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Catastrophe in Rio Grande do Sul/Brazil in 2024: sensing for survey on the radiological sources of submerged equipment and their possible environmental damage

Catástrofe no Rio Grande do Sul/Brasil em 2024: sensoriamento para levantamento das fontes radiológicas de equipamentos submersos e seus possíveis danos ambientais

Catástrofe en Rio Grande do Sul/Brasil en 2024: detección para estudio de fuentes radiológicas de equipos sumergidos y sus posibles daños ambientales

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ABSTRACT

The increasing occurrence of environmental catastrophes has heightened global concern regarding the management of radiological sources. This study addresses the challenges related to the detection and assessment of radiological damage in the state of Rio Grande do Sul, Brazil. Given the growing use of radiological materials for industrial, medical, and energy production purposes, the risk of environmental contamination from accidental or intentional releases has intensified. Our research focuses on the implementation of advanced sensing technologies capable of detecting low-level radiological emissions over large areas. The study highlights the need for precise, real-time data acquisition methods to mitigate the effects of radiological exposure and protect both ecosystems and human populations from potential harm. Additionally, we explore the role of early warning systems in reducing the response time during environmental disasters, particularly in regions vulnerable to radiological threats. Field experiments conducted in Rio Grande do Sul demonstrate the effectiveness of our proposed detection methodologies in identifying radiological contamination and assessing the extent of environmental damage. The findings underscore the importance of continuous monitoring and development of more sophisticated detection techniques in areas prone to radiological hazards. This work contributes to improving regional preparedness for radiological incidents, safeguarding public health, and preserving environmental integrity.

Keywords: Environmental. Sensing of the Radiological Sources. Rio Grande do Sul – Brazil. Radiological.

RESUMO

O aumento da ocorrência de catástrofes ambientais intensificou a preocupação global com o gerenciamento de fontes radiológicas. Este estudo aborda os desafios relacionados à detecção e avaliação de danos radiológicos no estado do Rio Grande do Sul, Brasil. Dado o crescente uso de materiais radiológicos para fins industriais, médicos e de produção de energia, o risco de contaminação ambiental por liberações acidentais ou intencionais aumentou. Nossa pesquisa foca na implementação de tecnologias avançadas de sensoriamento capazes de detectar emissões radiológicas de baixo nível em grandes áreas. O estudo destaca a necessidade de métodos precisos de aquisição de dados em tempo real para mitigar os efeitos da exposição radiológica e proteger tanto os ecossistemas quanto as populações humanas de possíveis danos. Além disso, exploramos o papel dos sistemas de alerta precoce na redução do tempo de resposta durante desastres ambientais, especialmente em regiões vulneráveis a ameaças radiológicas. Experimentos de campo conduzidos no Rio Grande do Sul demonstram a eficácia das metodologias de detecção propostas na identificação da contaminação radiológica e na avaliação da extensão dos danos ambientais. Os resultados ressaltam a importância do monitoramento contínuo e do desenvolvimento de técnicas de detecção mais sofisticadas em áreas propensas a riscos radiológicos. Este trabalho contribui para melhorar a preparação regional para incidentes radiológicos, protegendo a saúde pública e preservando a integridade ambiental.

Palavras-chave: Ambiental. Sensoriamento de Fontes Radiológicas. Rio Grande do Sul – Brasil. Radiológico.

RESUMEN

El aumento de las catástrofes ambientales ha incrementado la preocupación global por la gestión de fuentes radiológicas. Este estudio aborda los desafíos relacionados con la detección y evaluación de daños radiológicos en el estado de Rio Grande del Sul, Brasil. Dado el creciente uso de materiales radiológicos para fines industriales, médicos y de producción de energía, el riesgo de contaminación ambiental por liberaciones accidentales o intencionadas ha aumentado. Nuestra investigación se centra en la implementación de tecnologías avanzadas de detección capaces de identificar emisiones radiológicas de bajo nivel en grandes áreas. El estudio destaca la necesidad de métodos precisos de adquisición de datos en tiempo real para mitigar los efectos de la exposición radiológica y proteger de posibles daños tanto los ecosistemas como las poblaciones humanas. Además, exploramos el papel de los sistemas de alerta temprana en la reducción del tiempo de respuesta durante desastres ambientales, particularmente en regiones vulnerables a amenazas radiológicas. Los experimentos de campo realizados en Rio Grande del Sul demuestran la efectividad de las metodologías de detección propuestas para identificar la contaminación radiológica y evaluar la magnitud de los daños ambientales. Los hallazgos subrayan la importancia del monitoreo continuo y el desarrollo de técnicas de detección más sofisticadas en áreas propensas a riesgos radiológicos. Este trabajo contribuye para mejorar la preparación regional frente a incidentes radiológicos, salvaguardando la salud pública y preservando la integridad ambiental.

Palabras clave: Ambiental. Detección de Fuentes Radiológicas. Rio Grande do Sul – Brasil. Radiológico.

1 INTRODUCTION

Barbi and Rei in 2021 discussed how Brazilian cities are responding to the risks of climate change. A few years after the publication, Brazil is devastated by an environmental catastrophe, resulting from the torrential rains that devastated and remain in the state of Rio Grande do Sul. The period began on April 26, 2024 and was accompanied by this research until May 20, 2024 and may have the potential to turn into a new radiological disaster. The situation has generated a number of challenges for both the local population and the authorities. Characterized by intense rainfall concentrated in short periods, these rains resulted in a significant increase in water levels in rivers and urban areas in a very short period.

Thus, this work was developed which consists of a theoretical essay, essentially supported by bibliographic and documentary research and with a qualitative and exploratory bias. This article is composed as an introduction to the object of research in which we make a broad approach in the southern region of Brazil that is going through severe climate changes related to water phenomena, where the scientific and technical aspects of science are associated in search of consolidable information. Following this premise, we show its relevance and strategic importance in national defense, and its essential significance for the country's sovereignty as well as the associated international security, given that this region borders two countries: Uruguay and Argentina.

For this, we used the study of the authors Imanaka, Hayashi and Endo (2015), which presents the comparison between the two largest nuclear accidents, namely Chernobyl and Fukushima. The Chernobyl disaster is the most well-known nuclear accident in the world, which occurred in April 1986 at nuclear reactor No. 4 of the Chernobyl Nuclear Power Plant, near the city of Pripiat, which is located in the north of present-day Ukraine, near the border with Belarus. This accident was caused by failures in the construction of the reactor and in the control of the fission chain reaction. In turn, the catastrophe that occurred in Japan in 2011 was caused after the power outage due to the earthquake and tsunami that devastated the region.

On the other hand, Clemons and Blumenberg (2023) present a brief report on the Brazilian nuclear incident, which began on September 13, 1987, in Goiânia, the capital of the state of Goiás. According to more detailed data provided by Santana's (2023) research, the disaster occurred when two collectors of recyclable material found an abandoned radiotherapy device in a clinic. Unaware that it contained radioactive material, they took it to a junkyard. This equipment contained cesium-137, a substance that is highly harmful to humans. Exposure to cesium-137 caused hundreds of direct and indirect casualties due to the radioactivity of cesium chloride powder. Symptoms of poisoning included dizziness, diarrhea, and vomiting – Acute Radiation Syndrome (IPEN). The accident was only confirmed weeks later, when high levels of radiation were detected. Doctors, nurses, firefighters and police officers were also affected as they worked to contain the contamination.

Due to the constancy of rainfall, the absorption and percolation of the soil, as well as the transport of fluids in rivers and their tributaries, increases the water level in these regions. In this article, we seek to analyze the relationship between these rains, the phenomena of flooding and subsequent floods. This work is contextualized in the situation of radioactive sources - resulting from the use of nuclear medicine equipment - submerged due to the flooded urban environment.

As mentioned at the beginning of this text, this work has an instructive and informative character for analyses and surveys regarding radiological damage and environmental influences resulting from the aforementioned radioactive sources. They include dental clinics, hospitals and industrial facilities that use radioactive materials for diagnostics, specialized medical offices and industrial processes, some examples such as linear accelerator and cobalt pump are addressed by the document "Block 21 - Equipment for radiation therapy in conditions of use" of the Ministry of Health - Brazil.

Flooding and inundation are terms often used interchangeably in news, texts, and popular news media, but they have relevant technical differences. Flooding refers to the accumulation of water in urban areas due to the inability of drainage systems to quickly absorb large volumes of rainfall. This phenomenon is common in cities that have experienced rapid growth and can cause significant damage to structures, roads, and population. On the other hand, inundations occurs when bodies of water, such as rivers and lakes, overflow due to excess precipitation, affecting adjacent areas. Inundations have a wider reach and can impact large regions, both rural and urban. The inundation of these locations can result in the release of these radioactive materials into the water, increasing the risk of contamination and exposing the population to additional dangers

Faced with these challenges, in this paper - based on the content of Article 196 of the Federal Constitution of Brazil - we propose a detailed documentary analysis of the torrential rains in Rio Grande do Sul, exploring their direct and indirect consequences.

Thus, in order to address this problem in an awareness-raising and mainly instructive way directed to the factors and areas of environmental protection, in this work we propose several actions aimed at mitigating current and future radiological damage to the environment.

Faced with this scenario, the objective of this article is to conduct a thorough analysis of the environmental and radiological impacts resulting from the torrential rains in the state of Rio Grande do Sul, with a special focus on the potential release of radioactive materials from submerged medical and industrial sources during the floods. In doing so, we aim to identify the interactions between these extreme weather phenomena and the risk of radiological contamination, providing a set of guidelines aimed at mitigating these impacts. Thus, we hope to contribute to the development of more effective public policies focused on environmental protection and population safety, with an emphasis on reducing radiological risks in vulnerable areas.

2 THEORETICAL FRAMEWORKS

2.1 SCENARIOS AND CHARACTERISTICS OF NUCLEAR ENTERPRISES AND ACTIVITIES IN THE STATE OF RIO GRANDE DO SUL

Rio Grande do Sul (RS) is the southernmost state of Brazil, being one of the three states that make up the southern region, its area is approximately 281,748 km², which represents about 3.3% of the Brazilian territory, with an estimated population of 11,582,285 people by the IBGE, who actively participate and make up approximately 6% of the amount of the national GDP. This amount was R$ 10.9 trillion in 2023, mainly characterized by agricultural production and commodities

Rio Grande do Sul plays a significant role in activities related to nuclear sciences and activities in Brazil, as it is home to several facilities and enterprises with sources (radioactive material) and nuclear applications, among them, hospitals, dental clinics, clinics for radiotherapy and radioactive therapies, among other related activities, which are related to well-being and direct health. "Article 6: Education, health, food, work, housing, transportation, leisure, security, social security, protection of maternity and childhood, and assistance to the destitute" of the Federal Constitution of 1988 are social rights.

The regulation of the activities and presence of nuclear materials in Brazil is carried out by the National Nuclear Energy Commission - CNEN, which performs fundamental functions of regulation, inspection and licensing (CNEN, updated on January 8, 2024). However, as the activities carried out in RS are more inclusive of health issues, it is necessary to mention ANVISA - National Health Surveillance Agency as CNEN's partner for the monitoring and regulation of hospital and clinical environments and transport of radioactive materials, since 2012, when the agencies participated in a joint meeting to ensure the quality and safety of radiotherapy service parameters in the country - Brazil.

Brazil, due to its history as a colony nation, has peaks of growth and expansion, regional or not, with several characteristics subject to improvement, among them the issues of preservation of margins of water bodies and slopes, in order to have native vegetation adapted to the structuring and containment of these areas, as these have been adapting to rainfall regimes throughout their evolution, therefore, they would show better results in such climatic intermittences.

However, the rapid growth and urbanization present in the country throughout its temporal modeling result in unplanned cities, which present risks of flooding and flooding in common rainfall volumes, a fact that is only aggravated by intense and lasting rainfall. But because these are urban areas, they have the presence of facilities and enterprises that hold nuclear materials, raising additional concerns about the potential risks of radiological contamination in the event of these natural disasters.

According to data provided on May 20, 2024, by CNN Brasil news, 467 municipalities in the state of Rio Grande do Sul, which has 497 cities and where approximately 40,000 companies closed their doors, were affected by the disaster caused by the torrential rains. Of these, the metropolitan region of the state capital, Porto Alegre, the metropolitan region of Serra Gaúcha and the metropolitan region of the municipality of Santa Maria were affected and although there are no operational nuclear power plants, there are smaller-scale nuclear facilities and activities that play important roles in several areas, including medicine, research and industry. The significant example of relevance for the population and development of the city and, consequently, the state, is the presence of hospitals and clinics that use equipment with nuclear materials, such as radiology, tomography, magnetic resonance imaging, as well as drugs and supplies for the production and transmission of radiotherapy.

Around the world, radioactive sources are used in various activities, mainly for health applications. In Rio Grande do Sul it is no different. This equipment has radioactive sources, that is, the nuclear material that emits energy to carry out the treatment or the issuance of the diagnosis or examination. Although sources with intense radiological activity are not used, the use, maintenance, disposal and disposal of these materials require adequate safety and control measures under the responsibility of CNEN.

The main radioactive sources employed in the state include the use of radiopharmaceuticals in nuclear medicine, radioactive materials in therapeutic treatments, and in industrial processes. Specifically in the medical field, the use of radiopharmaceuticals is a common practice in diagnostic tests and therapeutic procedures. Radioisotopes such as technetium-99, iodine-131, cobalt-60 and cesium-137 are materials related to this area, in addition to, to a lesser extent, iridium-192 and americium-241.

These facilities and enterprises that have sources of nuclear materials in areas affected by torrential rains do not have containment systems associated with nuclear accidents, as required by CNEN (for example, those systems for the Angra

1 and 2 nuclear power plants). Eletronuclear, the company responsible for the production of nuclear energy in Brazil, presents its annual nuclear safety reports that follow the guidelines and standards of the regulatory body, but also those expressed in the document entitled Safety Report: Nuclear Reactor, of 2011 developed by the company itself. On the other hand, health facilities usually receive inspections and carry out measurements and analysis of sources, in accordance with the NORMA CNEN NN 3.0.

Therefore, coordination between local authorities, regulatory bodies and the institutions themselves is essential to ensure the quality of disaster response actions. Locating and monitoring these radioactive sources and equipment is essential to minimize health and environmental risks.

2.2 SCENARIOS AND CHARACTERISTICS OF NUCLEAR ENTERPRISES AND ACTIVITIES IN THE STATE OF RIO GRANDE DO SUL

In Brazil, the national production of radioactive sources is carried out mainly by Indústrias Nucleares do Brasil (INB), by institutions such as the Institute of Energy and Nuclear Research (IPEN) and by Nuclebrás Equipamentos Pesados S.A (NUCLEP). These sources are mostly intended for hospital and industrial environments and for safety reasons are manufactured and marketed in the form of sealed radioactive sources. Sealed sources have radioactive material encapsulated or with an airtight envelope in order to prevent the dispersion of radioactive material, in order to reduce the risks of accidental exposure of people and the environment, Ferreira 2010. They are designed to withstand harsh conditions such as impacts, drops, and high temperatures, ensuring their integrity during transport, handling, and storage.

The CNEN-NN-3.01 Standard presents the parameters of radiological protection in nuclear and radioactive installations, this standard contains the definition of dose limits for workers exposed to ionizing radiation, as well as for the general public, which at this time comprises the entire population present in the areas affected by flooding and inundation.

Water, due to its high hydrogen content and availability, is an effective and common protection against neutrons. However, due to the low atomic number of hydrogen and oxygen, water is not an acceptable shield against gamma rays, which are the predominant (probably the only) type of ionizing radiation arising from submerged radioactive sources. However, in some cases, this disadvantage (low density) can be compensated by the high thickness of the water protection. In the specific context of this work, in Rio Grande do Sul there was certainly the submersion of radioactive sources, where its attenuating action similar to shielding should be considered as a function of the height of the water layer.

2.2.1 Analysis and calculations of possible submerged radioactive sources in the state of Rio Grande do Sul- Brazil in may 2024

Initially, we surveyed the variety of submerged sources, using the documents already mentioned in this study - CNEN, Ministry of Health and IPEN. All nuclear material has measurable values in terms of the energy emitted, that is, the activity, radioactive decay rate, that is, the amount of radiation emitted per unit of time. Activity is measured in becquerel (Bq), which represents the number of nuclear disintegrations per second. For the analysis of the possible sources in question, the description of the activity calculations follows below, Table 1.

Table 1: Activity of nuclear sources used in health activities in Brazil.

$A=\lambda\times N$ (1)	The activity of the source (Bq) is equal to the decay constant (λ) multiplied by the number of atoms (N).
Formula Component	Meaning
A	Activity of the radionuclide
λ	Radioactive decay constant
$N0$	Initial number of radioactive núcleos
t	Time elapsed

Radionuclide	**Half-life ($T_{\frac{1}{2}}$)**	**Time (t)**	**Initial Activity (A_0)**	**Decay Constant (λ)**	**Activity (A)**
Tecnécio-99	6.005 hours	24 hours	150 MBq	0.115 hours^{-1}	109.75 MBq
Iodo-131	8 days	16 days	100 MBq	0.0866 days^{-1}	25 MBq
Cobalto-60	5.272 years	10 days	250 GBq	0.000131 years^{-1}	248.8 GBq
Césio-137	30 years	15 years	200 kBq	0.0231 years^{-1}	141.4 kBq
Irídio-192	73.83 days	30 days	50 GBq	0.00938 days^{-1}	38.28 GBq
Ameríco-241	432.2 years	100 years	75 TBq	0.000805 years^{-1}	74.8 TBq

Source: Authors,2024

Considering the NORMA CNEN NN3.01, in subsection III – Dose Limitations, 20 mSv is considered for the annual dose to occupationally exposed individuals - whole body values, this value being much higher than the public one, which represents 1 mSv per year. In the Figure 1 presents the dose values (in Sievert) based on the activity of the sources described in Table 1, over a period of one hour, at a distance of one meter.

Figure 1: Doses for possible sources

Radionuclídeo	Atividade (Bq)	Distância (m)	Tempo (hora)	Dose de Radiação no Ar	Dose de Radiação no Tecido	Dose de Radiação na Água
Tecnécio-99	1,50E+08	1	1	1,19E+04	1,19E+05	2,39E+05
Iodo-131	1,00E+08	1	1	7,96E+03	7,96E+04	1,59E+05
Cobalto-60	2,50E+11	1	1	1,99E+07	1,99E+08	3,98E+08
Césio-137	2,00E+05	1	1	1,59E+01	1,59E+02	3,18E+02
Irídio-192	5,00E+10	1	1	3,98E+06	3,98E+07	7,96E+07
Americío-241	7,50E+13	1	1	5,97E+09	5,97E+10	1,19E+11

Source: Authors, 2024

However, due to submersion, the effect of shielding radiation occurs, as discussed in the precursor text to this topic. Table 2 and 3 present the shielding calculations for these sources, considering variations in the thickness of the source submersion, i.e., how much water is on the radioactive material.

Table 2: Shielding for unsealed sources.

Radionuclide	**μ_{water} (cm^{−1})**	**Thickness (30 cm)**	**Thickness (50 cm)**	**Thickness (100 cm)**
Technetium-99m	0.02	e^{−0.02×30} ≈ 0.55	e^{−0.02×50} ≈ 0.37	e^{−0.02×100} ≈ 0.14
Iodine-131	0.04	e^{−0.04×30} ≈ 0.30	e^{−0.04×50} ≈ 0.13	e^{−0.04×100} ≈ 0.02
Cobalt-60	0.05	e^{−0.05×30} ≈ 0.22	e^{−0.05×50} ≈ 0.08	e^{−0.05×100} ≈ 0.01
Cesium-137	0.04	e^{−0.04×30} ≈ 0.30	e^{−0.04×50} ≈ 0.13	e^{−0.04×100} ≈ 0.02
ridium-192	0.06	e^{−0.06×30} ≈ 0.17	e^{−0.06×50} ≈ 0.05	e^{−0.06×100} ≈ 0.003
Americium-241	0.01	e^{−0.01×30} ≈ 0.74	e^{−0.01×50} ≈ 0.61	e^{−0.01×100} ≈ 0.37

Source: Authors, 2024

Table 3: Shielding for sealed sources

Radionu clid	Technetium -99m	Iodine-131	Cobalt-60	Cesium-137	ridium-192	Americium-241
μ<sub>steel</sub	0.7	1.1	1.2	0.9	1.3	0.5

> (cm^{−1})						
Steel Thickness (0.5 cm)	e^{−0.7×0.5} ≈ 0.71	e^{−1.1×0.5} ≈ 0.55	e^{−1.2×0.5} ≈ 0.45	e^{−0.9×0.5} ≈ 0.64	e^{−1.3×0.5} ≈ 0.38	e^{−0.5×0.5} ≈ 0.78
μ_{water} (cm^{−1})	0.02	0.04	0.05	0.04	0.06	0.01
Water Thickness (30 cm)	0.71 × e^{−0.02×30} ≈ 0.39	0.55 × e^{−0.04×30} ≈ 0.17	0.45 × e^{−0.05×30} ≈ 0.10	0.64 × e^{−0.04×30} ≈ 0.19	0.38 × e^{−0.06×30} ≈ 0.08	0.78 × e^{−0.01×30} ≈ 0.61
Water Thickness (50 cm)	0.71 × e^{−0.02×50} ≈ 0.26	0.55 × e^{−0.04×50} ≈ 0.07	0.45 × e^{−0.05×50} ≈ 0.03	0.64 × e^{−0.04×50} ≈ 0.07	0.38 × e^{−0.06×50} ≈ 0.02	0.78 × e^{−0.01×50} ≈ 0.48
Water Thickness (100 cm)	0.71 × e^{−0.02×100} ≈ 0.10	0.55 × e^{−0.04×100} ≈ 0.01	0.45 × e^{−0.05×100} ≈ 0.003	0.64 × e^{−0.04×100} ≈ 0.01	0.38 × e^{−0.06×100} ≈ 0.003	0.78 × e^{−0.01×100} ≈ 0.30

Source: Authors, 2024.

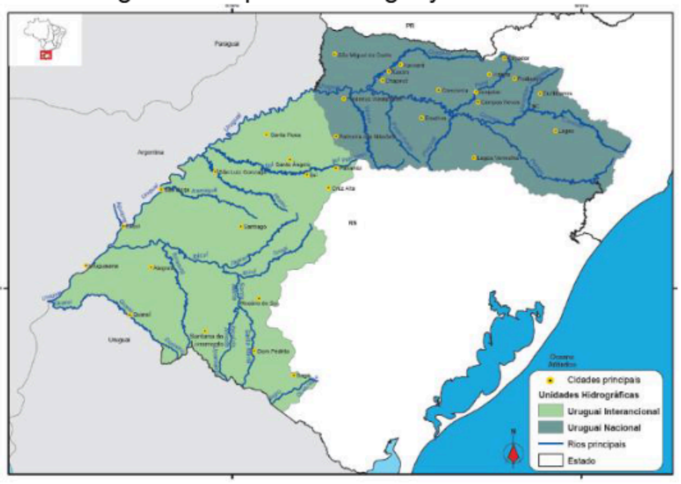
According to this calculated information, the doses received by the population of the state of Rio Grande do Sul would be within the limits provided for occupational doses.

2.3 THE SIZE OF THE CATASTROPHE

As discussed in the introduction of this work, the state of Rio Grande do Sul is currently in a situation of public calamity due to torrential rains, which result in flooding and inundation. The reduction of runoff, percolation and infiltration of stormwater permeates urban structures. However, the constancy of rainfall and its volume currently result in the waterlogging of soils and structures, extending the time for water to be incorporated back into the environment.

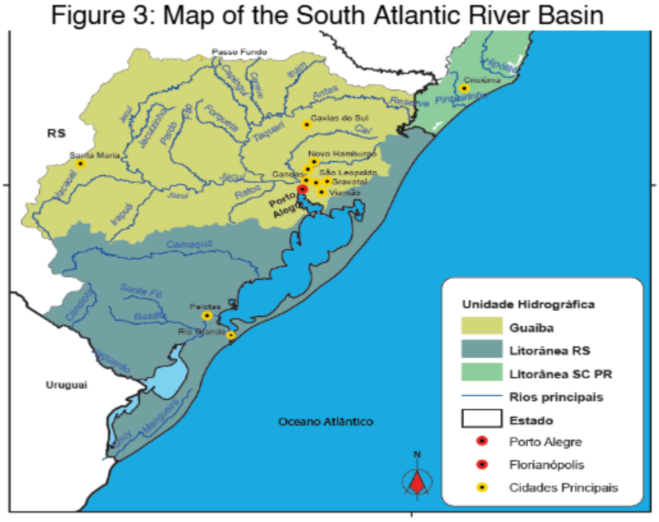
According to EBC - Empresa Brasil de Comunicação, due to its continental proportion, Brazil has about 12% of all fresh water available on the planet and about 20% of the underground water reservoirs, Rio Grande do Sul has in its territory almost entirely two of the 13 main hydrographic basins in the country, they are: the Uruguayan river basin (Figure 2) and the South Atlantic basin (Figure 3).

Figure 2: Map of the Uruguay River Basin



Source: https://www.antonioguilherme.web.br.com/blog/geracao-de-energia-eletrica/hidreletricas/hidrologia/bacias-brasileiras/. Acesso em: 20 de maio de 2024.

Figure 3: Map of the South Atlantic River Basin



Source: https://www.antonioguilherme.web.br.com/blog/geracao-de-energia-eletrica/hidreletricas/hidrologia/bacias-brasileiras/. Acessed on: 20 may 2024

The Guaíba River basin was considered the location with the most critical situation according to the media outlets of CNN Basil, Globo and Folha de São Paulo, not only because it comprises the metropolitan area of the state capital, but also because it is an area naturally susceptible to flooding and the cities adjacent to this basin and its tributaries are constantly affected by flooding and flooding. It is also the region where the highest number of fatalities from this tragedy are concentrated.

Rio Grande do Sul has one of the main hydrographic basins in the southern region of the country and plays a fundamental role in the local hydrography, as it covers cities such as Porto Alegre, Canoas, Guaíba, Eldorado do Sul, among others.

The main river is one of the three most relevant for the South Atlantic National Hydrographic Basin, it forms its large volume of water masses by the junction of the Jacuí, Sinos and Caí rivers, being a drainage river, that is, it is a tributary of its precursors, a region where other rivers flow. Although the Guaíba River basin does not belong to the Uruguay River basin, it influences through the connections and tributaries uniting the eastern and western regions of the state.

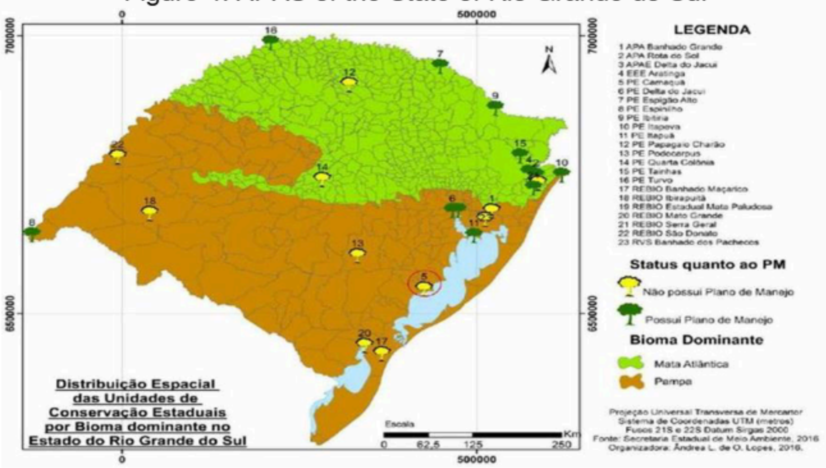
The affected areas of the state located in the extreme south of the country make up the union and presence of two biomes, they are: the pampa and the Atlantic Forest, sheltering a vast diversity of species of fauna and flora.

On July 18, 2000, the Federal Law was published, which regulates the creation of Nature Conservation Units and other measures, based on § 1, items I, II, III and VII of the Federal Constitution of 1988.

The UCs – Conservation Units have the premise of protecting at least 10% of the biomes and are distributed throughout the country in order to form a network of varieties of protected areas. ICMBio and the Chico Mendes Institute organize the availability of visitations in these areas of the 334 units.

The Environmental Protection Areas (APAs) are sustainable use UCs, with internal areas open to visitation and others intended for the protection and conservation of these environments and their species.

Figure 4: APAS of the State of Rio Grande do Sul



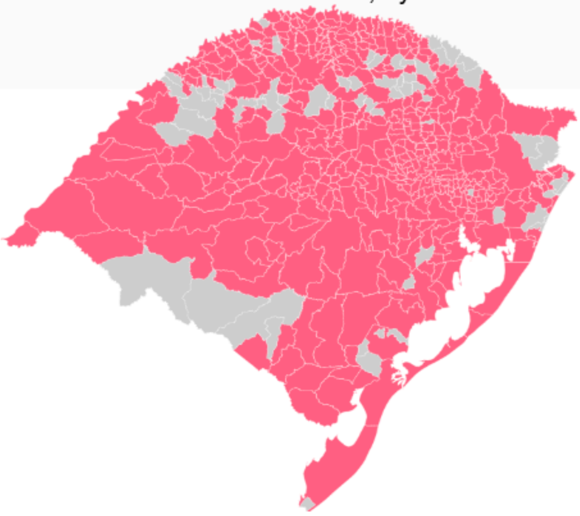
Source:
https://www.researchgate.net/publication/333353746_Zoneamento_Ambiental_do_Parque_Estadual_do_Camaqua-RS_Subsidios_ao_Plano_de_Manejo/figures. Acessed on 23 May 2024.

According to Figure 4, it is possible to observe that all conservation units in Rio Grande do Sul were affected, with both biomes being affected by the increase in the volume of rainfall. This fact directly interferes with the management and survival of species, whether vental, animal or fungal.

According to a 2014 publication on the website of the Government of the State of Rio Grande do Sul, at least 280 species of animals and plants threatened with extinction are located in its extension. In 2022 and 2023, Ibama carried out joint actions in the state with the objective of protecting and rescuing animal species, the three main ones: the pepper-billed bird (Saltator fuliginosus) with 61 specimens; the parrot or mountain parrot (Amazona pretrei), 37 animals; and the howler monkey (Alouatta guariba) with 21 animals. All have been affected by the current catastrophe.

The main question to be answered in this paper is: what is the potential size of a radiological disaster resulting from this environmental catastrophe? On May 5, 2024, it was published in the Official Gazette that 265 cities were classified as being in level III public calamity, that is, those with high damages and losses, also considering the death and disappearance of people. Figure 4 below shows a map of the state published on May 7, with the 467 cities affected.

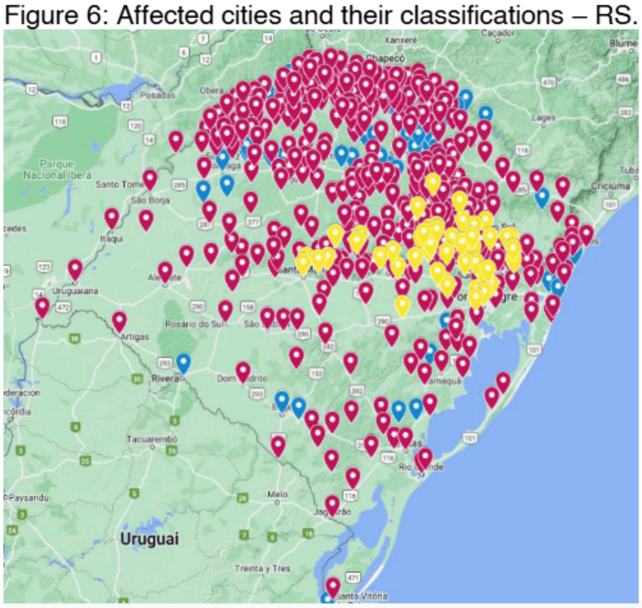
Figure 5: Cities affected in Rio Grande do Sul, by the torrential cuvas in 2024.



Source: https://valor.globo.com/brasil/noticia/2024/05/07/veja-o-mapa-do-rio-grande-do-sul-com-cidades-afetadas.ghtml. Acessed on 20 May 2024.

Of these cities, 48 cities have confirmed fatalities of 157 people as of May 20, 2023. Cities with these characteristics were marked with yellow pins, while cities with blue identification were removed from the situation of public calamity, and those in red were in a state of alert while performing rescue, safeguarding, and damage analysis services (Figure 6).

Figure 6: Affected cities and their classifications – RS.



Source: https://www.cnnbrasil.com.br/nacional/enchente-no-rs-mapas-interativos-mostram-locais-afetados-pela-chuva-veja/. Acessed on 20 May 2022.

Due to the scope of this natural catastrophe, we will not consider the possible amount of radioactive sources, but their variety, as there are at least 21 hospitals that perform services and treatments with radiotherapy, according to information from the Brazilian Society of Radiotherapy (SBRT). In addition to hospitals, we can find dental clinics and specialized laboratories in this region, that is, the minimum survey indicates the presence in the affected area of at least 21 possible radioactive sources. Thus, in response to the question raised above, the potential for radiological disaster in this region is immense.

3 METHODOLOGY

As this work is developed concomitantly with the events and consequences of the water catastrophe in the state of Rio Grande do Sul, it is necessary to unite several methodologies, not only to understand the current scenario, but also to make it possible to propose both forms of prevention for new similar situations that will certainly arise, as well as solutions for the possible radiological dispersion and its environmental consequences for the affected areas.

In the contextualization of the situation and the problem observed, we used documents and information from IPEN and CNEN for radiological issues and from IBAMA, ANA – National Water Agency, ICMBio and other platforms to compose the bibliographic review of this study in order to describe meteorological, geographical, environmental and even social conditions of Rio Grande do Sul, in order to interpret phenomena and events.

The quantitative analysis and survey are present in relation to the estimation of the minimum number of radioactive sources affected by these events as well as the impacted areas, the prediction and analysis of doses provided by these radioactive sources and the possible shielding of ionizing radiation provided by the water present in these inundations.

The critical analysis in the coverage of this work encompasses quantitative and qualitative factors, as well as the suggestion of protection measures and future monitoring, with the premise of assisting and protecting the population and the environments affected by this type of adversity.

4 RESULTS AND DISCUSSIONS

After a comprehensive analysis of the torrential rains and inundations that currently plague the state of Rio Grande do Sul, it was possible to identify numerous possible impacts, in the most diverse areas, activities and functionalities. The affected cities, listed from the radioactive sources mentioned above, add up to 467 cities, demonstrating the extent of the damage and the extent of the region's current challenges.

In addition, it was found that these intense rains resulted in material and structural losses, population displacements, among other damages not yet measured or observed, highlighting the urgency of response actions and measures, which are initiated primarily with the rescue and care of the population.

The environmental importance of the affected region is a crucial aspect of this study, as 23 PAs were identified, which serve as cradles of endemic species and as important habitats for local biodiversity, of which some are identified as threatened with extinction, that is, the degradation of these environments can represent a threat to the survival of these species and the integrity of these ecosystems.

Considering the presence of facilities likely to have radioactive sources in the state, accounting for at least 233 of them, it became evident the need to assess the risks associated with inundation in these areas, as the safety of these facilities directly implies the safety of the population and the environment, considering that radioactive contamination has extensive duration and multiple facets. As mentioned at the beginning of this work, although the origin of the heavy radioactive contamination derived from the Chernobyl accident was the explosion of a nuclear reactor, it serves as an example of the temporal extension that the effects derived from a radioactive accident can last.

Finally, the results of this study highlight the complexity resulting from the event, such as the preservation and activity of nuclear sources, the insertion of environmental parks in cities likely to have these radioactive sources, and the action of water as a shielding element.

However, CNEN published on May 20, 2024, that it "*conducts permanent assessments on the safety of facilities in Rio Grande do Sul with radioactive sources. These evaluations involve contact with Radiological Protection Supervisors and the collaboration of other government agencies. The aim is to ensure that radioactive sources comply with safety standards and that they do not pose risks to the population and the environment.*"

In the relationship between the submersion of radioactive sources and water, it is important to emphasize that, in the case of nuclear reactors, water acts as an attenuating and/or moderating element for the emitted energies, that is, its values are reduced due to the interaction with the environment. Considering the dispersion of the radiological material, such situations have a low probability of occurrence due to the action of water, considering that its hermetic stainless-steel envelopes isolate the radioactive material from the aqueous medium, allowing only the transfer of energy, and not the dissolution of the mineral matter, reducing and even avoiding the contamination of the media. On the other hand, the unsealed sources are liable to be dissolved and/or transported in the midst of the flows and large volumes of water that reach the regions of Rio Grande do Sul at this time, if they occur, it will be necessary to carry out contamination studies, which can start from the place of origin of the source and follow the flow of fluids from these regions. in order to demarcate the affected area(s). However, it is worth asking how long and in what types of media the material that seals these sources resists submerged in water or mud. Thus, submersion of sources and equipment with radioactive materials can result in different levels of contamination depending on various factors such as the type of radioactive material, the amount present, the depth of submersion, and the duration of exposure.

Table 4: Contamination Comparison for Sealed and Unsealed Sources in Water Submersion Situations

Font Type	Potential of Contamination	Influencing Factors	Control Measures
sealed nuclear sources	• low to moderate risk • Lower likelihood of radioactive material release • Reduced shielding effectiveness in aquatic environments	• Radioactive material contained in a hermetically sealed capsule • Implementation of physical barriers • Access control measures • Emergency and evacuation procedures	Continuous monitoring of capsule integrity
Unsealed Sources	• Moderate to High • Higher risk of release and dispersion of radioactive material • Greater likelihood of contamination due to submersion in water	• Radioactive material exposed to the external environment • Implementation of physical and chemical barriers • Decontamination and safe removal of radioactive material • Public education and awareness about the risks	Environmental monitoring

Source: Authors,2024.

Table 4 offers a comparative view of the different contamination potentials for sealed and unsealed sources in situations of submersion in water, information has been organized to facilitate the comparison between the environmental and endemic factors of the affected areas and whether or not it is possible.

It should be noted that the longer the submersion time and the inadequacy of the environments in which the sources are located, the greater the probability of damage to the equipment and containment measures of the sources. In addition, there may be possible overdoses in environments close to these facilities, also due to the shielding carried out by water, enabling environmental radiation.

Table 5: Relationship between Environmental and Endemic Factors and Radiological Contamination of Sealed and Unsealed

Factors	Impact on Radiological Contamination	Mitigation Measures
Environmentally Sensitive Areas	Increased risk of environmental damage due to radiological contamination	Continuous environmental monitoring

Potential for irreversible damage to delicate ecosystems	Implementation of environmental protection measures	
Threat to biodiversity and endemic species	Development of emergency response plans	
	Ecological restoration and habitat recovery	
Endemic Species	Risk of extinction of endemic species due to radiological contamination	Assessment and protection of critical habitats
Loss of genetic and ecological diversity	Implementation of conservation programs	
Disruption of ecological systems	Community education and engagement	
	Ongoing monitoring and research on species	

Sources: Authors, 2024.

What we observe in Table 5 is a relationship between Environmental and Endemic Factors and the link between these factors and radiological contamination for sealed or unsealed sources. Environmentally sensitive areas are those characterized by delicate ecosystems, unique biodiversity, and fragile habitats. In situations of radiological contamination due to flooding, these areas face a significant risk of irreversible environmental damage. Contamination can result in damage to local flora and fauna, due to changes in ecosystem processes. Threats to biodiversity and endemic species are of particular concern, as they can lead to loss of genetic and ecological diversity. To mitigate these impacts, it is crucial to implement environmental protection measures, such as habitat monitoring.

By comparing the submersion of radioactive sources in Rio Grande do Sul and the nuclear accident in Fukushima, Japan, it is possible to identify similarities and differences, as both events have nuclear factors, but so far the authorities of Rio Grande do Sul have not reported the loss, damage or dispersion of any radioactive source.

Considering the tsunami that affected the Fukushima nuclear complex, we have the following similarities: the exposure of nuclear materials to aquatic environments, and the floods and flooding in Rio Grande do Sul. In both cases, possible radiological contamination poses a significant threat to the environment and human health. The release of radioactive materials into natural environments can result in long-term environmental damage and affect local biodiversity.

The Fukushima nuclear accident was triggered by an earthquake followed by a tsunami in March 2011, which severely damaged the plant's nuclear reactors. On the other hand, floods in Rio Grande do Sul are climatic events, factors that differ in safety measures, response actions, and possible damage due to dispersion. Fukushima involved the massive release of radioactive materials from the damaged nuclear reactors, including elements such as iodine-131, cesium-137, and strontium-90. In the case of Rio Grande do Sul, the submersion of radioactive sources may involve smaller amounts of radioactive materials, as these are used for health activities, that is, both their activity and maintenance and monitoring are different, in addition to the variety of materials.

Table 6 presents this comparison between the similarities and differences between the events in a more succinct way, in order to inform response and monitoring strategies.

Table 6: Comparison of similarities and differences between Fukushima and Rio Grande do Sul events to inform response and monitoring strategies

Aspect	Fukushima Nuclear Accident	Submersion of Sources in Rio Grande do Sul
Cause of the Event	Earthquake followed by a tsunami in March 2011	Flooding due to extreme weather events
Scale of Radioactive Release	Massive release of radioactive materials from damaged reactors	Potential release of smaller amounts of radioactive materials, such as those used in medical and industrial applications
Nature of Radioactive Materials	Elements such as iodine-131, cesium-137, strontium-90	Radioactive sources used in medical and industrial applications
Exposure to Aquatic Environments	Yes	Yes
Potential for Environmental Contamination	Widespread contamination with global impacts	Potential localized contamination with regional impacts
Response and Consequences	Mass evacuations, widespread contamination, ongoing challenges with reactor decommissioning and decontamination	Localized emergency measures, requiring public health responses and environmental protection

Source: Authors, 2024

5 CONCLUSION

Article 196 of the Federal Constitution establishes that health is a right of all and a duty of the State, guaranteed through social and economic policies aimed at reducing the risk of disease and other health problems and at universal and equal access to actions and services for its promotion, protection, and recovery. Thus, it is the duty of the Brazilian State to guarantee this right also – and especially – in the current catastrophe in Rio Grande do Sul.

After an in-depth analysis of the intersection between extreme weather events, radiological contamination, and environmental and endemic impacts in the affected areas, it is clear that we are facing a complex and multifaceted scenario. The torrential rains and inundations recorded in Rio Grande do Sul have triggered a series of challenges, including the submersion of radioactive sources (sealed or not) and equipment containing radioactive materials.

Our findings indicate that while the doses received by the population of the state of RS fall within the limits prescribed for occupational exposure, variations in environmental conditions could alter these outcomes, underscoring the need for continuous monitoring.

It is crucial to recognize that radiological contamination in these circumstances can pose a serious threat not only to human health but also to the environment and local biodiversity. In this context, it is imperative to adopt effective prevention, mitigation, and response measures. This includes, in the future, the development and implementation of robust emergency plans that can be adapted and applied in other states of the federation. Such plans should include adaptable sensors and detectors for different locations and situations. Recommendations for future state and/or federal documents include continuous environmental monitoring, public education about the risks associated with radiological contamination, and the implementation of biodiversity conservation measures, as well as actions for the removal of sources in emergency scenarios, preventing degradation of their containment structures due to water exposure.

As a final consideration, we emphasize the importance of examinations and treatments using radioactive materials, and the necessity of integrating environmental conservation into these practices. These concepts, often approached as disparate, are crucial for the development and well-being of the population and the nation. However, this study has limitations, including the reliance on specific data sets that may not fully capture the variability of environmental conditions. Futures researchs should focus on expanding the dataset, incorporating real-time monitoring, and exploring the long-term impacts of radiological contamination in flood-affected areas. By addressing these areas, subsequent studies can build on the current findings and enhance our preparedness and response strategies for similar emergencies.

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