2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

ISBN: 978-65-594-1256-3

Groundwater Vulnerability and Contamination Risks on a Uranium Mining Site in a Water-Scarce Scenario in Caetité, Bahia, Brazil

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1. Introduction

It is known that uranium mining and milling facilities can impact groundwater resources [1]. The vulnerability of the groundwater to radiological contamination will be controlled to a certain extent by the interplay between infiltration and attenuation through the vadose zone (the layer that separates land surface and aquifers)[2,3]. Each groundwater system will have a particular configuration of the many factors involved in these dynamics, thus, each aquifer will present an intrinsic vulnerability to pollution from uranium production facilities [2]. Depending on the localization of the source terms and their contaminant loads, the groundwater risk to contamination can be further calculated [4]. Under arid and semiarid climates, the "infiltration" part of the balance may be limited both in quantity (low precipitation, high evapotranspiration) and in space (focused on the lowermost areas, as drainage networks and depressions)[5]. Consequently, despite the overall vulnerability in semiarid regions being expected to be low, some "extremely vulnerable" localized areas may occur. This issue can be aggravated also by social, political, and economical dimensions. For example, groundwater can be a sensitive resource for both locals and the national nuclear program. In Brazil, the only operational uranium mine – the uranium concentrate unit (URA) – is a nuclear facility located within the Brazilian semiarid, in the so-called "Droughts Polygon". Occasionally, disputes between stakeholders and the operator take place over groundwater resources, even disturbing the uranium production[6]. The assessment of groundwater vulnerability – and its outcomes – is a useful tool (1) to screen and identify areas that need more attention and, hence, resources allocation; (2) to give a scientifically plausible guidance for managers and policymakers towards groundwater sustainability; and (3) to communicate the spatial distribution of groundwater vulnerability with different stakeholders [7–9]. The objective of the present work is to map the intrinsic groundwater vulnerability and to calculate the risk to contamination of a water-scarce watershed containing a uranium mining and milling facility.

2. Methodology

The study area – the Caetité Experimental Basin (CEB) – is located in Caetité, Bahia (13°49'51"S 42°17'15"W), within the Brazilian semiarid (Bsh), and it consists of a c.a. 80 km² watershed containing the URA, operated by the Indústrias Nucleares Brasileiras (INB). The average rainfall is 700 mm per year (concentrated between November and January), and the temperature varyes around 20 °C. The annual potential groundwater recharge is around 10 %. The hydrogeology is dominated by fractured crystalline rocks (mostly granites and gneisses) and the vadose zone is dominated by Cambisols and Acrisols, with some Ferralsols near the topmost divides and indiscriminate hydromorphic soils along the drainage valley-bottoms. The drainage is ephemeral and runoff is observed only up to a few days after torrential events. The main source of water for both URA and locals is the groundwater [10].

Intrinsic Groundwater vulnerability at CEB was assessed by the conventional DRASTIC method [2]. This method is an index-based approach that evaluates the relative potential for groundwater contamination from pollution sources on land surface. The DRASTIC index uses seven parameters, all well known to control groundwater vulnerability, in a weighted-sum scheme, as follows:

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

Where *D* accounts for depth to groundwater, *R* for recharge rate, *A* for aquifer media, *S* for soil media, *T* for topography (slope), *I* for the impact of the vadose zone, and *C* for hydraulic conductivity of the aquifer system. The subscript *r* is the rating (from 1 to 10) and *w* is the weight (from 1 to 5), given to each parameter according to the DRASTIC methodology. The amplitude of DRASTIC values found at CEB were then categorized in equal intervals as very low, low, moderate, and high. The groundwater risk to contamination (*GRC*) was calculated following the methodology proposed by Wang et al. [4], summarized in Eq. 2:

$$GRC = DRASTIC \times HI_c \tag{2}$$

Where HI_c is the hazard index class (from 1 to 5). The Hazard Index for the hazard *j* (or source *j*) can be calculated using the following equations:

$$HI_j = \sum_{i=0}^{n} C_{ij} \times Q_{ij} \tag{3}$$

$$C_{ij} = 0.6T_{ij} \times 0.2M_{ij} \times 0.2D_{ij} \tag{4}$$

Where HI_j is the quantification of the hazard *j*; Q_{ij} is the infiltrating contaminant load due to contaminant *i* from hazard *j*; C_{ij} represents the behavior of the contaminant *i* from hazard *j*, while *T*, *M*, and *D* are the toxicity, mobility, and degradation properties of contaminant *i* from hazard *j*, surveyed from official standards, guidelines, and specialized literature. The geospatial thematic layers, as well as the vulnerability and risk maps, were generated on QGIS from freely available remote sensed data (e.g. LANDSAT, SRTM), and the BRA7010 Project database (e.g. soil, geology, drainage maps, water chemistry monitoring surveys) [11].

3. Results and Discussion

The areas with higher vulnerability, in terms of the DRASTIC index (Figure 1), are remarkably restricted to lower parts of the terrain (drainage network and hydromorphic soils). Although these areas were classified as presenting high vulnerability, the maximum DRASTIC value found at CEB was 137 ($\bar{x} = 91.25$, $\sigma = 10.76$), which can be considered low within the theoretical amplitude of this index (23 to 226). 90 % of the area falls into low or very low classes, while only 7 % were considered moderate, and 3 %, high. Although the overall vulnerability at CEB is low, some of the source-terms (hazards) are located near high-vulnerability areas. The hydrogeological parameters as geology , pedology, and topography (slope) indicate that infiltration is favored along the most elevated borders due to slope and soil properties. Depth to groundwater and recharge data indicate the hydroclimatological characteristics of the region. Although infiltration is favored by soil hydraulic properties at CEB, the slope controls groundwater recharge distribution, and the climate limits the water available to be stored in the aquifer system, and hence, the depth of the water table. The interplay of these factors will control the spatial distribution of the groundwater vulnerability to contamination from sources on land surface. The groundwater vulnerability map highlighted the importance of the areas with hydromorphic soils. These soils present high infiltration rates and occur at the main drainage network, where the water table remains close to the surface most of the year.

The groundwater risk to contamination assessment at CEB is still being conducted and are expected to be concluded by early November, where more conclusive results will be provided.

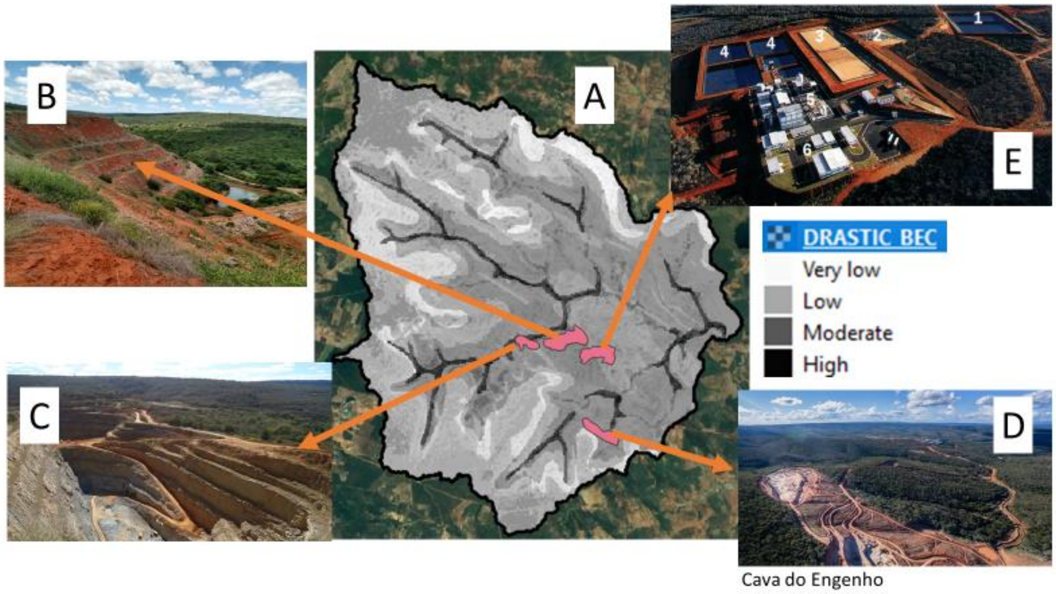

Figure 1 - Intrinsic Groundwater Vulnerability (DRASTIC) map and source-terms (hazards) location within the CEB. A – DRASTIC map; B – Waste-rock piles; C – Cachoeira mine pit; D – Engenho mine pit; E – processing facility (from 1 to 5), and administrative buildings (6).

4. Conclusions

Although some areas were classified as highly vulnerable in terms of the DRASTIC index, 90 % of the CEB was classified as having low or very low vulnerability. Some of the URA's source-terms are close to higher vulnerability areas, highlighting the sensitivity of these areas to the sustainability of the groundwater resources at CEB. It can be concluded that CEB has a low overall groundwater vulnerability to contamination sources at land surface.

Acknowledgements

The authors are grateful for the technical and financial support provided by the International Atomic Energy Agency (IAEA), to the Coordination for the Improvement of Higher Education (CAPES) for the doctorate scholarship granted to the first author. The authors appreciated the the field support and access to databases given by the Indústrias Nucleares Brasileiras (INB) for the development of this work.

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