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Technical Article

Sewage static system influence on the concentrations of nitrogen compounds in unconfined aquifers

Influência de sistemas estáticos de esgotamento sanitário nas concentrações de compostos nitrogenados em aquíferos livres

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ABSTRACT

This research aimed to investigate the relation between sanitary situation and groundwater quality, using the concentration of nitrogenous compounds. The aquifer studied is unconfined and situated in the periurban zone of Fortaleza (NE Brazil). Through the Geographic Information System (GIS), a relational database was created using data from the IBGE demographic census (2011), to analyze numbers of households linked to septic tanks or rudimentary cesspit. The groundwater quality was evaluated based on nitrogen compounds (N-NH_3^+; NO_2^-; N-NO_3^-), pH, and total dissolved solids (TDS). The highest concentrations of nitrates are found in areas with a higher density of septic tanks and rudimentary cesspit. Furthermore, nitrate was more present in water table above 6.6 m, mainly in the interfluvial zones, which have a high oxidation potential. The results contribute to the loss of contamination, based on the number of households with septic tanks and rudimentary cesspit, in unconfined aquifers, which were more vulnerable to contamination, mainly in peripheric expansions areas in the cities, where the deficit in sewage services tends to be high.

Keywords: water contamination; domestic effluents; groundwater quality.

RESUMO

Esta pesquisa teve como objetivo investigar a relação entre a situação sanitária e a qualidade da água subterrânea, usando concentrações de compostos nitrogenados. O aquífero estudado é do tipo livre e se encontra situado na zona periurbana da cidade de Fortaleza (NE Brasil). Através do Sistema de Informação Geográfica (SIG), foi criado um banco de geodados relacional utilizando dados do censo demográfico do IBGE (2011), analisando o número de domicílios vinculados a fossas sépticas e fossas rudimentares. A qualidade da água subterrânea foi avaliada com base em compostos nitrogenados (N-NH_3^+; NO_2^-; N-NO_3^-), pH e sólidos totais dissolvidos (STD). As altas concentrações de nitrato estão associadas a maior ocorrência de fossas sépticas e rudimentares, principalmente. Além disso, a ocorrência do nitrato ocorre em áreas de níveis estáticos acima de 6,6 m, principalmente nos setores interfluviais, que apresenta alto potencial de oxidação. Os resultados contribuem para predição da contaminação, tendo em vista a quantidade de domicílios com fossas sépticas e rudimentares, sobre aquíferos livres, que são mais vulneráveis à contaminação, sobretudo em áreas de expansão periférica da cidade, onde o déficit de esgotamento sanitário tende a ser maior.

Palavras-chave: contaminação hídrica; efluentes domésticos; qualidade da água subterrânea.

INTRODUCTION

Basic sanitation has been understood as the control of factors from the anthropic influence that can generate harmful effects on their physical and mental welfare (WHO, 2015). For this, it is essential to promote healthiness in the urban environment. The economic increase is necessarily linked to urbanization, population growth, and consumption. Thus, for the cities, meanly, the necessity of efficient sewage systems has been increasing (YAMAMOTO, 2008; NARAIN, 2012; BANANA *et al.*, 2015).

Domestic sewage has many organic compounds and high variable composition. Huang, Li and Gu (2010) attest that around 64% of the domestic sewage is organic material. Nitrogen compounds are the most critical contaminants in urban areas, the high concentrations occur due to sewage systems inefficiency (BARRETT *et al.*, 1999; FOSTER; CHILTON, 2004). Nitrate is the most problematic nitrogen compound due to the ionic form in water, and is not removed for conventional treatment (ZHAO *et al.*, 2012). Nitrate can generate complications in human health, such as: cancer, miscarriage, infant mortality, abdominal pain, and diarrhea (EBRAHIMI; ROBERTS, 2013).

The maximum permitted N-NO_3^- is 10 mg/L, whose concentration has been established on international drink-water quality legislation to avoid the methemoglobinemia. This disease could cause the death of children and aged people (BAIRD; CANN, 2011). Furthermore, there is evidence of the relationship

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between nitrate and nitrite ingestion and the occurrence of some cancer types, and worldwide the public policies neglect this fact, and do not define a maximum value for such risks (WALTERS, 1983).

In Latin America, water pollution is a serious problem in cities, especially due to the lack or inefficiency of sanitary sewage, which does not follow the horizontal growth of cities (TUCCI, 2008). In this context, Brazil is experiencing an acute crisis "The most critical regions are located in the vicinity of the further metropolitan areas, and the poor water quality is associated with the launch of domestic sewage" (BRASIL, 2006, p. 45). Only 57.6% of the Brazilian municipalities have sewage collection, and 70% of the sewage is treated (BRASIL, 2016).

As a consequence, in the Brazilian peri-urban reality, there is a widespread use of static sewage systems. The use of septic tanks as alternatives to the lack of a sewage collection system can lead to risks of contamination of the aquifers. According to Oliveira and Von Sperling (2011) and Vásquez-Suñe *et al.* (2010), the risk is depending on hydrodynamic conditions of the underground environment, as well as on the density of devices per unit area (usually in Km^2).

Different hydrodynamic conditions and types of aquifers offer distinctive strength to contamination. Hydrogeological features and aquifer vulnerability are important for predicting the comportment of contaminants (KAZAKIS; VOUDOURIS, 2015). Unconfined aquifers are geologic formations that had hydrogeologic proprieties able to reserve and transmit water in significant quantities, and this formation is in contact with the base of soil or with the atmosphere (FETTER, 1994). This type of aquifer had a piezometric level coinciding with atmospheric pressure (FREEZE; CHERRY, 1979), moreover, the groundwater level can be highly affected by pluvial recharge, often occurring as seasonal lagoons.

Unconfined aquifers are commons in coastal regions, due to the high supply of marine sediments. On the northwest coast of Brazil, these aquifers are defined as Sistema Aquífero Dunas (SAD) and Sistema Aquífero Barreiras (SAB). In Fortaleza City, these aquifers have high and medium vulnerability levels, respectively (PEIXOTO; CAVALCANTE, 2019). They have been more important for the water supply to important cities like Natal, Rio Grande do Norte, and other cities with minor expression, and in many coastal communities, somewhere these aquifers have been widely contaminated with nitrate.

In the city of Fortaleza, SAD and SAB are utilized as alternative water sources through manual and tubular wells. Cavalcante (1998) estimated that 60% of the population uses groundwater for domestic water supplies. The use of groundwater is more common in peripheral zones, but the deficits in sewage services promote the generalized use of static sewage systems, which uses mainly septic tanks and rudimentary cesspit, a risky situation for a population that utilizes groundwater for domestic use.

Peixoto (2016) showed that higher densities of septic tanks increase the involuntary artificial recharge of domestic effluents. The distinction between septic tanks and rudimentary cesspit has been discussed in the Brazilian standards NBR, 7229 (ABNT, 1997). The first is a cylindrical or prismatic unit that makes the treatment of the effluent for horizontal flow thought of sedimentation, flocculation, and effluent digests, while the rudimentary cesspits are the devices that do not obey the constructive and operational requisites established. It receives the effluents directly into holes and ditches that are coated or not with concrete material, without any mechanism to mitigate the contamination load.

This situation can offer risk to local communities that have used the groundwater and can promote contamination of this resource, contributing to a qualitative shortage of water. Therefore, it is necessary to understand the machismo of nitrate contaminations, and the relations with the use of statics systems of sewage as potential sources of contamination in unconfined aquifers. This research aims to investigate the relationship between the sanitary situation and the quality of groundwater, using the concentration of nitrogenous compounds. The results contribute to contamination loss, based on the sanitary quality of unconfined aquifers, which are more vulnerable to contamination, mainly in areas of peripheral expansions in cities, where the sewage service deficit tends to be high.

METHODOLOGY

Study area

The study area is located in the urban periphery of Fortaleza city, located in the Fortaleza Metropolitan Region, Northeastern Brazil (Figure 1). It corresponds to 4 urban sub-watershed that, together, cover 20,9 km^2. Fortaleza City has the fifth larger population in the country and registers a population growth of 75% in the last 20 years, and larger horizontal expansion (IBGE, 2011). The local rock outcrop consists of predominantly incoherent and porous sediments, dominated by sands and argillites from the Pliocene and Pleistocene ages (BRANDÃO, 1998).

Hydrogeological systems are represented by porous unconfined aquifer with wells having an outflow of 5.2 $m^3.h^{-1}$ on average (GOMES; CAVALCANTE, 2015). The crystalline bedrock outcrops in 17% of the territory municipal and below the porous aquifer, the rocks have consisted of gneisses, quartzites, and amphibolites of Upper Proterozoic age (CPRM, 2004).

Groundwater quality

We registered 64 wells between March and May 2016, georeferencing in Universal Transversal Mercator (UTM) Datum SIRGAS 2000/24S. 24 wells were selected for sampling, according to the following criteria:

- I - Existence of a technical construction profile;
- II - Wells in operation;
- III - Spatial distribution favorable to the representation of the study area;
- IV - Wells for domestic supply;
- V - Wells that supply more families.

The static level was evaluated, and groundwater was sampled the concentration of ammoniacal nitrogen were conditioned in frosted glass containers, while samples for pH, Total Dissolved Solid (TDS), and $N\text{-}NO_3^-$ and NO_2^- measurements were placed in polypropylene containers, according to methods recommended by APHA (1998) at the Environmental Geology Laboratory of *Universidade Federal do Ceará* (LAGEA/UFC).

Sanitary situation and GIS analysis

The sanitary situation was evaluated by data from the demographic census of (2010), by IBGE (2011). The connection of household numbers to septic tanks or rudimentary cesspits was addressed. The data were collected from the base map, formed by census sectors defined by IBGE, modeling a data bank in Geographic Information System (GIS) and used to analyze, manage, and present the information.

According to Bernhardsen (1999), the spatial analyses in GIS are based on relationships of features and attributes, which characterize the reality for the model integrated into data structures based on information and complex relationships. The GIS has been used in several studies of groundwater contamination analysis and prediction, especially in urban environments (LEE *et al*., 2003; LIU; WANG; JANG, 2013, GURDAK; QI, 2012; TUBAL *et al*., 2017).

Therefore, septic tank and rudimentary cesspit were carried out separately based on the normalization of the area of the census sectors (Equation 1).

$$D = n/A \qquad (1)$$

D = density of septic tanks or rudimentary cesspit;
n = number of septic or rudimentary cesspit;
A = area of the census sector considered.

In 93 censing sectors in the study area analyzed, descriptive statistics were applied to amplitude, central tendency, and dispersion measures for recognition of the class interval.

To recognize the origin of nitrogen compounds in groundwater, a land-use map produced by Peixoto (2016) was used, which based on the automated satellite image classification, defined the constructed areas, the not constructed areas, and are used for agriculture in the same study area.

Groundwater flow

Underground water flow was measured based on the hydraulic load from a static level of 27 wells. Hydraulic load or hydraulic potential is the mechanical energy of a moving liquid and, as postulated by Fetter (1994), is defined by (Equation 2)

$$h = z + p/\gamma \qquad (2)$$

h = hydraulic load;
z = elevation of the statics water level (m);
p = specific mass in volume;
γ = specific weight in volume.

Unconfined aquifers have p = 0, since the pressure at the top is equal to atmospheric pressure (Equation 3). Then h = z, and:

$$h = sl - (c - wh) \qquad (3)$$

h = hydraulic load;
sl = static water level (m);
c = altitude (m);
wh = well height in relation to the ground (m).

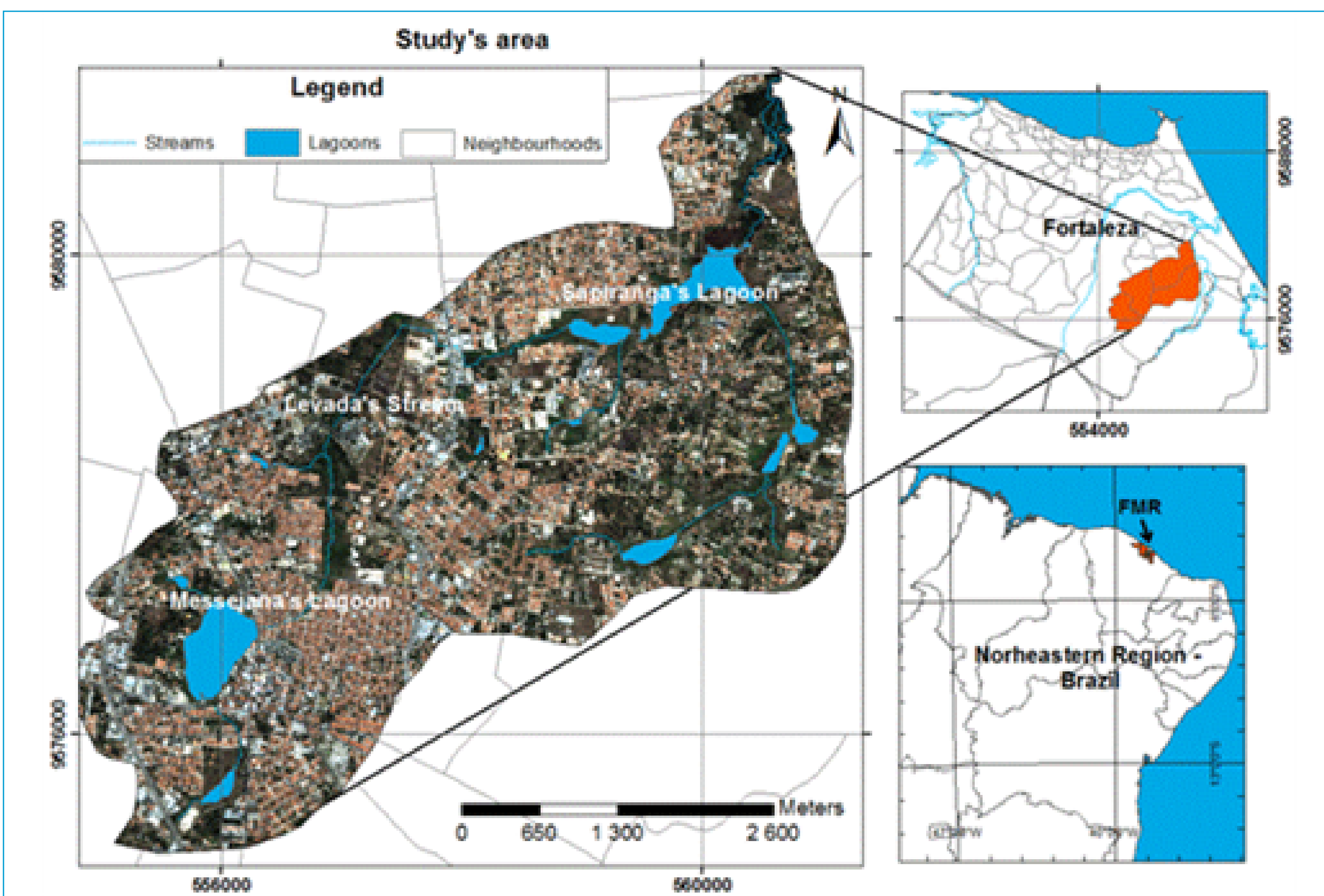


Figure 1 – Localization of the study area.

In unconfined aquifers, formed for consolidated or unconsolidated sediments, the underground flow map can identify recharge areas, especially when recharge is directly associated with the rainfall contribution, as well as the prediction and movement of contaminants in the groundwater.

Principal component analysis

Chemical analyses of nitrogen compounds ($N\text{-}NH_4^+$, NO_2^-, and $N\text{-}NO_3^-$), pH, and TDS were treated with multivariate statistical application, based on principal component analysis (PCA).

We used the free software ANDAD developed by Sousa and Sousa (2000) to identify two factorial plans, covering more than 70% of the information contained in the data (Table 1), this percentage is considered adequate for this analysis.

RESULTS AND DISCUSSION

Sanitary sewage

The sanitary sewage systems in the area consist of a cloacal or a static system. The first is collective, capturing effluents and transporting them to treatment stations, while the second integrates low-cost options, such as individual solutions, including several types of cesspits or tanks (OLIVEIRA; VON SPERLING, 2011). These cases also embrace septic tanks with higher costs. Banana *et al.* (2015) postulate that septic tanks are solutions for peri-urban areas with water supply infrastructure.

In the study area, 82% of domiciles use static sewage systems, favoring the incorporation of nitrogenous compounds in groundwater. This type of contamination was described by Lerner (2002), Foster and Chilton (2004), Almasri (2007), Peixoto and Cavalcante (2019), and Tubau *et al.* (2017) as frequent, and promote nitrate contamination of groundwater in an urban environment. Studies in Brazilian cities performed by Bernice (2010), Barbosa (2005), and Carneiro *et al.* (2009) placed septic and rudimentary septic tanks as the main source of nitrate contamination in urban areas.

In Brazil, the installation of septic tanks must not exceed the limit of 10 units/hectare or 1,000 units/Km^2 (ABNT, 1997). In American standards, density must not exceed 15/km^2 (USEPA, 1977). This limitation is considering an indirect relationship with the amount of contaminants supporting the underground environment. In the study area, there are 29 (30%) censing sectors which exceeded the limit of 1,000 unit/km^2, and the entire area has 13,188 rudimentary cesspits, while the quantity of septic tanks is 9,842 devices.

Groundwater quality

The pH values between 5.9 and 7.3 highlight an acidic tendency for groundwater (Figure 2). These data agree with those presented by Gomes and Cavalcante (2015), based on 120 samples of groundwater from the entire city of Fortaleza, considered 81% acidic. The mean value of TDS was 681.9 mg.L^{-1}, however, some anomalous values were recorded with TDS > 1,000 mg.L^{-1} and a standard deviation of 230 mg.L^{-1} (Figure 3). These relatively high values of TDS may be associated with the incorporation of salts provided from domestic effluents, as observed by Almasri (2007), Gao *et al.* (2012), and Samantara *et al.* (2015).

The analytical values of nitrogenous compounds presented favorable conditions to accumulations of $N\text{-}NO_3^-$. On the other hand, $N\text{-}NH_3$ and NO_2^- presented maximum values of 4.7 and 0.3 mg.L^{-1}, being detected in 4 and 6 samples, respectively.

Diffuse contamination was identified due to a high number of contaminating sources and the persistence of $N\text{-}NO_3^-$ in an aqueous way. In most concentrations, the areas of this compound suggest a diffuse behavior in the contamination process. Defining a plume of contamination converges to a regional diffuse, following the regional fluxes of groundwater (MITCHEL, 2005; HAYASHI *et al.*, 2009; LASSERRE; RAZACK; BANTON, 1999).

Table 1 – Information values of the factorial plans established by the PCA analysis.

Factorial plans	Information	Accumulated information
1	41.5	41.5
2	28.8	70.3
3	16.2	86.6

PCA: principal components analysis.

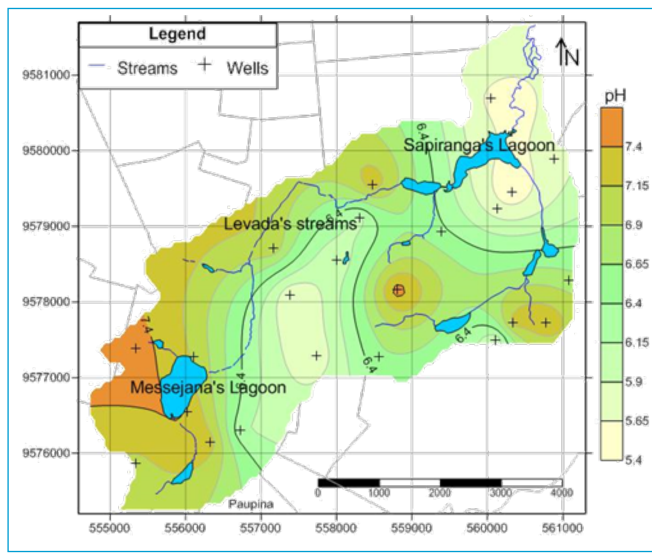


Figure 2 – Spatial distribution of pH.

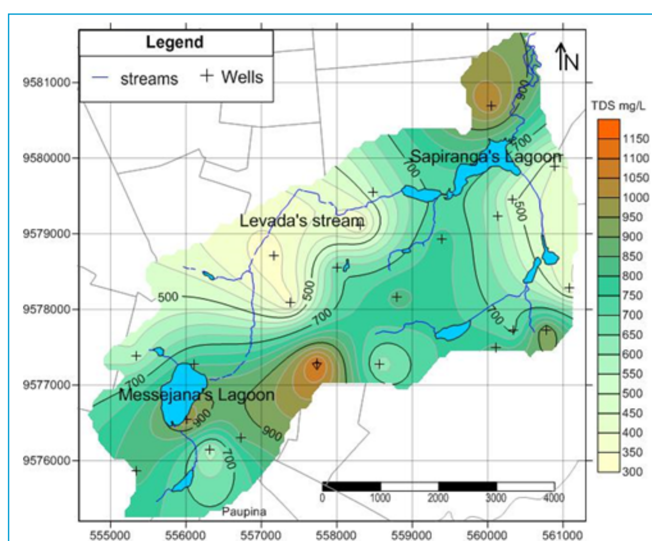


Figure 3 – Spatial distribution of total dissolved solids.

Analysis data showed correlations behavior to some variables. PCA allows to recognize most significant association parameters; for this, PCA has been widely used in hydrochemical and hydrogeological studies (MATIATOS, 2016); The PCA information of the first factorial plan was the positive correlation between N-NH_{4+}, NO_{2-}, and TDS (Figure 4). The association between N-NH_4^+ and NO_2^- can signify recent effluent contamination, as the preliminary mineralization of the nitrogen compounds present in domestics effluents results in this compound in an oxidizing environment (WILHELM; SCHIFF; ROBERTSON, 1996). Moreover, the NH_4^+, NO_2^-, and TDS clusters can result from the incorporation of salt from effluents, whose process increases only TDS value. Some authors postulated the anomalous value of the TDS is generally associated with an input of domestic effluents into the hydrogeological system, when high deficits occur in the sewage service , according to Gao *et al.* (2012) and Samantara *et al.* (2015). Moreover, the study area has the aforementioned characteristic and vulnerable aquifers can make this relationship more pronounced.

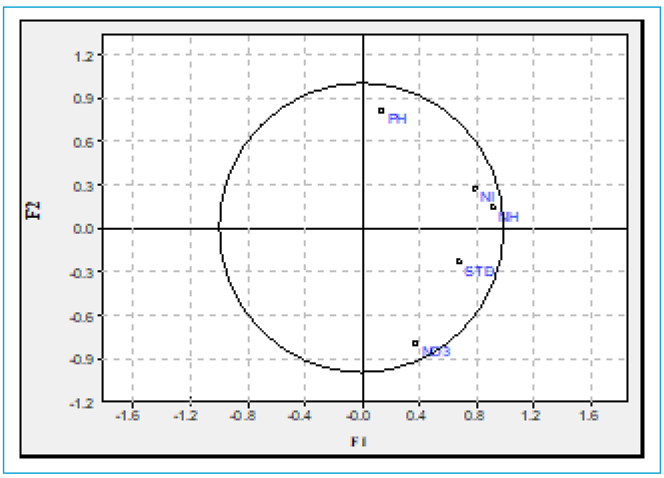


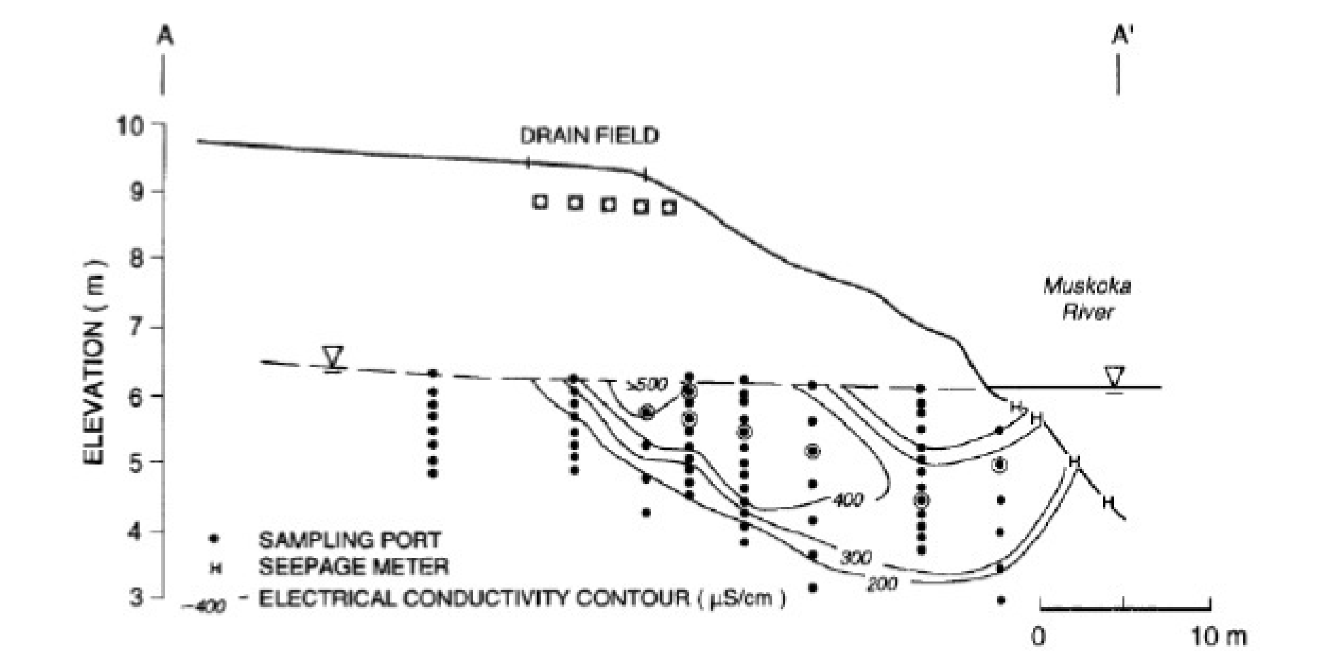
Figure 4 – Correlations in factorial plans.: NO3 = N-NO_3^-; NI = NO_2^-; NH = NH_3^+.

According to Wilhelm, Schiff and Robertson (1996), the contamination plume from septic tank contains a high concentration of N-NH_{4+}, and the electrical conductivity (EC), which has a high correlation with TDS, is elevated, decreasing as it approaches the borderline zone of the plume (Figure 5).

The information contained in factorial 2 shows a negative correlation between NO_3^- and pH. The decrease in pH has a biogeochemical relationship with oxidation of organic matter and nitrate contamination (HEM, 1959). Wilhelm, Schiff and Robertson (1996) and Liu, Wang and Jang (2013) suggest that increases in NO_3^- concentration in an aqueous way result in oxidation of NO_2^- and cause acidification of waters. In this study, we consider that the mechanism of nitrification, consuming alkalinity, and causing the pH decrease to be as described by Liu, Wang and Jang (2013), one can also observe the spatial relationship between low pH and high nitrate concentration, comparing Figures 2 and 6.

In groundwater, nitrate is controlled by nitrogen biogeochemistry. Generally, organic matter or other nitrogen compound source is incorporated into superficial or sub superficial soil parts, aerobic bacteria promote the ammonification process. Oxidant subsurface environment creates conditions to the action of Nitrobacter that transform ammonium into nitrite and immediately after, into nitrate. According to Chapelle (2000) and Braga (2002), natural sources of nitrogen can originate from the atmosphere, organic matter in decomposition, and animal excrements. However, human activities, in countries or cities, can produce effluents that incorporate nitrate in quantities above what is allowed in groundwater, causing contamination and damage to the use of this resource. Furthermore, other factors can promote influence, such as pluvial recharge, depth, and water table oscillations.

Nitrate contamination was noted in 41.6% of the samples, some samples have concentrations until 50% above the maximum value of the legislation. The interfluvial sector was the most affected due to the higher densities of static sewage



Source: Wilhelm, Schiff and Robertson (1996).

Figure 5 – Model to a value of electrical conductivity from domestic effluent deposited in a septic tank.

systems, associated with more favorable conditions for oxidation. While in areas close to local base levels (rivers and lagoons), there is less oxidation potential with the predominance of N-NO_3^- below 5 mg.L^{-1} (Figures 6 and 7).

The high densities of rudimentary cesspit are due to concentration increases of N-NO_3^+ in groundwater. While the density of septic tanks also demonstrated less spatial relation with groundwater contamination. According to Withers *et al.* (2014) and Meeroff *et al.* (2008), these devices represent the main contaminant source for domestic effluents in urban areas. Such conditions cause the high concentration of nitrogen compounds, mainly nitrate (OUYANG; ZHANG; CUI, 2014). Furthermore, the attenuation capacity is highly variable (WITHERS *et al.*, 2014).

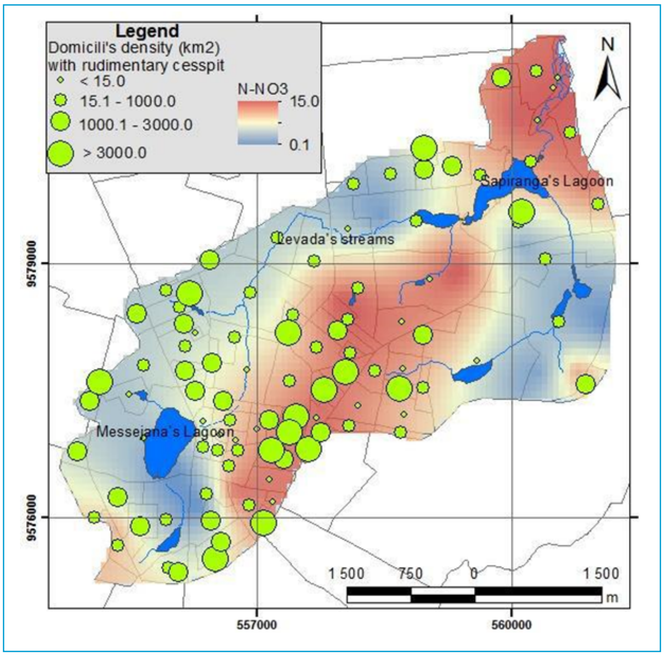


Figure 6 – Rudimentary cesspit and regional nitrate concentration.

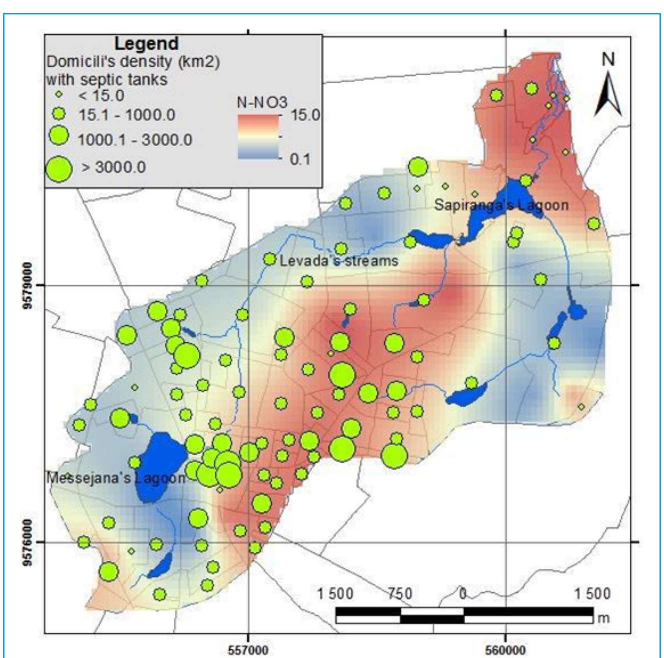
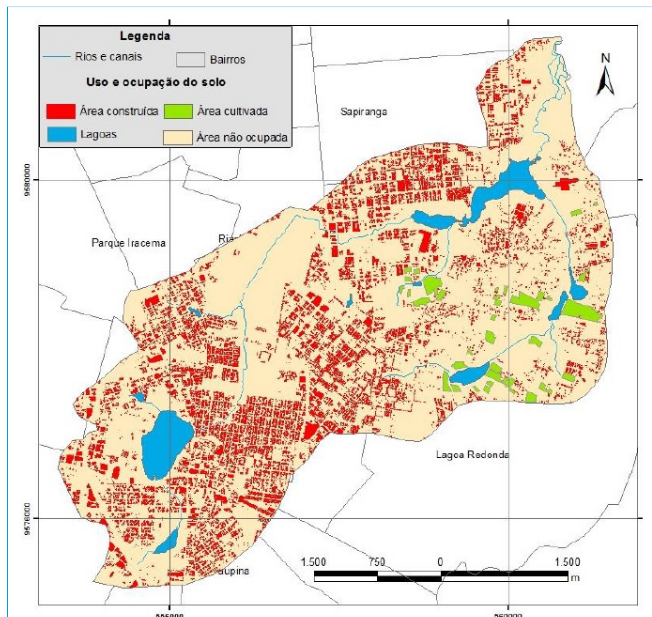


Figure 7 – Septic tanks and regional nitrate concentration.

The use of soil in the study area demonstrates the most of it is not used (Figure 8), while the contracted area (*area construída*) is significant (18.2%), considering that it is a peri-urban area (PEIXOTO, 2016). The agricultural use (*área cultivada*) is low (1.7%) and there is no significant relation with nitrate contamination, as the concentration of use occurs in the east, where there is no significant nitrate concentration. This evidences probable nitrate contaminations from domestic effluents.

The diffusion of the contamination

The configuration of the groundwater contamination in the central watershed area is due to groundwater flow, which has general SW-NE orientation Moreover, the fluvial and lacustrine systems in the area have been of effluent behavior. Near the base, levels of gradual decrease in nitrate concentration occur due to a more intensive reduction process (Figure 9).



Source: Peixoto (2016).

Figure 8 – Land use of study area.

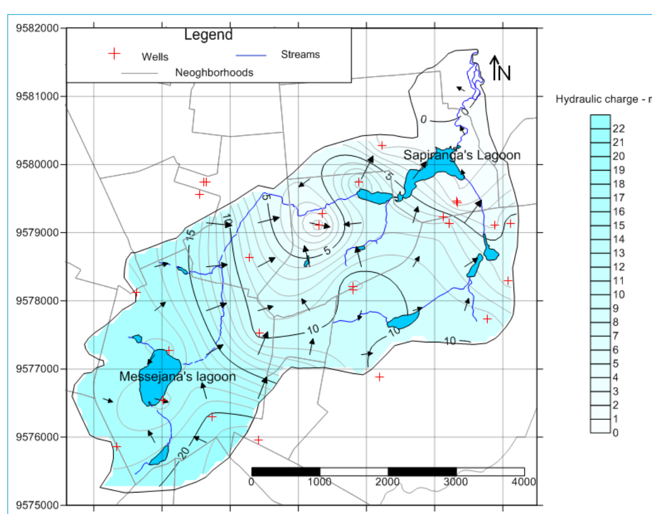


Figure 9 – Groundwater flow.

Demographic density and slums

Nitrate contamination has been spatially related to urban slums, which have been a call to IBGE as a subnormal agglomerate due to their high demographic density. In areas with demographic density above 4,000 hab/km^2, nitrate concentrations are > 7.5 mg.L^{-1}. Furthermore, the slums are situated in the contaminated area, especially, south-center and northwest of the area (Figure 10). The slums lack of urbanistic standard, public sewage services, and water supplies; therefore, they use alternative and individual water supplies and sewage systems represented for wells and rudimentary cesspit, respectively. This situation can generate a contamination cycle, where the groundwater is contaminated and the population uses this water to supply sources, producing a serious public health problem.

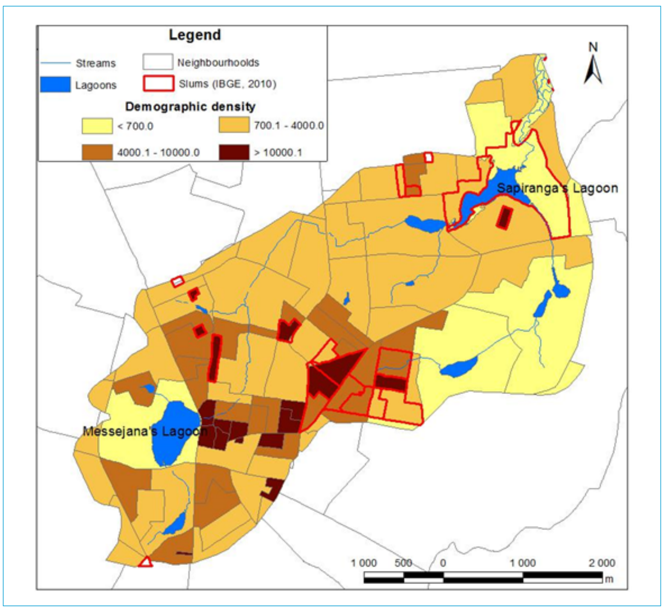


Figure 10 – Demographic density and slums.

CONCLUSION

The sanitary situation exerts a direct influence on nitrate concentrations in groundwater. The censing sector with larger septic tank densities are spatially associated with nitrate contamination, however, the density of rudimentary cesspit are most determinants to this contamination. The geographic position of the slums showed that they produce main factors to low water quality, due to low sanitary quality and inadequate urbanistic standards.

There is the natural factor favorable to a larger concentration of nitrate: the average statics level of groundwater above 6.6 m favors the oxidation of nitrogen compounds, and the concentration of nitrate as the oxidation process occurs in the sub-saturated zone, where oxygen is available. As the groundwater flow comes close to streams and lagoons, the reduction process decreases nitrate concentrations.

The situation observed in the study areas occurs mainly due to the main recharge areas having been most occupied, offering risks to nitrate contamination. Spatial sanitary strategies must be carried out for the protection of unconfined aquifer and public health.

AUTHORS' CONTRIBUTIONS

Peixoto, F. S.: Conceptualization, Data Curation, Validation, Writing – Original Draft. Writing — Review and Editing. Cavalcante, I. N.: Formal Analysis, Funding Acquisition, Supervision, Writing — Review and Editing.

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