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Environmental fragility applied in spring area in northeastern brazil

Fragilidade ambiental aplicada em área de manancial no nordeste brasileiro

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Abstract: Northeast Brazil is greatly affected by water scarcity, mainly due to unfavorable climatic characteristics. Due to the recent crisis, between 2010 and 2017, dozens of cities in the semi-arid region faced serious problems that exposed the fragility of current supply systems. Environmental studies on supply sources are necessary for territorial planning and the identification of vulnerabilities to degradation processes, aiming to adapt human needs to environmental viability. The objective of this work is to map the Environmental Fragility to the erosion of the Bonfim Lake Hydrologic System Basin (BLHSB), a set of lakes responsible for the supply of water to the Agreste region of Rio Grande do Norte (RN). Environmental Fragility in Geographic Information Systems (GIS) was used with the use of Multicriteria Analysis and Fuzzy Logic, to integrate the geoenvironmental attributes in order to verify the relationships between erosive processes of morphogenesis and pedogenesis associated with the silting up of the lake region of the source. 44.15 km² (61.15% of the area) had a Medium, High and Very High degree of Environmental Fragility, indicating the need for attention in relation mainly to land use regulations, given the existence of activities with high degradation power in in line with areas with considerable degrees of fragility.

Keywords: Water resources; Erosion; GIS.

Resumo: O nordeste brasileiro é muito afetado pela escassez hídrica proporcionada principalmente pelas características climáticas desfavoráveis. Devido a recente crise, entre 2010 e 2017, dezenas de cidades do semiárido enfrentaram sérios problemas que expôs a fragilidade dos atuais sistemas de abastecimento. Os estudos ambientais em mananciais de abastecimento são necessários para o planejamento territorial e a identificação das vulnerabilidades a processos de degradação, visando adequar às necessidades humanas à viabilidade ambiental. O objetivo deste trabalho consiste em mapear a Fragilidade Ambiental à erosão da Bacia Hidrográfica do Sistema Lacustre Bonfim (BHSLB), um conjunto de lagoas responsável pelo fornecimento de água à região Agreste do Rio Grande do Norte (RN). Foi utilizada a Fragilidade Ambiental em Sistemas de Informação Geográfica (SIG) com emprego da Análise Multicritério e Lógica Fuzzy, para integrar os atributos geoambientais a fim de verificar as relações entre processos erosivos de morfogênese e pedogênese associados ao assoreamento da região lacustre do manancial. 44,15 km² (61,15% da área) apresentou grau de Fragilidade Ambiental Médio, Forte e Muito Forte, indicando a necessidade de atenção com relação principalmente à regulamentos do uso do solo, dada a existência de atividades com alto poder de degradação em consonância com zonas com graus de fragilidade considerável.

Palavras-chave: Recursos hídricos; Erosão; SIG.

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1. Introduction

The search for resources to meet the needs of societies throughout history has increased as scientific, technological and economic developments demanded more insums (TRICART 1977, ROSS, 1994). Knowing that the natural environment is the main supplier of these resources, the relationships between explorers and suppliers became increasingly intimate, mainly due to the particularities of each region of the planet and how each human society developed and understood these relationships, often causing significant changes in landscapes, leading to environmental degradation and resource depletion (PASCUAL et al., 2017 ROCKSTRÖM et al., 2009).

The differences in the hydrological regime between the regions of Brazil made engineering solutions such as dams, wells, transposition channels and pipelines necessary to meet the needs of the population in relation to access to water. On average, 47% of Brazilian municipalities are supplied by surface water, 39% by underground springs and 14% use the mixed system, with both surface and groundwater (BRASIL, 2010).

In Brazil, water demand varies, both in the purpose and regionally, where the largest consumers are irrigation activities (66.1% of total consumption), urban and rural supply (11.6%), animal consumption (11.6%) and industry (9.5%). The remainder (1.2%) represents other types of consumption. From the regional perspective, the southeast has the highest water consumption, but in relation to demand and availability together, the northeast region presents greater difficulty, since the semi-arid climate present in much of its territory is characterized by high temperatures, low rainfall and high evaporation rates, facts that make the springs something fundamental for survival in the region , enabling the emergence and development of cities and mitigating the effects of drought, since they contribute ensuring water storage in rainy periods and supply in dry periods (BRASIL, 2019).

Given the recent history of water crisis in the semi-arid, especially between 2010 and 2017, the current reality proved to be quite fragile, many municipal supply systems collapsed due to the prolonged drought, occurring depletion of water sources and the need for rationing of use and rotation, which affected about 512,000 people (ANA, 2017; GODIM et al., 2017). In Rio Grande do Norte (RN) this reality was not different, from 2012 to 2017 several municipalities faced problems of reduction in reservoir volumes, flow decreases, interruptions in adduction systems and distribution networks, which confirmed the need for a deeper investigation regarding the vulnerability of each municipality in the state to water deficit. Therefore, new forms of territorial and water planning, assistance, infrastructure and integration are necessary (TROLEIS; SILVA, 2018).

As a way of coping with the problems of inland water scarcity, in the RN stands out the System of Monsignor Expedito Adductor or Agreste/Trairi/Potengi System, the largest potiguar adduction system, with about 315 km of extension, operated by the Water and Sewage Company of Rio Grande do Norte (CAERN). This system captures water from both The Bonfim Lake and seven tubular wells upstream of the Lacustre Bonfim System, with an estimated flow rate of 452L/s, in order to distribute to 30 municipalities and rural communities of Agreste Potiguar, benefiting an estimated population of 266,879 inhabitants (CARLOS, 2004; PEREIRA et al., 2000; PEREIRA et al., 2002; CASTRO et al., 2014).

Given the notorious importance of this source for the state, studies on the environmental vulnerability of the system when faced with the water crisis are necessary. To Oliveira et al. (2020) one of the ways to assess vulnerability to resource loss is to use methodologies that can and are adopted in territorial planning that takes into account the potentialities and weaknesses of the environment. Among the methods that can support the zoning of environmental vulnerability, Souza et al. (2019) highlight the universal equation of soil loss (USLE) and the environmental fragility index.

The concept of environmental potentiality involves everything that is necessary for life, whether through environmental resources or services, involving soil components, terrain, rocks, minerals, waters, climate, flora and fauna. Environmental fragility, on the other hand, can be represented by the susceptibility of the characteristics intrinsic to the functioning of the environment to undergo negative changes, and should be evaluated in an integrated way, that is, all physical, biotic and anthropic factors that make up the system should be taken into account. The study of environmental fragility proposed by Ross (1994) is fundamental for understanding the particularities inherent to each site, since it exposes the relationships between environmental components and makes it possible to find places with greater ease of suffering quality loss (ROSS, 1994; SPRÖL; ROSS, 2004; KAWAKUBO et al., 2005).

It is important to highlight that the quality and quantity of water in the springs are influenced by several variables, and may undergo changes naturally with variations in the hydrological regime, surface flow, temperature and vegetation cover or present variations from human activities through the release of effluents, irregular disposal of solid waste, water exploitation and land use and occupation without being considered technical aspects of the territory (BRASIL, 2019).

The changes caused by the use and occupation of the soil can cause siltation of watercourses and water bodies due to erosive processes resulting from the removal of native vegetation, soil preparation for agriculture, intensive and extensive livestock, urbanization, among others, breaking the natural dynamics of the environment, directly influencing the hydrological cycle and altering the surface runoff, with losses on water available for consumption (LAMBIN et al., 2003; ZHAO et al., 2013; CRUZ et al., 2017; ZORZAL-ALMEIDA et al., 2018; CARVALHO et al., 2019; ANJINHO et al., 2021).

Given the various variables involved, and for the occupation and rational use of the territory, it is necessary to take into account socioeconomic and environmental aspects, whether at the federal, state, regional and municipal scales (ROSS, 1994) or using the basin as a territorial unit of territorial planning and water management (BRASIL, 1997; SILVEIRA, 2001; TUCCI, 2001; MORALS; LORANDI, 2016).

The environmental planning of an hydrographic basin as a territorial unit for study must take into account the potentialities and constrains present in the whole area, and should place human societies as an integral part of the environment, since they compose and direct the use and occupation of the territory. The planning should be based on geomorphological, geological, pedological, climatological, land and vegetation use and cover analyses for the production of technical reports and preparation of thematic cartographic materials elaborated in the GIS environment. In this case, environmental fragility maps help decision-making and are relevant when faced with the environmental problems encountered (ROSS, 1994; KAWAKUBO et al., 2005; COSTA et al., 2015).

GIS consists of a set of techniques and methods for collecting geographic information, processing, analyzing and preparing cartographic documents, using computational tools (ROSA, 2005). The main relevance of GIS is versatility, which allows viewing images of Remote Sensing (SR), plotting graphs and creating correlations and correlations between the data obtained, corroborating the integrated analysis that is necessary for the study of fragility in delimited units (SCHIAVETTI; CAMARGO, 2002).

Moreover, the GIS allows working in spatial and time scales for a given area, so its application is gaining more and more space, mainly in the quantitative and qualitative analysis of water bodies such as lakes, rivers, lagoons, reservoirs and in the study of the respective hydrographic basins (SANTOS, 2013; MORALS; LORANDI, 2016).

Therefore, this study verified the degree of environmental fragility to the erosion of the BLHSB by applying GIS, in order to generate the cartographic products that support the territorial and environmental planning of the spring.

2. Geoenvironmental characterization

The BLHSB is located on the Eastern coast of RN, 25 km south from the state capital of Natal, with an area of 72.19 km² and UTM-Zone 25 South coordinates extreme 9,326 to 9,338 km N and 248 to 268 km E, covers part of the municipalities of Nísia Floresta and São José de Mipibú (Figure 1).

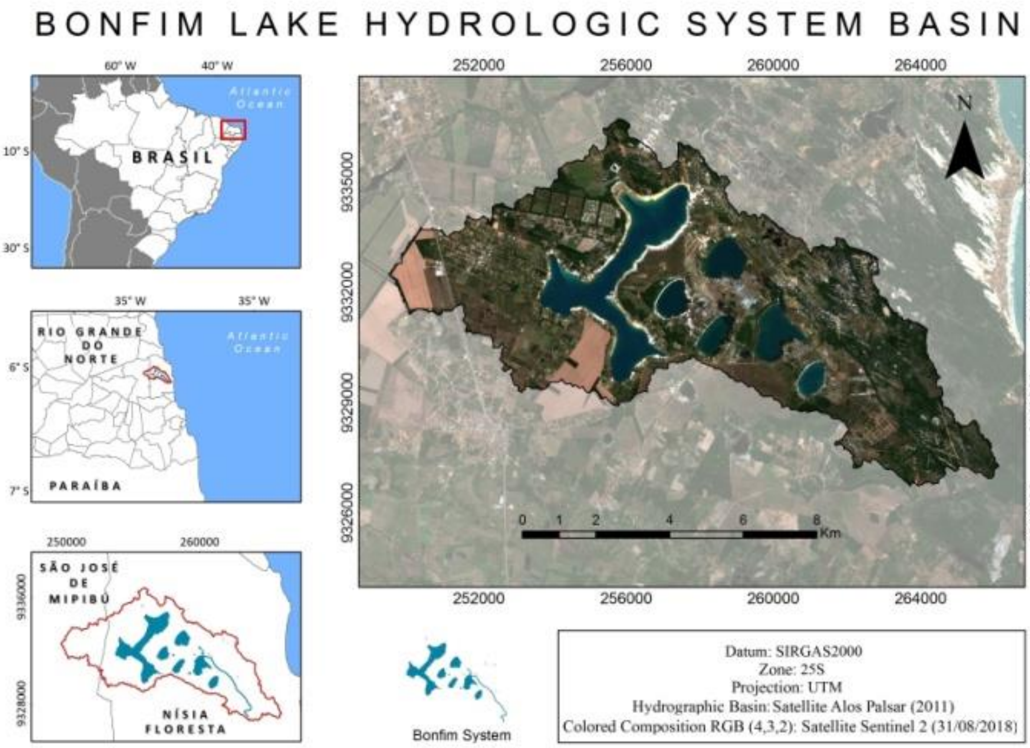

Figura 1 – Location Map.
Source: Author (2020).

The Bonfim Lake System was defined by Complementary Law Num. 003/2007 in its Art. 2nd as part of the natural heritage of the Nísia Floresta municipality and by Art. 40 as an Environmental Protection Zone of the municipality, also being part of State Decree Num. 14,369 of March 22, 1999 of the Environmental Protection Area of RN (APA Bonfim-Guaraíra). The APA Bonfim-Guaraíra was created to formalize the use, protection and preservation of the dune ecosystems, Atlantic Forest, mangrove, lagoons, rivers, watercourses, plant and animal species fromt its extension, which covers the municipalities of Nísia Floresta, São José de Mipibú, Goianinha, Senador Georgino Avelino, Tibau do Sul and Arês (RIO GRANDE DO NORTE, 1999; NÍSIA FLORESTA, 2007; SEMARH; IDEMA, 2008).

The BLHSB hydrology consists of six natural lakes connected, in subsurface, by the Dunas-Barreiras Aquifer: the Bonfim, Redonda, Urubu, Boa Água, Ferreira Grande and Carcará, which together occupy 9.87 km² (13.67%) of the total area of the basin (Table 1). The main one, the Bonfim Lake has 84.27 million m³ of maximum capacity, being considered the largest lake of RN and the largest reservoir used for supply located in the coastal region of the state (MELO et al., 2000; PEREIRA et al., 2002; CUNHA et al., 2014).

Table 1 – Characteristics of the ponds.

BLHSB			
Lakes	**Volume Max. (m³)**	**Depth Max. (m)**	**Area (km²)**
Bofim	84.268.211	31	6,12
Ferreira Grande	2.812.724	8	1,10
Redonda	3.720.090	8	0,64
Urubu	2.736.115	9	0,96
Boa Água	1.469.132	4	0,56
Carcará	1.570.979	4	0,49

Source: Costa (1997); Lucena (1999) apud SEMARH; IDEMA (2008). Author (2020).

The junction of all existing water bodies in the basin forms a water mirror of 10.10 km² (14%) of the watershed total area.

Figure 2 shows the geoenvironmental attributes used as: Geology, Pedology, geomorphological compartments, terrain shapes, hyphesometry and slope.

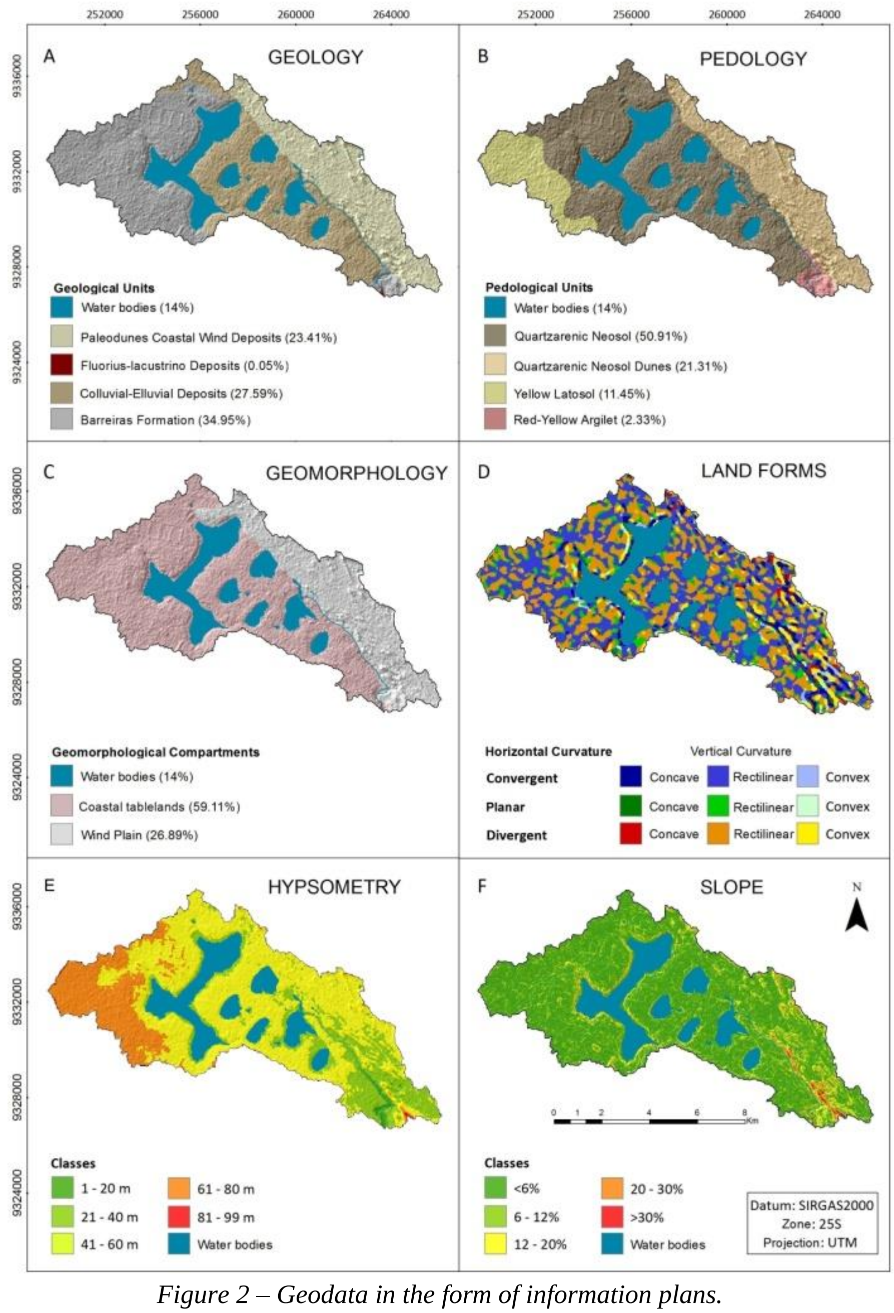

Figure 2 – Geodata in the form of information plans.
Source: Author(2020).

Surface geology is dominantly associated with sedimentary rocks of the Paleogen-Neogen periods covering precambrian crystalline rocks consisting of gneiss and migmatites (MELO *et at*., 2000; PEREIRA et al., 2000; BARRETO et al., 2004; OLIVEIRA, 2011).

The Barreiras Formation (25.23 km²) covers the west and southeast regions. The sediments of this formation have continental origin, typical of an interlaced river system, transitional for alluvial fans and coastal plains (RADAMBRASIL, 1981; MELO *et at*., 2000; PEREIRA et al., 2000; BARRETO et al., 2004; OLIVEIRA, 2011).

The central part is occupied by a peneplanization surface, forming the Colluvial-Elluvial Deposits (19.92 km²), composed of a coarse clastic sequence with unconsolidated sandy soil capping, mainly from erosion, weathering and leaching of precambrian rocks and sediments of the Barreiras Formation (RADAMBRASIL, 1981; MELO *et at*., 2000; PEREIRA et al., 2000; BARRETO et al., 2004; OLIVEIRA, 2011).

The South region of the basin, has a small portion of the Fluorius-lacustrino Deposit (0.04 km²) from the lagoon-estuarine region of Nísia Floresta-Papeba-Guaraíras. This deposit is the result of the meandering regime of watercourses in the region and characterized by the contribution of sandy clayey material, where it is possible to find diatomite and white clays (RADAMBRASIL, 1981; MELO *et at*., 2000; PEREIRA et al., 2000; BARRETO et al., 2004; OLIVEIRA, 2011).

The Paleodunes Coastal Wind Deposits (16.90 km²) covering the far east of the basin are composed of quartz sands of rounded, fine and medium grains, with whitish color (RADAMBRASIL, 1981; MELO *et at*., 2000; PEREIRA et al., 2000; BARRETO et al., 2004; OLIVEIRA, 2011) (Table 2).

Table 2 – Geological characteristcs.

Geology		
Geological Units	**Sediment**	**Period**
Paleodunes Coastal Wind Deposits	Sandy	Neogene-Paleogene
Fluorius-lacustrino Deposits	Fine sands, silt and clay	
Colluvial-elluvial Deposits	Clayey sand, unconsolidated sand and conglomeratic	
Barreiras Formation	sandstones, siltstones, claystones and conglomeratic	

Source: Barreto et al.*, (2004); CPRM (2006); Melo* et al.*, (2000); Pereira* et al.*, (2000); Oliveira, 2011; Adapted by the author (2020).*

The BLHSB is located within the Hydrogeological System of the Dunas-Barreiras Aquifer, composed of cemented quartzoarenitic rocks, which extend along the eastern coast of RN, from the municipality of Touros to the Paraíba state, within the Potiguar sedimentary basin (MELO et al., 2000; PEREIRA et al., 2000; MANOEL FILHO; CASTRO, 2002). The lake system is interconnected by the aquifer with underground flow converging from Bonfim Lake, with a dimension of 40 meters, to the Boa Cica stream with a dimension of 3.6 meters, which is the exutory stretch of the basin (LUCENA, 1999; PEREIRA et al., 2000).

The predominant type of soil is Quartzarenic Neosol (36.75 km²), formed by Dystrophic Quartzs Sands, originated from sediments of the Barreiras Formation. Physically, it is characterized by being deep or very deep, with little developed on horizon A, not hydromorphic, excessively drained, with sandy texture (clay <15%) low humidity (Table 3) (DNPEA/SUDENE, 1971; RADAMBRASIL, 1981; EMBRAPA, 2006; OLIVEIRA, 2011; NÍSIA FLORESTA, 2018).

The Dystrophic Marine Quartz Sands (Dunes) occupy 15.38 km² in the eastern region of the basin, being characterized by non-consolidated soils ranging from deep to very deep, non-hydromorphic, with sandy texture, excessively drained and with low clay contents (DNPEA/SUDENE, 1971; RADAMBRASIL, 1981; EMBRAPA, 2006; OLIVEIRA, 2011).

Table 3 – Soils that compose the BLHSB.

Pedology			
Soil	**Texture**	**Permeability**	**Clay**
Quartzarenic Neosol	Sandy	Very permeable	<15%
Quarzarenic Neosol (Dunes)			Between 15% and 35%
Yellow Latosol	Clayey sand		
Red-Yellow Argilet		Slow	>35%

Source: RADAMBRASIL (1981); Oliveira (2011); DNPEA/SUDENE (1971); Adapted by the author (2020).

The west is occupied by Dystrophic Yellow Latosol (8.27 km²) originating from the adjacent geological formations Barreiras and Colluvial-Elluvial Deposits, and can be identified by the presence of resistant minerals such as quartz in the soil, being highly weathered and with low clay/silt content. They are very deep soils, non-hydromorphic, ranging from well to moderately drained, with high permeability, very porly, of medium texture (with clay content in horizon B between 15% and 35%) and low clay activity (DNPEA/SUDENE, 1971; RADAMBRASIL, 1981; EMBRAPA, 2006; OLIVEIRA, 2011).

The smallest portion corresponds to the Dystrophic Red-Yellow Argilet (1.69 km²) and it is located in the southeast region of the basin, in slightly more wavy terrain being characterized by being a predominantly kaolinitic soil, deep, moderately drained, with sandy/medium texture on horizon A (clay content between 15 and 35%) and medium/clayey on the Bt horizon (clay content >35%) with low clay activity (DNPEA/SUDENE, 1971; RADAMBRASIL, 1981; EMBRAPA, 2006; OLIVEIRA, 2011).

In BLHSB there are two morphological domains, plateaus and dunes. The parabolic regions of dunes on the coast (19.42 km²) compose a flat/smoothly wavy surface of low altitude, where sedimentation processes overcome those of erosion, being called the Wind Plain (RADAMBRASIL, 1981; LUCENA, 1999; PEREIRA et al., 2003; IBGE, 2009).

In the west region the surface plateaus of the Coastal tablelands were identified (42.67 km²), which have flat-top terrain elaborated in sedimentary rocks. These plateaus are present on the entire coast of RN state, which cover the crystalline base to the west and form active marine cliffs to the east (RADAMBRASIL, 1981; LUCENA, 1999; PEREIRA et al., 2003; IBGE, 2009).

The altimetric dimensions range from 1 to 99 meters, decreasing as they approach the ocean. With regard to slope, the areas are dominated by slope from 0 to 6%. According to Pereira et al. (2003) such terrain features (slightly wavy with sandy capping) promote high infiltration rates and little surface runoff, leading to a low drainage density.

Regarding the climate, the area is located in domain **As** according to Köppen classification, where hot and humid conditions were identified and the climate was denominated as Tropical, with a dry summer (September to January/February) and rainy autumn-winter (February/March to August) (LUCENA, 1999; PEREIRA et al., 2000; ALVARES et al. 2013). Rainfall varies from 1,200 to 1,500 mm/year according to the Agricultural Research Company of RN (EMPARN), with winds coming from the Southeast direction of the sea. The average annual temperature is 27.1 ºC (SEMARH; IDEMA, 2008).

Due to the rainfall regime, it is possible to recharge significant aquifer that feeds the underground water system and contributes to the region's water potential, both with the lagoons and with perennial rivers. The region is known as being part of the Humid Valleys of RN (MANOEL FILHO; CASTRO, 2002).

The vegetation can be classified in Semidecidual Seasonal Forest (Atlantic Forest), Pioneer Formations, being also identified areas of contact between Savannah/Savannah-Estepic/Seasonal Forest and contact between Savannah (Cerrado)/Savannah-Estepic (Caatinga) (RADAMBRASIL, 1981).

3. Metodology

Primary matrix data were used to assemble the digital and georeferenced geographic database, such satellite images and secondary vector data, such as geology, geomorphology, pedology maps, among others (Table 4). The information plans were georeferenced in Time Zone 25S, the geodesic reference SIRGAS2000 was adopted and Mercator's Universal Transverse projection system (UTM) was used. The data were manipulated and integrated into the ArcGis 10.5 software (ESRI, 2017).

The delimitation of the basin was performed from the Digital Elevation Model (DEM) obtained from the images of the Advanced Land Observing Satellite (ALOS), PALSAR sensor (Phased Array type L-band Synthetic Aperture Radar) of microwave that operates in the L Band, using the algorithms of the Hydrology tool of spatial analyst tools. This DEM was also used for the hyphesometry and slope map, applying the Slope tool of the Raster Surface.

The ALOS satellite image was also used to elaborate the shaded terrain which was used to assign a 3D aspect to the maps.

The coverage and land use map was elaborated from the sentinel-2A satellite images, MSI sensor (Multispectral Instrument). From the colored compositions RGB (4,3,2) and false color (8,4,3), the visual interpretation of objects on the earth's surface was performed considering aspects such as color, tonality, size, context, shape, texture, pattern and location (FLORENZANO, 2011). Thus, the classification and manual vectorization in screen (heads-up) was performed (JENSEN 2009; LONGLEY et al., 2013) of the main types of use and coverage.

The methodology for empirical analysis of environmental fragility was based on Ross (1994 and 2012), derived from the concepts of Tricart Ecodynamic Units (1977) adapted from systems theory, which states that there is a relationship between dynamic balance, exchange of matter and energy of the environmental system components. The concept of Ecodynamic Units classifies the equilibrium as Stable (or Potential Instability), referring to natural areas that have not suffer of human actions, but which may suffer, or Unstable Ecodynamic Unit (or Emerging Instability), referring to environments whose anthropic interventions have already caused modifications (TRICART, 1977; ROSS, 1994; ROSS, 2012).

Table 4 – Geographic database.

Geographic Information Plan			
	Description	**Source**	**Spatial Resolution /Scale**
Hydrographic elements	BLHSB	Satellite Sentinel-2A (2018)	10m
Land use and land cover	Classes of use		
DEM	Altimetry/ Slope	JAXA/METI (2011)	12,5m
Geomorphology	Land form	TOPODATA (2011)	30m
	Relif compartments	RADAMBRASIL (1981); IBGE (2017)	1:250.000[1]
Pedology	Soil types		
Geology	Geological formations	CPRM (2006)	1:100.000[2]
Climate	Rainfall	RADAMBRASIL (1981); LUCENA (1999); SEMARH, IDEMA (2008); PEREIRA (2000); ALVARES *et al*. (2013)	

Source: Author (2020).

[1]Based on the mappings performed in the RADAMBRASIL project, such mappings are compatible with the level of detail 1:250,000, although printed in scale 1:1000,000.
[2]Although printed in scale 1:500,000, such mapping was performed using a planimetric base in a scale of 1:100,000.

Thus, areas with lower degrees of fragility indicate lower instability, greater potential for use/exploitation and lower vulnerability to damage; while the highest levels of frailties mean greater instability, low potential for use/exploitation and greater ecological sensitivity (ROSS, 1994; ROSS, 2012).

The attributes of the physical, biotic and anthropic media as well as their properties used in this investigation were: geology (lithology), pedology (texture, particle cohesion and thickness), geomorphology (dissection and pleasing), hypnometrics (availability of potential energy to be converted into kinetic energy through flow and consequent increase in the potential to promote erosion), slope (degree of slope of the terrain) , rainfall and land use and cover (human interference stems from different types of uses).

The multicriteria analysis began with the evaluation of the geoenvironmental characteristics of the attributes, which were individually classified from 1 to 5 according to the degrees of fragility to erosive processes, being Very Low = 1, Low = 2, Medium = 3, High = 4 and Very High = 5 (Table 5).

Table 5 – Weights and classes evaluated.

Fragility	Geological Unit
Low (2) **Medium (3)** **High (4)** **Very High (5)**	Barreiras Formation Fluorius-lacustrino Deposits Colluvial-Eluvial Deposits Paleodunes Coastal Wind Deposits
	Soil Types
Low (2) **Medium (3)** **High (4)** **Very High (5)**	Yellow Latosol Red-Yellow Argilet Quartzarenic Neosol Quartzarenic Neosol (Dunes)
	Morphological Domains
Very Low (1) **High (4)**	Coastal tablelands Wind Plain
	Hypsometryc Classes
Very Low (1) **Low (2)** **Medium (3)** **High (4)** **Very High (5)**	1m a 20m 20m a 40m 40m a 60m 60m a 80m 80m a 99m
	Slope Classes
Very Low (1) **Low (2)** **Medium (3)** **High (4)** **Very High (5)**	<6% 6-12% 12-20% 20-30% >30%
	Land Forms Classes
Very Low (1) **Low (2)** **Medium (3)** **High (4)** **Very High (5)**	Convergent/Concave Planar/Concave; Divergent/Convex Planar/Rectilinear; Convergent/Rectilinear Convergent/Convex; Planar/Convex Divergent/Convex
	Rainfall*
Medium (3)	Rainfall situation with uneven annual distribution, with dry periods in summer (September to January/February) and rainy winter (February/March to August), with a volume of 1,200 to 1,500 mm/year
	Land Use and land cover Classes**
Very Low (1) **Low (2)** **Medium (3)** **High (4)** **Very High (5)**	Sparse Atlantic Forest with Coastal Board, Riparian forest (1) Lot with herbaceous vegetation (2) Small rural properties, Pasture, Coconut Grove (3), sugarcane (4) Natural exposed soil and under preparation, dirt road (5)

Source: Ross (1994, 2012). Adapted by author (2020).

*The original proposal for assessing fragility did not consider the morphoclimatic domain that dominates much of the NE coastline in which summers are dry and rainy winter.
**Ross methodology (1994, 2012) does not indicate a degree of fragility for the urban area, considering that fragility is conditioned to the relationship morphogenesis x pedogenesis. This analysis is not feasible in urban areas given the difficulties in identifying such processes (COSTA et al., 2015).

After hierarchical weighting and equalization of cell size (12.5 x 12.5 meters), using as reference the DEM, the algebra of maps in environment GIS was performed using the weighted sum algorithm (Weighted sum – Spatial Analist tools). The classification of weights was established according to Ross (1994, 2012) and Crepani et al. (2001) as well as come from knowledge among the interdisciplinary team formed by Environmental Engineer, Geographer and Geologists.

For environmental analysis, techniques that represent natural phenomena are more complex, since they do not have static limits (COSTA et al., 2015). According to Cereda Junior (2011), Fuzzy Logic is appropriate to represent the natural and gradual transition between geospatial events through numerical decisions applied to the surface. The use of Fuzzy Logic contributes to address the inaccuracies of categorized attributes, and can reduce the propagation of errors through logical models (CALIJURI et al., 2007).

In this study, fuzzy linear logic [y=f(x)] (Fuzzy Membership) assumes values from 0 to 1, being incorporated into the Multicriteria Analysis in order to rescale the data, as exemplified in Eastman (2006). In this case, Fuzzy Logic was applied to each criterion in the overlay analysis of the raster set.

4. Results and discussion

The analysis of geoenvironmental attributes in conjunction with the use and cover of the soil (Figure 5) allowed a diagnosis of changes in the landscape in the spring, mainly considering that human activities are efficient in potentiating erosive processes and silting, which alters the natural conditions of water availability.

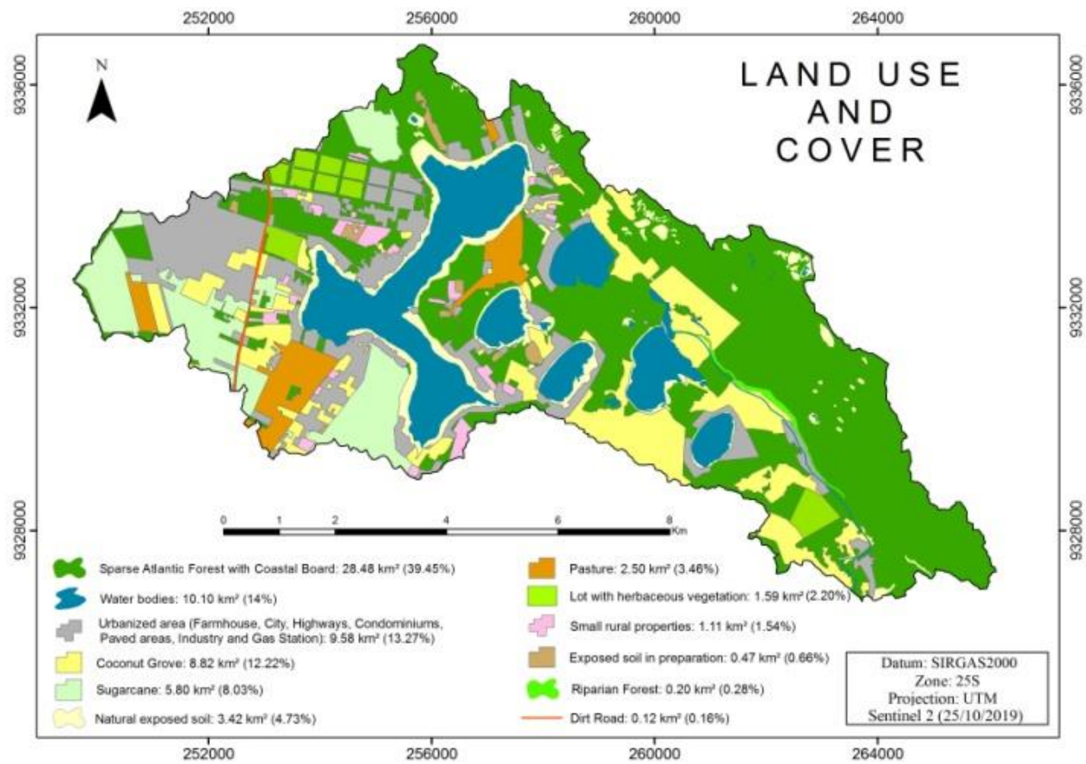

Figure 5 – Land use and cover.
Source: Author (2020).

The grades of greatest fragility (High and Very High) together totaled 7.94 km² (11%) and are located to the east, where there are influences from the Coastal Wind Deposits of Paleodunes, Quartzarenic Neosols (Dunes) and terrain, with the greatest variation of slope and greater presence of divergent/convex land forms (considering the horizontal/vertical profile), which act as areas of sediment sources not favoring the retention/deposition of particles (Figure 6).

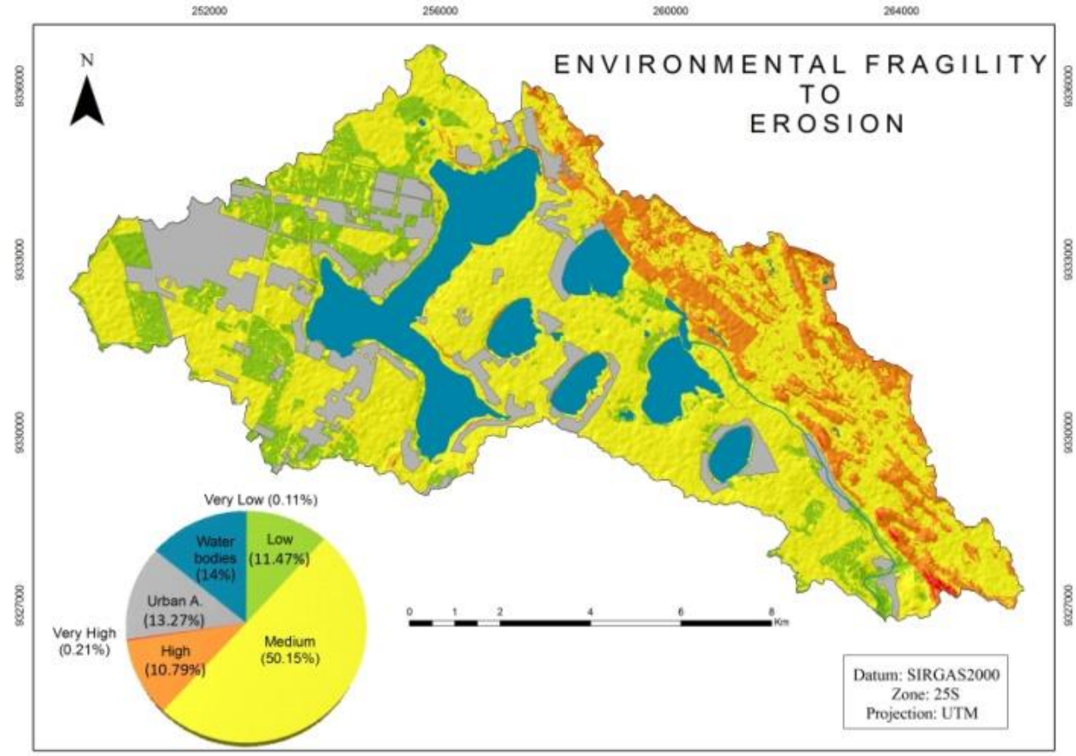

Figure 6 – Environmental fragility to erosion.
Source: Author (2020).

In the regions where there is the presence of Esparse Atlantic Forest of Coastal Board, there is the fixation of the unconsolidated material, composed predominantly of well-selected wind sands, however, in areas where the soil is exposed, even in a natural way, the process of material mobilization is favored.

The "Medium" degree of fragility was spatially predominant, with distribution throughout the basin, corresponding to 36.21 km² (50.15%). In the central region, where they are in the lakes, this predominance becomes more evident due to low slope (<6%) associated with divergent and convergent/rectilinear (horizontal/vertical) terrain shapes contained in the Tablelands that have lower degrees of fragility. On the other hand, there is the composition of sandy soils (Coluvium-Eluvionar cover in the form of Quartzarenic Neosols) that has a higher degree.

In areas of fragility classes that deserve greater attention (Medium, High and Very High), there are areas of permanent and intensive cultivation of fruit (Coconut culture) with minimum spacing of 7 to 10 meters that leave the sandy and friable soil exposed between the lines, making it more vulnerable to erosion (Figure 7 A) (CAVALCANTE, 2018).

According to Fontes et al. (2002), soil management between the lines of these perennial crops is an important prerequisite is to promote the aeration of the layer explored by the roots, facilitating the absorption of water and nutrients. Usually the disc plough is used to cut the soil until a certain depth and make the inversion of the cut area, with this, providing better physical conditions for the development of the crop. The advantage of this system is quite debatable, especially in Coastal tablelands. In many soils of this ecosystem, the "arable layer" is reduced to a few centimeters, causing this practice to accelerate the degradation of organic matter, leaving the soil more vulnerable to erosion.

Figure 7 – Coconut culture (A), exposed soil in preparation for sugarcane (B), cultivation, tree vegetation remains on exposed soil during the preparation for sugarcane (C), Land Road over Quartzarenic Neosol (D), partial view of Bonfim Lake *(E), accelerated erosive process (F).*
Source: Author (2020).

In temporary crops, such as sugarcane (Figure 7 B and C), large-scale mechanized operations that compact soils are necessary (SEVERIANO et al., 2010), including the use of vinasse for fertigation leads to the blockage of soil pores and, consequently, decrease permeability (ALVES, 2007; COSTA et al., 2015). In both cases, if performed improperly, it can intensify erosion and promote compaction. In the soils of the Coastal tablelands with cohesive subsurface layers, this effect is very serious, once that the combination of cohesive horizon with compacted layer tends to accelerate the degradation process and can create unsustainable situations for environmental preservation, such as increasing the surface runoff of rainwater (FONTES et al., 2002). As an aggravating factor, rainfall is concentrated in five to six continuous months (LUCENA, 1999; PEREIRA et al., 2000; ALVARES et al. 2013).

Extensive livestock activities (pasture) are concentrated in areas with medium degree of environmental fragility. According to Trimble and Mendel (1995) cattle are an important agent of geomorphological change due to trampling and soil compaction, because of these infiltration is reduced, favoring surface runoff and triggering erosive processes.

The Very Low and Low fragility portion constitutes 8.36 km² (11.58%) and is located predominantly in the western region of the spring, where urbanized areas are concentrated. The geoenvironmental attributes verified in the area were the sandstone of the Barreiras Formation, arranged in the form of Coastal tablelands in slightly steep terrain.

In large cities from Europe and North America, Jaeger et al. (2010) verified a new trend of urbanization, more fragmented and with higher consumption of land and natural resources. In this case, the occupation takes place in periurban areas, based on the mobility provided by the automobile and the desire to live in condominiums with surrounding green areas, occupying mainly lake environments. This is also the scenario seen in Natal, capital of RN state. However, in this case, urban growth often occurs in a precarious way, being self-produced by the residents themselves, without infrastructure conditions such as pavement and sanitation. In South America, Rolnik (2009) mentions that this form of urbanization is the result of a market that aims at immediate profit, expanding the city limits in a fragmented way, from initiatives of landowners and lotters.

Among human activities, urbanization is the one that most alters the natural conditions of the environment, reducing the coverage of natural vegetation, reducing rainwater infiltration, increasing surface runoff and increasing diffuse and concentrated pollution (COSTA et al., 2015). Schueler et al. (2009) reached the threshold of 10% to 15% of waterproofed surface in the form of urbanized areas within a spring to maintain the health of the water bodies that drain it.

According to Pereira et al. (2003) the western region of BLHSB is responsible for much of the recharge of the Dunas-Barreiras aquifer that will subsurfacely feed the lakes. Therefore, in the western region of BLHSB, because they are positioned in topographically higher areas, on porous and low steep terrain the changes, imposed by urbanization in the form of waterproofed surfaces, can hamper the natural process of infiltration of rainwater, delaying recharging. In subsurface, urbanized areas without basic sanitation are responsible for groundwater contamination caused by effluents from septic areas and leaks in sewage pipes, as well as the disposal of various waste directly in the soil or inside water bodies.

When urbanization advances on the springs, there are greater risks to contamination by domestic or industrial sewage and in the rain water network, as well as the inadequate disposal of solid waste in wastelands, along with the consequent eutrophication, reducing the availability of water in quality and quantity for the supply, making the treatment more expensive (TUCCI, 2001; TUNDISI et al., 2006).

In general, the environmental fragility of the spring is not only more expressive due to the low slope typical of sedimentary lands derived from the Barreiras Formation and the presence, even in a sparse way, of the Atlantic Forest of Coastal Board, which offers protection in the form of vegetation cover. In this case, although Quartzarenic Neosols favor erosive processes because they have low amounts of clays, which act as a link between larger particles, such configuration of the physical/biotic media tends to slow this process.

However, most of the sediments from surface erosion are deposited in the lakes that are natural reservoirs, among them, the Bonfim Lake (Figure 7 E) is used as a water source for inland cities (32 municipalities and 164 rural communities), providing water for 266,879 inhabitants (CUNHA et al., 2014). According to Bitar (1995) silting is one of the most serious impacts of erosion on the environment, unbalancing hydraulic conditions, promoting the loss of water storage capacity, the increase of chemical pollutants and consequent changes in aquatic life.

5. Final considerations

The BLHSB presented 44.15 km² (61.15%) areas with a considerable degree of Environmental Fragility (Medium, High and Very High) and only 8.36 km² (11.58%) identified with Very Low and Low degrees. In view of this result, attention is needed in relation to the use and occupation of the soil, since the various conditions such as: the expansion of urbanized areas, sugarcane plantation, pasture areas, in line with the characteristics of the soil, terrain, vegetation and geological conditions can favor processes that will negatively impact the quantity and quality of the water of the spring.

The methodology based on the analysis of environmental fragility to erosion helps to understand the vulnerability to the dissection of BLHSB terrain, allowing to identify areas require a greater degree of conservation, contributing to improve the understanding of the site while strengthening the database of the region, so that it is possible to ensure the maintenance of the lacustrine system as part of the State Conservation Unit and as an Environmental Protection Zone of the municipality that it is inserted.

The mapping of the environmental fragility of the basin along with the land use and occupation map showed that in fact the most fragile areas have the lowest human interventions, meaning that there is natural environmental fragility. On the other hand, it also showed that the areas of lower degree of fragility present several simultaneous anthropic activities, some with high harmful power to the environment with regard to erosive processes, such as pasture areas, sugarcane, coconut trees and urbanization, which can compromise the entire basin over time. Therefore, the monitoring of these activities with conservation practices should be performed.

This work can serve as a subsidy for the zoning of the municipalities of Nísia Floresta and São José de Mipibú, so that public policies of territorial planning can be applied properly, knowing the importance of this spring for the Rio Grande do Norte state and especially for the Agreste Potiguar region, avoiding that erosive processes of environmental degradation promoting the water availability and supply for the population can be continuous even in periods of drought more severe.

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