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Assessment of the environmental radiological impact in the emergency exposure phase through the simulation of a uranium mining tailings dam breach

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ABSTRACT

This work is aiming at estimating the radiation doses to members of the public in case of an emergency exposure situation related to a hypothetical uranium mining tailings dam rupture at the UDC - Decommissioning Unit of Caldas, MG, Brazil. The calculations will help to managing the exposures of emergency workers and residents in the region downstream the dam. The computer code chosen to perform the simulations was FLO-2D@ software. Due to the uncertainties involved, mainly regarding the waste rheology and activity concentrations and in parameters values to be used in the dose assessment, considerations were made for the study to present results derived from conservative assumptions. Through the creation of flood maps, it was possible to estimate the extent of the areas affected by the released materials. The results showed that in a scenario of the tailings dam breach, deposition of mud shall extend over 20 km downstream affecting an area of nearly 3 km^2. Total dose for a member of the public living in most affected areas would be around 43 mSv/y in the early phase after the accident. Although only shielding would be recommended under current radiation protection regulation, evacuation/relocation is suggested due to the presence of long-lived radionuclides. This protective measure would probably already be indicated by the accident itself, regardless of radiological reasons. More realistic assessment should be performed before returning people, considering long-term environmental transport and uses of the area. It must also be considered that long-term exposures have more restricted recommended acceptable levels than those for the emergency phase.

Keywords: **uranium tailings, dam breach, radiological assessment, FLO-2D**

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1. INTRODUCTION

It is known that mining and ore processing activities have the potential to significantly affect surface and groundwaters, soils, air, and biota of their neighborhood. The impacts of these activities depend on site-specific conditions [1]. If these activities are designed, implemented, operated, and monitored in accordance with international good practices, the environmental radiological impacts that may arise can be substantially reduced. However, extreme natural events can lead to the release of contaminants if facilities are not designed, built, and maintained to withstand these events, or if they fail to function as intended [2].

The UDC operated from 1982 to 1995 and constituted the first mining-industrial complex to produce uranium concentrate in Brazil. During the UDC's operating time, the mineral processing tailings were deposited in a tailings dam system, built in the early 1980s. To function as a containment, within the 450 m of the dam massif, a construction method was developed consisting of a core of clay-silt soil, equipped with sand filters. To protect the faces of the massif, larger rocks were placed, a process called rockfill [3].

In 2004, the operator signed a Term of Commitment for the Preparation and Presentation of the Plan for the Recovery of Degraded Areas - PRAD - to the UDC with the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA). In 2012, IBAMA approved the PRAD with the aim of defining the works and environmental recovery actions to be developed at the unit [4]. It is important to highlight that the PRAD [3], as well as all IBAMA environmental licensing documents, is in the public domain. Therefore, this work uses information from the PRAD.

After the occurrence of an "unusual event" at the dam, in September 2018, INB was requested by the federal Government to present an Emergency Action Plan for the dam. An audit pointed out that the system was seriously compromised due to infiltrations and that the dam was at risk of rupture [5]. Although it is known that repairs have been done at the dam [4], it was decided to study the consequences should such rupture occurs.

In the case of an incident occurring in a uranium mining tailings dam, in addition to the conventional impacts associated with a dam failure, one must also consider the radiological impacts on both man and the environment. Bearing in mind the UDC-INB Tailings Dam was design to receive the tailings of the uranium ore processing and considering the environmental potential radiological risks of a breach an d the subsequent dispersion of the mud containing radionuclides, the objective of this work was to make simulations of the dam breach and of the dispersion and deposition of this mud in the water bodies in the region, to draw maps with geolocation of the radioactive plume, and then calculate the resulting radiation dose to local people to evaluate the radiological impact that would result from this dam breach. Simple models have been used in the dose assessment, as a screening procedure, to give an idea of the doses expected to occur in the emergency phase of the accident, in support to emergency preparedness programs.

2. MATERIALS AND METHODS

Table 1 presents the main characteristics of the executive project of the tailings dam. The drainage area of the tailings dam is 0.86 km^2.

Table 2 presents the geotechnical parameters of shear resistance considered in the executive design of the dam, for the estimated values for the tailings and for the considered foundation material.

Table 1 - Characteristics of the tailings dam project [3].

DAM	
Crest elevation a.s.l.[1]	1.310 m
Crest width	10 m
Maximum height	42 m
Crest lenght	435 m
RESERVOIR	
Flooded area to W.L. [2]	Max 0.25 km^2
Reservoir volume to W.L.	Max 2.17 x 10^6 m^3
Maximum volume of tailings disposal	1.97 x 10^6 m^3

[1] a.s.l. = above sea level

[2] W.L. = water level

Table 2 - Geotechnical parameters of BR-UDC materials (adapted from [3])

Material	Specific Weight (g/cm^3)	Friction Angle Φ(°)
Rockfill	3	38
Core (landfill-clay material)	1.9	27
Filter (sand)	1.8	30
Transition (granular material)	1.8	32
Transition (running spout)	1.9	35
Foundation (rock)	2	40
Deposited material (waste)	2.6	24

The overflow from the tailings dam lake is released, after treatment, into the Soberbo River, which is part of the Verde River basin.

Even though modeling methods have experienced significant improvements, there is a small number of codes that are able to develop simulations with non-Newtonian fluids. Hyperconcentrated fluids, i.e., where the ratio between solid volume and total volume exceeds 20%, exhibit non-Newtonian behavior [6], and for this reason their simulations cannot be properly addressed by hydraulic models. As a result of the above, the model FLO-2D® was chosen to run the simulations in this paper, because it is capable to simulate the transport of sediments and mud flow and estimate floods of non-Newtonian fluids [7].

For the modeling of the dam breach, the FLO-2D code plugin for QGIS was used. FLO-2D is a robust code capable of simulating urban floods to dam breach in high resolution. The FLO-2D code plugin for QGIS allows Newtonian and non-Newtonian models to be built quickly, taking advantage of the wide range of tools available in the QGIS ecosystem. QGIS is an open source Geographic Information System (GIS) from an official project of the Open-Source Geospatial Foundation (OSGeo) [8]. The academic (free) version of the plugin for QGIS of the FLO-2D model (version 0.10.38) was used for the simulation.

For the pre-processing stage, the following compilation and insertion of data in the model were performed:

• Breach failure hydrograph (volume and duration time);

• Geotechnical characteristics of the dam;

• Geotechnical characteristics of the tailings;

• Digital Elevation Model – MDE; and,

• Land use and land cover data.

To estimate the breach failure hydrograph and the volume of material (tailings + water) released and the mud concentration from the failure of a tailings dam, FLO-2D uses the "Tailings Dam Tool". Parameters include dam geometry, tailings saturation, tailings shear strength and depth of water/tailings interface in the dam.

The FLO-2D presents three options to simulate a dam failure event: static failure, hydrological failure and seismic failure modes: static failure, seismic failure and hydraulic failure. The UDC is undergoing decommissioning, i.e., no explosions are supposed to occur; the site is also not expected to have earthquakes. Therefore, the seismic failure mode can be ruled out. According to the Federal Public Ministry [5], the unusual event that occurred in the overflow system could generate a failure due to piping. Thus, for the development of this work, a possible failure of the dam slope was considered leading to the use of the static failure mode.

The governing equations used in the FLO-2D model are the continuity and the momentum equation (Dynamic Wave Momentum Equation) and are described in the program manual [9].

Since the FLO-2D is a multidirectional flow model, average flow velocities are calculated across grid element boundaries, applying the equation of motion in one direction at a time with an explicit central finite difference numerical scheme.

To simulate a viscous mud flow, viscosity and yield stress variables are assigned according to the volumetric sediment concentration [9]. Data from the tailings in the UDC dam will result in high viscosity and moderate yield stress, with high sediment concentrations. This volumetric sediment concentration can then be attributed to the incremental water discharge for a time step in the discretized inlet hydrograph. The volume of incoming sediments may represent channel sweeping, erosion, or landslide.

By directing the mud flood or mud flow over an alluvial fan or floodplain, the FLO-2D model preserves continuity for both water and sediment. For each grid element and time step, the change in water and sediment volumes and the corresponding change in sediment concentration are computed. At the end of the simulation, the model reports the amount of water and sediment removed from the study area (outflow) and the amount and location of water and sediment remaining in the fan or channel (storage). This total sediment volume should be reviewed to determine if this is a reasonable sediment yield for the catchment. The extent of inundation of the mudflow and the maximum flow depths and velocities are a function of available sediment.

The geotechnical data of the dam contained in PRAD [3] was used, the topography used was based on the Digital Elevation Model (DEM) [10] with a resolution of 5 m, to carry out the pre-processing and the GIS (Geographic Information System) for the visualization and manufacture of cartographic products.

The official geodetic reference system of Brazil was used, the SIRGAS2000 Geocentric Reference System for the Americas 2000, Universal Mercator System (UTM), considering that the zone is the 23S, EPSG code: 31983. Data on hydrology, land use and land cover were imported from MAPBIOMAS [11] and from the website of SISEMA [12].

The modeling was carried out using the FLO-2D Plugin for QGIS, for which the scenarios were proposed, and the generated results were subsequently exported using the MAPPER program [9]. The post-processing consisted in analyzing and comparing the results of different time scenarios simulations and making the cartographic products in QGIS.

Assessment of environmental radiological impact can be performed as a function of soil concentration after plume passage and residual concentration in aqueous runoff. Significant exposure pathways for the exposed population group need to be considered in the assessment and these may include external exposure from radioactive material in soil, air or water, and internal exposure through inhalation and ingestion.

The models used in this work for dose calculation were adapted from models recommended by the International Atomic Energy Agency - IAEA (International Atomic Energy Agency) [13, 14] or models validated and used internationally for many years [15, 16]. The parameter values also derive from these models, from IAEA publications, from recommendations of the International Commission on Radiological Protection - ICRP (International Commission on Radiological Protection) and from data from the installation under study, collected from PRAD [3]. The dose factors are those contained in the CNEN Standard 3.01, currently in use in Brazil [17].

The calculations presented here represent a first approach to the dose assessment after a tailings dam breach with the deposition of a large thicknesses of mud containing radioactive materials in places close to residences in rural areas. The results should be seen as an approach to support emergency preparedness, to verify the need to take urgent protective measures.

Two exposed groups were considered in this work. The first group includes people who work to contain or verify the conditions of the accident, including those associated with radioprotection work, called emergency workers, but also includes those professionals who usually support the protection of the population in cases of conventional emergencies, such as such as policeman and firefighters, who must be considered as members of the public, since they may not have training in radiological protection. The exposure pathways considered were external exposure to the mud, inhalation of resuspended material from the mud, and the inadvertent ingestion of soil. The second group includes residents and the exposure pathways considered are external exposure to the mud, inhalation of resuspended material, inadvertent ingestion of soil and ingestion of milk contaminated by watering cattle in rivers contaminated by the plume dispersion.

The source term for exposure of workers and members of the public is the mud deposited along affected streams and rivers following runoff from the dam failure. The estimated concentration in the sludge was based on data from PRAD [3]. There is great uncertainty in this fundamental value for the entire calculation, since not all materials deposited in the dam are properly quantified. Besides the wastes from the uranium ore processing, the dam also received material from the decommissioning of a monazite processing unit in Brazil [18], and from the acid drainage treatment, calcium diuranate - DUCA. Although only the materials listed in Table 3 have their chemical characterizations described in the literature, these include about 93% by mass of the material discarded in the dam. As so, it was considered valid to carry out the dose assessment, to have an idea of the potential doses resulting from such a dam failure event.

For quantitative characterization of the chemical composition, not all relevant radionuclides have been properly described, and some approximations have been used. It was considered that the initial ore, before chemical processing, would be in secular equilibrium. As processing alters this equilibrium, when the concentration value of some radionuclide was not properly described, the following considerations were used:

- Th-228 concentrations in the ore and residue from monazite processing were considered to have been maintained in secular equilibrium with Th-232 after the processing, since they are the same chemical element and, therefore, this would have the same dissolution/concentration effect on both isotopes;
- for the uranium processing tailings, since operation finished more than 20 years ago, it was considered the Th-228 is already in equilibrium with its parent Ra-228;

- the Th-232/Th-230 ratio in the ore is maintained in the DUCA; and,
- Pb-210 and Po-210 are in secular equilibrium with Ra-226 in monazite waste and the concentrations of Ra, Pb and Po in DUCA are negligible

The dispersed mud considered in this study corresponds to the tailings originally at the dam, mixed with water, The activity concentration os the tailings is shown in Table 3.

Table 3 – Composition and activity concentration in the tailings [3].

	Processed U ore	**Mixed ore and residue from monazite processing**	**Solids from acid drainage treatment (calcium diuranate)**	**TOTAL (t)**
Quantity (t)	2.11E+06	2.07E+06	8.38E+04	4.27E+06
Radiological characterization (Bq/t)				
U-238	9.00E+03	1.88E+08	5.65E+07	9.24E+07
U-234	9.00E+03	1.88E+08	5.65E+07	9.24E+07
Th-230	7.14E+04	1.88E+08	5.65E+06	9.14E+07
Ra-226	2.50E+06	4.88E+05		1.47E+06
Pb-210	3.40E+06	4.88E+05		1.92E+06
Po-210	3.40E+06	4.88E+05		1.92E+06
Th-232	4.00E+04	2.62E+07	1.04E+06	1.28E+07
Ra-228	1.40E+06	6.80E+04		7.26E+05
Th-228	1.40E+06	2.62E+07	1.04E+06	1.34E+07

Direct external exposure of people to contaminated areas D_{ext}, was considered using the methodology proposed by the IAEA [14]:

$$D_{ext} = C_{mud} * (U_{outdoor} + U_{indoor} * FB_{soil}) * FCD_{ext} \qquad (1)$$

where C_{mud} is the mud concentration (Bq/m^3), Table 3, considering a density of 2.74 t/m^3 [3]. FCD_{ext} is the external dose conversion factor from contaminated soil, [19], FB_{soil} is the shielding factor of the building: 0.7 [20], and U is related to occupation rates:

$U_{outdoor}$ = fraction of time spent outdoors: 0.2 for residents [21] and 0.2 for workers, considering a working day at the site of 8 h/d, 220 d/y.

U_{indoor} = fraction of time occupied inside houses: 0.8 for residents [21] and 0 for workers.

Inhalation is due to the resuspension of particulates from the mud deposited on the ground. The model used in this work to estimate the concentration in air is the resuspension factor (*K*) method, where K is the resuspension constant, 1E-7 kg/m [14]. The inhalation dose, D_{ina}, is calculated by:

$$D_{ina} = C_{mud} * K * I_{ina} * (U_{outdoor} + U_{indoor} * FB_{air}) * FCD_{ina} \qquad (2)$$

Where:

I_{ina} = Annual inhalation rate, estimated from data derived from data provided by the ICRP [23] for different types of activities: 1 m3/h for residents and 2 m^3/h for workers.

FB_{air} = outdoor air concentration reduction factor by building: 0.4 [16]

FCD_{ina} = Inhalation dose factor, [19]

Inhalation of radon for members of the public was not included in this work. Radon, in relation to public exposure, is usually treated as an existing exposure situation, having its own limit for its concentration within dwellings. It should certainly be considered when assessing the long-term consequences of the accident, with a view to establishing remedial procedures. Such objective is not part of the scope of this work. However, worker exposure to radon outdoors was performed using the RESRAD [16] and NORMALYSA [15] software and the dose values obtained were considered negligible (<< 1 mSv/y).

The ingestion pathways considered were inadvertent ingestion of soil and the ingestion of milk. Intake of vegetable foods was not considered because these would be rendered unusable by the deposition of mud. However, this exposure pathway should be considered when in the existing exposure phase, since, in the long term, the affected area can be used again for agricultural purposes.

Contamination of milk is due to the ingestion of river water by cattle, which is a common practice in the region. The concentration in water (C_{water}) is calculated from the concentration in the mud using and the distribution coefficient (K_D) for each element. Values of K_D are those recommended by IAEA [23]. The concentration in milk (C_{milk}) is estimated by:

$$C_{milk} = (C_{mud} / K_D) * Q_{water} * F_m \qquad (3)$$

where Q_{water} is the water consumption by livestock, 60 L/d [14] and F_m is the transfer factor of incorporated material to milk, d/kg, also from IAEA [14].

The equation used to estimate the intake dose (D_{ing}) is:

$$D_{ing} = [(C_{mud} * I_{soil}) + (C_{milk} * I_{milk})] * FCD_{ing} \qquad (4)$$

Where:

I_{soil} = Annual inadvertent soil ingestion rate, kg/y, considered equal to that quoted by the RESRAD model (0.0365 kg/y) [24]

I_{milk} = Annual rate of milk intake by an adult, considered as 250 L/y, according to the “default” data of the RESRAD model [24]

FCD_{ing} = Inhalation dose factor, Sv/Bq, [19]

The total effective dose, D_{total}, is the estimated by:

$$D_{total} = D_{ext} + D_{ina} + D_{ing} \qquad (5)$$

The results obtained should be compared to the requirements of the current Brazilian regulation CNEN 3.01, and against the most recent recommendations of the IAEA [25].

CNEN Standard 3.01 [17] establishes that decisions regarding the adoption of urgent measures to protect the population, when a nuclear accident occurs, are based on the projected dose. The projected dose is the predicted dose that an individual would receive over a determined period if no protective action was implemented. The projected dose is estimated based on the conditions of the installation, forecasts of evolution of the accident, the probability of releases of radioactive materials to the environment and existing dispersion conditions.

Values adopted intervention and action levels must be applied to most individuals in the public. However, for some groups of the population that are subjected to markedly different risks to some protective measure, then it is appropriate to adopt differentiated values for these levels, in such a way that the adoption of the protective measure for these small groups is justified.

Intervention levels for public exposure for protective measures that apply to the cases described in this paper are summarized in Table 4.

The new IAEA recommendations for the public defines a range of 20 to 100 mSv, suggesting the need to effectively implementing a protective measure for doses at the top value of the range [25].

The ICRP, in its publication No. 109, despite recommending this same range, clarifies that values close to the lower limit of the range should always be used, exemplifying the possible need to eventually use higher values. Additionally, it is insistently stressed that, whatever the value chosen, this is a reference level for carrying out optimization processes [26].

Table 4. Generic levels of intervention for urgent protective actions [17]

Protective Action		Generic Intervention Level
Shelter		10 mSv
Evacuation		50 mSv
Resettlement	temporary	30 mSv in the first month
		10 mSv in a subsequent month
	permanent	1 Sv in a lifetime

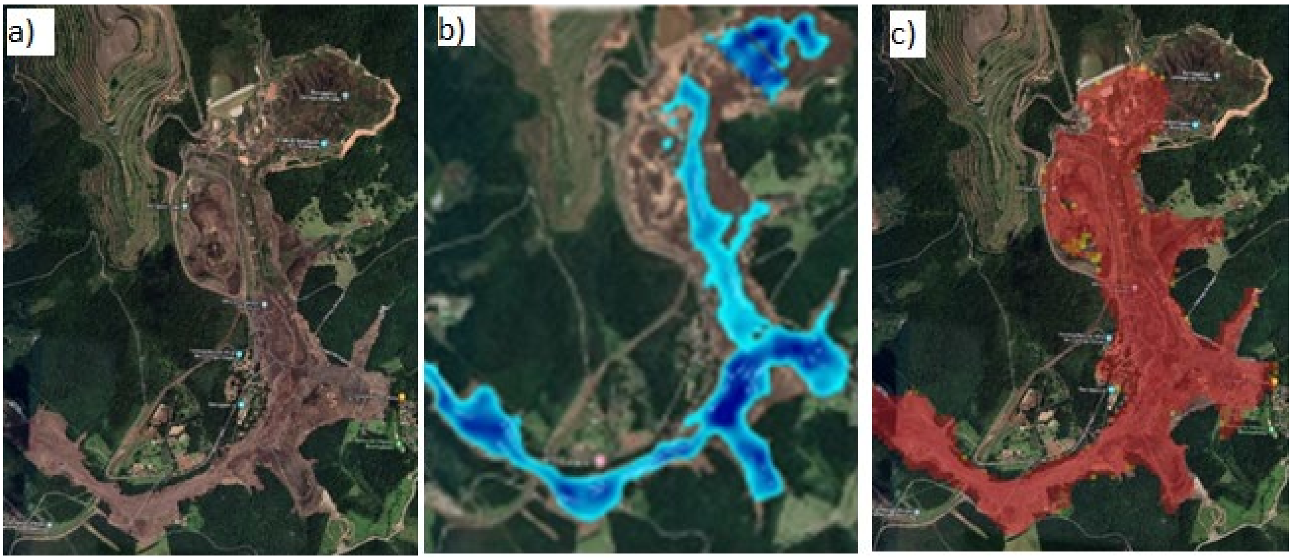
For workers, doses of up to 100 mSv can be accepted to avoid large collective doses; in exceptional situations (e.g., saving lives or avoiding catastrophic situations), doses of up to 500 mSv may be accepted for volunteer trained workers.

3. RESULTS AND DISCUSSION

The chosen model was first tested with data from the Feijão Creek Dam breach in Brumadinho - MG [27]. The geotechnical parameters of the materials contained in the waste from Feijão Creek Dam may be found in literature [28].

Figure 1 presents a comparison between flooding by real mudflow, a hydraulic model (Newtonian) Simulated with HEC RAS (blue) [27] and the mudflow model (non-Newtonian) from the study by case (red), simulated with the FLO-2D. It can be seen that the hydraulic model does not correctly represent the path taken by the mud, as the water is more fluid and tends to flow through preferential paths. The mud flow simulated in FLO-2D provides results closer to the reality. In this map it can be observed that for a simulation timeframe of 5 hours, there is an excellent overlapping with images provided by Google Earth [29].

Figure 1 - Comparison between flooding and real mud flow: satellite image (a); a hydraulic model simulated with HEC RAS (b) and the mud flow model simulated with FLO-2D (c).



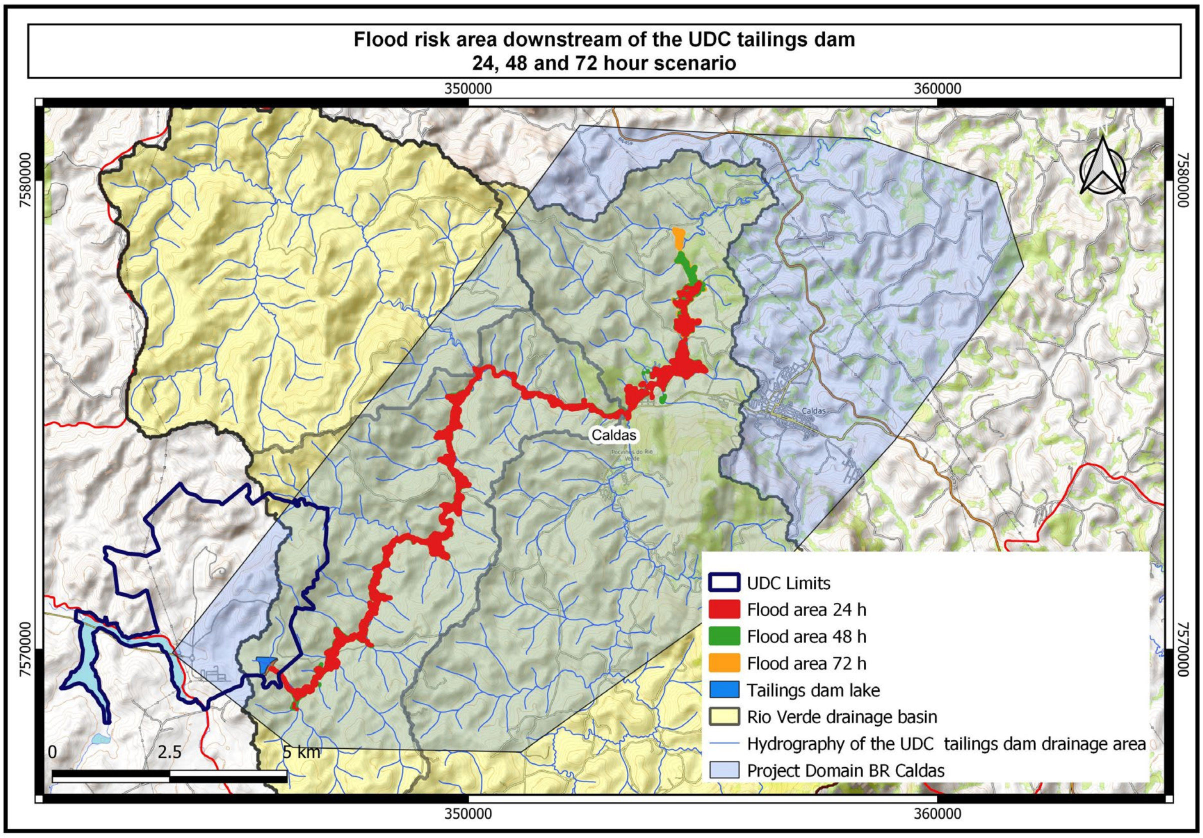
Sources: (a) Google earth [31]; (b) adapted from [29]; (c) this work.

The Tailings Dam Tool presents three possibilities for releasing the tailings volume for the preparation of the hypothetical breach failure hydrograph. The ANM Resolution No. 32 of 2020, demands that the worst damage scenario must be considered [30]. It was then chosen the scenario where the largest volume of waste was released, that corresponds to 62.4% of the total tailings in the dam, that correspond to a volume of 1,228,870 m^3, for assessing the consequences of the hypothetical UDC Tailings Dam breach. In the initial moment of the simulation, this volume becomes liquefied and completely drained to the area downstream the UDC Tailings Dam. According to PRAD [3] the geotechnical characterization indicates that the material present in the Dam is silty sand, without the presence of clay.

O'Brien and Julien [31] performed tests on sandy tailings and established a relationship for viscosity and yield stress according to their volumetric concentration. Thus, it was decided to use data from the closest density values. The Manning coefficient was considered 0.04, which is the default value of the program.

Figure 2 shows the area used in the modeling of the hypothetical UDC Tailings Dam breach, Caldas – MG. The modeled area has 89.91 km² with a grid of 30 x 30m downstream of the waste dam of the UTM until close to the limit of the municipality of Caldas. The objective was to evaluate the area, the velocity and the final thickness of the mud flow. The map also shows the areas flooded by the mud flow in three different time scenarios, 24 (red), 48 (green) and 72 hours (yellow). Most of the mud flow takes place in the first 24 hours, with proportionally little progression of the mud flow in the 48-hours scenario and even less in the 72-hours scenario.

Figure 2 - Flood Area Map downstream of the UDC Tailings Dam, Caldas – MG



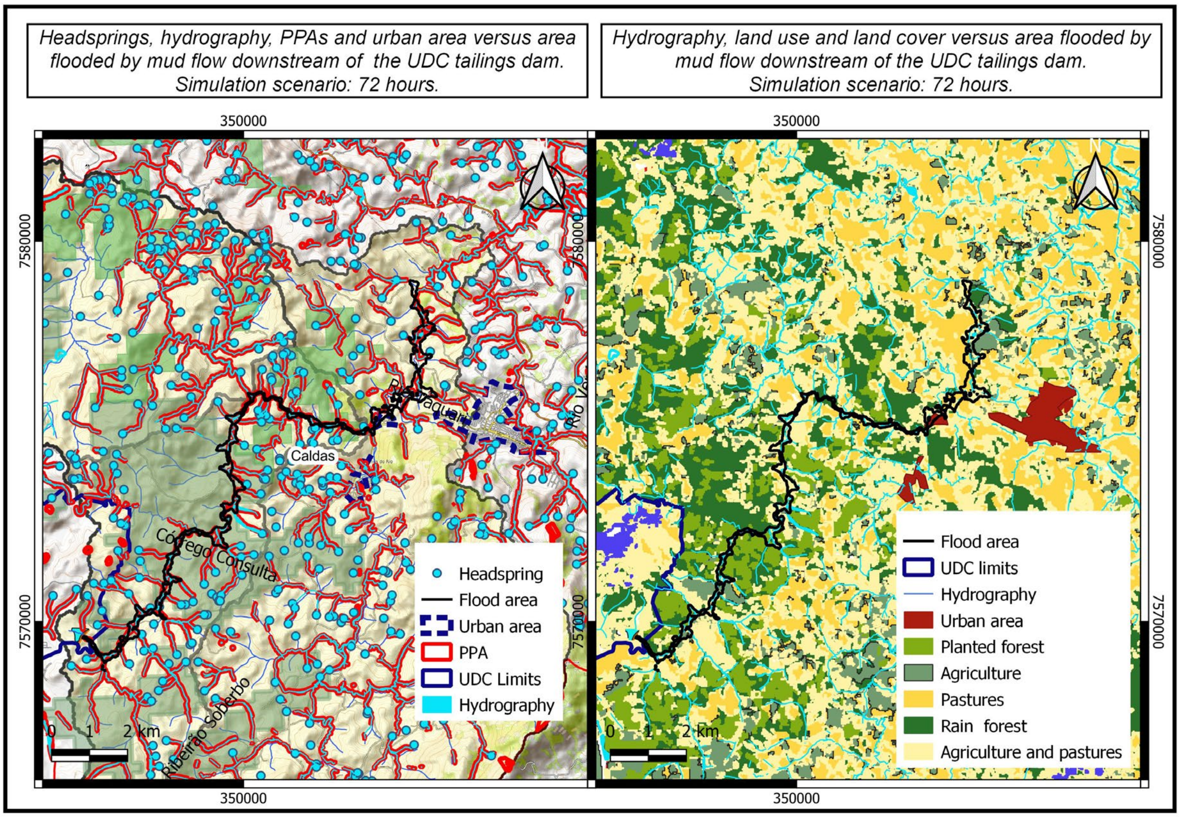
After 72 hours, the mud would cover a path of 19 km and the elevation ranged from 1295 m, the base elevation of the dam, to 1038 m, a difference in level of 257 m. At the beginning of the mud trail the velocities are higher, in the order of 1.2 - 1.5 m/s, and at the end of this path the velocity reduces to 0.24 – 0.36 m/s. There is a relationship between the decrease in mud flow velocity and the fact that after about 15 km the terrain becomes flatter, leading to a wider spread of the mud flow.

Figure 3a shows the maps with the springs, the hydrography, Permanent Protection Areas – PPA and the urban area that would potentially be affected by the flood caused by the mud flow. The shapefile layers of the springs, hydrography, preservation, and urban areas were downloaded from the SICAR [32]. The mud would impact the Soberbo creek, the Taquari River and part of the Verde River, silting up its bed and banks. It should be noted that in Brazil, springs, rivers, and their banks are defined by Law No. 12,651, of May 25, 2012, as a permanent preservation area (PPA) [33]. Consideration should also be given to potential contamination of the Grande River, as the Verde River is one of its tributaries.

Figure 3b presents the map of hydrology, land use and occupation affected by the mud flow. To make this map, land use and occupation data from MAPBIOMAS [11] was used; hydrology and urban area data were taken from SICAR data [32].

Figure 3 - Water springs, hydrography, land use and occupation the flooded area by mud flow

(a) **(b)**



Most of the flooded area passes through agricultural areas, pasture areas and forest areas, but it includes residential areas, such as the Dr. Nelson de Paiva district. The properties located in the region potentially affected by the flooding of the mud flow probably use the water for consumption, agricultural irrigation, and animal watering.

In Figure 4 we have the flood risk map due to the mud flow at the end of the 72 hours of simulation. Although the flood risk area is in a rural region, we can see in the highlighted area that at least a third of the Dr. Nelson de Paiva would be in an area at risk of flooding. However, it was seen that the allotment is in a region where the mud flow would arrive about 23 hours after the dam breach; in this way, there would be enough time for the evacuation of residents and interdiction of this area by activating the PAEBM, thus avoiding the loss of human lives. In the same figure we can see an aerial view of the Dr. Nelson de Paiva in Caldas – MG, located on the banks of the Verde River. After the hypothetical event, mud depth at this location can vary from 1.7 to 6.6 meters.

Figure 4. Flood Risk Map for 72 hours simulation and an example of urbanized area directly affected by the mud flow.

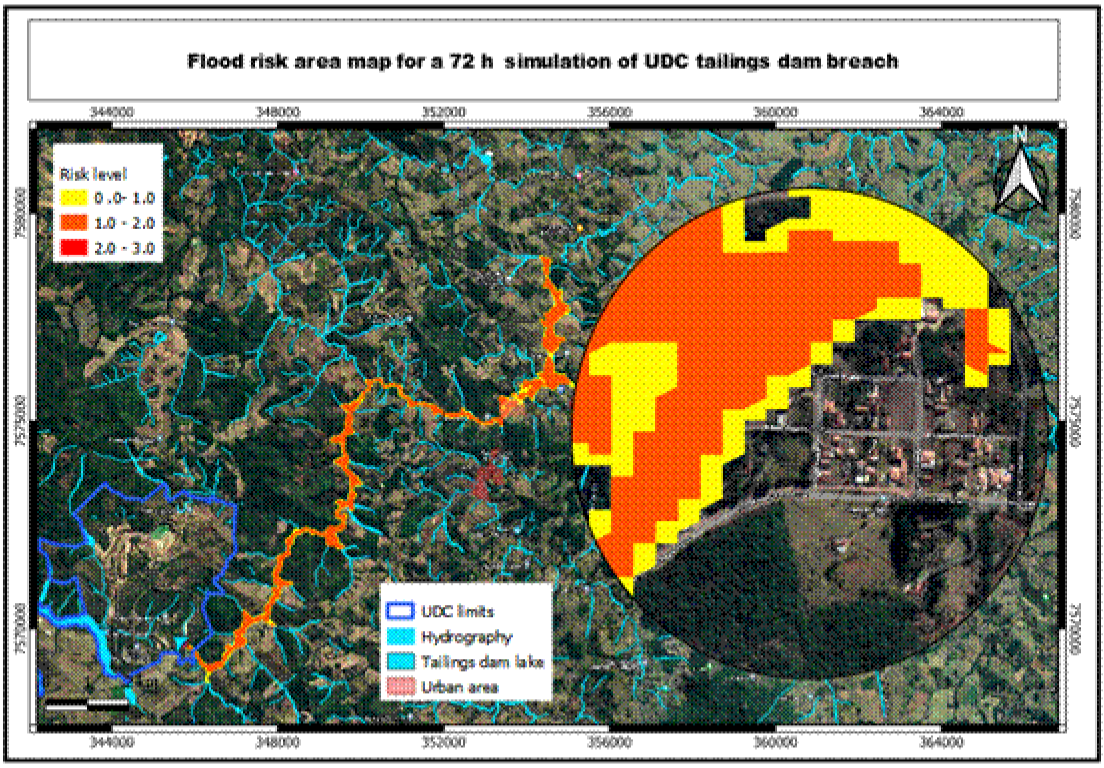


Table 5 presents a summary of the estimated doses by exposure pathway, for the two population groups considered in this work. The estimated total dose to the public was 38.7 mSv/y. Considering the region's original background, estimated at 5.75 mSv/y [34] the total dose would be around 44 mSv/y.

Table 5. Summary of estimated doses (mSv/y)

Exposure Pathway		**Worker**	**Resident**
External Dose from the Ground		14.9	32.8
	particulate inhalation	2.26	2.93
Internal Dose	soil intake	0.8	1.33
	milk intake	-	1.59
Total Dose from the accident		18.0	38.7

At the emergency phase, only intervention level for sheltering would be exceeded. However, considering the lack of a local structure adequate to protect the members of the public and the fact that the radionuclides in the mud are mostly long lived, evacuation/relocation would be a better option to protect people. These protective measures would probably already be indicated by the accident itself, regardless of radiological reasons. According to the current recommendations of the IAEA, nothing would need to be done, at least in terms radiological exposure at the emergency phase.

For the later stages of the accident, however, an analysis of the actual situation should be carried out, including the doses associated with radon inhalation and the return to other land uses and/or population habits. From the transition between emergency exposure and existing exposure, protection/remediation measures should be evaluated since the recommended reference levels for the other phases of the accident then is in the range 1 - 20 mSv.

The annual dose incurred by a member of the public is time dependent and mostly controlled by the rate at which radionuclides are leached from the contaminated zone, the rate of growth and decay of radionuclides, erosion rates and transport of contaminants through environmental pathways. Also, other exposure pathways may arise due to the long-term interaction between surface and underground water, concentration of sediments, spread of the contaminants to other areas, building new houses over dried mud, among others. It is then recommended that for later phases of the accident, models dealing with time dependent environmental transfers should be used to perform assessments.

4. CONCLUSION

This work aimed to estimate the radiation doses during an emergency situation arising from the hypothetical UDC uranium mining tailings dam breach, to support the management of the exposure of workers and residents in the region downstream of the dam. The computer code chosen to perform the dam breach simulation and the spread of mud in the surrounding environment was FLO-2D software.

The results from the simulations carried out, show that with the dam breach, there is a deposition of mud, characterized as radioactive material from the waste dam, with 19 km in length, occupying an area of 2,82 km^2.

The estimated total dose to the public, including local background, would be around 43 mSv/y. With these values, for the type of area affected and in the case of radionuclides with a long half-life, it would then be recommended to evacuate and relocate people from the affected areas. This protective measure would probably already be indicated by the accident itself, regardless of radiological reasons.

According to the current recommendations of the IAEA, nothing would need to be done, at least in terms of the emergency phase. For the later stages of the accident, however, an analysis of the actual situation should be carried out, as the recommended reference values for the other phases of the accident are on the range from 1 to 20 mSv.

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