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# Preliminary Evaluation of Possible Radiological Risks Arising from Floods in Rio Grande do Sul in 2024

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**Abstract**: In May 2024, extensive flooding impacted multiple cities in Rio Grande do Sul, Brazil, including the capital, Porto Alegre. This research evaluates the potential radiological and nuclear hazards resulting from these floods. 106 facilities that use radioactive materials in nearby regions were identified, of which 30 are located in the regions of interest, categorized based on IAEA risk standards. The flooding compromised containment and monitoring systems, heightening the risk of exposure to various hazardous materials, including radioactive substances. The floods affected high-risk sites in São Leopoldo and Canoas and moderate-risk sites in Porto Alegre and São Leopoldo. The study underscores the necessity of enhancing disaster preparedness and response systems to safeguard public health and the environment.

**Keywords:** flood, radiological risk, radiation safety, natural disasters, environmental contamination

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# Avaliação Preliminar dos Possíveis Riscos Radiológicos Decorrentes das Inundações no Rio Grande do Sul em 2024

**Resumo**: Em maio de 2024, severas inundações afetaram diversas cidades no estado do Rio Grande do Sul, Brasil, incluindo a capital, Porto Alegre. Este estudo avalia os possíveis riscos radiológicos e nucleares decorrentes dessas inundações. Foram identificadas 106 instalações que utilizam materiais radioativos em regiões próximas, das quais 30 estão localizadas nas regiões de interesse, classificadas de acordo com os padrões de risco da IAEA. As inundações comprometeram sistemas de contenção e monitoramento, aumentando o risco de exposição a materiais perigosos em geral, incluindo materiais radioativos e nucleares. Locais de alto risco em São Leopoldo e Canoas, e locais de risco moderado em Porto Alegre e São Leopoldo foram afetados pelas inundações. O estudo ressalta a necessidade de aprimorar os sistemas de segurança e resposta a desastres para proteger a saúde pública e o meio ambiente.

**Palavras-chave:** inundação, risco radiológico, segurança radiológica, desastres naturais, contaminação ambiental

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## 1. INTRODUCTION

In May 2024, the Brazilian state of Rio Grande do Sul experienced severe floods that significantly impacted several cities, including the capital, Porto Alegre. The Civil Defense of Rio Grande do Sul reported extensive material damage due to these floods [6]. According to *Agência Brasil*, over 78% of the municipalities in Rio Grande do Sul were affected by the heavy rains, leading to disruptions in public and private services, unprecedented devastation, and a significant portion of the population homeless [2]. This situation emphasizes the critical need for coordinated efforts to implement measures aimed at prevention, mitigation, and providing adequate local support for responding to disasters of this nature.

The floods have compromised containment systems and several monitoring points, potentially increasing the risk of accidental exposure to hazardous Chemical, Biological, Radiological, and Nuclear (CBRN) agents. This has left the population in the most severely affected areas without access to essential subsistence services. For instance, deactivating the Nova Santa Rita substation in the metropolitan region of Porto Alegre has compromised electricity transmission and heightened the risk of security system failures [3,6]. In addition to energy and water supply issues, food shortages and material losses threaten the population's livelihood. Floods can also severely impact health due to contamination by sewage and other decomposing organic materials in the water that have invaded inhabited dry areas. Stagnant water can also increase the risk of insect-borne diseases, such as dengue fever, after the waters recede [1]. Furthermore, the possibility of flooded areas containing radioactive materials exacerbates the crisis, posing significant environmental threats and contributing to radioactive contamination issues.

The study addresses potential contamination risks due to the spread of radionuclides. It's important to note that other radiological safety aspects also need consideration. For instance, the loss or theft of radioactive sources is a significant concern that should be a top priority when managing radioactive materials during crises.

This study is not intended to be definitive, nor does it intend to create protocols. The main objective was to survey the 30 facilities in the region of interest, located in Rio Grande do Sul that operate with radioactive material, verifying whether they were affected by the floods. Since the study was conducted conservatively (pessimistically), assuming that all facilities potentially located in flood-affected areas would be compromised, it was not verified whether the facilities identified in the region that operate with radioactive material, whether in industry, research, education, or health, were impacted by the floods. On the contrary, the condition was considered to be that all of them were affected by total loss. In addition, the aim was to analyze the degree of risk of contamination, provide a detailed address of these areas, and provide initial support to the agencies responsible for the decision-making process to safeguard the population.

## 2. LITERATURE REVIEW

Radiological and nuclear safety is a critical area that involves protection against the harmful effects of ionizing radiation. According to the IAEA (International Atomic Energy Agency) safety standards, categorizing radioactive sources is a fundamental procedure to clarify the risks associated with radiation sources [12]. Previous studies highlight that natural disasters can seriously compromise nuclear facilities, leading to possible releases of radioactive materials into the external environment [13]. A situation of release outside the facility, although not caused by a natural disaster, was faced by the Goiania radiological accident in 1987 in Goiás, Brazil [13]. Consequently, the National Nuclear Energy Commission (CNEN) created several standards to ensure control, traceability, and proper disposal of radioactive sources. These standards represent fundamental sources of information for carrying out this work.

In radiation protection and dosimetry, the activity of a radioactive source is a fundamental concept for assessing radiological risks. This measurement, which quantifies the rate of disintegration of unstable nuclei of radioactive materials per unit of time, is expressed in becquerel (Bq), representing one disintegration of the atomic nucleus per second. The old and considered classical unit is the curie (Ci), representing $3.7 \times 10^{10}$ Bq, or disintegrations per second. Understanding the phenomenon of activity and energy and the type of radiation emitted allows the implementation of effective control and protection strategies, such as appropriate shielding and the definition of restriction zones to minimize environmental radiological exposure. In natural disasters or accidents, adequate management of radiation sources is essential to ensure radiological safety and reduce the risk of contamination and exposure [16].

Regarding radiological and nuclear safety, a robust infrastructure has proven essential to minimize the risks associated with catastrophic events. Although they are distant in classification, it is critical to highlight the Fukushima accident that occurred in 2011 in Japan, where an earthquake followed by a tsunami resulted in one of the most severe nuclear accidents in history [12]. In Fukushima, despite the magnitude of the disaster, the robust structure of the nuclear power plant prevented an even greater catastrophe, demonstrating the importance of a resilient and well-prepared infrastructure to mitigate the risks associated with extreme events. To this end, the need for improved containment and monitoring systems to prevent the release of radioactive materials in the event of natural disasters compromising facilities was highlighted [12].

## 3. MATERIALS AND METHODS

The assessment of alleged impacts on facilities that operate with radioactive materials, regardless of their intended purpose, presupposes identifying the classes of radioactive materials used and, by extension, the risks of each facility according to the categorization established by the IAEA Safety Guide [11], which classifies the risks of radioactive sources and practices into five categories: very low, low, moderate, high and very high. The activity of each source was assessed based on D values, which indicate the amount of radioactive material that can cause harm to an individual, determined by the exposure time and the expected deterministic effects, whether fatal or not [9]. It is essential to highlight that D values are calculated based on realistic risk assessments and are not commonly accessible, although available in official IAEA publications [9]. Table 1 summarizes the categories, risk classification, descriptions, and examples.

**Table 1** - Risk classification, description, and examples [11].

| Category | Description | Examples |
|---|---|---|
| **1**<br>Very High | Extremely hazardous sources: These may cause permanent injury or be fatal within minutes | Radioisotope thermoelectric generators (RTGs), irradiators, teletherapy sources, and multi-beam sources (gamma knife) |
| **2**<br>High | Very hazardous sources: These may cause severe injury or be fatal with prolonged exposure | Industrial gamma radiography sources, high/medium dose rate brachytherapy sources |
| **3**<br>Moderate | Hazardous sources: This may cause injury if handled improperly | Fixed industrial meters with high activity sources, well drilling meters |
| **4**<br>Low | Low-risk sources: Unlikely to cause serious injury but require adequate control | Low-dose rate brachytherapy sources, bone densitometers, static eliminators |
| **5**<br>Very Low | Low-risk sources: Unlikely to cause injury | Low-dose rate brachytherapy ocular patches and electron capture devices |

The CNEN database was used as a research source to map and classify the facilities authorized to use radioactive sources in areas affected by the floods. The queries allowed filtering facilities by city, focusing on the regions affected by the floods. Thus, the facilities were categorized according to the types defined by CNEN, such as medical, industrial, and research, as described in Table 2. Although Table 2 presents a wide range of radionuclides associated with these applications, it does not necessarily reflect their confirmed presence in the region studied. The table includes radionuclides that may be present according to the type of facility, serving as a general and conservative reference for possible inventoried radioactive materials.

Based on this survey, a risk classification was carried out correlating the data reported in Table 1 with the guiding information in Table 2, thus generating a risk classification for each facility.

**Table 2** - Application areas, application types, and potential equipment [10].

| Application field | Type | Potential Radiation Sources |
|---|---|---|
| Medicine | Blood Irradiation<br><br>Nuclear Medicine | Blood irradiators (Cs-137),<br><br>Gamma cameras, PET detectors (Positron Emission Tomography) |
| | Radioimmunoassay | Analysis equipment with I-125 |
| | Radiotherapy | Linear accelerators, Co-60, Ir-192 |
| Industry | Irradiation by radiation-generating equipment | Particle accelerators |
| | Irradiation by source | Industrial irradiators with Co-60 |
| | Nuclear Gauges - Process Control | Fixed nuclear gauges with Cs-137 |
| | Nuclear Gauges - Portable Systems | Portable moisture gauges with Am-241/Be-9 |
| | Well logging | Logging equipment with Cs-137 |
| | Industrial radiography | Radiography equipment with Ir-192 |
| | Analytical techniques | XRF Analyzers (X-ray Fluorescence) with Fe-55 |
| | Industrial radioactive tracers | H-3, C-14 |
| | Source replacement | Various equipment containing sealed sources |
| Safety | Portable backscatter inspection devices | Backscatter X-ray devices |
| | Distribution of safety equipment | Inspection equipment without radioactive sources |
| | Body inspection | Body scanners with low radiation dose |
| | Baggage and container inspection | X-ray baggage scanners |
| | Maintenance of safety equipment | Maintenance equipment without radioactive sources |
| | Other safety equipment | Various may include metal detectors. |

**Table 2** - Application areas, application types, and potential equipment [10] (*Continuation*).

| Application field | Type | Potential Radiation Sources |
|---|---|---|
| Research | Research laboratory | Laboratories with various radioisotopes |
| Commerce | Source Storage | Storage containers for sealed sources |
| | Distribution of devices with unsealed incorporated sources | Medical and industrial equipment with unsealed sources |
| | Distribution of devices with sealed incorporated sources | Nuclear gauges, smoke detectors |
| | Distribution of radiation-generating equipment | Radiography equipment, accelerators |
| | Source distribution | Various, including Co-60, Cs-137 sources |
| | Radiopharmaceutical distributor | Distributors of Tc-99m pharmaceuticals |
| | Radioisotope production (Cyclotron) | Cyclotrons for F-18 production |
| | Radiopharmacy | Radiopharmacy equipment with Tc-99m |
| Services | Instrument calibration laboratory | Cs-137, Co-60 calibration sources |
| | Individual monitoring laboratory | Dosimetry monitors with various sources. |
| | Maintenance of emitting equipment | Maintenance equipment with radiation sources |

After identification and classification, each address was verified, and the geographic coordinates were obtained using Google Earth software, considering those registered in areas potentially affected by floods. This procedure ensured the precise location of the facilities in the region affected by the floods and in areas with little or no impact. This procedure allowed a more accurate risk assessment, identifying whether the areas most impacted by the floods would be at risk of accidental radiological exposure. In addition, it should be considered that, during the COVID-19 pandemic (2020-2023), new research centers or medical facilities were unlikely to be established in the region. Therefore, an assessment based on data from 2019 seems reasonable.

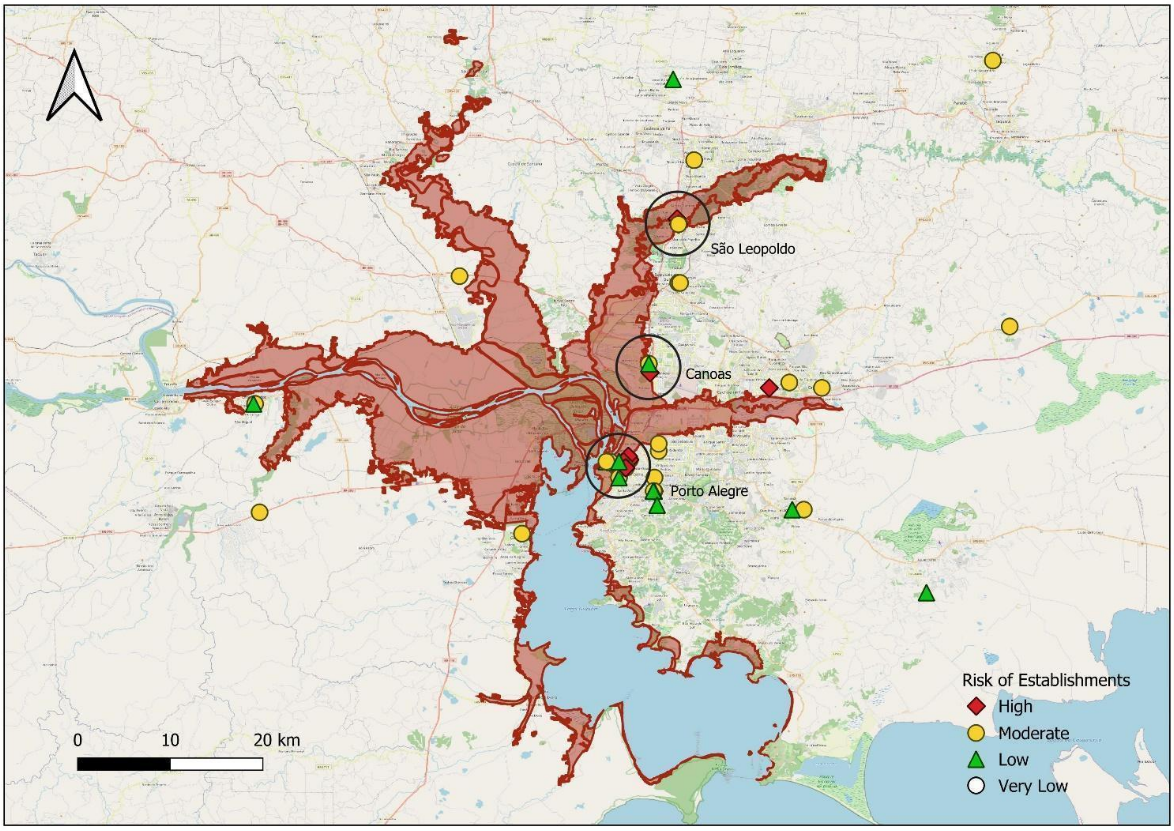
The hydrological data employed in this study were sourced from empirical research conducted at the Brazilian Hydraulic Research Institute (IPH), during investigations in June

2024. These data sets were meticulously compared against existing hydrological records to confirm the accuracy and appropriateness of the flood impact models applied to areas at risk. This comparative analysis ensures the reliability of the modeling approach in understanding and predicting flood impacts on vulnerable regions.

## 4. RESULTS

The risk classification and location of the facilities containing radioactive material were related to the flooded areas in the region, in studies carried out by the IPH of UFRGS and highlighted in Figure 1. The regions were mapped using QGIS software, a widely used open-source tool for geospatial analysis, based on the location data of potentially affected facilities. This demonstrates the impact of flooding in the regions that would be at risk of releasing radioactive material [14].

**Figure 1**: Mapping of facilities licensed to use radioactive materials.



According to the IAEA risk classification, several facilities have categories 1 and 2 sources, considered high risk due to their potential to cause serious harm to health, as classified in Table 2. Only one of these sources is sealed. Table 3 shows the type of application and the risk classification of each one.

**Table 3** - Types of nuclear application and risk classification in Porto Alegre, São Leopoldo, and Canoas.

| Application type | Porto Alegre (POA) | São Leopoldo (SLPO) | Canoas (CO) | Classification |
|---|---|---|---|---|
| Nuclear Medicine | 12 | 1 | 1 | 2 High Risk (POA), 6 Moderate Risk (POA), and 4 Low Risk (POA)<br>2 High Risk (CO, SLPO) |
| Blood Irradiators | 1 | - | - | 1 High Risk |
| Radiotherapy | 6 | 1 | - | 7 Low Risk |
| Source Distribution | 1 | - | - | 1 Low Risk |
| Industrial Radiography | - | 2 | 1 | 3 Moderate Risk |
| Cyclotron | 1 | - | - | 1 High Risk |
| Individual Monitoring Laboratory | 1 | - | - | 1 High Risk |
| Nuclear Gauges | - | - | 2 | 2 Low Risk |

*It is possible to come across cases of duplicate classification by the regulatory authority because the installation serves multiple purposes. In these situations, only the sources linked to the highest level of risk were considered.

It was observed that the application of radionuclides in nuclear medicine and research laboratories occurs in institutions authorized and certified by the CNEN in Canoas, São Leopoldo, and Porto Alegre. The radionuclides identified by the bibliographic research were: F-18, Ga-68, Ga-67, I-123, I-131, Lu-177, Ra-223, Sm-153, Tc-99m, Tl-201, Y-90, Cr-51, Zr-89, In-111, C-11, C-14, Ca-45, Cs-137, H-3, I-125, S-35 and P-32 [5].

Figure 1 shows that based on the flood coverage map in Rio Grande do Sul (RS), seven high-risk locations were affected by the floodwaters: one in São Leopoldo, one in Canoas, and five in Porto Alegre, while nine locations hosting facilities with moderate-risk material were affected: five in Porto Alegre, two in São Leopoldo and two in Canoas. Given that among the locations affected by the floods, the cities of Porto Alegre, Canoas, and São Leopoldo operate radioactive material of the highest risk, a more detailed assessment was carried out, and the data are presented in Figures 2 and 3.

Figure 2 shows the most active radioisotopes and their quantities, operated by nuclear medicine facilities registered by CNEN in Canoas and São Leopoldo. Figure 3 presents two graphs with information from Porto Alegre. Both show the radioisotopes in nuclear medicine facilities (Figure 3A) and research laboratories (Figure 3B) [5]. The unit of measurement used for intercomparisons is the millicurie (mCi), $10^{-3}$ Ci.

**Figure 2**: Radioisotopes with the highest activity in nuclear medicine facilities in (A) São Leopoldo and (B) Canoas.

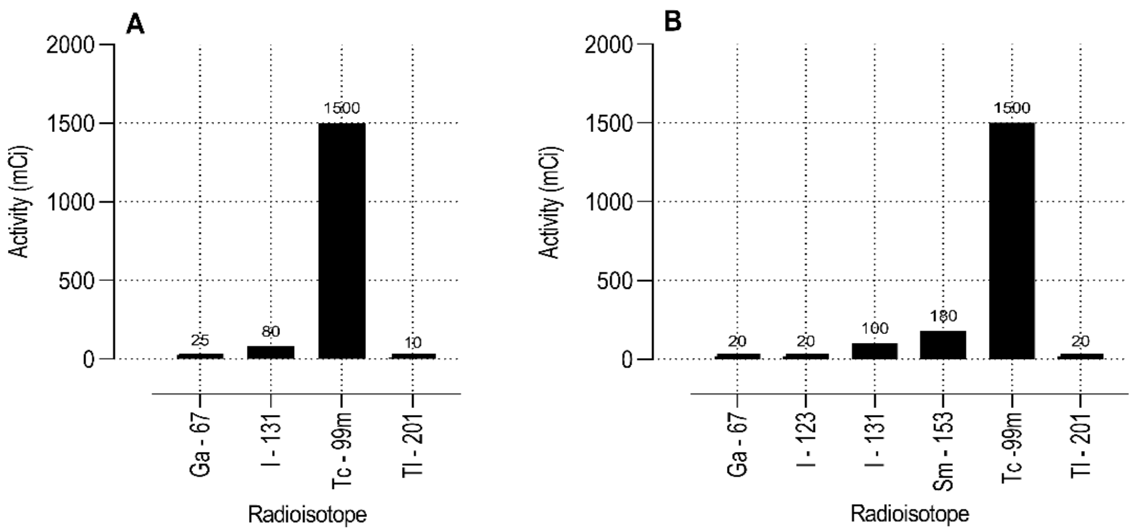
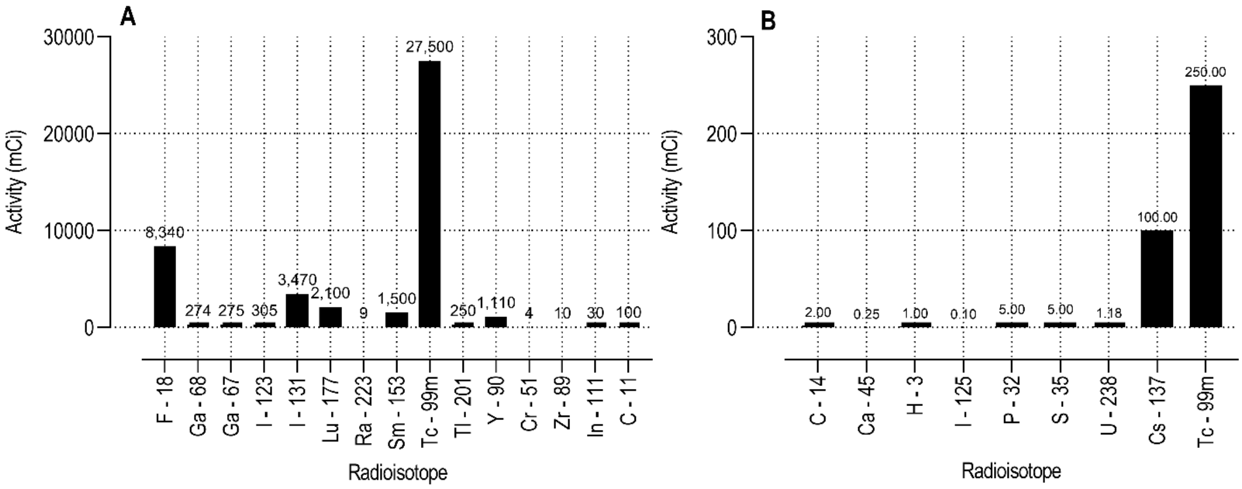


**Figure 3**: Highly active radioisotopes in nuclear medicine facilities (A) and research laboratories (B) in Porto Alegre.




## 5. DISCUSSION

The three cities that could have the highest risk of accidental exposure to radioactive material due to having been affected by the floods operate mainly with the element Tc-99m, as shown in Figures 2 and 3A, B. Because this radioisotope is widely used in scintigraphy procedures, a comparison was made between the maximum amount of radioactive material stored and the amount used in scintigraphy procedures using as a parameter the typical amount of activity of 4 mCi for glucose fluoride F-18 (18F-FDG), and 20 mCi for all others listed in Table 4 [4].

Table 4 compares the maximum radioisotopes found in affected areas with such facilities to the amount of radioactive material used in scintigraphy procedures. Values are given in mCi to facilitate direct comparison. This comparison seeks to clarify the differences in quantity between radioactive materials present and those used in medical procedures. It's important to note that some radioisotopes may not be commonly used in scintigraphic applications.

**Table 4** - Hypothetical comparison between the Maximum Amount of Radioactive Material Found in Flooded Areas and Scintigraphy Procedures.

| Radioisotope | Maximum Quantity (mCi) | Quantity in Scintigraphy Procedure (mCi) | Comparison in relation to scintigraphy |
|---|---|---|---|
| Tc-99m | 4000 | 20 | 200X ↑ |
| F-18 | 3200 | | 160X ↑ |
| I-131 | 1000 | | 50X ↑ |
| Sm-153 | 500 | | 25X ↑ |
| Ga-67 | 10 | | 0.5X ↓ |
| Cs-137 | 100 | | 5X ↓ |
| C-14 | 500 | | 25X ↑ |
| U-238 | 1.18 | | 0.06X ↓ |

The analysis reveals that some radioisotopes, such as Technetium (Tc-99m) and Glucose Fluoride (F-18), have higher amounts when compared to the dose used in scintigraphy procedures, that is, exposure to large quantities of some of these materials can be equivalent to 200 scintigraphy sessions. First, it is necessary to consider that, although such values seem high, they do not represent any risk, considering that radioisotopes used in scintigraphy procedures have a half-life of around a few hours, such as Tc-99m, which has a half-life of around 6 hours and is classified as a low-risk radioisotope, according to the IAEA classification.

The risk assessment, therefore, must take into account the classification of the element since other radioisotopes, such as Cs-137, although present in much smaller quantities, pose a greater risk since it is classified as high risk and is a high-intensity source with a long half-life (≈ 30 years). This comparison was adopted to explain the potential threat associated with the different radioisotopes found, considering that radionuclides have different decay behaviors and radiological characteristics. Thus, the comparison helps understand the context and scale of potential risks but does not imply that the radionuclides mentioned in the analyses, such as Cs-137 and U-238, are used in scintigraphy procedures.

Nuclear medicine facilities, for example, that have blood irradiators because they operate with Cs-137 as a radioactive source pose a high risk in the event of accidental release/exposure. The probability of photon production by decay of the Cs-137 source is 85.1% [10], and its decay product is gamma and beta radiation. Cs-137 sources were used in radiotherapy equipment (teletherapy), and currently, after gradual replacement over the years by linear accelerators (LINACs), they are no longer used for this purpose in Brazil. The only location that meets the conditions above and could pose some risk due to having been hit by the floods is Porto Alegre, with the caveat that this facility is not a nuclear medicine facility but a research laboratory, as seen in Figure 3B.

Suppose this or any other radioactive material is released due to flooding. In that case, the high volume of water will cause significant dilution, minimizing the impacts without causing immediate radiological damage to the population and the environment. An approximation of the dilution of the material can be made from the volume of water in Lake Guaíba, which was estimated at 30 billion cubic meters ($3.0 \times 10^{10}$ $m^3$), approximately (30 trillion liters) [7]. The dilution of any radioactive material in this volume results in low concentrations, even for those that pose the most significant risks. As reference values, the IAEA recommends tolerance levels for radionuclides in drinking water for some radioactive elements, as detailed in Table 5 [8].

**Table 5** - Tolerance levels for radionuclide concentrations in drinking water.

| Radionuclide | Tolerance concentration (Bq/L) |
|---|---|
| $^{3}H$ | $10^{3}$ |
| $^{14}C$ | $10^{2}$ |
| $^{90}Sr$, $^{131}I$, $^{134}Cs$, $^{137}Cs$, $^{238}U$ | $10^{1}$ |
| $^{226}Ra$,$^{228}Th$, $^{230}Th$, $^{232}Th$, $^{234}U$, $^{239}Pu$, $^{241}Am$ | $10^{0}$ |
| $^{210}Pb$, $^{210}Po$, $^{228}Ra$ | $10^{-1}$ |

These tolerance levels were assumed according to a conservative (pessimistic) approach and can be applied to both elements found in nature and artificial ones [8]. Comparing the elements presented in Table 5 with those found in the survey of facilities that could be subject to the risk of releasing radioactive material, Cs-137 is present in both. It has a tolerance of up to 10 Bq/L. The maximum amount of Cs-137 found, according to Table 4, is 100 mCi ($3.7x10^{9}$ Bq), and the volume of the Guaíba River is $30x10^{12}$ L; therefore, this element would be present at a concentration of $0.12x10^{-3}$ Bq/L, that is, around 10,000 times lower than the tolerated level, which reduces the risk to the population or the environment to negligible levels. The same assessment can be made with Tc-99m, found at a maximum of 4 Ci ($1.48x10^{11}$ Bq). Although Table 5 does not provide specific information for Tc-99m, it is possible to establish a comparison with I-131 since, according to the literature, they are radionuclides with similar applications and properties [15].

Considering this similarity, it was assumed that the recommended concentration level for Tc-99m in drinking water would be 10 Bq/L, the same reference value for I-131. Thus, considering the maximum amount of the element found, its concentration would be $5x10^{-3}$ Bq/L, approximately 2,000 times lower than the tolerance level proposed by the IAEA. In addition, Tc-99m has a half-life of approximately 6 hours [16], and thus, in 24 hours, its activity would have reached 1/16, leading to a significant reduction in its concentration.

Therefore, dilution results in concentrations that can also be neglected, although it is crucial to continue monitoring water quality and the presence of radioactive material. The presence of low levels of radioactivity resulting from dilution does not exclude the need for continuous precautions and constant evaluation, mainly to ensure that no significant environmental impacts occur.

Thus, this study showed that in a hypothetical situation where some radioactive material was released into the environment, especially those with higher risk and in more significant quantities, in the regions affected by floods in RS, such events pose reduced risks to the local population and the environment, either because they are low risk and have a short half-life or because they are diluted in large volumes of water, even those classified as high risk. However, it is necessary to consider that in the event of a leak, decision-making measures must be directed to the immediate notification of the competent authorities of the CNEN to coordinate safety responses to events of this magnitude. This includes protecting the population and containing the affected average perimeter. After containment, it is necessary to decontaminate the site and neutralize the radioactive material if possible. It is essential to conduct continuous monitoring to assess radiation levels, the extent of contamination and potential associated risks, and the necessary updating of inventories of radioactive and nuclear facilities. Furthermore, low-intensity radiation can be mistaken for background radiation, resulting in overlooked areas due to incompetence and possible internal contamination.

The study proposes that subsequent investigations be carried out in collaboration with CNEN to develop protocols to prevent or mitigate the risks associated with areas susceptible to flooding, as described in this study. Each risk classification can adopt safety measures appropriate to the identified risk level. Examples of safety measures that could be implemented include positioning fountains on higher floors, according to the risk classification; creating physical barriers to prevent floodwaters from entering establishments, using hermetic gates; installing alarms and sensors to signal rising water levels; developing evacuation procedures and safeguarding fountains according to pre-established alert levels. The survey and study of these areas susceptible to flooding can be carried out in collaboration with Civil Defense so that the protocols developed are applied effectively.

## 6. CONCLUSION

This study highlighted the importance of immediate disaster response measures, including notification of authorities, isolation of affected areas, if possible, decontamination, and transparent communication to the population. It is highly relevant to continually review and improve radiological and nuclear safety protocols, investing in robust infrastructure and specialized training to mitigate future risks. The assessment revealed that, although exposure to radioisotopes would not cause harm to the health of the population or the environment, flooding can compromise facilities operating radioactive materials and monitoring systems, increasing the risk of accidental exposure. Finally, improving safety and disaster response systems is necessary to protect public health and the environment, preventing future incidents and ensuring an effective response to adverse events.

## CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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