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Hydrogeological Characteristic and the Vulnerability Degree of the Aquifers from Municipality of Abaetetuba, Pará - Brazil

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Authors' contributions

All authors participated of the samples collection, date and statistical analysis and wrote the first draft of the manuscript.

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ABSTRACT

This study evaluated the quality of groundwater in the municipality of Abaetetuba (PA, Brazil 1°43'46" S e 48°52'27" W) based on the hydrogeological characterization and degree of vulnerability of the aquifer system. The municipality of Abaetetuba is practically all supplied by groundwater both by deep tubular wells and shallow pit wells (Amazonian wells), which present potential risk of contamination. Water and soils samples from 20 wells sampled between 2012 and 2016 were used. Physicochemical and microbiological analyzes served as a data base for mapping (GIS). Three hydrogeological domains were identified within the study area: Barreiras Group (predominant), Post-Barrier Sediments and Recent Sediments. Almost all of the samples presented microbiological levels above the MPV defined by the Brazilian legislation for water intended for human consumption. The DRASTIC and GOD vulnerability indexes presented values between 75 and 119 and 0.15 and 0.32 respectively, suggesting areas of 'low' to 'moderately-high' vulnerability. Local sources of pollution by coliforms have been identified due to lack of basic sanitation. Evidence of diffuse sources derived from vehicle washing and lubrication also have been identified. Although the Barreiras Group had deep semi-confined aquifers, a 'state of alert'

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was suggested for the areas that indicated the presence of fecal coliforms and with a high population density. Isovalues and vulnerability maps suggest areas that require further monitoring. A positive correlation between the DRASTIC Index and TDS in well water was established. The intense exploitation of groundwater especially in areas of great population density may be causing contamination of aquifers.

Keywords: Groundwater pollution; DRASTIC; GOD; GIS; aquifer vulnerability; Amazon.

1. INTRODUCTION

Approximately one-fifth of the world's total fresh water lies in the saturated zone of the groundwater environments [1], and hence needs to be protected from any contamination. With the exponential increase in demand for potable water, the number of wells drilled for supply each year increases further. Historical data show that in the last 30 years more than 300 million wells have been drilled in the world [2]. The US drills an average of 400,000 wells per year, with more than 200 million m^3 used by the Midwestern states of the country, in the arid and semi-arid zone of Nebraska to Texas [3]. Mexico City, one of the most populous cities in the world, is practically supplied by wells, and 75% of the European Community has public systems supplied by groundwater, reaching 90% in countries such as Germany, Belgium, Sweden and Denmark [4,5]. In Brazil, the lack of proper registration and control makes it difficult to establish a more accurate estimate of water demand. Despite this, it is estimated that more than 60% of the Brazilian population is being supplied by underground water, 45% of which is through tubular wells [6]. Cities such as Ribeirão Preto (SP) and Mossoró (RN), and state capitals such as Maceió (AL), Manaus (AM), Natal (RN) and Recife (PE) are practically supplied only by tubular wells [6,7]. In addition to serving the population directly, these resources are used in industry, agriculture (irrigation) and leisure. In the most populous region of Brazil (Southeast) between 75 and 90% of the population of the cities is supplied by wells [6,8].

Groundwater found in aquifer systems is stored water that accumulates over thousands of years, which under natural conditions are in a balanced state, controlled by recharge-discharge mechanisms and by the potentiometric load difference between the system fluvio-lacustre and underground. These waters are influenced directly by the climate (precipitation) and by the degree of permeability of the soils. Its movement underground is very slow, implying a high residence time. Contrary to the general idea, most groundwater is found in deep aquifers, of the non-draining confined type, whose upper and lower boundary layers are impermeable or semi-impermeable, limiting their use by deep wells.

The increasing global demand for groundwater combined with the urbanization process, which increases the area of paving and macrodrainage of public roads, reduces the flow of recharge, putting the aquifer reserves at risk. Reducing the recharge flow through the paving of large cities may cause lowering of the water table and the saturation zone of the aquifers themselves, and it is necessary to drill deeper wells to obtain a satisfactory flow. The quality of the groundwater is also being harmed by the infiltration of pollutants and contaminants through the soil (authors' note). The use of groundwater is becoming increasingly problematic due to lack of planning and lack of basic sanitation systems, especially in third world countries. Another problem to be solved is the high cost of the treatment system, necessary to meet drinking standards. In Brazil, the drinking standards are very discerning and defined by the Ministry of Health. Despite this, due to the high demand and the high cost of treatment, most of the tubular well water is distributed to the population without previous treatment, only with chlorination simple.

The Amazon region has an immense hydrological reserve resulting from the largest hydrographic basin and the largest underground aquifer in the world. However, the lack of basic sanitation services, together with the infiltration of pollutants and contaminants from dumps, cemeteries, gas stations, etc., undermine the use of this resource. The municipality of Abaetetuba in the State of Pará is practically all supplied by groundwater both by deep tubular wells and shallow pit wells (Amazonian wells), which are generally constructed without inspection, norms and environmental license, and presenting a potential risk of contamination. Studies developed in the municipality from Georadar (GPR) indicate signs of contamination of soils by hydrocarbons, which increase the risk of contamination of wastewater to the population

[9]. The objective of this research was to evaluate the quality of groundwater in the Municipality of Abaetetuba (PA, Brazil) based on the hydrogeological characterization and degree of vulnerability of the aquifer system. A technical-qualitative analysis of 20 tubular wells sampled between 2012 and 2016 was performed. Physical-chemical and microbiological analyzes of groundwater (alkalinity, acidity, total hardness, electrical conductivity, ionic concentration [Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, Cl^-_{dpd}, SO_4^{2-}, HCO_3^- and CO_3^{2-}], total coliforms and thermotolerant coliforms) served as a data base for making thematic maps, with the help of Geographic Information System tools. The results of the mapping were correlated with the use and occupation, soil type and socioeconomic impact for the region.

2. STUDY AREA

2.1 Physical Aspects

The municipality of Abaetetuba (1°43'46" S and 48°52'27" W, Fig. 1) belongs to the northeast mesoregion of the Pará State, 22 meters above sea level. Considered a pole-town, Abaetetuba is located 51 km S-W of Belém, and makes borders to the north with the city of Barcarena, and to the south with the cities of Moju and Igarapé-Miri. The municipality has a territorial area of 1610.6 km^2, being 57% of the total occupied by rural areas. According to Köppen's classification, the climate of the region is hot and humid, with high temperatures (27°C average) and high precipitation (2000 mm/year) [10,11]. The soils of the region are influenced by temperature and precipitation, causing leaching. There is a predominance of clay and sandy-clay soils, with low organic matter content and high aluminum concentration, which intensifies cation exchange processes [12]. According to the classification of the soils [13], predominantly Latosols Yellow Dystrophic soils associated with Hydromorphic Podzol and Concrete Lateritic soil are found. Gley soils and Eutrophic and Dystrophic Alluvial soils, especially in recent soils on beaches and islands, can also be observed. The relief of the region is flat and low with several coastal plains. The platform areas oscillate between 15 and 30 meters (average 20 m), and there are also lowland areas (<4 m), where occurs flooding. The primitive vegetation typical of the Amazonian practically no longer exists. The hydrographic network of the municipality is quite vast, sinuous and of strong asymmetry with several navigable stretches. The main rivers are Pará, Tocantins, Abaeté, Guajará de Beja, Arapiranga and Arienga [10,13].

2.2 Socioeconomic Aspects

The resident population of Abaetetuba in 2010 was 141,100 inhabitants with a population density of 87.6 inhabitants per km^2. By 2017 it was estimated a population of 153,380 inhabitants [6,10,11], which represents an increase rate of 8.7% in 7 years. The age pyramid is classic of third world countries, with a large base composed of young people between 15 and 25 years old, and a narrow top from 70 years old. The main economic activities in the region are commerce and services of the most diverse activities. Industrial activity has a small share in the local economy, but has been showing great growth in recent years, especially in the food and agro-forestry products sectors [11,14]. The schooling rate for children between 6 and 14 years old in 2010 was 97.7 and the average infant mortality rate was 9.25 deaths per 1000 live births [11]. The Municipal Human Development Index (MHDI) has grown in recent years, from 0.628 in 2010 to 0.751 in 2013 [6,15]. Despite this, socioeconomic development is still modest, and considering the aspects of basic sanitation, such as the supply of treated water, sanitary sewage, and rainwater and solid waste management, the municipality of Abaetetuba presents conditions that are still very precarious. Most of the population still does not have regular water supply. The poorer population excavates their own wells, generally not following building and well preservation standards, making the wells vulnerable to contamination.

3. MATERIALS AND METHODS

A technical-qualitative analysis of 20 tubular wells, sampled between 2012 and 2016, was performed using the physical-chemical (alkalinity, acidity, total hardness, electrical conductivity and ionic concentration) and microbiological (total and fecal coliforms) data determined by [16]. The medium values of the physical-chemical and microbiological parameters used in the calculations are presented in the Table 1. Technical information on the wells in the study area was obtained through contact with public and private sector companies, accessing technical reports from drilling and/or groundwater management companies, basin water user registry, and institutions of research of the respective area. Data provided by the SiAGAS/CPRM on registered wells (SIAGAS,

Fig. 2) [17] were consulted to aid in the hydrogeological characterization and geometric profile of the wells monitored. For the general configuration of the results, based on the physicochemical and microbiological patterns, the hydrogeological characteristic and the degree of vulnerability, the studies were mainly concentrated in the free aquifers of alluvial sediments of the Quaternary and semi-confined aquifers of Tertiary sediments of the Barreiras Group. The ionic balance [Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^- and CO_3^{2-}] expressed in meq/L and the ionic classification of groundwater were determined from the hydrochemical diagram of Piper [18] and Stiff diagram [19]. The data was processed using ExPiper©, Microcal Origin© 9.0 and AquaChem 3.7 software's. The hydrogeological classification included the analysis of the hydraulic conductivity, grain size, flow direction and relative permeability. Sampling quality control for ionic analysis was performed based on the ion balance (Ib%) calculation defined by [20] in equation 1.

The analyses were processed in the chemistry laboratories of UFPA/ICEN. In the sampled soils, gravimetric humidity (Gh %) and volumetric humidity (Vh %) were determined by difference of mass before and after the oven drying at 105 ºC (equations 2 and 3), and the density (kg/dm^3) were determined by the ratio gravimetric and volumetric humidity (equation 4). The results were compared with the calculation of the mass/volume ratio of the sampled soil using metallic cylindrical of 9.812×10^{-2} dm^3 volume (equation 5). The total porosity of the soil was estimated by the volume ratio of the solid and volume of saturation (equation 6, Table 2). The granulometric analysis was determined by the fractionated sieving method, using the TYLER series sieves with mesh openings between 2.0 and 0.032 mm. The percentage of silt and clay fractions (ϕ <0.063 mm) were determined by wet sieving with sodium hexametaphosphate $[NaPO_3)n.Na_2O]$ as dispersing agent. The saturation state of the soils was estimated by the application of a well-known volume of distilled water in a regular metal cylinder filled with soil. The analyzes followed recommendations and protocols from [21,22]. The hydrogeological classification was elaborated from the protocols described by [23], which takes into account the conversion of the geological units into hydrolytic units, differentiating the units in continuous or discontinuous, according to their geometric characteristics and forms of occurrence. Another possibility that the protocol considers is to identify the lithological types according to the dominant flow characteristics. The nomenclatures described to Belém and Ananindeua areas [24] and to the Legal Amazon [25] were applied. The geological uniformity of the mesoregion was considered, as a consequence of the territorial proximity and similar geometric configurations between the aquifers. The area between Belém Metropolitan Region (Belém-Ananindeua) and the municipalities of Bacarena and Abaetetuba (axis NE-SW) was defined as mesoregion.

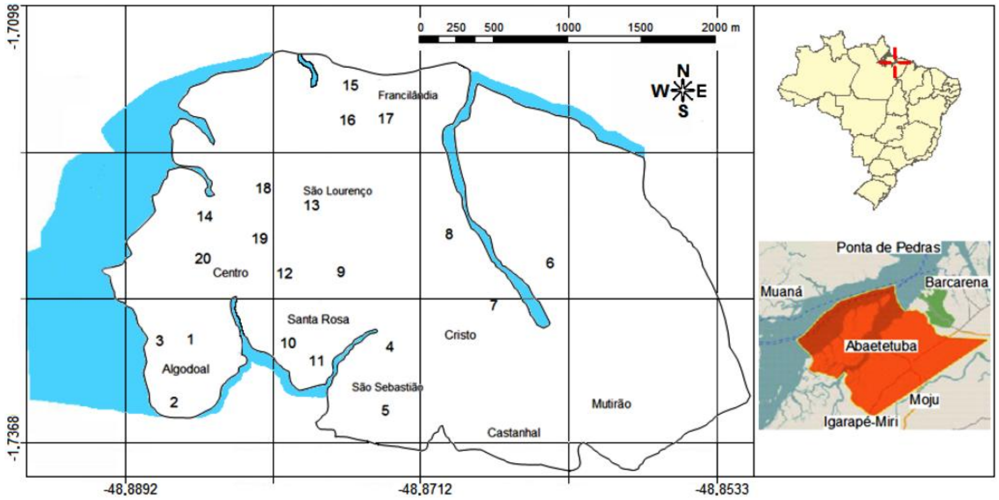


Fig. 1. Location of the municipality of Abaetetuba (Pará, Brazil) with indication of monitored tubular wells

(Source: CPRM/SIAGAS 2018 adapted in ArcGis © 9.3)

Table 1. Medium values of the parameters applied in the calculations to technical-qualitative analysis of the wells

Sites	Alk (mg/L)	Acid (mg/L)	Hard (mg/L)	EC (µS/cm)	Σcations (mg/L)	Σanions (mg/L)	TC*	FC*
1	4.0	52.0	10.3	294.0	55.5	60.4	39.3	3.7
2	52.0	18.0	73.4	100.4	170.4	73.0	97.3	7.2
3	10.0	72.0	18.2	265.0	88.0	82.5	97.3	7.2
4	2.0	38.0	7.7	52.6	14.7	10.1	105.4	7.8
5	22.0	90.0	34.0	111.4	99.3	48.5	121.9	8.4
6	6.0	34.0	12.8	35.7	34.9	12.7	301.5	20.8
7	8.0	56.0	15.6	70.8	46.5	22.2	312.3	21.5
8	4.0	18.0	10.5	95.2	36.4	18.9	472.5	30.5
9	4.0	36.0	10.3	109.9	31.4	25.6	385.8	28.6
10	6.0	28.0	13.0	73.2	41.9	23.8	21.3	2.2
11	49.0	10.0	68.6	154.0	198.0	68.7	22.0	2.3
12	2.0	83.0	7.5	56.2	18.4	15.2	77.4	8.1
13	2.0	96.0	7.8	204.0	35.9	44.2	171.0	12.7
14	54.0	12.0	76.1	135.5	195.7	74.9	411.6	30.5
15	22.0	77.0	34.2	85.2	89.4	38.0	385.8	28.6
16	38.0	6.0	55.2	37.1	129.4	47.5	411.6	30.5
17	53.0	35.0	74.5	202.0	198.5	94.2	398.7	29.5
18	62.0	7.0	86.2	188.5	181.8	83.3	398.7	29.5
19	58.0	6.0	81.5	124.0	181.3	70.8	585.0	40.3
20	50.0	22.0	70.6	167.0	187.6	84.6	411.6	30.5

**TC= total coliforms and FC= fecal coliforms both in NMP/100 mL*

Table 2. Summarized analysis of the calculations applied to the soils sampled in the wells

Analysis	Equation (eq.)	Description
Ion balance	$eq\,1:\quad Ib\,(\%) = \left\lvert \dfrac{\sum anios - \sum cations}{\frac{1}{2}(\sum anions + \sum cations)} \right\rvert \times 100$	
Gravimetric humidity	$eq.\,2:\quad Gh\,(\%) = \left(\dfrac{a-b}{b}\right)$	*a*= wet mass; *b*= dry mass
Volumetric humidity	$eq\,3:\quad Vh\,(\%) = \left(\dfrac{a-b}{c}\right)$	*c*= volume of the sample
Density	$eq.\,4:\quad d\,(kg/dm^3) = \dfrac{Vh}{Gh}$	
Mass/volume ratio	$eq\,5:\quad d\,(kg/dm^3) = \dfrac{soil\ mass}{\text{cylinder volume}}$	volume = 9.812 x 10^{-2} dm^3
Total porosity	$eq.\,6:\quad P(\%) = 1 - \dfrac{solid\ volume}{saturation\ volume} = 1 - \dfrac{d}{d_{mineral}}$	$d_{mineral}$= 2.66 g/cm
DRASTIC Index*	$eq.7: DI = \mathrm{D}_{RW} + \mathrm{R}_{RW} + \mathrm{A}_{RW} + \mathrm{S}_{RW} + \mathrm{T}_{RW} + \mathrm{I}_{RW} + \mathrm{C}_{RW}$	
GOD Index*	$eq.8: GI = G_W \times O_W \times D_W$	

**where the capital letter indicates the corresponding parameter; the subscript 'R' and 'W' refer to the variable rating and weight factor, respectively to [27] and [29]*

Several groundwater vulnerability assessment methods have been developed. The most part of that methods divide groundwater vulnerability assessment methods into three categories such as overlay and index methods, methods employing process-based simulation models and statistical methods [26]. The natural vulnerability of the groundwater studied was evaluated using the DRASTIC method [27], which takes into account the sum of the seven hydrogeologic factors of the region: depth to groundwater table (D m); aquifer recharge (R mm/year); aquifer media (A); soil media (S); topography (T %); impact of vadose zone (I), and hydraulic conductivity (C m/day; equation 7, Table 2), which are a combination of geologic, hydrogeologic, geomorphologic, and meteorological characteristics of an aquifer. In this study, depth to groundwater table (D) was obtained by subtracting the ground surface elevation from the average groundwater level of observation wells. The average annual net recharge of the aquifers (R) at Abaetetuba was estimated based upon Water Table Fluctuation method (WTF), where the average net recharge value varies from 40 to 60 mm/year. Aquifer media (A) was obtained using the available information on geological cross sections, geological survey and drilled well logs data. Soil media (S) was obtained based on available soil maps and grain size analysis of borehole samples of the region. Slope information of the topography (T) was extracted from the CPRM/SIAGAS [17]. The depth from ground surface to groundwater table in the study area is variable (25 to 90 m) with depth aquifers belonging mainly to Barreiras Group. Thus, the thickness of soil zone and thickness of remaining part of vadose zone were considered to estimate the impact of vadose zone (I). The values of hydraulic conductivity (C) were obtained from field pumping tests data and sieve analysis. The DRASTIC model developed by [27] is the most usual vulnerability mapping method, used as important instrument for groundwater planning and decision making. The final DRASTIC indexes can range from 26 (zero vulnerability) to 226 (very high vulnerability) according to [28]. To determine the vulnerability index by contamination, applied to isovalues maps, the GOD model proposed by [29] was used. Foster and Hirata [29] established this index from the product of three parameters (equation 8, Table 2): groundwater occurrence (G), which represents the type of occurrence of groundwater, with indices ranging from 0.0 (confined aquifers) to 1.0 (free aquifers); overall of litology of aquiperm (O), determined by geological mapping of the unsaturated zone and the lithological profile of the well, with values ranged between 0.3 and 1.0; and groundwater depth (D), referring to the depth of the static level, ranging from 0.3 to 0.9. The result is an index capable of identifying the vulnerability levels of the aquifers associated to the installed wells, and expressing their degree of natural resistance to the penetration of contaminants. To confirm the degree of vulnerability, the water quality standards for human consumption and their drinking water standard were applied, based on the Permissible Maximum Value (PMV) described in Ordinance N° 2914/2011 of the Ministry of Health [30]. The results were presented on maps of isovalues with interpolation using Surfer® Golden Software, 9.11 (2010) and ArcGis© 9.3 (2008) ESRI - USA.

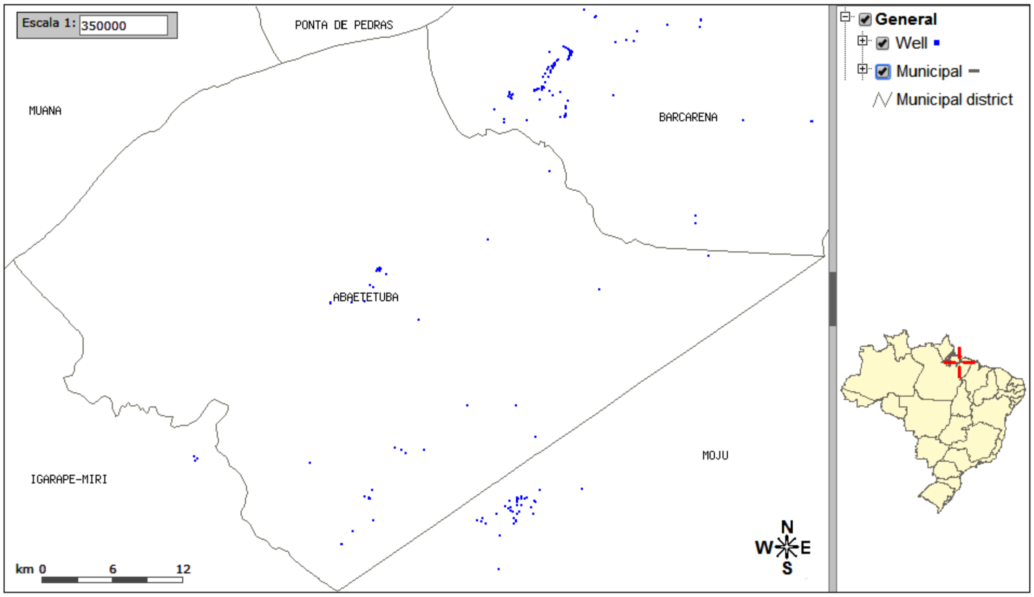


Fig. 2. Geopolitical limits of the municipality of Abaetetuba (Pará, Brazil) with the wells registered in the CPRM - Geological Service of Brazil

(Source: CPRM/SIAGAS 2018 adapted in ArcGis © 9.3)

4. RESULTS AND DISCUSSION

4.1 Geological and Hydrogeological Characterization

The investigation of the geological and hydrogeological aspects is fundamental for the study of the ionic composition of the waters, as well as to establish levels of vulnerability for the aquifers. In the Pará State, the Pirabas Formation, Barreiras Group, Post-Barrier Sediments and Recent Sediments (Quaternary) stratigraphic units were identified. These units are distributed in a discontinuous way, being possible to observe punctual and irregular outcrops in the macroregion. The Pirabas Formation (Miocene - Oligocene) is predominantly found in the NE direction of the Pará, and in parts of the cities of Belém and Ananindeua. Because it presents a transition to marine sediments, it is also found in the direction of the Marajó Island and in the coastal strips of the states of Maranhão and Piauí. The Barreiras, Post-Barrier Sediments and Quaternary Coverage geological units were identified in the mesoregion where the municipality of Abaetetuba is located. The Barreiras Group is used as a generic term for continental sediments. It is a designation applied to indicate non-fossiliferous clastic sediments friable and of intense colors that occurs almost uninterruptedly along the Brazilian coast, North and Northeast regions and in deposits of the Amazon valley [31]. It corresponds to ferruginous sandstones, siltstones, argillites and colored clays and unconsolidated clay-sandy and sandy-clay sediments. The sediments of the Barreiras Group usually have fine to medium granulometry, and can accumulate forming both cliffs in the coastal zone and sandy-clay banks on the banks of the Amazon Basin. Those sediments may also eventually be found as coarse sediments to conglomerates. According to [13,14], in Pará the Barreiras Group is adjusted over the Miocene to Mio-Pleistocene rocks. Post-Barrier Sediments belong to the Pleistocene and are associated with yellow sediments, unconsolidated, superimposed on the layers of the Barreiras Group. It consists of sandy-clay sediments, of medium to fine granulometry (from quartz to clay) with ferruginous concretions. Post-Barrier Sediments occurs primarily in the areas of floodplain, igarapés and islands especially in the direction NE, already in the limits with the municipality of Bacarena. Recent Holocene sediments are composed of unconsolidated sediments containing clays of reddish color and sandy of gray to brown coloration, with very variable granulation and presence of vegetal remains.

The alluvial processes derive from erosion - transport - sedimentation, acting on the flow of debris typical of alluvial fans or fluvial channels [31 and Note of the authors]. Of an essentially clastic nature, this stratigraphic unit is mainly found in the beaches of rivers and streams (flood plains) in the western boundary of Abaetetuba and in the Marajó and Guajará bays, in the direction NE of the municipality, associated to Coastal Deposits (Fig. 3). It is estimated that in the urban zone these sediments can present thicknesses of the order of maximum 10 m. The geological and geomorphological features exert a great influence on the hydrogeological conditions of the aquifers.

The city of Abaetetuba is predominantly inserted in the Pará River basin, presenting in the subsoil a significant reserve of water. Considering the protocols established by [17], consultations to geological and hydrogeological maps and from observations in the local drilling were identified in the mesoregion the hydrogeological domains Barreiras, Post-Barreiras and Aluviões (Table 3). These results are confirmed by the studies of [25] to elaborate the hydrogeological maps of the Legal Amazon. The Barreiras domain is located in most of the limits of the municipality of Abaetetuba, except for the lowland areas (Fig. 3), where alluvial sediments predominate. It is the main aquifer captured by the wells of the region. They are aquifers generally confined to semi-confined, depending on the degree of discontinuity of the lower and upper layers. It presents a matrix of heterogeneous granulometry and variable thickness, and its recharge occurs by contribution of the overlapping layers, or through precipitation in the outcrop areas. The Barreiras aquifer presents depth of occurrence between 25 and 90 m, and flow from 10 to 70 m^3/h. The Post-Barreiras hydrogeological domain is characteristic of free to semi-confined aquifers (free with coverage) and with variable depth, but generally less than 25 m and flow less than 5 m^3/h. These characteristics make the wells vulnerable to sources of contamination, which can reach the water table. The Post-Barreiras domain consists of alluvial sands, as well as fine to medium sandy and clay-sandy materials. The aquifers of Recent Sediments can be divided into free or free with coverage, whose recharge occurs directly through rainfall. Its depth of occurrence is less than 10 m, and shallow wells excavated in the lowland areas belong to this hydrogeological domain. The discharge occurs through rivers, springs and wells, with an average flow 10 m^3/h. The alluvium is a permoporous domain, with good water storage capacity, but not significant in the region of Abaetetuba. In these cases, a vertical sequence of coarse sandy and pebbles at the base up to silts and clays at the top was observed, with a thickness of 10 m. It was also identified the Marajó Domain [17] (Fig. 3), towards the Atlantic Ocean, on the N-NE axis of the continental area. These are miocene and postmyocernic sedimentites with abundant plant remains, deposited by the influx currents from the Marajó basin [31 and Note by the authors]. In periods of high tide, the strong inflow transports the sedimentitos to the channels of the water network of the mesoregion Belém - Abaetetuba.

The sampled sites comprise the districts of Francilândia, São Lourenço, Centro, Algodoal, Santa Rosa, São Sebastião and Cristo (Fig. 1). The majority of the wells monitored are located in a semi-confined aquifer, with the exception of sites 15 and 16, which indicate the presence of free to free with coverage. The results of the granulometric analysis suggest predominance of a surface layer of sandy-clay soil with similarity between sites 4 to 9 (I-S group), 13 to 16 (group II-S) and 18 to 20 (group III-S); of yellow soil for sites 10 to 12 (group IV-S), and sandy soil at sites 1 to 3 and 17 (group V-S). The results for the bottom sediments suggest a predominance of clay soils with similarity between the sites 1 to 12, 15 and 16 (group I-F); and sandy course soils at sites 13 and 14 and 17 to 20 (group II-F). The physical environment (soil texture) indicates the greater or lesser potential of infiltration capacity of organic and inorganic contaminants, including microorganisms, in the sedimentary column. In this case, the highest resistance to percolation of contaminants in the first layers of soil was observed in the Santa Rosa neighborhood (sites 10 to 12, Fig. 1).

From the grain size and degree of soil saturation results, the relative permeability (Rp) of the soils in the wells monitored was estimated as a function of residual saturation. The permeability coefficient of a porous medium is dependent on the type of liquid present in the system (usually water). There is also the possibility of different non-miscible liquids (e.g. water and oil). Also interfere in the degree of permeability the type of texture of the soil. For the soils of the study area, the calculations suggest that 100% water saturation is obtained with 93.4% Rp; while at 50% saturation only 6.9% of soil Rp is needed (Fig. 4). The coefficient of Rp decreases exponentially until it reaches the point S_{iw} (irreducible saturation point of water), when Rp tends to zero and water becomes effectively immobilized. Knowledge of the degree of relative permeability of soils helps in understanding the mechanisms of pollutant and contaminants transfer in the sedimentary column. The dynamics of the contaminants in the soil is explained through mass transfer mechanisms by advection, dispersion and/or attenuation [32]. The advection consists of the mechanism where the contaminants follow the vectorial flow, presenting a direct relation with the velocity of percolation in the soil. The dispersion consists of the mechanism responsible by the reduction of the pollutants concentration in the percolation fluid, be for hydrodynamic dispersion or molecular diffusion. The attenuation is the reduction of pollutants transported by the advection or dilution of these from physical-chemical and biological reactions [32 and Note by the authors]. In this case, the concentration of oxygen in the interstitial waters is the regulating factor of the oxidation reactions, especially of the organic compounds. Of the three mass transfer mechanisms, the attenuation is the one that requires more attention, because it can be temporary. This occurs when the pollutants are not reduced from the oxireduction reactions, being simply adsorbed to the soil particles. This is an important aspect in the case of metallic elements, whose availability in the water column depends directly on pH and alkalinity [12,33]. Considering an efficient buffer system, without large variations of the alkalinity, the metal ions are adsorbed to the clay particles [12] and remain suspended in the total solids. This can compromise the quality of the well water.

4.2 Physical-Chemical and Microbiological Characterization

The waters of the analyzed wells are mineralized with values of electrical conductivity varying from 35.8 to 295.3 (average 128.1±73.3 µS/cm). The hydrogeochemical results presented in the Piper Diagram (Fig. 5A) indicated the predominance of calcium chlorinated groundwater with concentrations ranging from 3.5 to 102.1 (43.6±39.4 mgCa/L) and from 1.8 to 68.9 (19.0±17.6 mgCl/L), and calcium bicarbonate waters with concentrations of $\Sigma(HCO_3^-$ and $CO_3^{2-})$ varying between 2.6 and 74.8 (mean 30.7±28.1 mg/L). The oscillation found in the ionic concentration is due to small variations in ionic levels in the soils of the area. For the cations, the Ca^{2+} and Mg^{2+} contents did not vary with the depth of the well, while the Na^{+} decreased gradually with the increase of the depth. Those behaviors are associated, between other factors, to the absorption processes. The anion contents remained stable in the water column, except for HCO_3^- that gradually decreased with increasing depth. The levels of HCO_3^-, CO_3^{2-} and Ca^{2+} observed in the waters demonstrate natural processes of interaction between water and rock in the carbonate domain. Cl^- observed in the wells may be associated with climatic factors such as precipitation followed by percolation of the adjacent soil. Since chlorine is not very abundant in the rocks that make up the geology of the Metropolitan Region of Belém, its occurrence in groundwater must be associated with the rainwater and the influence of the sea through the proximity of the brackish waters of the Marajó Bay, to the West of the area studied [24]. The Cl^- ion is present in all natural waters, usually from the leaching of ferromagnesian minerals from igneous rocks and evaporitic rocks [20,24]. Groundwater has Cl^- normally less than 100 mg/L. The various natural interactions experienced by groundwater generally do not influence the increase of this factor. Therefore, the increase in chloride concentrations can mean anthropic activities, especially industrial waste and sanitary sewage.

Table 3. Hydrogeological domain of the aquifers found in the municipality of Abaetetuba

Domain	Epoch	Type	Location
Barreiras	Mio-Pleistocene	Confined to semi-confined	most part of municipality
Post-Barreiras	Pleistocene	Free with coverage	Várzea, igarapés, islands
Aluviões	Holocene	Free	Floodplain

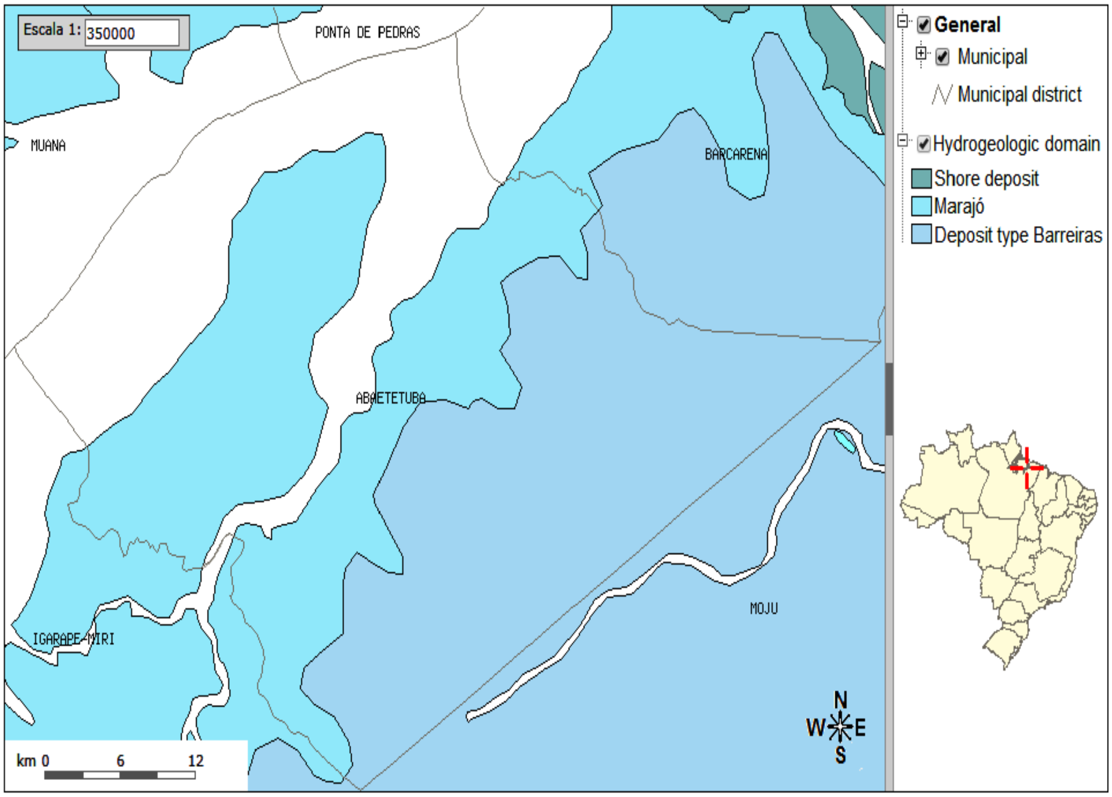


Fig. 3. Hydrogeological domains observed in the limits of the municipality of Abaetetuba (Pará, Brazil)

(Source: CPRM / SIAGAS 2018 adapted in ArcGis © 9.3)

A spatial similarity analysis (Cluster with WPGA) of the ionic balance confirmed the presence of four classes of wells: group I-S formed by sites {1,3,9,12 and 13} with more chlorinated and less calcic water; group II-S {2,11,14,16,18 and 19} with more calcic and less chlorinated waters; and groups III-S {4,7,8 and 10} and IV-S {5,6,15,17 and 20} with intermediate concentrations for Cl^- and Ca^{2+} ions. The ionic concentrations in meq/L represented on lines in the Stiff Diagram confirm the results of the ion balance, with an elongated hexagon with vertices in the calcium and chloride ions (Fig. 5B). From the maximum values obtained for the determined cations and anions, the following order of ionic concentration can be established: $Ca^{2+} > HCO_3^-/CO_3^{2-} > K^+ > Cl^- > Na^+ > Mg^{2+} > SO_4^{2-}$. Electric conductivity (EC) isovalues maps and the Σ cations within the district boundaries were elaborated (Figs. 6A and 6B). The results of the ionic balance confirm a high cation exchange capacity that occurs in clay and sandy loam soils with high concentration of Al^{3+} [12], characteristics present in the Yellow Latosol Distrophic in association with Hydromorphic Podzol and Concrete Lateritic present in the area of study. The most important mineral sources found in the region are feldspars (plagioclase and potassic), Muscovite and Biotite, and Mg^{2+} and Cl^- are all easily weathered, forming salts that are quite soluble in the water and possibly being adsorbed (cations) by the clay particles. Considering the PMV for the ionic composition, established by Ordinance N° 2914 of the Ministry of Health [30], the waters of the wells monitored are in accordance with the pattern of acceptance of consumption.

Considering the microbiological parameters determined by [16], all analyzed wells presented some level of contamination by total coliforms. Concentrations of coliforms ranged from 21 to 585 NMP.100/mL, with sites 6 to 9 and 14 to 20 having values above 300 NMP.100/mL. This pattern of contamination was also observed for fecal coliforms (*E. coli*), which ranged from 2 to 40 NMP.100/mL (mean 19±12 NMP.100/mL). The presence of bacteria in the Coliform group is indicative of contamination of the environment by fecal matter from warm-blooded organisms. Contamination of groundwater by coliforms reveals a serious public health problem, suggesting that sanitary quality is inadequate, indicating a risk situation for the population that uses these waters. Based on current Brazilian legislation, which establishes as a standard for human consumption the "total absence" in 100 mL of sample [30], the indicative of coliforms, both total and fecal, in all wells sampled, even at low levels, is alarming. According to [30], the presence of faecal coliforms in a 100 ml water sample leads to non-compliance and invalidates the use of this resource. Isovalues maps of the microbiologic parameters monitored in the wells were proposed (Figs. 6C and 6D).

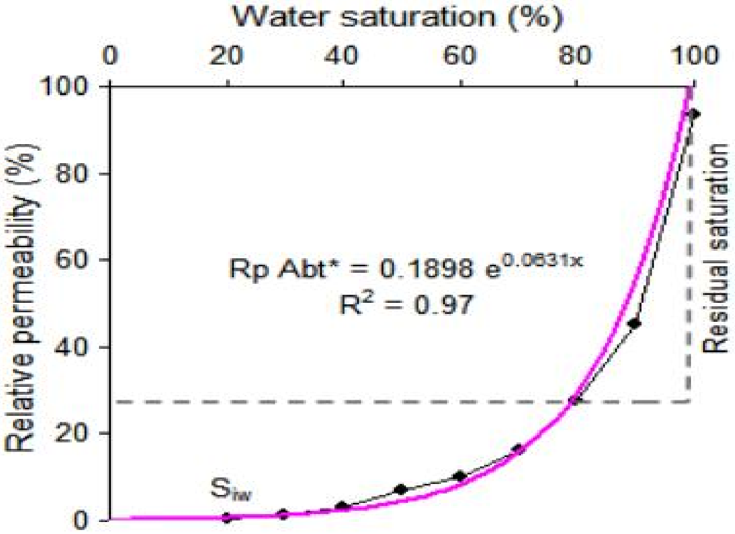
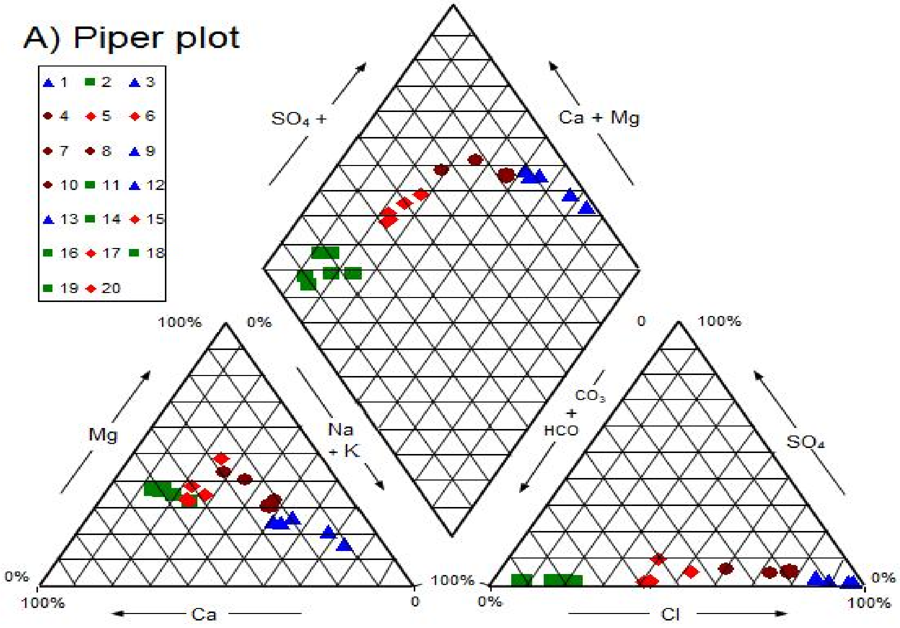


Fig. 4. Water permeability curve for the 20 monitored wells (mean - black line) and trend curve (pink line)

S_{iw} = irreducible saturation point of water; Abt = Abaetetuba


A) Piper plot

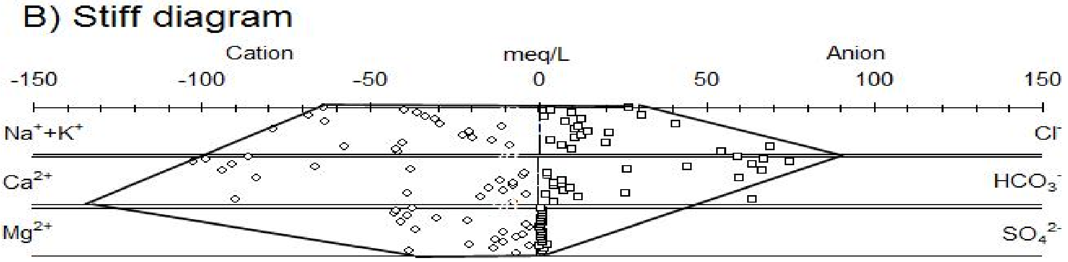

B) Stiff diagram

Fig. 5. A) Piper Diagram and B) Stiff diagram for the cations and anions determined in the waters of the 20 wells monitored, municipality of Abaetetuba – PA

Residential wells are generally poorly constructed, not obeying construction engineering standards and techniques. Usually they are wells excavated manually, without any concern for safety and hygiene, making them easily susceptible to microbiological contamination. These wells are preferably found on the outskirts of the city, often close to pits, which cause a serious problem for the preservation of water quality. According to [24], the most worrying situation is when the pollutants go beyond the confining layers to reach the deep aquifers. In these cases, the rupture of the rocky confinement makes possible the fecal contamination of the aquifers considered less vulnerable.

4.3 Vulnerability Index

The study of aquifer vulnerability allows identifying areas more susceptible to contamination, due to the use and occupation of the soil and the capacity of the physical environment to provide some level of natural protection to the water system. This protection depends on the hydrogeological [34] and geological characteristics of the environment. The vulnerability to pollution of an aquifer will be different from one pollutant to another. The vulnerability assessment can be conducted for a specific contaminant, defined as 'Specific Vulnerability' or in general, for any contamination defined as 'Intrinsic Vulnerability' [35]. For this reason, vulnerability indexes include several hydrogeological parameters in their calculations. The results of the calculation of the DRASTIC Index [27], already multiplied by the respective weighting factors, were presented in isovalues map for the wells monitored (Fig. 7A). The DRASTIC Index ranged from 75 to 119, suggesting areas of 'moderate' to 'moderately-high' vulnerability. By definition, low vulnerability corresponds to the areas that present in the unsaturated zone a lithology composed of the mixture of clay, fine sand and silt, with water level above 25 meters. Moderate vulnerability suggests the presence of areas where exploitable groundwater occurs (when the extraction overtakes the recharge), with a depth between 5 and 15 meters and underlies a material of medium to low permeability. In this case, the parameters depth to groundwater table (D), aquifer recharge (R) and soil media (S) were determinant for the classification of the risk of pollution of aquifers. The results of the calculation of the GOD Index [29] were presented in isovalues map for the wells monitored (Fig. 7B). The GOD Index ranged from 0.15 to 0.32, suggesting areas of 'low' to 'medium' vulnerability, thus confirming the trend observed by the DRASTIC Index. The comparison between DRASTIC vulnerability index and distribution patterns of the values of total solids dissolved (TDS) indicates areas where enhanced values of the TDS have been detected correspond with those with higher DRASTIC ratings. The categorized TDS map was showed as isovalues (Fig. 7C), and the TDS levels map and DRASTIC Vulnerability Index map were overlaid to obtain similarity. As result, using raster calculator and spatial analyst in ArcGis© 9.3 a raster map was generated in order to show the correlation between the two parameters (Fig. 7D), and the values corresponding to the data overlap oscillated within the range -3 to 3.

According to Parallel et al. [36], the vulnerability to aquifer pollution can be defined as the sensitivity of groundwater quality to a pollutant load, based only on the intrinsic characteristics of the aquifer. Pollution and contamination of aquifers can occur in three ways: a) local sources - highly concentrated and reaching the aquifer at one point; b) linear sources - resulting from the infiltration of contaminated surface waters (streams and streams); and c) diffuse sources - in low concentration, however

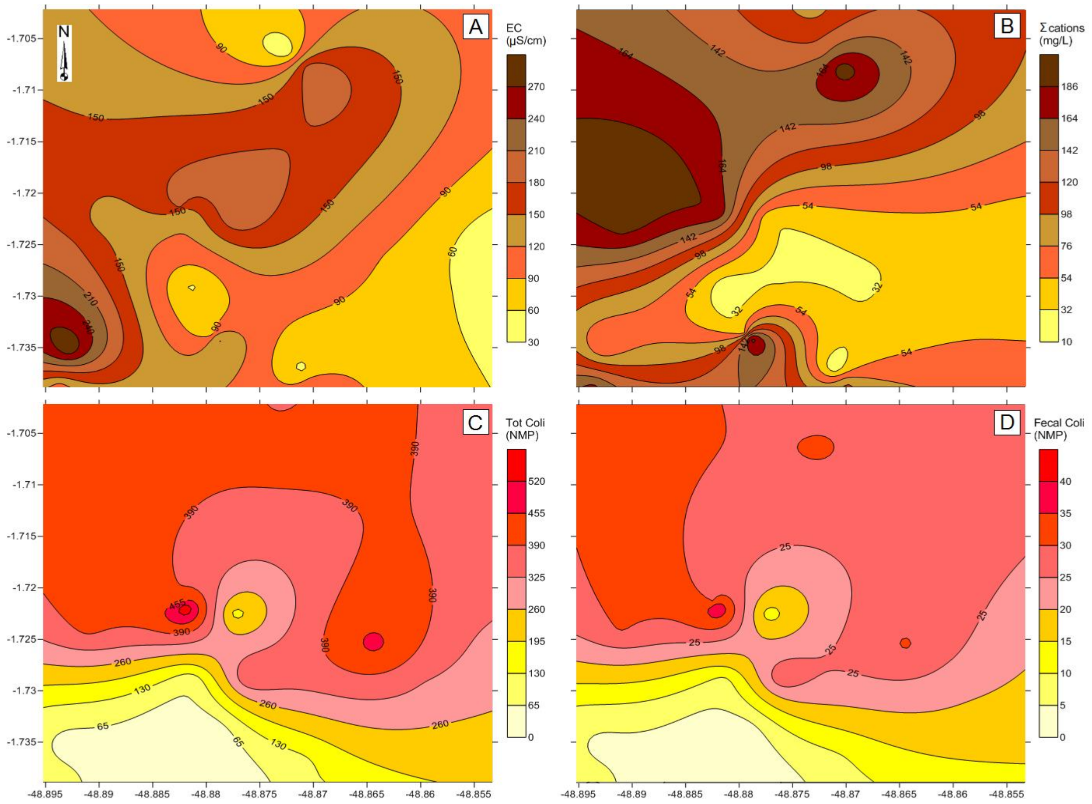


Fig. 6. Isovalues for the parameters: electrical conductivity (EC, 6A); Σ cations (6B); total coliforms (6C) e faecal coliforms (6D) for the 20 wells monitored in the Municipality of Abaetetuba (Pará State, Brazil)

Surfer® Golden Software, 9.11 (2010) and ArcGis© 9.3 (2008) ESRI – USA

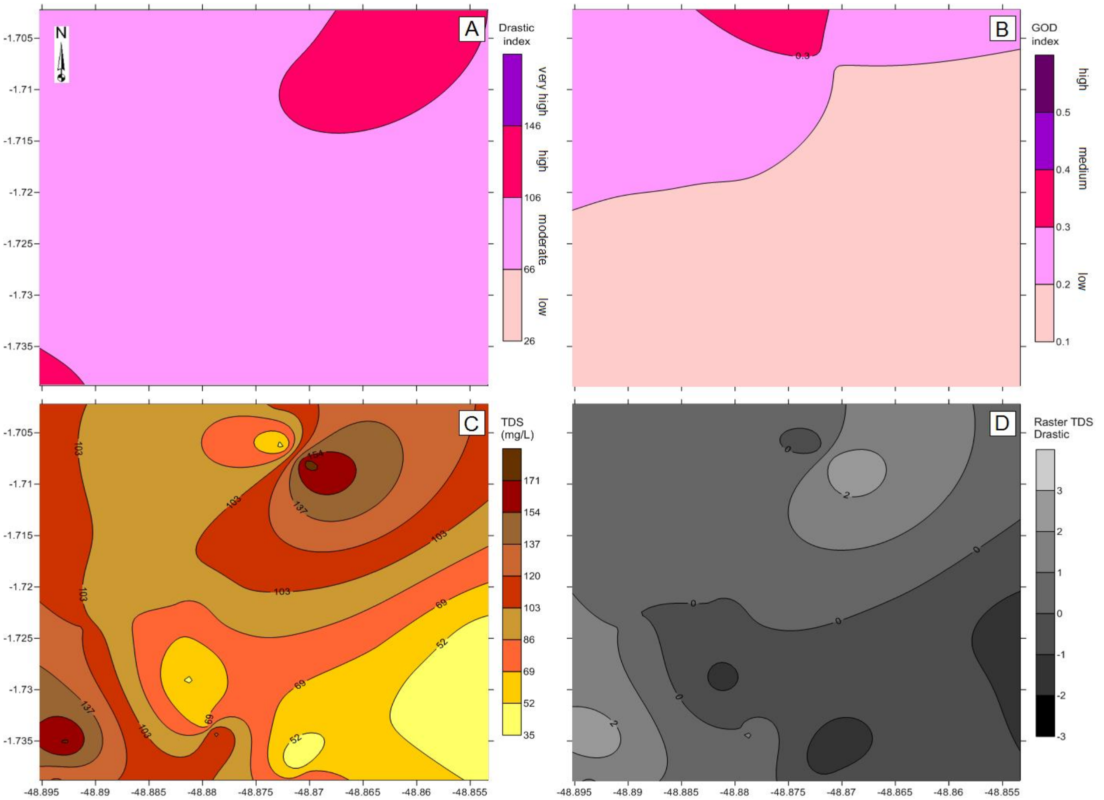


Fig. 7. Isovalues for the parameters: DRASTIC Vulnerability Index (7A); GOD Vulnerability Index (7B); TDS (mg/L) (7C) and correlation between categorized TDS and DRASTIC vulnerability maps (7D) for the 20 wells monitored in the Municipality of Abaetetuba (Pará State, Brazil)

Surfer$^{®}$ Golden Software, 9.11 (2010) and ArcGis$^{©}$ 9.3 (2008) ESRI – USA

contaminating large areas because the pollutants are transported by rain, wind and agricultural activities. In the municipality of Abaetetuba, the main pollutant source observed was local. The lack of basic sanitation, especially sewage treatment, can generate several local sources, which continuously contaminate the wells, especially with fecal coliforms. Another local source that requires attention is the production of wastes from the washing and lubrication of vehicles (oils and greases), which has a high contaminant power. The use of septic tanks in large quantities in the region, precisely to compensate for the lack of sewage collection and treatment, can also cause pollution, in this case as a diffuse source.

Considering the local geological and hydrogeological aspects, and the fact that the Barreiras Group is predominant in the municipality, with partially deep and semi-confined aquifers, even if little thick, it can be said that the degree of vulnerability of the region is acceptable. In other words, the aquifer system in Abaetetuba is little vulnerable to contamination. The highest risk of contamination of the water is due to the wrong handling of the wells, in this case having superficial bacterial contamination. However, aquifers with zones of moderate vulnerability may, in the long term, undergo changes in the quality standard due to the presence of contaminants with mobility and effective persistence, such as metallic ions, hydrocarbons and poorly soluble salts. It should be understood that the results presented in this item are derived from the calculation of indices and, therefore, are subject to failure. Relevant information to identify areas considered potentially polluting, such as use and occupation of the land, are not included in the applied indexes. Thus, although the results were satisfactory, with low to moderately-high vulnerability ratings, a "state of alert" should be maintained for areas that indicated the presence of fecal coliforms and with a high population density. Preliminary studies based on the permeability and depth of the water table indicated the possibility of more vulnerable areas in the N-NE axis, towards the municipality of Bacarena.

The unsaturated layer, located in the upper part of the hydrogeological system, and the filtration capacity of the porous material that constitutes the aquifer, both exert important protection to groundwater quality, acting as a natural system of treatment of tailings, acting as a filter of the aquifers [37]. However, special attention should be given to recharge areas, which can increase the degree of vulnerability of an aquifer through the presence of contaminants. The recharge sites may be susceptible to contamination, depending on the porosity and thickness of the sedimentary matrix that surrounds the aquifer. Over-exploitation of groundwater can also lead to serious environmental problems, such as reduction in the production capacity of wells; infiltration of low-quality groundwater from other more superficial aquifers; induction of lateral flows of brackish or saline water; and support loss of soil, resulting in stability problems of the built-up areas. Among the several applications, the results can help in the indication of areas susceptible to contamination; planning and land use; choice of suitable sites for new well drilling; and choice of locations for network installation to monitor and evaluate water contamination.

5. CONCLUSION

The investigation of the geological aspects identified the stratigraphic units Barreiras, Post-Barrier Sediments and Recent Sediments (Quaternary) in the mesoregion where the municipality of Abaetetuba is located. The presence of the hydrogeological domains Barriers, Post-Barriers and Aluviões were also confirmed. The wells monitored are mostly belonging to the Barreiras aquifer, of medium to high depth and predominantly semi-confined with some porosity. The waters of the analyzed wells are mineralized, and their ionic balance, established by the Piper Diagram, suggested the presence of calcium chlorinated and calcium bicarbonate. The Stiff Diagram confirmed the results of the ionic balance. The results also confirm high cation exchange capacity, which occurs especially in clay-sandy and sandy- clay soils. The order of the ionic concentration for the 20 wells monitored was established as: $Ca^{2+} > HCO_3^-/CO_3^{2-} > K^+ > Cl^- > Na^+ > Mg^{2+} > SO_4^{2-}$. All wells showed some evidence of contamination by fecal coliforms (*E. coli*) remaining outside the standards of potability established by Ordinance N°. 2914 of the Ministry of Health [30]. The groundwater vulnerability maps, produced using the DRASTIC and GOD methods, suggested areas of 'low' to 'moderately-high' vulnerability, and the parameters depth to groundwater table, aquifer recharge and soil media were determinant for the classification of risk of pollution of aquifers. Despite this, the Barreiras aquifer in the semi-confined and free areas may be becoming susceptible to microbiological contamination, mainly due to the inadequate use and lack of maintenance of most wells. The intense exploitation of groundwater, especially in areas of great population density, may be contributing to the contamination of aquifers. For this reason, a 'state of alert' has been suggested for these areas. The maps of isovalues and vulnerability indicated areas that require greater environmental monitoring.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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