

Spatiotemporal mapping and statistical analysis of the raw water quality exploited from tube wells in a karst region in southern Brazil

Mapeo espacio-temporal y análisis estadístico de la calidad del agua bruta explotada a partir de pozos tubulares en una región cárstica del sur de Brasil

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ABSTRACT

Monitoring the drinking water quality in alternative water supply systems is extremely important, as untreated water can contain many contaminants. This study used secondary data, from 2016 to 2021 of nine tube wells in an urban area over the karst region of Ponta Grossa, a city in southern Brazil. The statistical analysis of the raw water quality parameters evaluated, such as total coliforms (TC), *Escherichia coli*, turbidity, and fluoride indicated that 35 % of the samples were non-potable. A variable spatial distribution was identified between the years, mainly because of the higher contamination rates of the raw water samples related to the microbiological parameters. The analysis evidenced a correlation between rainfall and the parameters of TC ($p = 0.002$) and *Escherichia coli* ($p = 0.037$). Some wells were identified as vulnerable, particularly after rainfall, increasing the risk of underground water contamination and becoming a critical factor in the spread of waterborne diseases.

KEYWORDS: Groundwater Quality, Microbiological Contamination, Heatmap, Human Consumption, Rainwater.

RESUMEN

Monitoreo de la calidad del agua potable en sistemas alternativos de abastecimiento es extremadamente importante, ya que el agua no tratada puede contener muchos contaminantes. Este estudio utilizó datos secundarios, de 2016 a 2021, de nueve pozos entubados en el área urbana sobre la región cárstica de Ponta Grossa, una ciudad en el sur de Brasil. El análisis estadístico de los parámetros coliformes totales (CT), *Escherichia coli*, turbidez y fluoruro, indicó que 35 % de las muestras no eran potables. Se identificó una distribución espacial variable entre los años, esto se debió principalmente a las mayores tasas de contaminación de las muestras de agua cruda relacionadas con los parámetros microbiológicos. Se evidenció una correlación entre las precipitaciones y los parámetros de CT y *Escherichia coli* ($p = 0,002$ y $0,037$). Se determinó que algunos pozos eran vulnerables, especialmente después de las lluvias, lo que aumentaba el riesgo de contaminación de las aguas subterráneas y se convertía en factores crítico de propagación de enfermedades transmitidas hídricamente.

PALABRAS CLAVE: Calidad de las aguas subterráneas, Contaminación microbiológica, Mapa de calor, Consumo humano, Agua de lluvia.

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Mapeamento espaço-temporal e análise estatística da qualidade da água bruta explorada de poços tubulares em uma região cárstica no sul do Brasil

RESUMO

O monitoramento da qualidade da água potável em sistemas alternativos de abastecimento é extremamente importante, uma vez que a água não tratada pode conter muitos contaminantes. Este estudo utilizou dados secundários, de 2016 a 2021, de nove poços tubulares em uma área urbana da região cárstica de Ponta Grossa, uma cidade no sul do Brasil. A análise estatística dos parâmetros de qualidade da água bruta avaliados, como coliformes totais (CT), *Escherichia coli*, turbidez e fluoreto, indicou que 35 % das amostras eram impróprias para consumo. Uma distribuição espacial variável foi identificada entre os anos, principalmente devido às maiores taxas de contaminação das amostras de água bruta relacionadas aos parâmetros microbiológicos. A análise evidenciou uma correlação entre a precipitação e os parâmetros de CT ($p = 0,002$) e *Escherichia coli* ($p = 0,037$). Alguns poços foram identificados como vulneráveis, particularmente após a chuva, aumentando o risco de contaminação da água subterrânea e se tornando um fator crítico na propagação de doenças veiculadas pela água.

PALAVRAS-CHAVE: Qualidade da Água Subterrânea, Contaminação Microbiológica, Mapa de Calor, Consumo Humano, Água da Chuva.

Cartographie spatiotemporelle et analyse statistique de la qualité de l'eau brute exploitée à partir de puits tubulaires dans une région karstique du sud du Brésil

RÉSUMÉ

La surveillance de la qualité de l'eau potable dans les systèmes d'approvisionnement alternatifs est extrêmement importante, car l'eau non traitée peut contenir de nombreux contaminants. Cette étude a utilisé des données secondaires, de 2016 à 2021, provenant de neuf puits tubulaires dans une zone urbaine de la région karstique de Ponta Grossa, une ville du sud du Brésil. L'analyse statistique des paramètres de qualité de l'eau brute évalués, tels que les coliformes totaux (CT), *Escherichia coli*, la turbidité et

le fluor, a indiqué que 35 % des échantillons étaient non potables. Une distribution spatiale variable a été identifiée entre les années, principalement en raison des taux de contamination plus élevés des échantillons d'eau brute liés aux paramètres microbiologiques. L'analyse a révélé une corrélation entre les précipitations et les paramètres de CT ($p = 0,002$) et *Escherichia coli* ($p = 0,037$). Certains puits ont été identifiés comme vulnérables, notamment après les pluies, augmentant le risque de contamination de l'eau souterraine et devenant un facteur critique dans la propagation des maladies d'origine hydrique.

MOTS-CLÉ: Qualité de l'Eau Souterraine, Contamination Microbiologique, Carte de Chaleur, Consommation Humaine, Eau de Pluie.

Mappatura spaziotemporale e analisi statistica della qualità dell'acqua grezza estratta da pozzi tubolari in una regione carsica nel sud del Brasile

SOMMARIO

Il monitoraggio della qualità dell'acqua potabile nei sistemi alternativi di approvvigionamento idrico è estremamente importante, poiché l'acqua non trattata può contenere numerosi contaminanti. Questo studio ha utilizzato dati secondari, dal 2016 al 2021, di nove pozzi tubolari in un'area urbana nella regione carsica di Ponta Grossa, una città del sud del Brasile. L'analisi statistica dei parametri di qualità dell'acqua grezza valutati, come coliformi totali (CT), *Escherichia coli*, torbidità e fluoro, ha indicato che il 35 % dei campioni era non potabile. È stata identificata una distribuzione spaziale variabile tra gli anni, principalmente a causa delle maggiori percentuali di contaminazione dei campioni di acqua grezza relative ai parametri microbiologici. L'analisi ha evidenziato una correlazione tra le precipitazioni e i parametri di CT ($p = 0,002$) ed *Escherichia coli* ($p = 0,037$). Alcuni pozzi sono stati identificati come vulnerabili, in particolare dopo le piogge, aumentando il rischio di contaminazione dell'acqua sotterranea e diventando un fattore critico nella diffusione di malattie trasmesse dall'acqua.

PAROLE CHIAVE: Qualità dell'Acqua Sotterranea, Contaminazione Microbiologica, Mappa di Calore, Consumo Umano, Acqua Piovana.

Introduction

Public water supply, in terms of quantity and quality, is a growing concern for humankind¹. Due to population growth, intensive economic activities, and periods of scarcity, the demand for water per inhabitant is greater than the supply capacity, thus causing the need for alternative sources².

In recent years, severe droughts in Brazil have caused water crises that compromised the water supply to the population, due to the low levels in reservoirs³. As a result, researchers from the Geological Survey of Brazil have suggested the use of groundwater as a more viable alternative, due to its high availability and low cost⁴. As the demand for alternative water solutions increased substantially, the wells granted in Paraná State quadrupled between 2017 and 2018⁵. Therefore, the monitoring of quality indices for consumption is of vital importance, as the lack of care in the protection of wells is a common practice, which enables contamination of aquifers by sources from anthropic activities⁶.

Soil can retain chemical and microbiological contaminants by acting as a natural filter. This happens through mechanisms like adsorption and chemical degradation of pollutants. However, not all of these mechanisms are equally effective at removing contaminants. This makes certain aquifers, especially those in places with highly fractured consolidated rocks or high porosity and permeability, particularly vulnerable to pollution⁷.

The karst groundwater resources are particularly vulnerable to contamination⁸. The city of Ponta Grossa is located in the sandstone region of the Furnas Formation. This area exhibits typical dissolution features such as Furnas (dolines), humid and dry depressions, caves, sinkholes, and water upwellings, indicating the presence of a karst region developed in non-carbonate rocks of the Furnas Formation⁹. This means that chemical and microbial contaminants can easily enter the subsurface and spread rapidly in the pipeline network without sufficient soil attenuation,

mainly due to conflicts of land use and occupation with disordered urban growth in environmentally vulnerable areas¹⁰.

Notably, monitoring and controlling groundwater quality often present difficulties, especially in individual sources that include springheads, wells, or fountains. Such challenges derive from the priority given to monitoring conventional water supply systems, which occurs through distribution networks, the main procedure of urban supply in Brazil¹¹.

In accordance, microbiological and physicochemical monitoring of water quality is a crucial tool to indicate the tendency and priority areas for water pollution control. Several studies¹² have evaluated the parameters of water quality from wells. In 2005 the Brazilian Ministry of Health created the Human Drinking Water Quality Surveillance Program (VIGIAGUA) to monitor microbiological and physicochemical parameters of drinking water in standard supply and alternative modalities. However, long-term analysis is still incipient in Brazil.

Considering these issues, the approach of temporal analysis aims to determine potential changes in the parameters over an extended period and then identify variations in groundwater contamination levels. The study can help assess the risk associated with drinking water quality by analyzing geospatial data. This can aid public authorities in making informed decisions, especially since there is a lack of specific studies on the water quality from tube wells in the region. The objective of this study is to present the spatial and temporal changes in the raw water quality used for drinking. The data used for the analysis consists of 296 water samples collected from nine private tube wells within a karst system (Furnas Formation) in Ponta Grossa, Paraná. The data covers the period from 2016 to 2021.

Materials and methods

Study Area

The area is located in the city of Ponta Grossa, in the Central-Eastern Region of the State of Paraná, in Brazil (Figure 1), situated in Zone 22S between the UTM

¹ UNESCO, 2022.

² Brasil, 2006. Brasil, 2018.

³ Ferrari; Signor, 2023, 8.

⁴ IAT, 2021. Hirata et al., 2019.

⁵ Paraná, 2020a.

⁶ Pitkänen et al., 2010. Almeida et al., 2019. Hoaghia et al., 2021. Jeranoski; Wiecheteck, 2024. Silva; Peixoto, 2024.

⁷ Freeze; Cherry, 2017. Ravbar et al., 2023.

⁸ Goldscheider et al., 2020. Hoaghia et al., 2021.

⁹ Melo et al., 2011. Melo et al., 2015. Pontes et al., 2021.

¹⁰ González et al., 2022.

¹¹ Queiroz et al., 2012. Mata et al., 2022.

¹² Silva; Da Hora; Oliveira, 2017. Laureano et al., 2020. Moreira; Kopp; Nardoci, 2021.

Figure 1. Location of the city of Ponta Grossa in the state of Paraná



Source: Own elaboration based on Melo et al., 2011 (modified).

-SIRGAS2000 coordinates E: 584866.95 and N: 7223778.6. It has a subtropical, humid climate, classified by Köppen as Cfb¹³, with an average annual precipitation of 1,480 mm (2016-2021)¹⁴. Additionally, there is a noticeable trend of urban growth over the karst system of the Furnas Formation¹⁵.

Data Collection

Initially, we collected the analytical data from all the alternative water supply systems in Ponta Grossa registered in the VIGIAGUA program and available on the Brazilian Open Data Portal, specifically in the Basic Surveillance Parameters section. After that, we selected nine tube wells with reliable and consistent data, including more than three samples each year from 2016 to 2021, to improve accuracy and dependability. We disregarded the 2020 data because of the COVID-19 pandemic, which resulted in a lack of representative analyses.

After identifying the wells with the most significant sampling numbers, we conducted a specific breakdown of elements using the LibreOffice Calc software. The data available were sorted into categories including the well name, location, collection date, and the values of total coliforms (TC), *Escherichia coli* (*E. coli*), turbidity, and fluoride.

Microbiological and physical-chemical analysis

The Brazilian National Guideline for Water Sampling Plan¹⁶ defines the parameters studied. TC, *E. coli*, and turbidity were selected due to their importance as basic indicators of the microbiological drinking water quality. In addition, fluoride was chosen because its deficiency or excess is an evaluative parameter of public health, as defined in the Brazilian Basic Sampling Plan.

We acquired the data from the local Brazilian Health and Sanitary Surveillance, as displayed on the Brazilian Ministry of Health website. This data comes from samples of raw water collected from regularly monitored

¹³ Maack, 2012.

¹⁴ IAT, 2023.

¹⁵ Melo et al., 2011. Pontes et al., 2021.

¹⁶ Brasil, 2016.

wells. To collect and preserve the samples, the health surveillance technicians followed the standard operating procedures recommended in the Standard Methods for the Examination of Water and Wastewater¹⁷, as outlined in the Guide to Drinking Water Sample Collection of Paraná¹⁸.

As a standard procedure, the health surveillance technicians routinely collected two samples from each tube well at the surface taps, using sterile vials. This is done to ensure the elimination of any impurities or contaminants that could affect the analysis results. We used a 100 mL flask for microbiological analyses (TC and *E. coli*) and a 200 mL flask for physical-chemical parameters (turbidity and fluoride). The collected water samples were analyzed also in accordance with the Standard Methods at the Water Resources Laboratory of the State University of Ponta Grossa using the Enzyme Substrate Test: 9223-B for microbiological analysis, Nephelometric method: 2130-B for turbidity and Colorimetric Method SPADNS: 4500-F-D for fluoride.

Vulnerability Mapping

To accurately locate the tube wells used for human consumption, we used a Garmin GPS model 10X to georeference each tube well. We also conducted interviews and gathered data from the owners and/or technical managers of the wells to identify and describe the types of use and activities at the establishments where the wells are installed. Additionally, we estimated the depth of the wells and the number of people they serve.

We used the QGIS 3.16.13 software to interpolate the quantitative data using the Kernel density estimator. Kernel interpolation is a method for estimating the intensity of a phenomenon by an area value, using a radius of influence that defines the neighborhood of the point to be interpolated and an estimation function with "convenient" phenomenon smoothing properties¹⁹.

In the QGIS 3.16.13 software, the "Distance Matrix" algorithm is utilized to compute the mean distance, standard deviation, as well as the minimum and maximum distance from each well. These values are used to determine the final radius value. We used the quartic function, Equation 1, for the estimation function. In this function, the computation of the weights depends

on the distance - close wells have greater weight than distant wells, but the decrease is gradual. The interpolation function (h) is given as a function of the Euclidean distance (R) between the point located and the observed event.

$$h(R) = \left(\frac{3}{\pi}\right) * (1 - R^2)^2 \quad (1)$$

After specifying the radius and selecting the function, we generated the Kernel density maps (heatmaps) by averaging the parameter values from 2016 to 2021 using the "Heat Map (Kernel Density Estimation)" algorithm in QGIS 3.16.13 software. Therefore, it is essential to assess the intensity of the results from their close values, as the values from distant points. To facilitate the identification of concentration regions for the parameters, we reclassified the resulting raster into distinct concentration classes: very low (blue), low (green), medium (yellow), high (orange), and very high (red).

Statistical Analysis

Because the data are environmental, independent, and random, we converted the results from total coliforms and *E. coli* to a common logarithm. This transformation (CFU/100mL to log CFU/100mL) provides higher precision in the statistical analyses, a higher coefficient of determination, a lower coefficient of variation, and lower standard errors.

The Shapiro-Wilk normality test determines that the concentrations of the raw water quality parameters do not have a normal distribution ($p < 0.001$) due to their high seasonal variability. In this study, we performed the statistical analysis using descriptive analysis and the Kruskal-Wallis H test for non-parametric data with more than three groups to assess the variability of the results from 2016 to 2021. In the analyses indicating the presence of significant differences ($p \leq 0.05$), we performed the multiple comparisons in pairs (Dwass-Steel-Critchlow-Fligner test), with a 5 % probability for comparison of the average, using the Jamovi software v2.2.5.

We performed Spearman's rank correlation matrix at a 5 % probability level to determine the correlation between the parameters. The correlation coefficients were evaluated according to the hierarchy²⁰ and defined

¹⁷ Baird, Eaton, Rice, Bridgewater, 2017.

¹⁸ Paraná, 2020b.

¹⁹ Câmara; Carvalho, 2004. Victoriano, 2020.

²⁰ Baba et al., 2014.

them as: 0.00 to 0.19 = very weak, 0.20 to 0.39 = weak, 0.40 to 0.69 = moderate, 0.70 to 0.89 = strong, and 0.90 to 1.00 = very strong. In addition, we quantified the rainfall volume from the data collected in the 48 hours before all sampling, combined with the environmental data from the HIS (Hydrological Information System) of the Itaiacoca meteorological station - code 2549052²¹. Similarly, we assessed the correlation between the microbiological and physical-chemical data and the tabulated precipitation volume using Spearman's coefficient.

Results and discussion

Table 1 demonstrates the qualitative data of the tube wells, including the geographic coordinates, the main activity where the wells are located, estimated depth, and the number of people who use water from the wells. Figure 2 indicates the spatial distribution of the wells within the urban perimeter of Ponta Grossa.

Interviews with the people in charge of the sites offered the estimated depth data and the number of people who use water from the wells. Scattered throughout the city's urban area, the wells range in depth from 30 to 220 meters, although there is no information about the depth of exploitation of P2 and P9. The tube wells P2, P5, and P6 are the most significant, as they supply a greater number of people, providing water to more than 3,100 consumers. Due to the majority of wells

being commercial or customer-service establishments where there is variation in the number of people in these locations during weekends or holidays, the number of water consumers can vary daily.

Statistical Analysis

We obtained descriptive statistics for the parameters analyzed in each well, including the minimum, maximum, median, first, and third quartiles (Table 2). Additionally, we determined the statistical variances between the wells for each parameter.

Individually the microbiological parameters presented the highest percentage of samples outside the potability standards, at 34 % for TC and 7 % for *E. coli*. The presence of these microorganisms in raw water may cause waterborne diseases in humans²². The other parameters were also analyzed individually, as for the turbidity and fluoride parameters, 99 % of the samples were within the maximum permitted value (MPV) according to the Brazilian Potability Standard - Portaria MS 888/2021²³, indicating that the physical-chemical parameters evaluated have no direct effect on water quality, thereby being virtually harmless to consumers.

Statistically significant differences among each well ($p < 0.05$) were obtained for log values of TC (CFU/100mL) and *E. coli* (CFU/100mL). As shown in Figure 3, it is possible to identify the clusters indicated by the DSCF test with 95 % confidence.

Table 1. General data of tube wells

WELL	COORDINATES (UTM) X Y		MAIN ACTIVITY	ESTIMATED DEPTH (M)	ESTIMATED NUMBER OF WATER CONSUMERS
P1	586968,2	7225396,1	Sports Club	220	315
P2	588991,2	7224219,1	Education	*NI	1000
P3	584646	7224947,6	Residential Building	130	36
P4	583571,5	7224642,4	Supermarket	60	221
P5	583118,1	7225254,8	Hospital	180	783
P6	588069	7223554,8	Hospital	150	368
P7	586497,5	7220657,7	Education/Dorms	30	290
P8	580823,3	7223603,2	Gas Station	145	42
P9	584088,1	7222128,8	Education	*NI	78

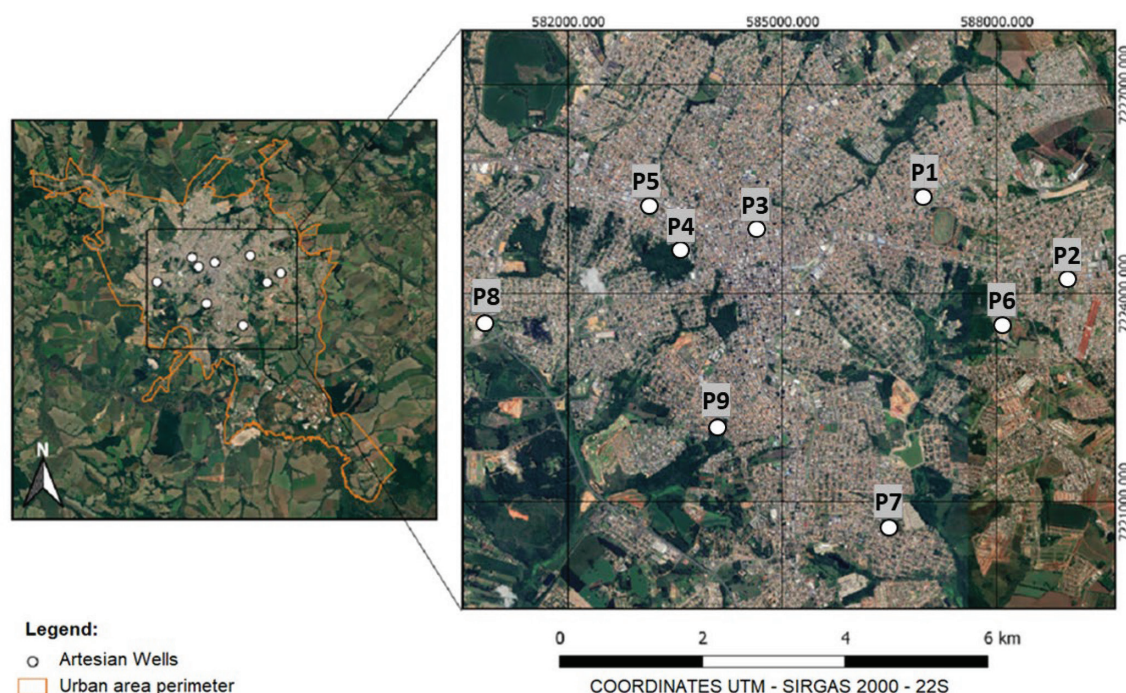
Note: *NI = No Information.

Source: Own elaboration.

²¹ IAT, 2023.

²² Ahmad et al., 2020. WHO, 2017. Ravbar et al., 2023.

²³ Brasil, 2021.

Figure 2. Location of the city of Ponta Grossa in the state of Paraná

Source: Own elaboration.

The statistical analyses showed a high variability of TC distribution classes in all wells, and P8 presented the highest median value (48 CFU/100mL). However, P1, P4, and P7 had at least one analysis above the detection limit of the analysis method (2,398 CFU/100mL); only P4 was classified as an outlier. Furthermore, P6 and P9 complied with the potability standard in 100 % of the analyses.

Other studies²⁴ indicated the presence of TC in more than 30 % of groundwater samples from tube wells in the state of Paraná, which points to the vulnerability of groundwater in different locations in the state, highlighting the problems faced.

When identifying the presence of outliers in the tube wells, it may seem that some values are discordant with the group. As they are real environmental data, their results are highly variable. P3 and P8 had remarkable results, exhibiting high maximum values, 234 and 209 CFU/100mL, respectively. Although only 3 % of P3 diverged from the drinking water standards, 29 % of samples from P8 showed the presence of *E. coli*, particularly due to structural issues of the tube well and lack of maintenance²⁵, categorizing it as a high sanitary risk point. The P5, P6, and P9 presented water quality

compatible with the Brazilian drinking water standards in 100 % of the analyses.

It was identified statistically significant differences in the wells ($p < 0.05$) for turbidity and fluoride. As shown in Figure 4, it is possible to identify the clusters indicated by the DSCF post hoc tests, with 95 % confidence.

Figure 4 shows that only P5 had samples above the MPV for turbidity although the distribution of samples in P5 was statistically equal to the other wells. As this is a particular case, its samples were above the maximum value allowed for the experiment. Considering that all average turbidity values are below 0.465 NTU (P7), we delimited the two samplings above the MPV as outliers as they did not significantly interfere with the quality of the raw water for human consumption of P5 over the years. Despite the Kruskal-Wallis H test indicating statistical differences in the wells, all the medians of the distribution values are less than 5 NTU (MPV), complying with the standards for drinking water established by Ministerial Ordinance GM/MS 888/2021²⁶. P3 and P4 presented the lowest average of turbidity, 0.21 NTU and 0.18 NTU, respectively.

As previously stated, many values appear as outliers as well. Data such as these are often important because

²⁴ Vicente et al., 2021. Blanc et al., 2019.²⁵ Jeranoski; Wiecheteck, 2024.²⁶ Brasil, 2021.

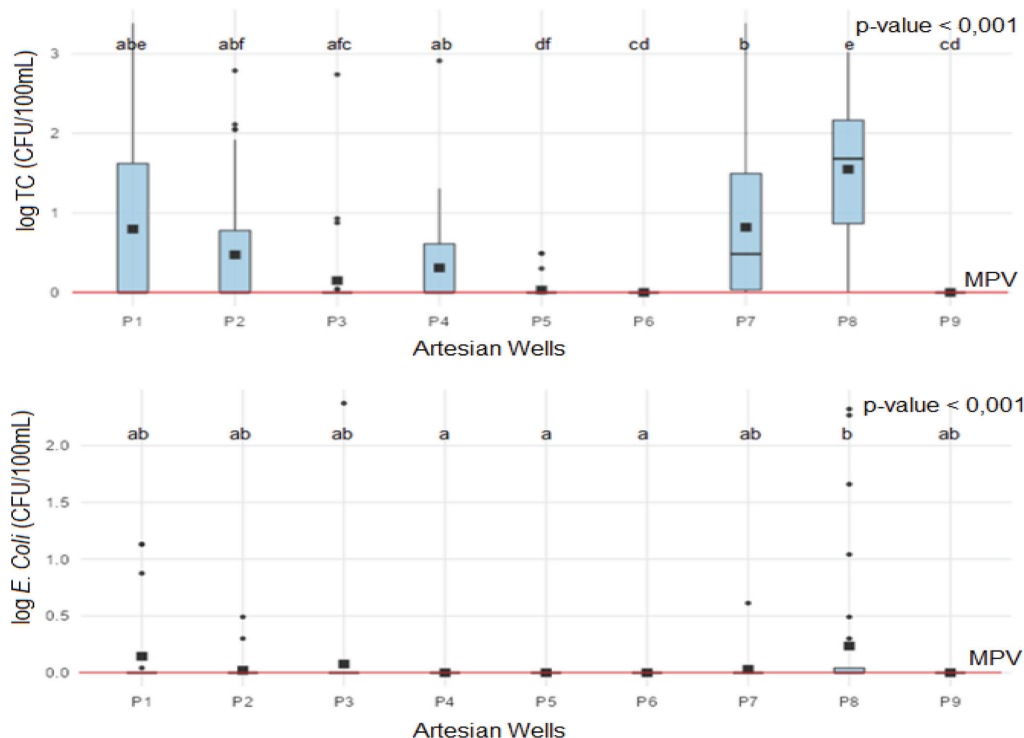
Table 2. Descriptive statistics of physical-chemical and microbiological parameters

Well	N	Parameter	Minimum	Maximum	Median	1° Quartile	3° Quartile
P1	22	Turbidity	0.08	1.30	0.24	0.17	0.36
		Fluoride	0.00	0.60	0.14	0.00	0.24
		log TC	0.00	3.38	0.00	0.00	1.62
		log E.coli	0.00	1.13	0.00	0.00	0.00
P2	38	Turbidity	0.08	1.44	0.27	0.17	0.27
		Fluoride	0.00	1.73	0.31	0.03	0.31
		log TC	0.00	2.79	0.00	0.00	0.00
		log E.coli	0.00	0.49	0.00	0.00	0.00
P3	31	Turbidity	0.09	0.71	0.21	0.15	0.33
		Fluoride	0.00	0.79	0.04	0.00	0.15
		log TC	0.00	2.74	0.00	0.00	0.00
		log E.coli	0.00	2.37	0.00	0.00	0.00
P4	46	Turbidity	0.07	1.30	0.18	0.15	0.28
		Fluoride	0.00	0.60	0.00	0.00	0.17
		log TC	0.00	3.38	0.00	0.00	0.61
		log E.coli	0.00	1.13	0.00	0.00	0.00
P5	43	Turbidity	0.08	9.98	0.25	0.15	0.46
		Fluoride	0.00	0.38	0.10	0.00	0.17
		log TC	0.00	0.49	0.00	0.00	0.00
		log E.coli	0.00	0.00	0.00	0.00	0.00
P6	39	Turbidity	0.11	1.96	0.35	0.20	1.12
		Fluoride	0.00	1.05	0.12	0.00	0.27
		log TC	0.00	0.00	0.00	0.00	0.00
		log E.coli	0.00	0.00	0.00	0.00	0.00
P7	24	Turbidity	0.11	2.33	0.46	0.30	0.66
		Fluoride	0.00	0.84	0.07	0.00	0.44
		log TC	0.00	3.38	0.48	0.03	1.50
		log E.coli	0.00	0.61	0.00	0.00	0.00
P8	35	Turbidity	0.08	1.30	0.23	0.17	0.33
		Fluoride	0.00	0.43	0.09	0.00	0.16
		log TC	0.00	3.02	1.68	0.86	2.17
		log E.coli	0.00	2.32	0.00	0.00	0.04
P9	18	Turbidity	0.11	1.02	0.19	0.15	0.39
		Fluoride	0.00	0.26	0.00	0.00	0.13
		log TC	0.00	0.00	0.00	0.00	0.00
		log E.coli	0.00	0.00	0.00	0.00	0.00

Note: TC = Total coliforms (CFU/100 mL); *E. coli* = *Escherichia coli* (CFU/100 mL); Turbidity (NTU).

Source: Own elaboration.

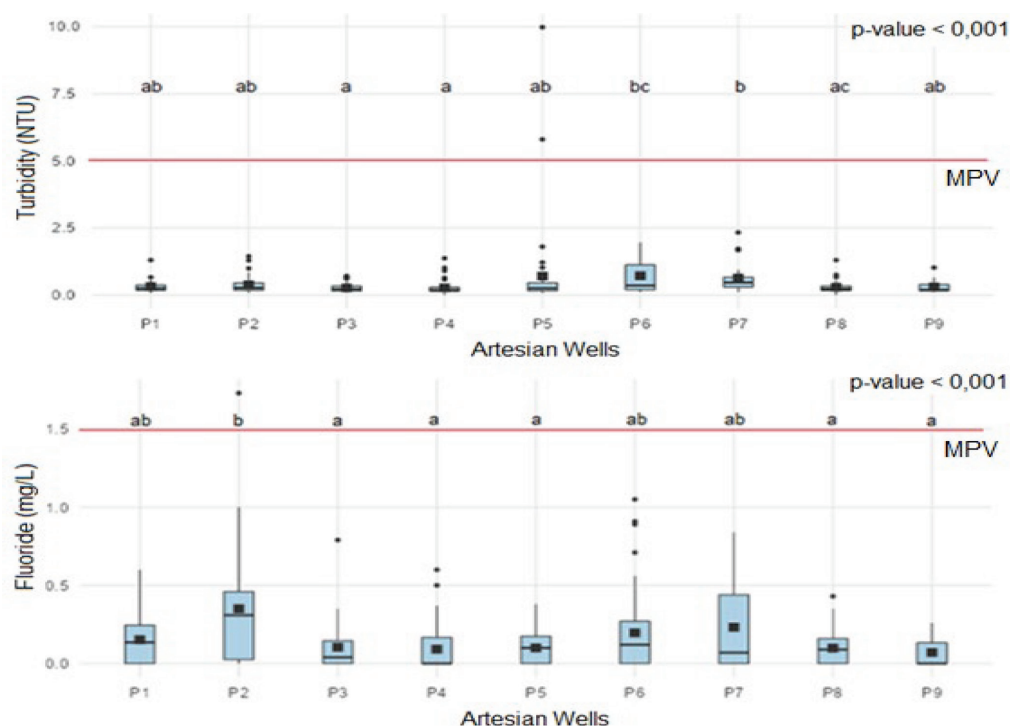
Figure 3. Statistical difference of the parameter distributions for TC and *E. coli* in the tube wells (Kruskal-Wallis H-test, N = 296)



Note: Wells with distributions labeled with the same letter do not differ statistically from each other by DSCF post-hoc tests at 5 %.

Source: Own elaboration.

Figure 4. Statistical difference of distributions for turbidity and fluoride in the tube wells (Kruskal-Wallis H-test, N = 296)



Note: Wells with distributions labeled with the same letter do not differ statistically from each other by DSCF post-hoc tests at 5 %.

Source: Own elaboration, 2024.

they represent independent values that may indicate risk factors. Regarding the water quality, data considered to be an outlier by the detection methodologies normally applied does not always mean an error or an anomaly²⁷. It is possible that the two outliers in our study were caused by abnormal behavior, such as unusual rainfall, typing errors, or unsanitary conditions.

Furthermore, further studies reported turbidity in water samples from tubular wells ranging from 0.57 to 2.31 NTU, below 5 NTU which is the MPV for drinking water²⁸. Their conclusion corroborates with previous works conducted in Brazil²⁹. In addition, considerably low turbidity values guarantee a clear appearance in the exploited water, encouraging the indiscriminate consumption of untreated raw water, even though it may seem visually suitable for drinking.

Nonetheless, translucent water does not assure its drinkability, because microorganisms are not visible to the naked eye. As a result, diarrhea and other waterborne diseases may occur from the consumption of untreated or even incorrectly handled water³⁰. Despite the high levels of compliance with the turbidity standard, it is essential to disinfect raw water with specific treatments before consumption, at least filtration and disinfection.

Figure 4 shows the outliers for fluoride, such as in P2 with a concentration of 1.73 mg/L, which exceeded the MPV of 1.5 mg/L established by the Brazilian legislation. Although P2 had the same data variation as P1, P6, and P7, it differed statistically from P3, P4, P5, P8, and

P9, suggesting that there is an impact on the drinking water quality.

Fluoride is predominantly used in the preventive and therapeutic action of dental caries. However, its concentration above the MPV may cause dental fluorosis, aesthetic problems, cancer and bone fractures³¹. Fluoride is typically found in groundwater due to the decomposition of rocks and soil, in addition to surface runoff and infiltration of fertilizers in agricultural areas or industrial wastewater³².

However, the urban region of Ponta Grossa does not present high concentrations of fluoride in natural groundwater sources. Fluoride concentrations in exploited groundwater are not affected by contamination from fertilizers and industrial effluents. In this work, the raw water was by the potability standards and, consequently, does not represent risks of dental fluorosis for the consumers.

Data Correlation

Table 3 shows the results obtained from Spearman's correlation matrix through the mean values of the water parameters analyzed from the wells. The correlation was done with the results of each parameter individually and the precipitation in the last 48 hours before the water samples collection.

Values of TC and *E. coli* ($p = 0.037$ and 0.002), with coefficients of 0.10 and 0.16 respectively, are related

Table 3. Spearman one-tailed correlation matrix of the studied parameters and precipitation volume

Correlation Matrix	Rainfall (48h)	log <i>E. coli</i>	log TC	Turbidity	Fluoride
Rainfall (48h)	-				
log <i>E. coli</i>	0.16 $p = 0.002^*$	-			
log TC	0.10 $p = 0.037^*$	0.46 $p < 0.001^*$	-		
Turbidity	-0.03 $p = 0.687$	0.05 $p = 0.205$	0.00 $p = 0.492$	-	
Fluoride	-0.10 $p = 0.954$	-0.16 $p = 0.997$	0.03 $p = 0.312$	0.09 $p = 0.059$	-

Note: Precipitation (mm/48h); TC = Total coliforms (CFU/100 mL); *E. coli* = *Escherichia coli* (CFU/100 mL); Turbidity (NTU); Fluoride (mg/L); *: significant value.

²⁷ Nascimento et al., 2021.

²⁸ Boadi et al., 2020.

²⁹ Daronco et al., 2024. Andrade et al., 2020.

³⁰ Brasil, 2006. WHO, 2017.

³¹ Frazão et al., 2011.

³² Ahmad et al., 2020.

to the rainfall, 48 hours before the water samples collection. Despite showing low levels of correlation, this result converges with other studies that have presented an interaction between the microbiological raw water quality and rainfall volumes. Furthermore, a moderate positive correlation (coefficient of 0.46) was obtained between the microbiological parameters, which indicates accurate results, as fecal coliforms (*E. coli*) are a directly related subgroup of TC³³.

Cumulative rainfall showed a significant association ($p < 0.05$) with both concentrations of *E. coli* and TC contamination. As in other studies, the occurrence of rain 48 hours before water sampling increased the likelihood of thermotolerant and fecal coliform proliferation in the groundwater³⁴.

Hence, rainfall influences the vertical and horizontal flow of bacteria at the soil interface, encouraging the contamination of unprotected and vulnerable groundwater in a karst region. It indicated that microbiological contamination during rainy periods and poor sanitary conditions of the wells are interrelated. Additionally, the high permeability of the soil and the existence of openings and cavities in the soil formations increase the rate of microbiological contamination, resulting in more vulnerability of karst areas³⁵.

The urban growth of Ponta Grossa shows a tendency to expand over a karst region, accentuating the risks of contamination of the surface and underground water sources, especially given that the groundwater of some private wells is vulnerable to anthropogenic activities³⁶. A fundamental role in reducing the risk of contamination in areas of greater environmental fragility is to protect wells and regulate the sanitary conditions closely, to prevent negative impacts on the water quality. Particular attention should be paid to large-scale rainfalls and floodings, as pollutants are expected to be transported through the soil, particularly through fractures, dolines, cavities, and sinkholes, potentially contaminating groundwater used for drinking.

Spatial distribution of results

The annual average data were used to represent the spatiotemporal mapping (Figure 5). The yearly comparison for *E. coli* showed high quantities in P8 in 2016 and 2019, exceeding the value of 50 CFU/100 mL. However, P3 and P7 exceeded 10 CFU/100 mL on average. The other wells (P1, P2, P4, P5, and P6) presented an average range from 0 to 9 CFU/100 mL, where the raw water can be classified as probably safe for consumption³⁷.

We identified a spatial distribution of risk indices above 100 CFU/100mL in many wells, especially during 2016, with the worst TC results. The pattern of distribution between 2017 and 2019 does not show much variation. However, an increase in the average TC occurred in 2021, approaching the scenario presented in 2016.

We emphasize P9, placed outside the contamination range (0 CFU/100mL) during the studied period. It has presented results within the MPV established by the Brazilian legislation, thus ensuring that there is quality protection for groundwater in the covered area by that well. It is crucial to ensure hygienic practices around tube wells and protect them from anthropogenic activities to minimize contamination pathways. Comprehensive water resources management measures can be the solution to maintaining water quality, especially measures to prevent the transport of microbiological contaminants through rainfall.

Regarding the distribution of fluoride and turbidity (Figure 5), 99 % of the analyses were below the MPV, consequently, they did not generate large visual variations in the heat maps. The average concentration of fluoride did not exceed 1.0 mg/L, and we did not identify any elevated values that could pose a risk to human consumption of raw water.

There was a visual variation in fluoride levels in 2016 in almost all wells, except in the P4 and P5, which showed results below 0.1 mg/L. In previous years, spatial variations ranged between 0.1 and 0.5 mg/L.

The annual average of the parameters did not reach the critical values established by the Brazilian legislation, 5.0 NTU for turbidity and 1.5 mg/L for fluoride, at any time. The highest turbidity values are presented in 2019, with the average results close to 2 NTU in P2 and P5. However, the turbidity values did not exceed the average of 1 NTU in the other years.

³³ Brasil, 2013.

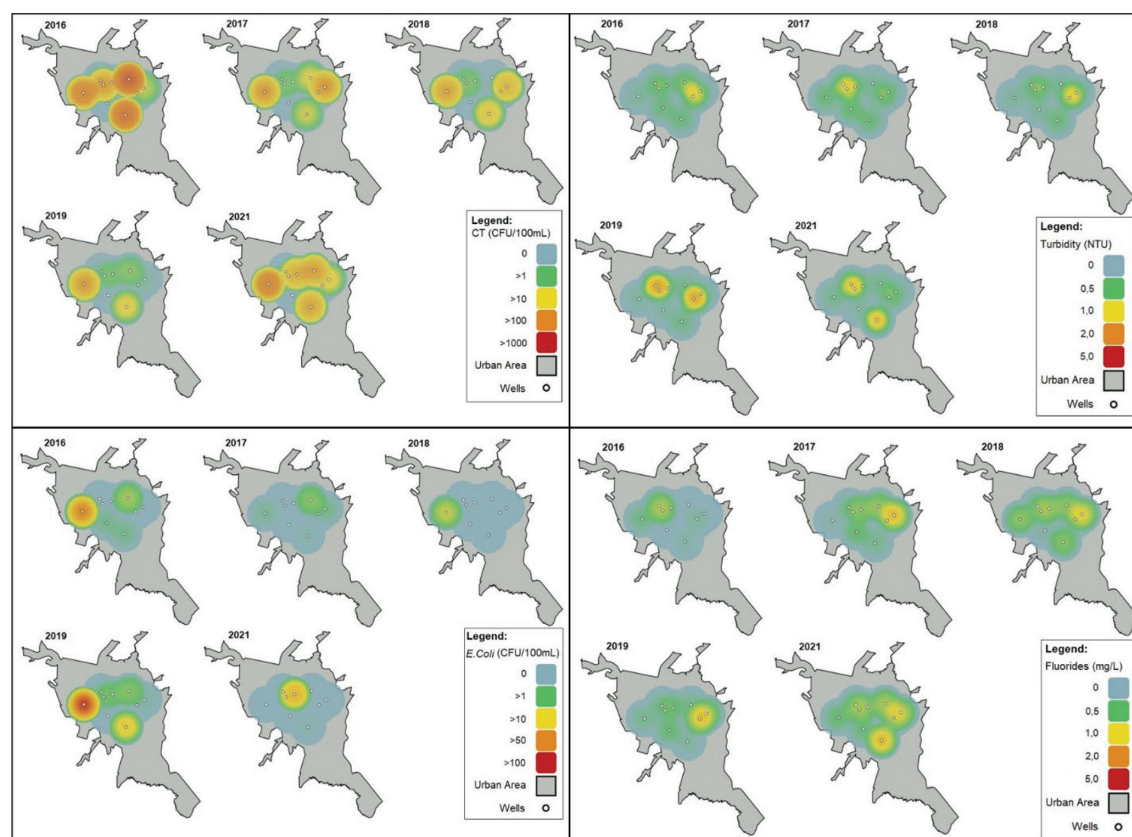
³⁴ Andrade et al., 2022, 840, 156311. Alemayehu et al., 2020, 192. Buckerfield et al., 2019, 5, 100038.

³⁵ Andrade et al., 2022, 840, 156311. Bauer et al., 2013, 85, 318–326. Ravbar et al., 2023.

³⁶ Pontes et al., 2021. Jeranoski; Wiecheteck, 2024.

³⁷ WHO, 2011.

Figure 5. Spatiotemporal mapping of the microbiological and physical-chemical water quality in the wells (2016-2021)



Source: Own elaboration, 2024.

The statistically significant temporal ($p < 0.05$) results of Spearman's correlation tests suggest that there are variations in the parameters analyzed in the tube wells over time (2016 to 2021). Additionally, P3, P5, and P9 exhibited consistent results in the four parameters during the years, with no statistically significant difference ($p > 0.05$). External land use and land cover interferences in the vicinity of the wells may not have a direct impact on the results.

Overall, the results showed that most of the wells maintained stable concentrations of the water quality parameters during the evaluated period. The greatest changes were in the fluoride concentrations, below the MPV, evident in 6 of the 9 wells. For turbidity, TC, and *E. coli*, statistical differences occurred in only 1 of the 9 wells.

Although the results of TC and *E. coli* did not vary significantly in this study, 35 % did not meet the MPV defined by the Brazilian Legislation. Furthermore, specific environmental interferences, such as occasional rainfall or infiltration, may lead to changes in concentrations that are not primarily driven by

seasonality³⁸. This indicates that the sanitary conditions around certain wells have been inadequate since at least 2016 and may have worsened over the years due to a lack of maintenance on their structures.

In monitoring individual wells, parameters such as TC, *E. coli*, turbidity, and fluoride are easy to measure and provide useful information about drinking water quality. However, they only offer a general overview. While these methods allow for quick decision-making due to their flexibility, they are also more subjective because they do not consider other important factors such as sanitary conditions and well infrastructure.

Conclusions

The results of the water quality during the period studied revealed concentrations of microbiological

³⁸ Atherholt et al., 2016. Jeranoski; Wiecheteck, 2024.

parameters that could pose risks to human health. The high numbers of CFU/100 mL of *E. coli* that we can find in the raw water of some wells are related to the contamination of groundwater after rainfall, especially due to the urban growth over a karst region, leading to serious risks to human health when the water is ingested. The consumption of this untreated raw water facilitates the transmission of waterborne pathogens, as it creates an access route for humans.

The region requires specific preservation policies for its environmental risk prevention, management of groundwater resources, as well as educational activities. We suggest promoting campaigns to orient the population about the raw water disinfection of alternative water supply systems, especially in rainy seasons, to ensure the health of the people who use the water from the wells.

In addition, conducting a proper preliminary assessment for new drilling and ensuring adequate protection perimeters around the wells must be a priority, as well as developing a guidance program to properly repair and maintain the infrastructure of already installed private wells, implementing and ensuring the hygienic-sanitary protection of the surrounding land use.

Because of environmental conservation and the improvement of the population's health, we advise further work focusing on the detailed determination of complementary microbiological and physical-chemical parameters, especially in the vulnerable karst regions, as the indicators in the National Drinking Water Quality Guidelines are still restricted to just a few parameters to groundwater exploration for human consumption

Data availability statement

All relevant data are included in the paper.

Conflict of interest

The authors declare there is no conflict.

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