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Potential Risk of Contamination of the Dunas-Barreiras Aquifer System by Anthropic Activities in a Source Area in Northeastern Brazil

Potencial Risco de Contaminação do Sistema Aquífero Dunas-Barreiras por Atividades Antrópicas em Área de Manancial no Nordeste brasileiro

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Abstract: The Dunas-Barreiras Aquifer system is in the NE region of Brazil, near the eastern coast of Rio Grande do Norte, and in it, one finds the Bonfim Lake System. Such aquifer is used for the supply of about 300,000 people, is characterized as free and is composed of a single system, although the dunes and the Barreiras Formation have specific characteristics. From a Multicriterion Analysis, involving maps algebra and Weighted Linear Combination of physical, biotic and anthropic attributes, in Geographic Information Systems (GIS) environment, the present work proposes to identify, in 1:100.000 scale, areas with higher potential risks of groundwater contamination in the area covered by the Bonfim System. The results point that 46.14% of the spring presented contamination potentials Medium, Strong and Very Strong. On the other hand, areas with despicable potential covered 39,73% represented by semi-natural areas, without the presence of anthropic activities. The spatialization of the potential risk of contamination of the underground water of this spring aims to help in the decision making, public and private, contributing for the territorial planning of the municipalities of São José de Mipibu and Nísia Floresta, presenting areas in which the anthropic use should be delayed, prioritizing the conservation.

Keywords: Groundwater Contamination; Land use and land cover; Anthropic activities; Environmental modeling; GIS; Multicriteria analysis.

Resumo: O sistema Aquífero Dunas-Barreiras está localizado na região NE do Brasil, próximo ao litoral oriental do Rio Grande do Norte, e nele, encontra-se o Sistema Lacustre do Bonfim. Tal aquífero é utilizado para o abastecimento de cerca de 300.000 pessoas, é caracterizado como livre e é composto por um sistema único, embora as dunas e a Formação Barreiras possuam características específicas. A partir de uma Análise Multicritério, envolvendo álgebra de mapas e Combinação Linear Ponderada de atributos do meio físico, biótico e antrópico, em ambiente de Sistemas de Informação Geográfica (SIG), o presente trabalho se propõe a identificar, em escala 1:100.000, áreas com maiores potenciais riscos de contaminação das águas subterrâneas na área abrangida pelo Sistema Bonfim. Os resultados apontam que 46,14% do manancial apresentou potenciais de contaminação Médio, Forte e Muito Forte. Por outro lado, áreas com potencial Desprezível abrangeram 39,73% representadas por áreas seminaturais, sem a presença de atividades antrópicas. A espacialização do potencial risco à contaminação das águas subterrâneas desse manancial visa auxiliar tomadas de decisão, pública e privada, contribuindo para o planejamento territorial dos municípios de São José de Mipibu e Nísia Floresta, apresentando áreas em que uso antrópico deveria ser retardado, priorizando a conservação.

Palavras-chave: Contaminação de Águas Subterrâneas; Uso e cobertura da terra; Atividades antrópicas; Modelagem Ambiental; SIG; Análise multicritério

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1. Introduction

Groundwater accounts for 99% of all liquid and fresh water on planet Earth, providing half of the volume abstracted for domestic use by the global population, estimated at 7.8 billion (WWAP, 2022). In addition, groundwater is of fundamental importance in water and food security and may be affected by changes in the hydrological cycle resulting from changes in the climate pattern (IPCC, 2021).

On a global scale, in regions of scarcity, such as arid and semi-arid climate zones, groundwater is the main source responsible for freshwater supply (GLEESON, 2020). In these regions, especially those located in developing countries, groundwater plays a strategic role for economic and social progress, as, in addition to supply, it is a primary input for the progress of human activities (WWAP, 2022) and for the implementation of sustainable development, as well as (for the supply of) water for long periods, even during a period of intense drought (CHENINI; ZGHIBI; KOUZANA, 2015; PARKINSON; HUNT, 2020; BUSICO et al., 2020). However, seasonalities, which are related to natural cycling rates and are exacerbated by intense uses and climate change, have increasingly influenced the availability of this resource to meet regional demands (IPCC, 2021).

The need to increase groundwater exploitation to meet growing demand (COSTA et al., 2015; BONSOR et al., 2018; VANN et al., 2020) has increased concern about the quality of this resource (RAZANDI et al., 2015; FILIPPIS et al, 2020). Successive evidence points to the degradation of groundwater reserves caused by increasing environmental pollution from anthropogenic activities, putting the quantity and quality of this resource at risk (RAZANDI et al., 2015).

Worldwide, anthropogenic activities have drastically altered the natural conditions of soil cover, reduced the natural area and increased the area of impervious cover, mainly in the form of urbanized and industrialized areas, bringing negative environmental consequences (TUNDISI et al., 2008; DELINOM et al., 2009; ZHAO et al., 2015; MARTÍNEZ et al., 2014; ZHAI et al., 2021). These areas, when occupied without the adoption of technical criteria and sanitary infrastructure, end up being marked by the presence of septic and black tanks, leaks from the sanitary sewage network, insertion of effluents in rainwater galleries, infiltration of industrial effluents into the soil, leaks from service stations and dumps (SÃO PAULO, 2019). Consequently, pollutants such as nitrate (NO3-), chloride (Cl-), sulfate (SO42-) and pathogens, among others, are released and can reach the saturated zone, contributing to the decline in the quality of groundwater reserves (DEVIC; DJORDJEVIC; SAKAN 2014; DANIELA et al., 2017, MARIJIć et al., 2017).

In rural areas, the sources of contamination are mainly from the large number of agrochemicals used in agriculture, so the indiscriminate use of fertilized nitrogen has emerged as a diffuse source of pollutants worldwide (FARJAD et al., 2012; RUFINO et al. 2019; MACHATE et al., 2021). In both urbanized and rural areas, nitrate and sulfate concentrations have been an indicator of groundwater contamination (POWELL et al., 2003; DEVIC; DJORDJEVIC; SAKAN, 2014; CETESB, 2018; VIGLIOTTI; BUSICO; RUBERTI, 2020). In the study area, Castro et al. (2014) found an advance of the urbanized area of the municipality of Nísia Floresta over the Bonfim System (SB), more precisely over the area surrounding the wells of the first battery of the Monsenhor Expedito Pipeline. In fact, one of these wells reached, at the time, the concentration of Nitrate (NO3-) of 9.21 mg/L, being close to the maximum permissible limit for human consumption of 10 mg/L (BRASIL, 2017).

The need to protect groundwater resources combined with land use planning has led to the mapping of areas that represent a greater potential for groundwater contamination (MARANGON, et al., 2017; COSTA, et al., 2019). Such zoning is an important tool to support decision-making for territorial and water planning (COSTA, et al., 2015; PIGA, et al., 2017; COSTA, et al., 2020).

Different approaches have been proposed to map groundwater vulnerability, such as: statistical models that express vulnerability in terms of impacts of human activities (WANG et al., 2010; MALAKOOTIAN; NOZARI, 2020; MACHATE, et al, 2021), impacts of agriculture (VIRGLIOTTI; BUSICO; RUBERTI, 2020), simulations with numerical and statistical modeling (LA TORRE et al., 2020; SUN et al., 2020) and overlay techniques in a GIS environment (RAZANDI, 2015; OROJI, 2019; COSTA, et al., 2020; EASWER et al., 2022). Multicriteria analysis is a tool used in large areas of knowledge, such as health, engineering, environment, process management, technology, being interesting for small and large decision making favoring the crossing of simultaneous information; in addition to making the decisions of the specialists more assertive, this tool allows several adjustments in the model depending on the scale of work considered (JAHAN; EDWARDS, 2013; REN et al 2020). Thus, Multicriteria Analysis in a GIS environment, among the overlapping techniques, is advantageous in the acquisition and computational processing of geo-environmental data in the form of georeferenced information plans. The results have been shown to be balanced and reliable when applied to the potential for aquifer contamination (PIGA, et al., 2017; COSTA, et al., 2019).

Globally, the DRASTIC (ALLER et al., 1987), GOD (FOSTER, 1987), SINTACS (CIVITA, 1994) and COP (VÍAS et al., 2002; 2006) methods are used in the prediction of aquifer contamination. DRASTIC is represented by indices that make up the methodology, such as: Depth to water table (D), Net recharge (R), Aquifer type (A), Soil medium (S), Topography (T), Impact of vadose zone (I) and Hydraulic conductivity (C) (ALLER et al., 1987). The indices are classified based on the superposition of factors, from a linear combination, considering the hydrogeological characteristics, however this configuration demonstrates the intrinsic sensitivity of the system, not considering the characteristics exogenous to it (SAIDI; BOURI; DHIA, 2009; RAMA et al., 2022;). The GOD methodology aims to assess aquifer vulnerability. This model has the characteristics of using the combination of only three variables: Aquifer Type (G); Lithology and Degree of Consolidation of the Vadose Zone or Confining Layers (O) and Depth of the water level or the confining base of the aquifer (D) (FOSTER, 1987; FOSTER; HIRATA, 1988). Thus, the GOD presents some deficiencies from the activities that are not intrinsic to the systems, directly presenting the vulnerability closer to natural conditions, not considering anthropic variables (GOMES; MENDONÇA; CAVALCANTE, 2018; PEIXOTO; CAVALCANTE, 2022).

In the studied area, groundwater supplies about 300,000 people and its quality and quantity are directly linked to land use and land cover. In view of this, the present work aims to evaluate the intrinsic and extrinsic vulnerability, generating the potential risk of contamination of the Dunas/Barreiras Aquifer System, through a multicriteria approach in the Bonfim System (SB).

2. Study Area

The Bonfim System (SB) is located on the eastern coast of the state of Rio Grande do Norte (RN), 25 km south of Natal, the state capital, covering part of the municipalities of Nísia Floresta and São José do Mipibu (Figure 1). The SB is positioned in the hydrographic basins of the Trairi and Potengi rivers, in an area of diffuse flow over sedimentary terrain of the Barreiras Formation and dune fields, comprising an area of 72.19 km². The SB stands out for its high-water potential and for comprising one of the most relevant water supply systems in the state of Rio Grande do Norte, in terms of groundwater and surface water collection. The Monsenhor Expedito adductor system is responsible for capturing approximately 1750 m³/h and for supplying 285 to 300 thousand inhabitants in 30 municipal seats and 240 rural communities (ASSEMBLEIA RN, 2021).

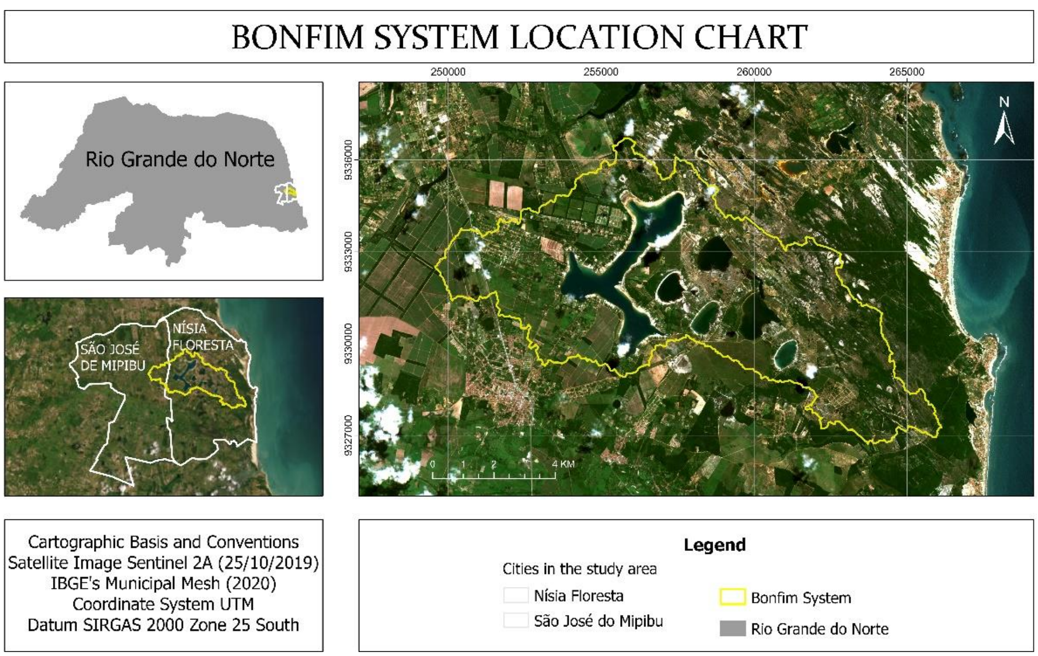

Figure. 1 – Location of the study area.
Source: Author (2022).

2.1 Climate

Rio Grande do Norte has its geographical position in the northern east. RN is directly influenced by two Disturbed Current Systems: to the north and to the east. In winter, the state can be hit by some repercussions of Cold Fronts when they manage to overlap the lower latitudes, causing frontal and post-frontal rains along the coast, while the hinterland of the state is under the action of the South Atlantic Tropical High, with stable weather (NIMER, 1979). According to Feitosa

& Melo (1997), the SB is in the humid valley region of RN and these characteristics justify a rainfall (annual average of 1,721mm between 1984 and 2019) (MELO; FIGUEIREDO, 1990; CASTRO et. al., 2014).

2.2 Lithological units and hydrogeology

In addition to the landscape, environmental and tourist importance, the SB also has social and economic importance, both for the region in which it is inserted and for all RN, serving as a source for the Monsenhor Expedito water main, which is 315 km long. The adductor system was designed in the early 1990s to supply 1,627.2 m³/h, from the water catchment in Lagoa do Bonfim and through seven deep wells surrounding the lagoon. However, aiming at a higher flow, new complementary studies were carried out, such as the studies carried out by SEMARH (2008), in order to define new conditions of exploitation for human supply; thus, twelve more deep tube wells were installed in 2011 in the Boa Cica stream, downstream of the lagoons, from which another 750 m³/h are captured.

This water potential can be related to the lithohydrological characterization of the SB, in which four geological units are found, all from the Quaternary period, namely: Recent continental eolian deposits (Q2ec), Vegetated coastal eolian deposits (Q2elv), Sandy and sandy-clay deposits (Q2da) and old marine and continental deposits (Q1mc). In common, they are unconsolidated covers composed of sediments ranging from sandy to sandy-clayey with grain size ranging from fine to very coarse sand, sometimes with conglomeratic fraction (CRPM, 2014) (Figure 2).

Accordingly, the hydrogeology is composed of a single system, the Dunas-Barreiras aquifer, in which each has its specific characteristics. The Dunas aquifer consists of unconsolidated aeolian deposits formed by fine to medium sandy sediments and sometimes silty-clayey (CPRM, 2012; CPRM, 2014). Although these sediments serve as conductors of infiltrated water to the Dunas/Barreiras, they have a small, saturated thickness, making productivity generally very low, with a capture flow rate of $1 \leq Q$ (m³/h) < 10. It is characterized as a typically free aquifer with high porosity and hydraulic conductivity (K (m/s) $\cong 10^{-4}$), and the wells have an average depth of 5 m (SERHID, 1998[a]; CPRM, 2014; ALVES, 2020). The Barreiras aquifer consists of sandy-clayey to silty-clayey unconsolidated to semi-consolidated sediments, locally with conglomerate fractions. Of continental origin, it has an average thickness of around 80 m. It is located throughout the central, northwest and southeast portions, has a free character with hydraulic conductivity ($10^{-4} \leq$ K (m/s) $< 10^{-2}$) and high-water potential ($50 \leq Q$ m³/h < 100). Corroborating the hydraulic conductivity values, when it determined that, in the vicinity of the coastline, the hydraulic conductivity (K) is of the order of 10^{-4} m.

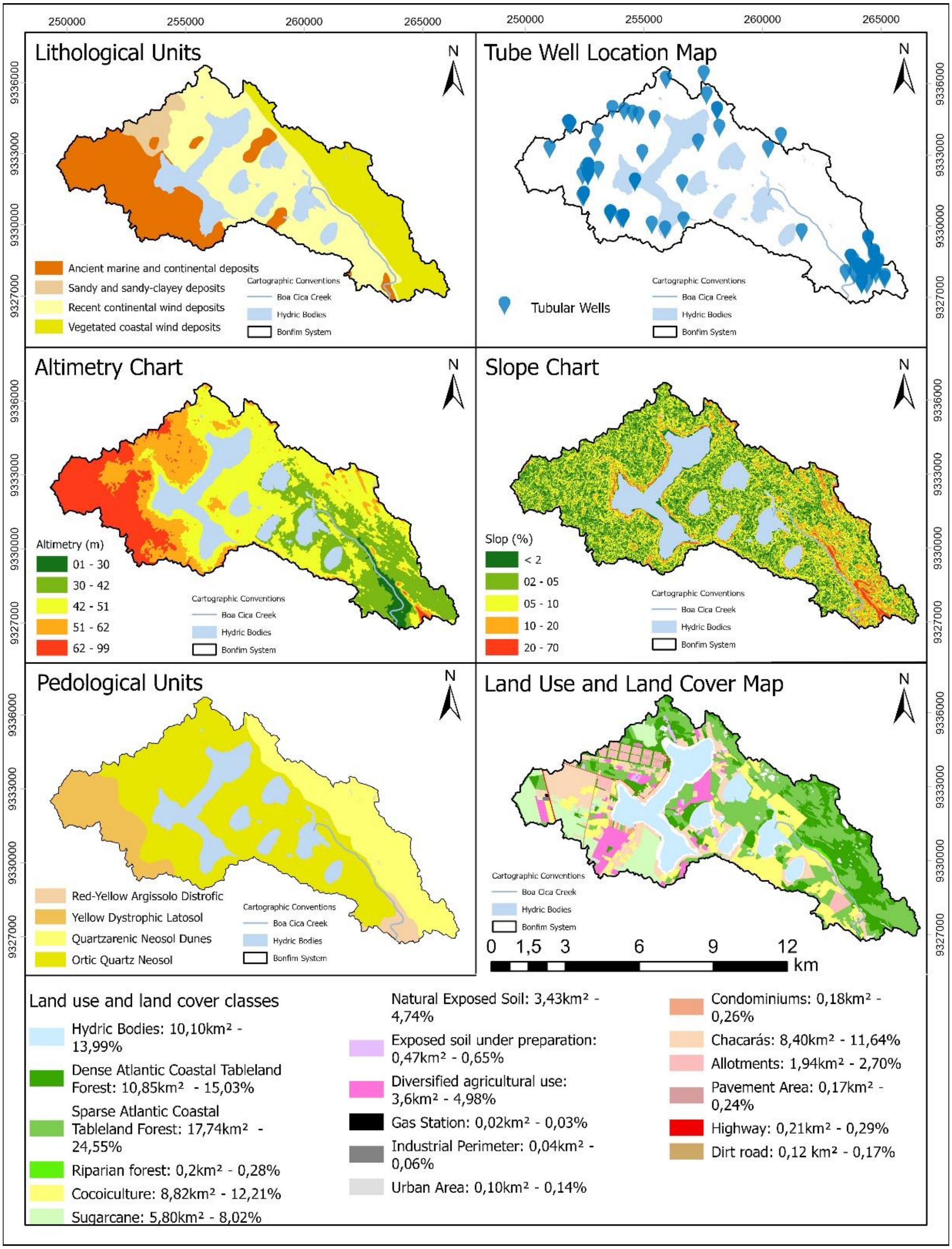

Figure. 2 – Spatial information used in the studies.
Source: Author (2022).

2.3 Relief

The SB is divided into two geomorphological domains: the coastal trays, located to the west, presenting a flat relief derived from sedimentary rocks, and the wind plains, which are characterized by undulations and low altitude, in which the erosion process is overcome by sedimentation (PEREIRA et al., 2003; IBGE, 2009). In general terms, almost all the study area has low slopes, favoring infiltration, with values ranging between 2% and 20%.

2.4 Pedological units

The region is predominantly composed of Quartzarenic Orthic Neosols (RQo), corresponding to 50.89% of the total area (36.74 km²). Comprising mainly the central region of the SB, it is composed of dystrophic quartz sands and low clay contents, less than 15%, originating from the Barreiras Formation (RADAMBRASIL, 1981; EMBRAPA, 2006). The neosols, due to their sandy texture, have higher rates of percolation of water in the soil, in order to enhance the infiltration of precipitated water in these areas (SUDENE, 1971; EMBRAPA, 2006).

To the east predominates the Neossolo Quartzarênico dunes (Dn), composed of dystrophic marine quartz sands, occupying 21.32% of the total area of the SB (15.39 km²). The physical characteristics of this group correspond to unconsolidated soils, also from the Barreiras Formation, aggregating low clay contents, having high draining power and with greater depths (RADAMBRASIL, 1981; EMBRAPA, 2006).

The Dystrophic Yellow Latosol (LAd) originating from the Barreiras Formation is located west of the SB, with 11.45% of the total area (8.27 km). This soil has a deeper profile, being more weathered than the Quartzarenic neosols, having a moderate to high permeability (SUDENE. 1971; RADAMBRASIL, 1981; EMBRAPA, 2006).

The Dystrophic Red Yellow Argisol (PVAd) occupies a smaller area of the SB, located to the south/southeast, is non-hydromorphic, dominantly clayey, deep and moderately draining, corresponding to 2.33% of the total area (1.69 km²) (SUDENE. 1971; RADAMBRASIL, 1981; EMBRAPA, 2006).

2.5 Land Use and Cover

The largest proportions were mapped as Dense and Sparse Atlantic Forests of Coastal Tableland, Riparian Forest and Water Bodies with 38.99 km² (54%). Following, agricultural uses are found, occupying 30.61 km² (43%). The other uses were classified as anthropic activities, involving industrial areas, condominiums, gas stations, dirt roads, highways and others with 2.8 km² (3%)

3. Methodology

Figure 3 presents a flowchart that summarizes the methodology employed in the work.

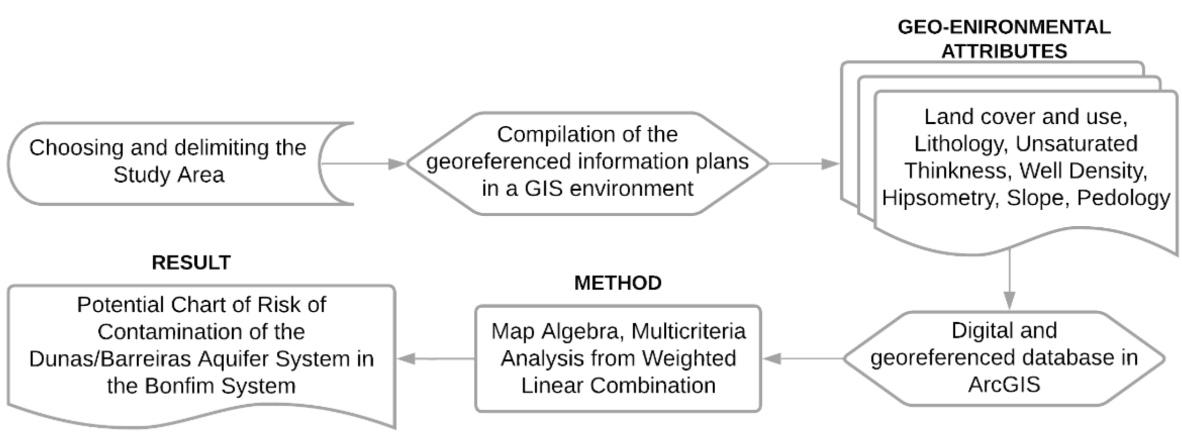

Figure. 3 – Flowchart of the methodology employed in the work.
Source: Author (2022).

To assemble the digital and georeferenced geographic database, primary matrix data were used, such as satellite images and secondary (vector), such as geological, geomorphological, pedological, land use and land cover maps and the Digital Elevation Model (DEM). The information plans were georeferenced in the 25S zone, and the SIRGAS2000 geodetic reference and UTM projection system were adopted. The data were manipulated and integrated in ArcGIS 10.5 and ArcGIS Pro software (Table 1).

Table 1 –. Geographical information used to assemble the database.

Information plans	**Description**	**Source**	**Spatial resolution/scale**
Land use and land cover	Use classes	Satélite Sentinel 2A (ESA, 2019), Paiva *et al.* 2021	10 x 10 m
Digital Elevation Model	Hypsometry/Declivity	ALOS – PALSAR JAXA/METI (2011)	12,5 x 12,5 m
Pedological Units	Soil types	IBGE (2017)	1:250.000*
Hydrogeology	Well Density Unsaturated area	SERHID (1999), Pereira (2000), SEMARH (2012)	-
Lithological units	Geological Formation	Folhas geológicas SB-25-V-C-V: CPRM (2012) e SB.25-Y-A-II E III: CPRM (2014)	1:100.000

* Although printed at a scale of 1:1,000,000, these mappings were carried out at a level of detail of 1:250,000.

Source: Author (2022).

The land cover and land use map were prepared from Sentinel-2A satellite images, acquired on 10/25/2019, MSI (Multispectral Instrument) sensor, used by Lobo de Paiva et al (2022). From the RGB color compositions (4,3,2 and 8,4,3), the author performed the visual interpretation and vectorization on canvas of the objects on the earth's surface.

To generate the maps of unsaturated thickness and density of tube wells, data from SERHID (1999), PEREIRA (2000) and SEMARH (2012) were used, and the spatialization of 122 tube wells was performed, including producing wells and monitoring wells. The interpolation of groundwater level data for the preparation of the unsaturated thickness map was performed using the Inverse Distance Weighted (IDW) tool (MITAS, MITASOVA; 1999). For the well density map, the calculation of the number of recurrence of wells per units of radius of influence was used, weighted by distance, constituting the Kernel index (OLIVEIRA, OLIVEIRA; 2017).

3.1 Map algebra and multicriteria analysis in a GIS environment

Map algebra consists of a pixel-by-pixel association of each location on a map (EASTMAN, 2003; TOMLIN, 1990). For the algebra to be performed, all information plans must be georeferenced and with the same pixel size (TOMLIN, 1990; MALCZEWSKI, 2004), in this case, 26.5 x 26.5 meters were used taking as reference the adopted working scale (1:100,000). The vector information plans were transformed into the matrix format (raster) reclassifying them for assigning the weights, weights defined by a multicriteria analysis.

According to Valente, Petean and Vettorazzi (2017), from the incorporation of geospatial information on the physical, biotic and anthropic environments, multicriteria evaluation in a GIS environment has been efficient to define priority areas as a subsidy to territorial planning. Thus, the methodology used to identify areas with the greatest potential for groundwater contamination was based on multicriteria analysis. According to Costa et al. (2019) and Valente (2005), the judgment of weights can be made using a numerical scale of reference through literature review, consultation with experts and/or based on experiences already developed in the area of interest.

Land use directly affects the risk of groundwater contamination to a greater or lesser extent. According to Nanni et al. (2005), the risk is caused not by the intrinsic characteristics of the aquifer, but by specific characteristics, such as the existence of polluting activities, a dynamic factor, which can be controlled. Therefore, a scaling in values was elaborated from the anthropization of land use, so that for areas that still preserve semi-natural vegetation (Dense Atlantic Forest/Sparse Coastal Tableland), the weighting value was considered negligible, considering that the impact of the presence of vegetation is positive. Regarding the areas of diversified agricultural uses, highways, gas stations, urban areas, among other uses that reflect negative impacts, weights were assigned according to the negative impact of the activities developed, as well as chemicals used (Table 2).

As for geological characteristics, vulnerability is directly related to the type of lithological units, with sandstones, siltstones and claystones being graded. In this case, the sandier sedimentary geological units, such as recent continental eolian deposits and vegetated coastal eolian deposits, have greater intrinsic vulnerabilities. On the other hand, sandy-clay deposits and old marine and continental deposits have more clayey characteristics, having a capacity to retain more leaching in their environment. Therefore, higher weights were assigned to sedimentary deposits with lower pollutant attenuation capacity.

The unsaturated thickness is directly related to the depth of the groundwater level. Therefore, the lower the thickness of the unsaturated zone of the terrain, the higher the intrinsic vulnerability of the aquifer system.

The fact that the density of tube wells was considered is justified by the fact that some wells may be outside the construction standards, which implies porous and permeable sedimentary geological materials connected with other sources of pollution, such as septic tanks and sewers. It is worth mentioning that, according to the National Sanitation Information System (SNIS) (2019), only 0.63% of the population of the municipality of São José do Mipibu and 4.76% of the population of Nísia Floresta were contemplated with a sewage collection network.

The relief was represented by hypsometry, thus, hypsometric classes with lower altitudes were considered with greater potential for contamination, as they represent places of greater accumulation and infiltration of surface runoff.

The degree of slope of the relief is related to the higher or lower speed of surface runoff, favoring the water to flow through the surface or infiltrate, respectively. Thus, in steeper slopes, where greater surface runoff prevails, the lowest weights were provided. On the other hand, flat regions, with slopes ranging from 0 to 2% or up to 5%, which directly favor the infiltration of water into the terrain, received higher weights of greater valuations.

The properties of soils and sediments interfere with the retardation and percolation of pollutants into aquifer units. This behavior can be conditioned by granulometry and hydraulic conductivity. These intrinsic properties define how potentially contaminating solutions can reach the saturated zone. Thus, the weights were established based on the texture and permeability attributes of the soils, where sandy texture represents the highest contamination potentials.

According to Costa et al. (2019), the multicriteria analysis must be carried out by a multidisciplinary team of specialists, which will assign weights and restrictions to each evaluated attribute. After the hierarchization of each evaluated attribute, the Weighted Linear Combination (PLC) was performed (VOOGD, 1983). The execution of the weighted sum was performed from the information plans: land cover and use, lithological classes, unsaturated thickness, density of wells, hypsometry, slope and pedology. The attributes were compared individually, on a gradual scale considering a variation from 0 to 5, according to the peculiarities of each attribute regarding intrinsic vulnerability or specific vulnerability. In this perspective, the following weightings were defined: Negligible = 0, Very Low = 1, Low = 2, Medium = 3, Strong = 4 and Very Strong = 5, as can be seen in Table 2.

Table 2 –. Weights assigned to the information planes for the realization of the map algebra.

Weighting	**Land cover and land use classes**	**Attribute weight (0 and 1)**
Negligible (0)	Dense Atlantic Forest of the Coastal Tableland Sparse Atlantic Forest of the Coastal Tableland Riparian Forest, Hydric Body	(0,20)
Very Low (1)	Natural exposed soil	
Low (2)	Dirt Road, Allotments	
Medium (3)	Diversified agricultural use, Exposed soil in preparation, Coconut cultivation	
High (4)	Chacarás, Sugar Cane, Industries, Paved Areas	
Very High (5)	Gas Station, Highways, Urban Area, Condominiums	
	Lithological units	
Low (2)	Old marine and continental deposits	(0,20)
Medium (3)	Sandy and sandy-clay deposits	
High (4)	Vegetated coastal eolian deposits	
Very High (5)	Recent continental aeolian deposits	
	Unsaturated thickness classes (m)	
Very Low (1)	42,05 – 33,89	(0,20)
Low (2)	33,89 – 25,72	
Medium (3)	25,72 – 17,56	
High (4)	17,56 – 09,39	
Very High (5)	09,39 – 01,23	
	Well density class (Qnt/radius)	
Very Low (1)	0,001 – 1,201	(0,13)
Low (2)	1,202 – 2,405	
Medium (3)	2,406 – 3,607	
High (4)	3,608 – 4,810	
Very High (5)	4,811 – 6,012	
	Hypsometry classes (m)	
Very Low (1)	99 – 80	(0,06)
Low (2)	80 – 60	
Medium (3)	60 – 40	
High (4)	40 – 20	
Very High (5)	20 – 1	
	Slope classes (%)	
Very Low (1)	> 20	(0,06)
Low (2)	10 – 20	
Medium (3)	5 – 10	
High (4)	2 – 5	
Very High (5)	< 2	
	Pedological units	
Low (2)	Dystrophic Red-Yellow Argisol	(0,15)
Mediun (3)	Yellow Latossolo Distrófico	
High (4)	Quartzarenic Neosol Ortico	
Very High (5)	Quartzarenic Neosol Dunes	

Source: Author (2022).

4. Results and discussion

4.1 Unsaturated Thickness and Well Density

Figure 4 shows the maps depicting the unsaturated thickness of the Dunas-Barreiras aquifer system and the density of wells. The unsaturated thickness, as being the distance between the ground surface and the top of the saturated zone, was verified through measurements of the depths of static groundwater levels from tube wells and piezometers obtained in SERHID (1999), PEREIRA (2000) and SEMARH (2012). The density of wells is understood as the recurrence rate of tube wells found per radius of influence.

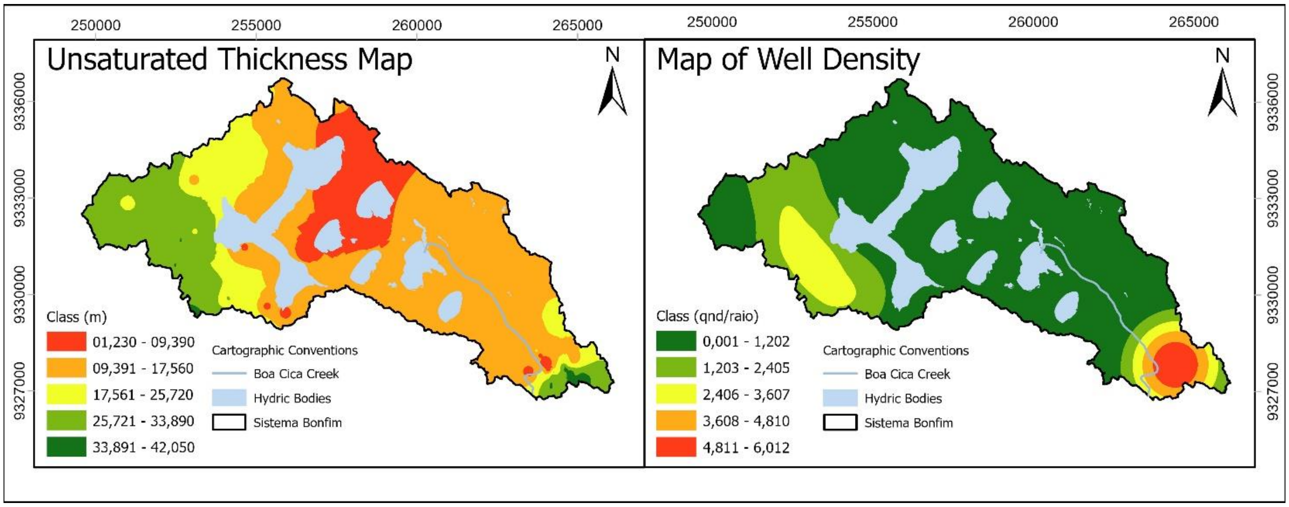

Figure 4a – Unsaturated Thickness, Figure 4b – Bonfim System Well Density.
Source: Author (2022).

Manoel Filho and Castro (2002) highlight infiltration as one of the factors influencing the relevant saturated thicknesses favoring aquifer recharge and groundwater renewal. This condition associated with the ease of groundwater abstraction and the excellent quality in its natural condition has enabled the water supply capacity for various sectors of the state, especially for supply. However, it is necessary to pay special attention to the density of wells in the region in view of the sustainability of the aquifer in terms of its quantitative and qualitative aspects.

4.2 Potential Risk of Contamination

From the crossings of the georeferenced and weighted information plans (Land use and cover, lithological classes, unsaturated thickness, well density, altimetry, slopes and pedological classes), it was possible to recognize the areas with greater or lesser potential risk of contamination, as presented in the Bonfim System Potential Risk of Contamination Chart (Figure 5).

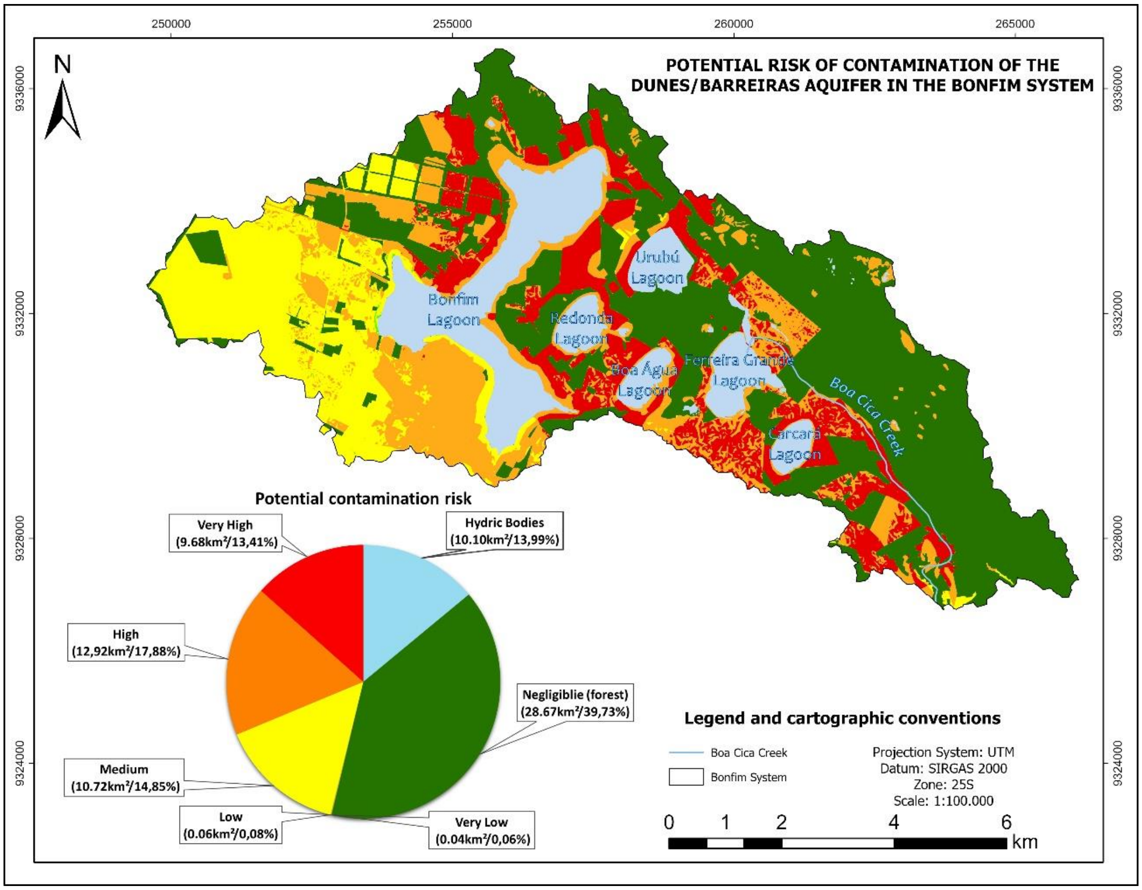

Figure 5 – Potential Contamination Risk Chart for the Bonfim System.
Source: Author (2022).

The greatest potential risks of groundwater contamination are represented by the classes called very high, high and medium, which total 33.32 km² in terms of territorial area. The potential risks classified as negligible cover an area of 28.67 km² (39.73%), which are associated with the areas of forest and the water mirror, where there is no anthropic activity mapped.

The very high risk potential involves an area of 9.68 km² (13.41%) covering the northwest, central and southeast portions of the SB. The lithologies are presented in this portion as recent continental eolian deposits and vegetated coastal eolian deposits with high porosity and hydraulic conductivity (K (m/s) $\cong 10^{-4}$) (ALVES, 2020). Geologically, they are represented by fine to medium sands, well rounded and selected. This sandy texture gave rise to the oritic quartzarenic neosols (<15% clay) of high permeability (between 10^{-3} and 10^{-1} cm/s), where unsaturated thickness ranging from 1.23 to 17.56 meters predominates. In these regions, agricultural uses such as sugarcane and coconut cultivation and the presence of farms, with the use of septic tanks, constitute the main sources of contamination.

The potential risk classified as high involved the largest territorial area, with predominance to the west of the Bonfim Lagoon and in regions of transition from Atlantic Forest to areas with anthropic activities and comprises 12.92 km² or 17.88%. The western portion of the SB presented, for the most part, the potential risk of contamination Medium involving an area of 10.72 km² equivalent to 14.85% of the analyzed area. The presence of gas stations, industrial facilities, sugarcane and coconut cultivation, diversified agricultural use and the presence of farms contribute to this potential risk. In the specific case of the presence of farms, these have the disposal of domestic effluents, through septic tanks and tanks.

The class of Potential risk of contamination Medium is predominantly presented in the western portion of the SB, corresponding to anthropic activities such as industrial areas, paved areas, farms, allotments, sugarcane and coconut cultivation, exposed soil in preparation, and diversified agricultural use. Considering the attributes evaluated, this potential class is associated with the presence of sediments with a sandy-clay matrix, the type of soil (Dystrophic Yellow Latosol with sandy-clay texture and with a permeability coefficient between 10^{-6} and 10^{-4} cm/s), in addition to the expressive thickness of the unsaturated layer (between 33.89 and 42.05 m) in much of the area and the low density of wells (<4 per km²). However, attention should be paid to the low degree of slope of the relief, where slopes below 10% predominate, which consequently favors higher water infiltration rates, as well as the infiltration of possible contaminants derived from human activities and leaching from the land itself.

The regions of the SB that presented the potential risk very low and low were almost negligible, thus, it was present in only 0.10 km², involving 0.12%. The areas classified as very low and low potential risk of contamination are associated with uncovered areas, which manifest themselves naturally in interdunal regions, on the banks of the system's lagoons and in transition zones of dense / sparse Atlantic forests of coastal tabuleiro and small areas with diversified agricultural use. Physically, these areas are positioned at higher altimetric levels (between 61 and 80 m), where the yellow latosol of sandy-clay texture predominates (between 15 and 35% clay), with a permeability coefficient between 10^{-6} and 10^{-4} cm/s, superimposed on sandstones interspersed with siltstones and claystones of the Barreiras Formation. The unsaturated thickness is mostly in the range of 17.56 m to 42.05 and the area has a medium density of wells (<4 per km²).

The potential risk classified as Negligible represents the areas of Sparse and Dense Atlantic Forest of Tabuleiro Litorâneo, dominantly; this region remains as semi-natural areas, without the presence of anthropic activities and water bodies.

According to the map of land use and land cover (Figure 2) and the chart of the potential risk of contamination of the Bonfim System (Figure 5), the impacts on the water system, surface or underground, are mainly related to the presence of many residences, whose main device for collecting effluents is the septic tank, and to agricultural crop areas. The other situation that deserves to be highlighted, even though it constitutes a low percentage of land use and occupation, is the gas stations.

As for the impacts arising from the presence of septic tanks, these comprise one of the most deflagrating sources of groundwater pollution, since they potentiate the concentrations of nitrate, which can be mobilized from the upper layers of the soil to the water and represents the final stage of the oxidation of organic matter (APOITIA, 2003; FEITOSA et al., 2008). Thus, since nitrate ion is a persistent contaminant, especially in oxidizing environments such as groundwater, where it is strongly stabilized and difficult to dilute or remove by simple water treatment processes, it is an indicator that needs to be monitored, especially in tube wells of the public supply network. Castro et al. (2014) found nitrate concentrations close to the maximum permissible limit, which is 10 mg/L, as established in Consolidation Ordinance No. 5, of September 28, 2017. The occurrences of these concentrations were mainly in well PT 07, located southwest of the study area, where there are more houses.

The other source of water contamination by nitrate is agricultural cultivation areas, which, depending on the management, may cause drastic effects. In this case, there is the practice of monoculture in the area, related to the cultivation of sugar cane and coconut, so that the practice of monoculture leads to a nutritional imbalance of the soil plant and, therefore, the number of pests and diseases increases over the years (ALTIERI; PONTI; NICHOLLS, 2012; RAMJEGATHESH et al., 2012). In view of the situation, it becomes essential to apply pesticides, fertilizers and fertilizers so that there is no loss of product/productivity.

Pesticides appear as an effective and economical way to improve yield, from a productive point of view, but, on the other hand, they can have serious consequences for the environment, directly and indirectly contaminating the air, water, soil and the general ecosystem, causing serious risks to the health of living beings (RIMAL et al., 2019). One of the alternative measures for the control of pests and diseases in coconut cultivation is by the conventional method of spraying/micro-spraying or by fertigation, which can be performed mechanically or manually with a dose of pesticides and fertilizers already diluted in water (LAMICHHANE et al., 2016). Thus, this culture ends up becoming a source of diffuse pollution, which presents harmful compounds, such as captan, chlorothalonil, carbendazim, lafenurom, among other inorganic compounds, in addition to organic compounds used to increase soil fertility (BRITO et al., 2002). Consequently, all this load of organic and inorganic compounds that are dispersed/inserted in various ways in sandy soils of coconut crops directly increases the potential risk of groundwater contamination, which can generate irreparable damage to the source if these pollutants manage to be leached throughout the pedological profile in the SB.

In relation to sugarcane cultivation, its by-product - vinasse - has concentrations of potassium, calcium, magnesium, sulfur and micronutrients, being reused as fertilizer for the cultivation itself, however, it has a polluting power up to one hundred times greater than domestic sewage (SILVA et al. 2007). Thus, the cultivation of sugarcane in sandy soils of high permeability and lower unsaturated thickness (1.23 to 9.39 meters) directly favors the leaching of these contaminants into the underground water reserve.

As for the sources of contamination that fuel stations comprise, these can increase the risk of contamination if they are not in compliance with the regulations in force. For a long time, gas stations used iron tanks buried in the ground. Over the years, these tanks have become susceptible to corrosion, causing leaks and consequent contamination of soil and groundwater (COSTA et al. 2019). Currently, gas stations are subject to their own regulations regarding safety and environmental standards, however, the activity still handles contaminants such as: Benzene, Toluene, Ethylbenzene and

Total Xylenes (BTEX) and Polycyclic Aromatic Hydrocarbons (PAHs). These compounds have denser physical characteristics than water, have low solubility and are highly toxic and persistent on the surface, which can cause irremediable damage to the aquifer (TEIXEIRA et al., 2009). Thus, although small, the area that includes gas stations may represent a potential risk of contamination due to inorganic substances derived from petroleum if the minimum guidelines for fuel storage and supply areas are not met.

Considering the current mapping of land use and occupation and the map of the potential risk of contamination of the Bonfim System, together with the natural characteristics and the intrinsic vulnerability of the Dunas/Barreiras Aquifer System in the Bonfim Lake Complex, it is necessary to highlight some points related to recharge and surface runoff.

According to Manoel Filho and Castro (2002), the Bonfim lake region develops on a Tertiary-age tableland with extensive coverage of homogeneous and unconsolidated eolian sands with high infiltration capacity, thus being responsible for the absence of a surface drainage network and possibly for the formation of lagoons on these tableland sediments. The predominance in the area is of a free type of aquifer system, locally presenting semi-confined sectors, so this predominance of the free aquifer allows a situation of interaction with the lagoons of the region. The authors also point out that, in a situation where the intensity of rainfall is greater than the infiltration capacity of the soil, this behavior can generate recharge of maximum intensity and "run-off", a situation that can cause runoff to interior depressions at isolated points, creating infiltration basins from which groundwater domes are formed. Manoel Filho and Castro (2002) complement the interpretation of this behavior by pointing out that, if the water table is shallow, the basins can reach it quickly and originate permanent ponds, connected with groundwater. Otherwise, the basins form temporary ponds with suspended water, which disappears after the deep percolation process to the water table is completed. This same study considered the surface runoff negligible for the water balance, elaborated by the Thornthwaite method (Thornthwaite & Matter 1957), which indicated an average recharge estimate of 485.0 mm/year.

In view of the above, it can be seen that, in the same way that there is a favorability for the aquifer to be recharged with precipitation waters, there is also the favoring of a feeding of the underground water system from these waters with concentrations of pollutants related to the sources of contaminations discussed and consequent potential risk of contamination.

4. Final considerations

A large portion of the SB, portraying 46.14% of the area, presented considerable levels of potential risk of groundwater contamination (Medium, Strong and Very Strong), only 0.14% of the area presented Very Low and Low potential. On the other hand, 39.73% of the area presented negligible contamination potential, as it is covered by Dense/Sparse Atlantic Forest of Tabuleiro Litorâneo that remains as semi-natural areas, without the presence of anthropic activities, not offering great risks to groundwater contamination and 13.99% occupied by surface water bodies.

The potential sources of contamination risks are related to the presence of anthropic interventions, such as gas station, highway, industrial areas, paved areas, condominiums, farms, allotments, sugarcane cultivation areas, exposed soil in preparation and areas with coconut cultivation. In addition to these, there is a process of urban expansion characterized by the presence of farms and condominiums, which dominantly have individualized sanitation systems, being crucial to raise the potential risk level of groundwater contamination. The gas station has its possible contaminants linked to hydrocarbons, petroleum derivatives, which easily extrapolate the support capacity of the system raising the potential risk of contamination by inorganic compounds. So little different, the highways, in addition to waterproofing large areas and affecting the entire region inserted, whether the physical environment or the biotic, carry a large load of metals and heavy metals. This discharge, due to the low degradation capacity of these metals, increases the risk of contamination. The activity of coconut farming is related to the use of pesticides, fungicides and herbicides. The cultivation of sugarcane includes the use of fertigation with vinasse, which is rich in potassium, calcium, magnesium, sulphur and micronutrients. In this type of activity, the use of agrochemicals is common and represents a great potential risk of contamination of aquifers.

In this context, we highlight the seven wells of the first catchment battery of the Monsenhor Expedito Pipeline, which are in areas with Medium to Strong potential, which may compromise the potability standard of these waters, used by about 300 thousand people who use this water daily.

At the state/national level, the National Environmental Policy, Law n 6.938, of August 31, 1981, has in its instruments the Zoning and Environmental Licensing. Thus, this work serves as a parameter and instrument for land use management to be used by environmental agencies, such as the Institute for Sustainable Development (IDEMA/RN) and IBAMA. Regarding surface and groundwater, RN has a State Water Resources Policy, established by State Law No. 6908, of July 1, 1996, which brought, in Article 2 of Chapter I, the granting of the right to use water as an essential instrument for the management of water resources. Accordingly, Decree No. 13.283 of March 22, 1997, deals with the regulation of the granting of the right to use water resources and the licensing of water supply works provided for in Law No. 6908/96. The body responsible for groundwater concessions is the Water Management Institute (IGARN).

For the private sector, an integrated view between anthropic activities and the physical/ biotic environments favors the understanding of the implications that the enterprises may cause considering the current situation of potential risk of contamination of some areas in the SB, or even understand the level of implication that they may face in an environmental licensing or in a grant of the right to use water in that region.

References

ALLER, L et al. DRASTIC: a standardized system 542 for evaluating groundwater pollution potential using hydrogeological settings. US *Environmental Protection Agency*, Ada, Oklahoma, 641.

ALTIERI, M. A.; PONTI, L.; NICHOLLS, C. I. Soil Fertility, Biodiversity and Pest Management. *Biodiversity And Insect Pests,* [s.l.], p. 72-84, 15 maio 2012. John Wiley & Sons, Ltd. DOI: http://dx.doi.org/10.1002/9781118231838.ch5.

ALVES, R. S. *O papel de falhas como condutos hidráulicos a partir da análise de modelos numéricos e geoelétricos* - o exemplo do aquífero Barreiras-RN. 2020. 144 f. Tese (Doutorado) - Curso de Programa de Pós Autora: Orientador: Tese Nº 62/PPGG outubro de 2020 Natal, Brasil. Pós-Graduação em Geodinâmica e Geofísica, Centro de Ciências Exatas e da Terra, Universidade Federal do Rio Grande do Norte, Natal/RN, 2020.

APOITIA, L. F. M. *Caracterização preliminar do quimismo das águas subterrâneas em Cuiabá - MT*. 2003. 130 f. Dissertação (Mestrado em Geologia) - Departamento de Geologia, Universidade Federal do Paraná, Curitiba, 2003.

ASSEMBLEIA RN, TV. *Audiência Pública sobre a revitalização da Lagoa do Bonfim*. Youtube, 16 de nov 2021. Disponível em: <https://www.youtube.com/watch?v=TJSrZ9S22j4&ab_channel=TVAssembleiaRN>. Acesso em: 25 de mai 2022

BONSOR, H. *et al*. *Seasonal and Decadal Groundwater Changes in African Sedimentary Aquifers Estimated Using GRACE* Products and LSMs. Remote Sensing, [S.L.], v. 10, n. 6, p. 904, 8 jun. 2018. MDPI AG. http://dx.doi.org/10.3390/rs10060904.

BRASIL. (2017). Ministério da Saúde. Gabinete do Ministro. Portaria de consolidação n.º 5, de 28 de setembro de 2017. Consolidação das normas sobre as ações e os serviços de saúde do Sistema Único de Saúde. Anexo XX - *Do controle e da vigilância da qualidade da água para consumo humano e seu padrão de Potabilidade.* Diário Oficial da União, Brasília, DF. 825p.

BRITO, N. M. *et al*. *Determination of pesticide residues in coconut water by liquid extraction and gas chromatography with electron-capture plus thermionic specific detection and solid-phase extraction and highq performance liquid chromatography with ultraviolet detection*. Journal Of Chromatography A, [s. l], v. 1, n. 957, p. 201-209, mar. 2002. https://doi.org/10.1016/S0021-9673(02)00351-5

BUSICO, G.*et al*. *A novel hybrid method of specific vulnerability to anthropogenic pollution using multivariate statistical and regression analyses*. Water Research, [S.L.], v. 171, p. 115386, mar. 2020. Elsevier BV. http://dx.doi.org/10.1016/j.watres.2019.115386.

CASTRO, V. L. L. *et al. Comportamento do nitrato em poços tubulares no entorno da Lagoa do Bonfim – Nísia Floresta/R*N. Águas Subterrâneas, [S.L.], p.1-13, 2014. Disponível em: https://aguassubterraneas.abas.org/asubterraneas/article/view/28315/18

CETESB, Companhia Ambiental do Estado de São Paulo. *Poluição das águas subterrâneas.São Paulo: SP*, 2018. Disponível em:https://cetesb.sp.gov.br/aguassubterraneas/informacoesbasicas/poluicao-das aguassubterraneas/#:~:text=As%20principais%20fontes%20potenciais%20de,atividades%20industr iais%2C%20como%20ind%C3%BAstrias%20qu%C3%ADmicas%2C.

CHENINI, I.; ZGHIBI, A.; KOUZANA, L. *Hydrogeological investigations and groundwater vulnerability assessment and mapping for groundwater resource protection and management: state of the art and a case study*. Journal Of African Earth Sciences, [S.L.], v. 109, p. 11-26, set. 2015. Elsevier BV. http://dx.doi.org/10.1016/j.jafrearsci.2015.05.008.

Civita, M. *The Maps of Groundwater Vulnerability to Pollution: Theory and Practice*. Quaderni di Tecniche di Protezione Ambientale, Pitagora., 1994.

COSTA, C. W. *et al. Combinação de atributos naturais e antrópicos na definição do potencial de contaminação de aquíferos, sudeste do Brasil*. Sociedade & Natureza, [S.L.], v. 32, p. 657-673, 11 set. 2020. EDUFU - Editora da Universidade Federal de Uberlandia. http://dx.doi.org/10.14393/sn-v32-2020-56221

COSTA, C. W. *et al. Potencial de Contaminação de Aquíferos por Atividades Antrópicas da Bacia do Ribeirão do Meio - Município de Leme - SP*. Revista Brasileira de Recursos Hídricos, v. 20, p. 218-225, 2015. http://dx.doi.org/10.21168/rbrh.v20n1.p218-225

COSTA, C. W. *et al. Potential for aquifer contamination of anthropogenic activity in the recharge area of the Guarani Aquifer System, southeast of Brazil*. Groundwater For Sustainable Development, [S.L.], v. 8, p. 10-23, abr. 2019. Elsevier BV. http://dx.doi.org/10.1016/j.gsd.2018.08.007.

CPRM – Serviço Geológico Do Brasil. Carta Geológica Folha SB.25-V-C-V. Natal. 2012. Escala 1:1.000.000.

CPRM – Serviço Geológico Do Brasil. Carta Geológica Folha SB.25-Y-A-II E III. Natal. 2014. Escala 1:1.000.000.

CPRM, Serviço Geológico Do Brasil. Mapa Geológico do Estado do Rio Grande do Norte. Ministério de Minas e Energia – Secretaria de Geologia, Mineração e Transformação Mineral. Brasília, 2006. Escala 1:500.000.

DANIELA, D.et al. *Nitrate trends in groundwater of the Campania region (Southern Italy)*. Environmental Science And Pollution Research, [S.L.], v. 26, n. 3, p. 2120-2131, 14 dez. 2017. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s11356-017-0978-y.

DELINOM, R. M. et al. *The contribution of human activities to subsurface environment degradation in Greater Jakarta Area, Indonesia*. Science Of The Total Environment, [S.L.], v. 407, n. 9, p. 3129-3141, abr. 2009. Elsevier BV. http://dx.doi.org/10.1016/j.scitotenv.2008.10.003.

DEVIC, G.; DJORDJEVIC, D.; SAKAN, S. *Natural and anthropogenic factors affecting the groundwater quality in Serbia*. Science of the Total Environment, [s. l.], v. 468–469, p. 933–942, 2014. http://dx.doi.org/10.1016/j.scitotenv.2013.09.011.

EASTMAN, J.R. *Decision Support: Decision Strategy Analysis*. Clark university (Ed.). IDRISI Andes Guide to GIS and Image Processing. Worcester: Clark Labs, 2006.

EASWER, Vishal *et al*. Vulnerability mapping of the Paravanar sub-basin aquifer (Tamil Nadu, India) in SINTACS model for efficient land use planning. Environmental Research, [S.L.], v. 204, mar. 2022. Elsevier BV. http://dx.doi.org/10.1016/j.envres.2021.

EMBRAPA, Empresa Brasileira de Pesquisa Agropecuária. *Sistema Brasileiro de Classificação de Solos*. 2. ed. Brasília, DF. 2006. 286 p. Disponível em: https://www.infoteca.cnptia.embrapa.br/handle/doc/338818.

FARJAD, B. *et al*. *Groundwater intrinsic vulnerability and risk mapping*. Proceedings Of The Institution Of Civil Engineers - Water Management, [s.l.], v. 165, n. 8, p. 441-450, set. 2012. Thomas Telford Ltd. DOI: http://dx.doi.org/10.1680/wama.10.00018.

FEITOSA E. C.; MELO J.G. *Relatório Diagnóstico dos dados e Informações disponíveis*. Plano Estadual de Recursos Hídricos. Natal, 1997. Secretaria Estadual de Recursos Hídricos/Hidroservice engenharia Ltda.

FEITOSA, F.A.C *et al*. Serviço Geológico Do Brasil - CPRM. *Hidrogeologia: conceitos e aplicações*. Rio de Janeiro: CPRM: LABHID, 2008. 812 p.

FILIPPIS, G. de *et al*. *Water Quality Assessment*: a quali-quantitative method for evaluation of environmental pressures potentially impacting on groundwater, developed under the m.i.n.o.re. project. International Journal Of Environmental Research And Public Health, [S.L.], v. 17, n. 6, p. 1835, 12 mar. 2020. MDPI AG. http://dx.doi.org/10.3390/ijerph17061835.

FOSTER, S.; HIRATA, R. *Determinacion del riesgo de contaminacion de agues subterraneas, una metodologia basada em datos existents*. Lima: Centro Panamericano de Ingenieria Sanitária y Ciências del Ambiente-Cepis, 1991. 81 p.

FOSTER, S.; VENTURA, M.; HIRATA, R. *Poluição das águas subterrâneas: um documento executivo da situação da América Latina e Caribe com relação ao abastecimento de água potável*. São Paulo: Instituto Geológico, 1993. 55 p.

GLEESON, Tom. *Global Groundwater Sustainability*. Groundwater, [S.L.], v. 58, n. 4, p. 484-485, 11 mar. 2020. Wiley. http://dx.doi.org/10.1111/gwat.12991.

GOMES, M. C. R.; MENDONÇA, L. A. R.; CAVALCANTE, I. N. *Mapping of Vulnerability and Risk of Groundwater Pollution in the Eastern Portion of the Araripe Sedimentary Basin, Ceará, Brasil*. Anuário do Instituto de Geociências - Ufrj, [S.L.], v. 41, n. 3, p. 252-259, 4 dez. 2018. Instituto de Geociencias - UFRJ. http://dx.doi.org/10.11137/2018_3_252_259.

IBGE, Instituto Brasileiro de Geografia e Estatística. *Manual Técnico de Geomorfologia*. 2 ed. Rio de Janeiro: IBGE, 2009. 175p

IPCC AR6 (Intergovernmental Panel on Climate Change). DOUVILLE, H., K. RAGHAVAN, J. RENWICK, R.P. ALLAN, P.A. ARIAS, M. BARLOW, R. CEREZO-MOTA, A. CHERCHI, T.Y. GAN, J. GERGIS, D. JIANG, A. KHAN, W. POKAM MBA, D. ROSENFELD, J. TIERNEY, O. ZOLINA, 2021: *Water Cycle Changes. In Climate Change 2021*: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, 2021, p. 1055–1210.

JAHAN, A. EDWARDS, K.L. *Multi-criteria Decision-Making for Materials Selection*. Ali Jahan, Kevin L. Edwards. Butterworth-Heineman. 31-41 p.2013. ISBN 9780080993867. https://doi.org/10.1016/B978-0-08-099386-7.00003-9.

KUMAR, R. de *et al*. Strong hydroclimatic controls on vulnerability to subsurface nitrate contamination across Europe. Nature Communications, [S.L.], v. 11, n. 1, dez. 2020. Springer Science and Business Media LLC. https://doi.org/10.1038/s41467-020-19955-8

LA TORRE, G. L. *et al*. Assessment and Monitoring of Fish Quality from a Coastal Ecosystem under High Anthropic Pressure: a case study in southern italy. International Journal Of Environmental Research And Public Health, [S.L.], v. 17, n. 9, p. 3285, 8 maio 2020. MDPI AG. http://dx.doi.org/10.3390/ijerph17093285.

LAMICHHANE, J. R. *et al*. *Toward a Reduced Reliance on Conventional Pesticides in European Agriculture*. Plant Disease, [s.l.], v. 100, n. 1, p. 10-24, jan. 2016. http://dx.doi.org/10.1094/pdis-05-15-0574-fe.

LOBO DE PAIVA, A. M. *et al*. *Fragilidade Ambiental aplicada em área de manancial no Nordeste brasileiro*. Revista de Geociências do Nordeste, [S. l.], v. 8, n. 1, p. 128–147, 2022. http://dx.doi.org/10.21680/2447-3359.2022v8n1ID24368.

MACHATE, D. J.*et al. High Concentration of Heavy Metal and Metalloid Levels in Edible Campomanesia adamantium Pulp from Anthropic Areas*. International Journal Of Environmental Research And Public Health, [S.L.], v. 18, n. 11, p. 5503, 21 maio 2021. MDPI AG. http://dx.doi.org/10.3390/ijerph18115503.

MALAKOOTIAN, M.; NOZARI, M. *GIS-based DRASTIC and composite DRASTIC indices for assessing groundwater vulnerability in the Baghin aquifer, Kerman, Iran*. Natural Hazards And Earth System Sciences, [S.L.], v. 20, n. 8, p. 2351-2363, 26 ago. 2020. Copernicus GmbH. http://dx.doi.org/10.5194/nhess-20-2351-2020.

MALCZEWSKI, J. *GIS-based land-use suitability analysis*: A critical overview. Progress in Planning, v. 62, n. 1, p. 3-65, 2004. Elsevier BV. http://dx.doi.org/10.1016/j.progress.2003.09.002

MANOEL FILHO, J.; CASTRO, V. L. L. *Avaliação e Explotação do aquífero Dunas-Barreiras na região do sistema lacustre do Bonfim-RN*. In: XII Congresso Brasileiro de Águas Subterrâneas, Florianópolis, 2002.

MARANGON, F. *et al. Land use and groudwater resourses potential vulnerability to contamination*. Agriculture & Forestry, v. 63, p. 211-222, 2017. http://dx.doi.org/10.17707/AgricultForest.63.1.25

MARIJIć, V. F. *et al*. *Influence of technological and municipal wastewaters on vulnerable karst riverine system, Krka River in Croatia*. Environmental Science And Pollution Research, [S.L.], v. 25, n. 5, p. 4715-4727, 2 dez. 2017. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s11356-017-0789-1.

MARTÍNEZ, D. *et al*. Distribution and origin of nitrate in groundwater in an urban and suburban aquifer in Mar del Plata, Argentina. Environmental Earth Sciences, [S.L.], v. 72, n. 6, p. 1877-1886, 13 fev. 2014. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s12665-014-3096-x.

MELO, J. G.; FIGUEREDO, E. M. *Comportamento hidráulico e vulnerabilidade do sistema aquífero Dunas/Barreiras à poluição na área de Natal (RN)*. Revistas Águas Subterrâneas, São Paulo, v. 13, n. 1, p. 1-12, 9 dez. 1990. DOI: https://doi.org/10.14295/ras.v13i1.11298.

MITAS, L. MITASOVA, H. *Spatial Interpolation. Geographical Information Systems*: Principles, Techniques, Management and Applications, [S.L], GeoInformation International, Wiley, 481-492, 1999.

NANNI, A. S. *et al. Vulnerabilidade natural e risco de contaminação do aquífero Serra Geral pela suinocultura na região das missões - RS*. In: SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS, 16., 2005, João Pessoa. Anais... [S.l.: s.n.], 2005. Disponível em: <www.dpi.inpe.br/spring/portugues/arquivos_publicacoes/ xvi_sbrh.pdf>.

NIMER, E. *Um modelo metodológico de Classificação de Climas*. Revista Brasileira de Geografia. Vol 41, n. 4, p. 59-89. Rio de Janeiro, 1979.

OLIVEIRA, U. C.; OLIVEIRA, P. S. Mapas de Kernel como Subsídio à Gestão Ambiental: Análise dos Focos de Calor na Bacia Hidrográfica do Rio Acaraú, Ceará, nos Anos 2010 a 2015. Espaço Aberto, PPGG - UFRJ, Rio de Janeiro, V. 7, N.1, p. 87-99, 2017 87. ISSN 2237-3071.

OROJI, B. *Groundwater vulnerability assessment with using GIS in Hamadan–Bahar plain, Iran*. Applied Water Science, [S.L], v. 9, n. 8, p. 1-13, 25 out. 2019. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s13201-019-1082-x.

PARKINSON, S.; HUNT, J. *Economic Potential for Rainfed Agrivoltaics in Groundwater-Stressed Regions. Environmental* Science & Technology Letters, [S.L.], v. 7, n. 7, p. 525-531, 1 jun. 2020. American Chemical Society (ACS). http://dx.doi.org/10.1021/acs.estlett.0c00349.

PEIXOTO, F. S.; CAVALCANTE, I. N. *Vulnerabilidade aquífera e risco de contaminação da água subterrânea em meio urbano*. Geologia USP. Série Científica, [S. l.], v. 19, n. 2, p. 29-40, 2019. DOI: 10.11606/issn.2316-9095.v19-142384. Disponível em: https://www.revistas.usp.br/guspsc/article/view/142384.

PEREIRA, R. *Caracterização Hidrológica do Sistema Lacustre Bonfim – RN*. 2000. 212p. Tese (Doutorado). Instituto de Geociências. Universidade Federal do Rio de Janeiro - UFRJ.

PEREIRA, R. *et al. Avaliação do impacto da captação d'água na Lagoa Do Bonfim, RN - Brasil*. Águas Subterrâneas, [S.L.], v. 16, 6, n. 1, p.75-84, 9 dez. 2002. DOI:http://dx.doi.org/10.14295/ras.v16i1.1301.

PEREIRA, R. *et al. Caracterização Hidrogeoquímica Do Sistema Lacustre Bonfim, Rio Grande Do Norte – Brasil*. Águas Subterrâneas, [s.l.], p.1-15, 2000. Disponível em: https://aguassubterraneas.abas.org/asubterraneas/article/view/23915.

PEREIRA, R. *et al. Estado da Arte da Bacia Hidrogeológica do Sistema Lacustre Bonfim-RN, Nordeste do Brasil*. Águas Subterrâneas, [S.L.], v. 17, n. 1, p.41-47, 9 dez. 2003. DOI: http://dx.doi.org/10.14295/ras.v17i1.1311.

PIGA, F. G *et al. Multi-criteria potential groundwater contamination and human activities: Araras watershed, Brazil*. Revista brasileira de recursos hídricos, v. 22, p. e56, 2017. http://dx.doi.org/10.1590/2318-0331.0217170052.

POWELL, K. L. *et al. Microbial contamination of two urban sandstone aquifers in the UK*. Water Research, [S. l.], v. 37, n. 2, p. 339–352, 2003. https://doi.org/10.1016/S0043-1354(02)00280-4.

RADAMBRASIL. Secretaria Geral. Ministério das Minas e Energia. *Projeto RADAMBRASIL*: Folhas SB.24/25 Jaguaribe/Natal; geologia, geomorfologia, pedologia, vegetação e uso potencial da terra (Levantamento de Recursos Naturais). Rio de Janeiro, 1981. 745 p. 23 v.

RAMJEGATHESH, R. *et al*. *Root (wilt) disease of coconut palms in South Asia – an overview*. Archives Of Phytopathology And Plant Protection, [s.l.], v. 45, n. 20, p. 2485-2493, dez. 2012. Informa UK Limited. DOI: http://dx.doi.org/10.1080/03235408.2012.729772

RAZANDI, Y. *et al*. Application of analytical hierarchy process, frequency ratio, and certainty factor models for groundwater potential mapping using GIS. Earth Science Informatics, [S.L.], v. 8, n. 4, p. 867-883, 26 abr. 2015. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s12145-015-0220-8.

REN, J. *et al*. *Multi-criteria Decision-Making for Materials* Selection.,Waste-to-Energy, Academic Press. 153-176 p. 2020. https://doi.org/10.1016/B978-0-12-816394-8.00006-9.

RIMAL, B. *et al*. *Effects of land use and land cover change on ecosystem services in the Koshi River Basin, Eastern Nepal*. Ecosystem Services, [S.L.], v. 38, p. 100963, ago. 2019. Elsevier BV. http://dx.doi.org/10.1016/j.ecoser.2019.100963.

RUFINO, F *et al*. Evaluating the suitability of urban groundwater resources for drinking water and irrigation purposes. Environmental Monitoring and Assessment, [S.L.], v. 191, n. 12, 25 nov. 2019. Springer Science and Business Media LLC. http://dx.doi.org/10.1007/s10661-019-7978-y

São Paulo. Conselho Estadual de Recursos Hídricos, Câmara Técnica de Águas Subterrâneas. *Nitrato nas águas subterrâneas: desafios frente ao panorama atual* / São Paulo. Conselho Estadual de Recursos Hídricos, Câmara Técnica de Águas Subterrâneas; Claudia Varnier (coord.). - São Paulo: SIMA / IG, 2019. 128p.

SEMARH, Secretaria de Meio Ambiente e dos Recursos Hídricos; IDEMA, Instituto De Desenvolvimento Sustentável e Meio Ambiente do Rio Grande Do Norte. *Perfil do seu município: Nísia Floresta*. Natal, 2008. 35 p. Disponível em: http://adcon.rn.gov.br/ACERVO/idema/DOC/DOC000000000013946.PDF.

SERHID, Secretaria Estadual de Recursos Hídricos. *Política Estadual de Recursos Hídricos*, Estado do Rio Grande do Norte. Natal, 1998a.

_______, Secretaria Estadual de Recursos Hídricos. *Pesquisa Hidrogelogica do Complexo Lagunar do Bonfim*. Estado do Rio Grande do Norte. Natal, 1998b.

_______, Secretaria Estadual de Recursos Hídricos. *Monitoramento da primeira bateria de poços da Adutora Monsenhor Expedito*. Estado do Rio Grande do Norte. Natal, 1999.

_______, Secretaria Estadual de Recursos Hídricos. *Estudo de Identificação, Avaliação de Alternativas de Captação e Elaboração de Projeto Básico para a Captação das Águas da Adutora Monsenhor Expedito*. Estado do Rio Grande do Norte. Natal, 2002.

_______, Secretaria Estadual de Recursos Hídricos. *Quantificação da Oferta Hídrica da Lagoa do Bonfim. Estado do Rio Grande do Norte*. Natal, 2004.

SHARMA, A *et al*. *Corrigendum to "Organochlorine pesticide, endosulfan induced cellular and organismal response in Drosophila melanogaster"*. Journal Of Hazardous Materials, [S.L.], v. 379, p. 120907, nov. 2019. Elsevier BV. http://dx.doi.org/10.1016/j.jhazmat.2019.120907.

SILVA, M. M. N. et al. *A crise hídrica no estado do Rio Grande do Norte*. In: Congresso Técnico Científico da Engenharia e da Agronomia, 2016, Foz do Iguaçu, Pr. Anais. Foz do Iguaçu: Brasil, 2016. p. 1-4.

SNIS, Sistema Nacional de Informações Sobre Saneamento. *Mapa de indicadores de Esgoto*. Disponível em: < http://appsnis.mdr.gov.br/indicadores/web/agua_esgoto/mapa-esgoto>.

SUDENE, Superintendência para o desenvolvimento do Nordeste; DNPEA, Divisão de Pesquisa Pedológica. *Levantamento Exploratório: reconhecimento de solos do estado do Rio Grande do Norte*. Recife: DNPEA/SUDENE, 1971. 536p. Disponível em: https://www.embrapa.br/busca-de-publicacoes/ /publicacao/330796/levantamentoexploratorio-reconhecimento-de-solos do-estado-do-rio-grande-do-norte. Acesso em: 24 fevereiro 2021.

SUN, Y.*et al. Response of a Coastal Groundwater System to Natural and Anthropogenic Factors: case study on east coast of laizhou bay, china*. International Journal Of Environmental Research And Public Health, [S.L.], v. 17, n. 14, p. 5204, 18 jul. 2020. MDPI AG. http://dx.doi.org/10.3390/ijerph17145204.

TANG, Z. *et al*. *Forecasting land use change and environmental impact at a watershed scale*. Journal of Environmental Management, v. 76, n. 1, p. 35-45, 2005. DOI: https://doi.org/10.1016/j.jenvman.2005.01.006.

TEIXEIRA, W.; FAIRCHILD, T. R.; TOLEDO, M. C. M.; TAIOLI, F. (org.). Decifrando a Terra. 2. ed. São Paulo: Companhia Editora Nacional, 2009. 526 p

TOMLIN, D. *Geographic information systems and Cartographic Modelin*g. Prentice Hall, New York, 1990

TUCCI, C. E. M. *Gestão integrada das águas urbanas*. Revista de Gestão de Águas da América Latina - REGA, v. 5, n. 2, p. 71–81, 2008.

TUNDISI, J. G. *et al. Conservação e uso sustentável de recursos hídricos*. In: BARBOSA, F.A. Ângulos da água: desafios da integração. Belo Horizonte: Editora UFMG, 2008. p. 83-157.

FOSTER, S. *Fundamental Concepts in Aquifer Vulnerability, Pollution Risk and Protection Strategy*: International Conference, 1987, Noordwijk Aan Zee, the Netherlands Vulnerability of Soil and Groundwater to Pollutants. Netherlands Organization for Applied Scientific Research, The Hague, 69-86.

VALENTE, R. O. A. *Definição de áreas prioritárias para conservação e preservação florestal por meio da abordagem multicriterial em ambiente SIG*. 2005. 137 p. Tese (Doutorado em Recursos Florestais) – Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba, 2005. Disponível em:. Acesso em: 02 fevereiro 2021

VALENTE, R. O. A.; PETEAN, F. C. S.; VETTORAZZI, C. A. *Multicriteria Decision Analysis for Prioritizing Areas for Forest Restoration*. Cerne, v. 23, n. 1, p. 53 60, 2017. https://doi.org/10.1590/01047760201723012258

VANN, S. *et al*. Delineation of Seawater Intrusion Using Geo-Electrical Survey in a Coastal Aquifer of Kamala Beach, Phuket, Thailand. Water, [S.L.], v. 12, n. 2, p. 506, 12 fev. 2020. MDPI AG. http://dx.doi.org/10.3390/w12020506.

VÍAS, J. M. *et al. Preliminary proposal of a method for contamination vulnerability mapping in carbonate aquifer*s. Em, Karst and Environment, Hidrogeology Journal, v.14, n.6, 75 83,2002.,

VÍAS, J. M. *et al. Proposed method for grandwater vulnerability mapping in carbonate (karstic) aquifers: the COP method*. Application in two pilot sites in Southern Spain.

VIGLIOTTI, M.; BUSICO, G.; RUBERTI, D. *Assessment of the Vulnerability to Agricultural Nitrate in Two Highly Diversified Environmental Settings*. Environments, [S.L.], v. 7, n. 10, p. 80, 29 set. 2020. MDPI AG. http://dx.doi.org/10.3390/environments7100080.

VOOGD, H. *Multicriteria evaluation for urban and regional planning*. Londres: Pion, 1983.

WANG, J. Z. *et al. Disturbing degree of mankind activities to groundwater in the Hutuo River Valley area*. Bull Soil Water Conserv, v. 30, n. 2, p. 65-69, 2010.

WWAP (UNITED NATIONS WORLD WATER ASSESSMENT PROGRAMME/UN-WATER). The United Nations *World Water Development Report 2022*: Groundwater Making the invisible visible. Paris, UNESCO. 2022.

ZHAI, H. *et al*. Understanding S*patio-Temporal Patterns of Land Use/Land Cover Change under Urbanization in Wuhan, China, 2000–2019*. Remote Sensing, [S.L.], v. 13, n. 16, p. 3331, 23 ago. 2021. MDPI AG. http://dx.doi.org/10.3390/rs13163331.

ZHAO, S. *et al*. *Spatial and Temporal Dimensions of Urban Expansion in China*. Environmental Science & Technology, [S.L.], v. 49, n. 16, p. 9600-9609, 3 ago. 2015. American Chemical Society (ACS). http://dx.doi.org/10.1021/acs.est.5b00065.