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Francisco Odécio Sales
(Organizador)

Conhecimentos pedagógicos e conteúdos disciplinares

das ciências exatas e da terra

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APRESENTAÇÃO

A obra “Conhecimentos pedagógicos e conteúdos disciplinares das ciências exatas e da terra aborda uma série de livros de publicação da Atena Editora, em seu I volume, apresenta, em seus 26 capítulos, discussões de diversas abordagens acerca do ensino e educação. As Ciências Exatas e da Terra englobam, atualmente, alguns dos campos mais promissores em termos de pesquisas atuais. Estas ciências estudam as diversas relações existentes da Astronomia/Física; Biodiversidade; Ciências Biológicas; Ciência da Computação; Engenharias; Geociências; Matemática/ Probabilidade e Estatística e Química. O conhecimento das mais diversas áreas possibilita o desenvolvimento das habilidades capazes de induzir mudanças de atitudes, resultando na construção de uma nova visão das relações do ser humano com o seu meio, e, portanto, gerando uma crescente demanda por profissionais atuantes nessas áreas. A ideia moderna das Ciências Exatas e da Terra refere-se a um processo de avanço tecnológico, formulada no sentido positivo e natural, temporalmente progressivo e acumulativo, segue certas regras, etapas específicas e contínuas, de suposto caráter universal. Como se tem visto, a ideia não é só o termo descritivo de um processo e sim um artefato mensurador e normalizador de pesquisas. Neste sentido, este volume é dedicado aos trabalhos relacionados a ensino e aprendizagem. A importância dos estudos dessa vertente, é notada no cerne da produção do conhecimento, tendo em vista o volume de artigos publicados. Nota-se também uma preocupação dos profissionais de áreas afins em contribuir para o desenvolvimento e disseminação do conhecimento. Os organizadores da Atena Editora, agradecem especialmente os autores dos diversos capítulos apresentados, parabenizam a dedicação e esforço de cada um, os quais viabilizaram a construção dessa obra no viés da temática apresentada. Por fim, desejamos que esta obra, fruto do esforço de muitos, seja seminal para todos que vierem a utilizá-la.

Francisco Odécio Sales

SUMÁRIO

CAPÍTULO 21

RISK ASSESSMENT FOR EXISTING MINE TAILING STORAGE FACILITIES IN BRAZIL

Data de aceite: 20/08/2021

Rafaela Baldi Fernandes
Ph.D. Departamento de Engenharia Civil, Universidade do Estado do Rio de Janeiro. Rio de Janeiro, RJ, Brazil

Mònica Novell Morell
BSc. Department of Geoscience and Engineering, Delft University of Technology (TU Delft). Delft, The Netherlands

Siefko Slob
PhD. Cohere Consultants. Amersfoort, The Netherlands

ABSTRACT: This study described is a quick scan of all Tailing Storage Facilities (TSF) in the state of Minas Gerais, Brazil. The objective was to perform analyses, based on gathering information related with TSF's dimensions, purpose, structure and current state. Publicly available data has been used to determine which TSF are most critical. For the most critical dams, a downstream estimation of the drainage path has been performed and the primary and secondary flooding areas due to failure of those dams is estimated. A risk matrix is used to visualise which TSF have the highest risk; additionally, some mitigation and prevention measures are suggested. The report starts with a brief introduction with the present situation in Minas Gerais, as well as a technical description of the project with the results obtained.
KEYWORDS: Dam, Failure, Risk, Management.

RESUMO: Este estudo apresenta um panorama sobre as barragens de rejeito no estado de Minas Gerais, Brasil. O objetivo consiste em analisar estas estruturas baseando-se em informações referentes à dimensão, propósito, tipo de estrutura e estado atual, tendo sido utilizados dados públicos para determinar quais barragens eram mais críticas. Para as barragens mais críticas, elaborou-se uma estimativa da mancha de inundação nas áreas de jusante, primárias e secundárias, decorrente do estudo de ruptura. A matriz de risco foi utilizada para visualizar quais barragens apresentavam maior risco e, adicionalmente, foram sugeridas medidas de mitigação e prevenção de danos. O documento apresenta uma breve introdução da situação atual das barragens em Minas Gerais, além de uma descrição técnica do projeto e dos resultados obtidos.
PALAVRAS - CHAVE: Barragem, Rupturas, Risco, Gerenciamento.

1 I INTRODUCTION

In Brumadinho, on January 25th, 2019, a mine tailing storage facility, dam B-I, from the Vale S.A. mining company failed, which caused 250 casualties and more than 100 people were missing. Nevertheless, it was not the first time that an incident like this one took place; in 2015 near the town of Mariana, the Fundão TSF also failed. The owner of this TSF was the company SAMARCO, a joint venture between Vale S.A. and BHP Billiton.

Cameras were placed around B-I for

monitoring purposes, so there are videos of the failure in real time. Those videos clearly show a slope failure starting from the crest and extending to an area just above the starter dam. The crest of the dam dropped and the area around the toe region bulged outwards before the surface of the dam broke apart. The total collapse happened in less than 10 seconds with $9.7*10^6\,m^3$ of mudflow that flowed downstream at a high speed (Robertson et al., 2019).

When a dam fails, loss of life, environmental, human and economic damage are direct consequences of such an event, which depend on the magnitude of the mudflow and its velocity. Therefore, early warning is essential for saving lives in areas at risk for mudflows.

2 I TYPES OF TAILINGS DAMS

Tailing dams are embankments made of waste material, product of many years of mining activities. These occupy large areas and hold large volumes of fine-grained tailing material. There are three different types of construction methods for tailing dams: upstream, downstream and centerline (see Figure 1).

- Upstream: the first dike is constructed at ground level in a valley, hence the valley walls become the support for the tailing sides. The mining waste is hydraulically placed behind the dike and once all the volume is filled up, a second dike is constructed on top of the previous one. Part of the new dike will be placed on top of the first one and the remaining part on top of the waste, moving the crest further upstream. This procedure can be done multiple times, creating an upstream dam with 3 or more different sub-dams, which are laying on top of each other. The height and volume of the structure will drastically increase every time, making it very unstable, since part of the dam is resting in weak material from mining activities, probably saturated and prone to liquefaction (Dutch Risk Reduction Team, 2019).
- Downstream: the first dike is also constructed at ground level in a valley. Once the volume behind the dam is as its maximum, the next dam is placed on top of the previous one, but the extra support needed is placed in front of the starter dike, thus raising the crest further downstream. This method requires more material and available space for the upcoming new dams.
- Centerline: like both other methods, the starter dam is at ground level. When subsequent raising is required, material is placed on the tailing and the existing embankment. Thus, the crest will raise vertically.

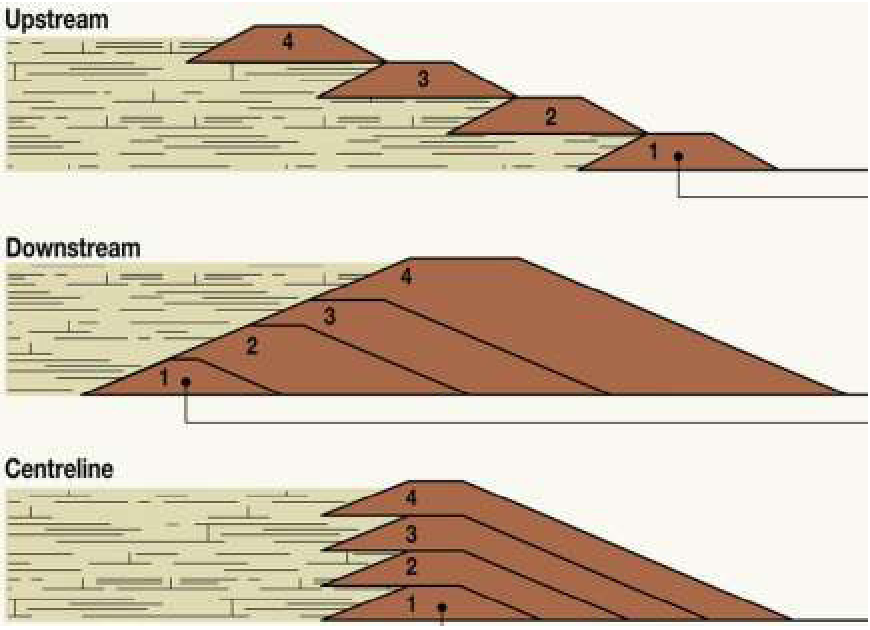

Figure 1. Types of tailing dams. (Source: www.grida.no)

From the three construction methods, tailing dams constructed by the conventional upstream method are the most unstable. Their shear strength and pore pressure conditions are difficult to characterize. If the groundwater pressure increases, seepage or liquefaction might happen, thus the dam could collapse, allowing the material to flow out, uncontrollably (Martin, 1999).

Now, there are 430 tailing dams in the state of Minas Gerais, from which 50 were designed and constructed in the same way as dam B-I. 30 of them are still operational and the other 20 are filled up with their maximum capacity.

2.1 Classification organizations

One of the main issues with those dams is that it is unclear how they were designed, constructed, and operated. In some cases, the dam raises higher than what had been originally planned. Additionally, proper documentation related with the design and construction methods is lacking (Dutch Risk Reduction Team, 2019).

In order to classify all the dams in Brazil, there are several classification systems: *FEAM* (Fundação Estadual do Meio Ambiente), *ANM* (Agência Nacional de Mineração) and *ANA* (Agência Nacional de Águas), like described in Fernandes (2020). The three organizations classify all dams in Minas Gerais according to several properties related with the structure of the dam itself and also the risk associated. For all three organizations, there are properties which are the same within all three databases, such as: TSF name, company owner, coordinates, volume and height. Nonetheless, for each system there are additional features that give extra information on those dams.

2.1.1 FEAM: Fundação Estadual do Meio Ambiente

Fundação Estadual do Meio Ambiente published a database with 700 entries. In addition to the previous characteristics, information related with the risk associated is given.

The hazard level is divided in three different categories (I, II, III), which depend on the combination between only two different values of V_c. Each attribute has specific value of V_c according to its magnitude (*FEAM*, Sistema Estadual de Meio Ambiente e Recursos Hídricos, 2018). The characteristics considered and the given values for V_c are displayed in Table 1:

Height [m]	Volume [m^3]	Cities Nearby	Environmental Impact	Structures Nearby
H<15 V_c =0	V_r<500.000 V_c =0	None V_c =0	Low V_c =0	None V_c =0
15<H<30 V_c =1	500.000<V_r<5 m V_c =1	Barely V_c =2	Medium V_c =1	Some V_c =1
H>30 V_c =2	Vr>5 m V_c =2	Some V_c =3	High V_c =3	Large V_c =2
-	-	Large V_c =4	-	-

Table 1. Assessment criteria for environmental impact for a TSF. (Source: *FEAM* (2018)).

The three different categories are defined according to the sum of two values of V_c:

- Low impact in the area. Class I: $V_c \le 2$;
- Medium impact in the area. Class II: $2 < V_c \le 5$; and
- High impact in the area. Class III: $V_c > 5$,

On February 25, 2021 a new resolution was published, regulating new devices for classifying dams and auditors. However, data with this new database have not yet been released.

2.1.2 ANM: Agência Nacional de Mineração

Agência Nacional de Mineração also published a TSF database with 850 entries. Apart from the most common properties, there are also some different characteristics (*ANM*, Agência Nacional de Mineração, 2019).

A. Risk level (CRI): associated risk according to the structural and technical characteristics of the dams. The categories are:

- High
- Medium

- Low

B. Potential damage associated (PDA): degree of damage in the environment in case of failure. It is linked with the volume of the reservoir (V_r in m^3). The categories are:

- Very high ($V_r \geq 50*10^6$)
- High ($25 < V_r < 50*10^6$)
- Medium ($5 < V_r < 25*10^6$)
- Low ($500.000 < V_r < 5*10^6$)
- Very low (V_r r ≤ 500.000)

C. Class: product between CRI and PDA. Class A corresponds to the most critical state. The categories can be seen in Table 2:

	PDA		
CRI	*High*	*Medium*	*Low*
High	A	B	C
Medium	B	C	D
Low	B	C	E

Table 2. Different classes according to CRI*PDA. (Source: ANM, 2019).

D. Emergency level: according to a team of experts, the need for a TSF to be improved:

- Level 1: irregularity detected
- Level 2: risk under control
- Level 3: imminent failure

2.1.3 ANA: Agência Nacional de Águas

Agência Nacional de Águas makes an annual database with all the dams (19.388 structures) in Brazil in order to present their current state. Because it is a general database, there are dams which belong to different organisations, such as *IMAC* - Instituto de Meio Ambiente do Acre or *IPAAM* - Instituto de Proteção Ambiental do Amazonas (*ANA*, Agência Nacional de Águas e Saneamento Básico, 2019).

ANA's database contains most dam structures of the country, but not all of them. From that database, only the TSF that belong to *ANEEL* (Agência Nacional de Energia Elétrica) are added in the final database (905 entries).

3 I RESULTS

3.1 Final database of all mine tailing storage facilities

After analysing all the excel files, there are some discrepancies between the three databases. When looking at the same structure, it is possible that it has the same name in all files, but different coordinates, identification code or information regarding the risk associated.

A unique database that would contain information from all sites was developed from different databases. Therefore, after combining all inputs, merging the information, and making sure that some were not doubled, a final database with 743 entries was obtained. The following table (see Table 3) shows the 10 most critical tailing dams in Minas Gerais. All of them are upstream dams, with a high CRI and PDA and sorted by their height.

The database contains the exact location of each TSF along with other metadata. Since some mine tailing dams were repeated in two or three original databases (*ANM*, *FEAM* or *ANA*), then all the inputs that were duplicated had been merged into a unique entry. The final database is exported into a shapefile, which can be uploaded in QGis. QGis allows to view all the TSF locations with for instance Google Satellite as a background image (see Figure 2). The Attribute Table of the shapefile contains all the metadata from the excel file, therefore it is easy to locate one TSF and check its information.

TSF Name	Organization	Elevation of the crest (H) [m asl]	Dam Height [m]	Volume [m^3]	CRI	PDA	Class	Class	Emergency Level
Campo Grande	ANM+FEAM	940	99.3	$23 * 10^6$	High	High	A	III	Level 1
Forquilha I	ANM+FEAM	1175	98.3	$13 * 10^6$	High	High	A	III	Level 3
Barragem de Rejeitos	ANM	972	89	$5 * 10^6$	High	High	A		Level 2
Forquilha II	ANM+FEAM	1173	88	$23 * 10^6$	High	High	A	III	Level 2
Sul Superior	ANM+FEAM	923	85	$6 * 10^6$	High	High	A	III	Level 3
Forquilha III	ANM+FEAM	1099	77	$19 * 10^6$	High	High	A	III	Level 3
Doutor	ANM+FEAM	751	77	$38 * 10^6$	High	High	A	III	Level 2
ED Xingu	ANM	965	70	$6 * 10^6$	High	High	A		Level 1
Grupo	ANM+FEAM	1140	39	$1 * 10^6$	High	High	A	III	Level 2
Vargem Grande	ANM+FEAM	1282	35	$10 * 10^6$	High	High	A	III	Level 1

Table 3. The 10 most unstable tailing dam facilities. (Source: *ANM* and *FEAM*).

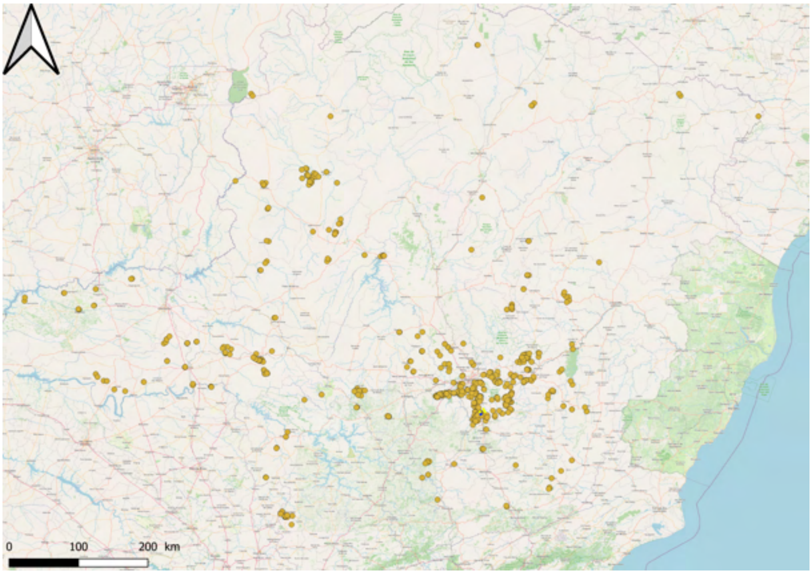

Figure 2. TSF locations in Minas Gerais, visualization with QGis.

3.2 Risk assessment: primary Impact Zone

To assess the impact of dam failure, the flooding area has been estimated according to the geometry and volume of the reservoir and the downstream area. According to Federico and Cesali (2015), there are several empirical relationships that allow a preliminary approximation of run-out distances. In this project, the formula suggested by Corominas (1996) is used to determine the primary impact zone in case of dam breach.

The equation estimates the angle of reach (*α*), which is the ratio of the elevation difference between the highest point of the granular mass before sliding and the more advanced point of deposit after sliding (*H*) and the total travelled distance of the waste material (*L*) (see equation 1).

$$\tan(\alpha) = \frac{H}{L} \tag{1}$$

Corominas (1996) also suggested an empirical expression that links the H/L ratio with the total volume of the mass (*V*) for all kinds of landslides (translational slides, rockfall, avalanches, debris flows, mudflows). It is noted that the ratio decreases when the total volume increases, thus the larger the volume the larger is the travelled distance (*L*). The formula proposed is:

$$\frac{H}{L} = 0.973 \cdot V^{-0.105} \tag{2}$$

From the database created, the volume of each reservoir is given, therefore the ratio *H/L* is known from equation 2. The value obtained can be used to estimate the angle of reach with equation 1.

Additionally, an energy-based approach has been carried out with QGis. Before collapse, the waste volume has a certain potential energy, which after failure becomes partly kinetic and partly potential energy. To estimate the flooding area in case of dam breach, the idea is to create an energy plane that has the same height as the dam at that specific location (respect mean sea level) and the same angle of reach found with equation 1. Then, the energy plane is extended downstream and above the topography, until a certain point where the energy plane will cross the surface.

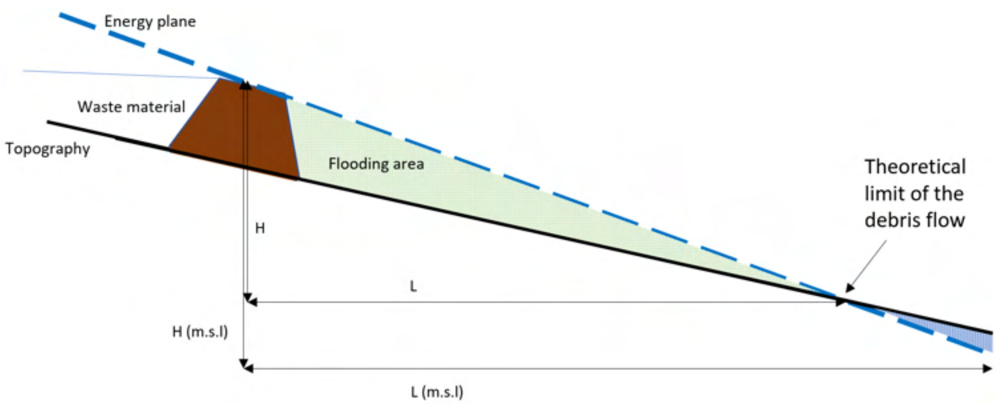

Figure 3. Sketch of the energy plane along with the topography.

As it was mentioned before, the energy plane has a certain slope, which is higher than the topography (Figure 3). This 2D plane is created with a first line that follows the crest width of the dam and a second parallel line located at a certain distance (*L*) from the TSF. The angle of reach found determines the slope of the energy plane, and with the *H* value, *L* can be calculated. Then, the second line will be moved in parallel at a specific distance *L* from the crest dam; elevation value assigned at that line will be the one of the drainage paths at that exact cutting point (line-drainage path). Once both lines are located, lineal interpolation between these two allows to fill in all the missing elevation values and have the final energy plane. The interpolated map needs to have the same cell size and dimensions as the Digital Terrain Model (*DTM*) of the area.

To determine the flooding area, it is possible to subtract the DTM from the interpolated map. When the energy plane is above the topography, all the area in between will have positive values, which corresponds to the flooding area (green area in Figure 3). When the energy plane crosses the topography, that theoretical limit corresponds to the area at risk for flooding by debris flow.

To demonstrate the aforementioned method, equation 2, 1 and the energy model have been validated with the characteristics of the dam B-I failure.

3.2.1 Validation of the formula with dam B-I

Because there is enough public data about the disaster of dam B-I, it is possible to back calculate the flooding area and the angle of reach. The volume of the first flood wave is known ($V = 9.7 * 10^6\, m^3$), so the angle of reach (α) can be measured following equation 2 and then equation 1.

To verify the previous result, the energy plane is created with QGis to check whether L (yellow line from Figure 5) from the equations is consistent with the extent of the flooding area from Ghahramani et al. (2020) studies. The elevation of the crest was 920 m (m.s.l) and the dam's height 80 m. According to Ghahramani et al. (2020), the furthest point of the deposit after failure was at 5.5 km of the TSF (following a straight line) and at 740 m (m.s.l) (see Figure 4 for a sketch of the situation). The energy plane in QGis can be seen in the following picture. It is a raster layer created with Interpolation TIN tool between the two lines (see Figure 5).

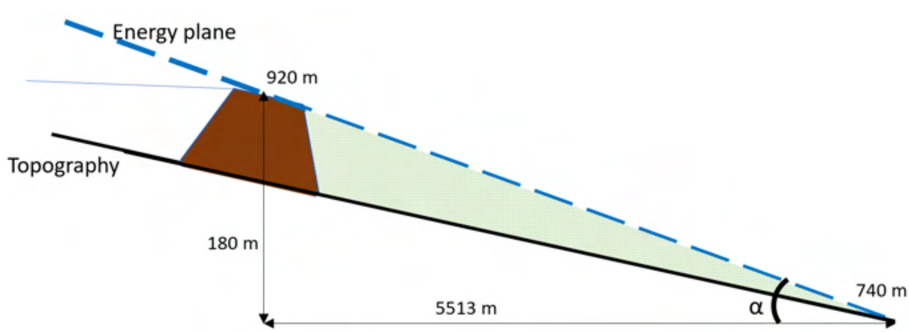

Figure 4. Sketch of the energy plane according to the dam B-I disaster.

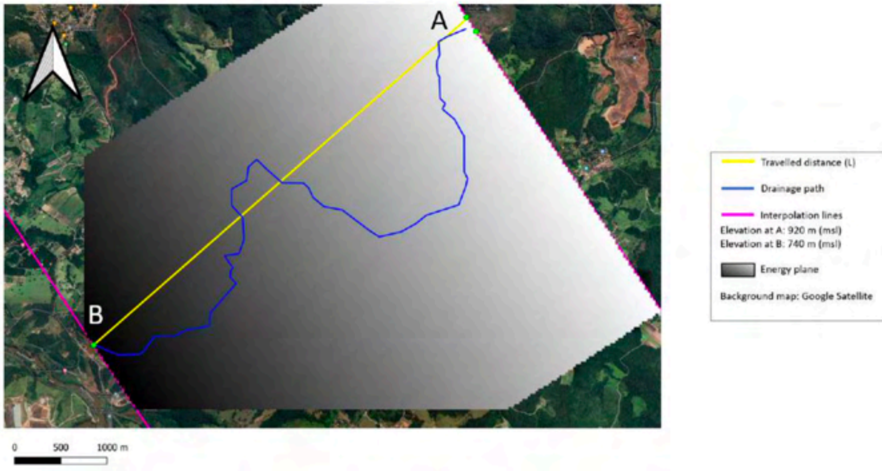

Figure 5. Energy plane created from the two purple lines.

The resulting flooding area is showed in red in Figure 6 and the blue line represents the drainage path that the waste material followed after failure. The primary impact zone after failure, according to Ghahramani et al. (2020), is showed in red in Figure 7, which has the same extent as the one found with the energy plane with QGis.

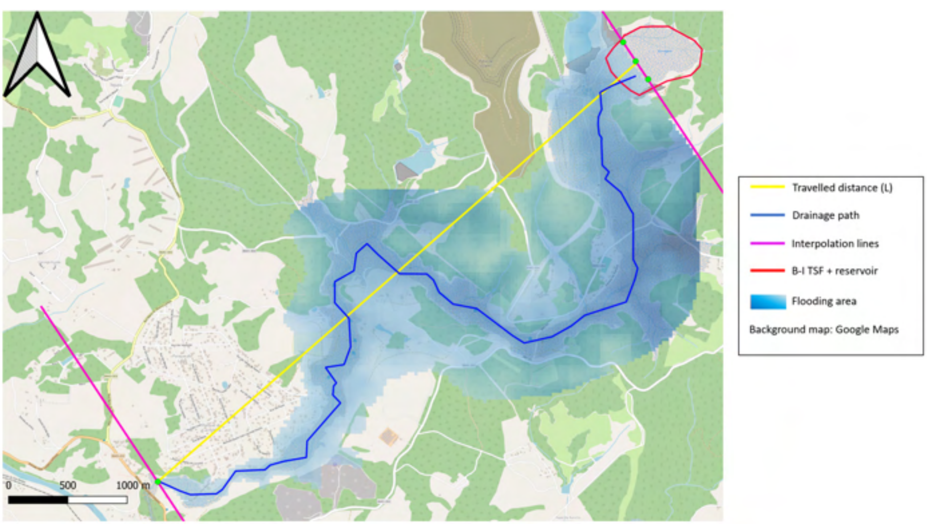

Figure 6. Flooding area for the dam B-I disaster. (QGis approach).

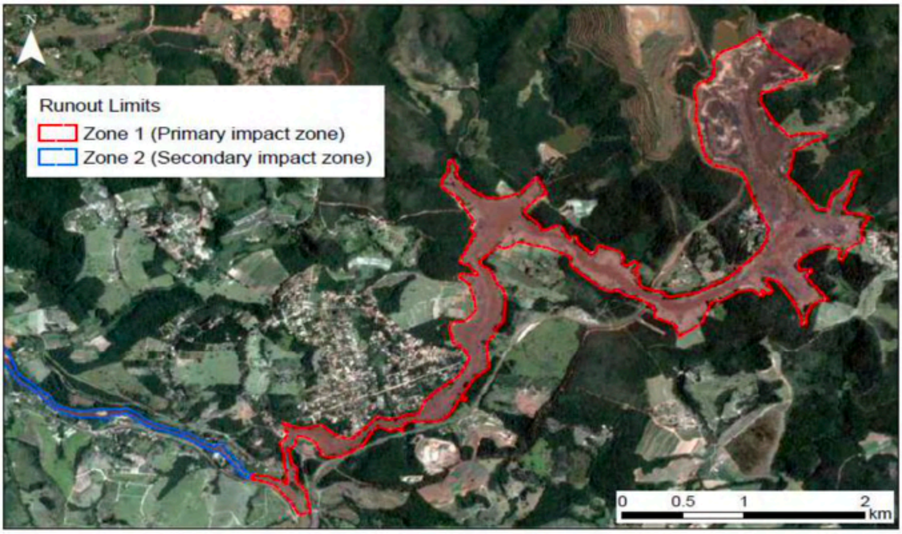

Figure 7. Primary impact zone according to Ghahramani et al. (2020).

Comparing Figure 6 and 7, the flooding area obtained with QGis (red area in Figure 6) is wider along the drainage path than the primary impact zone according to Ghahramani et al. (2020). QGis acts as a conservative method, as the flooding area near the dam is over estimated. In the lower range, QGis underestimates that area as it is less than reality. Further studies could be carried out to narrow down the affected area in the entire zone.

Therefore, it can be concluded that the aforementioned method, first use the empirical relationship presented by Corominas (1996) to calculate the angle of reach and secondly, create energy plane to subtract from it the topography; it is an accurate approach to determine the deposit in case of failure of mine tailing dams, and the consequent impact of the first wave.

3.2.2 Campo Grande Dam

According to Table 3, Campo Grande Dam is the highest TSF and it has been analysed to visually represent the potentially hazardous area in case of a dam breach. Campo Grande is an upstream dam which belongs to the Mariana complex and Alegria mine, although its lifespan ended in 2017. From the ANM database it can be seen that Campo Grande contains 23 million m^3 of waste material, it has a height of 99.3 m and it is situated at an elevation (crest level) of 940 m with respect to mean sea level.

First of all, the angle of reach is α = 9.3º, it is calculated according to the given volume of Table 3, equation 2 and equation 1. H is the elevation of the crest respect to mean sea level (H =940 m). Thereafter, with α and H, the horizontal extension of the energy plane can be determined (see Figure 3 for a sketch). This measured distance, L = 5727 m, is projected in the DTM of the area along a straight line that starts in the TSF's crest (yellow line in Figure 8). The line that follows the crest width is copied and moved in parallel downstream at a certain distance *L*, and its elevation is the same as the drainage path at that cutting point. Interpolation between those two lines is done and finally, subtraction of the DTM from the interpolated map. The resulting red area corresponds to the primary impact zone after dam failure (see Figure 8).

From Figure 8, the red area corresponds to the flooding area in case of dam breach, since the energy plane is above the topography. Furthermore, it is possible to have additional red zones because there are other valleys in the area, but those red zones are not representative for the Campo Grande failure.

In accordance with the procedure explained before, one might expect that the flooding area would be extended until the second line. However, it is important to consider the topography of the area. The drainage path has been converted into a layer of points and for each point, the elevation is assigned. It can be proved that the topography is not always decreasing along the path, therefore the primary flooding area is reduced. Although, it will continue flowing downstream, since it follows the Piracicaba river course.

Figure 8. Flooding area in case of Campo Grande failure.

3.2.3 Others mine tailing storage facilities

The others TSF's from Table 3 are also analysed. The procedure is the same as the one described in section 3.2.2. The results can be seen in the following table (see Table 4) and the resulting maps in the Appendix.

According to the results obtained, it is possible to have a general overview of the estimation could be used as a first approach to delimit the risk area in case of dam failure. To complete the risk assessment, the following section introduces which mine tailing dams involve higher risks and their level of exposure due to collapse along with mitigation measures.

Name	Elevation of the crest [m a.s.l.]	Elevation Downstream [m a.s.l.]	Dam Height [m]	Volume [m^3]	H/L ratio
Campo Grande	940	852	99.3	$23 * 10^6$	0.1641
Forquilha I	1175	945	98.3	$13 * 10^6$	0.1746
Barragem de Rejeitos	972	801	89	$5 * 10^6$	0.1916
Forquilha II	1173	942	88	$23 * 10^6$	0.1643
Sul Superior	923	756	85	$6 * 10^6$	0.1889
Forquilha III	1099	903	77	$19 * 10^6$	0.1670
Doutor	751	711	77	$38 * 10^6$	0.1558
ED Xingu	965	871	70	$6 * 10^6$	0.1884
Grupo	1140	891	39	$1 * 10^6$	0.2228
Vargem Grande	1282	791	35	$10 * 10^6$	0.1801

Name	Reaches Angle [°]	L' [km]	Drainage path length [km]
Campo Grande	9.3	5.7	2.8
Forquilha I	9.9	6.7	9.4
Barragem de Rejeitos	10.9	5.1	8.7
Forquilha II	9.3	7.1	9.9
Sul Superior	10.7	4.9	11.3
Forquilha III	9.5	6.6	12.1
Doutor	8.9	4.8	4.0
ED Xingu	10.7	5.1	5.2
Grupo	12.6	5.1	17.0
Vargem Grande	10.2	7.1	5.9

Table 4. Values obtained for the most 10 unstable TSF.

3.2.4 Risk management plan

From the previous results, a risk matrix is created to estimate the level of risk of each TSF by considering the category of Hazard, which is associated with the distance of the flooding area along the drainage path against the category of Exposure, which quantifies the number of man-made infrastructures encountered along the drainage path.

The exposure axis is made according to the number of structures along the drainage path and a vulnerability number ranging from 1 to 5 that has been assigned to different possible constructions (see Table 5). For each TSF analysis, every single structure affected by the flooding area is considered and the average value of vulnerability is calculated respect 5. The hazard axis is the ratio of the drainage path extension by 5. Thus, a 5x5 risk matrix can be created.

Both axes go from 1 to 5, being 1 the lowest threat. Once plotted the calculated values of hazard vs. exposure, it can be seen the position of each tailing dam and its risk involved, according to the background colour of the chart (see Figure 9).

Structure	Vulnerability
Cities	5
Roads	3
Train tracks	3
Mining complex	3
Other TSF	2

Table 5. Risk values assigned for each structure.

When analysing the previous chart, for instance, Grupo dam provides a threat in terms of the length of its drainage path, but since the level of exposure is less than 2, it means that not many man-made structures will be compromised, in this case, only roads and train tracks. Sul Superior and Vargem Grande are the TSF with highest level of exposure, but Sul Superior has a larger drainage path, hence it is located near the moderate-risk zone. In case of failure, both principal flooding areas would impact cities and roads. But, in the case of Sul Superior, it would also affect a mining complex; and Vargem Grande would damage several train tracks.

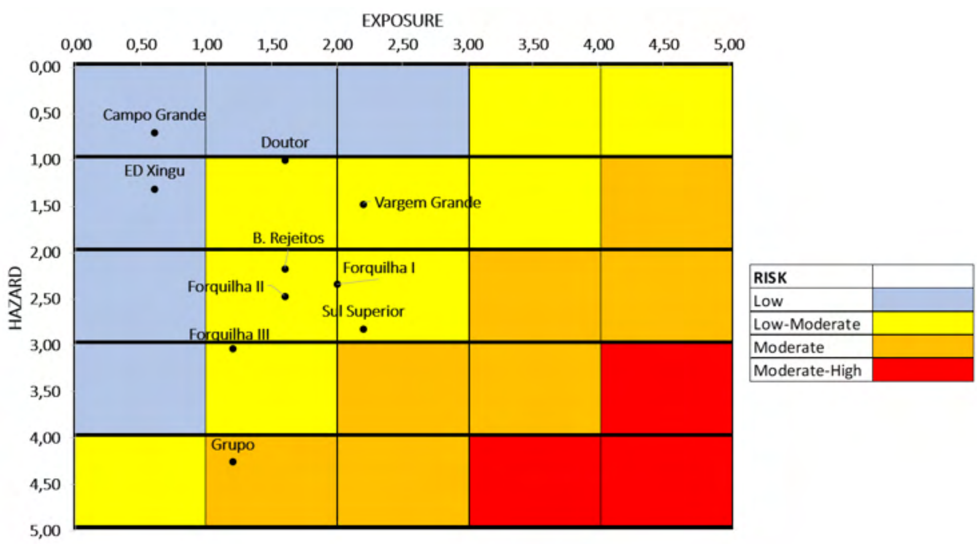

Figure 9. Risk matrix.

Most dams fall in the category of Low-Moderate risk, except Grupo dam, which is in a higher category. Within this level, the number of structures encountered, and the length of the drainage path make the difference. However, none of the dams is within the Moderate-High level; to be in the red area, the length of the drainage path should be at least 12 km and pass through more than one city, roads and train tracks.

Although the risk involved depends on several inputs, it is true that possible failure would imply socio- environmental effects that will persist for a long period of time. A risk reduction campaign would involve defining the present level of risk and try to reduce it to an acceptable value and implement an emergency plan to ensure the safety of the citizens nearby.

There are two different approaches to minimise the risk. On one hand, try to improve the current structure of the dam; on the other hand, damage containment mechanisms for the downstream valley and an emergency response plan for citizens in case of accident.

In order to improve the present conditions of mine tailing dams, a general maintenance of the structure should be carried out, as well as an improved surveillance and monitoring plan. Another option is to excavate wells outside of the danger area, with the aim to lower the water level in the dam and avoid liquefaction or seepage. Now, Vale S.A. is performing a decommissioning process in some upstream dams; the plan is based on imminent closure of those dams and start removing all the waste material in order to recover the previous environment.

The downstream area is at high risk in case of accident, because, unlike water, the mass of tailings is such that it can cause great damage, much greater than that of an equivalent flood of water, demolishing buildings rather than just flowing through them. Thus, approaches to risk reduction for the downstream valley system include the preparation of inundation maps, estimation of the time of arrival of the flood wave at different locations, the duration of inundation, implementation and maintenance of emergency warning procedures and systems (Penman, 2001).

As an example, in the case of the Sul Superior dam, a Rolled-Compacted Concrete (RCC) containment dam is being constructed downstream of it (see Figure 10). This dam has a volume of 175.000 m^3 and it is built in lifts of 40 cm (Dutch Risk Reduction Team, 2019).

Figure 10. RCC containment dam below Sul Superior.

3.3 Risk assessment: Secondary Impact Zone

The sections before were focused on the damage evaluation within the area. However, it is also important to consider the final extension and the negative effects that such failure would cause in the long term. Concha Larrauri and Lall (2018) presented a model to estimate the volume released of tailings and the maximum distance travelled by them. Different parameters are needed, such as the total impounded volume (V_T) in m3 and the dam's height (*H*) in m.

First of all, from the impounded volume it is possible to estimate the total volume of tailings that could be released (V_F). According to Rico et al. (2008), the total volume of tailings due to failure typically ranges from 10 to 35% of the impounded tailings volume. For this section, it is assumed that the volume data from Table 3 is V_T, since not the entire mass retained by the dam will flow out.

The formula suggested by Concha Larrauri and Lall (2018) to calculate V_F is:

$$V_F = 0.332 \cdot V_T^{0.95} \quad (3)$$

Once the volume is known, the variable H_f is introduced to consider the potential energy associated with the previous released volume:

$$H_f = H \cdot (\frac{V_F}{V_T}) \cdot V_F \quad (4)$$

Finally, the maximum run-out distance (D_{max}) can be calculated:

$$D_{max} = 3.04 \cdot H_f^{0.545} \quad (5)$$

Using the equations, the maximum run-out distance reached by tailing materials along the drainage path is displayed in the following Table 6.

Some of the results obtained regarding the maximum run-out distance (D_{max}) are not consistent with the ones found before (Table 3). For example, in the case of Grupo dam, where the model proposed by Concha Larrauri and Lall (2018) suggests a travelled distance of 7.51 km in total, whereas with the QGis approach the distance measured is 17.0 km, only for the primary impact zone.

Name	Dam Height [m]	Volume [m^3]	Final Volume (V_f) [m^3]
Campo Grande	99.3	$23 * 10^6$	$6.5 * 10^6$
Forquilha I	98.3	$13 * 10^6$	$3.7 * 10^6$
Barragem de Rejeitos	89	$5 * 10^6$	$1.6 * 10^6$
Forquilha II	88	$23 * 10^6$	$6.5 * 10^6$
Sul Superior	85	$6 * 10^6$	$1.8 * 10^6$
Forquilha III	77	$19 * 10^6$	$5.6 * 10^6$
Doutor	77	$38 * 10^6$	$10.4 * 10^6$
ED Xingu	70	$6 * 10^6$	$1.9 * 10^6$
Grupo	39	$1 * 10^6$	$0.4 * 10^6$
Vargem Grande	35	$10 * 10^6$	$2.8 * 10^6$

Name	H_f	Runout Distance (D_{max}) [km]
Campo Grande	183.8	52.1
Forquilha I	107.2	38.8
Barragem de Rejeitos	43.6	23.8
Forquilha II	161.6	48.6
Sul Superior	47.1	24.8
Forquilha III	122.8	41.8
Doutor	222.5	57.8
ED Xingu	39.7	22.6
Grupo	5.3	7.5
Vargem Grande	29.7	19.1

Table 6. Maximum run-out distances for each mine tailing dam.

This deviation can be caused by the different values of volume used, since the QGis method used the total volume of the reservoir. However, the Concha Larrauri and Lall (2018) method does not consider the topography of the area, thus it could be the case of possible obstacles along the drainage path that would reduce the run-out distance in reality.

3.3.1 Risk management plan

To reduce the impact in response to dam failure, a risk management plan evaluates the effects involved in the entire downstream area affected, which in the long term will be more environmental and social related. Mining industries produce large volumes of waste, which are stored in impoundments behind dams and in case of collapse, all this material would flow out.

Environmental impacts in the downstream area depend on the magnitude and the toxicity of the materials. The ensuing discharge into river systems would affect the water quality, thus the aquatic and human life. Therefore, it would be necessary a study regarding the type of material involved, the usage of water of the polluted river and the impact on the flora and fauna. Spillage of tailings dam in the environment have immediate negative effects in the surroundings. If clean-up operations are not performed, chemical concentrations in the environment will decrease over time, due to aqueous dilution and sedimentation of other materials (Kossoff et al., 2014).

There are some mitigation measures which can be carried out in order to reduce the impact, but completely erasing the damage would not possible. A first option is to add chemicals into the polluted soils to reduce the mobility of the contaminants or neutralize its negative effects. Secondly, the construction of barriers to contain the waste material and prevent it from spreading further. Nevertheless, the most common practice is to remove the spillage material from the affected area and store into another location (Kossoff et al., 2014).

4 I CONCLUSIONS AND RECOMENDATIONS

Mine tailing dam failures are a serious threat to the downstream environment and human-made structures, because the sudden release of large quantities of tailings into river catchments poses a serious threat to animal and human health. This report presents a simple and effective method to determine the primary flooding area in case of dam failure. It is based on the empirical relationship presented by Corominas (1996), which allows to determine the angle of reach, thus the length of the deposit in the horizontal plane.

The first challenge encountered was the amount of data available, but at the same time the contradictions in it regarding same structures. From the database created, it is possible to identify the TSF based on their risk level, however, it is not possible to derive the (geotechnical) stability or safety factor. This requires a very specific analysis, which falls outside the scope of this study. The first step of the project was to create a general database with all available information from all structures. Now, it is possible to visualise in QGis the location and the metadata of all TSFs in Minas Gerais.

From the results in Table 4 and according to Corominas' empirical relationship the more volume involved in failure, the smaller is the value of angle of reach. Thus, more volume means that the travelled distance by the waste material will increase, so the energy plane will be less steep. With the angle of reach, the energy plane was created according to elevation values and the initial flooding area obtained. It is important to check the topography of the area, because it is possible that the flooded area is smaller than expected because of irregularities along the drainage path, such as a sudden change in the slope downstream the dam.

The risk matrix created outlines which TSF has the highest risk, which is defined by the factor of hazard in combination with the exposure to the hazard. Therefore, the mine tailing dam Sul Superior is the most vulnerable of all TSF, because of the man-made structures along its drainage path, even though Grupo dam has a more extensive flooded area.

The results provide in this study are a starting point to have a first idea of the areas affected by a debris flow resulting from a dam failure. However, the procedure followed is useful, it is at the same time manual and slow. Some recommendations for further studies would imply using complex flow models to obtain more accurate results and to automatise the procedure to analyse more possible failure dams.

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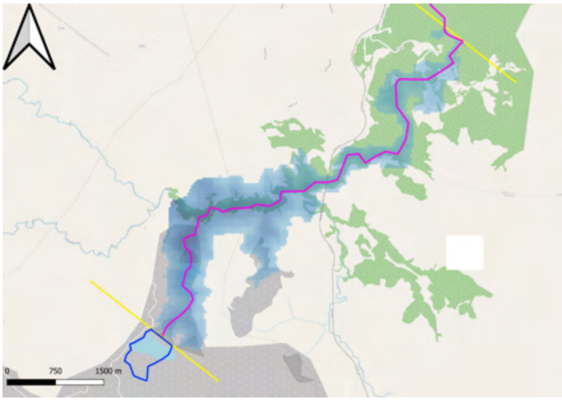
NOTE

This material is part of the studies at Delft University of Technology - Internship at Cohere Consultants, in Amersfoort, by Mònica Novell Morell.

APPENDIX



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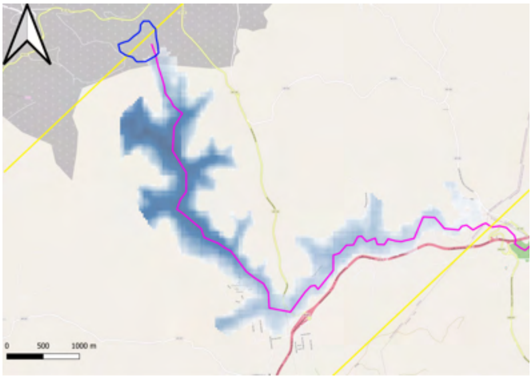
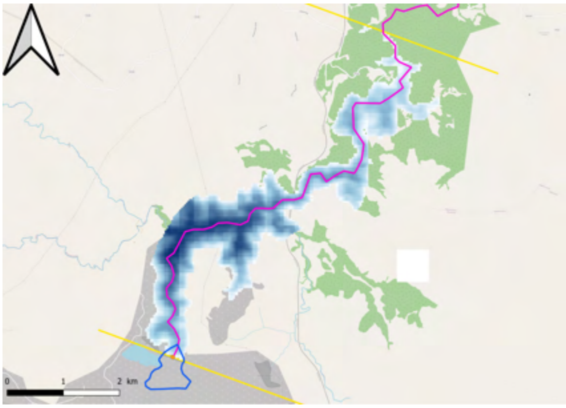
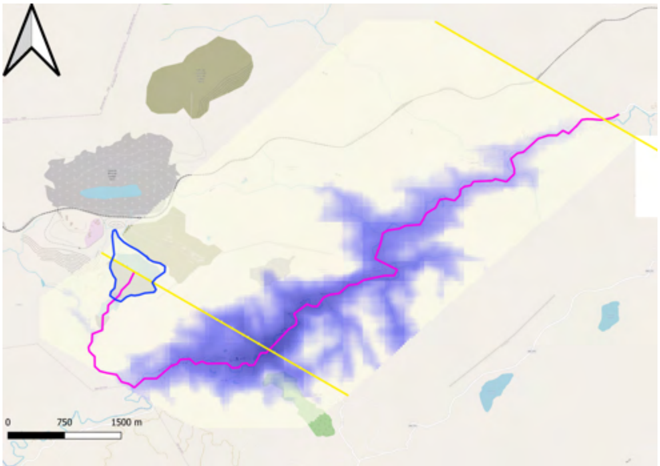


2. BARRAGEM DE REJEITOS

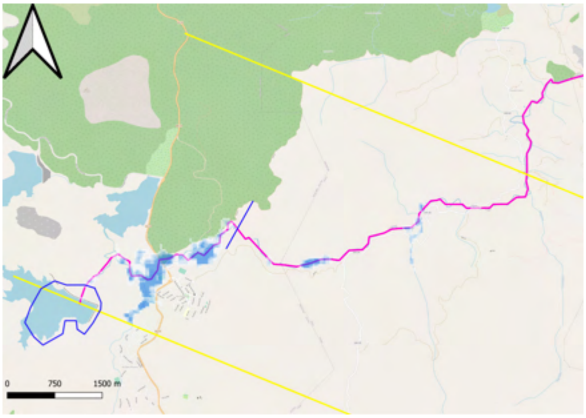


3. FORQUILHA II

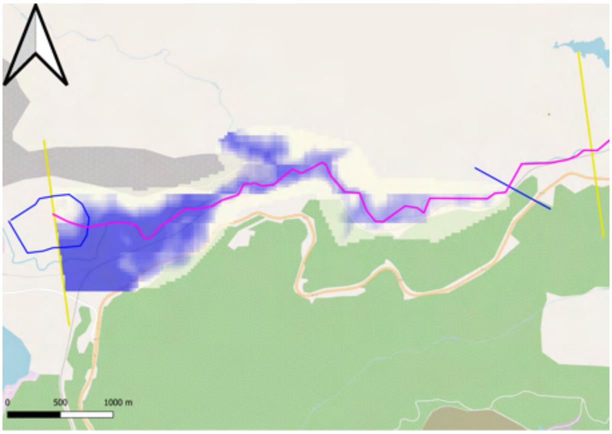


4. SUL SUPERIOR

5. FORQUILHA III



6. DOUTOR



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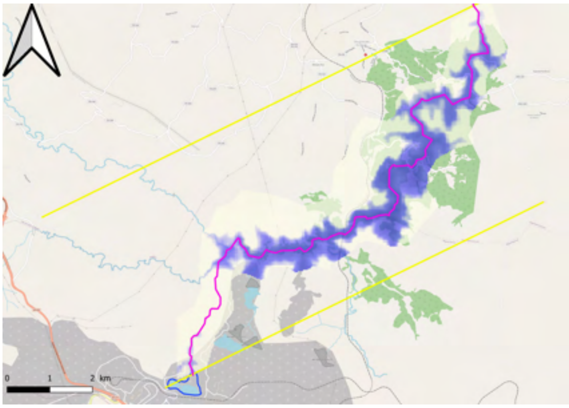
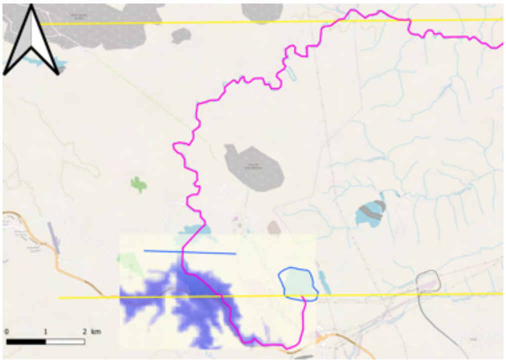


8. GRUPO



9. VARGEM GRANDE

LIST OF SYMBOLS AND ABBREVIATIONS

ANA: Agência Nacional de Águas

ANEEL: Agência Nacional de Energia Elétrica

ANM: Agência Nacional de Mineração

CRI: Risk level

D_{max}: Run-out distance

DTM: Digital Terrain Model

FEAM: Fundação Estadual do Meio Ambiente

H: Elevation difference

H_f: Variable for the potential energy

IMAC: Instituto de Meio Ambiente do Acre

IPAAM: Instituto de Proteção Ambiental do Amazonas

L: Total travelled distance

m.s.l: mean sea level

PDA: Potential damage associated

TSF: Tailing Storage Facilities

V: Volume of the mass

V_c: Hazard level

V_F: Total volume

V_r: Volume of the reservoir

V_T: Impounded volume

α: Angle of reach

ÍNDICE REMISSIVO

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