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Evaluation of the quality of groundwater in the municipality of Ji-Paraná, Rondônia, in the Brazilian Amazon region

Groundwater quality can be affected by many factors. The objective of this study was to assess the quality of groundwater and map the flow direction, to identify possible sources of contamination in the districts of Nova Londrina and Nova Colina (Ji-Paraná, Rondônia). Water samples were collected in September 2015 and February 2016 in 20 wells in Nova Londrina and in December 2016 and April 2017 in 15 wells in Nova Colina. The turbidity, pH and electrical conductivity (EC) were measured in loco. The microbiological parameters were determined by the membrane filtration method in a chromogenic medium, and the total dissolved solids (TDS) were measured by the gravimetric method. The nutrients ammonia, nitrite, nitrate, dissolved phosphorus and total phosphorus were ascertained by the spectrophotometric method and the underground flow was obtained by applying the Surfer 8.0 software. Through principal component analysis (PCA) it was possible to detect that the TDS, total coliforms, pH and EC had important contributions to formation of the groundwater axes in Nova Londrina, while the variables EC, nitrate and well and cesspit depths contributed in Nova Colina. The groundwater flow did not differ among the months studied, and was mainly in the northwest-southeast direction in Nova Londrina and from the southeast to other regions in Nova Colina.

Keywords: Wells; Nitrates; Sanitation; Flow direction; Principal component analysis.

Avaliação da qualidade da água subterrânea no município de ji-Paraná, Rondônia, região Amazônica brasileira

A água subterrânea tem sofrido alteração da sua qualidade devido diversos fatores. A presente pesquisa teve o objetivo de avaliar a qualidade da água subterrânea e mapear a direção do fluxo visando identificar possíveis fontes de contaminação nos distritos de Nova Londrina e Nova Colina (Ji-Paraná/RO). A água foi coletada nos meses de setembro/15 e fevereiro/16 em 20 poços de Nova Londrina e nos meses de dezembro/16 e abril/17 em 15 poços de Nova Colina. A análise de turbidez ocorreu por meio de um turbidímetro de bancada. O pH foi determinado por pHmetro e condutividade elétrica - CE por meio de condutivímetro, obtidas in loco. A análise microbiológica foi realizada pelo método de membrana filtrante em meio cromogênico e sólidos totais dissolvidos –STD conforme o método gravimétrico. Os nutrientes, amônia, nitrito, nitrato, fósforo dissolvido e fósforo total foram determinados pelo método espectrofotométrico e o fluxo subterrâneo foi obtido pelo software Surfer 8.0. Por meio da análise de componentes principais - ACP foi possível analisar que as variáveis STD, coliformes totais, pH e CE apresentam importante contribuição para formação dos eixos da água subterrânea de Nova Londrina e as variáveis CE, nitrato e cotas do poço e da fossa para de Nova Colina. O fluxo subterrâneo não foi diferente entre os meses estudados, sendo predominante no sentido noroeste sudeste (Nova Londrina) e sudeste para as demais regiões (Nova Colina).

Palavras-chave: Poços; Nitratos; Saneamento; Direção de fluxo; Análise de componente principal.

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INTRODUCTION

Water is a natural resource essential to life, so access to it is legally guaranteed to all people. To secure this right, it is important to carry out water balance and quality studies (ANA, 2012). About 97% of the fresh water of the Earth is located underground, and is the principal source to maintain rivers and lakes (BAIRD et al., 2011). In Brazil, some municipalities do not have public water systems that serve all inhabitants. Besides this, many people with access to the public water supply prefer to use well water for various reasons, such as lack of trust in the water quality and the fee charged (IBGE, 2010; ALBUQUERQUE FILHO et al., 2011).

However, groundwater pollution is a potentially serious problem, caused by infiltration of polluted surface water, including by agricultural chemicals and raw sewage (CARAVANTES et al., 2014; FERREIRA et al., 2015; LAUREANO et al., 2019).

In the state of Rondônia, problems of groundwater contamination have been identified by several researchers. Ferreira et al. (2014) analyzed the water from catchment points in the district of Boa Esperança, municipality of Ji-Paraná, and identified the influence of leachate from an inactive garbage dump on the water quality, including the presence of heavy metals. Cremonese et al. (2015), studying the same area, found the presence of mercury in all groundwater samples, a matter of serious concern due to the toxicity and ability for bioaccumulation of this element.

Among other studies conducted in the state, we can mention those carried out in the municipalities of Presidente Médici by Laureano et al. (2019), Vilhena by Oliveira et al. (2015) and in the community of Santa Rosa, near the Jaru Biological Reserve, by Ferreira et al. (2015), who observed contamination of groundwater by coliforms including *E. coli*, indicating pollution by domestic sewage.

Nunes et al. (2012), when analyzing the water from wells located near a truck farm in Ji-Paraná, observed contamination by nitrate, which is harmful to health of the local people due to the increased risk of methemoglobinemia, lymphoma and stomach cancer (BAIRD et al., 2011). The objective of this study was to identify the groundwater quality in a municipality in the Amazon region and the main sources of contamination, by determination of the water flow direction and principal component analysis.

MATERIALS AND METHODS

Study area

The study area was composed of the districts of Nova Londrina and Nova Colina, belonging to the municipality of Ji-Paraná, located in the center-east part of the state of Rondônia, in the Machado River Basin of the Amazon Hydrographic Region. The predominant climate is moist and hot tropical, with annual average temperature of 25 ºC, average maximum of 32 ºC and minimum of 21 ºC, and total yearly precipitation of 1,962. 8 mm (RONDÔNIA, 2012).

The two districts are served by the public water system under the responsibility of the Ji-Paraná municipal government together with the state water and sewer service provider (COMPANHIA DE ÁGUA E ESGOTO DE RONDÔNIA – CAERD). In Nova Londrina the water intake is from an underground spring and 376 of the 528 residences have active hookups, while the other 152 residences are supplied by their own wells (CAERD, 2016). In turn, in the district of Nova Colina the water is obtained from a surface spring, and of the 256 residences, 134 have active connections and the other 122 use wells (CAERD, 2016).

Sampling

To perform a homogeneous sampling, the map of each district was divided into four quadrants and four or five residences with wells were selected from each. All told, 20 residences were chosen in Nova Londrina (points 1 – 20) and 15 in Nova Colina (points 1 – 15).

The samples were collected in September 2015 (dry season) and February 2016 (wet season) in the district of Nova Londrina, and in December 2016 (wet season) and April 2017 (wet-dry transition season, called ebb season) in Nova Colina. The geographic coordinates and altitude were determined with a GPS device (Garmim Etrex Vista H 2,8”), and the water level in each well was determined with a measuring tape. The characteristics of the wells were also recorded, such as type of lining and cover.

The water samples were collected in plastic bottles (500 mL) with top open at the moment of collection, lowered into the well with an instrument designed for sampling groundwater. The samples were kept refrigerated until analysis in the Limnology and Microbiology Laboratory (LABLIM) of Federal University of Rondônia (UNIR), Ji-Paraná Campus, which occurred within 24 hours after collection.

Microbiological, physical and chemical analyses and underground flow determination

The presence of *Escherichia coli* and total coliforms was determined by the membrane filtration method with chromogenic medium, as described by the Standard Methods for the Examination of Water and Wastewater – APHA et al. (1995).

The water temperature and electrical conductivity (EC) were measured with a conductivity meter (Amber Science, model 2052), and the potential of hydrogen (pH) was determined with a pH meter (Orion, model 250 A), in both cases *in loco*, while the turbidity was measured in the LABLIM with a bench turbidity meter (Hach, model 2100 P).

The concentrations of nutrients (ammonia, nitrite, nitrate, dissolved and total phosphorus) were measured by the spectrophotometric method as described in APHA et al. (1995). The underground flow direction was determined and the information tallied by means of the Surf 8. 0 software, using the kriging method, which interpolates point data.

Statistical analysis

The data were submitted to principal component analysis (PCA), a multivariate method that reduces the variables into linear combinations that form components, enabling the discernment of temporal patterns (periods analyzed) and spatial patterns (among the wells). The projection of each sample in the new system of axes generated scores for organization and visualization in the form of biplots.

RESULTS

Principal component analysis (PCA)

The PCA showed that the first two axes of the quadrants analyzed were responsible for explaining 42. 75% of the variance of the physical, chemical and microbiological data in Nova Londrina (Figure 1).

The values reported in Table 1 allow understanding the importance of each variable in the construction of the components. The highest contribution values occurred for the variables TDS, TC and *E. coli* for axis 1 (0. 839, 0. 804 and 0. 646) and of the variables pH, EC and ammonia for axis 2 (0. 709, 0. 608 and 0. 568). This can also be noted from Figure 2, because the vectors that are longer and nearer the axes indicate their greater contribution.

Table 1: Contribution of the variables (loadings) in the first two axes of the principal component analysis for the physical, chemical and microbiological variables in the district of Nova Londrina

Variables	Abbreviations	Principal Components	
		Axis 1	Axis 2
Well-cesspit distance	D_WT	-0. 448	-0. 416
Temperature	T	-0. 042	-0. 263
Potential of hydrogen	pH	0. 089	**0. 709**
Electrical conductivity	EC	0. 559	**0. 608**
Total dissolved solids	TDS	**0. 839**	0. 127
Turbidity	Turb	0. 118	-0. 329
Total coliforms	TC	**0. 804**	-0. 050
Escherichia coli	*E. coli*	**0. 646**	-0. 342
Ammonia	Ammonia	-0. 345	**0. 568**
Nitrite	Nitrite	0. 475	-0. 058
Dissolved phosphorus	DP	-0. 402	0. 456

For the wells in Nova Colina, the first two axes explained 49. 56% of the total variation of the data, with EC, nitrate, total phosphorus (TP) and turbidity being the variables with the greatest contribution to the component of axis 1 (0. 815, 0. 770, 0. 730 and 0. 728), and well depth and cesspit depth, dissolved phosphorus (DP) and well-cesspit distance having the greatest contributions to axis 2 (0. 744, 0. 731, -0. 610 and 0. 598) (Figure 2; Table 2).

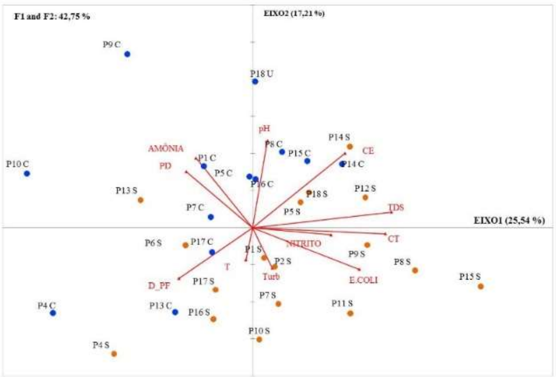

Figure 1: PCA representation of the collection points in Nova Londrina in relation to the mean values of the physical, chemical and microbiological parameters in the months denoting the dry period (September) and wet period (February).

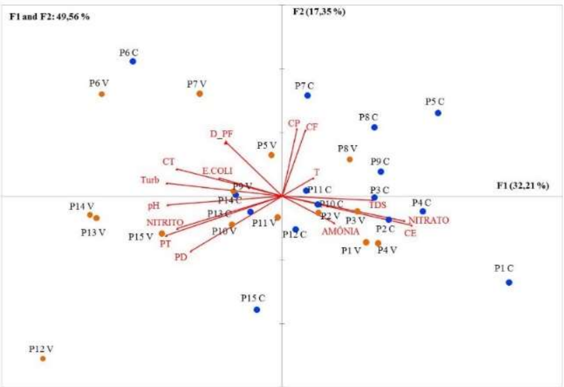

Figure 2: PCA representation of the collection points in Nova Colina in relation to the mean values of the physical, chemical and microbiological parameters in the months denoting the wet period (December) and ebb period (April).

Table 2: Contribution of the variables (loadings) in the first two axes of the principal component analysis for the physical, chemical and microbiological variables in the district of Nova Colina

Variables	**Abbreviations**	**Principal Components**	
		Axis 1	**Axis 2**
Well-cesspit distance	D_WT	-0. 354	**0. 598**
Cesspit depth	STD	0. 147	**0. 731**
Well depth	WD	0. 092	**0. 744**
Temperature	T	0. 196	0. 200
Potential of hydrogen	pH	-0. 722	-0. 096
Electrical conductivity	EC	**0. 815**	-0. 322
Total dissolved solids	TDS	0. 568	-0. 044
Turbidity	Turb	**-0. 728**	0. 143
Total coliforms	TC	-0. 665	0. 302
Eschirichia coli	*E. coli*	-0. 396	0. 200
Ammonia	Ammonia	0. 326	-0. 297
Nitrite	Nitrite	-0. 662	-0. 358
Nitrate	Nitrate	**0. 770**	-0. 273
Dissolved phosphorus	DP	-0. 575	**-0. 610**
Total phosphorus	TP	**-0. 730**	-0. 435

Underground flow direction

The predominant groundwater flow in Nova Londrina (Figures 3 (a) (b)) was in the northwest to southeast direction. No differences in this flow were observed in the months representative of the seasonal periods analyzed, as can be seen in Figures 3a and b.

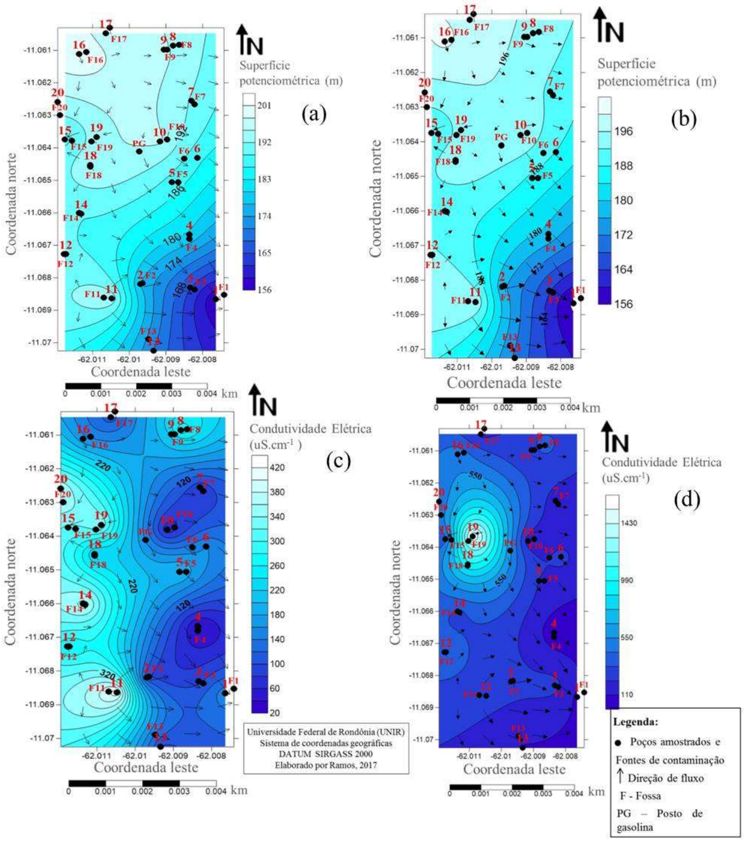

Figure 3: Flow direction maps (a) (b) and cartogram of the values of electrical conductivity (µS. cm^{-1}) (c) (d) of groundwater in the district of Nova Londrina in the dry (a) (c) and wet months (b) (d).

The cartograms (Figures 3 (c) (d) and 4) showed that among the variables that were higher than the legal limits, the highest concentrations of contaminants were concentrated in different regions in the months representing the periods analyzed.

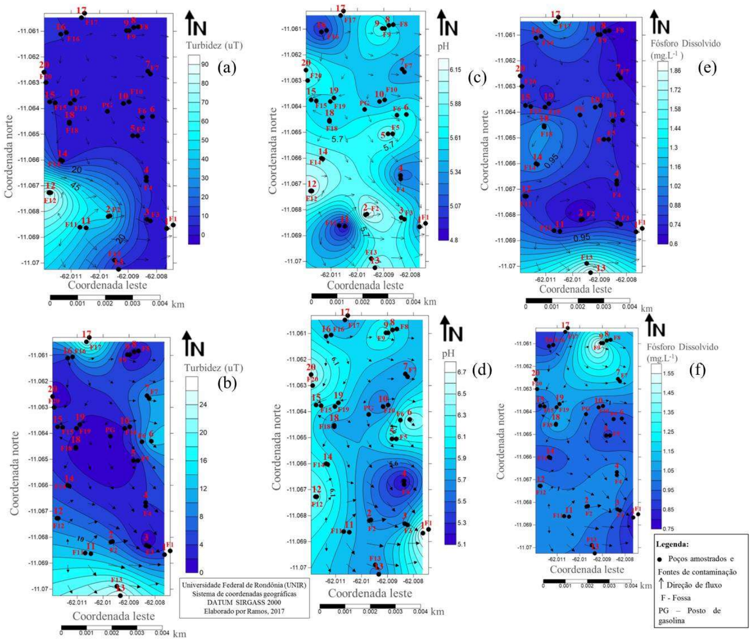

Figure 4: Cartogram of the turbidity values (uT) (a) (b), pH (c) (d) and dissolved phosphorus (e) (f) of groundwater in Nova Londrina (Ji-Paraná, RO), in the dry (a) (c) (e) and wet months (b) (d) (f).

In Nova Colina, the underground flow was predominantly from the southeast to the other regions, with wells 6, 5, 7 and 3 having divergent flows and wells 15, 4, 1 and 3 convergent flow.

As can be noted in Figures 5 (a) (b), there also were no differences in the underground flow between the months representing the periods analyzed. In turn, the cartograms (Figures 5 (c) (d), 6 and 7) indicate that for the variables that were above the legal limits, the highest contaminant values were concentrated in different regions among the months representing the periods analyzed.

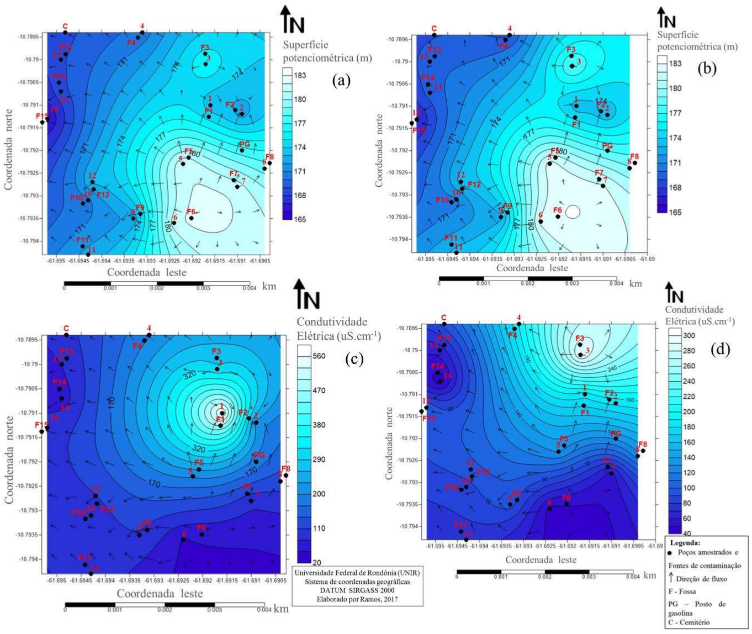

Figure 5: Flow direction maps (a) (b) and cartogram of the values of electrical conductivity (µS. cm^{-1}) (c) (d) of groundwater in the district of Nova Colina in the dry (a) (c) and ebb months (b) (d).

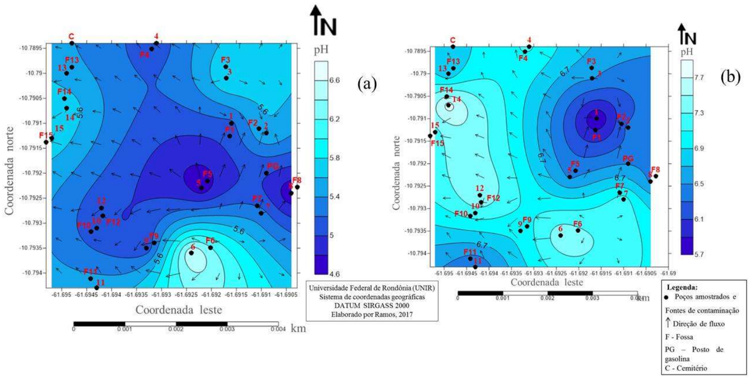

Figure 6: Cartogram of the values of pH of groundwater in Nova Colina (Ji-Paraná, RO) in the wet a (a) and ebb months (b).

DISCUSSION

Principal component analysis (PCA)

Figure 1 shows that for the groundwater in Nova Londrina there was high correlation between TC and nitrite, and also between ammonia and dissolved phosphorus (DP), because the angle between the vectors indicates stronger or weaker correlation between the variables (the smaller the angle, the stronger the correlation). The figure also shows that the variables ammonia and DP were influenced by pH and had strong correlations with the EC values.

The grouping of the variables *E. coli*, TC, nitrite and turbidity indicates that the contamination by particles and organic load were more strongly correlated in the dry month in wells 1, 2, 7 to 11 and 15, attributed to the greater concentration due to the reduced water level. An opposite process occurred for ammonia and DP, which were higher in the wet month in wells 1, 5, 7, 9 and 10. This can be related to the higher entry of organic pollutants in the wet period.

Investigating the correlation between water quality variables, Moura et al. (2015) found that the concentrations of nitrate in groundwater in rural areas of the municipality of São José do Rio Preto (state of São Paulo) were strongly correlated with the levels of bicarbonate ions originating from degradation of organic matter as well as dissolution of carbonates and feldspars.

Menezes et al. (2014), studying groundwater in the municipality of Alegre, Espírito Santo, found a significant correlation between pH and Ca^{+2} (r= 0. 48) and also between Ca^{+2}, TDS and Na^{+}, and deduced that for the majority of the groundwater samples, these parameters originated from a common source, implying the sharing of similar release mechanisms, possibly related to rock weathering.

Nunes et al. (2012), studying groundwater in an area near a truck farm in Ji-Paraná, found that seasonality had little influence on this parameter (pH), as also found in our study (see the points that were influenced by the variable in Figure 1). Meschede et al. (2018) also did not observe the influence of seasonality on the pH values of groundwater in the region of Santarém, Pará.

The pH level of the water samples from Nova Colina can be related both to the characteristics of the region's soil and also the intense microbial activity, which was not observed in the water samples from Nova Londrina, as shown by Figure 2 by the almost right angles between pH on the one hand and *E. coli* and TC on the other.

Figure 2 shows a high correlation between several variables of the water samples from Nova Colina, in particular the strong correlation of EC, nitrate and ammonia, indicating that the EC values of the groundwater in Nova Colina are influenced by the concentrations of these important nutrients, suggestive of contamination by organic loads.

Direction of groundwater flow

Figure 3s (a) (b) show that wells 11 and 16 had divergent flow direction, making them less susceptible to contamination from the other wells. However, observance of well 11 (W11) and cesspit 11 (C11) indicated a possible converging flow from the tank to the well, unlike the case of C16 and W16.

Another important observation is that wells 1 and 15 had converging flows, with medium to high vulnerability to contamination from other wells and cesspit. In this respect, Duarte et al. (2016), analyzing the vulnerability of aquifers in the municipality of Humaitá, Amazonas, found that the flow behavior occurred from the area with high vulnerability to areas with medium and low vulnerability to contamination. This is a worrying situation, since contamination of the aquifer can degrade the quality of the urban water supply.

Figures 3 (c) (d)) indicate the existence of a contamination plume based on the parameter EC. The highest values of this parameter were found in wells 11, 14 and 2, suggesting the plume converges to the southeastern region of the map. This was expected due to the groundwater flow represented by the potentiometric surface. However, since well 19 has tubular characteristic, we suggest that the high EC values of the groundwater feeding well 19 are due to the soil characteristics.

The contamination plume observed based on the turbidity (Figures 4 (a) (b)) reveals the movement of particles according to the underground flow direction, with possible influence of well 11, with formation of a central area free from this influence due to the characteristic of the flow direction (Figures 3 (a) (b)).

The PCA was more secure regarding the variation of pH between the periods (Figures 4 (c) (d)), indicating the alteration of this variable is related to contamination by organic matter due to the intense microbiological activity, because the lowest pH values occurred in widely scattered spots, following the underground flow direction in the months analyzed.

There were high concentrations of DP (>0. 02 mg. L^{-1}) throughout the Nova Londrina region, mainly due to contamination by domestic sewage. The highest concentrations occurred at scattered points, as can be observed in Figures 4 (e) (f). Because of particular contamination by phosphorus, well 13 might have been subject to the influence of the high potentiometry of well 11, and wells 8 and 9 might have felt the influence of the use of manure and synthetic fertilizers by farmers in the northern region (rural area), not represented on the cartogram.

It is important to mention that cesspit C6, C2, C14, C12 and C9 are located in areas where the underground flow converges to wells W6, W2, W15, W10 and W9, respectively.

In the region where a cemetery is located, the flow was found to converge from other regions, while in the region where a filling station is located (FS), the flow diverged from the station to well 2.

The EC values in the groundwater of Nova Colina followed the flow direction (Figures 5 (c) (d)), but the highest values were found in the northeastern region in both periods analyzed. The same was observed in the cartogram for $N\text{-}NO_3^-$ (Figures 6 (a) (b)). In the wet month, this concentration occurred in the region with low potentiometry (point of lowest potentiometric surface), while in the ebb month it happened in at the region with high potentiometry (point of highest potentiometric surface), indicating a strong influence of the cesspit at point 3 on the contamination plume under analysis.

Figures 6 (c) (d) indicate that the highest turbidity values were concentrated in the southeastern region (region with high potentiometric surface) and northwestern region (region with low potentiometric surface) in the wet and ebb periods, indicating that the contaminants that increase the turbidity are continuously introduced in the groundwater, as revealed by the PCA, be it by dropping of solid materials into the wells or by the wells' shallow characteristic.

The lowest pH values were concentrated in the center-east and eastern regions in the wet month and in the northeastern and southeastern regions in the ebb month. These were the regions with the highest levels of $N\text{-}NO^-_3$.

Based on the principal component analysis and the groundwater flow direction, supported by the cartograms of the most important variables, it is unquestionable that the groundwater in the districts of Nova Londrina and Nova Colina is being degraded by the entry of domestic sewage, with other factors contributing to this contamination being the wells' characteristics and the farming and livestock breeding activities at specific points.

Piga et al. (2017) also concluded that the contamination of the groundwater observed in the municipality of Araras, São Paulo, was associated with subpar well construction and management, associated with highly urbanized surrounding areas.

In the case of the groundwater in Nova Londrina and Nova Colina, we cannot exclude the possible influence of other factors, such as soil characteristics, mobility of elements in the water, and previous land use and occupation of the area.

Besides explaining the characteristics of contamination plumes, the flow direction can also contribute to the definition of recharge zones (ARÉVALO et al., 2013).

Some concentrations could not be explained by the flow direction and the PCA results, both for Nova Londrina and Nova Colina. These discrepancies can be related to the occurrence of reverse flows due to unequal distribution of wells and concentration of wells as certain points, as observed by Oliveira et al. (2019).

CONCLUSIONS

The results showed that the groundwater in the districts of Nova Londrina and Nova Colina suffers contamination by organic matter, mainly domestic sewage (fecal matter), making it unfit for human consumption without treatment. The variables that were in violation of the standards for potability were turbidity, pH and microbiological variables in both districts, along with dissolved phosphorus in Nova Londrina and nitrate in Nova Colina.

The underground flow was found to occur predominantly in the northwest to southeast direction (Nova Londrina) and southeast to the other regions (Nova Colina), indicating that cesspit were the main source of contamination, along with the entry of rainwater, facilitated by the characteristics of the wells, such as the covers and lining, and contamination related to the land use and occupation of surroundings, observed in a few cases.

The principal component analysis provided a better understanding of the effects of the variables on the quality of the groundwater in Nova Londrina and Nova Colina. These results along with the cartograms were sufficient to achieve the objectives of this study.

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