doi.org/10.15392/2319-0612.2026.3109
Braz. J. Radiat. Sci., Rio de Janeiro
Jul-Sep 2026, 14(3) | 01-21 | e3109
Editor(s): Dr. (Prof.) Bernardo Maranhão Dantas
Dr. (Prof.) Alfredo L. Ferreira Filho
Submitted: 2026-02-20
Accepted: 2026-03-24

Original Article

Groundwater vulnerability and radioecological hazard assessment in a semiarid watershed within the context of uranium mining in Caetité, Brazil

Sobrinho[a], G. A. N.; Fernandes[b], N. F.; Araújo[c], V. P.; Franklin[a*], M. R.

[a]Institute of Radiation Protection and Dosimetry, Brazilian Nuclear Energy Commission, Av. Salvador Allende 3773 - Barra da Tijuca, Rio de Janeiro, Brazil.
[b]Geosciences Institute, Federal University of Rio de Janeiro, Cidade Universitária - Rua Athos da Silveira Ramos, 274, Bloco I, sala 20, Rio de Janeiro, Brazil.
[c]Institute of Nuclear Engineering, Brazilian Nuclear Energy Commission, Cidade Universitária - R. Hélio de Almeida, 75 - Ilha do Fundão, Rio de Janeiro, Brazil.

*Correspondence: mariza.franklin@ird.gov.br

Abstract: In arid and semiarid watersheds, groundwater is the most reliable source of water all year-round, being used for domestic, agricultural, and industrial purposes. In such a context, conflicts over groundwater quality and/or supply are not rare. The lack of communication tools between the stakeholders hinders conflict resolution. A categorical example of such areas can be found at the Caetité Experimental Basin (CEB), where, from time to time, conflicts between stakeholders and the Uranium Production Unit (URA) take place. The CEB is a headwater, semiarid, ephemeral, hard-rock watershed, and groundwater vulnerability and radioecological hazard studies in this area are rare and outdated. Therefore, the present work aimed to map groundwater vulnerability and radioecological hazards posed by the URA to the CEB groundwater system through three index-based methodologies: the standard DRASTIC model, a locally-adapted DRASTIC-URA, and the Radioecological Hazard Index (RHI). Although most of the CEB presents low intrinsic groundwater vulnerability, the areas under the source terms are not equally vulnerable, and the most hazardous source term, from the point of view of radioecological impacts, is close to a highly vulnerable area. Such maps and indexes may be proven useful as a screening and communicative tool, since they illustrate the groundwater vulnerability distribution at CEB, as well as provide a way to compare it to other areas around the world.

Keywords: groundwater vulnerability, DRASTIC, uranium mining, radioecological hazard, semiarid hydrogeology.

Copyright © 2026 Authors.

doi.org/10.15392/2319-0612.2026.3109
Braz. J. Radiat. Sci., Rio de Janeiro
Jul-Sep 2026, 14(3) | 01-21 | e3109
Editor(s): Dr. (Prof.) Bernardo Maranhão Dantas
Dr. (Prof.) Alfredo L. Ferreira Filho
Submitted: 2026-02-20
Accepted: 2026-03-24

Vulnerabilidade da água subterrânea e avaliação do perigo radioecológico em uma bacia semiárida no contexto da mineração de urânio em Caetité, Brasil

Resumo: Em bacias hidrográficas áridas e semiáridas, as águas subterrâneas constituem a fonte de água mais confiável ao longo do ano, sendo utilizadas para fins domésticos, agrícolas e industriais. Nesse contexto, não são raros os conflitos relacionados à qualidade e/ou ao abastecimento dessas águas. A falta de ferramentas de comunicação entre as partes interessadas representa um obstáculo à resolução de conflitos. Um exemplo emblemático dessas áreas pode ser encontrado na Bacia Experimental de Caetité (CEB), onde, de tempos em tempos, ocorrem conflitos entre as partes interessadas e a Unidade de Concentração de Urânio (URA). A CEB é uma bacia hidrográfica de cabeceira, semiárida, efêmera e de rocha dura, e os estudos sobre vulnerabilidade das águas subterrâneas e riscos radioecológicos nessa área são escassos e desatualizados. Portanto, o presente trabalho teve como objetivo mapear a vulnerabilidade das águas subterrâneas e os perigos radioecológicos representados pela URA para o sistema de águas subterrâneas da CEB por meio de três metodologias baseadas em índices: o modelo DRASTIC padrão, um DRASTIC-URA adaptado localmente e o Índice de Risco Radioecológico (RHI). Embora a maior parte da CEB apresente baixa vulnerabilidade intrínseca das águas subterrâneas, as áreas sob os termos de fonte não são igualmente vulneráveis, e o termo de fonte mais perigoso, do ponto de vista dos impactos radioecológicos, está próximo a uma área altamente vulnerável. Tais mapas e índices podem se mostrar úteis como ferramenta de triagem e comunicação, uma vez que ilustram a distribuição da vulnerabilidade das águas subterrâneas na CEB, além de fornecerem uma maneira de compará-la com outras áreas ao redor do mundo.

Palavras-chave: vulnerabilidade da água subterrânea, DRASTIC, mineração de urânio, perigo radioecológico, hidrogeologia de semiárido.

Copyright © 2026 Authors.

1. INTRODUCTION

In arid and semiarid areas, groundwater is the most reliable and, sometimes, the only year-round available source of water. Sustainable management of water resources is a crucial and expensive activity, especially under such climatic constraints [1]. In these areas, conflicts over water usage are common, as evidenced in the semiarid region of northeastern Brazil. The Caetité Experimental Basin (CEB), located in Bahia State, is a rural, headwater, ephemeral watershed underlain by a fractured hard-rock aquifer, containing the only active uranium production center in Brazil, the Uranium Production Unit (URA). Evidence suggests that the groundwater system has a fast turnover time, which contributes to its vulnerability [2]. This nuclear installation is operated by Indústrias Nucleares do Brasil (INB) and, occasionally, conflicts over groundwater resources occur in the city of Caetité. The lack of visual tools to ease tension and facilitate communication among stakeholders appears to be a hindrance. Maps are efficient graphical tools that can aid in filling this communication gap [3], especially through the use of groundwater vulnerability maps.

The concept of groundwater vulnerability conveys the susceptibility of adverse effects imposed by contaminant loads from the land surface, implying that the unsaturated zone has varying protective capacity over groundwater systems [4]. Groundwater vulnerability screening and mapping tools can be used not only to prioritize protective, monitoring, and remediation efforts [5] but also to graphically represent the fragility of a given groundwater system. The term vulnerability in the present work should not be confused with risk or probability [6]. Probability is the quantified likelihood of a deleterious event (0 to 100%), while risk is the quantified magnitude of a probable deleterious event.

Hazard identification is the first step towards risk characterization and management [7]. A hazard, in the context of groundwater, can be defined as a potential source of contamination resulting from anthropogenic actions on the surface. Vulnerability and hazard assessments can

 Copyright © 2026 Authors

OPEN ACCESS

be a cost-effective way of visualizing and communicating the fragility of a groundwater system and the plausible relationships between hazard and contamination [8]. Most groundwater vulnerability mapping systems are purpose-constrained to support decision-making and should illustrate the spatial variation of the potential vertical pathways of contamination [9]. The most common type of groundwater pollution potential assessment is "intrinsic groundwater vulnerability" mapping, which considers only the characteristics of the hydrogeologic setting, regardless of the presence and/or type of contaminants on the surface [10].

There is no standard methodology for groundwater vulnerability assessments [11], and the most widely used approaches to this purpose are qualitative index-based GIS-aided methodologies, notably the DRASTIC method and its adaptations [12]. Also, DRASTIC parameters can be modified for a refined representation of local hydrogeologic settings [5]. Although more recent and sophisticated AI-based approaches have been proposed to optimize the DRASTIC method [13], their use requires sufficient groundwater contamination data to train the models, which are often unavailable.

Risk and probability assessments are cumbersome and cost-demanding, while the semi-quantitative Hazard Index approach can be used to support groundwater management at a much more accessible level [8].

These so-called qualitative and semi-qualitative index-based methods consist basically of (1) the selection of relevant/available thematic layers; (2) the ranking/weighting of the selected layers; (3) the integration of the superposed layers into a numeric index; and, (4) the categorization of the computed values into classes (e.g., from low to high). Usually, this procedure is performed in a Geographic Information System (GIS) environment, resulting in a map of groundwater vulnerability and, depending on the hazards distribution, on a hazard map. The advantages of these methods are operational (abundance of GIS tools and available digital databases), structural (simplicity and flexibility of the methodology), and communicational (stakeholders can see intuitive color schemes related to the groundwater system). The numerical value of the calculated index does not necessarily reflect the

 Copyright © 2026 Authors

OPEN ACCESS

CC BY

probability or risk of contamination, but rather the relative (qualitative) importance of a given area compared to others. Such importance or relevance consists in the concurrence of factors that are well-known to favor or hamper groundwater contamination.

Previous assessments at CEB are scarce and outdated. The operator, using GOD and POSH methods based on pre-operational data and a coarse pre-1997 digital elevation model (DEM), classified most of the area (93%) as having negligible to low vulnerability, except for narrow patches along the drainage system [14]. The limitations of the DEM used at that time likely underestimated local variation in the potentiometric surface and drainage delineation. Following this scheme, all source terms in the area (Figure 1) were considered by the operator in their study as having a high pollution potential. In addition, (a) the industrial plant and the tailing ponds were considered as having a low to moderate risk; (b) the solid waste pile, moderate risk; and (c) the Cachoeira open pit mine, the highest pollution risk level. Also, the POSH-based hazard and risk evaluations considered the chemical risks but not the radioecological ones.

Therefore, the present work aimed to assess groundwater vulnerability and radioecological hazards posed to the groundwater system in an experimental headwater basin in a semi-arid climate in the context of uranium mining and beneficiation through index-based methodologies.

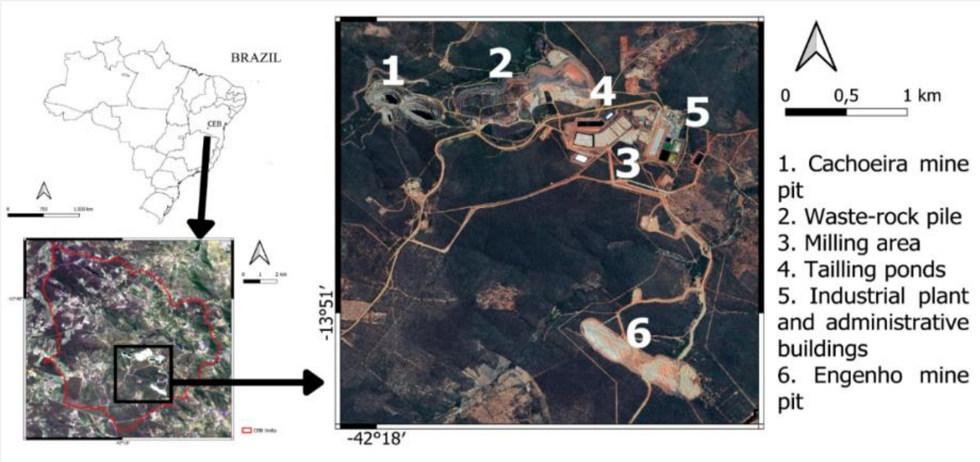
2. MATERIALS AND METHODS

2.1. Study area

The Caetité Experimental Basin (CEB) (Figure 1) is an 81 km^2 watershed located in Caetité, Bahia State, Brazil (13°49'51"S 42°17'15"W). The CEB contains the only uranium production center in Brazil, the URA, operated by INB, a Brazilian state-owned company.

OPEN ACCESS

Figure 1: Caetité's Experimental Basin (CEB), in red, and the Uranium Production Unit (URA), in detail. Numbers 1 to 6 are the source terms of the URA, except for the administrative buildings (5b).



The study area is under a semi-arid climate (Bsh), with an average rainfall of c.a. 700 mm, concentrated during summer (November to January); the average temperature is around 20 °C; and the estimated average evapotranspiration is 920 mm per year [15]. Since the early 90's, and more intensively between the years 2011-2016, the region has experienced the most severe drought ever recorded in the history of the Brazilian semi-arid region [16]. Besides the national meteorological stations at Caetité, the INB maintains a meteorological station within its area monitoring air temperature, precipitation, air moisture, and atmospheric pressure since 2000.

The topography at CEB varies from around 718 to 1000 masl and can be described as a gentle relief with flattened hilltops and smooth divides. The drainage system is tectonic fault-controlled, and the streams are ephemeral.

The CEB is located within the Lagoa Real Complex, in the Caetité Massif. CEB's hydrogeological setting consists of a fractured aquifer system underlain by crystalline hard rock and covered by a relatively deep vadose zone. The volume of water cycling in this system depends on the semiarid climate budget, and hence groundwater is expected to be restricted to the fractured zone. The uranium resources in the Caetité region amount to 87,000 tonnes distributed across 17 mineral deposits. The Cachoeira deposit, located within the Cachoeira sub-basin, contains c.a. 17,000 t U. From 2000 to 2015, the INB produced 3,750 t U_3O_8 by open-pit mining followed by heap leaching. Upon depletion of the Cachoeira deposit, the

 Copyright © 2026 Authors

adjacent Engenho deposit, located in the Engenho sub-basin, was brought into operation in 2020, employing the same extraction and processing methods. A comprehensive description of the geological setting in which the CEB is located can be found in [17].

The operator identified four major soil classes: Inceptisol, Ultisol, hydromorphic soils, and Oxisol [18]. The regolith cover can vary from absent in outcrops to 48 m deep at the hilltops, but the most frequent profile consists of a soil cover of less than 10 m deep, above a fractured hard-basement [14].

About 90 % of CEB's land use (LU) and Land Cover (LC) is either Cerrado (79.0 %), Capoeira (11.1 %), or bare soil (5.4 %). Only 0.1 % is built-up area, while the remaining 4.4 % is distributed between grasslands (3.6 %) and agriculture (0.8 %) [19].

2.2. DRASTIC-GIS models

The standard vulnerability map is referred to herein as DRASTIC [5], while the map produced by modifications of the original DRASTIC model using local-specific data is referred to as DRASTIC-URA. The modifications consisted of changing the ranges of the layers *D*, *R*, *T*, and *C*, using local values instead of default values.

The DRASTIC index can be integrated as a weighted sum, following Equation 1:

$$D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w = DRASTIC \qquad \text{Eq. 1}$$

where *D* is Depth to water; *R* is net Recharge; *A* is for the Aquifer media; *S* indicates the Soil media; *T*, the Topography; *I* is the Impact of the vadose zone; while *C* is the hydraulic conductivity of the aquifer. *w* is the layer-related weight, and *r* is the rating given to each range.

It can be assumed that the longer the path for a contaminant from the surface to cross the vadose zone and reach the groundwater, the more it retards the plume and increases the chance for its attenuation [5]. The D-layer accounts for this assumption. The mine operator monitored 55 wells at CEB in March 2004 and found a strong linear relationship ($r^2 = 0.98$)

 Copyright © 2026 Authors

OPEN ACCESS

between groundwater level and topography [14]. This relationship was used to generate the digital potentiometric model of CEB.

The DRASTIC method categorizes groundwater levels in ranges, attributing a rating for each range (Table 1). Following this categorization, the groundwater level digital model was converted into a "D-factor" layer. The same data were categorized using local range magnitudes (Table 1), and a "local D-factor" was then generated.

Infiltrating water is the main carrier of contaminants from the land surface into groundwater. Hence, annual net groundwater recharge is expected to be directly proportional to groundwater vulnerability [5]. According to [20], natural recharge at CEB varies from 2.9 to 16.4 $mm.year^{-1}$ (0.4 to 2.3% of annual precipitation). Similar rates were found elsewhere for the fractured aquifer system [21]. Following the DRASTIC methodology, this value of net recharge falls within the lowest range (Table 1) and receives the smallest rate (DR = 1), and hence, the R-layer was rated a single value for the conventional DRASTIC calculations.

To increase the local resolution of the vulnerability assessment map, the local groundwater recharge range and the groundwater recharge potential map [20] were used to generate the local R-layer for the DRASTIC-URA calculations.

The A-layer accounts for the properties of the aquifer related to the flow system. Depending on how consolidated or unconsolidated, porous or fractured, an aquifer is, the ratings of this parameter will reflect the easiness for water movement within the aquifer [5].

According to the hydrogeological domains identified by the operator [14], the geological map was used to generate this raster layer following the DRASTIC rating system (Table 1). This layer was used for both calculations: DRASTIC and DRASTIC-URA.

The S-layer represents the capacity of the soil to attenuate a percolating contaminant plume, while the I-layer is rated according to relevant impeding layers above the water table [5]. The soil map and the soil profile surveys performed by the operator [22,14] were used to derive both layers. The S-layer ratings followed the most restrictive textural class per profile.

 Copyright © 2026 Authors

OPEN ACCESS

CC BY

The I-layer grouped non-hydromorphic soils as "Sand and Gravel with significant Silt and Clay" (rating 4) and hydromorphic soils as "Sand and Gravel" (rating 8). Both layers were used for DRASTIC and DRASTIC-URA calculations (Table 1).

The T-layer represents the likelihood of runoff or infiltration taking place due to the slope of the land surface [5]. The steeper the slope, the higher the chances of runoff, and hence, the lower the groundwater vulnerability at a given point, and vice versa. This factor receives the smallest weight of all seven DRASTIC factors (TW = 1). The slope layer was derived from the Shuttle Radar Topography Mission (SRTM) digital model [23] in QGIS. For the conventional DRASTIC map, the T-factor raster was created following the default ranges and rating values (Table 1). For the DRASTIC-URA calculations, local ranges were used to generate a local T-layer by categorizing the local slope amplitude into five equal ranges (Table 1).

The C-layer indicates the rate at which a contaminant would move away from the entering point due to the hydraulic conductivity of the aquifer [5].

Since hydraulic conductivity at CEB is remarkably low, varying from 10^{-8} to 10^{-5} m.s^{-1} [14], the entire CEB falls into the smallest rating range according to the standard DRASTIC methodology (Table 1). Thus, a single value was attributed for the C-factor (CR = 1). For the DRASTIC-URA calculations, a local C layer was generated by categorizing the local amplitude of measured hydraulic conductivities into 6 classes, matching the default DRASTIC rating system (Table 1).

 Copyright © 2026 Authors

OPEN ACCESS

CC BY

Table 1 : Rating and Weighting schemes for DRASTIC and DRASTIC-URA methods.

PARAMETER	RANGE		RATE (r)	WEIGHT (w)
	DRASTIC RANGES	LOCAL RANGES		
	[m.b.s.l.]			
Depth to Water (D)	0 - 1.5	7.97 - 8.25	10	5
	1.5 - 4.6	8.25 - 8.53	9	
	4.6 - 9.1	8.53 - 8.81	7	
	9.1 - 15.2	8.81 - 9.10	5	
	15.2 - 22.9	9.10 - 9.38	3	
	22.9 - 30.5	9.38 - 9.66	2	
	>30.5	9.66 - 9.94	1	
	[mm.year^{-1}]			
Recharge (R)	0 - 50.8	2.9 - 5.6	1	4
	50.8 - 101.6	5.6 - 8.3	3	
	101.6 - 177.8	8.3 - 11.0	6	
	177.8 - 254	11.0 - 13.7	8	
	> 254	13.7 - 16.4	9	
	Geology			
Aquifer Media (A)	Massive Shale	"Weathered Metamorphic/Igneous" and "Sand and Gravel"	1 - 3 (2)	3
	Metamorphic/Igneous		2 - 5 (3)	
	Weathered Metamorphic/Igneous		3 - 5 (4)	
	Glacial Till		4 - 6 (5)	
	Bedded Sandstone, Limestone, and Shale Sequences		5 - 9 (6)	
	Massive Sandstone		4 - 9 (6)	
	Massive Limestone		4 - 9 (6)	
	Sand and Gravel		4 - 9 (8)	
	Basalt		2 - 10 (9)	
	Karst Limestone		9 - 10 (10)	
	Soil limiting layers			
Soil media (S)	Nonshrinkin and Nonaggregated Clay	"Nonshrinkin and Nonaggregated Clay " and "Clay Loam"	1	2
	Muck		2	
	Clay Loam		3	
	Silt Loam		4	
	Loam		5	
	Sandy Loam		6	
	Shrinking and/or Aggregated Clay		7	
	Peat		8	
	Sand		9	
	Gravel		10	
	Thin or Absent (< 25.4 cm)		10	
	Slope [%]			
Topography (T)	0 - 2	0 - 13	10	1
	2 - 6	13 - 26	9	
	6 - 12	26 - 39	5	
	12 - 18	39 - 52	3	
	>18	52 - 65	1	
	Vadose zone limiting layers			
Impact of vadose zone (I)	Confining Layer	"Sand and Gravel with significant Silt and Clay" and "Sand and Gravel"	1 (1)	5
	Silt/Clay		2 - 6 (3)	
	Shale		2 - 5 (3)	
	Limestone		2 - 7 (6)	
	Sandstone		4 - 8 (6)	
	Bedded Limestone, Sandstone, Shale		4 - 8 (6)	
	Sand and Gravel with significant Silt and Clay		4 - 8 (6)	
	Metamorphic/Igneous		2 - 8 (4)	
	Sand and Gravel		6 - 9 (8)	
	Basalt		2 - 10 (9)	
	Karst Limestone		8 - 10 (10)	
	[m.s^{-1}]			
Hydraulic conductivity (C)	4.72E-07 - 4.72E-05	9.46E-08 - 4.50E-06	1	3
	4.72E-05 - 1.41E-04	4.50E-06 - 8.90E-06	2	
	1.41E-04 - 3.30E-04	8.90E-06 - 1.33E-05	4	
	3.30E-04 - 4.72E-04	1.33E-05 - 1.77E-05	6	
	4.72E-04 - 9.43E-04	1.77E-05 - 2.21E-05	8	
	> 9.43E-04	> 2.21E-05	10	

2.3. Radioecological Hazard Index

An adaptation of the methodology described in [8] was used in the present work. A semi-quantitative Radioecological Hazard Index (RHI_j) was developed by integrating the contribution of mobile radionuclide loads and aspects of their behavior for source terms on the land surface. The RHI_j was calculated following equation 2:

$$RHI_j = \sum_{i=0}^{n} C_{ij} \times Q_{ij} \quad \text{Eq. 2}$$

where RHI_j is the radioecological hazard index of the source term j; C_{ij} is the contribution of radionuclide i from source term j due to its behavior; and Q_{ij} is the normalized (0 to 1) potentially infiltrating contaminant load of radionuclide i from source term j. The term C_{ij} was calculated from equation 3:

$$C_{ij} = 0.6R_{ij} + 0.2M_{ij} + 0.2D_{ij} \quad \text{Eq. 3}$$

where R_{ij}, M_{ij}, and D_{ij} are normalized (0 to 1) ratings for radiotoxicity, mobility, and degradation of radionuclide i from source term j, respectively. In this equation, the decimal factors are importance weights proposed by [8], meaning that mobility and degradation are equally important, and both are considerably less important than toxicity from the point of view of groundwater protection. For the present work, the chemical toxicity was not considered.

Specific activity ($Bq.g^{-1}$) [24] was used to quantify radiotoxicity. Mobility was accounted for in terms of average distribution coefficients (*Kd*) in soils [25], and degradation, which indicates persistence of a given radionuclide in the system, was calculated in terms of its half-life times [26]. These data are presented in Table 2.

 Copyright © 2026 Authors

OPEN ACCESS

Table 2 : Radionuclide data used to quantify radiotoxicity, mobility, and degradation. *Kd* is the liquid-to-solid distribution coefficient. $t_{1/2}$ is the half-life.

RADIONUCLIDE(*i*)	SPECIFIC ACTIVITY [Bq.g^{-1}]	***Kd*** [L.kg^{-1}]	$t_{1/2}$ [years]
^{nat}U	2.54E+04	2.00E+02	4.47E+09
^{nat}Th	4.06E+03	1.90E+03	1.41E+10
^{226}Ra	3.63E+10	2.50E+03	1.60E+03
^{228}Ra	8.66E+12	2.50E+03	5.75E+00
^{210}Pb	3.26E+12	2.00E+03	2.22E+01

Three source terms were chosen according to their permanence and available data [27,28]. A comprehensive inventory and characterization of all source terms was not available at the time of this investigation. However, some of the source terms that were already inventoried by the operator (e.g., milling area, heap leach piles, Engenho mine pit) could not be considered for this study, given the lack of information about mobile aqueous phases and/or mobilization rates. Therefore, only the waste rock pile, the Cachoeira mine pit, and the tailing ponds (Figure 1) were considered in this study. Due to their permanence and radiological composition, these source terms may in fact be the most relevant from the groundwater vulnerability and risk perspective. The main radionuclides in the study area, their respective concentrations, and the calculations of RHI_j are presented in Table 3. The mobile radionuclide concentrations were used for the contaminant load calculations. To represent the waste rock pile, the water that drains beneath the pile was sampled during January 2003, and its average (n = 3) concentration was used for the calculations. The water that accumulates from both rainfall and eventual groundwater emanations at the bottom of the Cachoeira mine pit was sampled (n=4) for radionuclide activities during the same period. The supernatant water from the tailing ponds was monitored, and the multiannual average (2002 to 2006) was used in the calculations.

The calculated *RHIj* is shown in Table 3. The source terms (i.e., hazards), in terms of *RHIj*, are ranked as follows: Tailings ponds (*RHIj* = 0.10) < waste rock pile (*RHIj* = 0.56) < Cachoeira open pit (*RHIj* = 0.64).

 Copyright © 2026 Authors

OPEN ACCESS

Table 3 : RHI_j calculations for three source terms at the CEB.

RADIONUCLIDE(i)	WASTE ROCK PILE (j) [Bq.L^{-1}]	Q_{ij}	T_{ij}	M_{ij}	D_{ij}	C_{ij}
^{nat}U	1.15E+00	0.37	0.00	0.00	0.32	0.06
^{nat}Th	1.29E-01	0.00	0.00	0.74	1.00	0.35
^{226}Ra	2.88E+00	1.00	0.00	1.00	0.00	0.20
^{228}Ra	2.59E-01	0.05	1.00	1.00	0.00	0.80
^{210}Pb	2.25E+00	0.77	0.38	0.78	0.00	0.38
					RHI_j	0.56
RADIONUCLIDE(i)	CACHOEIRA MINE PIT (j) [Bq.L^{-1}]	Q_{ij}	T_{ij}	M_{ij}	D_{ij}	C_{ij}
^{nat}U	4.22E+00	0.93	0.00	0.00	0.32	0.06
^{nat}Th	1.03E-01	0.00	0.00	0.74	1.00	0.35
^{226}Ra	3.96E+00	0.87	0.00	1.00	0.00	0.20
^{228}Ra	2.28E-01	0.03	1.00	1.00	0.00	0.80
^{210}Pb	4.53E+00	1.00	0.38	0.78	0.00	0.38
					RHI_j	0.64
RADIONUCLIDE(i)	TAILING PONDS (j) [Bq.L^{-1}]	Q_{ij}	T_{ij}	M_{ij}	D_{ij}	C_{ij}
^{nat}U	4.83E+02	1.00	0.00	0.00	0.32	0.06
^{nat}Th	1.72E+00	0.00	0.00	0.74	1.00	0.35
^{226}Ra	4.22E+01	0.08	0.00	1.00	0.00	0.20
^{228}Ra	4.39E+00	0.01	1.00	1.00	0.00	0.80
^{210}Pb	2.08E+01	0.04	0.38	0.78	0.00	0.38
					RHI_j	0.10

3. RESULTS AND DISCUSSIONS

Most of the area (91%) was classified as having low (77%) or very low (14%) vulnerability, with some areas presenting high (5%) to very high (4%) vulnerability (Figure 2). DRASTIC values varied from 64 to 134 ($\bar{x}$ = 91 ± 11). According to the modified approach, the DRASTIC-URA, the CEB was classified as having very low (32%), low (38%), high (27%), and very high (4%) vulnerability (Figure 3). DRASTIC-URA values varied from 58 to 193 ($\bar{x}$ = 118 ± 23).

The areas with lower vulnerability are evenly widespread, while those with higher vulnerability are limited to elongated patches. Source terms are located mostly in low to high-vulnerability areas, but parts of the Cachoeira and Engenho mine pits are close to very high-vulnerability areas.

OPEN ACCESS
CC BY

Figure 2: DRASTIC index vulnerability map.

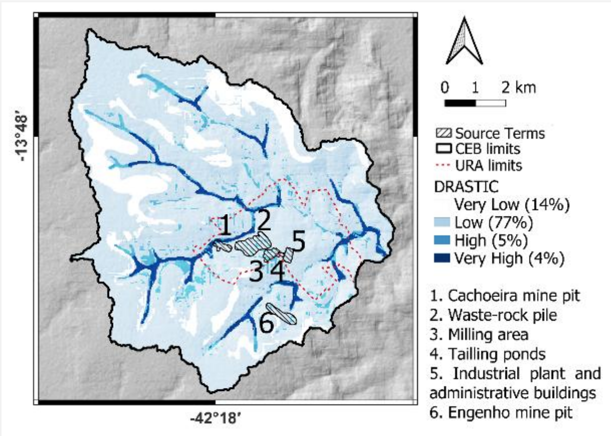
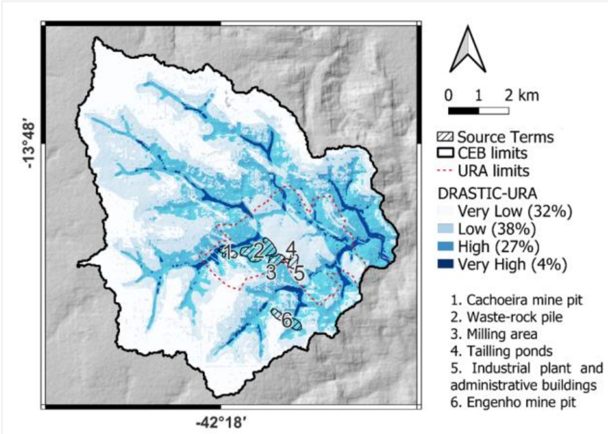


Figure 3: DRASTIC-URA index vulnerability map.



Both DRASTIC and DRASTIC-URA maps (Figures 2 and 3) followed the same general tendency reported by the operator using the GOD method [14], that is, the more vulnerable areas being concentrated at the valley bottoms, and the less vulnerable ones at the topmost areas. The DRASTIC map indicates the groundwater vulnerability at CEB in comparison to the natural diversity of hydrogeological settings around the world (default DRASTIC amplitude), while the DRASTIC-URA provides a way of discriminating the local variation of groundwater vulnerability at CEB (local amplitude). For context, Mondal et al. [29] found DRASTIC values varying from 39 to 132 in a fractured granitic terrain in India, while El Mountassir et al. [30] reported values varying between 114 and 191 in an area with karstic and porous aquifers. The DRASTIC index can vary theoretically between 23 and 230; therefore, the DRASTIC values found at CEB – falling in the lower portion of the DRASTIC range – can be considered low. According to the DRASTIC assessment, most source terms at the CEB are located in low vulnerability areas (Figure 2). However, according to the DRASTIC-URA map (Figure 3), it can be noticed that the vulnerability of the groundwater system beneath almost all source terms is higher than expected according to the standard DRASTIC map. While the DRASTIC map shows that groundwater vulnerability at CEB is considerably low compared to other hydrogeological settings around the world, the DRASTIC-URA provides a more detailed map showing that areas classified as low

OPEN ACCESS

vulnerability by the DRASTIC method are not equally vulnerable. Factors D and I (W=5) dominate the vulnerability signal, followed by R (W=4). Because R and C received a uniform value across the basin in the standard DRASTIC, their spatial contribution only becomes visible in the DRASTIC-URA (Figure 3).

Coincidentally, RHI_j followed the same pattern as the chemical pollution risk classification reported by the operator according to the POSH method [14]. The hazard assessment performed in the present work is limited not only by the lack of data on the radionuclide inventory in all source terms present at the CEB, but also by its dynamics. For example, although an enormous amount of waste rock (about 12,210,000 t) and consequently a considerable mass of radionuclides are present in the waste rock pile, the rate at which they are liberated from the bearing minerals and percolated out of the pile is not known. It is worth highlighting the proximity between the Cachoeira and Engenho mine pits and the drainage channels, which are areas of higher vulnerability in both DRASTIC and DRASTIC-URA maps. The Engenho mine pit could not be included in the RHI_j due to the lack of aqueous-phase data for post-2020 operations. However, its operational and hydrogeological similarities to Cachoeira suggest that this source term is likely to present the same radioecological hazard profile.

Beyond the scientific description of the groundwater system, vulnerability and hazard maps at the CEB serve two operational purposes. First, they support risk-based prioritization of monitoring and containment efforts by identifying the coincidence of vulnerable zones and high-hazard source terms – in this case, the drainage valley near the Cachoeira and Engenho pits. Second, they provide an objective cartographic basis for stakeholder dialogue in a region where groundwater disputes have historically escalated to operational interruptions at the URA. Eventually, by providing a shared understanding of the vulnerability of groundwater resources, groundwater vulnerability maps can help to promote constructive dialogue and collaboration among stakeholders, leading to better outcomes for all involved.

OPEN ACCESS

4. CONCLUSIONS

The DRASTIC map illustrated the vulnerability of groundwater at CEB within the broader context of hydrogeologic systems worldwide, while the DRASTIC-URA is a graphical representation of the local variation in groundwater vulnerability at CEB. The DRASTIC map reflected the expected low vulnerability of a semiarid hard rock watershed, while the DRASTIC-URA highlighted that, although most of the watershed presented low vulnerability, areas beneath the source terms are not equally vulnerable. The RHI_j assessment indicated that, among the three analyzed source terms, the relatively most hazardous source, i.e., the Cachoeira open pit, although being in a low vulnerability area, is close to a drainage valley, which is classified as a highly vulnerable area. The Engenho mine pit is expected to share the same radioecological hazard profile. The results presented herein can be useful both for management purposes as well as for eventual communication with stakeholders about groundwater vulnerability and radioecological risks at the CEB, since they illustrate and provide a means of comparison of the CEB with other areas around the world, as well as locally, between different points at the CEB.

ACKNOWLEDGMENT

The authors are grateful for the support offered by the Brazilian Nuclear Industries (INB) during field work for data collection and for their assistance in providing CEB environmental characterization data. The first author is grateful for the doctorate scholarship received from the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES).

OPEN ACCESS

CC BY

FUNDING

This research was funded by the Technical Cooperation Program of the International Atomic Energy Agency (IAEA), Project Number BRA7010, and partially by the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES).

CONTRIBUTORSHIP

Conceptualization: MRF, GANS

Methodology and Formal Analysis: GANS

Investigation: GANS, VPA, MRF, NFF

Funding acquisition and Supervision: MRF, NFF

Project administration: MRF

Writing – original draft: GANS

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study and the derived data supporting the conclusions of this study are available upon reasonable request to the corresponding author.

 Copyright © 2026 Authors

OPEN ACCESS

CC BY

REFERENCES

[1] SENENT-APARICIO, J. *et al.* Evaluating Groundwater Management Sustainability under Limited Data Availability in Semiarid Zones. **Water**, v. 7, n. 12, p. 4305–4322, ago. 2015.

[2] ARAÚJO, V. P. de *et al.* Groundwater isotopic variations in a uranium mining site: subsidies for contamination studies. **Brazilian Journal of Radiation Sciences**, v. 5, n. 2, p. 01–23, 2017.

[3] STIEB, D. M. *et al.* Using maps to communicate environmental exposures and health risks: Review and best-practice recommendations. **Environmental Research**, v. 176, p. 108518, set. 2019.

[4] FOSTER, S.; HIRATA, R.; ANDREO, B. The aquifer pollution vulnerability concept: aid or impediment in promoting groundwater protection? **Hydrogeology Journal**, v. 21, n. 7, p. 1389–1392, nov. 2013.

[5] ENVIRONMENTAL PROTECTION AGENCY (EPA). **DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings**. [S. l.]: Robert S. Kerr Environmental Research Laboratory, 1987.

[6] BAALOUSHA, H. M. Vulnerability, probability and groundwater contamination risk. **Environmental Earth Sciences**, v. 76, n. 11, p. 384, maio 2017.

[7] KARAMOUZ, M.; AHMADI, A.; AKHBARI, M. **Groundwater hydrology: engineering, planning, and management**. 2. ed. Boca Raton: CRC Press, 2020.

[8] WANG, J.; HE, J.; CHEN, H. Assessment of groundwater contamination risk using hazard quantification, a modified DRASTIC model and groundwater value, Beijing Plain, China. **Science of The Total Environment**, v. 432, p. 216–226, ago. 2012.

[9] FOSTER, S. S. D. *et al.* Aquifer pollution vulnerability concept and tools–use, benefits and constraints. **Groundwater vulnerability assessment and mapping**. IAH-selected Papers, v. 11, p. 2–9, 2007.

[10] IBE, K. M.; NWANKWOR, G. I.; ONYEKURU, S. O. Assessment of Ground Water Vulnerability and its Application to the Development of Protection Strategy for the Water Supply Aquifer in Owerri, Southeastern Nigeria. **Environmental Monitoring and Assessment**, v. 67, n. 3, p. 323–360, mar. 2001.

OPEN ACCESS

BY

[11] AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM). **Guide for Selection of Methods for Assessing Groundwater or Aquifer Sensitivity and Vulnerability**. [S. l.]: ASTM International, 2015. Disponível em: http://www.astm.org/cgi-bin/resolver.cgi?D6030-15. Acesso em: 26 jan. 2021.

[12] ADUCK, J. N.; MUFUR, A. M.; FONTEH, M. F. A Review of Methods to Assess Groundwater Vulnerability to Pollution. **American Journal of Environmental Protection**, v. 13, n. 4, p. 93–107, set. 2024.

[13] GÓMEZ-ESCALONILLA, V.; MARTÍNEZ-SANTOS, P. A Machine Learning Approach to Map the Vulnerability of Groundwater Resources to Agricultural Contamination. **Hydrology**, v. 11, n. 9, p. 153, set. 2024.

[14] INDÚSTRIAS NUCLEARES DO BRASIL (INB). **Estudo Hidrogeológico Ambiental para Caracterização do Potencial de Contaminação dos Solos e Água Subterrânea na Área da Unidade de Concentrado de Urânio (URA) em Caetité - BA**. Caetité: INB, 2004.

[15] INSTITUTO DE RADIOPROTEÇÃO E DOSIMETRIA (IRD). **Sustainable Management of Groundwater in Caetité, Bahia, BR**. [S. l.]: IRD, 2009. Relatório final.

[16] MARENGO, J. A. *et al*. Climatic characteristics of the 2010-2016 drought in the semiarid Northeast Brazil region. **Anais da Academia Brasileira de Ciências**, Rio de Janeiro, v. 89, n. 2, p. 0-0, 2017.

[17] LOBATO, L. M. *et al*. U–Pb geochronology of the Lagoa Real uranium district, Brazil: Implications for the age of the uranium mineralization. **Journal of South American Earth Sciences**, v. 58, p. 129–140, 2015.

[18] PLANARQ. **Estudo de Impacto Ambiental do Complexo Uranífero Mínero-Industrial de Lagoa Real, Caetité, BA**. [S. l.: s. n.], 1997.

[19] FERREIRA, C. E. G.; FERNANDES, N. F.; FRANKLIN, M. R. Mapeamento do uso e cobertura das terras da Bacia Hidrográfica do rio Vacas, Caetité –BA, para subsidiar o gerenciamento dos recursos hídricos. *In*: REUNIÃO BRASILEIRA DE MANEJO E CONSERVAÇÃO DO SOLO E DA ÁGUA, 18., 2010, Teresina. **Anais...** Teresina: [s. n.], 2010.

[20] SOBRINHO, G. A. N. **Processos De Recarga E Avaliação Da Vulnerabilidade À Contaminação Da Água Subterrânea Em Áreas De Mineração De Urânio**. 2023. Tese (Doutorado em Radioproteção e Dosimetria) — Instituto de Radioproteção e Dosimetria, Rio de Janeiro, 2023.

 Copyright © 2026 Authors

OPEN ACCESS

[21] WALCZUK, A.; CAMPOS, J. E. G.; AZEVEDO, J. H. de. Fractured and porous aquifer recharge in semiarid regions and the relevance of soil covers: A review for Caetité area, Bahia, Brazil. **Journal of South American Earth Sciences**, v. 159, p. 105525, jun. 2025.

[22] INDÚSTRIAS NUCLEARES DO BRASIL (INB). **Estudo de Impacto Ambiental - EIA do Complexo Uranífero Mínero-Industrial de Lagoa Real**. Caetité: INB, 1997. v. 1.

[23] OPENTOPOGRAPHY. **Shuttle Radar Topography Mission (SRTM) Global**. [S. l.], 2013.

[24] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). **A Basic Toxicity Classification of Radionuclides**. Vienna: IAEA, 1963. (Technical Report Series).

[25] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). **Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments**. Vienna: IAEA, 2010.

[26] INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA). **Live Chart of Nuclides: nuclear structure and decay data**. Disponível em: https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html. Acesso em: 13 fev. 2025.

[27] INDÚSTRIAS NUCLEARES DO BRASIL (INB). **Relatório Final de Análise de Segurança – RFAS, Gerenciamento das águas**. [S. l.]: INB, 2007.

[28] INDÚSTRIAS NUCLEARES DO BRASIL (INB). **Programa de monitoração ambiental operacional e de efluentes e rejeitos da mina cachoeira e pré-operacional da mina do engenho**. Caetité: INB, 2020.

[29] MONDAL, N. C. *et al.* Determining shallow aquifer vulnerability by the DRASTIC model and hydrochemistry in granitic terrain, southern India. **Journal of Earth System Science**, v. 126, n. 6, p. 89, set. 2017.

[30] EL MOUNTASSIR, O. *et al.* GIS-based assessment of aquifer vulnerability using DRASTIC model and stable isotope: a case study on Essaouira basin. **Arabian Journal of Geosciences**, v. 14, n. 4, p. 321, fev. 2021.

OPEN ACCESS

LICENSE

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material.
To view a copy of this license, visit http://creativecommons.org/ licenses/by/4.0/.