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Radiometric Characterization of Pandeiros River Basin (Minas Gerais - Brazil)

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Abstract: This study aimed to establish reference values (RVs) for the total gamma radiation count rate in the Pandeiros River Basin (PRB), Minas Gerais, Brazil, to evaluate the potential of natural radionuclides as tracers for sediment transport. Five stations (S-1–S-5) were designated along the basin, from upstream to downstream, for *in situ* radiometric measurements. The complexity of PRB sediment dynamics is attributed to land use practices, erosion, and the inactive Pandeiros Small Hydroelectric Power Plant (SHP). Fieldwork campaigns were performed to capture seasonal variability and collect georeferenced data via on-foot surveys and navigation (using a portable spectrometer). Data processing included Geographic Information Systems (GIS), R programming language, and MS Excel. A comparative analysis with previous studies showed low radiation levels in the PRB, with lower and upper thresholds of 31 and 122 counts per second (cps), respectively, and an average of 61 cps. Natural radiation within the basin poses no risks to local communities, with lower and upper thresholds of 0.13 mSv/year and 0.37 mSv/year, respectively, significantly below regulatory limits (1 mSv/year) defined by the National Nuclear Energy Commission (*Comissão Nacional de Energia Nuclear* - CNEN) and the International Commission on Radiological Protection (ICRP). No substantial evidence of sediment transport was identified through radiometric measurements during the analyzed time intervals. The definition of the RVs for these variables can play an essential role as baselines in future investigations.

Keywords: natural radionuclides; radiometric mapping; sediment transport; baseline.

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Caracterização Radiométrica da Bacia do Rio Pandeiros (Minas Gerais - Brasil)

Resumo: Este estudo teve como objetivo estabelecer valores de referência (VRs) para a taxa de contagem de radiação gama total na Bacia do Rio Pandeiros (BRP), Minas Gerais, Brasil, para avaliar o potencial dos radionuclídeos naturais como rastreadores de transporte de sedimentos. Cinco estações (S-1–montante até próximo a jusante, para medições radiométricas in-situ. A complexidade da dinâmica dos sedimentos da BRP é atribuída às práticas de uso da terra, erosão e à inatividade da Pequena Central Hidrelétrica (PCH) dos Pandeiros. Campanhas de campo foram realizadas para capturar a variabilidade sazonal e coletar dados georreferenciados por meio de levantamentos a pé e navegação (utilizando um espectrômetro portátil). O processamento de dados incluiu Sistemas de Informação Geográfica (SIG), linguagem de programação R e MS Excel. Uma análise comparativa com estudos anteriores mostrou níveis baixos de radiação na BRP com limites inferiores e superiores de 31 e 122 cps, respectivamente, com uma média de 61 cps. A radiação natural dentro da bacia não representa riscos para as comunidades locais, com limites inferiores e superiores de 0,13 mSv/ano e 0,37 mSv/ano, respectivamente, significativamente abaixo dos limites regulamentares (1 mSv/ano) definidos pela Comissão Nacional de Energia Nuclear (CNEN) e pela Comissão Internacional de Proteção Radiológica (ICRP). Nenhuma evidência substancial de transporte de sedimentos foi identificada por meio de medições radiométricas durante os intervalos de tempo analisados. A definição de VRs para essas variáveis pode desempenhar um papel essencial como *baseline* em investigações futuras.

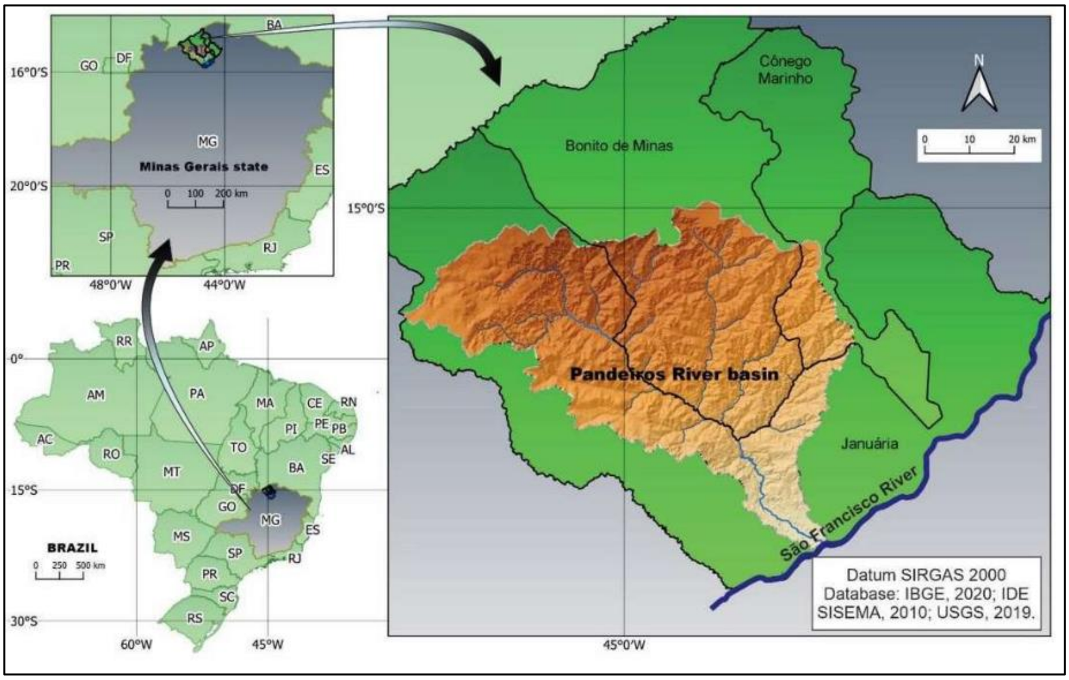
Palavras-chave: radionuclídeos naturais, mapeamento radiométrico, transporte de sedimentos, baseline.

1. INTRODUCTION

Sediment tracers are among the most effective tools for evaluating sediment behavior, transport routes, destinations, and deposition [1]. Radioactive isotopes are used as artificial tracers in nuclear techniques for hydrogeological investigation. However, the use of nuclear technologies requires significant caution, as evidenced by the limited number of studies on the environmental and human impact of radioactive tracers in hydrological research [2].

The IAEA-coordinated research project "Development of Radiometric Methods and Modelling for Sediment Transport Measurement in Coastal Systems and Rivers," conducted by the Center for Development of Nuclear Technology (CDTN), proposes an alternative method based on natural radiation. Integrated with the aforementioned project, this study aimed to establish reference values (RVs) for the total gamma radiation count and dose rates in the Pandeiros River Basin (PRB) in northern Minas Gerais, Brazil (Fig. 1).

Figure 1: Location and geographical boundaries of the Pandeiros River Basin (PRB).



Source: [3].

Hence, the following research question was posed: "How can RVs for total gamma radiation count rate be established in PRB regions to evaluate natural radionuclides as sediment tracers?"

The PRB has been extensively studied due to the significant impacts of historical land-use practices and intensive gully (*voçoroca*) formation [4] (Fig. 2). Agricultural activities amplify sediment removal, leading to quantities that surpass the carrying capacity of watercourses and resulting in deposition and silting [5].

Figure 2: Gullies in the northern portion of the Pandeiros River Basin (PRB).

Source: [6].

Anthropogenic influences have devastated natural areas of the PRB [7], with impacts such as *vereda* deterioration, riparian forest removal, and side road construction affecting marshy areas by reducing the water supply and causing siltation [8]. "*Vereda*" refers to any headwaters stream smaller than a river [9]. Increases in secondary roads and drainage diversions have contributed to gully erosion [10], whereas land use and occupation have accelerated erosion along basin watercourse channels [4].

These erosive processes impact ecosystem dynamics, particularly in PRB wetlands [3], which are crucial areas for aquatic life and the local economy with regard to tourism and recreational potential [5, 6, 10, 11]. The Pandeiros Small Hydroelectric Plant (SHP), constructed in 1957 and shut down in 2008 [12], adds complexity to the sedimentary dynamics of the PRB, leading to severe reservoir siltation [5].

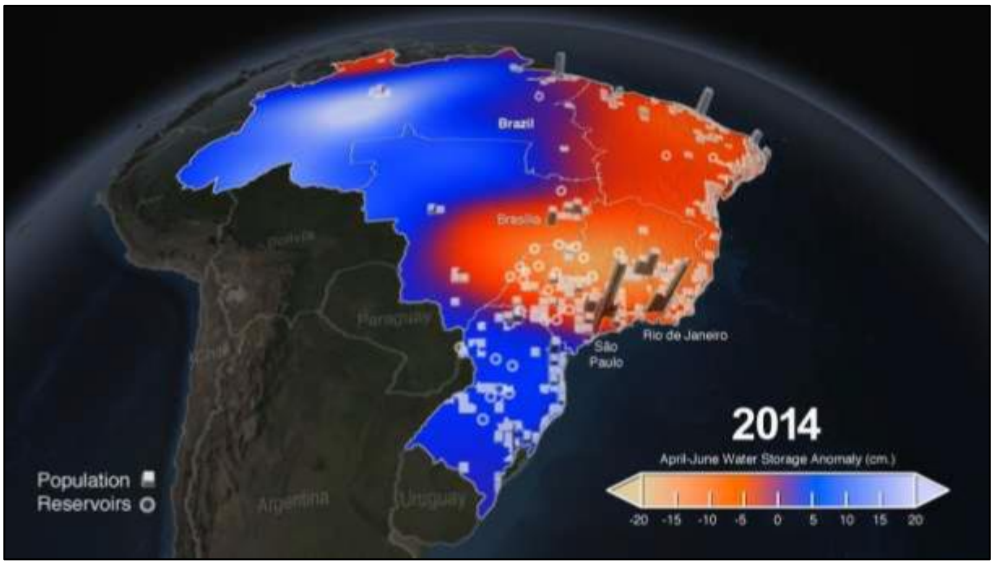
Current studies on decommissioning the SHP [13] include opening floodgates to remove sediment before dismantling the dam [5], as executed by CEMIG, the SHP concessionary, in January 2023 [14]. This process was part of environmental research to comply with the regional environmental supervision of northern Minas Gerais (SUPRAM, NM) requirements. SUPRAM NM commanded the CEMIG to study the socio-environmental impact of the Pandeiros SHP dam [14]. Hence, it is important to evaluate the environmental impact of sediment release due to the discharge maneuvers executed by the CEMIG.

The vulnerable socioeconomic conditions prevailing in the territory contribute to the PRB's intricacy. According to the digital portal *Atlas do Desenvolvimento Humano no Brasil*, Bonito de Minas, a key city within the basin, has a low Municipal Human Development Index (MHDI) of 0.537, close to the nation's lowest MHDI of 0.418 in Melgaço (Pará) [15]. To contextualize, an MHDI between 0.700 and 0.799 was deemed high, and values between 0.800 and 1.000 were considered to be remarkably high. Brazil's current national MHDI is 0.766 [15].

The United Nations' Sustainable Development Goal (SDG) 1, "No Poverty," aims to universally eliminate poverty. SDG 6 focuses on "ensuring availability and sustainable management of water and sanitation for all," while SDG 15 targets the protection, restoration, and sustainable use of terrestrial ecosystems, forest management, combating desertification, halting and reversing land degradation, and stopping biodiversity loss [16]. Despite these efforts, the Intergovernmental Panel on Climate Change (IPCC) report "Climate Change 2022: Impacts, Adaptation and Vulnerability" highlights that water resources remain highly vulnerable because of fragile governance that prioritizes capital interests [17].

Global water scarcity is becoming increasingly dire, as new data reveal a significant shift in the distribution of freshwater resources [18]. NASA's study, using Gravity Recovery and Climate Experiment (GRACE) mission satellites from 2002 to 2016, quantified terrestrial water storage trends. The eastern region of Brazil, particularly Minas Gerais and Bahia, endured severe droughts with notably low rainfall in 2012, 2014, and 2015, leading to reduced terrestrial water storage (Fig. 3).

Figure 3: Anomaly detected by GRACE for water storage in Brazil from April to June 2014: areas in red and orange represent water losses, and areas in blue represent gains.



Source: [19].

The GRACE satellite pair conducted an assessment based on observations of how water resources respond to human impacts and climatic variations worldwide, thereby providing a model for evaluating and predicting emerging threats to water and food security.

Several trends identified in this mission may require comprehensive investigation and attribution [18]. However, the conclusions indicate warnings regarding the neglect of water-resource management.

The Pandeiros River Conservation Unit (*APA do Rio Pandeiros*) was established by the Minas Gerais government in 1995 to protect the PRB effectively [8]. However, degraded areas and exposed soil are evident throughout the PRB [11].

As the largest sustainable use conservation unit in Minas Gerais, *APA do Rio Pandeiros* aims to balance nature conservation with sustainable water use and to protect the biological diversity of marginal lagoons, streams, waterfalls, *veredas*, and the only swampy wetland area in the state of Minas Gerais (Pantanal-like), thereby restricting activities that could jeopardize its environmental resources [7]. Depending on the rainfall, this swampy wetland, known as the *"Pantanal Mineiro,"* approximately 2,000–5,000 ha, forms downstream the basin [20].

The PRB, crucial for sustaining populations and ecosystems, also encompasses a significant portion of the territory acknowledge as the "*sertão*" whose landscapes have inspired the renowned writer João Guimarães Rosa from Minas Gerais. Amidst the backdrop of mountains, plateaus, rivers, and *veredas*, Rosa created characters for his narratives, such as in "*Grande Sertão: Veredas*", portraying the lives of people with a history as tragic as it is inspiring [21].

Rosa's works demonstrate mastery in describing the beauty of these landscapes and the richness of details of the natural heritage found in the Minas Gerais hinterlands. Indeed, the "Pandeiros River" is mentioned in the novel "*Grande Sertão: Veredas*".

> We followed the stream that flows out of Lake Sussuarana, and which is joined by the Jenipapo and Vereda-do-Vitorino, then empties into the Pandeiros River, this one has singing waterfalls, and its waters are so tinted that parrots flying over it argue, screaming: "It's green! It's blue! It's green! It's green!" Blessed waters, so near now." [9].

Considering the significance of the miscellaneous socio-environmental context of the PRB, research focusing on this territory is essential. The scientific findings pertaining to the

PRB elucidate complex issues in the area and establish a foundation for developing tailored public policies for the region.

The established RVs for the total gamma radiation count and dose rates can provide information on the natural environmental radioactivity of the PRB. The RVs for the dose rate were derived from the simultaneously collected data using identical measurement equipment. The PRB results were compared to the values set by national and international regulatory bodies for compliance evaluation. Thus, the RVs obtained for both the variables can serve as a baseline for the region.

Baselines are essential for environmental assessments because they provide crucial information on environmental and socioeconomic aspects and act as comparative benchmarks for complex pre- and post-anthropogenic activities [22]. The diagnostic phase of this complex fluvial system and aspects of potentially harmful human activities and structures precede the impact prediction, relevant mitigation proposals, and effective monitoring scheme design. The lack of such data spurs campaigns to evaluate natural radionuclides in regional sediments and to establish local RVs.

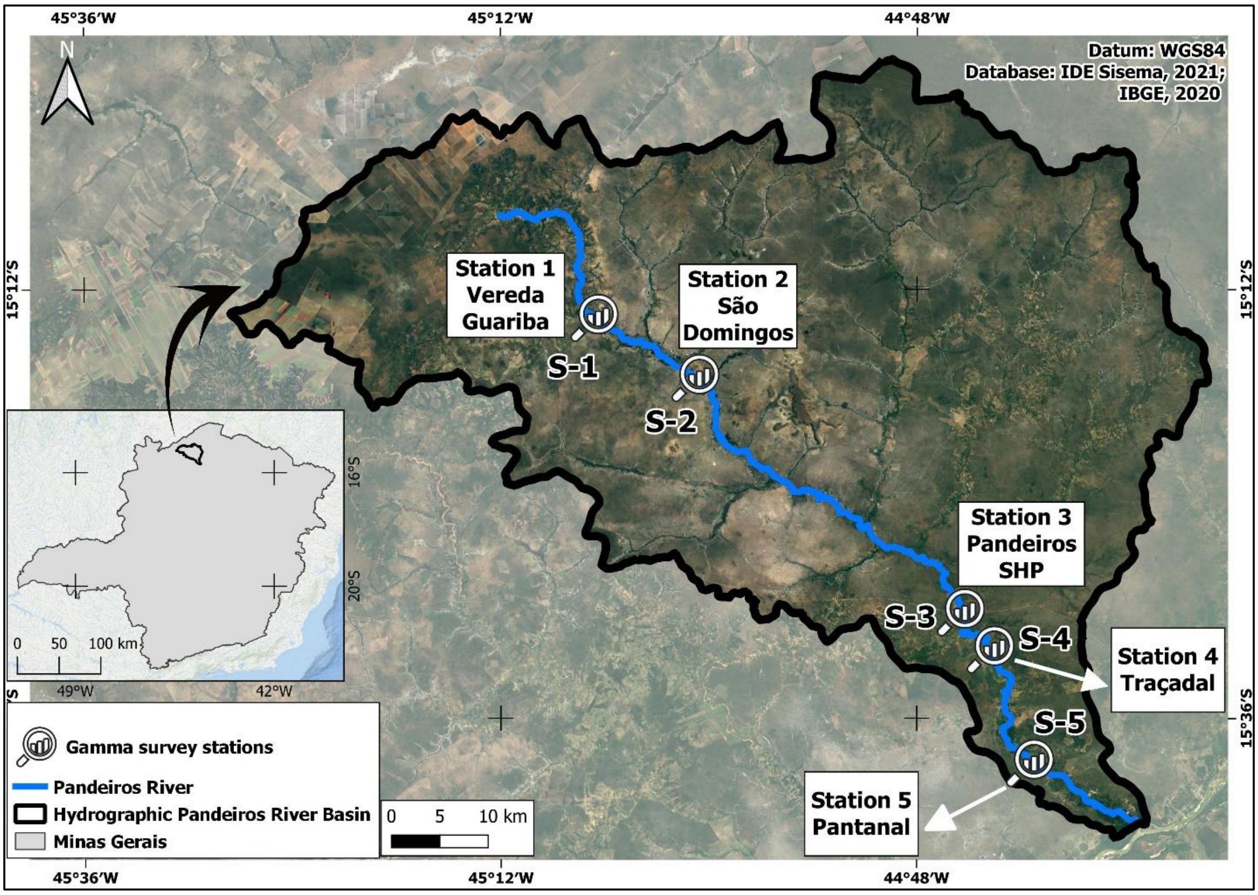
2. MATERIALS AND METHODS

2.1. Data Acquisition

The site selection for data collection in the PRB aimed to cover both the upstream and downstream regions for a comprehensive system analysis (Fig. 4). Accessibility via primary or secondary roads was also a key criterion, given the restrictive traffic conditions and the unpaved main road (BR-479). Priority was given to locations where measurements could be conducted, both in the main channel of the Pandeiros River, using a small boat, and on foot along its banks.

The ATAS Scanner AT6101C measures gamma radiation (total counts per second, cps), dose rate (ambient dose equivalent, μSv/h), and other variables. The system operates with a handheld personal computer (HPC) for control and display and continuously transmits data from the radiation detection units to the HPC via Bluetooth. The gamma radiation detection unit (BDKG-11M) features a NaI(Tl) (thallium-doped sodium iodide) scintillator with dimensions of Ø 63×63 mm (Fig. 5) [23, 24].

Figure 4: Location of gamma survey stations within the Pandeiros River Basin.



Source: authors.

Figure 5: ATAS Scanner AT6101C: (a) Backpack; (b) BDKG-11M: gamma radiation detection unit; (c) BDKG-04: detection unit (not used in this study); (d) BDKN-05: neutron detection unit (not used in this study); (e): handheld personal computer (HPC).

Source: [23].

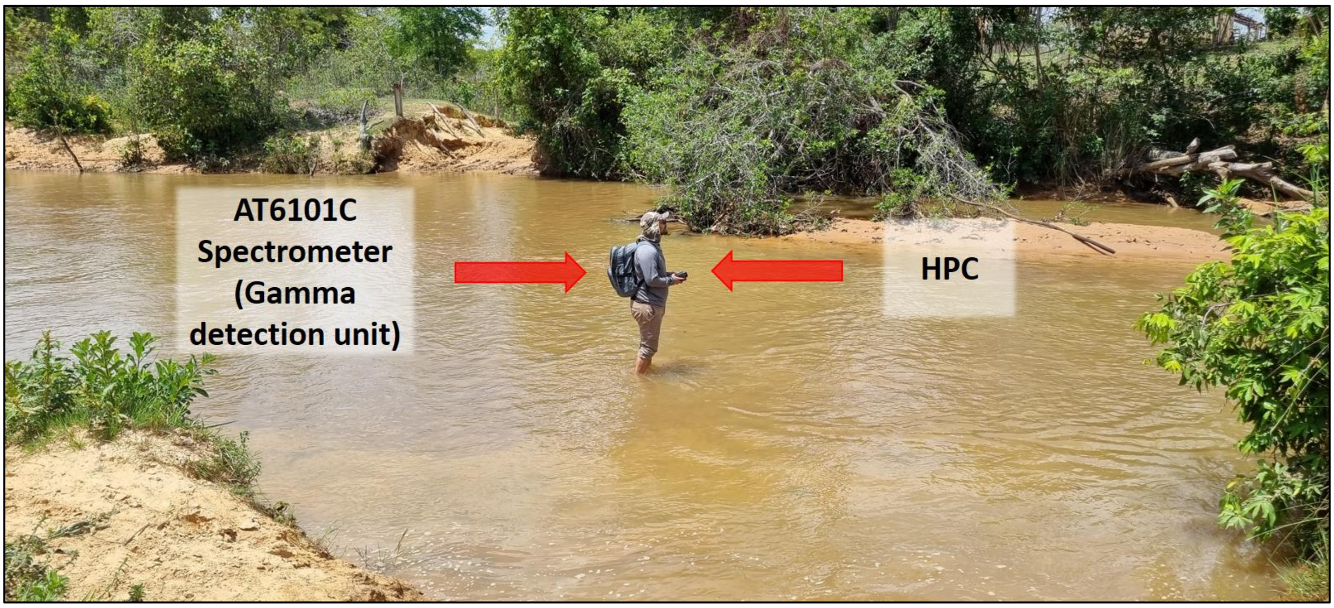
Prior to operation, the gamma radiation detection unit requires stabilization and background radiation measurements. In "scanning" mode, the spectrometer measures variables georeferencing the data with GPS. This information is digitally stored in the HPC device [23, 24]. Calibration of the gamma-radiation detection unit was performed using the standard accessory provided (Fig. 6), which involves acquiring and verifying the spectrum and the 1461 keV energy peak of potassium in the standard sample (potassium fertilizer) [23, 24]. Raw data were then collected from the selected positions.

In situ gamma surveys were conducted in two different ways: by an operator walking on foot and carrying the device in a backpack at a height approximately close to one meter above the ground (just above the waist and below the chest), and placed on the floor of a small boat for measurement in certain watercourses of the Pandeiros River. The spectrometer is portable and can be easily transported using a backpack, which is part of the equipment (Fig. 7).

Figure 6: ATAS Scanner AT6101C spectrometer calibration.

Source: authors.

Figure 7: ATAS Scanner AT6101C spectrometer operation.



Source: authors.

2.2. Data Processing

The raw data collected by the spectrometer were initially transferred to a computer where further processing was performed. A significant benefit of ATAS Scanner AT6101C is its ability to store data correlated with geographical location [25]. This simplifies the manipulation of Geographic Information Systems (GIS) and data visualization. Raw data handling was performed to consolidate datasets. To check for possible inconsistencies, MS Excel [26] and the R programming language [27] were used.

The raw data were first organized into spreadsheets and categorized by type and location. The data were then cleaned to eliminate discrepancies or errors, such as records of geographical coordinates lacking values of the total gamma radiation count rate and/or dose rate. This step ensured that only data points with actual values of the variables of interest were retained for further analysis.

The consolidated data were prepared for spatial analysis by data processing, which involved georeferencing the information by associating the geographic coordinates with each data entry and generating the corresponding vector files (ESRI shapefiles). Gamma radiation count rates were stored in plentiful text files (.txt) that contain numerous lines of records. Despite the inclusion of geographic coordinates, this file type was impractical for GIS manipulation. To resolve this issue, an R script was created to convert text files into vector files, facilitating their integration into GIS-compatible digital formats. The dose rate variable was recorded in Keyhole Markup Language files (.kml), offering greater compatibility with GIS. However, to optimize the spatial analysis, it was converted into vector files. These processes have facilitated the creation of cartographic products.

The next phase entailed gathering and compiling public geographical data to obtain georeferenced information about the study area and its surroundings. This includes details of the geology, hydrology, border boundaries, and polygons of areas of interest, such as the PRB polygonal. All vector data were standardized using the WGS84 geographic reference system. Two cartographic techniques were used to assess the distribution of the total gamma radiation count rate and dose rate: 1) point representations classified via the natural breaks (Jenks) algorithm, and 2) spatial interpolation using the traditional Inverse Distance Weighting (IDW) algorithm.

Classification based on the Jenks natural break algorithm categorizes data according to inherent groupings within the dataset. Jenks algorithm aggregates similar values and differentiates classes by maximizing the differences between them and establishing class boundaries where significant differences in data values exist, resulting in well-defined and distinct classes [28].

The IDW interpolation methodology postulates that geographically proximate data points exhibit greater similarities than those at greater distances. The algorithm uses nearby quantified values to ascertain the value of an unquantified location. Consequently, points closer to the forecast location exert greater influence on the estimated value than those at greater distances. Thus, the IDW algorithm asserts that each measured point has a local impact that diminishes with distance, attributing greater weight to proximal points and less to distal ones [29].

A 30-meter buffer was added around the survey path to define the surface interpolation boundaries, covering all measurement points. Thus, the IDW-interpolated surface extended 30 m beyond the path of the device. Data management, GIS operations, and thematic map creation were conducted using QGIS 3.16 [30], ArcGIS 10.4 [31], and Google Earth Pro 7.3 [32].

The Median ± 2 * Absolute Median Deviation (mMAD) statistical technique was used to establish the RVs, that is, the upper and lower thresholds, for the variables. The mMAD technique requires a dataset to follow a normal distribution [33]. The Shapiro-Wilk test assessed the distribution of the data, revealing a pattern that was not normally distributed.

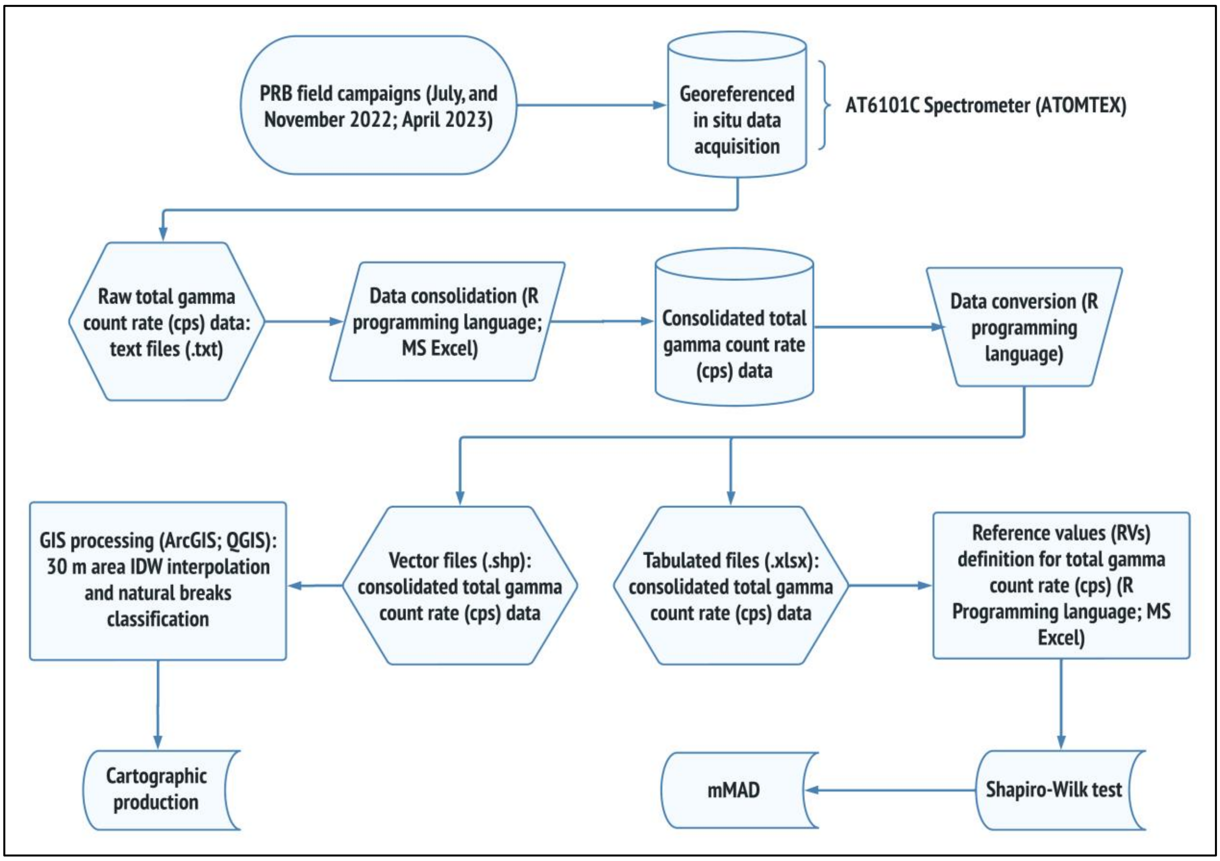
Thus, the data were logarithmically transformed (Log10) to determine the RVs using the mMAD method and then reverted to their original scales in cps or μSv/h.

$$MAD\ (y) = 1{,}4826 \cdot median_i(|\,median_j(y_i) - y_i|)$$

$$mMAD = 10^{(median_{(y)} \pm 2 \cdot [MAD_y])}$$

A study comparing the mMAD and Tukey's Inner Fence (TIF) techniques on simulated lognormal data showed that mMAD detected outliers more effectively, regardless of the sample size [33]. As the number of outliers increased, the mMAD performance remained superior. TIF, often used in boxplots, includes Q1 (first quartile), Q3 (third quartile), AIQ (interquartile range), TIFLI (lower threshold), and TIFUS (upper threshold) [33]. Therefore, this study employed the mMAD technique to establish RVs. The workflow for the total gamma radiation count rate (cps) data is shown in Fig. 8.

Figure 8: Workflow of the total gamma radiation count rate (cps) data.



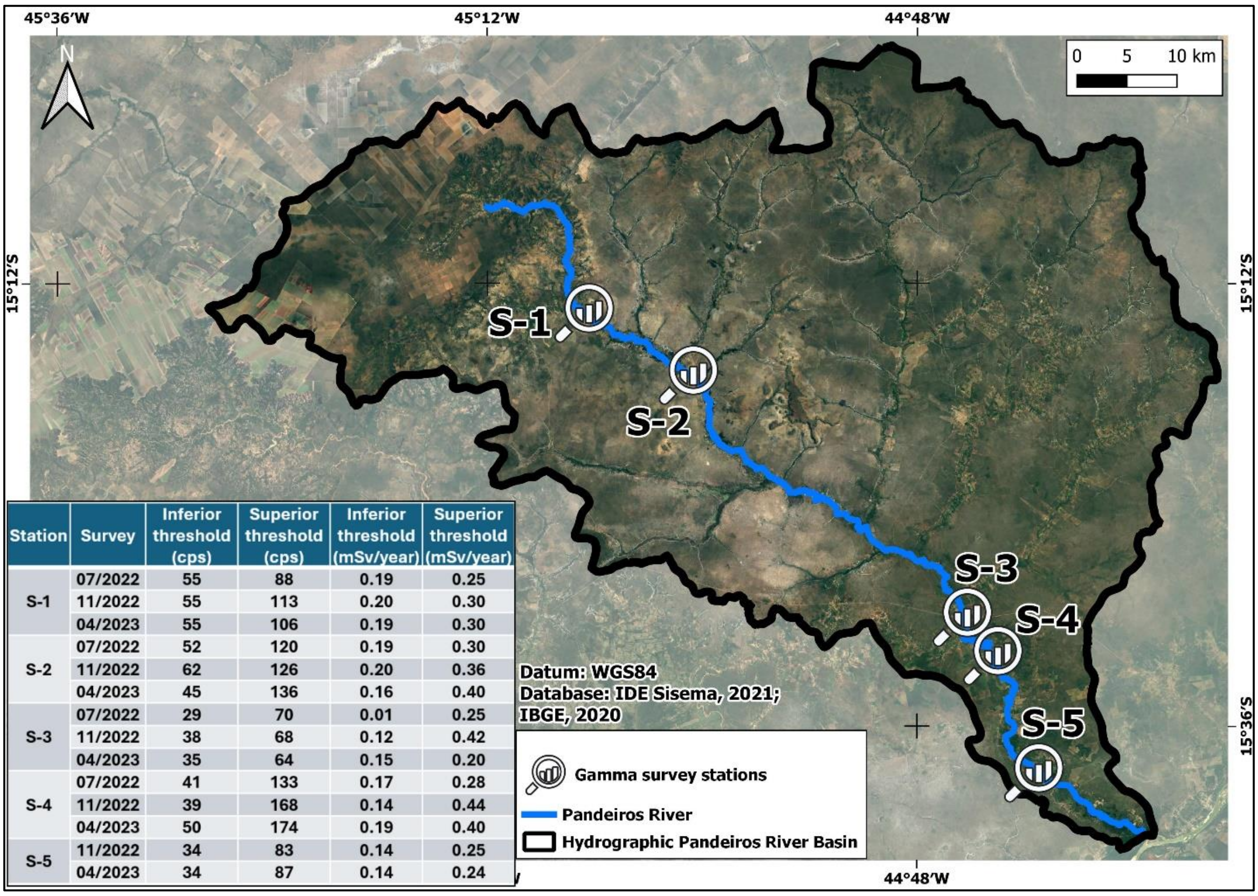
Source: authors.

3. RESULTS AND DISCUSSIONS

The RVs calculated from the mMAD method suggest a relative stability for the total gamma radiation count and dose rates in the PRB (Fig. 9). Seasonal variations between the dry and rainy periods did not significantly affect the data because the RVs after the rainy period were analogous to those during the dry period as well as the median values (Table 1).

For stations S-1, S-2, and S-3 (Fig. 10, 11, and 12), there was a minor increase in the median total gamma count rate from July 2022 to November 2022, followed by a decline in April 2023, approaching the levels observed in July of the previous year.

Figure 9: Total gamma radiation count rate (cps) and dose rate (mSv/year) RVs within the PRB.



Station	Survey	Inferior threshold (cps)	Superior threshold (cps)	Inferior threshold (mSv/year)	Superior threshold (mSv/year)
S-1	07/2022	55	88	0.19	0.25
	11/2022	55	113	0.20	0.30
	04/2023	55	106	0.19	0.30
S-2	07/2022	52	120	0.19	0.30
	11/2022	62	126	0.20	0.36
	04/2023	45	136	0.16	0.40
S-3	07/2022	29	70	0.01	0.25
	11/2022	38	68	0.12	0.42
	04/2023	35	64	0.15	0.20
S-4	07/2022	41	133	0.17	0.28
	11/2022	39	168	0.14	0.44
	04/2023	50	174	0.19	0.40
S-5	11/2022	34	83	0.14	0.25
	04/2023	34	87	0.14	0.24

Source: authors.

Table 1: Median values of the total gamma radiation count rate (cps).

STATION	SURVEY	MEASUREMENTS TAKEN	MEDIAN (CPS)
S-1	07/2022	1,297	69.6
	11/2022	1,465	78.7
	04/2023	2,906	76.3
S-2	07/2022	499	78.7
	11/2022	395	88.2
	04/2023	609	78.0
S-3	07/2022	1,645	45.3
	11/2022	1,019	50.7
	04/2023	2,151	47.3
S-4	07/2022	5,515	74.0
	11/2022	2,241	80.7
	04/2023	2,588	94.0
S-5	11/2022	892	52.9
	04/2023	1,961	54.3

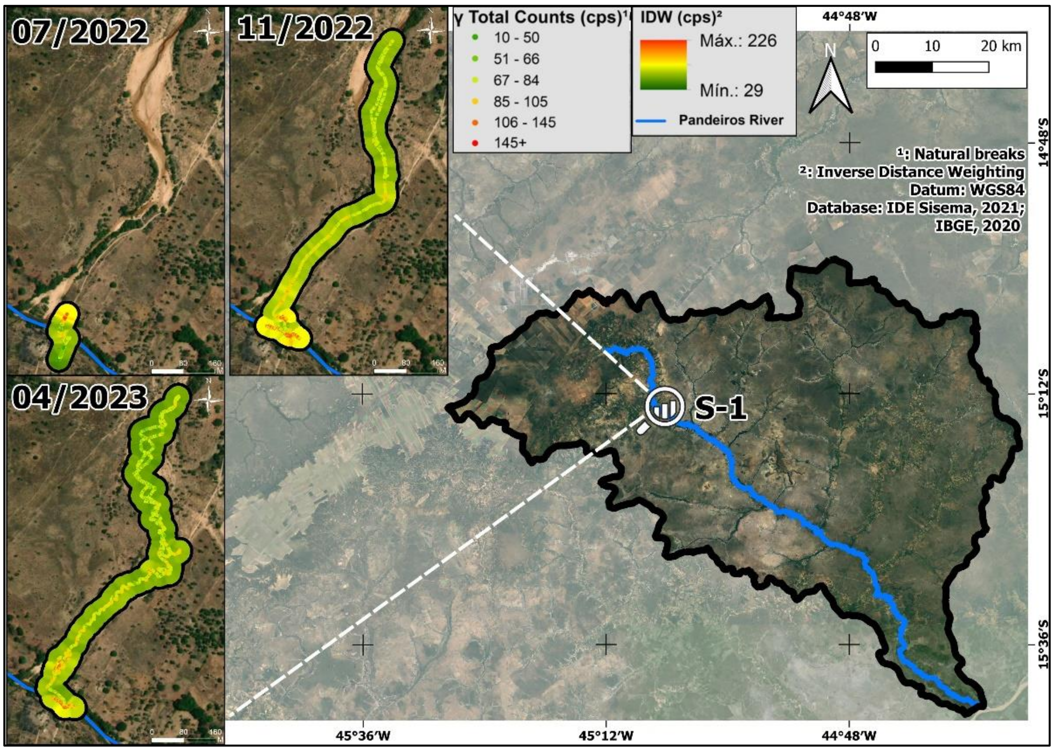
The geological domain [34-37] yielded comparable total gamma radiation count rates for S-1 and S-2, both of which are in the Posse Formation and Quaternary sedimentary cover, with median values ranging from 69.6 to 88.2 cps over the months. In contrast, S-3, which was also in the same domain, had lower median values of 45.3 to 50.7 cps. This difference could be related to measurements taken only by the boat in S-3, with the water column shielding gamma radiation from the riverbed sediment.

Station S-4 (Fig. 13) exhibited a notable trend, with the median total gamma radiation count rate increasing from 74 cps in July 2022 to 80.7 cps in November 2022 and 94 cps in April 2023. S-4 recorded the highest thresholds for gamma radiation, likely due to limestone and calcarenite in the Sete Lagoas Formation [34-37]. Uranium is partially oxidized to form a hexavalent state, producing the soluble uranyl ion U^{6+} [38], which forms complexes with anions such as CO_3^{2-}, resulting in various soluble species [39]. Consequently, uranium can be transported and deposited in limestone.

The January 2023 floodgate opening at the CEMIG SHP Pandeiros may have caused sediment transfer from S-3 to S-4, explaining the higher RV and median total gamma radiation count rate in S-4 by April 2023. Measurements in S-4, conducted along riverbanks and nearby areas on land and water, indicate significantly higher levels in terrestrial regions compared to fluvial areas.

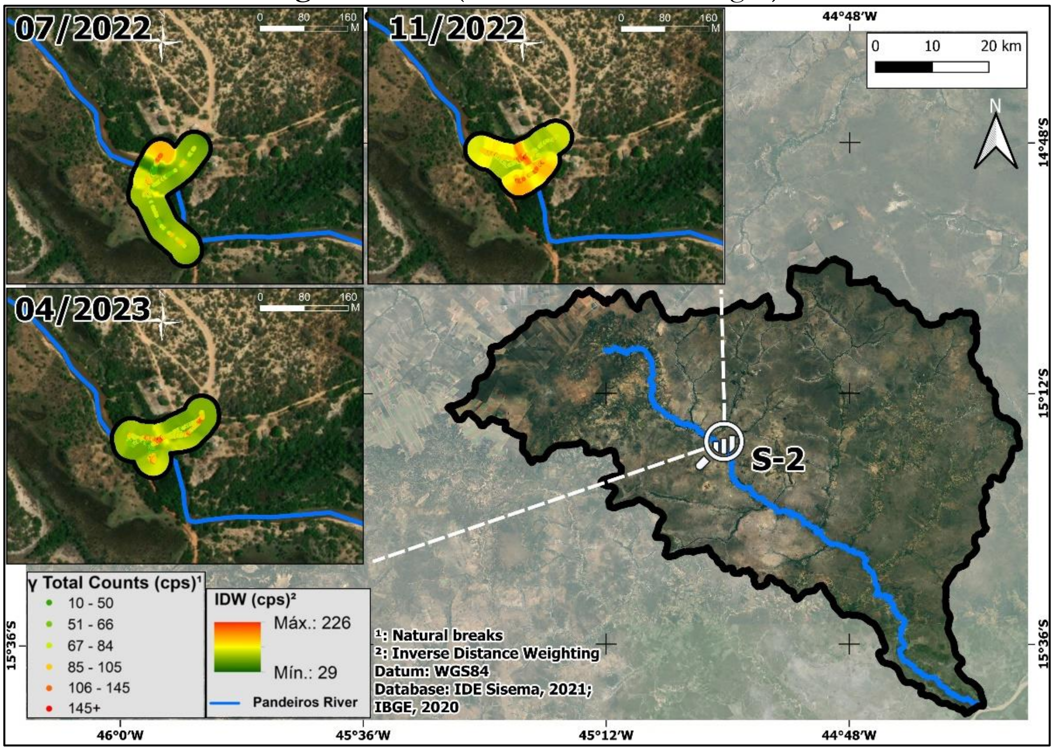
The geological context of Quaternary clay-sand alluvial deposits in S-1, S-2, and S-3 is present at S-5 (Fig. 14), which also includes Neogene sedimentary cover [34-37]. However, S-5's gamma radiation count rate was lower than those of S-1 and S-2 and similar to that of S-3. This might be due to the measurements being taken by boat along the Pandeiros River and, to a lesser extent, near the river channel, similar to the method used at S-3. Although no measurements were taken at S-5 in July 2022, the values recorded in November 2022 and April 2023 were similar, indicating stable gamma radiation at this station over the analyzed months (Fig. 10).

Figure 10: S-1 (Station 1: Vereda Guariba).



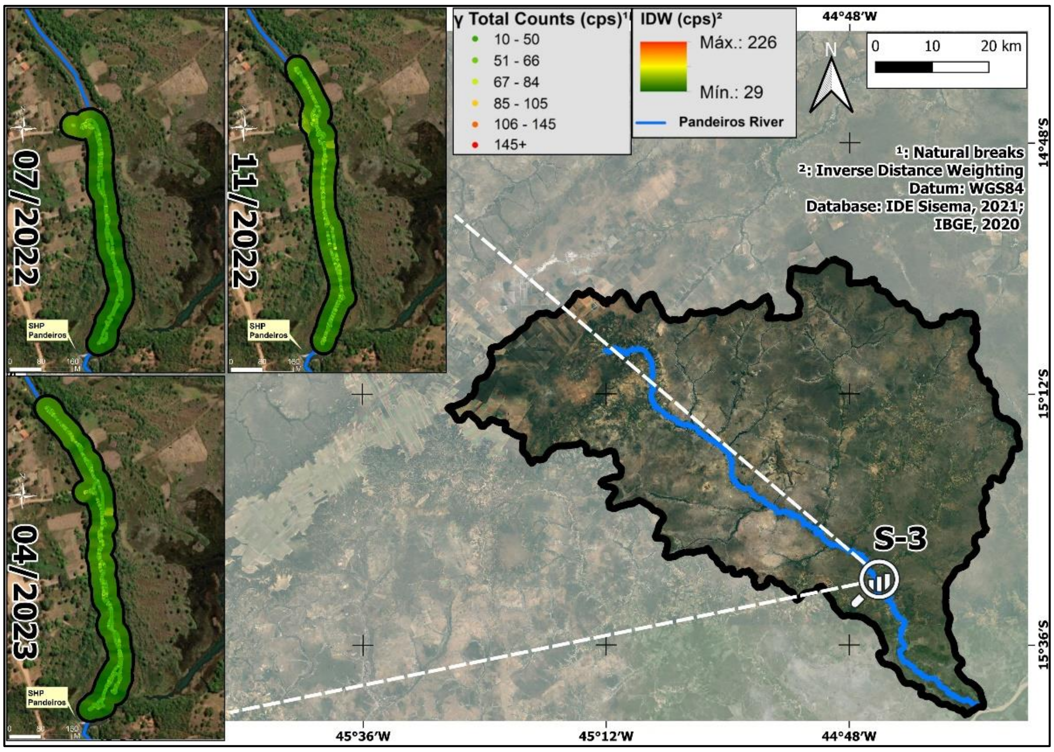
Source: authors.

Figure 11: S-2 (Station 2: São Domingos).



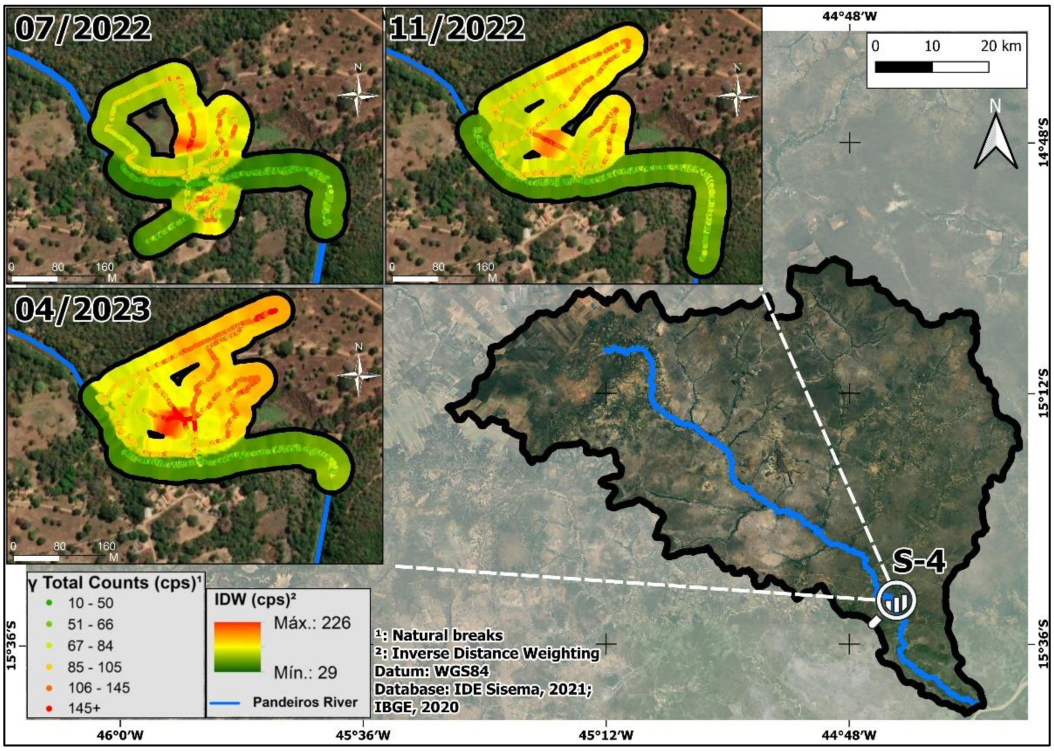
Source: authors.

Figure 12: S-3 (Station 3: Pandeiros SHP)



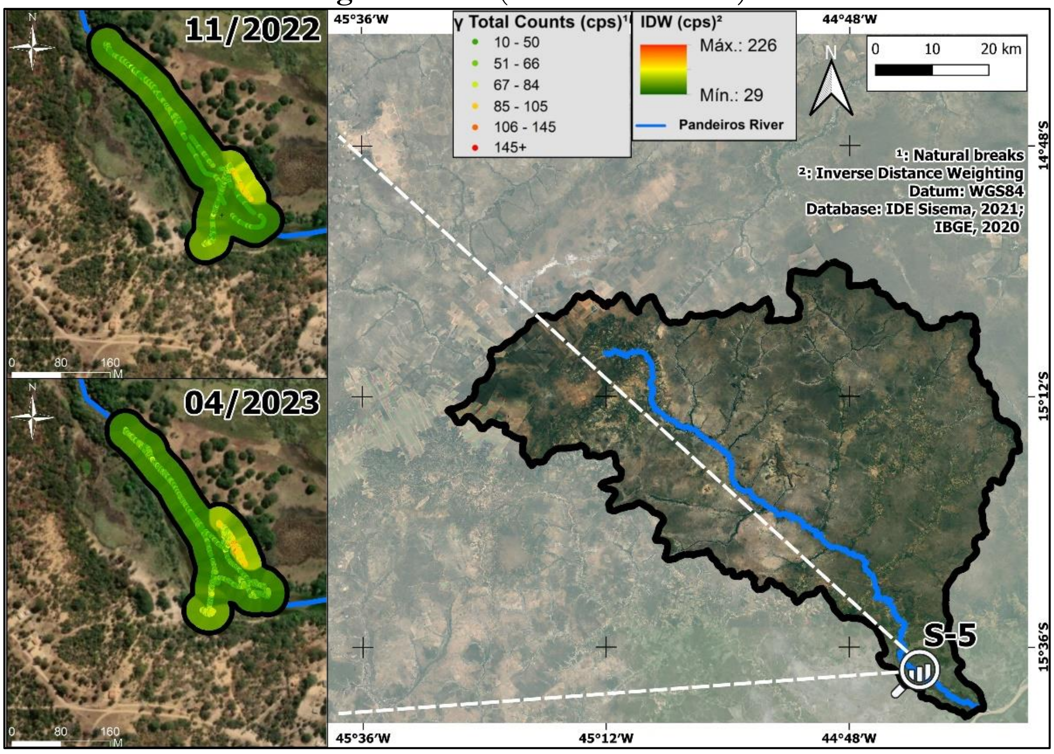
Source: authors.

Figure 13: S-4 (Station 4: Traçadal)



Source: authors.

Figure 14: S-5 (Station 5: Pantanal)



Source: authors.

To compare the total gamma radiation count rate and dose rate values with those of other studies, the RVs (mMAD) were calculated using data from all stations and months (Tables 2 and 3).

The lower and upper RVs for the PRB were 31 cps and 122 cps, respectively, averaging 61 cps. These results are similar to those for groundwater and surface waters in the Borrachudo and Indaiá River sub-basins (Minas Gerais, Brazil) [40], and are close to the values for sand near Praia da Areia Preta (Espírito Santo, Brazil). However, they differ significantly from the values associated with monazite sand from the same location [41].

The similarity with documented values for soil and limestone rock outcropping in the Irecê region of Bahia [38] is notable. This contrasts with values from soils in the Maciço Sienítico Piquiri region (Rio Grande do Sul, Brazil) [42], phosphate rocks from the Esh-Shidiya and Al-Hisa mines (Jordan) [43], and Quaternary alluvium on Gosmdochi Island (South Korea) [44].

The radiation dose rate thresholds of 0.13 mSv/year and 0.37 mSv/year indicate that the annual dose rate in the PRB is significantly lower than the global average of 2.4 mSv/year [45]. Moreover, all values were under half the annual limit established by CNEN and the ICRP, which is 1 mSv/year [46, 47]. The results show notable proximity to the minimum value recorded in Manaus (0.22 mSv/year), in contrast to the maximum value observed in Belo Horizonte (3.27 mSv/year) [48].

Table 2: Natural radiation (cps) in different studies and locations.

REGION	MATERIAL	TOTAL COUNTS PER SECOND (CPS)	REFERENCE
Pandeiros River Basin (PRB), Minas Gerais, Brazil	Sediments and surface water	Inferior threshold: 31 Superior threshold 122 Average: 61	Present study
Irecê Region, Bahia	Outcropping limestone rocks and soil	45 — 80 Average: 50	[38]
Sub-basins of the Borrachudo River and the	Surface water	60 — 140 Average: 97.73	[40]

REGION	MATERIAL	TOTAL COUNTS PER SECOND (CPS)	REFERENCE
Indaiá River, Minas Gerais, Brazil			
Sub-basins of the Borrachudo River and the Indaiá River, Minas Gerais	Surface water	60 — 180 Average: 95.91	[40]
Maciço Sienítico Piquiri, Rio Grande do Sul, Brazil	Soil	130 — 1,045 Average: 600	[42]
Surrounding areas of Praia da Areia Preta, Guarapari, Espírito Santo, Brazil	Beach sand	60 — 150	[41]
Praia da Areia Preta, Guarapari, Espírito Santo, Brazil	Monazite beach sand	1,000 — 15,000	[41]
Esh-Shidiya and Al-Hisa mines, Jordan	Phosphate rocks	300 — 550	[43]
Gosmdochi Island, South Korea	Quarternary Alluvium	2,650	[44]

Table 3: Natural radiation dose rate parameters.

REGION/PARAMETER	DOSE RATE (mSv/year)	REFERENCE
Pandeiros River Basin, Minas Gerais	Inferior threshold: 0.13 Superior threshold: 0.37 Average: 0.22	Present study
Belo Horizonte, Minas Gerais	3.27*	[48]
Manaus, Amazonas	0.22*	[48]
Average annual global exposure to natural radiation sources	2.4	[45]
Occupationally exposed individuals	20**	[46]
General public	1**	[46]
Situations offering social benefit, but without direct individual benefit and where there is no information, training, or individual assessment for exposed individuals in normal situations	1**	[47]

*: Conversion to mSv/year by authors; **: Annual threshold.

4. CONCLUSIONS

This study established reference values (RVs) for the total gamma radiation count rate and dose rate in the Pandeiros River Basin (PRB) through in situ radiometric measurements supported by R programming, GIS, and mMAD statistical analyses. The findings indicated that radiation levels were below previously recorded values in other areas and below the regulatory limits set by CNEN and ICRP, thereby confirming a negligible radiological risk to local populations. The defined RVs provide an important diagnostic baseline for environmental assessments, particularly for evaluating the impact of the SHP Pandeiros dismantlement. Radiometric data indicated no significant sediment transport or temporal variations in the radiation distribution during the monitored periods, although limited sampling necessitates continuous monitoring to account for potential seasonal or spatial influences. Future studies should prioritize analysing radioactivity distribution across sediment grain-size fractions to enhance tracer applicability, alongside hydrochemical and physicochemical investigations of water-sediment interactions to elucidate radionuclide behaviour in biphasic systems. These steps would refine the monitoring framework and improve the understanding of the natural radioactivity dynamics in the PRB.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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