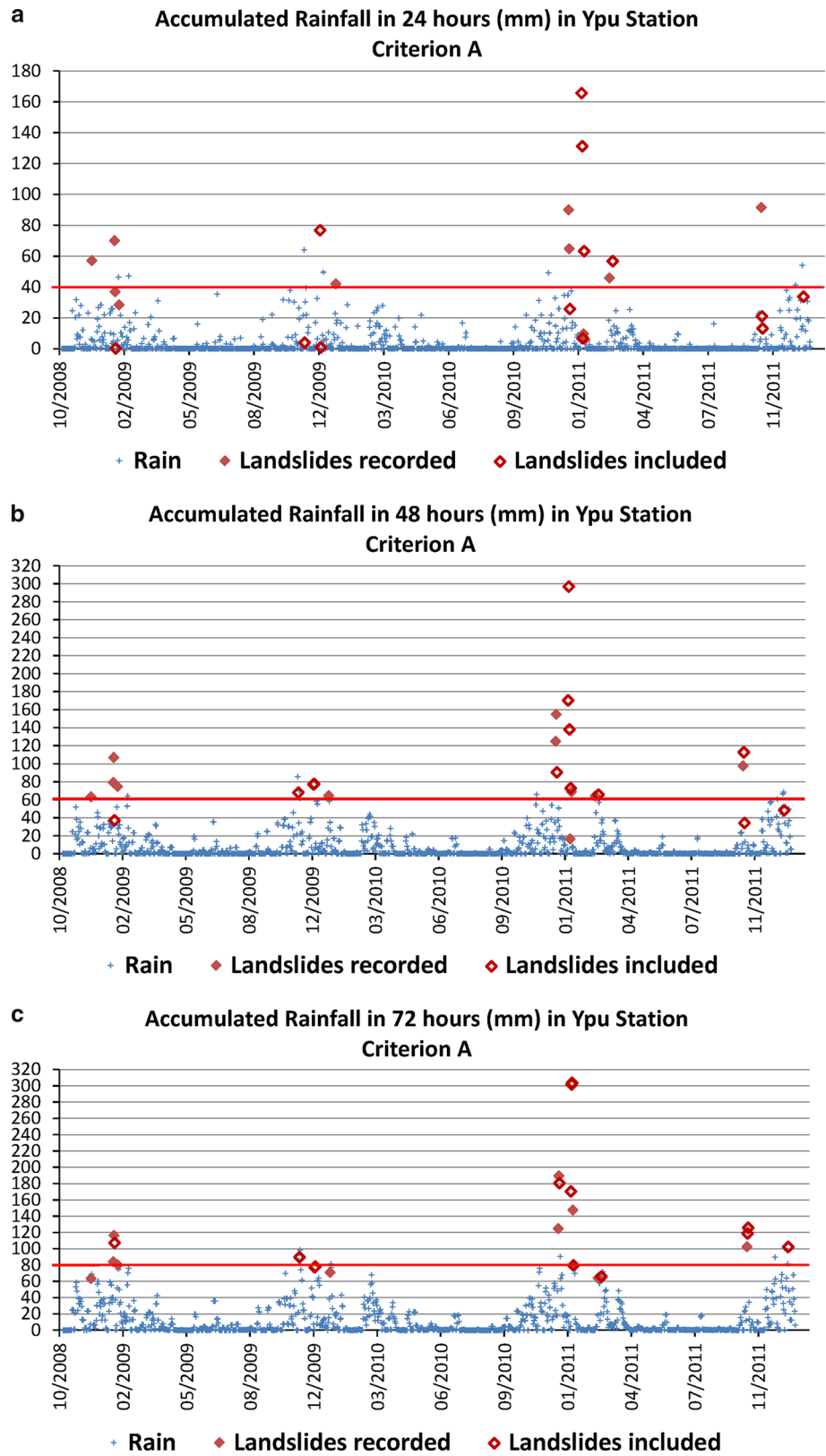


Fig. 5 Monthly rainfall at Ypu station (columns) (mm); monthly climatological rainfall (continuous curved line) (mm); average rainfall at Ypu (continuous straight line) (mm); climatological average rainfall (dotted straight line) (mm)—November 2008–November 2011

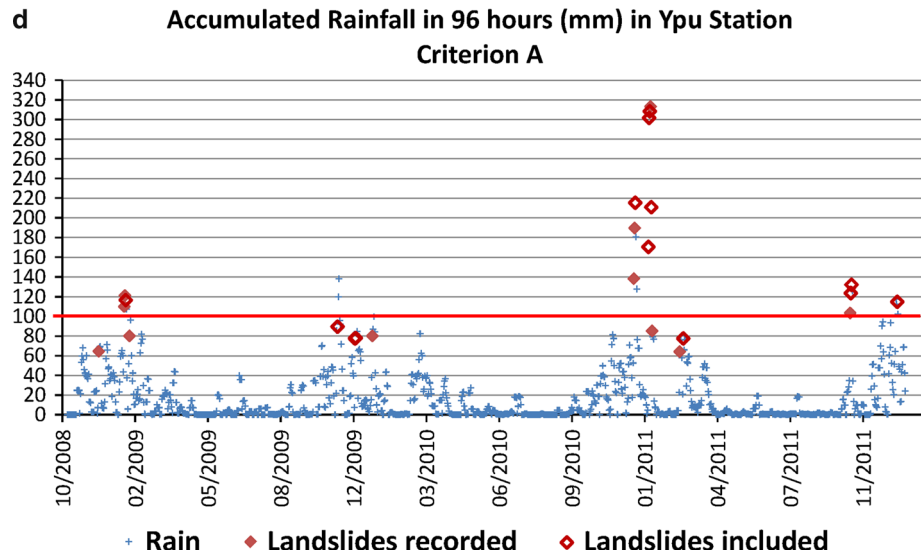
Fig. 6 Accumulated rainfall distributions for 24, 48, 72 and 96 h in advance with respect to each day—November 2008–November 2011; landslides detected accordingly with criterion A are marked as *diamonds filled* and *opened*; *straight line* depicts the adopted threshold



period; that is, the average rainfall for the rain gauge was approximately 18 % higher than the average climatological rainfall between November 2008 and December 2011.

Figure 6 shows the relationship between cumulative rainfall 24, 48, 72 and 96 h without landslides (blue cross) to the cumulative rainfall with landslides (red diamonds).

Fig. 6 continued



To consider only the landslides associated with weather causes criterion A was applied, which is based on accumulated precipitation according to Table 1. Thus, the diamonds filled in red represent slips registered in the Civil Defense of Nova Friburgo database that have weather cause. Empty red diamonds are slips data associated with weather causes, included due to the delay in landslides database. In total, 24 dates were marked as fulfilling the criterion A (red diamonds filled and empty). It was possible to determine thresholds that discriminate rainfall events with landslides of those without any records. These values correspond to the rates of 40 mm in 24 h, 60 mm in 48 h, 80 mm in 72 h and 100 mm in 96 h, in the criterion A (the least restrictive).

Although the criteria B and C are shown in Table 1, the results for them were not presented since the application of Criterion A for the Nova Friburgo municipality was enough to define rain thresholds that can trigger landslides.

Figure 7 is similar to Fig. 6, but with the application of T criterion in association landslides by weather causes. The criterion T is more restrictive than the criterion A with respect to the selection of which slip event is associated with rainfall. Because of this, the number of considered landslides associated with the rainfall diminishes, since it must meet increasingly higher rainfall rates, making the thresholds found to have an increasing tendency since the criterion turns to be more restrictive. However, it is noteworthy that generally these higher thresholds associated with more restrictive criteria do not separate only events with landslides from those without occurrences, but they identify events made up of multiple landslides and even major disasters, as shown in Fig. 7, highlighting the distribution of accumulated rainfall in 24, 48, 72 and 96 h. According to the rainfall data available for the Ypu station, only four dates of landslides met this criterion, being three

of them (November, 12, 13 and 14, 2011) associated to the so-called “Mega Disaster”. The thresholds correspond to rates of 85 mm in 24 h, 130 mm within 48 h, 180 mm in 72 h and 210 mm in 96 h. The data in Fig. 7 warn that rainfall events that reach these thresholds can be associated with new disasters in Nova Friburgo.

According to Figs. 6 and 7, Table 2 was produced by substituting the data Ypu station by precipitation from TRMM precipitation data (pixel highlighted in Fig. 4). Although TRMM data have reasonable correlation with data from Ypu station (correlation 0.5—Table 3) was clearly identified precipitation thresholds for the occurrence of landslides due to weather causes only to criterion A (32 records). These thresholds are similar to those obtained with the data of Ypu station also for criterion A. This result encourages the use of TRMM as an alternative to in situ data in the City of Nova Friburgo. On the other hand, the use of T criterion resulted in only 2 slips records by weather causes, which prevented the detection of a threshold for the occurrence of landslides.

Table 3 shows the values of Bias, RMSE, coefficient of variation of RMSE (CV-RMSE) and correlation (CORR) calculated from the accumulated rainfall in 24 h obtained by the TRMM satellite and by the rainfall station Ypu for the period between November 2008 and December 2011. The results revealed that the TRMM overestimated the total accumulated rainfall in Ypu station (positive BIAS), presenting a high RMSE (12.8 mm) and high coefficient of variation of the RMSE. The correlation ($R^2 = 0.25$) was significant at the level of confidence of 95 % with value similar to that observed in other studies that used TRMM data (Nicácio 2008; Paca 2008; Pedrosa 1994). In terms of average value, the sample mean for TRMM dataset presented results very close to that found for the rain gauge Ypu, with rainfall of 5.4 mm and 4.3 mm, respectively.

Fig. 7 Accumulated rainfall distributions for 24, 48, 72 and 96 h in advance with respect to each day—November 2008–November 2011; landslides detected accordingly with criterion T are marked as *diamonds filled* and *opened*; *straight line* depicts the adopted threshold

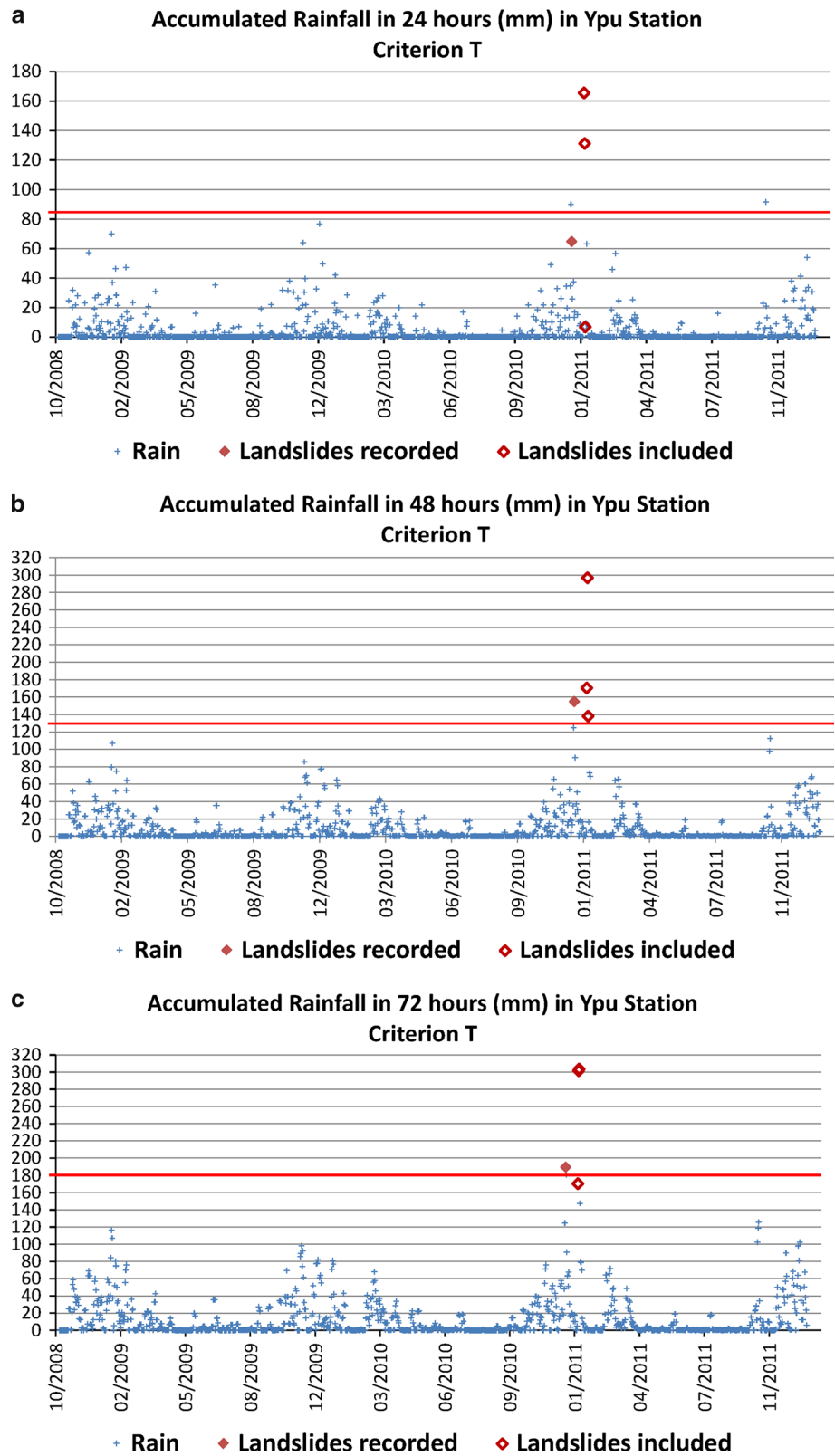


Fig. 7 continued

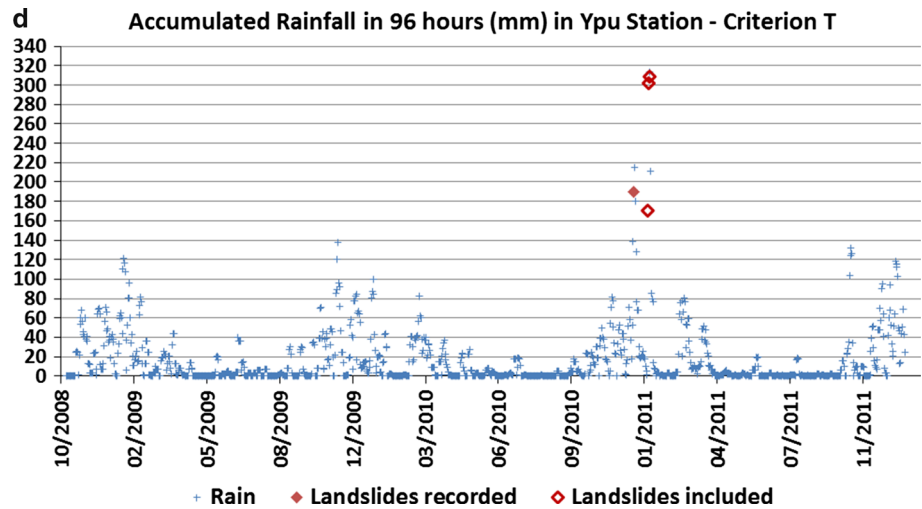


Table 2 TRMM rainfall thresholds for 24, 48, 72 and 96 h

Criterion	Threshold (TRMM)			
	24 h	48 h	72 h	96 h
A	40 mm	70 mm	90 mm	100 mm
T	^a	^a	^a	^a

^a Threshold was not obtained by the method

Table 3 Statistical measures for datasets TRMM and Ypu station

TRMM × Ypu	
BIAS (mm)	1.2
RMSE (mm)	12.8
CV—RMSE	3.0
CORR	0.5

Conclusions

We conclude that the most urbanized region of Nova Friburgo concentrates most of the records of landslides. Between November 2008 and December 2011, the summer seasons presented accumulated rainfall above the climatological rainfall, while the winter seasons behaved very close to the climatological rainfall in the studied region. On average, the mean value of the rainfall time series from the rain gauge Ypu was above the mean climatological rainfall by 18 %.

The rainfall time series of the rain gauge Ypu allowed the defining of rainfall thresholds from which landslides in Nova Friburgo can be forecasted. The values found were:

- Rainfall of 40 mm/h in 24 h or;
- Rainfall of 60 mm/h in 48 h or;
- Rainfall of 80 mm/h in 72 h or;
- Rainfall of 100 mm/h in 96 h.

It should be emphasized that these thresholds were obtained by the less restrictive criterion “A” because we showed that this threshold is enough to trigger landslides. Thus, it is recommended that this criterion should be used operationally for issuing warnings. The remaining criteria (B, C and T) have generated thresholds that might lead to multiple or even catastrophic landslides due to high rate of accumulated rainfall.

The TRMM dataset proved to be a good alternative to evaluate the correlation between rainfall and mudslides as it allowed obtaining thresholds near or equal to those found with the rainfall data of Ypu station. In comparing the data from TRMM and the rainfall observed data, the average values of both series were very close, and the correlation coefficient, though relatively low (CORR = 0.5), is consistent with those values obtained in other studies that used TRMM rainfall. It is noteworthy to mention that the evaluation was performed with a single rain gauge and a single pixel of the satellite and still showed to be consistent in this situation, though probably the major factor for obtaining high values for RMSE. Although it is recommended to use this satellite information on larger spatial scales, the results indicated that the TRMM data showed a similar trend with respect to the rainfall measured on the ground.

The thresholds found for Nova Friburgo might serve as a basis for issuing weather warnings as well as for the implementation of an early warning system about the possibility of large landslides. It is recommended that this research work be extended for a longer period in order to be able to evaluate the influences of interannual meteorological systems at larger scales with rainfall events associated with landslides in the studied region. Moreover, it is also important to compare the spatial information from weather radar data, which is not available up to this moment in the region, to TRMM dataset, in order to verify

the performance of the remotely sensed satellite data for different rainfall events. Finally, it is also suggested that other rainfall rain gauges be installed to provide a better assessment and understanding of the rainfall spatial distribution in Nova Friburgo and nearby regions of the mountainous of RSRJ.

Acknowledgments First, we would like to thank CNPq, a Brazilian educational agency that provided the scholarship for the first author. A special thank you goes to Secretaria de Defesa Civil de Nova Friburgo and to Instituto Estadual do Ambiente, RJ (INEA) for providing landslide and rainfall datasets. The authors would like also to thank the Civil Engineering Program of Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia (COPPE)—Universidade Federal do Rio de Janeiro (UFRJ) through the support of the Laboratory of Water Resources and Environmental Issues (LABH2O) and the Department of Meteorology—Institute of Geosciences (IGEO)—Universidade Federal do Rio de Janeiro (UFRJ) with respect to data and infrastructure provided by these institutions for this research. The authors would like to express their sincere appreciation to the financial support for the work, which came through Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ)—Project PEC/COPPE-FAPERJ014/2010(2010–2012), Project FAPERJ—Process E-26/103.116/2011 (2012–2014) and Project FAPERJ—Pensa Rio—Edital 19/2011 (2012–2014)—E26/110.753/2012, Project CNPq Edital Universal No. 14/2013—Process 485136/2013-9, which is focused on rainfall-runoff modeling and on the corresponding issue of water balance and soil moisture with respect to extreme events, Secretaria de Educação Superior (SESu)—Ministério da Educação (MEC)-CAPES-AUX-PE-PET-1228/2009(PET CIVILUFRJ), educational agencies of the Brazilian government. The authors would like also to recognize the support of CPRM, INEA, ANA, EMBRAPA, and INMET, for the continuous support of the research in hydrometeorology in Brazil. In addition, the authors would like to recognize the support of the *Tropical Rainfall Measuring Mission* (TRMM). The TRMM data were processed by the *TRMM Science Data and Information System* (TSDIS) and the TRMM Office; they are archived and distributed by the Goddard Distributed Active Archive Center. TRMM is an international project jointly sponsored by the Japan National Space Development Agency (NASDA) and the *U.S. National Aeronautics and Space Administration* (NASA) Office of Earth Sciences.

References

- Aleotti P (2004) A warning system for rainfall-induced shallow failures. *Eng Geol* 73(3):247–265
- Cascini L, Bonnard C, Corominas J, Jibson R, Montero-Olarte J (2005) Landslide hazard and risk zoning for urban planning and development. In: Hungr R, Fell R, Couture R, Eberhardt E (eds) *Landslide risk management, proceeding of the international conference on landslide risk management*, Vancouver, Canada. A.A. Balkema Publishers, Taylor & Francis Group, London, pp 199–235
- Costa Nunes AJ (1982) Recuperation of roads subjected to intense rains. *Tech J Eng Soc Bahia* 1:3–12
- D'orsi RN (2011) Correlação entre pluviometria e escorregamentos no trecho da Serra dos Órgãos da Rodovia Federal BR-116 RJ (Estrada Rio-Teresópolis). Tese (Doutorado em Engenharia Civil), COPPE/UFRJ, Rio de Janeiro, RJ
- Dantas ME, Shinzato E, Medina AIM, Cássio RS, Amaury CF (2001) Diagnóstico Geoambiental do Estado do Rio de Janeiro—CPRM. http://www.cprm.gov.br/publique/media/artigo_geoambientalRJ.pdf. Acesso em 29 Mar 2012
- Dowling CA, Sant PM (2013) Debris flows and their toll on human life: a global analysis of debris-flow fatalities from 1950 to 2011. *Nat Hazards*. doi:10.1007/s11069-013-0907-4
- Glade T, Crozier M, Smith P (2000) Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical “Antecedent Daily Rainfall Model”. *Pure appl Geophys* 157(6-8):1059–1079
- Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity–duration control of shallow landslides and debris flows: an update. *Landslides* 5(1):3–17
- Huffman G, Adler R, Bolvin D, Gu G, Nelkin E, Bowman K, Hong Y, Stocker E, Wolff D (2007) The TRMM multisatellite precipitation analysis (TCMA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J Hydrometeorol* 8:38–55. doi:10.1175/JHM560.1
- IBGE (Instituto Brasileiro de Geografia e Estatística) (2007). <http://www.ibge.gov.br/cidadesat/>. Acesso em 29 Mar 2012
- Keefer DK, Wilson RC, Mark RK, Brabb EE, Brown WM, Ellen SD, Zarkin RS (1987) Real-time landslide warning during heavy rainfall. *Science* 238(4829):921–925
- Lifen X, Meng X, Xu X (2013) Natural hazard chain research in China: a review. *Nat Hazards* 70:1–29
- Lumb P (1975) Slope failures in Hong Kong. *Q J Eng Geol* 8:31–65
- Nicácio RM (2008) Evapotranspiração real e umidade do solo usando dados de sensores orbitais e a metodologia SEBAL na bacia do rio São Francisco. Tese (Doutorado em Engenharia Civil), COPPE/UFRJ, Rio de Janeiro, RJ
- Nunes LH (2015) Urbanização e Desastres Naturais. Oficina de Textos, São Paulo. ISBN 978-85-7975-179-0
- Paca VHM (2008) Análise de informações satelitais e dados convencionais da rede pluviométrica como contribuição a modelagem hidrológica na região Amazônica - Estudo de caso: bacia do Rio Guamá—Pará. Dissertação (Mestrado em Engenharia Civil), COPPE/UFRJ, Rio de Janeiro, RJ
- Pedrosa MGA (1994) Análise de correlações entre pluviometria e deslizamentos de taludes. Tese (Doutorado em Engenharia Civil), COPPE/UFRJ, Rio de Janeiro
- Seluchi ME, Chou SC (2009) Synoptic patterns associated with landslide events in the Serra do Mar, Brazil. *Theoret Appl Climatol* 98(1-2):67–77
- Sengupta A, Gupta S, Anbarasu K (2010) Rainfall thresholds for the initiation of landslide at Lanta Khola in north Sikkim, India. *Nat Hazards* 52(1):31–42
- SMADUS - Secretaria do Meio Ambiente e Desenvolvimento Urbano e Sustentável da Prefeitura Municipal de Nova Friburgo (2013). Disponível em. <https://meioambientedigital.pmnf.rj.gov.br/user/geoespacial/geoinformacao>
- Soares EP (2006) Caracterização da precipitação na região de Angra dos Reis e a sua relação com a ocorrência de deslizamentos de encostas. Dissertação (Mestrado em Engenharia Civil), COPPE/UFRJ, Rio de Janeiro, RJ
- Tatizana C, Ogura AT, Cerri LES, Rocha MCM (1987a) Análise de correlação entre chuvas e deslizamentos—Serra do Mar—município de Cubatão. Anais do 5º Congresso Brasileiro de Geologia e Engenharia, vol 2. São Paulo, pp 225–236
- Tatizana C, Ogura AT, Cerri LES, Rocha MCM (1987b) Análise de correlação entre chuvas e deslizamentos—Serra do Mar—município de Cubatão. Anais do 5º Congresso Brasileiro de Geologia e Engenharia, vol 2. São Paulo, pp 237–248
- Wasowski J (1998) Understanding rainfall-landslide relationships in man-modified environments: a case-history from Caramanico Terme, Italy. *Environ Geol* 35(2-3):197–209