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Analysis of flood warning and evacuation efficiency by comparing damage and life-loss estimates with real consequences related to the São Francisco tailings dam failure in Brazil

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Abstract. Using mathematical modelling and computer simulations, economic damages and life loss estimates are results that, when prospectively designed based on the comparison of different flood alert scenarios that can be implemented, provide important insights for the elaboration of more robust alerts and the most effective emergency planning. The purpose of this work is to evaluate the use of flood damage and life loss models in floods caused by tailings dams through the application of these models in the real case of the São Francisco dam failure, which occurred in January 2007 in the city of Miraí, in Brazil. The models applied showed agreement with the actual damage observed, and the impact of different lower efficient alert systems showed more catastrophic scenarios in terms of loss of life. The results of this work indicate the potential benefits of using these consequences in risk assessment and may help the brazilian and international legislation on dam safety in new regulations.

1 Introduction

The benefits provided to society by the construction of dams of different types and purposes are undeniable. However, the failure of these structures may represent high damage potential to downstream valleys (Proske, 2018). From 1915 to 2022, a total of 257 tailings dams in the world suffered accidents accounting 2,650 fatalities (Piciullo et al., 2022). The rate of tailings dam failures (1.2 %) is higher by two orders of magnitude than the value of 0.01 % reported for conventional dams (ICOLD, 2001; Azam and Li, 2010). In addition to the fact that tailings dams are historically more vulnerable than conventional dams (Rico et al., 2008a), these dams generally present a much more significant risk to the environment due to physicochemical characteristics of materials that may be stored in their reservoirs (Kossoff et al., 2014; Fernandes et al., 2016; Rotta et al., 2020; Guimarães et al., 2022).

North America and Europe are the continents with higher records of accidents involving these structures (Rico et al., 2008b; Azam and Li, 2010). However, from 2000 to 2022, Brazil alone accounted for 11 tailings dam accidents, with consequences of different orders (economic, socioenvironmental, and cultural). Three of these accidents took place in 2019, including the Brumadinho dam failure, which killed more than 250 people (Project Chronology of Major Tailings Dam Failures, 2022).

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

Prospective flood impact assessment is an extremely effective tool for supporting emergency planning and decision-making processes (Apel et al., 2004; Merz et al., 2010). Specifically in flood events, the main social relevant impacts are loss of life and/or economic damage, which are both objectively quantifiable and more relevant in the public perception of disasters (Jonkman et al., 2003). Several methods are available for evaluating loss of life and economic damage related to floods. Extended literature reviews were realized by Merz et al., (2010) for flood economic damage evaluation and by Jonkman et al., (2016) for flood loss of life evaluation. Since then, other relevant studies and models were achieved for economic damage (Gerl et al., 2016; Bombelli et al., 2021) and loss of life evaluations (Huang et al., 2017; Li et al., 2019; Mahmoud et al., 2020; Ge et al., 2021, 2022; Jiao et al., 2022). In addition, recent computational advances and software developments allow to perform more robust damage simulations (e.g., LifeSim and Life Safety Model). Although, the international studies that focused on tailing dams impact assessments are rare. Lumbroso et al. (2021) performed life-loss simulations related to Brumadinho (Brazil) tailings dam failure. No studies focused on both tailing dams failure economic and loss of life assessments were identified. This is one of the main topics explored in this paper.

Among the recent tailings dam disasters that occurred in Brazil, we analyse the rupture of the São Francisco mining tailings dam, in Miraí city, Minas Gerais State. This accident took place in 2007. It caused several damages in the downstream valley, including the flooding of around 300 to 500 dwellings, generating economic and environmental losses. Although a high risk was observed, no fatalities were registered. This accident represents an opportunity for research purposes once it presents a particular case of efficiency of evacuation and it was the object of some national studies (Pimenta de Ávila, 2007; Rocha, 2015; Veizaga et al., 2017) and media coverage, which provides relatively detailed data concerning the real flood extents and its consequences.

Even when considering natural floods, there are few studies comparing the results of prospective analyses with actual surveys (Molinari et al., 2019). The application of predictive models for estimating impacts under these conditions is of great scientific interest both for validating the use of models against observed data and for estimating potential impacts in more or less favorable conditions with the success of the observed evacuation, through the simulation of hypothetical scenarios.

In this context, this paper evaluates how accurate life-loss and damage models may be for estimating tailigns dam failure floods impacts and alert and evacuation efficiency for loss of life alleviation. Furthermore, it perfomrs, in an unprecedented way for tailings dams, the application of models to estimate economic damage and loss of life together. In addition to the objective of representing the real accident, we simulated different scenarios for warning and evacuation, validating and comparing the results with actual observed data, revealing the benefits of using models to guide flood warning and evacuation systems implementation.

2 Case study - The Miraí accident in 2007

The São Francisco dam was a structure for storing tailings from the effluent generated in the bauxite washing process of *Mineração Rio Pomba Cataguases Ltda*. The dam was located eight kilometers from the urban center of Miraí, a city located

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

in the Zona da Mata of Minas Gerais State (Figure 1). This city was directly impacted by the breach wave. The São Francisco tailings dam reservoir was 34 meters high, with a length of 90 meters, a width of 9 meters, and a capacity of approximately 3.8 million cubic meters.

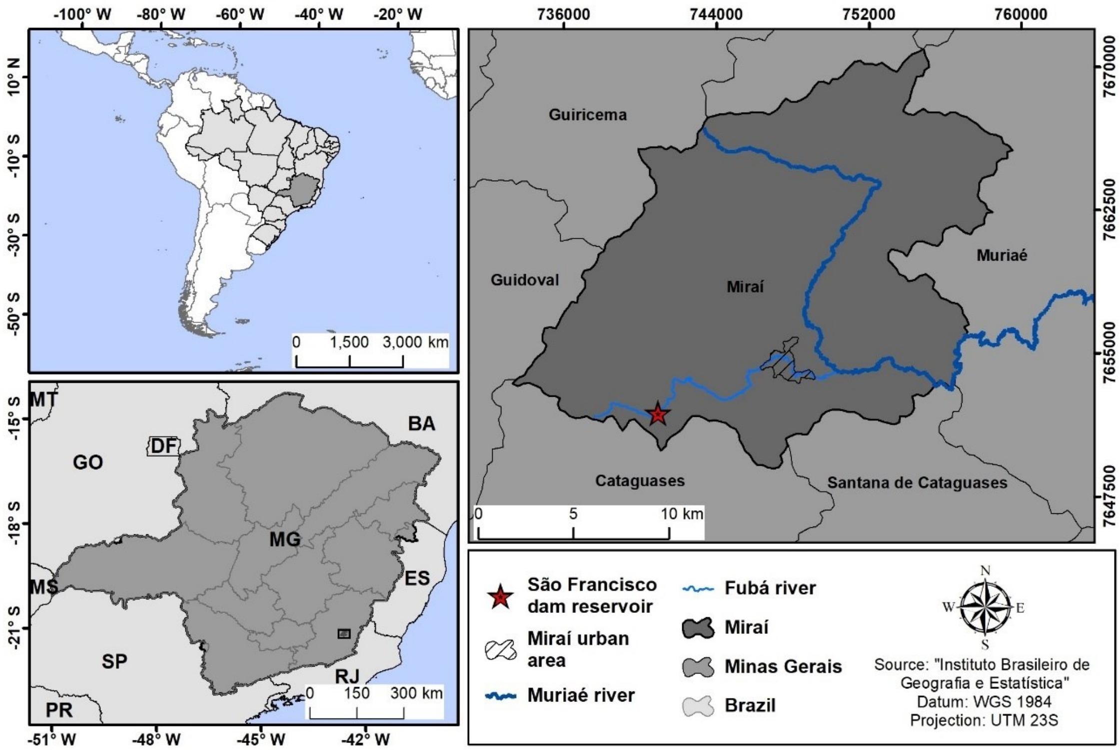

Figure 1: Location map of the São Francisco Dam in Miraí city (MG) – Brazil.

The Miraí accident occurred on January 10, 2007. At around 3:00 a.m., the water level in the reservoir rose rapidly due to an intense rainfall of 121.3 mm, which lasted four hours. The water started to overflow through the surface spillway and through the contact of the massif with one of the dam abutments, causing the latter to collapse due to the rapid erosion caused by the volume and speed of the water. According to local estimates, the collapse started around 3:30 a.m. on that day. About 82% of the volume of mud stored in the reservoir spread through the Fubá River (which crosses the urban area of Miraí city) and continued beyond the confluence with the Muriaé River. Figure 2 shows the Miraí accident and the extent of the observed inundation area, outlined using satellite images and aerial photographs (Rocha, 2015).

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

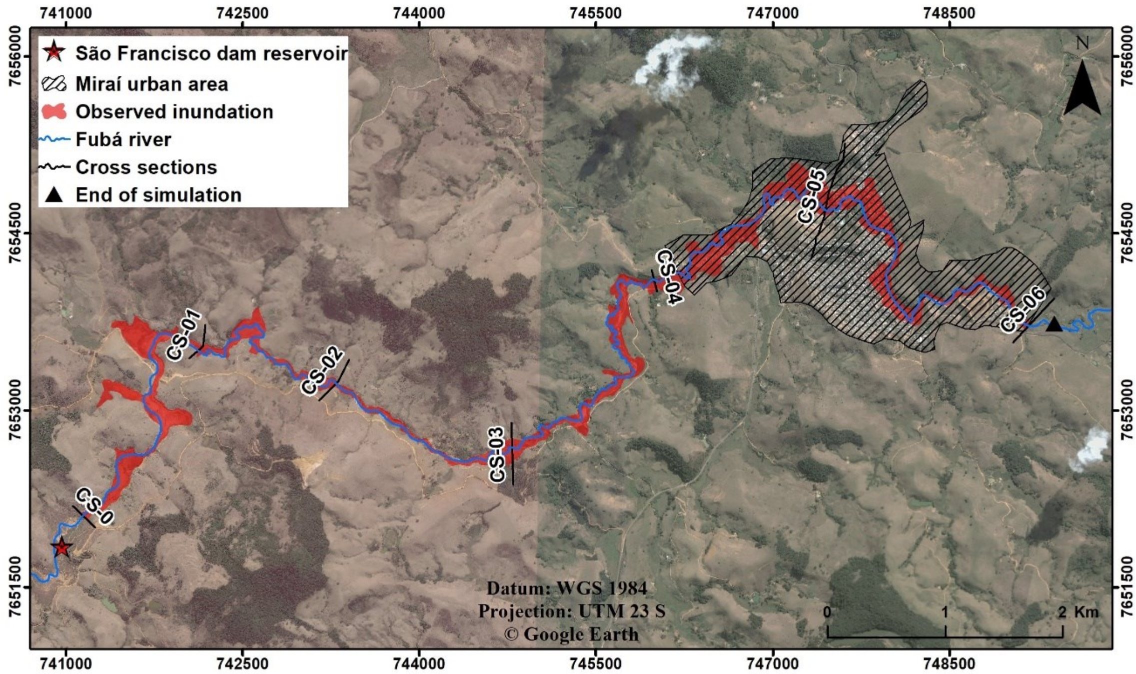

Figure 2: Observed inundation area after the São Francisco dam breach, Miraí – MG.

80 According to local studies, during the rainfall event period, the dam watchman noticed the rapid rise in the water level in the structure and notified the Military Police about the imminent danger of rupture when the water level of the reservoir was about 30 cm from the crest of the dam. After receiving the warning, at about 3:30 a.m., the local Military Police went through the streets of Miraí city, helping on the successful evacuation of the whole population during the night. Regarding the economic damage to the infrastructure of the city, the municipal government estimated a value of approximately 74 million reais (14.149 million dollars, using the average exchange rate for the first half of 2022 with a value of 5.23), which is around nine times the city's annual budget. This estimate did not include the damage to residents due to the loss of personal objects, furniture, and household structure. Other consequences of the event were the death of fish and the interruption of water supply in several cities.

3 Method for achieving the prospective evaluation of flood impacts

There are several methods for analyzing and quantifying economic damage (Merz et al., 2010). Nevertheless, due to the difficulty in specifying indirect and intangible damage, the methods usually focus on direct tangible damage. For estimating this type of damage, Merz et al. (2010) consider the following aspects: characterization and classification of assets at risk; quantification of impacts on flood-exposed assets at risk; and association of the potential damage to assets through the use of damage models which relates assets typology and flood characteristics to damage economic potential.

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

In turn, the methods for assessing loss of life rely on behavioral assessment and macroeconomic indicators (Jongejan et al., 2005). However, the monetary specification of loss of life is complex due to the intangible characteristic of this type of damage. Risk assessments usually address fatalities directly and quantitatively, without monetary attribution (Jonkman et al., 2003). Prospective quantification of direct loss of life comprises three main factors: first, the number of people potentially at risk; then, the effectiveness of evacuation and shelter strategies, thus determining the number of people who may be exposed to the event; and, finally, the fatality rate estimate, which is the ratio between the number of fatalities and the number of flood-exposed people (Jonkman et al., 2008).

There are several models for estimating loss of life, as presented in the literature review made by Jonkman et al. (2016). Among these models, we highlight LifeSim (Aboelata and Bowles, 2005), which is an agent-based model, used in this research. LifeSim simulates the outcomes of event exposure, and its methodology links the loss of life to the evacuation of people or their success to find a safe shelter. Besides the model allows the estimation of economic damages. The full version of the model is integrated into HEC-LifeSim v.1.0 (USACE, 2018). This version is the most used in North American consultancy and insurance companies (Needham et al., 2016), and it is being also widely used worldwide (Risher et al., 2017; Hill et al., 2018; Kalinina et al., 2018; Leong-Cuzack et al., 2019; Wang, 2019; Tomura et al., 2020; Bilali et al., 2021; Kalinina et al., 2021; Silva et al., 2021; Bilali et al., 2022).

Based on these principles, the impact assessment methodology presented in this article consists of three parts: (1) using accident data to model the amplitude of the tailings flood wave, to map the flood extent, and to delimit the affected region; (2) estimating damage and loss of life-based on the analysis of exposure and vulnerability of the urban area of Miraí city; and (3) developing prospective scenarios for warning and evacuation to estimate the success of the proposed measures.

3.1 Dam breach modelling and flood wave mapping

In the HEC-RAS (Hydrologic Engineering Center - River Analysis System) model, the propagation of the flood wave is given by solving the Shallow Water equations (Brunner, 2021). In two-dimensional modelling using the HEC-RAS version 6.3, the channel and the floodplain were subdivided into nonoverlapping cells to form a grid for solving the equations. The digital elevation model (DEM) used to generate the numerical grid was obtained by the Shuttle Radar Topography Mission (SRTM), with one arc-second spatial resolution (30 meters). The Fubá river channel was inserted by using the AGREE method (Hellweger and Maidment, 1997), with later correction of the river profile and insertion of topobathymetric points. This correction reduced the average error from 3.6 meters (DEM) to 1.2 meters (topobathymetric survey).

This grid can be structured by cells of any shape, with a maximum of eight faces. These cells can be orthogonal or not; however, if there is orthogonality in all or part of the grid, the solution of the applied numerical method has an advantage in computational speed. A hybrid discretization scheme that combines finite differences and finite volumes is used for solutions to Shallow Water equations. Furthermore, the Shallow Water equations can be simplified, resulting in the diffusive wave model. However, simplification is not recommended for the present study since it addresses a dam failure, which denotes highly dynamic flood waves (Brunner, 2021). The variation in speed in these situations can be highly drastic in space and

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

time, and diffusion wave simplification does not include the terms of local acceleration (change of speed over time) and convective acceleration (change of speed over space). The grid in this study was structured with 10-meter cells, being refined to five meters in the region of the Fubá River channel (Figure 3). The Eulerian-Lagrangian Method was used to solve shallow water equations on flood propagation. The databases used for constructing the model and the maps were obtained by Rocha (2015) in a detailed local analysis of the accident.

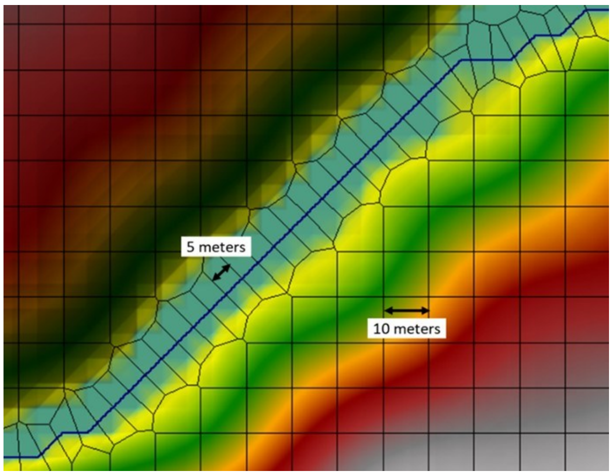

Figure 3: Structuring of the numerical grid used in HEC-RAS.

Volumetric solid concentration in the waste stream is usually higher than 20 % (O'Brien and Julien, 1985). In these cases, there is a variation in fluid viscosity, the flow being considered as non-Newtonian (Gildeh et al., 2021). Some studies present techniques to model the flow resistance of non-Newtonian fluids (Jeyapalan et al., 1983; Jin and Fread, 1999; Rico et al., 2008a; Bernedo et al., 2011; Gildeh et al., 2021; Larrauri Concha and Lall, 2018; Piciullo et al., 2022). Studies on the applicability of some of these techniques (Travis et al., 2012; Melo, 2013; Martin et al., 2015; Rocha, 2015; Machado, 2017) demonstrate the capacity and limitations of tailings flood wave modelling adopting a Newtonian fluid.

For the case under study, analyses from a minor incident in 2006 during dam raising showed that the reservoir sludge had a volumetric solid concentration of 12 %, which consequently, allows the representation of the flow as aqueous according to the definition proposed by O'Brien and Julien (1985). Therefore, no technique was used to represent tailings flow resistance, without prejudice to the simulation.

As done for traditional flood modelling, different Manning coefficients were determined for each class of land use and occupation determined by the Maximum Likelihood method, using Landsat 5 image (orbit 217 and point 75) of 10/15/2005. The classes considered were (Figure 4): dense vegetation; sparse vegetation; exposed soil; urbanized area; and water body, with respective coefficients of 0.160; 0.035; 0.025; 0.100; and 0.040, as proposed by the Natural Resources Conservation Service (NRCS, 2016).

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

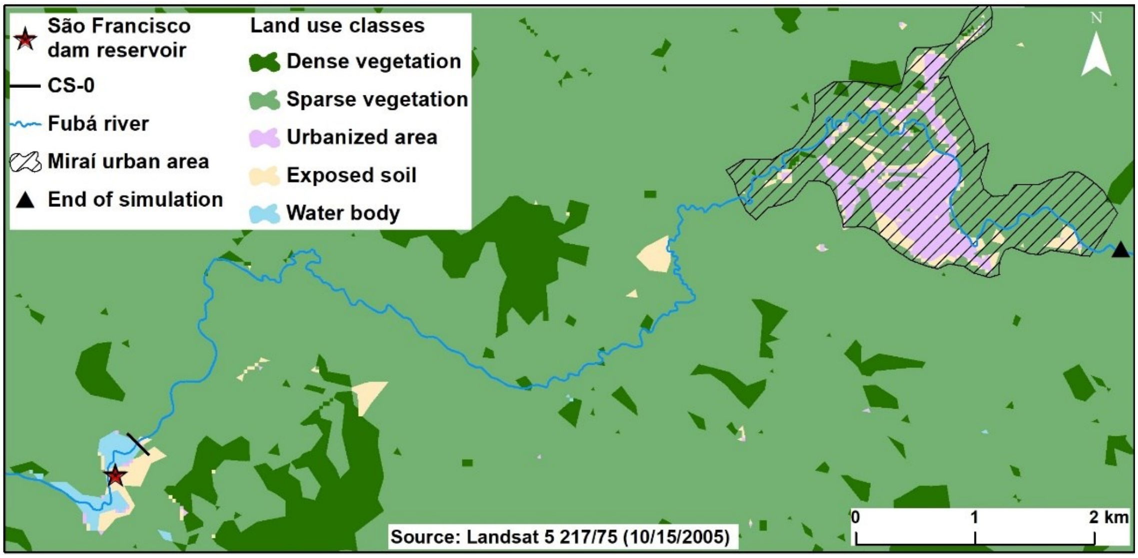

Figure 4: Map of land use and occupation - Manning coefficients.

The affluent hydrograph to the São Francisco dam reservoir was developed considering: the rainfall accumulation of 121.3 mm in four hours, the estimate of effective rainfall by the Curve Number (CN) method (NRCS, 1997), and the transformation of this effective rainfall into a runoff by the synthetic unit hydrograph method. The reconstruction of the accident (Rocha, 2015) led to the conclusion that the gap was 34 meters high, 70 meters wide at the top, and four meters wide at the bottom, and it developed in four and a half hours. Considering the affluent hydrograph calculated with a peak of 72 m^3 s^{-1}, the quota-volume curve, with 18 % of the material retained in the reservoir, and the quota-discharge curves of the spillway, the breach hydrograph was developed by the author starting at 03 h 30 min, with a peak flow of 422 m^3 s^{-1}, and peak and base time of 1 hour and 57 minutes and 3 hours and 54 minutes, respectively. This breach hydrograph was used as upstream boundary condition of the model. As downstream boundary condition, normal depth was adopted in a section approximately 220 meters away from the urban area under analysis (the most fitted flow condition), not influencing the study area.

Regarding the spread of the tailings flood wave, the simulated inundation boundary comprised 1.171 km^2, equivalent to 89.4 % of the total observed (1.310 km^2). Figure 5 shows the envelope of the simulated inundation area, highlighting the urban region of Miraí.

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

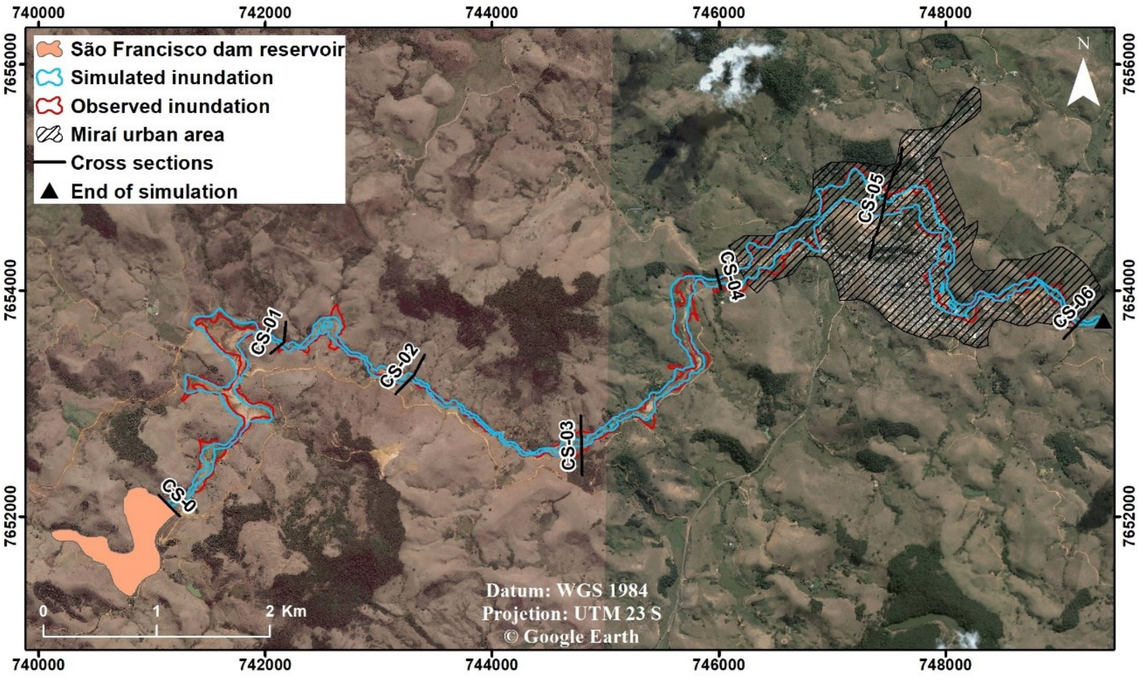

Figure 5: Inundation boundary simulated with HEC-RAS and observed from the São Francisco dam breach.

Despite having similar percentages, the inundation boundary shows noticeable differences. The simulation had area overestimation and underestimation of 16.0 % and 26.3 %, respectively, when compared to the observed flood map. These discrepancies are clearly a consequence of inaccuracies related to the DEM used, which tends to overestimate altimetry in areas with buildings and more robust vegetation, consequently reducing flood depths in these areas. Meanwhile, due to the low resolution of the model, the lack of details on altimetric obstacles that could obstruct wave propagation may lead to the overestimation of hydraulic parameters in flat areas (Paiva et al., 2011; Yamazaki et al., 2012; Saksena and Merwade, 2015; Jarihani et al., 2015).

Analyzing the flood hydrograph propagation through the sections indicated in Figure 5, one can perceive greater damping of the peak flow in flatter regions. These regions provide an increase in flood wave spread in comparison to regions of high slopes with embedded valleys, which, in turn, provide higher propagation speeds (Figure 6). The stretch between CS-0 and CS-01 comprises two large areas of flatland floodplain and extensive floodplain. Such topographic characteristics are also observed to a lesser extent in the stretch between CS-03 and CS-05. In turn, the stretch between CS-01 and CS-03 comprises a high slope region. In the urban region, between CS-05 and CS-06, there was no significant damping of the peak flow, only a delay in peak time. This is probably because the flood wave already reaches the urban area of Miraí city damped with low flow speeds. Table 1 presents the synthesis of the results for each cross section analyzed.

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

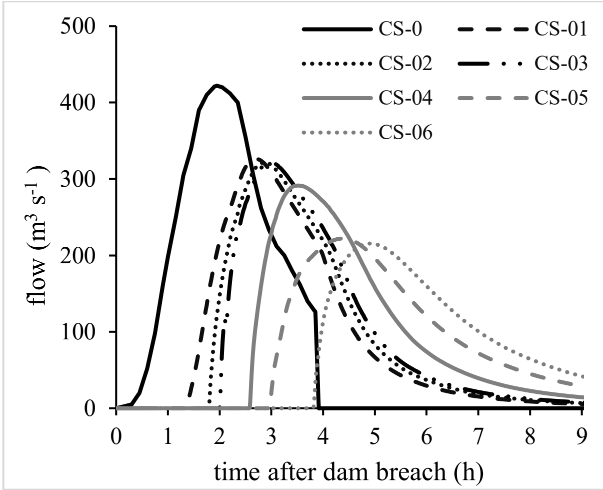

Figure 6: Breach hydrograph of the tailings wave propagation.

Table 1: Synthesis of the results of the tailings wave propagation.

Cross section	**Location downstream of the dam (m)**	**Peak flow (m^3 s^{-1})**	**Maximum depth (m)**	**Maximum speed (m s^{-1})**	**Time of arrival (min)**	**Time to maximum depth (min)**
CS-0	0	422	3.88	6.43	0	117
CS-01	3.004	326	5.22	4.55	83	163
CS-02	5.005	322	4.14	4.05	108	172
CS-03	6.994	321	7.12	1.74	132	186
CS-04	9.996	291	5.62	3.97	155	260
CS-05	12.006	222	6.05	1.49	179	278
CS-06	14.017	216	4.43	2.07	229	295

Even though some differences between simulation and observation were highlighted, the spread of the flood wave was consistent with the actual event that occurred in 2007. Witnesses reported that the evacuation in the first neighborhood of the urban region took place at dawn. Table 1 shows that the time of arrival in the section closest to the start of the urban area (CS-04) occurs around 2.5 hours of the simulation, which is equivalent to 6:00 a.m. on the day of the event.

For the urban area of Miraí city, the object of the analysis of subsequent consequences, there were also discrepancies between the simulated and actual boundary (Figure 7). As for the entire study region, the simulated and the observed area differed noticeably, totaling 0.488 km^2 and 0.579 km^2, respectively. Area overestimation and underestimation in the simulation corresponded to 10.8 % and 26.5 %, respectively. Again, evidencing the consequences of inaccuracies related to

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

the DEM used. Despite this difference, adjustments were made to the exposure and vulnerability analysis to the assessment of loss of life in order to represent the accident simulation more reliably, as will be detailed throughout this paper.

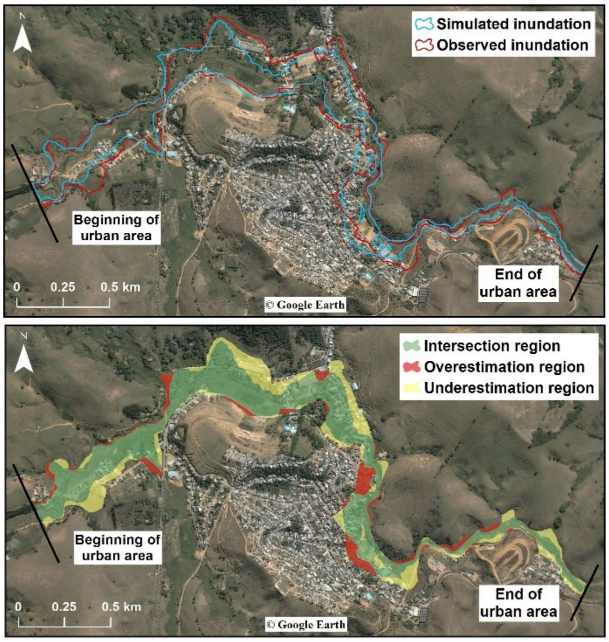

Figure 7: Cutout of the envelope of the inundation boundary simulated and observed from the São Francisco dam breach in Miraí city.

3.2 Potential damage and expected loss of life modelling

The agent-based life loss estimation model used (HEC-LifeSim v.1.0.1) is structured using a modular modelling system (Zhuo and Han, 2020). In this system, each module exchanges information with other modules through a database that includes multiple layers and tables of the geographic information system (GIS). The model also presents the uncertainty module, which allows the insertion of uncertainty boundaries in several input parameters. Propagation of these uncertainties occurs with Monte Carlo simulations. The four modules present in the methodology are: "flood routine", which contains a set of networks representing flood characteristics throughout the inundated area and period; "shelter loss", which simulates the exposure of people and buildings during each event as a result of building submergence and structural damage potencial; "warning and evacuation", which simulates the distribution of the population at risk after the warning issuance; and "loss of life", which estimates fatalities through probability distributions (USACE, 2018).

Exposure and vulnerability analyses were carried out to prepare an inventory of buildings presenting and characterizing the structures and populations at risk in the flood-affected region. The following information was consolidated for buildings and population in the shelter loss module: dwellings location, occupation type, construction material, number of floors, and population under and over 65 years of age (mobility criterion). The affected population and number of households were determined by a set of regular statistical grids integrating data from different sources and aggregated in incompatible

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

geographic units (IBGE, 2016). For each grid in the flood-affected region (Figure 8), households were geographically allocated with the aid of satellite images, and the population per household was considered homogeneously across the entire grid. Once the impacted area is majorly occupied by residential buildings and because the breach occurred during the night, outside business hours, other types of construction were not considered in the study.

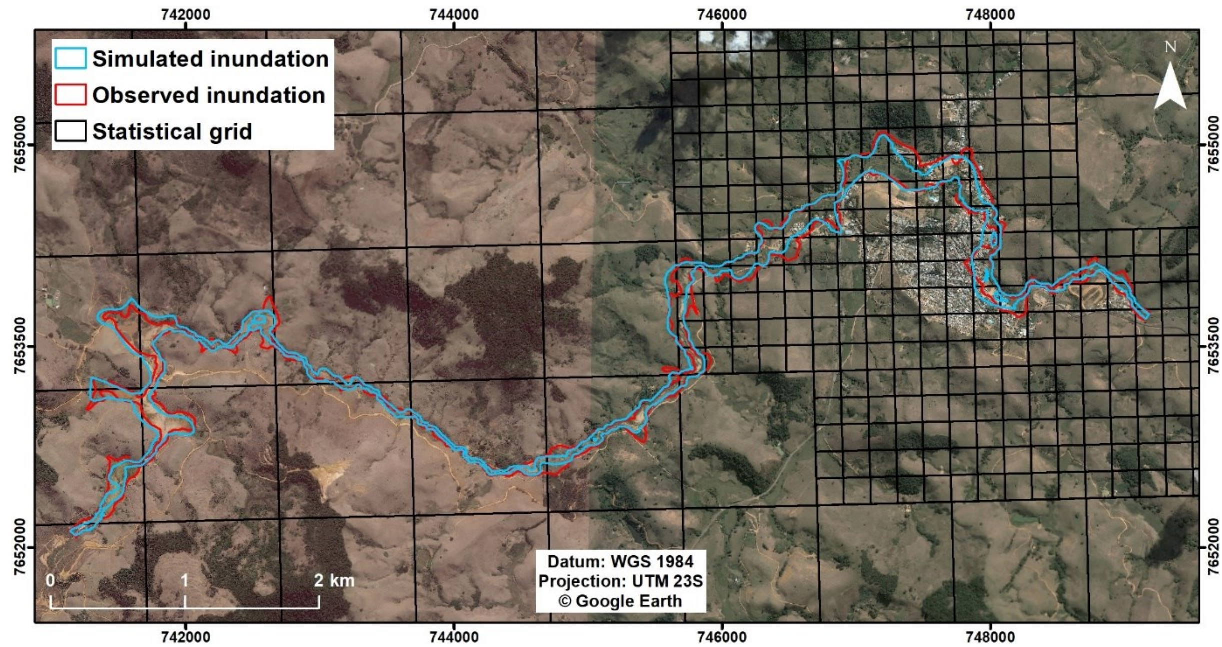

Figure 8: Statistical grid in the flood-affected region.

The exact number of buildings directly impacted by the flood wave in 2007 is uncertain, but it was estimated through local studies at the number of 300 to 500. When using the observed estimated flood boundary, we identify that 358 households may have been affected (354 in the urban area and 4 in the rural area). The simulated flood boundary indicates 311 buildings (308 in the urban area and 3 in the rural area) (Figure 9).

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

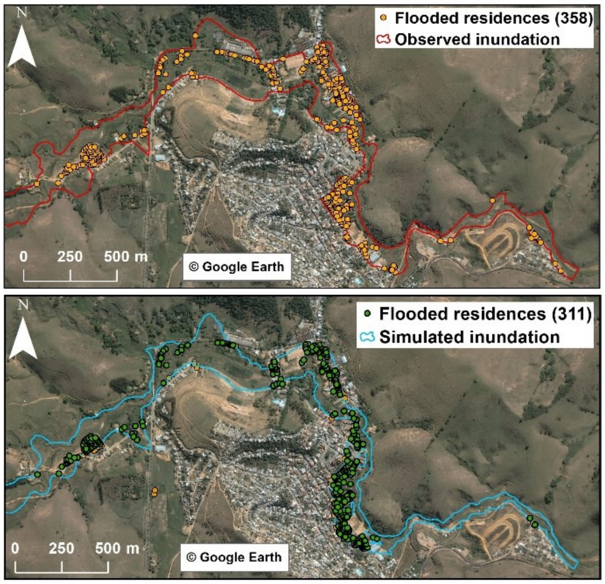

Figure 9: Zoom in the urban area of Miraí city indicates the households potentially affected by the observed and simulated inundation boundary.

To characterize households and the population obtained by the statistical grid, samples of households and people existing in the 2010 Brazilian Demographic Census microdata were used, which is the main reference for characterizing the population in Brazilian urban areas. For confidentiality of research informants, the smallest geographic unit for identifying microdata is the weighting area, which is formed by grouping census sectors (IBGE, 2011). Therefore, the results obtained considering the weighting areas of interest were arranged proportionally and distributed evenly in the affected region. Each element of the sample was multiplied by its sample weight to represent the population.

The sample of households also enabled the determination of construction material, occupation type, and social class, which is essential for damage evaluation purposes. The construction materials considered were masonry and wood. Occupation types were adopted considering the building codes presented by Gutenson et al. (2018): single-family home (RES1); temporary accommodation (RES 4); institutional dormitory (RES 5); and asylum or orphanage (RES 6). The social class was defined using the average monthly family income defined for each class as proposed in the Brazil Economic Classification Criterion 2010 from the Brazilian Association of Research Companies (ABEP, 2012). The sample of people enabled the determination of the population under and over 65 years of age that were present at home at night, using the variable "return home".

Statistical grids showed that 1,537 households were affected by the flood, corresponding to a population of 4,675 people. The Microdata analysis considered the only weighting area existing for Miraí city. A total of 4,209 households were obtained in the considered weighting area, in which there is a predominance of single-family residential typology, masonry

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

construction material, and social classes C and D (Table 2). The total population in the weighting area was 13,808, with 94.6 % being present at home at night (Table 3).

Table 2: Data obtained from the 2010 Brazilian Demographic Census microdata on households in the affected region of Miraí city.

Type of data	Occupation type*				Construction material		Class**			
	RES1	RES4	RES5	RES6	Wood	Masonry	A	B	C	D
Microdata	4,132	0	22	55	0	4,209	141	478	1553	2037
%	98.2	0.0	0.5	1.3	0.0	100.0	3.4	11.4	36.9	48.4
Region of interest	1,509	0	8	20	0	1,537	51	175	567	744

* (RES1) single-family home; (RES 4) temporary accommodation; (RES 5) institutional dormitory; and (RES 6) asylum or orphanage, defined according to Gutenson et al. (2018).
** Socioeconomic classes A, B, C, and D, with A being the highest and D the lowest, according to criteria established by ABEP (2012).

Table 3: Data obtained from the 2010 Brazilian Demographic Census microdata on the population in the affected region of Miraí city.

Type of data	Population at home at night		
	Total	< 65 years	> 65 years
Microdata	13,062	11,724	1,338
%	94.6	84.9	9.7
Region of interest	4,422	3,969	453

By the analysis performed, the population at night directly affected was 1,033 and 868, for the extent of observed and simulated flooding, respectively. To minimize the possible effects of overestimating and underestimating the extent of the flood on the number of buildings and people directly affected, we constructed an alternative scenario of exposure and vulnerability analysis. In this scenario, the number of people allocated to the residences within the simulated inundation boundary was increased to equal the number of people affected according to what was found in the observed area. This excess number of 165 people was randomly allocated to the affected households according to the extent of the simulated flood, keeping the percentages in Table 3.

For building submergence in HEC-LifeSim, it is proposed three flood head limits physically defined by the interaction between existing shelter and depths thresholds: "chance zone", "compromised zone", and "safe zone". Chance zone refers to a condition where flood victims are typically swept downstream or trapped underwater, and survival depends largely on chance. Compromised zone refers to a condition where the shelter has been severely damaged, increasing the exposure of flood victims to violent floodwaters. On the other hand, the safe zone is typically dry, and life-loss probability is virtually

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

zero. For structural damage in buildings, stability is defined by speed and depth criteria, also considering occupation type, construction material, and the number of floors. HEC-LifeSim allows the use of several stability criteria, among these the criteria of RESCDAM (2000) and USACE (1895).

The warning and evacuation module represents the distribution and behavior of the population during the flood event, including each emergency planning zone (EPZ) in the affected area. This process has several milestones that are separated by time lag intervals as shown in the timeline in Figure 10.

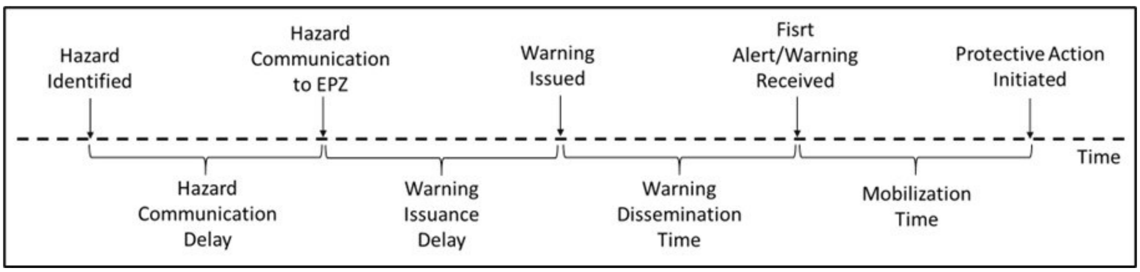

Figure 10: Warning and evacuation timeline.

Source: USACE (2018).

The timeline starts from the identification of the imminent threat and presents the first delay in communicating the threat to managers. In both situations, there are no studies that assist in determining these values; therefore, the user must determine the time considering the characteristics of the case under study. In contrast, the choice of time in the other three subsequent delays is supported by the studies and equations of Sorensen and Mileti (2015a, 2015b, 2015c, 2015d, 2015e). In the identification of the threat and all delays, it is possible to insert uncertainty in the input data.

For the dynamics of evacuation, the modified transport model of Greenshields et al. (1935) is used to represent the effects of traffic density and road capacity on vehicle speed, and the short path algorithm of Dijkstra (1959) is used to determine the path with the shortest travel time to the destination. If the vehicle or people are reached by the flood during the evacuation, the stability criteria defined by Aboelata and Bowles (2005) is used. If these criteria are exceeded, the affected population is allocated to the chance zone; if not exceeded, the population is allocated to the safe zone.

For the representation of the warning and evacuation timeline, the delays for each step in Figure 10 were determined. Based on the information regarding the watchman's perception of the imminent danger before the breach, the period between the threat identification time and the communication to the emergency planning zone was determined as a uniform distribution from 0 to 30 minutes before the dam breach. This interval corresponds to the period between the perception of the watchman and the start of the collapse of the dam. For warning issuance delay, a triangular probability distribution was adopted with minimum, most likely, and maximum values of 0, 15, and 30 minutes, respectively. The other two stages, with their respective uncertainties, were defined through the relationship between the characteristics of the warning that occurred at the event and the recommendations of Sorensen and Mileti (2015a, 2015d). These authors adjusted models through historical

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

cases and defined coefficients to represent a certain type of existing warning system and population characteristics. Figure 11 shows the 90 % confidence interval for the percentage of the population mobilized after the alert was issued (which is the sum of these last two delays). By the median, the entire population starts evacuating 150 minutes after the alert is issued.

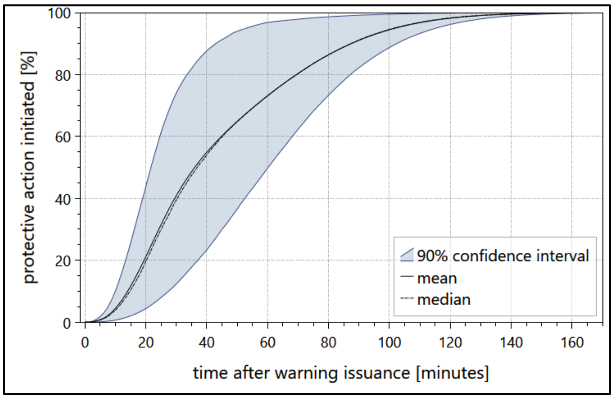

Figure 11: Combined dissemination and mobilization time for the evacuation scenario in the Miraí accident.

The fatality distribution curves, obtained by McClelland and Bowles (2002) and updated by USACE (2018) through the analysis of historical cases of mainly dam breach floods, were applied in the loss of life module. To determine the economic damage, the empiric equations of Nascimento et al. (2007) were inserted in HEC-LifeSim for each social class affected by the flood. The curves relate the depth (h) in meters to the damage in R$ m^{-2} (Reals per built projected area square meter) to the structure of the property and its contents. The built area of the affected households was estimated in the function of national social classes, as defined by Nascimento et al. (2006). Table 4 presents the equations and ranges of built area for each social class.

Table 4: Model for economic damage and the most frequent range of built area as obtained by Nascimento et al. (2007) for each social class.

Class	Damage (R$ m^{-2})	Built area (m^2)
A	90,832 + 39,334.ln(h)	200 – 250
B	103,938 + 43,844.ln(h)	100 – 150
C	74,685 + 27,388.ln(h)	50 – 100
D	18,049 + 33,364.√h	25 – 75

After 1,000 interactions (value used in studies applying HEC-LifeSim), the economic damage was estimated in R$ 1.01 million to R$ 1.95 million for the 311 households affected directly by the simulated flood. Corrected by a factor of 169.12 % (based on the Broad National Consumer Price Index – IPCA in June 2022), this value corresponds from R$ 2.72 million to R$ 5.23 million in 2022 (US$ 521 thousand to US$ 1.00 million).

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

According to the public registry, five hundred lawsuits related to property material damage were filed by residents against the mining company following the accident. Several of these lawsuits, judged between 2012 and 2013, resulted in indemnities ranging between 956 and 1,530 US dollars (STJ, 2014). Assuming that this indemnity range was allocated to each household and applying it to all 311 affected households, a range between R$ 1.56 million and R$ 2.49 million is obtained in 2012. By using the IPCA-based correction factor of 89,67 %, this value corresponds from R$ 2.95 million to R$ 4.72 million in 2022 (US$ 564 thousand to US$ 902 thousand). Thus, on average, this range of indemnity values was close to the simulated economic damages for households (between 4,64 and 8,92 thousand reais per household impacted according to the corrected value for the year 2012) (US$ 888 to US$ 1.71 thousand).

Regarding the estimated loss of life, the values obtained following the actual event, with a median of zero fatality. On average, 99.97 % of the population escaped the flood. Fatalities were estimated in 67 of the 1,000 interactions, whose frequency of occurrence was: 1 fatality in 65 interactions; 2 fatalities in 1 interaction; and 3 fatalities in 1 interaction.

The successful evacuation of the population, with an average of 99.97 % of the population escaping the flood, is explained by the relationship between the flood timeline and the warning and evacuation. As demonstrated in the analysis of the spread of the tailings flood wave, the flood water reaches the beginning (CS-04) and end (CS-06) of the urban area in approximately 2.5 hours and 4 hours, respectively. Such periods were sufficient for mobilization to occur. Considering the most extreme negative combination of the times defined for the warning and evacuation process, the population is fully mobilized in approximately three hours.

For the alternative scenario of exposure and vulnerability, in 65 interactions fatalities were estimated, whose frequency of occurrence was: 1 fatality in 6 iterations; 2 fatalities in 58 iterations; and 3 fatalities in 1 iteration. This result indicates that the model fitted the real event and the difference in the population directly affected by the extent of observed and simulated flooding did not influence the estimated loss of life.

Furthermore, in all 66 iterations in the base scenario that resulted in one or two fatalities the loss of life concerned the population over 65 years of age, who was not mobilized for evacuation and, therefore, was allocated to some of the flood risk areas. The same result was noticed in 62 of 64 iterations in the alternative scenario. This behavior indicates the impact on the divergent submergence thresholds defined by Aboelata and Bowles (2005) to represent the mobility criterion. For the chance zone, the threshold is 4.58 m and 1.82 m for people under and over 65 years of age, respectively.

3.3 Analysis of warning and evacuation efficiency

An effective warning system is dependent on several factors and is essential for selecting appropriate emergency management (Rogers and Sorensen, 1989; Lumbroso and Davison, 2018; Tonn and Guikema, 2018; Kolen et al., 2020). To assess the success of the warning and evacuation with a view to a good representation of the simulations in comparison with the observed data, we developed, beyond the actual "optimistic" scenario that occurred, three more scenarios: "pessimistic", "moderate", and "unknown" (Table 5). The simulations were executed for both base and alternative scenarios of exposure and vulnerability. The period between the time of identification of the hazard and the communication to the emergency

https://doi.org/10.5194/egusphere-2022-1393
Preprint. Discussion started: 3 January 2023

planning zone was considered null, and the three remaining steps, warning issuance delay, warning dissemination, and mobilization time (Figure 10), were defined through the recommendations of Sorensen and Mileti (2015a, 2015b, 2015e) for issuance and dissemination of the warning and mobilization of the population.

Table 5: Model for economic damage and the most frequent range of built area as obtained by Nascimento et al. (2007) for each social class.

Scenario	Description
Optimistic	It represents the real scenario that occurred in the event on January 10, 2007, and it is characterized by reports that detailed the accident, as described in section 3.2. In this scenario, the evacuation was successful, with the entire population mobilizing, on average, 150 minutes after the alert was issued.
Pessimistic	It represents the worst possible scenario, using limited alerting technologies. Therefore, any emergency response is improvised. Affected communities are unlikely to believe that they have a serious threat or that they may face events that require a rapid response.
Moderate	It represents an intermediate scenario, using a combination of traditional technologies, but not advanced technology. About population, it indicates the situation that most represents a community given a mix of existing factors. However, he considers that this community does not have effective emergency planning.
Unknown	It represents a scenario in which, a priori, the existing alert system in the affected region is not known. In this way, the range of uncertainty inserted in the stages of the alert and evacuation process is greater, resulting in high variability in the estimate of the loss of life.

For simulating these three additional scenarios, the difference between the two different exposure and vulnerability scenarios was noticed (Figure 12), in all situations the median of the alternative scenario was higher by 2 fatalities compared to the base scenario, 21 and 23 for the pessimist, 13 and 15 for the moderate, and 15 and 17 for the unknown scenario. In addition to verifying the high impact of the level of efficiency of the alert and evacuation system, the observed and adopted optimistic scenario in the evacuation process was confirmed in the real representation of the event that occurred in 2007. In all the standard curves of Sorensen and Mileti (2015a, 2015b, 2015e) use to represent the delay in issuance of the alert, the dissemination of the alert, and in the mobilization, the estimates of the loss of life were higher than those obtained throughout these scenarios.

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Preprint. Discussion started: 3 January 2023

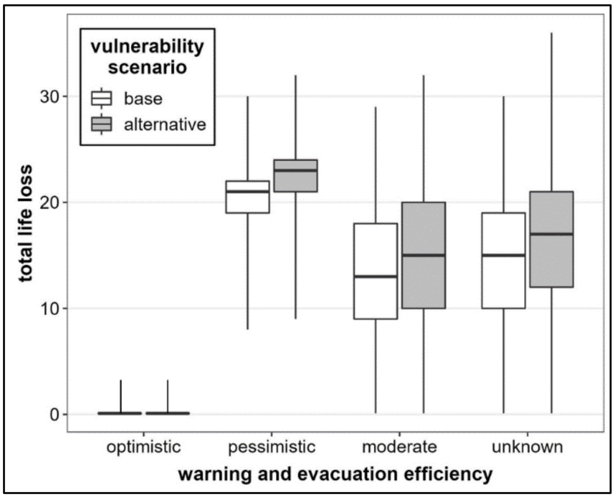

Figure 12: Life loss estimation for different scenarios of warning and evacuation efficiency.

4 Conclusions

Risk assessment is an extremely effective tool to assist in the emergency planning requested for tailings storage structures under Brazilian law through. The hydrodynamic modelling showed satisfactory results mainly due to the similarity in the time the flood wave arrives, which is one of the main parameters in loss of life modelling since it correlates completely with the time available for evacuation of the population at risk. The modelling of the economic damage was similar to the indemnity values per household. The model was also capable to represent loss of life estimates was also came close to the values obtained in the event that occurred. However, in this specific case, the low concentration of solids in the flow may have been one of the factors that contributed to the success of the results obtained. We emphasize the need to carry out studies of this type for other real accidents with greater solid loads so as to expand the possibilities raised in this study.

The estimates acquired throughout the development of this case study were adherent to observed data, which sustained the great potential of the use of these modelling technics for planning purposes. Besides, one of the great advantages of HEC-LifeSim is the possibility of dynamically simulating the evacuation of the population. The best suitability of this model in tailings dam failure events can be achieved by changing the model standards. Several criteria are editable, and changes in these criteria could assist in representing the physicochemical characteristics of the tailings.

In addition to HEC-LifeSim showing the ability to simulate the non-occurrence of fatalities like the one that occurred in the event, the model also made it possible to speculate on scenarios that take into account lower alert and evacuation efficiencies, which resulted in much more catastrophic scenarios in terms of loss of life. The result of this work is similar to Lumbroso et al. (2021) who, using the Life Safety Model and in a perspective of reducing fatalities, also verified the impact of the warning system on estimating the loss of life in the event of the Brumadinho tailings dam failure.

Finally, this study is a pioneer in exploring models to estimate economic damage and loss of life in floods from tailings dam failure. In this sense, it shows the potential efficiency of the models currently widely used for flood simulation. A greater understanding of the application of these models in tailings flow can subsidize brazilian and international legislation on dam safety by considering these consequences in risk assessments.

Code and data availability

Code and data will be made available on request.

Competing interests

The authors declare that they have no conflict of interest.

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