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Analysis of the Levels of Alteration of Aquifers Caused by the Installation of Wind Farms on Dunes on the Coast of Ceará, Brazil

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ABSTRACT

This research evaluated the levels of alteration of aquifers caused by installation of wind farms on dunes on the coast of Ceará, using the GOD and POSH methods of vulnerability, underground flow, and the application of multivariate analysis to subsidize the monitoring of groundwater quality in the area. There were three stages of field study: registering the wells and pollution sources, measuring the water levels, and groundwater sampling for laboratory analysis. The results obtained with the GOD method demonstrate the predominance of moderate- to high natural vulnerability of the aquifer to pollution in the areas close to the wind park in the district of Amarelas (Xavier and Ziu beach) and revealed high pollution loads according to the POSH method. The directional vectors of the underground flow are meaningful for Xavier Beach (high vulnerability), the center of Amarelas (moderate vulnerability), Tapuiu and Montevideo (low vulnerability). This indicated that the wind farm may have a potential impact on the lowering of groundwater in the area. From the multivariate analysis, it is evident that the groundwater characteristics are strongly related to the geological formation of the wells (Dunas and Barreiras), showing all samples within the Tolerable Maximum Value for human consumption for TDS, hardness, turbidity, and pH. It is vital to carry out preliminary studies of the aquifers underlying the areas where wind farms are to be installed, considering the levels of vulnerability and the risks of pollution and alteration of the water supply.

Keywords: groundwater, sedimentary aquifer vulnerability, wind power.

Análise dos Níveis de Alteração dos Aquíferos a partir da Instalação de Parques Eólicos sobre Dunas no Litoral do Ceará, Brasil

RESUMO

A pesquisa objetivou avaliar os níveis de alteração dos aquíferos a partir da instalação de parques eólicos sobre dunas no litoral do Ceará por meio dos métodos de vulnerabilidade GOD e POSH, fluxo subterrâneo e aplicação da análise multivariada para subsidiar no monitoramento da qualidade da água subterrânea na área. Foram realizadas três etapas de campo: cadastro dos poços e fontes de poluição, medição de nível d’água e coleta de amostras de água subterrânea para análises laboratoriais. Os resultados obtidos com o método GOD demonstram o predomínio de moderada a alta vulnerabilidade natural do aquífero à poluição nas áreas do entorno do parque eólico do distrito de Amarelas (praia de Xavier e Ziu) que estão próximas ao parque eólico e que foram classificadas de acordo com o método POSH, com elevadas cargas poluidoras. Os vetores direcionais do fluxo subterrâneo estão com sentido para a praia de Xavier (vulnerabilidade alta), sede de Amarelas (vulnerabilidade moderada), Tapuiu e Montevidéu (vulnerabilidades baixas), significando que o parque eólico pode ser um potencial impacto no rebaixamento do lençol freático na área. A partir da análise multivariada, observa-se que as características das águas subterrâneas estão fortemente relacionadas com a formação geológica dos poços (Dunas e Barreiras), conferindo todas as amostras dentro do Valor Máximo Permitido para consumo humano para STD, dureza, turbidez e pH. Ressalta-se a importância em realizar estudos preliminares dos aquíferos subjacentes às áreas onde pretende-se instalar parques eólicos, considerando-se os níveis de vulnerabilidade e os riscos à poluição e alteração do aporte hídrico.

Palavras-chave: água subterrânea, energia eólica, vulnerabilidade de aquífero sedimentar.

1. INTRODUCTION

Wind energy production in Brazil and specifically on the coastal zone of the State of Ceará, has made significant progress in recent years. It is considered one of the most promising renewable natural sources, a fact highlighted by the growing national and international demand for this new alternative energy. Although wind energy is categorized as "clean energy", the operation and, especially, the construction of wind farms on the coastal zone in dune environments result in significant socio-environmental impacts.

In 2009, a wind farm was set up around the communities of Xavier and Ziu in the district of Amarelas, located in the municipality of Camocim, on the west coast of the state of Ceará, about 200 meters from the east end of the densification of houses on the beach strip. It is one of Ceará's largest wind-power generation centers, with a capacity of 104.4 MW. There are 50 wind turbines in an area of approximately 1,040 ha, causing socio-environmental problems in the area. It is worth emphasizing that this area is formed by sandy sediments (dunes), where the water table is near the surface, on average one meter deep. Meireles (2011) found that the windward sides and slip faces in the fixed and mobile dunes have probably altered the hydrostatic level of the water table, influencing the flow of groundwater and the composition and spatial range of interdunal lagoons.

This research is therefore extremely relevant, since the licensing of the wind farm in question by the state environmental agency, the Environmental Superintendence of Ceará (SEMACE), was completely arbitrary. According to CONAMA Resolution n° 303 of March 20, 2002, dunes are defined as Areas of Permanent Preservation (APP) and thus the construction of an industrial-sized infrastructure, such as a power-generation plant, is not permitted. Furthermore, the Simplified Environmental Report (RAS) carried out by the enterprise failed to conduct a study on the vulnerability of the sediment aquifer and the possible impacts of the wind turbines, which are over 50 meters high and are made from tons of steel and concrete that require foundations tens of meters deep (Gorayeb *et al.*, 2018).

Research focus should consider the vulnerability of aquifers due to the characteristics of the materials that cover the saturated zone and confer some degree of protection to the groundwater against an imposed anthropic-contamination load (Foster and Hirata, 1988 *apud* Hirata and Fernandes, 2008). These characteristics include the ability to hydraulically degrade and / or prevent the entry of surface contaminants originating from human activity (Hirata and Fernandes, 2008). In this case, as well as the construction and maintenance of the park, the exogenous materials used in the wind towers' foundations may negatively influence the quality of the water table by the direct contact of their components with water, especially in the rainy period when the hydrostatic level is closer to the surface. There is also a fishing village (Xavier Beach) and the town of Ziu, belonging to the district of Amarelas, that have no sanitary sewage infrastructure or systematic collection of solid waste. Added to this scenario is the fact that several residents raise small animals, such as pigs, chickens, goats, and sheep without an adequate infrastructure.

Thus, it is vital to apply vulnerability assessment methods to aquifers, because this will make it possible to know the factors that compromise water quality and the threats of pollution (Santos *et al.*, 2010).

In the last three decades, the development of models and techniques for mapping the vulnerability and pollution risk to aquifers as a tool for their protection has increased. Several methods for aquifer vulnerability assessment have been developed (GOD, DRASTIC, SINTACS, POSH, and others); their efficacy depends directly on the quality of the data needed to define the parameters involved. According to Meira *et al.* (2014), the GOD (Groundwater occurrence, Depth to groundwater table) and POSH (Pollutant Origin, Surcharge Hydraulically) methods are conceptually simple and require bases that are, to a certain extent, accessible. These methods are often used to assess the natural vulnerability of the sediment aquifer (Cutrim and Campos, 2010; Boufekane and Saighi, 2013; Löbler and Silva, 2015; Duarte *et al.*, 2016; Gomes *et al.*, 2018). Thus, the use of such methods enables an assessment of the natural situation, the potential and risk of pollution in a given area.

The GOD method assesses the hydraulic accessibility level of the saturated zone, as a function of the degree of confinement of the aquifer, the depth of the static level and the attenuation capacity of the contaminants along the vadose zone (Foster *et al.*, 2002). While the POSH method addresses the possibility of generating a pollutant load by identifying the toxic substances stored and / or handled and the existence of hydraulic loading associated with these substances in the process or at their destination. This method is based on the following aspects: location of the polluting activity, start and end of the operation, type and size of the activity and use or availability of water (Hirata and Fernandes, 2008).

Studies evaluating the quality of groundwater generally use many hydrochemical variables in their classification, which are in turn correlated with each other, making it difficult to understand their interrelationships. By applying multivariate statistical methods, it is possible to reduce the number of variables, define their correlations, identify those that are responsible for the dispersion of observations and show the similarity between groups (Brito *et al.*, 2006). These methods identify the most significant variables in natural and / or anthropic terms and have been employed in different areas. In the context of groundwater resources, Brito *et al.* (2006), Cloutier *et al.* (2008), Salgado *et al.* (2011), and Gomes and Cavalcante (2017), among others, have used this statistical tool to support the monitoring and qualitative management of groundwater, especially in regions of high socio-environmental vulnerability, such as the area surrounding the wind farm on Xavier Beach and in the localities of Ziu, Tapuiu and Montevideo, all belonging to the district of Amarelas, Camocim, Ceará.

Given this situation, the research evaluated the vulnerability and risk of pollution of the sedimentary aquifer surrounding the wind farm in the district of Amarelas (Camocim, Ceará). The premise was that the installation of the wind farm on the dunes had impacted distribution of groundwater and groundwater confinement standards. Multivariate analysis was applied to support the monitoring of groundwater quality. The survey of basic water quality data can be used in the diagnosis, administration, and continuous management of the area by the company and by the public authorities. It can also give a positive return to the 50 families who live in the surroundings of the park, some about 200 meters away from the towers, whose way of life and routines have been transformed since the implantation of the wind power plant.

2. MATERIALS AND METHODS

2.1. Location and characterization of the study area

The study area involves the Xavier Beach and the localities of Ziu, Tapuiu, and Montevideo, all belonging to the district of Amarelas, located in the municipality of Camocim, on the west coast of Ceará, located 400 km from the capital, Fortaleza (Figure 1).

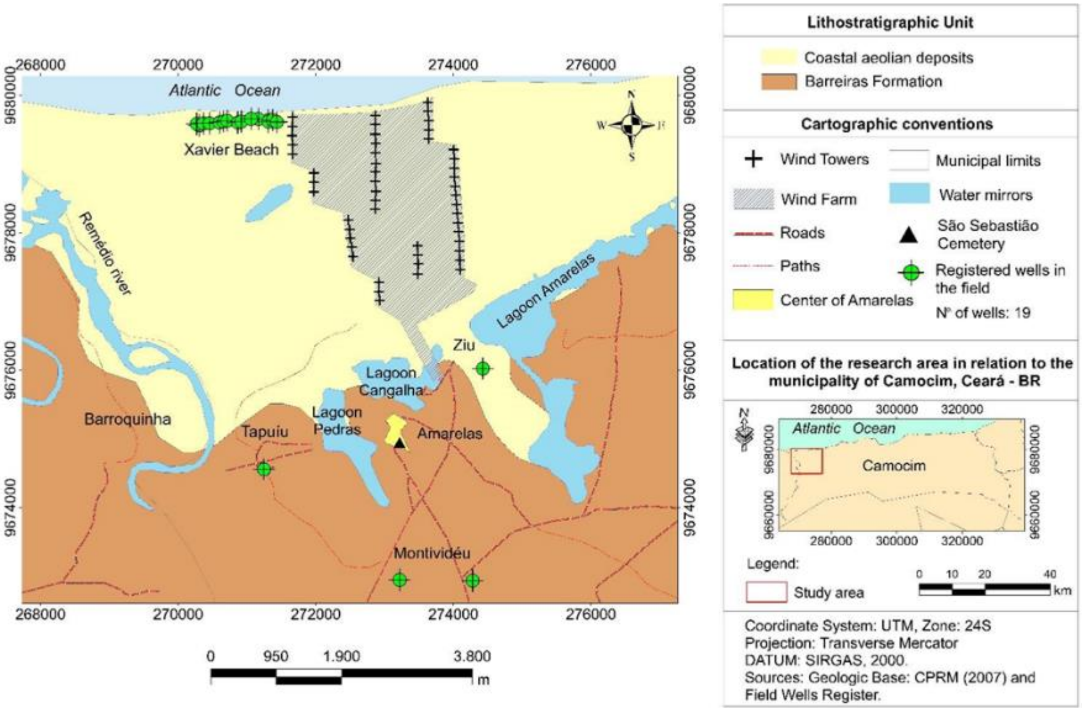

Figure 1. Location of the study area, Lithostratigraphic Unit and groundwater samples analyzed.

Geologically, the area is composed of Neogene (Barreiras) and Quaternary sediments (coastal aeolian deposits). The Barreiras Formation is formed by immature textural and mineralogical sedimentary deposits, composed of varying-toned clayey sandstones with conglomerate beds and posterior nodules at the base and with significant biological variation, with intercalations of more- and less permeable levels. According to Alheiros and Lima Filho (1991) and Moura *et al.* (2016), the presence of primary sedimentary structures indicative of currents with sea movement suggests predominantly continental origin, mainly by intertwined river channels. Coastal wind deposits (dunes) are formed by very well selected quartz or quartzofeldspathic sands of fine- to medium granulation, possibly composed of reworked marine bioclasts. Its most recent deposits arranged in the nearest portion of the shoreline. According to Meireles (2011), the dunes are classified as barcana, barcanoid and transverse types. They occur in association with environmental systems defined by the beach strip, interdune lagoons, fluviomarine and sprinkler plains (on Holocene marine terraces). As for mobility, the furniture type predominates and, located more inland and preferably south and southwest of the furniture, there are fixed dunes (arboreal vegetation cover and the occurrence of eolianites).

In the area one can distinguish two distinct sedimentary aquifers: Barreiras aquifer and Dunas aquifer, where both accumulate considerable volumes of groundwater and are responsible for supplying most of the coast of the state of Ceará. The Dunas Aquifer occurs in the region of the municipality, consisting of extremely homogeneous, thin areas, with effective diameters of 0.15 to 0.25 mm and thicknesses between 15 and 25 m. Occasionally, clayey and clayey beds occur from the very variation of the deposition energy of the grains. They are generally overlying the Barreiras Formation and the regional average static level is 6.0 m and the average flow rate obtained from shallow tubular wells (depth less than 20m) is 6.0 m^3/h. The Barreiras Aquifer has a large facies variation, sediment thickness between 20.0 to 60.0 m and differentiated silica-clay-sandy intercalations that lead to different hydrodynamic parameters, both vertically and horizontally, with the sandy levels representing the main ones in terms of aquifer vocation (Cavalcante, 1998 *apud* Gomes and Cavalcante, 2017).

The area has a mild semi-arid hot tropical climate, with a mean temperature of 26 to 28°C and a mean annual rainfall of 1,032.3 mm, with a rainy period from January to April (IPECE, 2015).

2.2. Well logging, water level measurement and groundwater sampling

In the first field stage (July 2017), 19 wells were registered near the areas where the wind farm is installed (Figure 1), in order to collect data on the geographic coordinates (GPS Garmin and Trex), depth and the first static level measurement (using a Jaciri static level electro-sound meter with a 100 meter capacity) of the wells, besides a survey of the potential sources of pollution.

In the second field stage (February 2018), the second static level measurement was carried out to verify the variation of the water level in the two different periods. It is noteworthy that only 18 wells had the static level measured in situ because well P19 is buffered, making it impossible to measure the water level, so it was only used for water sampling.

In the third stage (March 2018), groundwater samples were collected for physical-chemical and bacteriological analyses. Plastic 1000 ml bottles were used to collect the physicochemical samples for analyses, and a universal collector with an 80 ml cap for the bacteriological analyses. After the collection, the bottles and the collectors were refrigerated and subsequently sent to the NUTEC Laboratory (Ceará Industrial Nucleus Technology Foundation), located in Fortaleza/CE to perform the laboratory procedures. The methodology used in the physicochemical and bacteriological analyses was based on the *Standard Methods for the Examination of Water and Wastewater* (APHA *et al.,* 1998).

The selection of the wells was based on the water use and their spatial distribution, seeking the best characterization of the area, resulting in more representative information of the physical environment.

2.3. The natural vulnerability of aquifers and pollution risk

The GOD methodology (Foster and Hirata, 1988 *apud* Hirata and Fernandes, 2008) was used to assess the vulnerability of the aquifers. This methodology involves the following stages: 1) G (groundwater occurrence) - identifies the type of groundwater confinement, subsequently indexing this parameter in the range of 0.0 - 1.0; 2) O (overall lithology of the aquiperm) - specifies the strata of coverage of the saturated zone of the aquifer by the degree of consolidation with the probable presence or absence of permeability by fissures and the type of lithology with indirect dynamic-effective porosity, matrix permeability and moisture content of the unsaturated zone or specific retention. This leads to a second score, on a scale of 0.4 - 1.0. Finally, 3) D (depth) - an estimate of the depth to the water table (from unconfined aquifers) or from the depth of the first main groundwater level (for confined aquifers), with a subsequent classification on the scale of 0.6 - 1.0.

The ultimate vulnerability index of the aquifer is the product of the three indices of these parameters. Thus, the natural vulnerability of the aquifer to pollution is obtained, which can be classified as "insignificant" (values between 0 and 0.1), low (0.1 and 0.3), "medium" (0.3 and 0.5), "high" (0.5 and 0.7) and "extreme" (0.7 and 1.0). The parameters G and O were obtained from constructive / lithological profiles of the wells acquired in the Groundwater Information

System - SIAGAS and the map of lithostratigraphic units (Figure 1), and the parameter D was obtained using *in situ* well water level measurements (July 2017 and February 2018).

The IDW (Inverse Distance Weighting) method (Landim, 2000) was used to interpolate the G, O and D parameters, as in comparison with other interpolators it was the one that best represented the data distribution. Afterward, the QGIS 2.18 Raster Calculator tool was used to multiply the data (G, O, and D) in the raster format, pixel by pixel, to generate a new image. Each pixel has an assigned value equal to the multiplication result values of the original images. This image was then converted from a vector format visualization (polygons) to a GRID format, in order to generate the natural vulnerability map of the aquifer.

The identification of potential sources of pollution was carried out in the field (July 2017) and later this information was tabulated and classified using the POSH method (Foster *et al.*, 2002), which classifies the contaminant load potential in the subsoil at three qualitative levels: reduced, moderate and high.

After the characterization of the potential sources of pollution, the mapping of the pollution risk was performed in QGIS 2.18 by multiplying the vulnerability mapping (obtained by the GOD method) with the classification of the pollutant loads (classification by the POSH method), following the same method as the vulnerability mapping.

2.4. Groundwater flow

In the flow mapping, a map of hydraulic charge isolines and flow vectors was developed for 2018, considering the static depth of 18 wells measured *in situ*. The altimetric base used in this mapping consisted of a topographic map with 5 meter isolines, developed by the IPECE (Economic Research and Strategy Institute of Ceará). A geostatistical treatment was carried out by *kriging* the data, using the *Surfer* software (version 8). This interpolation method is based on the principle that close points in space tend to have similar values if compared with the farthest points.

The objective of this map was to discover the direction of the underground water flow in the research area and, consequently, to show the possible impact of the wind farm installed in the dune environment, lowering the static groundwater level.

2.5. Multivariate statistical methods

For the qualitative evaluation of the groundwater, ten (10) groundwater samples were collected (March/2018) for physicochemical and bacteriological analysis. These data were processed in the *SPSS Statistics software*, Version 17.0.

For the analyzed variables (pH - hydrogenation potential, EC - electrical conductivity, turbidity, color, TDS - total dissolved solids, total hardness, Na^+, K^+, HCO_3^-, Cl^-, SO_4, N-NH_3, N-NO_2, N-NO_3, Fe, P, DO - dissolved oxygen, BOD - Biochemical Oxygen demand, hexane and total and fecal coliforms) multivariate analysis procedures were used. This involved factorial analysis by the principal components method and hierarchical grouping analysis. According to Brito *et al.* (2006), the principal factors classify the variables of greater participation in each factor, defining those that should be monitored, thus reducing costs with the analysis of variables of minor importance in water quality. The Principal Component Analysis method was used to extract the factors. In the group analysis, groups are formed from measures of distance between observations in each factor. In this step, *Ward's* method was used as the hierarchical grouping criterion and the similarity measure used was the squared Euclidean distance, which is often used in water quality studies (Yidana *et al.*, 2008; Salgado *et al.*, 2011; Gomes and Cavalcante, 2017). The assessment of the suitability of groundwater for human consumption was carried out according to the potability standard of the Ministry of Health Ordinance N°. 5 of 28/09/2017.

3. RESULTS AND DISCUSSION

3.1. The current situation of the wells

In the field (July 2017), 19 shallow (excavated) and deep (tubular) wells located near the areas where the wind farm is installed were visited and registered. Of these, 15 shallow wells were located on Xavier Beach (P1 to P15) and four deep tubular wells (P16 to P18) around the Amarelas urban area. It is noteworthy that 18 wells are active, and their waters are used for human supply.

The static level of 18 of the 19 wells visited was measured *in situ* (July 2017 and February 2018) Of these, 15 were less than 5 m deep (shallow or groundwater), and three have values greater than 10 m, varying from 12 to 22 m. Static levels lower than 5 m reflect the behavior of the water captured in the Dunas aquifer (Xavier Beach), where the static level averaged 2.7 m (July 2017) and 3.0 m (February 2018). This corroborates Meireles (2011), who showed the morphological changes in the dune field caused by reflexes on the hydrostatic level, changes in the seasonal bed of interdunal lagoons and new occurrences on the dune field. These changes are directly related to the construction stages of the installation of the wind farm in 2007. These alterations in the dunes can be accessed on the website of the company responsible for the engineering project (Lomacon), which provides photos of the earthworks, cutting, and paving the dunes in its widely divulged portfolio.

It was verified in the field that, in the community of Xavier, interdunal lagoons were filled in to build access roads for the wind turbines, with the consequent reduction of water levels, corroborating the results and analyses of Meireles (2011), Mendes *et al.* (2016) and Gorayeb *et al.* (2018).

Silva (2012) emphasizes that dune preservation requires the avoidance of any construction, the opening of paths for vehicles, the construction of drainage channels, the removal of sand, motorsports, and depositing rubbish.

3.2. Natural aquifer vulnerability and pollution risk

The examination of hydrogeological characteristics permitted the classification of the area by the occurrence of groundwater in an unconfined form (free aquifers), with G Index values varying from 0.6 to 1.0. The characterization of the layers of strata evidenced the predominance of aeolian sands overlain by sandstones and conglomerates, giving a variation between 0.6 and 0.7 on the O Index. Measurements of the groundwater level showed that 83% of the area has levels below 5 m, 11% between 5 and 20 m and 6% between 20 and 50 m; therefore, the D indices were 0.9, 0.8 and 0.7, respectively.

The results obtained by the GOD method indicate that the vulnerability of aquifers in the study area varies from low to high (between 0.29 and 0.54), with a predominance of moderate to high vulnerability (Figure 2).

In the northern part of the area, where the Dunas aquifer predominates, the indices obtained (0.54) indicate high vulnerability to the detriment of the consolidation of the vadose zone, predominantly formed of aeolian sands (more vulnerable than the second lithotype) and the influence of more shallow static levels (<5 meters deep). These indices cover all the terrain where the wind farm was built, 200 meters away from the extreme east of the densification of the houses of the community of Xavier. Furthermore, the area does not have a sewage network; wastewater is removed through septic tanks or cesspits. According to Foster et al. (2002), this sanitation system involves the percolation of the effluent liquid in the soil, and in permeable soil profiles, this results in recharging the aquifer. Solid waste, which should be periodically removed and discarded elsewhere, often remains in the soil and is progressively leached out by rainwater or other infiltrating fluids. Even when well-constructed and operated, septic tanks generate nitrogen compounds loads (initially in the form of ammonia, but usually in the form of a more stable nitrate) capable of contaminating the aquifers. Besides nitrates, cesspits are also associated with microbiological contamination (pathogenic bacteria, viruses, and protozoa), a situation observed by Mendes et al. (2016), who identified numerous and recurrent cases of waterborne diseases among the families living in Xavier Beach, especially children and the elderly, such as diarrhea, vomiting, fevers and skin diseases. Hirata and Fernandes (2008) state that high vulnerability means that the aquifer is vulnerable to many pollutants except those that are less mobile and persistent (hydrocarbons, aromatic compounds, bacteria, viruses, salts, and nitrates).

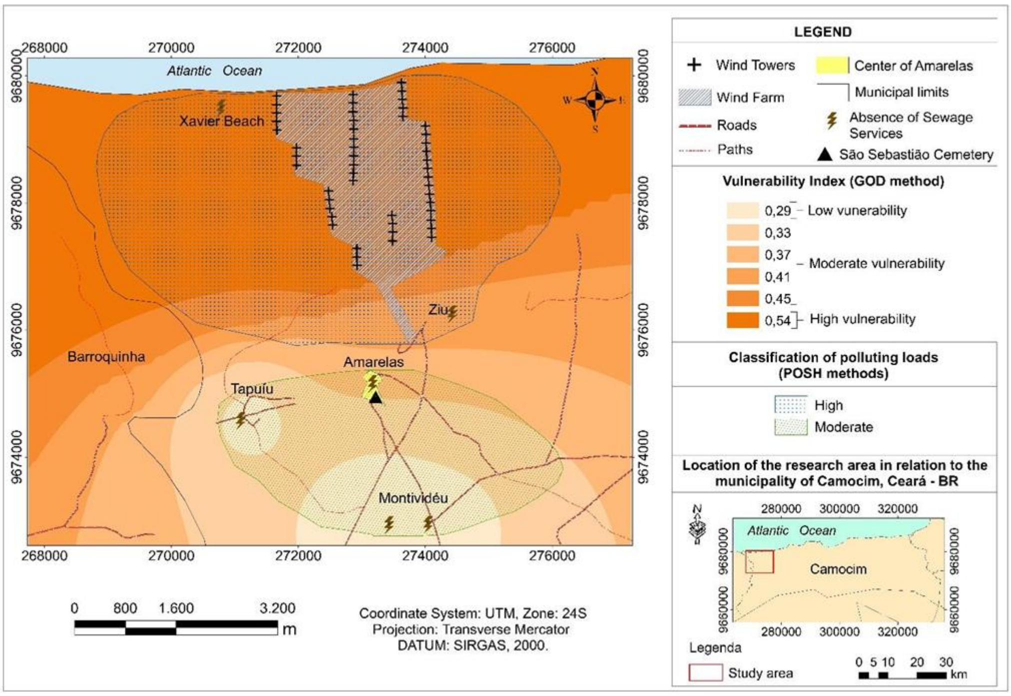

Figure 2. Index of vulnerability and risk of groundwater pollution in the study area (July 2017 and February 2018).

The areas of moderate (0.33, 0.37, 0.41 and 0.45) and low (0.29) vulnerability occur in the central and southern areas, associated mainly with the Barreiras Formation (sandstone and conglomerate). These moderate- and low indices are influenced by deeper static levels (> 10 meters depth) and the lithology (sandy strata). These indices include the center of Amarelas, Tapuiu, Ziu, and Montevideo, where there are a cemetery and septic tanks. According to Hirata and Fernandes (2008), in the case of the moderate index, the area is vulnerable to continuously discarded and leached pollutants (salts, nitrates, and hydrocarbons), while the low index area is only vulnerable to persistent contaminants in the long term, when uninterruptedly and widely discarded and leached (salts and nitrates).

The degree of confinement and the depth of the static level was determinant in the differentiation of the vulnerability in the area between the high, moderate, and low indexes.

From the data obtained in the field, the primary potential sources of pollution in the area were identified, and the contaminant-load potential in the subsoil was classified using the POSH method. According to Foster *et al.* (2002), the risk of pollution of an aquifer is determined by the interaction between the vulnerability of the aquifer as a consequence of the natural hydrogeological context and the contaminant load applied to the environment, resulting from anthropic activities.

In the research area, the risk of contamination of the Dunas and Barreiras aquifers, resulting from the integration of vulnerability data with the contaminant load, were classified as "high" within the wind park and in the areas that cover Ziu and Xavier Beach (coastal aeolian deposits) and "moderate" in the center of Amarelas, Tapuiu and Montevideo (clay sandstones of the Barreiras Formation). Similar results were found by Moura *et al.* (2016).

Bianchi (2014) observes that wind farms located on the dune area, designated as a Permanent Preservation Area (APP), face an extensive technical and legal debate with environmentalists about the environmental damage caused by the installation and operation of the wind turbines, especially issues involving changes to the landscape and the modification of the relief caused by the intense removal of sand.

Studies of the environmental impact caused by construction and disordered occupation in dune areas (Dantas *et al.*, 2006 and Silva, 2012) also demonstrate the pronounced lowering of the water table, promoting irreversible changes in the dune ecosystem.

3.3. Groundwater flow

According to the underground water flow map (Figure 3), the highest values of potentiometric surface are in the center of the area (where the Wind Park, Ziu and the center of Amarelas are located) associated with moderate to high vulnerability indexes (0.33 to 0.54).

In this area, there is the presence of a water divider, in the isolines of 4.6 and 5.2 meters, agreeing with a high topography formed mainly by the dunes. This implies that areas with a higher hydraulic gradient will have an acceleration in contaminant dispersion if there is a potential source of contamination in the area. The driving force or groundwater flow is a consequence of hydraulic potential. If the fluid has the same hydraulic load at any point, there is no flow. But if there is a difference in load (hydraulic gradient), the water flows in the direction where the hydraulic load decreases. The lowest hydraulic potential (<1.6 m) is on the boundary of the area.

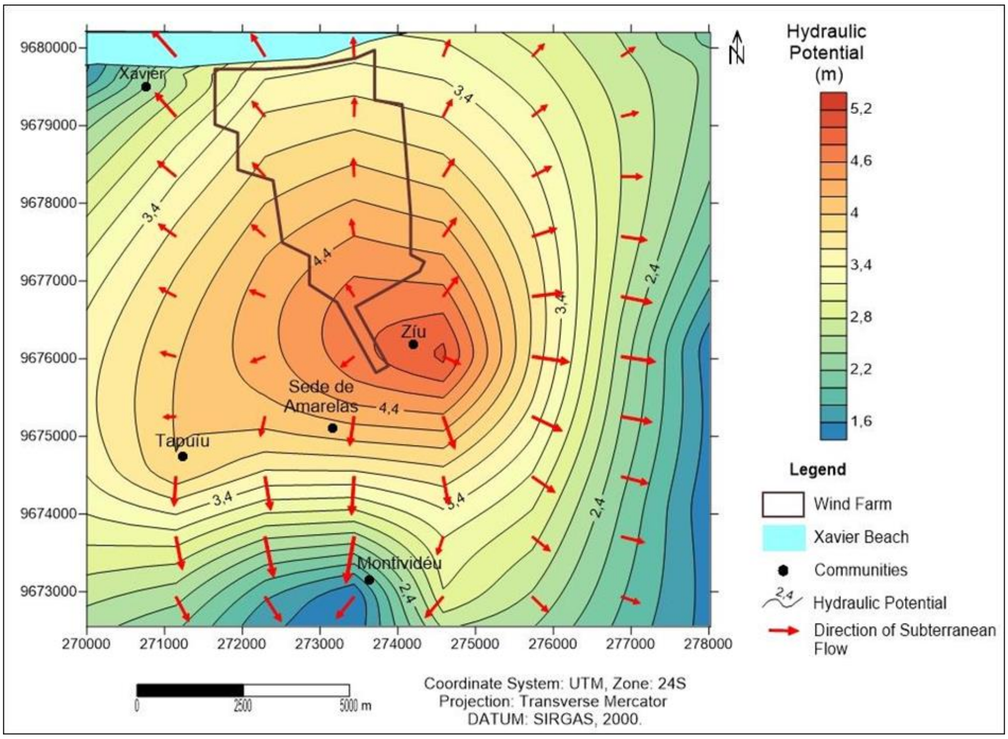

Figure 3. The underground flow around the Wind Park on the Xavier Beach and Amarelas District, Camocim, Ceará - Brazil (February / 2018).

3.4. Multivariate statistics

The factorial analysis by the principal component method was initially performed with 21 variables (pH, EC, turbidity, color, TDS, total hardness, Na^+, K^+, HCO_3^-, Cl^-, SO_4, $N\text{-}NH_3$, N-

NO_2 , N-NO_3, Fe, P, OD, BOD, hexane, and total and fecal coliforms) analyzed in March 2018. Four simulations were necessary to achieve a satisfactory result, taking into account the criteria adopted for this analysis, significantly reducing the number of variables in the last simulation

The final simulation resulted in 6 variables (EC, TDS, total hardness, turbidity, HCO_3 and pH) and presented two factors that adequately described the variation of the data (Table 1). The value of *KMO* was 0.639 and the *Bartlett* statistical tests of sphericity were significant at $p < 0.01$. The two factors together account for 88% of the cumulative total variance. Factor 1 (EC, TDS, total hardness and turbidity) is strongly related to the salinity and anthropogenic influence in the chemical composition of these waters, whose factorial loads are higher than 0.840, indicating that they are the most significant in the characterization of the water quality in the study area. Factor 2 (HCO_3 and pH) corresponds to 18% of the variance of the sample set. This result was already expected due to the strong correlation between pH and bicarbonate concentrations since most bicarbonate ions (HCO_3^-) and carbonates (CO_3^{-2}) in groundwater are derived from CO_2 in the atmosphere and the soil.

As a result of the higher factorial loads of the variables that make up the two factors, the six variables of water quality in the area can be represented by Factor 1 - salinity component (mineralization) and presence of suspended matter (turbidity) and Factor 2 - component of alkalinity. These variables are determinant in the characterization of groundwater quality.

Table 1. Factorial charges and variance explained in the factorial analysis of the variables assessed, after rotation using the varimax method (March/2018).

Variable	**Factor 1**	**Factor 2**
Total hardness (mg L^{-1})	**0.950**	0.015
Hydrogenation potential - pH	0.446	**0.833**
Bicarbonate (mg L^{-1})	0.070	**0.934**
Electrical conductivity - EC (µS/cm)	**0.840**	0.457
Total dissolved solids – TDS (mg L^{-1})	**0.840**	0.447
Turbidity (UT)	**-0.887**	-0.221
Variance explained by factors (%)	70.169	18.639
Accumulated variance (%)	88.808	

The cluster analysis was performed to evaluate the chemical similarity of groundwater in each factor (1 and 2). The number of clusters was defined based on the first large difference among re-scaled clustering coefficients. These coefficients revealed cutoff point 2 (higher precision) (Figure 4).

According to the variables of Factor 1 (EC, TDS, total hardness and turbidity), three similar groups were generated, consisting of 50% (5 wells), 40% (4 wells) and 10% (1 well) of the samples analyzed in the Groups 1, 2 and 3, respectively (Figure 4).

Group 1 is represented by wells that capture the Dunas (P8, P10) and Barreiras aquifers (P16, P17, and P19) and characterized by high salt concentration in the water. The EC was between 613 (P16) and 687 µS/cm (P19). The TDSs ranged from 345 (P16) to 387 mg/L (P19). All the samples were within the permitted limit (1000 mg/L TDS) for potable water for human consumption in accordance with Ordinance N°. 5 of 2017 of the Ministry of Health (MS). The total hardness of the samples reached a maximum of 237 mg/L (P16), within the limits allowed (500 mg/L) by the MS Ordinance. The turbidity of the waters is at most 1.3 UT (P8), also within the Tolerable Maximum Value of the current Ordinance (5.0 UT).

Group 2 consists only of wells that capture the Dunas aquifer (P1, P4, P12, and P15) and with intermediate salinity waters. The EC was between 498 (P4) and 588 µS/cm (P12). The

TDS ranged from 279 (P4) to 330 mg/L (P12), all the samples were within the permitted limit (1000 mg / L TDS) for drinking water according to Ordinance N°. 5 of 2017 of the Ministry of Health (MS). The total hardness of the samples reached a maximum of 185 mg/L (P4), within the limits allowed by the MS Ordinance (500 mg/L). The water turbidity reached a maximum of 4.5 UT (P12), also being within the Tolerable Maximum Value of the current Ordinance (5.0 UT).

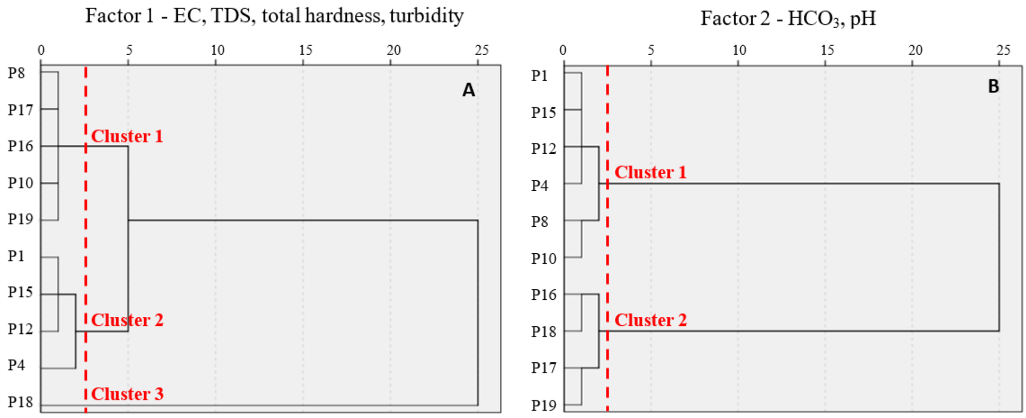

Figure 4. Dendrograms resulting from the hierarchical clustering analysis of variables explained by Factors 1 (A) and 2 (B) – March/2018.

Group 3 is a well in the Barreiras aquifer (P18), which has low water salinity and has water of a better quality compared to groups 1 and 2, except turbidity. The EC and TDS reached 270 µS/cm and 152 mg/L, respectively, being within the allowed limit (1000 mg/L of TDS) for drinking water for human consumption by Ordinance N°. 5 of 2017 of the Ministry of Health (MS). The total hardness of the sample was 104 mg/L, also within the limit allowed (500 mg/L) by the MS Ordinance. The turbidity reached 6 UT, being outside the Tolerable Maximum Value of the current Ordinance (5.0 UT). This is probably due to the absence of sanitary protection of the well, which allows the entrance of impurities, increasing the turbidity of the water.

When analyzing the territorial implications of the implementation of wind farms in the coastal zone of Ceará, as well as the resulting environmental conflicts and resistance, Araújo (2016) found that the availability of freshwater in the water table has been one of the local population’s main concerns. According to residents, even in periods of prolonged drought in the state, the level of water available for human consumption has never been as low as the average in recent years, leading to suspicion that this process is aggravated by wind farms that have been installed in the region.

The burial and compaction of the dunes tend to hinder the infiltration of rainwater into the water table, and there may be significant changes in the local hydrostatic dynamics, such as the reduction of the spatial range of the interdunal lagoons that emerge from the groundwater and even the reduction of the volume available for human consumption (Meireles, 2011). According to Araújo (2016), residents are also concerned about the quality of water, which in some places is "yellowish in color, unfit for drinking and food preparation."

According to the variables of factor 2 (HCO_3 and pH), two groups of similar samples were generated, consisting of 60% (6 wells) and 40% (4 wells) of the samples analyzed in Groups 1 and 2, respectively (Figure 4).

In Group 1, the wells that capture the Dunas aquifer (P1, P4, P8, P10, P12, and P15) are present and have a higher similarity of the investigated variables and higher water quality in relation to Group 2. They are characterized by alkaline waters (100% of the samples), ranging from 7.5 to 7.9, where all samples are within the permitted limit (6.0 to 9.5) by Ordinance N°. 5 of 2017 of the Ministry of Health. According to Hounslow (1995), the highest values of pH are usually found in waters with a predominance of Na^+ and Ca^{++} ions or in water rich in bicarbonates; polluted waters are generally more acidic. Group 1 presented the highest concentrations of bicarbonate (140 to 198 mg/L).

Group 2 is composed of wells that capture the Barreiras aquifer (P16, P17, P18, and P19) and had a lower water quality than Group 1. They are also characterized by alkaline waters (75% of the samples), ranging from 6.5 to 7.8. All the samples are within the permitted limit (6.0 to 9.5) established by Ordinance N°. 5 of 2017 of the Ministry of Health. They presented low concentrations of bicarbonate (60 to 112 mg/L) in relation to Group 1. According to Silva amd Bonotto (2006), the lower values of bicarbonate indicate areas of recharge and increase according to the direction of the underground flow.

From these results, it can be observed that the characteristics of the groundwater are strongly related to the geological formation of the wells studied. Similar results were also found by Gomes and Cavalcante (2017). Therefore, monitoring measures can be performed based on the hydrochemical elements determining water quality (EC, TDS, total hardness, turbidity, $HCO_{3,}$ and pH) identified by factorial analysis. These measures can be focused on soil conservation and the better use of groundwater by the communities of Amarelas, especially those that are in the surroundings of the wind park, like the Ziu and Xavier Beach.

4. CONCLUSIONS

The results obtained with the application of the GOD method demonstrate the predominance of moderate- to high natural vulnerability of the aquifer to the pollution in the surrounding areas of the wind farm in the Amarelas district, especially Xavier Beach and Ziu, which are close to the park and have high polluting loads.

The directional flow vectors are meaningful for Xavier Beach (high vulnerability), the center of Amarelas (moderate vulnerability), Tapuiu and Montevideo (low vulnerabilities). The wind farm installed in the dunes is a potential impact on the lowering of the groundwater in the area.

The vulnerability map of the pollution risks facilitated the identification of the areas most susceptible to pollution (Xavier Beach and Ziu), offering data to managers of the Amarelas district in future land-use and occupancy plans. Further studies can be carried out on the positioning of these potential sources of pollution (wind farms, septic tanks, small animal farming without adequate infrastructure).

From the grouping of the samples in Factors 1 and 2, it is evident that the characteristics of the groundwater are strongly related to the geological formation of the wells studied, showing that all the samples are within the Tolerable Maximum Value for human consumption for TDS, hardness, turbidity and pH. It is noteworthy that in qualitative terms, groundwater in the area is not being impacted by possible contamination from wastewater, debris or effluents generated in the area by the wind farm, even though it is located in an area with a high vulnerability index and high contaminant load.

Continuous (during both dry and rainy seasons) monitoring of the groundwater located downstream and upstream of the wind farm and communities is recommended, as the district of Amarelas does not have any sanitary sewage infrastructure or systematic collection of solid waste.

Annual monitoring of the static level of the wells (every four months) around the wind farm is also recommended, in order to confirm the lowering of the water levels in the area over time.

Finally, it is essential to carry out preliminary studies of the aquifers underlying the areas where wind farms are to be installed, considering the levels of vulnerability and the risks to pollution and changes in the water supply.

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