ASSESSMENT OF DIGITAL TERRAIN MODELS IN DAM BREAK SIMULATION STUDIES

Avaliação de modelos digitais de terrenos em estudos de simulação de rompimento de barragens

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Abstract:

Dams are structures built for controlling the flow of water for many useful purposes such as water supply, power generation, retention of mining and industrial waste, as well as recreation and flood control. However, they bring together some risk of dam body collapse causing damage for the dam downstream areas. Therefore, hypothetical dam break studies which provide mapping of areas potentially attainable in the event of a rupture are especially important for planning actions aiming minimization of associated losses. The aim of this research is to assess the degree of adherence or similarity between flood maps obtained by simulation studies and those effectively obtained from the collapse itself occurred in Dam I owned by Vale SA on January 25, 2019. The study focuses mainly on comparing the effects over the simulated flood maps caused by use of different representation of dam downstream topography relief, namely Shuttle Radar Topography Mission (SRTM), Advanced Land Observing Satellite from Alaska Satellite Facility (ALOS_ASF) and Airborne Laser Scanning (ALS) models. The simulations were performed using the HEC-RAS software developed by the US Army Corps of Engineers considering hypothesis of strong influence of relief in flood mapping results. In this way, three simulation tests were carried out for evaluation and discussion. In the first simulation, the digital terrain model derived from ALS was used. The second simulation was carried out associating

the digital surface model ALOS_ASF with a spatial resolution of 12.5 m. Finally, the SRTM digital elevation model with 30 m spatial resolution provided by the United States Geological Survey (USGS) was used in third simulation. Results showed better adherence to simulations using data from ALS. This was verified by visual analysis over high resolution orthorectified images and by calculating statistics indicators such as the (F) index. Conclusions pointed out that flood patches resulting from simulation are critical tools for taking actions involving areas and populations to be affected, so the best relief model technologies like ALS data should be used in simulation.

Keywords: Dam break simulation, Dam flood maps, Digital elevation models.

Resumo:

Barragens são estruturas construídas para controlar o fluxo de água para muitos fins úteis, como abastecimento de água, geração de energia, retenção de resíduos de mineração e industriais, bem como, recreação e controle de enchentes. No entanto, elas trazem algum risco de colapso do corpo da barragem causando danos às áreas a jusante da barragem. Portanto, estudos hipotéticos de rompimento de barragens que forneçam mapeamento de áreas potencialmente atingíveis em caso de rompimento são especialmente importantes para o planejamento de ações que visem à minimização das perdas associadas. O objetivo desta pesquisa é avaliar o grau de aderência ou similaridade entre os mapas de inundação obtidos por estudos de simulação e aqueles efetivamente obtidos do próprio rompimento ocorrido em 25 de janeiro de 2019 na Barragem I de propriedade da Vale SA. O estudo se concentra, principalmente, na comparação dos efeitos sobre os mapas de inundação simulados causados pelo uso de diferentes representações do relevo topográfico a jusante da barragem, nominalmente, Shuttle Radar Topography Mission (SRTM), Advanced Land Observing Satellite disponibilizado pela Alaska Satellite Facility (ALOS_ASF) e modelos de Varredura Laser Aerotransportado (ALS). As simulações foram realizadas utilizando o software HEC-RAS, desenvolvido pelo Corpo de Engenheiros do Exército Americano, considerando a hipótese de forte influência do relevo nos resultados do mapeamento de inundações. Desta forma, foram realizados três testes de simulação para avaliação e discussão. Na primeira simulação, foi utilizado o modelo digital de terreno derivado do ALS. A segunda simulação foi realizada associando o modelo digital de superfície ALOS_ASF com resolução espacial de 12,5 m. Por fim, o modelo digital de elevação SRTM com resolução espacial de 30 m fornecido pelo United States Geological Survey (USGS) foi utilizado na terceira simulação. Os resultados mostraram melhor aderência às simulações usando dados do ALS. Isso foi verificado por análise visual em imagens ortorretificadas de alta resolução e pelo cálculo de indicadores estatísticos como o índice (F). As conclusões apontaram que manchas de inundação resultantes de simulação são ferramentas críticas para a tomada de ações envolvendo áreas e populações a serem afetadas, portanto, as melhores tecnologias de modelos de relevo como dados de ALS devem ser utilizadas na simulação.

Palavras-chave: Simulação de rompimento de barragens; Envoltórias de inundação de barragens; Modelos digitais de elevação.

1. Introduction

Dams are structures built with the function of retaining or controlling the flow of water for power generation, water supply, flood control, irrigation, recreation, among other activities. They are also built for the purpose of retaining and treating mining and industrial wastes.

However, implementing a dam brings together the risk of any event that can imply dam body failure (Raman and Liu, 2019). The dam breaching risk is minimal but should not be overlooked because of the harmful consequences for the downstream areas, which can be more or less impacted depending on the characteristics of the hydrological basin, the relief of potentially floodable areas, the population occupation, besides several other factors to be considered, depending on the dam project characteristics.

Due to the risks associated with dams, several studies on the effects of an eventual rupture have been carried out for decades (Almeida, 2002; Brasil, 2005; Lauriano, 2009), with important initiatives in Europe, dating since 1994 (Wang and Kahawita, 2002; Wahl, 2005; Wang et al. 2006). In Brazil, due to the occurrences observed in the last few years (Fundão dam in Mariana, 2015, Herculano Mineração dam in Itabirito, 2014 and also a dam in Miraí, 2007), studies and standards have been produced by regulatory institutions and agencies, such as ANA (National Water Agency) and by ANM (National Mining Agency) in a more intense way, aiming to provide greater security for dam projects (ANM, 2017; ANM, 2020; Brasil, 2020).

In this context, hypothetical dam collapse studies also known as dam break studies are included, which provide, among others, the mapping of areas potentially attainable in the event of a burst, also called simulated flood maps. Such derived mapping products are essential information for planning actions aiming to minimize the loss of human life, the environmental impacts and socioeconomic effects associated to the event of a possible collapse.

The use of information technologies, such as Geographic Information Systems (GIS) and associated tools, particularly remote sensing resources, are of fundamental importance in dam break simulation studies (Álvarez et al. 2017), as long as the flood maps associated with spatial analysis and remote sensing images bring to light the probable limits of the flood on the terrain.

As part of the simulation work, an important primary data for processing the dam break simulation is the Digital Terrain Model (DTM) data, which can comes from free cost sources such as Shuttle Radar Topography Mission (SRTM), Advanced Spaceborne Thermal Emission and Reflection Radiometer - Global Digital Elevation Model (ASTER-GDEM) and Advanced Land Observing Satellite (ALOS) project managed by Alaska Satellite Facility (ASF), as well as from others free cost sources. Alternatively, a commonly used high quality DTM source with associated costs is the Airborne Laser (Light Amplification by Stimulated Emission of Radiation) Scanning (ALS).

Studies dealing with different applications, as well as discussions related to the important role of DTM, have been addressed in papers such as Polidori et al. (2014), Ferreira (2014), Morais (2017), Morais et al. (2017), Scalco et al. (2018), França et al. (2019) and Orlandi et al. (2019).

The flood maps resulting from dam break studies are used as a basis for risk maps building and in assignments of weights and values for the risks associated with an eventual break (Machado, 2017). Thus, as important as the delimitation of the flood boundaries is its accuracy or adherence to the ground truth. Unfortunately, it can only be verified after an accident occurred by making a comparison between the simulated mapping situation and the actually observed situation.

Recently, in January 25, 2019 a disaster has occurred in Dam I of Córrego do Feijão mine, an upstream tailings dam located in Brumadinho, Minas Gerais, Brazil. The dam, owned by the Brazilian company Vale SA, was built in 1976 for the storage of iron ore tailings. It lied at an average elevation of 86 m, occupied an area of 250,000 m^2 and held over 12,000,000 m^3 of tailings. The disaster left over 250 dead and, 2,700,000 m^2 of forests, spread out over the 98 km path of the slurry flow, were destroyed. The dam was inactive, had no lake and there was no operational activity in progress (Raman and Liu, 2019; Vale, 2019).

In this context, the aim of this research is to assess the degree of adherence (similarity to the ground truth) of the flood maps obtained in the dam break studies carried out in Dam I. Such degree of similarity is evaluated by comparing the mappings resulted from simulation studies with the areas effectively reached due to the collapse of this Dam I.

The study focuses on the different ways the relief of dam downstream areas can be represented and on the different effects that the choice of representation model has in the delimitation of the flood resulting from simulation studies of dam rupture. So, it can be evaluated if the use of free available surface models, such as those derived from SRTM and from ALOS PALSAR ASF project, are suitable for this type of analysis.

There is a consensus among altimetry data users that ALS (Airborne Laser Scanning) models with embedded acquisition costs are more accurate than freely available digital elevation models such as SRTM and ALOS_ASF. It is also expected that the most accurate DTM produces the best simulated flood map. This can be certified comparing

with an available accurate reference. The best reference for comparison is that one effectively resulting from the observed situation after the rupture event, which is now readily available for use in the present study.

Thus, the simulations were carried out with the objective of demonstrating the hypothesis of the strong influence of the different forms of downstream relief representation (DTM) in the delimitation results of the flood. How the simulated flood maps resulting from models of different accuracies behaved compared to observed flood maps? So the main contribution of the present paper is analyzing the behaviors of simulated flood maps resulting from free cost low quality DTM (SRTM, ALOS_ASF) and cost embedded high quality DTM (ALS) compared to the flood effectively observed and evaluate if the use of surface models such as those derived from SRTM and ALOS_ASF are suitable for this type of analysis.

Some of the major questions are: what are the effects of using these free available models in dam break simulation studies and what would be the consequences of that uses? What is the associated error due to the use of the free cost models? Which amounts of areas have been mapped as flooded for excess or for lack and which are affecting urban locations? Would it be feasible or not to use a free model to predict the flood patches? If it is not, then an ALS model should be used because the cost is certainly much lower than that of a dam rupture. Considering the effects of a dam break disaster and also the cost of implementing dam projects, are the costs of acquiring the ALS data relevant for companies of this dimension such as Vale SA?

2. Dam Break Simulation

The dam break simulation studies consist of mathematical modeling for building different scenarios of ruptures such as mining, industrial waste, multiple uses or hydroelectric dams. They produce much important information about the areas downstream the dams, highlighting flood maps and hydrograms (transit times, flows maximum, and so on). It is the entrepreneur duty to carry out these studies that can present many differences relative to methods and costs, depending on the engineering solutions taken by the entrepreneur (Rocha, 2015).

These studies are part of the National Dam Safety Policy (PNSB), enforced by Law number 12,334, December 20, 2010 (Brasil, 2010). The Policy goal is providing regulation, definition of safety and monitoring parameters, as well as actions to reduce the risk of accidents and their consequences.

The flood maps resulting from the dam break studies are obtained from the estimation and calculation of maximum flooded quotas, speeds, and maximum discharges through flood wave propagation models along the downstream valley (Lauriano, 2009).

Because of the simulation nature of the study several uncertainties associated with the methodology, input data and hydrodynamic models can be introduced in the running process so generating inaccurate results that can compromise the correct actions to be taken for minimizing the damages in case of possible rupture. Thus, several studies have been carried out to better understand these uncertainties and to identify which are the variables and parameters more sensitive that deserve a greater attention.

An example of this approach can be seen in Tschieldel (2017), when assessing the uncertainties related to the parameters Manning coefficient, gap parameters, reservoir volume and topography of the downstream valley. Another study (Rocha, 2015) evaluates the hydrodynamic models provided by HEC-RAS and FLO-2D, the Manning coefficient, the rupture hydrogram and the topography accuracy of downstream valley, suggesting that topography may be the main factor in flood patches prediction. The commercial software FLO-2D, published by FLO-2D software inc. since 1993, is designed for two-dimensional flood or mud-flood routing and the basics concepts of its logical operation can be found in Wu, Liu and Chen (2013).

The HEC-HAS (Hydrologic Engineering Center - River Analysis System) is a hydrodynamic modeling software

used in this case study. It has been extensively used in many studies such as Boussekine and Djemili (2016), Machado (2017), Álvarez et al. (2017), Faria et al. (2019), Raman and Liu (2019) and Abbas, Abbodi and Ibrahim (2020) dealing with dam break simulations, parameters, uncertainties and related issues. HEC-HAS is a free-access hydrodynamic simulation software developed by the US Army Corps of Engineers that allows simulations to be carried out with permanent or non-permanent flow in a one-dimensional and two-dimensional form based on Saint Venant's equations. The model equations for the HEC-HAS two-dimensional (2D) version are well described in many literature works (Machado, 2017; Álvarez et al. 2017; Faria et al. 2019; Raman and Liu, 2019 and Abbas, Abbodi and Ibrahim, 2020) where further details can be found.

Briefly, the simulation requires insertion of hydraulic parameters, collapse hydrogram and Manning coefficient into hydrodynamic model. It is also required the association of a digital model representing the valley topography surface downstream the dam, where the flood movements should be simulated. The simulation results provide the flood delimitation as well as the speed, depth, and time of arrival in sections of interest. As the study focuses in the topography downstream the dam questioning whether free cost DTM are suitable for simulation analysis, follows a brief description of relevant details of each DTM data used in this research.

SRTM is based in InSAR (Interferometry of Synthetic Aperture Radar) data collected in single pass mode during the Endeavour space shuttle mission carried out in year 2000. Because the elevation information provided by the SRTM was obtained by processing the information collected by C band of microwaves spectrum with the signal returning from earth surface objects (not reaching the ground level) the DTM is a Digital Surface Model (DSM) type. Complete details of the SRTM mission can be found in Farr et al. (2007). Some SRTM applications and accuracy discussions is found in Morais et al. (2017). The data of SRTM version v3 were used in this study downloaded from Earth Explorer site (https://earthexplorer.usgs.gov/).

ALOS_ASF is a refinement of data collected by SRTM mission processed by the Alaska Satellite Facility (ASF) for use in the ALOS PALSAR (Phase Array L-band Synthetic Aperture Radar) Radiometric Terrain Correction (RTC) project. ALOS_ASF DEM data is available by ASF in 12.5 m pixel grid and is referred to WGS84 ellipsoid surface. In this study the data was reduced to geoid surface using the geoidal undulation model MAPGEO2015 available from Brazilian Institute for Geography and Statistics (IBGE). Due to its derivation from microwaves C band the ALOS_ASF altimetry is also referred to the earth surface objects (DSM). The ALOS_ASF data used in this study were obtained from the ASF site (asf.alaska.edu) where further details can be found.

ALS is based in the integration of three advanced technologies: Global Navigation Satellite System (GNSS), laser emitter and receiver systems and inertial measurement unit technologies. Further descriptions and details of ALS can be found in Lemmens (2017), Morais (2017) and Morais et al. (2017). The data used in this study were collected in 2016 and 2019 by conventional laser profiling techniques with point density of 1 pulse per square meter. Trimble's Harrier 68I sensor and Applanix inertial system (Model POS AV 150) integrated with dual frequency (L1/L2) GNSS receiver. Verification from ground control points of accurate known geodetic position determined by GNSS static method produced an overall accuracy of 0.3 m, assessed by the Root Mean Square Error (RMSE) estimator, attesting the quality compatible to maps of 1.0 m contour lines vertical equidistance, according to class "A" defined in Decree-Law No. 89,817 (Topocart, 2017).

3. Material and Methods

The working methodology is focused on how and under what conditions using different types of digital elevation models influences the delimitation of the flood and what are the impacts that may arise from the choice of each model evaluating if surface models such as those derived from SRTM and ALOS_ASF are suitable for this type of analysis Figure 1 shows an overall view of the main working steps and the interactions of the stages.
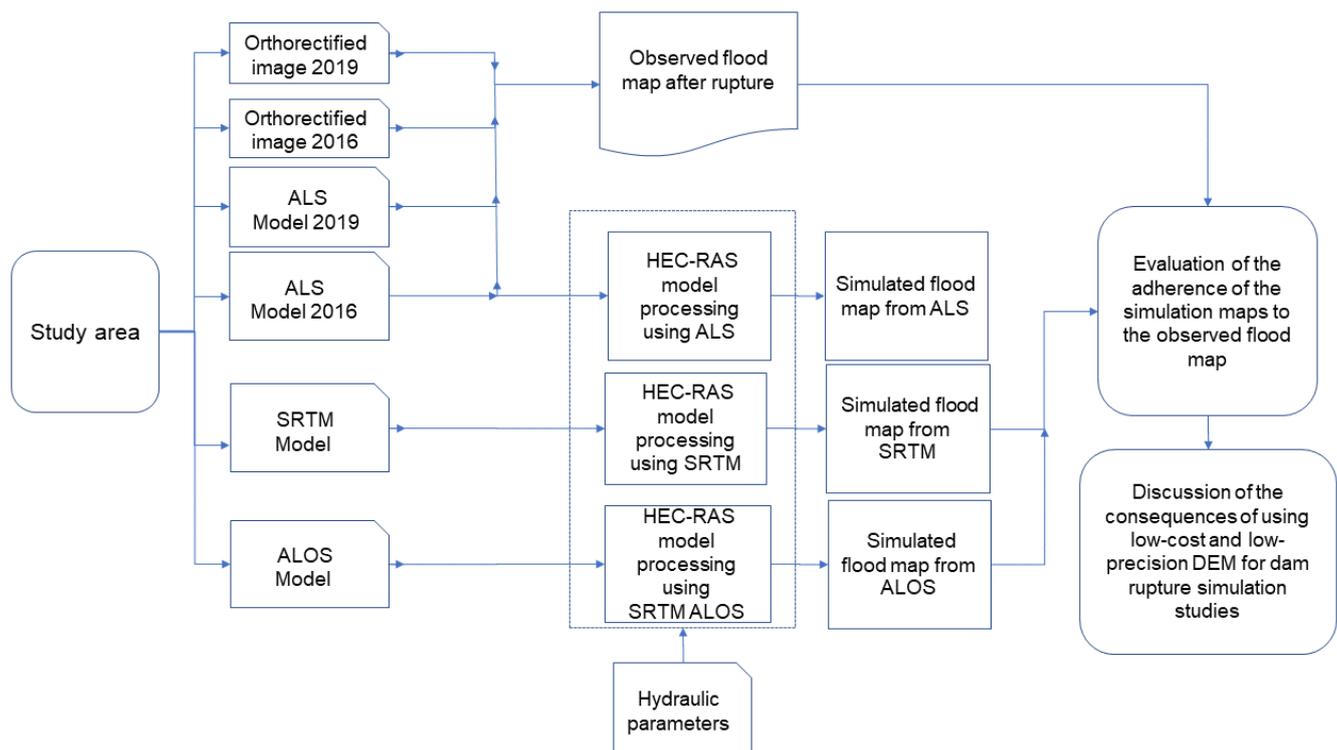
Figure 1: Workflow of the research methodology linking the main steps. Source: the authors.

The study begins with collecting all the geospatial data available about the study area. After defining the limits of the study area two photogrammetric orthoimages were generated, one represents the landscape situation in the area before the collapse and the other the area immediately after the collapse of Dam I. These data were used to evaluate, in a GIS environment, the relationship between flood maps generated by simulation and the actual limits of flood that were produced by the collapse, represented in the photogrammetric images that were taken few days after the dam failure. In another process three simulated flood maps were produced, each one based on one of the three selected digital models, ALS, ALOS_ASF and SRTM.

3.1 Study area

The study area comprises the region potentially flooded by the Dam I collapse. The accident was responsible for the contamination of neighborhood water bodies reaching the Paraopeba River, the watershed main river (Dutra and Elmiro, 2020). The area is situated in the municipality of Brumadinho, in Brazilian state of Minas Gerais as illustrated in Figure 2. This scenario was chosen just because it provides an unparalleled opportunity to effectively evaluates the flood patches conformity of simulated studies when compared to that of ground truth, that is, the areas effectively impacted by the dam failure itself.
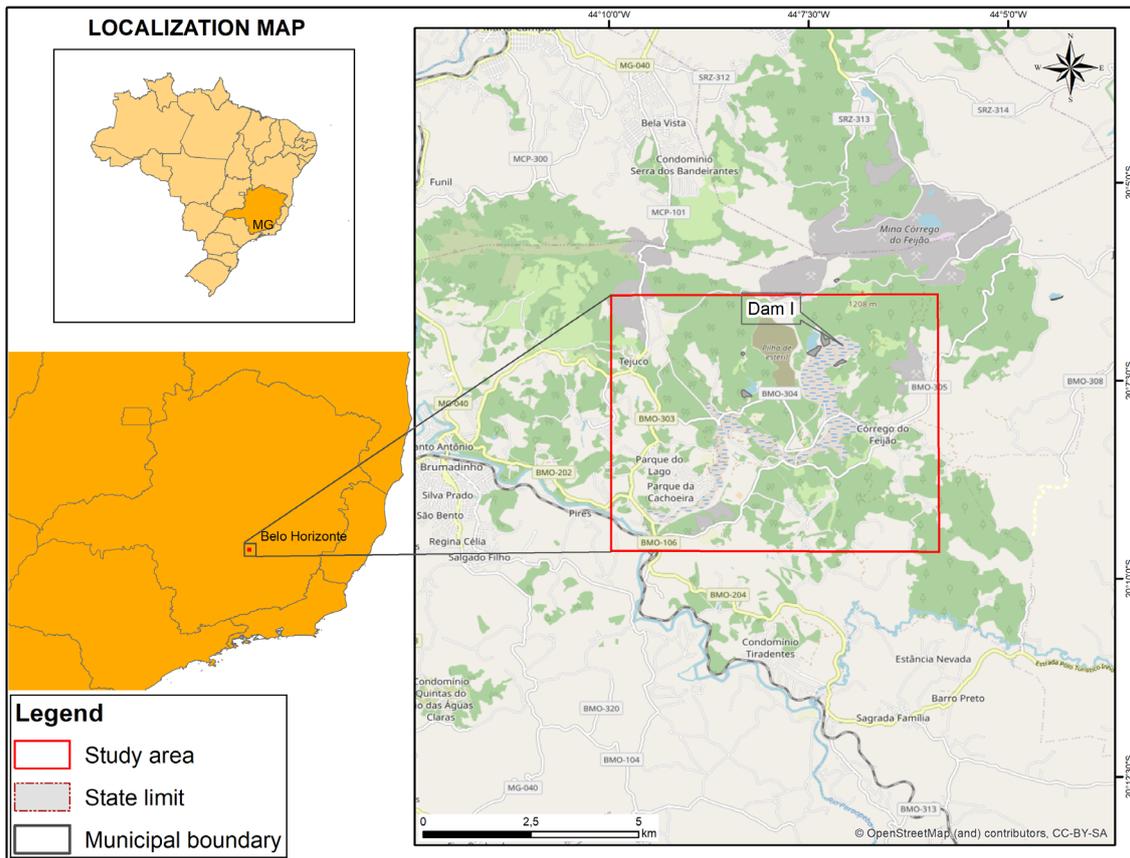
Figure 2: Study area location showing geographic position of Dam I collapse in municipality of Brumadinho, Minas Gerais, Brazil. Source: the authors.

Dam I (Figure 3) containing mining tailings is part of the Córrego do Feijão mine, in the municipality of Brumadinho, located in central part of Minas Gerais Brazilian state. It was built for the disposal of tailings generated in the beneficiation plant in 1976 by Ferteco Mineração being acquired and operated by Vale SA since April 27, 2001. It was assembled by using the upstream method, with a height of 86 m and a peak length of 720 m (VALE, 2019).

Figure 3: General view of Dam I mining tailings, an integral part of the Córrego do Feijão mine. Source: Vale S.A.

3.2 Delimitation of the impacted area

High resolution orthophoto images obtained through aerial photogrammetric survey performed before and after the collapse of Dam I were used for the delimitation of the area impacted by the dam burst. The photogrammetric mapping project carried out by Fototerra company adopted the use of large format digital camera Z1 DMC, 120 mm of focal length, 106.16 mpixel, 12 bits of radiometric resolution and red, green, blue and near infrared spectral bands.

The aerial images were taken with a GSD (Ground Sample Distance) of 0.2 m. The images were verified from ground control points in order to generate orthoimages with accuracy compatible to scale 1:5.000. Using these orthoimages, taken before and after the collapse, it was possible to trace the areas affected and analyzing visual differences, as shown in Figure 4, where could be seen, for the same place, differences between before (Figure 4a) and immediately after the collapse (Figure 4b).
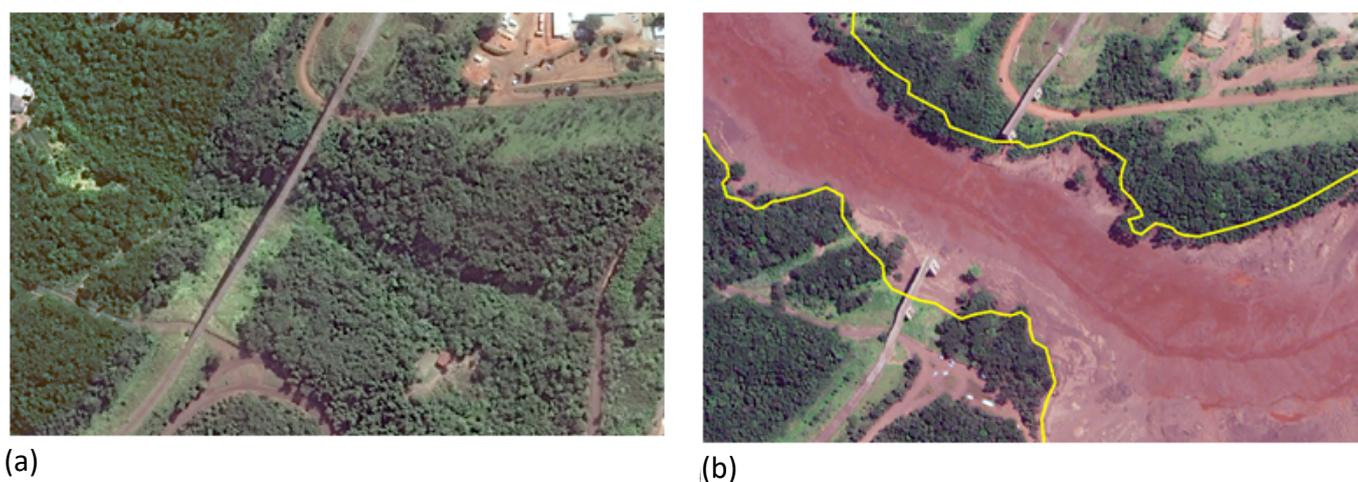

(a)   (b)

Figure 4: Photogrammetric orthoimages showing the landscape situation downstream the Dam I, a) before the dam collapse, b) after the dam collapse. Source: the authors.

In the regions covered by dense vegetation, where delimitation of impacted areas over the orthophotos was difficult, the difference between digital terrain models from ALS obtained before and immediately after dam rupture was also calculated in order to increase the accuracy of delimitation lines. Both ALS dataset, obtained before and after dam rupture, had similar technical characteristics.

3.3 Hydraulic parameters

The present work focuses on assessing the impact of using different sources for topography relief representation on the simulation results of dam burst, thus, the hydraulic parameters were made available by Vale SA through technical reports originated from studies carried out by water resources specialized companies and were kept constant and unchanged in all the simulations instances. Further details on these parameters can be found in Potamos (2018) through the collection of technical reports.

The rupture hydrogram graphically represents the variation of the effluent flow of the dam over time, with the peak flow being characterized at the top of the hydrogram at a given time (Faria et al. 2019). The collapse hydrogram, shown in Figure 5 was used as input in this research. It considered the hypothesis of instantaneous

collapse of the Dam I, without taking into account the premise of gradual development of the gap limited by the time of formation (Potamos, 2018).
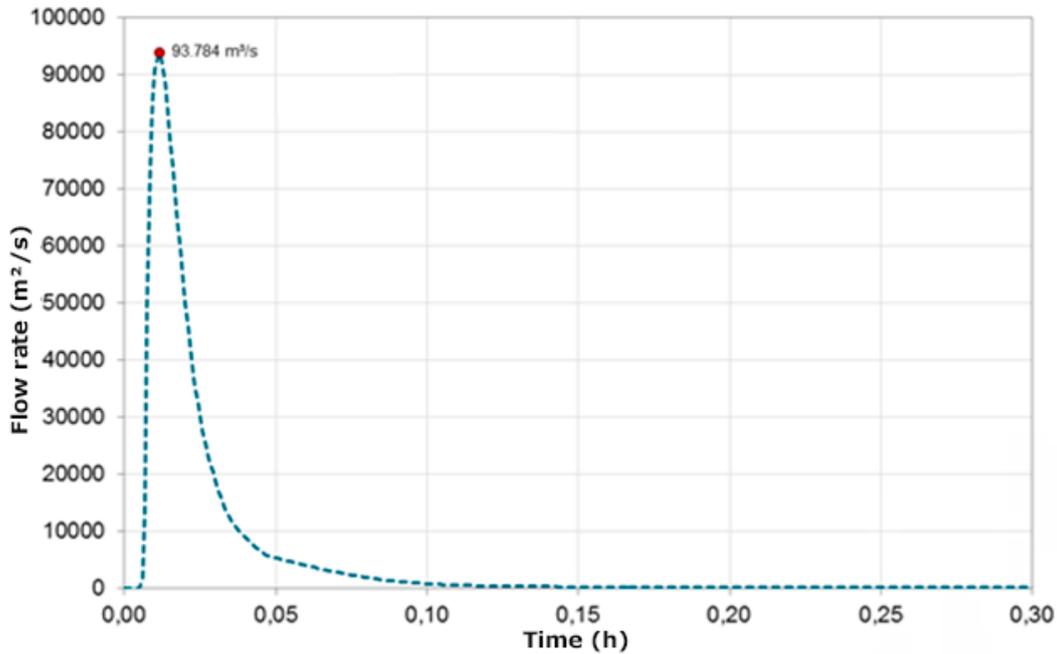

Figure 5: Collapse Hidrogram considering the hypothesis of instantaneous break of the Dam I. Source: Potamos (2018)

The Manning coefficient is a factor associated with the resistance of the fluid through the channel, being responsible for the loss of pressure in the flows due to the viscosity of the fluid and the roughness of the channel. It is of great importance for obtaining models that aim to study the behavior of floods and sediment transport through channels (Abbas, Abbodi and Ibrahim, 2020). The values used in this research for the Manning coefficient originate from a land use and classification map produced and described in technical reports by water resources specialized companies (Potamos, 2018). Table 1 shows the variation of the Manning coefficient depending on the type of soil cover.

Table 1: Values of Manning's roughness coefficients for classes of land use. Source: Potamos (2018).

Class	Roughness coefficient – Manning (n)
Water body	0,025
Uncovered soil and degraded areas	0,030
Pasture and man-made fields	0,040
Rocky outcrop	0,045
Mining and associated structures	0,055
Forest	0,080
Urban area	0,100

3.4 Collapse simulation

The simulations were performed using the HEC-RAS software, an acronym originated from the Hydrologic Engineering Center (HEC) River Analysis System (RAS), which is a free-access hydrodynamic simulation modeling software developed by the US Army Corps of Engineers. The two-dimensional (2D) version was used in this case study.

As the simulations were achieved devising the hypothesis of the intense influence of the different DTM data in the delimitation results of the flood map, three simulations were carried out for evaluation and discussion differing mainly in the input parameter concerning the digital elevation model.

In the first simulation, the digital terrain model derived from ALS was used. The second simulation was carried out associating the digital surface model related to ALOS_ASF with a spatial resolution of 12.5 m. Finally, the digital elevation model with 30 m of spatial resolution derived from SRTM data provided by the United States Geological Survey (USGS) was used in the third simulation.

3.5 Assessment of results adherence

A previous step of adherence assessment is an evaluation of the models ALS, ALOS_ASF and SRTM based in a relative comparison to increase the consistency of the study. It is well known, either by technical descriptions or by literature studies (Morais, 2017; Morais et al. 2017; Scalco et al. 2018; França et al. 2019 and Orlandi et al. 2019) that ALS has the best accuracy among the three models, thus an internal evaluation was performed by extracting the basic statistics (minimum, maximum, mean, standard deviation and RMSE) from the models ALS, ALOS_ASF and SRTM, and also from the subtraction models (ALS-ALOS_ASF) and (ALS-SRTM). These statistics values provide a general view of ALOS_ASF and SRTM accuracy compared to ALS for checking if they corroborate literature studies.

The adherence assessment consists of comparatively analyzing each of the three simulated flood maps (from ALS, ALOS_ASF and SRTM) with the real flood patches mapped. In this sense, evaluating the adherence of the results means evaluating how much the boundaries of the flood patches resulting from the simulations approximate the observed real flood patches, and how similar their shapes are to the shapes of the real flood patches, indicating a parallelism between the simulated and real boundaries.

Another strong analysis of adherence is checking the occurrence or not of invasions inside the real observed flood patches by the boundaries of the simulated flood patches. If so, it would mean that areas effectively flooded would be outside the areas predicted by the simulation. This would result in the exclusion of areas that would actually be hit in the event of a disruption, causing mistakes in all planning activities for rescue operations.

An effective way of evaluating results, regarding to quality of the relief representativeness downstream the dams can be observed in the studies of (Machado, 2017; Vianini Neto, 2016 and Rocha, 2015), in the sensitivity analysis stage of the digital surface models used in dam rupture retro analysis, cases in which there is a real area for comparison, through an indicator (F) that expresses quantitative measures for an objective assessment. Additional studies on this type of assessment can be found in Hunter (2005), Mason et al. (2009), Schumann et al. (2009) and Stephens et al. (2014).

The indicator (F) is based on an analysis by means of binary pattern comparison, made pixel-by-pixel, where all cells are analyzed and classified under the conditions of observed / predicted (A), not observed / predicted (B) and observed / not predicted (C). The variations of the indicator were investigated and well described in studies such as Hunter (2005) and Stephens et al. (2014) which proposed different formulations, combining the classes A, B and C in different ways, where each combination has a specific characteristic. Table 2 shows the formulations for obtaining

the different variations of binary comparison measures from cells types A, B and C. The first line of the table refers to the bias component of prediction (F) that should be unity (unbiased) for a perfectly reliable prediction.

Table 2: Performance indicators for use in simulation studies, by variations of (F) index calculated from cells types A, B and C, based on pixel-by-pixel analysis. Source: adapted from Rocha, 2015.

Name	Equation	Inteval	Characteristics	ALS	ALOS	SRTM
F	$\dfrac{A + B}{A + C}$	$(0,\infty)$	Balance between under and overestimation of flood	1,318	2,069	2,021
Critical success or $F^{<2>}$	$\dfrac{A}{A + B + C}$	$(0,1)$	Reduces the influence of the size of the flooded area	0,757	0,456	0,462
$F^{<3>}$	$\dfrac{A - C}{A + B + C}$	$(-1,1)$	Penalizes flood underestimation	0,756	0,438	0,440
$F^{<4>}$	$\dfrac{A - B}{A + B + C}$	$(-1,1)$	Penalizes flood overestimation	0,515	-0,069	-0,054

4. Results

Table 3 shows descriptive statistics (minimum, maximum, mean, standard deviation and RMSE) extracted from models ALS, ALOS_ASF, SRTM and subtraction models (ALS-ALOS_ASF) and (ALS-SRTM). By analyzing these statistics values it is possible to infer basic conclusions about ALOS_ASF and SRTM accuracy compared to ALS and ensures their adherence to studies of literature.

Table 3: Basic statistics from the models ALS, ALOS_ASF and SRTM and from the subtraction models (ALS-ALOS_ ASF) and (ALS-SRTM). Source: the authors.

Digital Elevation Model	Maximum (m)	Minimum (m)	Mean (m)	Standard Deviation (m)
ALS	1116,02	694,86	771,01	51,73
ALOS_ASF	1118,40	693,40	774,02	51,49
SRTM	1120,00	693,00	774,39	50,97
ALS-ALOS_ASF	54,68	-39,35	-2,92	5,15 (RMSE)
ALS-SRTM	58,67	-52,47	-3,37	6,56 (RMSE)

Figure 6 shows the flood map observed after the collapse of Dam I. This flood map is used a reference for comparison with the results obtained in the simulations using the three different digital models ALS, ALOS_ASF and SRTM, allowing an analysis about what are the differences, which situations are possible, what are the impacts on the necessary actions resulting from the simulation studies of dam break and evaluate if the use of surface models such as those derived from SRTM and ALOS PALSAR are suitable for this type of analysis.
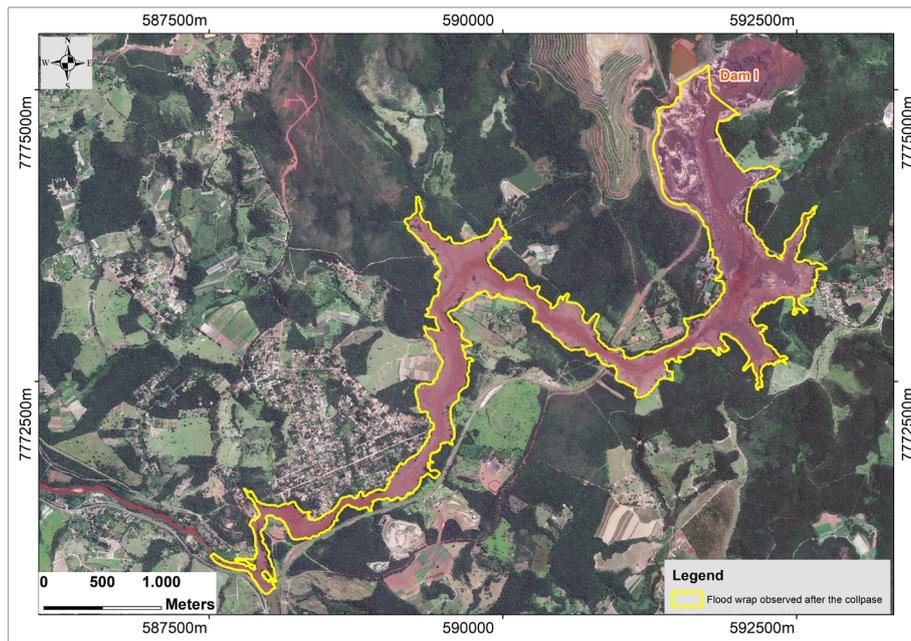
Figure 6: Delimitation of the area impacted by the Dam I rupture effectively observed after collapse. Source: the authors.

The simulated flood boundaries resulting from the digital surface models ALS, ALOS_ASF and SRTM overlaid with the flood boundaries observed after the rupture are shown in Figure 7. By qualitatively comparing these flood map overlay results, it can easily be seen that the flood map obtained by using the ALS model is the one most closely related to the actual observed flood patches. Some relative parallelism and an approximate coincidence between both are clearly observed.
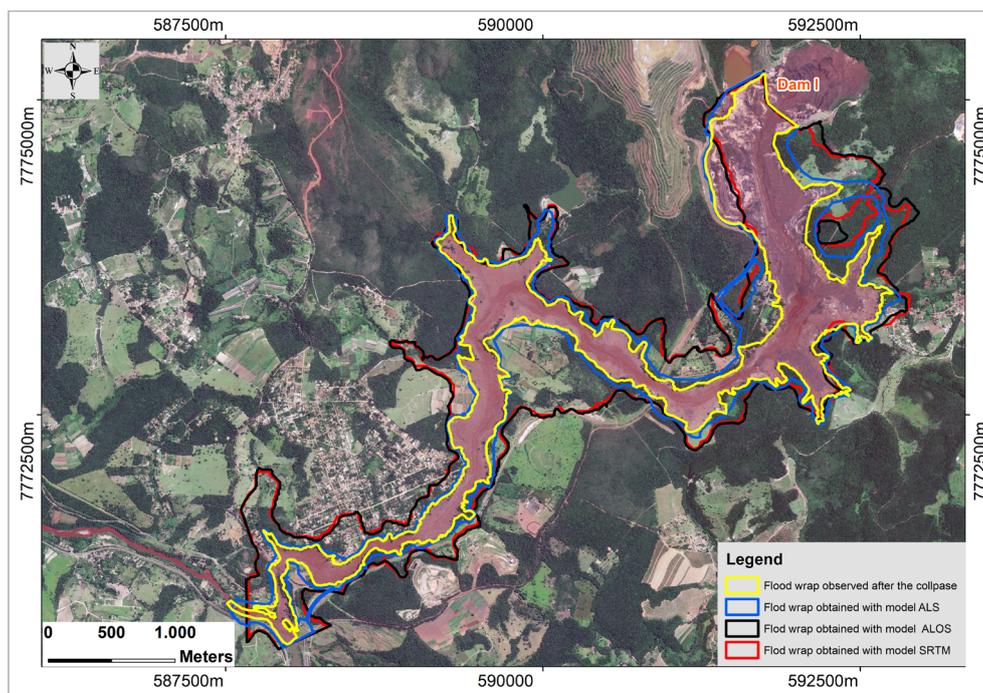

Figure 7: Simulation flood boundaries resulting from the ALS, ALOS_ASF and SRTM models overlaid with the flood observed after the Dam I rupture. Source: the authors.

In order to accomplish the quantitative assessment regarding the elevation models performance, a comparison of the flood map obtained in the simulations versus flood observed after the collapse of Dam I was carried out by using analysis of the (F) statistics indicator and by calculating the percentage of areas predicted for each digital surface model.

The results are summarized in Table 4 and in the graphs presented in Figure 8. Table 4 shows the quantitative area values obtained in the simulations, considering the extent of the observed flood, with respective variations relatively to the area observed after the collapse, as well as the values obtained for the factor (F) in different approaches.

Table 4: Performance indexes and area variations, considering the area of observed flood. Source: the authors.

DTM	Area (km^2)	Variation in relation to the impacted area (%)	F	$F^{<2>}$	$F^{<3>}$	$F^{<4>}$
ALS	3.80	32.00	1.318	0.757	0.756	0.515
ALOS_ASF	5.74	99.00	2.069	0.456	0.438	-0.069
SRTM	5.60	94.00	2.021	0.462	0.440	-0.054

Figure 8a shows the approaches of (F) statistics indicator and Figure 8b shows the percentage variations of flooded area in the form of graph.

(a)   (b)
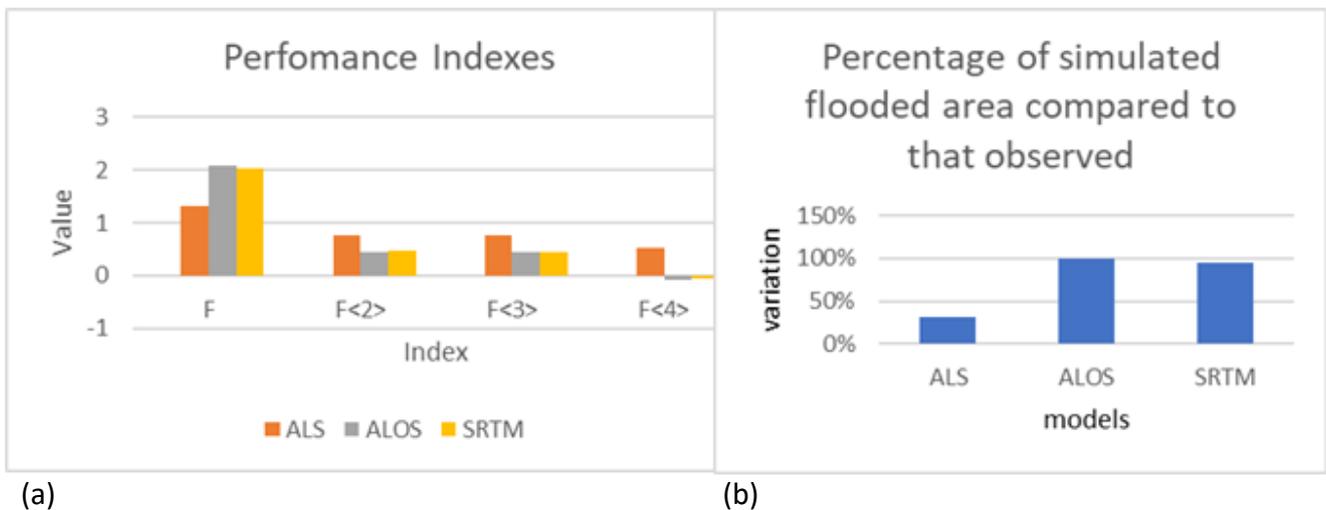
Figure 8: Summary of quantitative assessment a) Performance indexes for simulations with the use of different digital elevation models b) Variation of the flooded areas obtained in the simulations, compared to the flood observed after collapse. Source: the authors.

Figure 9, Figure 10 and Figure 11 present the classification of the flooded areas used to calculate (F) indexes, respectively, for models ALOS_ASF, SRTM and ALS.
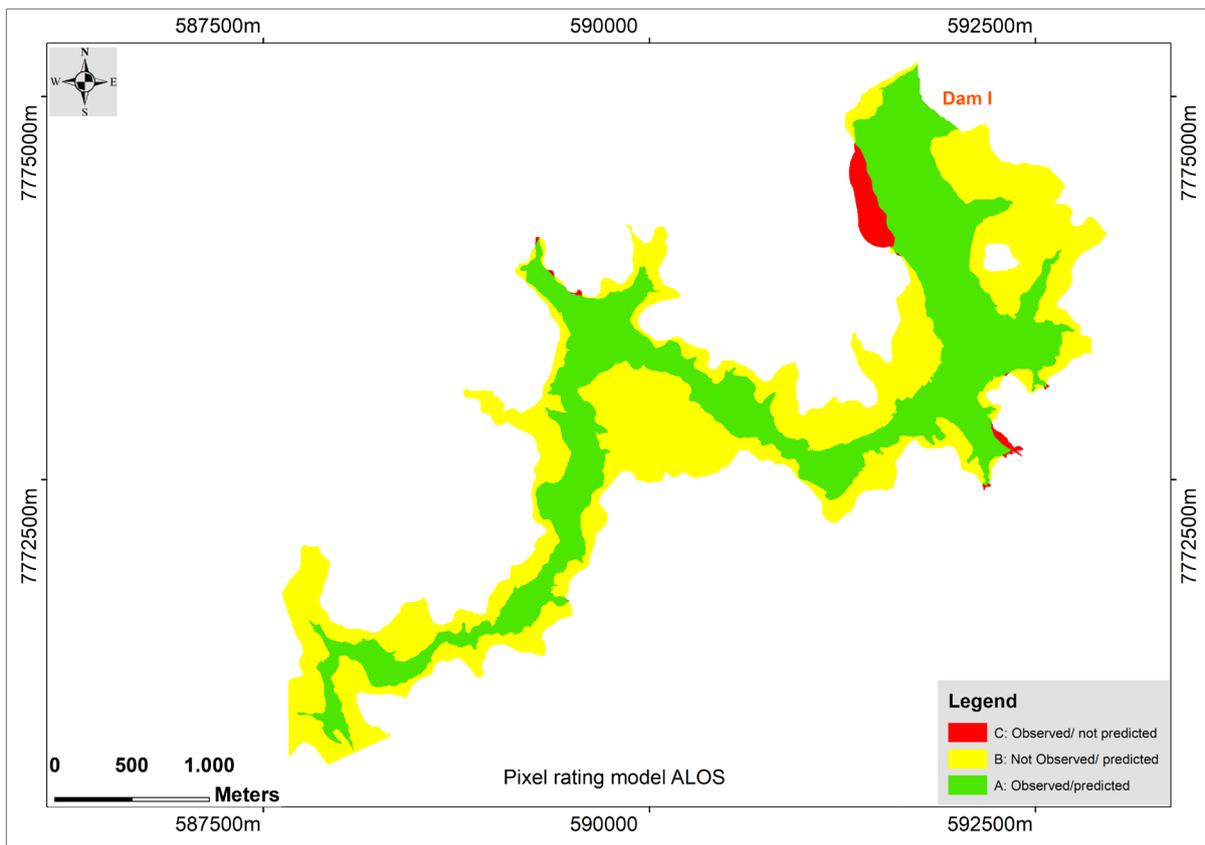
Figure 9: Classification of flood areas used to calculate the (F) index for ALOS_ASF model. **Source**: the authors.
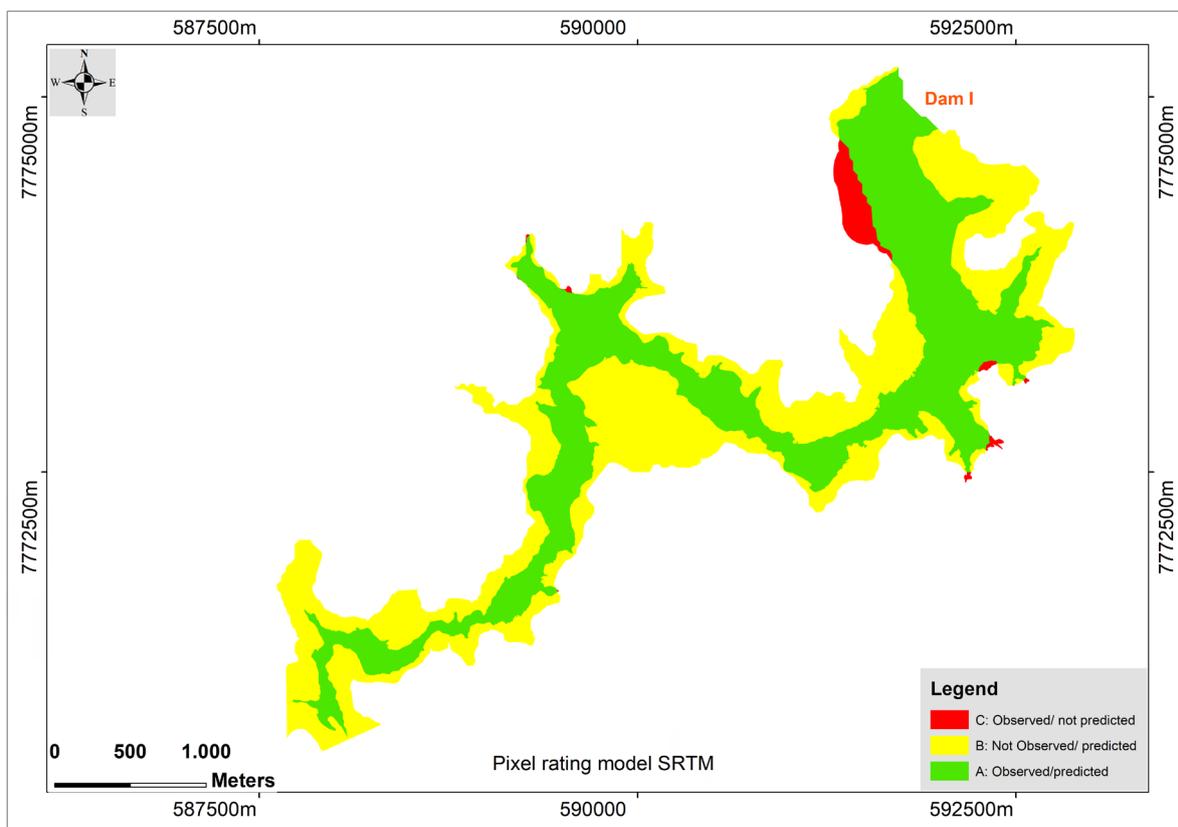

Figure 10: Classification of flood areas used to calculate the (F) index for SRTM model. **Source**: the authors.

Figure 11 shows the classification of areas by types A, B and C for the flood map obtained through the ALS model.
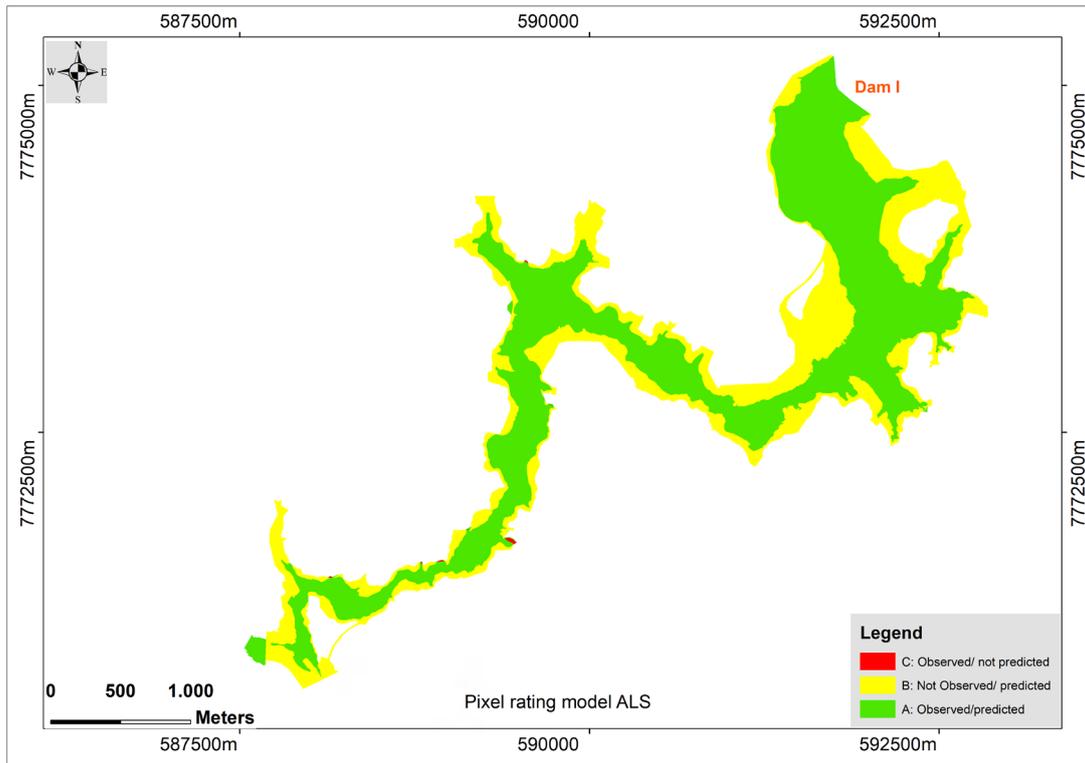

Figure 11: Classification of flood areas used to calculate the (F) index for ALS model. Source: the authors.

Figure 12 shows examples of places where type B areas can be identified. It is possible to note that a lot of areas mapped in the simulation results using the models were not observed after the rupture, so contributing to a decrease in the performance index.
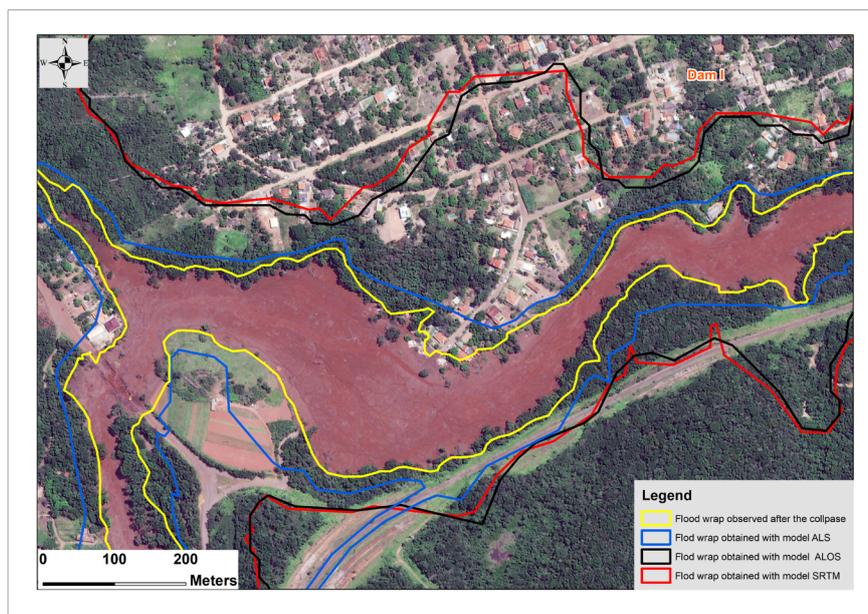

Figure 12: Type B areas, according to ALOS_ASF and SRTM models. Source: the authors.

5. Discussions

Table 3, presented in Results Section, briefly confirms the altimetry models conformity to literature studies and the technical descriptions published by models producers (Morais, 2017; Morais et al. 2017; Scalco et al. 2018; França et al. 2019 and Orlandi et al. 2019). The free cost low quality models presented an overall similar quality with a slight advantage for the ALOS_ASF over SRTM. Because both are referred to the earth surface objects (DSM), besides other factors, they overestimated the ALS by a height of about 3 m, presenting an absolute Root Mean Square Error (RMSE) of about 6 m. The similarities between both can be partially explained by their origin based in the same source of data obtained from C-band radar interferometry. Although ALOS_ASF present a 12.5 m spatial resolution it is derived from interpolations and resampling operations over the same original source of SRTM.

From the analysis of the results shown in Figure 7 to Figure 12 and Table 4 it can be inferred an overall similarity in the behavior of simulated flood based in the free cost models ALOS_ASF and SRTM. By analyzing (F) performance index presented in Results Section (Table 4 and Figure 8a) that measures a balance between the flood underestimation and overestimation (simulations can include areas that would not be impacted by dam breach or exclude areas that can actually be reached by breach), it is possible to observe higher values for both models ALOS_ASF and SRTM, which indicates an increase in simulated flooded areas by using these free cost topography relief models. The same effect can also be seen from the variations observed in the percentage of the simulated flood areas compared to that observed (Table 4 and Figure 8b presented in Results Section).

The values obtained for indexes $F^{<2>}$ and $F^{<3>}$ (Table 4 and Figure 8a presented in Results Section) present better results for simulation using the ALS model. The results for these indexes also point out to a great similarity between the free cost models ALOS_ASF and SRTM. Both models presented similar behaviors in the simulation results related to the amount of areas of the types predicted and not observed (B) and not predicted and observed (C), as presented in Figure 9 and Figure 10 in Results Section.

The $F^{<4>}$ index, whose main objective is to evaluate the overestimation of flooding, again indicated a better performance of the simulation with the model ALS, presenting negative results for the simulations obtained with both models ALOS_ASF and SRTM. That is because in the simulations with the free cost models, the number of cells correctly classified was less than the amount predicted in excess. See Figure 11, presented in Results Section, to observe the areas of types A, B and C for the flood map obtained through the ALS model.

The differences observed by the application of performance index in its different approaches agree with the results obtained in the study carried out by Vianini Neto (2016), which found better results in the indexes calculated by using ALS digital terrain model when compared to simulation using SRTM model with 30 m of spatial resolution.

The results presented also corroborate the conclusions of the study carried out by Rocha (2015), which found an overestimation in the flood simulated by using the SRTM model. The overestimation was also found in the flood obtained with the ALOS_ASF model.

The results confirmed the observations made by Rocha (2015), reporting that the representation of the relief has a great influence on the forecast of areas with flood potential resulting from dam break studies, pointing out that the ALS model, with associated costs, has a better adherence than the free ALOS_ASF and SRTM models.

It is important to note the similarity in the behavior of the flood maps obtained by using the ALOS_ASF and SRTM models, mainly in the inclusion of areas, which were not affected by Dam I collapse as can be seen Figure 12, presented in Results Section, that shows examples of places where type B areas can be observed. This inclusion of type B class for both models indicate an increase in the area not observed and present in the simulation results, contributing to a decrease in the performance index.

An interesting point to be noted is that in the result obtained in the simulation using the ALS model, the

percentage of area fitting the condition observed and unforeseen is very close to zero, meaning that almost all observed flood was predicted in the simulation using the ALS model, different from the results obtained using the ALOS_ASF and SRTM models. It must be emphasized that the exclusion of areas with potential to be reached in the event of a collapse is more dangerous because it compromises prevention and rescue actions.

Regarding the costs of using ALS model, compared to free cost models (ALOS_ASF and SRTM), it can be evident that such costs may be diluted in the total amount of the dam project, especially considering the possible impact caused by free cost modeling inaccuracies in the event of an accident. Less accurate modeling based on free cost DTM/DSM may include many extra areas that would never be reached in the event of a possible disruption, unnecessarily increasing the costs of restrictive measures to be taken to these areas and putting unnecessarily on alert populations that would never be reached in the event of a dam collapse. It is important to note that the preventive measures must last for the life of the enterprise, perhaps extending for more than 50 years.

6. Conclusion

Going back to the introductory hypothetical questions that motivated this research and based in the considerations and findings mentioned in results and discussions of this study the conclusion of the work highlights the major points that follow.

All simulations from ALS, ALOS_ASF and SRTM overestimated the observed flood, what becomes convenient because of its conservative nature. However, the free cost models almost doubled the flood overestimation, indicating that free cost models considerably increase the costs of planning actions for minimizing the impacts and the effects associated to a possible collapse.

Flood maps from free cost models provided some invasions inside the real observed flood boundaries. So, areas effectively flooded were outside the areas predicted by the simulation. These areas were actually hit by the disruption and, fortunately, they were located outside urban patches. This type of simulation error is very dangerous because it compromises prevention and causes mistakes in all planning activities for rescue operations.

Free cost models generate flood maps with much more uncertainties in the flood delimitations. So, although their value for many other useful purposes, they could not be recommended to predict flood in dam break studies. Because of these free cost models uncertainties and the eventuality of excluding affected areas in the simulated mappings, ALS models are recommended for dam break simulation studies.

Even though ALS models have associated costs, such costs are much lower than those associated to a poor dam break simulation, in case of a rupture. Also, considering the drastic effects of a dam break disaster, in addition to the high cost of implementing dam projects, the costs of acquiring the ALS data has little relevance for large mining companies like Vale SA.

AUTHOR'S CONTRIBUTION

Rodrigo Pereira Lima contributed to the elaboration and consolidation of all phases of the manuscript under the guidance of Marcos Antônio Timbó Elmiro and Marcelo Antonio Nero. The three authors had a very interactive involvement in the stages of writing and organizing the text, in the bibliographic research, in the scientific basis, in the establishment of methodologies, in the testing of software and in the analysis of results.

Marcos Antônio Timbó Elmiro and Marcelo Antonio Nero contributed as supervisors of the research work

conducted by Rodrigo Pereira Lima and participated in the general supervision of the different stages, such as review and organization of the text, bibliographical research indications, construction of theoretical foundations, structuring of methods and research materials, analysis and discussion of results.

Plínio da Costa Temba and Luiz Henrique Guimarães Castiglione contributed with reviews and guidelines related to the tests and applications of cartography, geodesy and laser surveys, analyzing maps and data consistencies.

Bráulio Magalhães Fonseca contributed with reviews and guidelines related to geoprocessing applications, digital elevation models, tests of simulation software, in addition to text reviews and data and method consistencies.

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Erratum

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