



Evaluating the impact of a cemetery on groundwater by multivariate analysis

Elias D. Saba · Jordana M. Saba ·
Thiago A. Mendes · Anselmo E. de Oliveira

Received: 18 July 2022 / Accepted: 27 December 2022 / Published online: 6 January 2023
© The Author(s), under exclusive licence to Springer Nature Switzerland AG 2023

Abstract Water analyses in conjunction with hydrological and geotechnical investigations were carried out to assess the potential for groundwater contamination from the decomposition of buried human bodies. Water samples were collected from 2007 to 2018 in three monitoring wells built within the cemetery area. Water quality was evaluated based on the determination of 25 analytical parameters (20 physical–chemical and 5 microbiological). Laboratory data reported by the local sewage water company for water collected in household cisterns located outside

the cemetery area were also evaluated. Multivariate analysis showed a similar pattern between iron content, turbidity, and rainfall data collected at the rainfall station closest to the study area. This behavior is a direct consequence of soil leaching (oxisol). The physical characterization of the soil of the unsaturated area above the aquifer indicates that the absorption of body waste by the soil is favored, preventing surface contaminants from reaching the aquifer. This work also found that the water samples collected outside the cemetery area do not comply with the Brazilian limits for drinking water. In conclusion, water samples collected from monitoring wells located within the cemetery area have little to none impact on both subsurface and underground contamination.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10661-022-10895-y>.

E. D. Saba · J. M. Saba
QUINOSAN, Laboratório Químico Ltd, SIG Qd 1,
Lt. 495, Ed. Barao do Rio Branco, loja 07, Brasília,
DF 70610-410, Brazil
e-mail: elias.quinosan@gmail.com

J. M. Saba
e-mail: jordana.quinosan@gmail.com

T. A. Mendes
Civil and Environmental Engineering Department, IFG,
Av. Universitária Vereador Vagner da Silva Ferreira,
Aparecida de Goiânia, GO 74968-755, Brazil
e-mail: thiago.mendes@ifg.edu.br

A. E. de Oliveira (✉)
Laboratory of Theoretical and Computational Chemistry,
Chemistry Department, UFG, Goiânia, GO 74690-900,
Brazil
e-mail: elcana@ufg.br

Keywords Aquifer · Water analysis · Oxisol ·
Multivariate analysis · Human remains

Introduction

The accumulation of corpses buried in cemeteries is a common practice in various cultures. As the population and cities grow, some urban areas became closer to cemeteries. In addition, the increase in the number of buried bodies is also a consequence of population growth.

Biological, physical, and chemical agents promote the decomposition of matter from bodies buried in cemeteries and this process derives

from a series of potentially polluting compounds (Żychowski & Bryndal, 2014). Therefore, they represent an environmental risk to the soil and aquifers located in their area of influence, which are vulnerable to pollution due to transport processes (Reddy et al., 1981) and to the storage of large amounts of decomposing bodies (Neckel et al., 2017). Thus, the monitoring of physical–chemical and microbiological parameters is essential to estimate the degree of contamination of groundwater.

In Brazil, population growth reached 0.7% from 2016 to 2017. In 2018, we added one person to the population, on average, every 19 s. With this constant increase in population, residential, commercial, and industrial areas are occupying new areas, including the regions neighboring the cemeteries. This aspect of territorial engineering has drawn the attention of the scientific society that has been conducting studies around cemeteries, pointing out the patterns of urban expansion and changes in the processes of contemporary cities from the perspective of soil and groundwater contamination (Alnsour, 2016; Zhang et al., 2016).

This is the scenario found around the Jardim Metropolitano Cemetery located in the city of Valparaíso de Goiás, GO, Brazil (Jardim Metropolitano Cemetery, 2022), in which there was an expansion of its surrounding residential area from 2008 (Supplementary Information, Fig. B1A) to 2019 (Supplementary Information, Fig. B1B).

In general, aquifers, whether at a deeper or shallower level, Fig. 1, can be affected by how land is

used and occupied (Silva et al., 2017). Such interferences can contribute to change the amount of water they can store and/or can impact water quality (Marengo et al., 2008).

Groundwater is therefore a high-quality natural resource that requires little sewage treatment and low collection cost (Bohn & Goetten, 2015). It is consolidated as a strategic alternative to meet the current demand for water for human use (Fijani et al., 2013). Therefore, for the sustainable management of any natural resource, the first step is to assess if it is subject to contamination.

Human activity at the surface can alter and induce new mechanisms of aquifer recharge, altering the quality, frequency, and rate of groundwater recharge (Costa et al., 2019). That is why cemeteries, like any other place that can affect the natural conditions of groundwater and soil, are classified as activities that present a risk of environmental contamination (Lahr & Kooistra, 2010).

Groundwater contamination sources around the cemetery were evaluated through physical–chemical and microbiological analyses of water quality between 2008 and 2018. Three monitoring wells were built within the cemetery area for water sampling. A geotechnical investigation was also carried out to obtain the physical characterization of the soil, in order to contrast the results of the quality of the water found in the aquifer with the characteristics of the soil, which is the main filter for polluting contaminants in the region's aquifer. Water quality data from household cisterns located around the cemetery collected by the

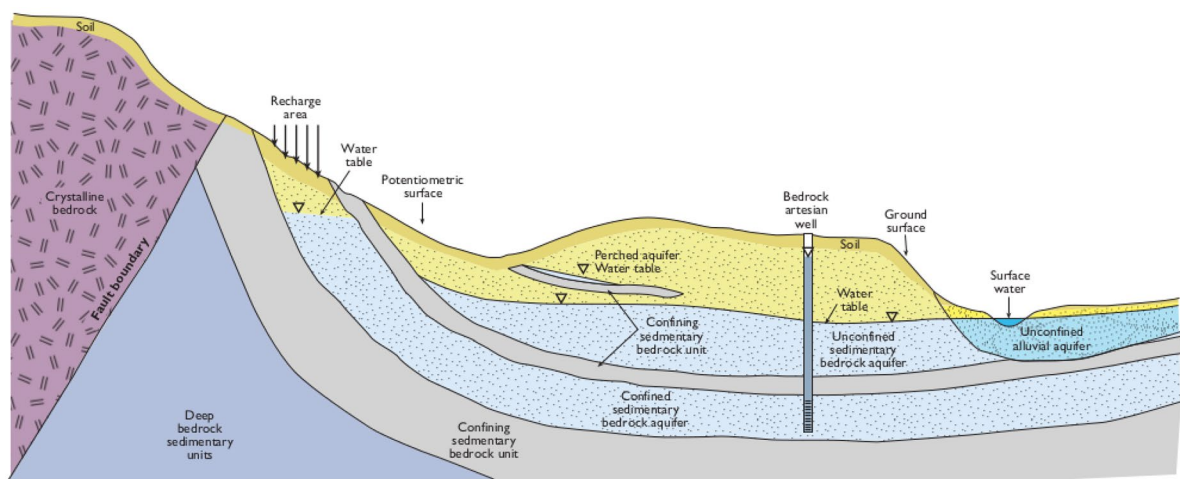


Fig. 1 The main types of aquifers (Barkmann et al., 2020)

local water and sewage treatment company were also analyzed to compare them with those collected from monitoring wells located inside the cemetery. In addition, hydrological investigations were carried out with the aim of diagnosing and delimiting the watershed that includes the cemetery.

Therefore, this article aims to evaluate the impact of the areas of influence of a cemetery on the water table. Physicochemical and microbiological parameter data collected over 11 years were analyzed to assess the potential impact of waste from decomposing bodies on groundwater pollution. The studies were also supported by hydrological and geotechnical investigations of the Fundo River basin and complementary analyses of water from neighboring cisterns located in the vicinity of the cemetery.

Material and methods

This research was divided into four stages: (a) collection of water samples in loco; (b) physical–chemical and microbiological analysis of water; (c) data analysis; and (d) hydrological and geotechnical investigations.

The cemetery and methods of burial

The Jardim Metropolitano Cemetery and Crematorium of Valparaíso de Goiás is located on the outskirts of Brasília DC, in the state of Goiás, Brazil, in an area of 300,000 m² (Supplementary Information, Fig. B1). It averages 40 burials per month, with records showing around 10,000 burials since it opened in 1998 (data from the COVID-19 pandemic is not included).

Both in-ground and above-ground entombments are realized. In-ground structure consists of a 0.05-m-thick concrete slab below a 3-niche unit having a 2 m depth also made of concrete. A 0.6-m layer of soil is placed over the niche. Above-ground entombment structures present pairs of 3-niche units on the top of a 0.05-m-thick concrete slab.

Collection of water samples

To ensure the quality of the groundwater, three monitoring wells MW01, MW02, and MW03

(Supplementary Information, Fig. C1) were built inside the cemetery, following Brazilian standards (ABNT NBR 15495–1, 2007). Wells MW01 and MW02, 10 m deep and 122 m apart, were built close to the ground burial area. A reference well (MW03, 40 m deep) was built outside the area of influence of the cemetery's contamination, 780 m away from MW02.

The groundwater level in wells MW01 and MW02 varies between 8.50 m in the dry season and 4.50 m in the rainy season; in well MW03 it varies between 40 m in the dry season and 34 m in the rainy season. The dry season occurs between May and September (Supplementary Information of rainfall in the area of research, Fig. F1).

In total, 115 water samples were collected and analyzed between 2007 and 2018, but the final dataset contains the results of 104 samples. The results of samples collected in 2007 (4 samples) and 2017 (7 samples) were considered outliers due to contamination from well drilling and ants, respectively.

In order to compare the water quality around the cemetery with data collected from monitoring wells inside the cemetery, the data for a set of 10 samples collected in 2017 in 10 household cisterns located in the vicinity of the cemetery site by the local station water and sewage treatment company (SANEAGO, 2022) was also analyzed.

Physicochemical and microbiological analyses of water

After collection, the water samples were kept between 2 and 6 °C in the QUINOSAN Chemical Analysis Laboratory Ltd (QUINOSAN, 2022). Water quality monitoring was evaluated for 25 analytical parameters (20 physical–chemical and 5 microbiological) following Brazilian standards (CONAMA, 2005; CONAMA, 2008). Table A1 (Supplementary Information) presents the maximum contaminant level (MCL) for 24 analytical parameters. For oxygen, the minimum level is 6 mg L⁻¹ for surface water and a limit of detection (LoD) of 0.1 mg L⁻¹.

The physical–chemical and microbiological analyses were carried out following the Standard Methods for the Examination of Water and Wastewater (Rice et al., 2017). The equipment used in each analysis is also presented in Table A1 and all samples were analyzed in the QUINOSAN lab.

Data analysis

The water analysis dataset contains the results of 25 analytical parameters, 20 of which are physical–chemical and 5 microbiological, for 104 samples collected in the three monitoring wells. The residential cisterns dataset contains the results of 10 samples, measured without replicates. R software version 4.0.4 (R Core Team, 2021) was applied for computing descriptive statistics and the R package *vegan* version 2.5–7 (Oksanen et al., 2020) was employed for both principal component (PCA) and redundant data analyses (RDA).

PCA consists of reducing the dimensionality (variance) of a large dataset, transforming it into a new smaller set (principal components) maintaining the variation present in the original collection, allowing the identification of patterns, and highlighting their similarities and differences. The principal components are calculated using a variance/covariance matrix or singular value decomposition, generating eigenvectors, which represent the directions of space, and eigenvalues, representing the scale factor, length, magnitude, and robustness of the eigenvector (Varmuza & Filzmoser, 2008).

RDA is a multivariate analysis technique for two sets of variables, where normally one set is explanatory, while the other is dependent. The method selects the best linear combination of environmental variables that generates the smallest residual sum of squares. RDA can be understood as an extension of the PCA, since the canonical ordering vectors are linear combinations of the response variables of the explanatory set. Thus, RDA is simply a PCA, with a restriction on the site scores (Jongman et al., 1995).

Hydrological and geotechnical investigations

The hydrological investigations included the diagnosis and delimitation of the watershed that includes the cemetery. This study includes the evaluation of the drainage network of the Rio Fundo basin (Supplementary Information, Fig. C1) in addition to the verification, delimitation, and understanding of the underground aquifer and its influence on percolating behavior. In addition, both the topographic profile and the hypsometry of the soil surface were also evaluated in the land use map, according to slope classes

proposed by the Brazilian Agricultural Research Corporation (EMBRAPA, 1979).

Rainfall data were collected from the rainfall station closest to the study area (INMET, 2022) to assess the influence of percolation and other hydrological (infiltration and runoff) and geotechnical (erosion) processes. The data referring to the rainfall factor, which were used in the graph in Fig. 3, represent the total precipitation in the month of sample collection.

A Digital Elevation Model (DEM) from Topodata (Valeriano & Rossetti, 2008) was used to delimit the watershed, the hypsometry, and the slope of the study area. Topodata is an altimetric product made available by the National Institute for Space Research of Brazil (INPE, 2022) for the entire Brazilian territory. It is accomplished through the refinement of DEM produced globally by the Shuttle Radar Topography Mission (SRTM, 2022) and made available by the United States Geological Survey (USGS, 2022) with a spatial resolution of 30 m. It is processed automatically by the Qgis software, version 3.10, using SIRGAS 2000 datum and geographic-type cartographic projection.

The land use map was manually generated from a satellite image made available for free by Google Earth, in the year 2019, and validated with field visits.

For the drainage network and underground aquifer system, data provided by the local State Geoinformation System of Goiás (SIEG, 2022), Brazil, were used. The drainage network is designed by the Brazilian Institute of Geography and Statistics (IBGE, 2022) on a scale of 1:100,000. In turn, the aquifer systems were surveyed by the Superintendence of Geology and Mining of the State of Goiás on a scale of 1:1,000,000.

Through geotechnical investigations, the physical characterization of the soil and the determination of the hydraulic conductivity and the soil–water retention curve (SWRC) were carried out.

The soil liquid and plastic limits followed the ABNT NBR 6459 (2016) regulatory standard. Soil plasticity index followed ABNT NBR 7180 (2016) and grain size analysis followed ABNT NBR 7181 (2016). The specific gravity of the soil samples was measured from a dry sample taking the weight-to-volume ratio and SWRC were obtained using a WP4C Dewpoint Potentiometer from Decagon Devices. It is important to know the geotechnical characteristics of the soil, to

verify the ability to filter contaminants through the soil and to infiltrate fluids.

This step was divided into two phases. Phase 01 included the collection of deformed and undisturbed samples near the monitoring wells MW1 and MW3 (see Supplementary Information, Fig. C1 for the location of the wells) to carry out the geotechnical laboratory tests. Samples were collected at a depth of 0.3, 1.0, and 2.0 m. Phase 02 included the physical characterization of the soil (determination of hygroscopic moisture, granulometry with and without deflocculants, and SWRC).

Natural and hygroscopic moisture, compaction, limits, and granulometry tests were performed for deformed samples. Density, SWRC, and hydraulic conductivity tests were performed for undisturbed samples. The results of the suction tests were based on the use of shaft translation equipment, the Fredlund cell model (low suction up to 500 kPa), and the Dewpoint Water Potentiometer model WP4C from Decagon Devices Inc. (high suction, from 500 to 10^5 kPa).

Results and discussion

Water quality of monitoring wells located within the cemetery area

Ten of the twenty physicochemical parameters (phosphorous, manganese, chromium, ammonia, nitrite, nitrate, lead, mercury, silver, and cadmium) were found below the LoD (Supplementary Information, Table A1) for all samples. For microbiological parameters, only one (mesophyll) out of five was detected. In the end, 11 parameters (10 physical–chemical and 1 microbiological) presented values above the LoD. Table 1 summarizes the statistical data distribution for all 11 statistically significant analytical parameters measured in the three monitoring wells.

Alkalinity, hardness, TDS, and mesophyll levels (Table 1) were always found below MCL according to Brazilian drinking water quality standards (Supplementary Information, Table A1) for all three monitoring wells. As a result, 7 of the 25 analytical parameters presented values that can be of statistical significance in this work for the aquifer data. Patterns of these variables over the sampled years (from 2008 to 2016 and 2018) were estimated using

smoothed functions (cubic polynomial) and are presented in Fig. 2.

Some pH values in Fig. 2A are below the recommended minimum level (pH=6.0, horizontal dashed line) and are related to the intense leaching of lateritic soil (Dwevedi et al., 2017). This soil becomes acidic due to the tropical climate and its mineralogical composition. The main composites such as Ca, Mg, K, and P are leached for years due to rainfall in such a way that the components of lower geochemical mobility such as Fe and Al (oxyhydroxides) are more abundant (Camapum de Carvalho et al., 2012). The profiles of the three monitoring wells are very similar and express the same trend among themselves, indicating that the pH is not influenced by the activity of the cemetery.

Most of the results obtained for dissolved oxygen (Fig. 2B) are less than 6.0 mg L^{-1} (dashed horizontal line). When compared to surface water, the oxygen level in groundwater is expected to be lower (Mendes et al., 2019) since the aquifer is limited by the dynamics of oxygen exchange with atmospheric air (Fig. 1). Results for MW01 and MW02 indicate a similar pattern. On the other hand, the oxygen levels of samples collected in well MW03 do not seem to have the same trend as the other two monitoring wells. These results indicate that the level of dissolved oxygen in groundwater is better than that obtained for shallower waters, as MW03 has a depth of 40 m.

The trend found between the curves fitted to the dissolved oxygen data in wells MW01 and MW02 (Fig. 2B) is different from that verified with the data from MW03. This same behavior was also found for conductivity (Fig. 2C), turbidity (Fig. 2D), and iron (Fig. 2E). In addition, the result found for turbidity strongly indicates no influence from the cemetery in the aquifer. The turbidity values were, in general, below MCL for MW01 and MW02 (Fig. 2D).

Many samples showed iron levels above the MCL (Fig. 2E). However, this result is not related to the influence of the cemetery, as the level of iron in the human body is about 9 mg kg^{-1} (Cook et al., 2003). Thus, the main source of iron that may be affecting both analyzed iron contents and turbidity comes from the oxisol, a tropical red earth that has a high content of iron oxides (Hasiotis et al., 2007).

Most of the COD and BOD results (Fig. 2F, G, respectively) are above the MCL. However, the fitted

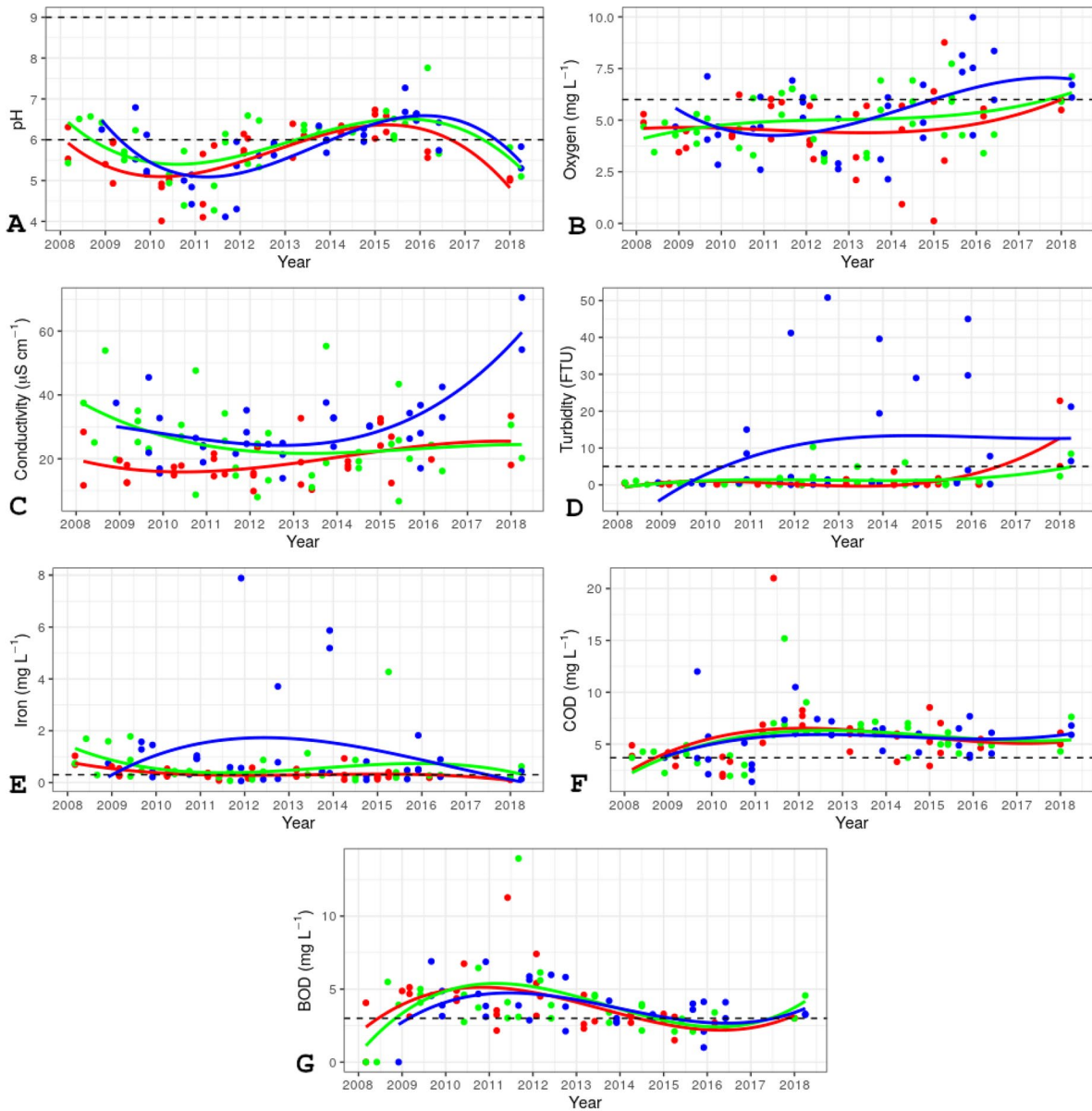


Fig. 2 Water quality parameters measured over the years for the three monitoring wells (● MW01; ● MW02; ● MW03): pH (A), oxygen (B), conductivity (C), turbidity (D), iron (E), chemical oxygen demand (COD) (F), and biological oxygen

demand (BOD) (G). The horizontal dashed lines indicate Brazilian standards (see Supplementary Information, Table A1), and solid lines represent smoothed conditional means using a third-degree polynomial fit

COD and BOD data for MW01 and MW02 show the same pattern as the reference well, MW03, indicating that the cemetery is not influencing the aquifer.

Through the analyses carried out so far, it is possible to conclude that, according to Brazilian standards, the aquifer was not being contaminated by the cemetery.

Multivariate analysis

Multivariate data analysis applied to aquifer data included monthly rainfall data collected from the INMET database (INMET, 2022). A data matrix of 104 observations/samples by 10 variables (with seven variables from Table 1, one for monitoring wells, one

Table 1 Statistical data for 104 aquifer water samples collected from three monitoring wells located in the Jardim Metropolitan Cemetery of Valparaíso de Goiás, Brazil, from 2008 to 2016 and 2018

Analysis	Statistics ^h						
	Min	Q1	Med	Mean	Q3	Max	SD
Alkalinity ^a	3.79	7.59	11.38	11.86	15.18	26.56	4.81
pH	4.01	5.39	5.93	5.79	6.28	7.76	0.71
Oxygen ^a	0.12	4.05	4.88	4.98	6.03	9.98	1.62
Conductivity ^b	6.69	17.06	23.75	24.74	30.60	70.50	11.02
Hardness ^a	3.79	8.16	8.16	10.55	12.24	40.82	6.33
Turbidity ^f	0.02	0.19	0.51	5.62	2.90	54.10	12.30
Iron ^a	0.06	0.22	0.36	0.72	0.70	7.89	1.17
TDS ^{a,c}	6.10	14.54	20.42	20.83	26.00	51.30	8.50
COD ^{a,d}	1.37	4.00	5.36	5.51	6.48	21.00	2.58
BOD ^{a,e}	0.00	2.90	3.40	3.82	4.57	13.95	1.90
Mesophyll ^g	0.00	14.50	29.50	46.08	58.25	422.00	56.60

^a mg L⁻¹

^b μS cm⁻¹

^c total dissolved solids

^d chemical oxygen demand

^e biological oxygen demand

^f FTU

^g CFU mL⁻¹

^h *min, max*, minimum and maximum; *Q1 and Q3*, 1st and 3rd quartiles; *med*, median; *SD*, standard deviation

for year, and one for rainfall) was employed to run both constrained (RDA) and unconstrained (PCA) axes.

The first constrained axis, RDA1 (monitoring wells), explains 7.3% of the variance, while the second, RDA2 (year), explains 2.2%. On the other hand, the first unconstrained axis, PC1, explains 25%, and the second, PC2, explains 17%. This means that the aquifer dataset is not structured by the two explanatory variables monitoring wells and year. The PCA biplot can be seen in Fig. 3 and the similarities found for iron, turbidity, and rain factors strongly corroborate the fact that both iron and turbidity are influenced by intense soil leaching due to rainfall.

Water quality in the vicinity of the cemetery

To assess the quality of the water consumed by residents neighboring the cemetery, the local water and sewage treatment company (SANEAGO) collected water samples in 2017 in cisterns of some residences. The summary of laboratory reports can be seen in Table 2.

All alkalinity, manganese, nitrite, and TDS values were found below MCL in Table 2 and six samples had pH values below 6. Although the MCL for

conductivity is not specified by Brazilian standards (see Supplementary Information, Table A1) its values for 8 samples were above the maximum value of 70.50 μS cm⁻¹ found for the monitoring wells analyzed inside the cemetery (Table 1). Only two samples presented iron values above the MCL and only one presented nitrate content above the MCL.

As can be seen, physical–chemical data collected in the cisterns around the cemetery show some differences. But the biggest impact on water quality comes from the two microbiological parameters Total coliforms and Escherichia coli. Consequently, the results in Tables 1 and 2 indicate that this contamination cannot be related to the activity of the cemetery, as these two microbiological parameters were reported to be absent in all samples collected inside the cemetery.

Hydrological and geotechnical investigations

Hydrological investigations

The Fundo River watershed in which the cemetery is located comprises an area of 8.42 km² and a perimeter of 14.27 km, with a large part of its area in an

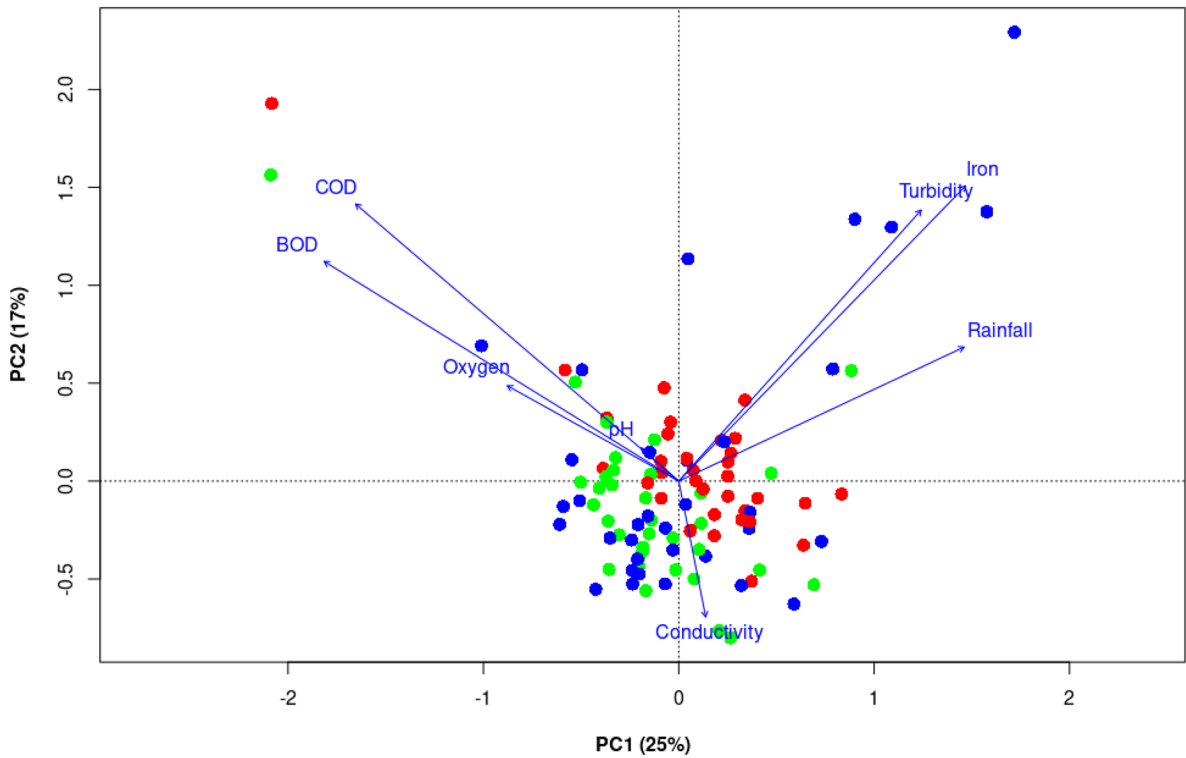


Fig. 3 Biplot of principal component analysis of aquifer data. The colored dots represent monitoring wells (● MW01; ● MW02; ● MW03). This graph explains 42% of the variance in the data

Table 2 Analysis of the water quality of 10 samples collected^d in household cisterns located outside the cemetery area

Analytes	Home cisterns									
	A	B	C	D	E	F	G	H	I	J
Alkalinity ^b	10	21	12	10	3.89	80	13	40	50	30
pH	5.71	5.66	5.70	5.61	3.89	6.15	5.85	6.12	6.37	6.98
Conductivity ^c	16.19	99.80	162.20	100.70	83.60	148.70	23.24	98.20	155.80	135.60
Iron ^b	0.50	0.20	0.03	0.01	0.12	0.02	0.00	0.27	0.12	0.33
TDS ^b	8.90	54.89	89.21	55.39	45.98	81.79	12.78	54.01	85.69	74.58
Nitrite ^{b,e}	0.002	ND	0.012	0.003	ND	ND	0.002	0.004	0.012	0.009
Nitrate ^b	0.6	6.7	6.1	7.1	25.6	0.4	0.8	2.2	4.5	3.6
Manganese ^b	0.024	0.031	0.025	0.015	0.020	0.020	0.028	0.031	0.022	0.336
Total Coliforms ^d	P	P	P	P	P	P	P	P	P	P
Escherichia Coli ^d	A	P	P	P	A	P	P	P	P	P

^a no replicates; source: SANEAGO (local state water and wastewater treatment company)

^b mg L⁻¹

^c μS cm⁻¹

^d P, present; A, absent

^e ND, non detected (below LoD)

urban environment or modified with some fragments of vegetation (Supplementary Information, Fig. C3).

Fig. C4 (Supplementary Information) shows the physical characteristics of the existing relief in the Fundo River basin such as slope (Supplementary Information, Fig. C4A), hypsometry (Supplementary Information, Fig. C4B), and land use (Supplementary Information, Fig. C4C).

From a topographic (slope and hypsometry) and hydrogeological point of view, the locations of the monitoring points were strategically chosen (located) to better understand the percolation behavior of water and its transported compounds and their interference with groundwater, as they preferentially follow the sloping nature of the terrain.

Fig. C4A (Supplementary Information) shows the slope of the terrain that complements the hypsometry (Supplementary Information, Fig. C4B). It is noticed that the drainage networks that make up the Rio Fundo hydrographic basin, in the main channel of this river, present a higher percentage of slope varying from 3.0 to 20.0%. At the basin limits the slope varies from 20.0 to 45.0%, and in the upstream section from 0.0 to 3.0% (Supplementary Information, Fig. C4B and Table 3). Thus, based on the physical characteristics of the terrain in the study area (Supplementary Information, Fig. C4) the location of well MW03 is quite representative for monitoring surface and underground water flows. Both the lines and the flow length of the drainage network converge to the main watercourse, that is, the underground aquifer that feeds and forms part of the Fundo River towards the MW03 well.

Thus, significant changes in the water quality parameters of the monitoring well MW03 in relation to the other two (MW01 and MW02) may be due to both the flow and the decomposition of the leachate from the cemetery towards the watercourse, which was not perceived in this study over the monitoring time (Tables 1 and 2 and Fig. 3).

Analyzing the hypsometry (topography), the basin area has a maximum altitude of 1,102 m (basin limit) and a minimum altitude of 891 m (mouth of the Fundo River) representing a total difference of 211 m, while the height of the source of the Fundo River is 1010 m. Thus, it is inferred that almost half of the total gap in the watershed comprises the maximum altitude stretch and the location of the cemetery.

Table 3 Relief classes^a and areas in relation to the slope of the watershed where the Jardim Metropolitano cemetery is located

Slope (%)	Relief	Area	
		km ²	%
0.0–3.0	PLANE	1.34	15.91
3.0–8.0	SMOOTH-WAVY	4.15	49.29
8.0–20.0	WAVY	2.71	32.19
20.0–45.0	STRONG-WAVY	0.22	2.61
45–75.0	MOUNTAINOUS	0.00	0.00
> 75.0	STRONG-MOUNTAINOUS	0.00	0.00
Total area (km²)		8.42	

^a following reference EMBRAPA (1979)

It is important to highlight that, in relation to the maximum altitudes, there is a lower variability of the classes, reflecting a lower contribution of the surface runoff velocity and a greater propensity to infiltration, which cannot be guaranteed due to the high level of waterproofing. On the other hand, from the middle of the basin to the mouth, the classes become wider and with lower altitudes, reflecting less flat terrain.

Regarding land use, the cemetery is strongly influenced by the runoff of part of the rain that cannot infiltrate the soil in the highest part of the Fundo River basin. This is because this is where most of the waterproofing of this watershed is located. Even the watershed having this characteristic of land use and occupation upstream of the cemetery, the monitored results of the groundwater quality parameters did not show significant changes, considering the values of the standard deviations of the samples analyzed over the study time (Table 1), showing the potential of the soil in relation to the filtering power of contaminants.

Thus, the land use map enabled the identification and showed little variability of the soil surface in the area and surroundings of the cemetery. This allowed us to carry out a smaller number of samples to identify the hydraulic conductivity of the soil, k_{sat} , which can be influenced by up to 240% depending on the type of equipment and methodology adopted, which can be very time-consuming, difficult to perform and high cost, in addition, given the numerous attributes of the soil that can interfere in its determination (Lumb, 1966; Nagy et al., 2013; Uzielli, 2008).

Geotechnical investigations

Seven undisturbed soil samples of the cemetery (study site) measuring 0.4 m^3 were collected at different sites (three near the graveyard, one between MW01 and MW02, and three near MW03) at three different depths (0.3, 1.0, and 2.0 m). All samples were wrapped in paraffin, preserving their original characteristics. Based on physical indices (specific gravity, plastic and liquid limits, plasticity index, soil moisture, and hygroscopic water) and Atterberg limits (results not shown), the untreated sample was classified as sandy silt. The soil sample treated with sodium hexametaphosphate (SHMP) was classified as silty clay. The difference observed in the classification of soils with and without the use of SHMP indicates that this soil is lateritic, highly porous, and with bimodal porous behavior.

Two types of soils were characterized based on SWRC (Supplementary Information, Fig. D5) and particle-size distribution plots (Supplementary Information, Fig. E6): clayey and silty with bimodal structural behavior, *i.e.*, macro and micropores.

The graveyard clayey soil does not fit the description of a typical clayey soil due to its structural characteristics such as hydraulic conductivity and soil percolation. There are cement and a high content of iron and aluminum oxides (red or yellow oxisols) that are characteristic of highly weathered soils.

Highly weathered tropical soils such as the one in the cemetery under study often present clay aggregates formed by cementing agents, typically iron and aluminum oxides and hydroxides (Camapum De Carvalho & Gitirana Jr., 2021). The presence of clay aggregates produces pore-size distributions with markedly distinct pore-size families. These are often referred to as macro and micropores. The presence of macro and micropores results in bimodal soil–water characteristic curves (SWRC). The macropores are associated with a highly variable and compressible pore volume, and low air-entry value and may result in high saturated hydraulic conductivities. The micropores correspond to rigid intra-aggregate pores, present high air-entry values and do not contribute, in a significant way, to the overall hydraulic conductivity of the soil (Perotti et al., 2022).

A saturated hydraulic conductivity of $4.1 \times 10^{-5} \text{ ms}^{-1}$ indicates a weathered tropical soil like fine sands, as typical clayey soils have values between 10^{-10} and 10^{-6} ms^{-1} (Kardena et al., 2014). Even considering a clay percentage greater than 50%, the conductivity value

is like sandy soil (Araki, 1997) with fast flow velocities in unsaturated porous soils for suction under natural field conditions (up to 100 kPa).

Very fractured or very granular materials, such as soils composed of coarse sand and gravel, are not suitable for the surface layers of the cemetery. These types of soils have high hydraulic conductivity and low capacity to retain contaminants, causing the waste from decomposing bodies to percolate into the aquifer. And that was not the soil found in the Jardim Metropolitan cemetery.

On the other hand, anaerobic conditions prevail in thin soils such as clays ones, as their hydraulic conductivity is very low, hindering the process of gradual human decomposition. Again, this is not the soil of the cemetery, as it has good drainage capacity for suction under natural field conditions (up to 100 kPa, Supplementary Information, Fig. D5) due to the presence of micro- and macropores. Thus, the soils found in the cemetery can be considered suitable for this type of activity due to their physical, granulometric, and flow characteristics (hydraulic conductivity, k).

Even when compacted or when there is a large amount of water (intense precipitation), the soils of the cemetery still have the same hydromechanical behavior, that is, high hydraulic conductivity and porosity. As an example, the soil sampled in MW01 (0.30 m) when in the optimal compaction (optimal soil moisture of 28% and compacted dry specific mass of 1.51 g cm^{-3}) still has a porosity of approximately 45%. It represents a reduction of only 10% in porosity in relation to its natural (uncompacted) state.

Conclusion

Multivariate analysis of water data collected from three monitoring wells located in the cemetery area showed a similar pattern between iron and turbidity contents and rainfall. This result is a direct consequence of soil leaching (oxisol).

Water samples collected in areas outside the cemetery do not meet Brazilian standards for drinking water. Since two microbiological parameters (total coliforms and *Escherichia coli*) were reported to be absent in all samples collected within the cemetery, this contamination cannot be related to cemetery activity.

Differences observed in the classification of the soil above the aquifer with and without the use of sodium

hexametaphosphate indicate it as a laterite soil, highly porous, and with bimodal behavior. This soil has a great capacity to retain contaminants and for suction above natural field conditions (up to 100 kPa) it has a very low hydraulic conductivity. Therefore, the unsaturated area above the aquifer favors the absorption of the waste from decomposing bodies, preventing these wastes from reaching the aquifer. In general, the favorable topographic and hydromechanical behavior of the soil favors the low impact of the cemetery groundwater.

In the end, this multidisciplinary study concluded that the water samples collected inside the cemetery area have little to none impact on both subsurface and underground contamination.

Acknowledgements The authors thank Prof. Dr. André L. B. Cavalcante, Civil and Environmental Engineering Department at the Universidade de Brasília, for both soil-water retention curves and Particle-size distribution plots.

Author contribution Initiated the study: Saba, E.D., and de Oliveira, A.E.; Conceived and designed the experiments: Saba, E.D.; Analyzed the data: de Oliveira, A.E., and Mendes, T.A.; Wrote the paper: Saba, E.D., Saba, J.M., Mendes, T.A., and de Oliveira, A.E.; All authors read and approved the manuscript.

Funding Funding de Oliveira, A.E. has received research support (DT fellowship) from CNPq.

Availability of data and materials The datasets used and analyzed during this article are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

ABNT NBR 15495-1. (2007). Monitoring wells of ground water and granular aquifers - part 1: design and construction. *Brazil Association of Technical Standards*.
 ABNT NBR 6459. (2016). Soil - liquid limit determination. *Brazil Association of Technical Standards*.
 ABNT NBR 7180. (2016). Soil - plasticity limit determination. *Brazil Association of Technical Standards*.
 ABNT NBR 7181. (2016). Soil - grain size analysis. *Brazil Association of Technical Standards*.

Alnsour, J. A. (2016). Managing urban growth in the city of amman, Jordan. *Cities*, 50(4), 93–99. <https://doi.org/10.1016/j.cities.2015.08.011>

Araki, M. S. (1997). *Aspectos relativos às propriedades dos solos porosos colapsíveis do Distrito Federal*. Master Thesis, Universidade de Brasília, Brazil.

Barkmann, P. E., Broes, L. D., Palkovic, M. J., Hopkins, J. C., Bird, K. S., Sebol, L. A., & Fitzgerald, F. S. (2020). ON-010 Colorado Groundwater Atlas. *Geohydrology*. Colorado Geological Survey, Retrieved October 20, 2022, from <https://coloradogeologicalsurvey.org/water/colorado-groundwater-atlas>

Bohn N., & Goetten, W. J. (2015). Groundwater governance in the states of são paulo, paraná, santa catarina and rio grande do sul: An analysis from the instruments of the national water resources policy. In *2015 Ninth International Conference on Complex, Intelligent, and Software Intensive Systems* (pp. 430–435).

Camapum De Carvalho, J., & Gitirana Jr., G. D. F. (2021). Unsaturated soils in the context of tropical soils. *Soils and Rock*, 44(3). <https://doi.org/10.28927/SR.2021.068121>

Camapum De Carvalho, J. C., Gitirana Jr., F. N., & Carvalho, E. T. L. (2012). *Tópicos sobre infiltração: teoria e prática aplicadas a solos tropicais*. Faculdade deTecnologia.

CONAMA. (2008) Resolution 396, April 3, 2008. Brazilian Environment Council, Retrieved October 20, 2022, from <http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=562>

CONAMA. (2005). Resolution 357, March 17, 2005. Brazilian Environment Council, Retrieved October 20, 2022, from <http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=459>

Cook, J. D., Flowers, C. H., & Skikne, B. S. (2003). The quantitative assessment of body iron. *Blood*, 101(9), 3359–3363. <https://doi.org/10.1182/blood-2002-10-3071>

Costa, C. W., Lorandi, R., Lollo, J. A., & Santos, V. A. (2019). Potential for aquifer contamination of anthropogenic activity in the recharge area of the guarani aquifer system, southeast of brazil. *Groundwater for Sustainable Development*, 8, 10–23. <https://doi.org/10.1016/j.gsd.2018.08.007>

Dwevedi, A., Kumar, P., Kumar P, Kumar, Y., Sharma, Y. K., & Kayastha, A. M. (2017). 15 - soil sensors: Detailed insight into research updates, significance, and future prospects. In A. M. Grumezescu (Ed.), *New pesticides and soil sensors* (pp. 561–594). Academic Press. <https://doi.org/10.1016/B978-0-12-804299-1.00016-3>

EMBRAPA. (1979). *Serviço nacional de levantamento e conservação de solos: Reunião técnica de levantamento de solos, 10*. Brazilian Agricultural Research Corporation. Retrieved December 31, 2022, from <https://ainfo.cnptia.embrapa.br/digital/bitstream/item/212100/1/SNLCS-Miscelania-1-1979.pdf>

Fijani, E., Nadiri, A. A., Moghaddam, A. A., Tsai, F. T. C., & Dixon, B. (2013). Optimization of drastic method by supervised committee machine artificial intelligence to assess groundwater vulnerability for maragheh–bonab plain aquifer, iran. *Journal of Hydrology*, 503, 89–100. <https://doi.org/10.1016/j.jhydrol.2013.08.038>

Hasiotis, S. T., Kraus, M. J., & Demko, T. M. (2007). Chapter 11 - climatic controls on continental trace fossils. In W. Miller (Ed.), *Trace fossils* (pp. 172–195). Elsevier, Amsterdam. <https://doi.org/10.1016/B978-044452949-7/50137-6>

IBGE. (2022). *Brazilian Institute of Geography and Statistics*. Retrieved October 20, 2022, from <https://www.ibge.gov.br>

- INMET. (2022). Historical annual data. *Brazilian Institute of Meteorology*. Retrieved October 20, 2022, from <https://portal.inmet.gov.br/dadoshistoricos>.
- INPE. (2022). *Brazilian Institute for Space Research*, Retrieved October 20, 2022, from <https://www.gov.br/inpe/pt-br>.
- Jardim Metropolitan Cemetery. (2022). Retrieved October 20, 2022, from <https://www.jardimmetropolitano.com.br/goias-df-contato>.
- Jongman, R. H. G., Braak, C. J. F., & Van Tongeren, O. F. R. (1995). *Data analysis in community and landscape ecology*. Cambridge University Press. <https://doi.org/10.1017/CBO9780511525575>
- Kardena, E., Helmy, Q., & Funamizu, N. (2014). Biosurfactants and soil bioremediation. In N. Kosaric, & F. V. Sukan (Eds.), *Biosurfactants: Production and utilization-processes, technologies, and economics* (pp. 327–360). CRC Press. <https://doi.org/10.1201/b17599-19>
- Lahr, J., & Kooistra, L. (2010). Environmental risk mapping of pollutants: State of the art and communication aspects. *Science of the Total Environment*, 408(18), 3899–3907. <https://doi.org/10.1016/j.scitotenv.2009.10.045>
- Lumb, P. (1966). The variability of natural soils. *Canadian Geotechnical Journal*, 3(2), 74–97. <https://doi.org/10.1139/t66-009>
- Marengo, J., Nobre, C., Tomasella, J., Cardoso, M. F., & Oyama, M. D. (2008). Hydro-climatic and ecological behavior of the drought of amazonia in 2005. *Philosophical Transactions of the Royal Society B*, 363(1498), 1773–1778. <https://doi.org/10.1098/rstb.2007.0015>
- Mendes, T. A., Silva, R. F., Nunes, R. M., Silveira, I. C., Borba, L. L., Gitirana Jr, G. F. N., Rebolledo, J. F. R., & Pereira, S. A. S. (2019). Monitoreo de la calidad del agua de los lagos artificiales y naturales de los parques públicos urbanos de la ciudad de Goiânia - GO. *Ciência e Natura*, 41, e58. <https://doi.org/10.5902/2179460X39232>
- Ministry of Health of Brazil. (2017). Portaria de consolidação n. 5, September 28, 2017. Retrieved October 20, 2022, from <http://portalarquivos2.saude.gov.br/images/pdf/2018/marco/29/PRC-5-Portaria-de-Consolida---o-n---5--de-28-de-setembro-de-2017.pdf>
- Nagy, V., Milics, G., Smuk, N., Kovács, A. J., Balla, I., Jolánkai, M., Deákvári, J., Szalay, K. D., Fenyvesi, L., Štekauerová, V., Wilhelm, Z., Rajkai, K., Németh, T., & Neményi, M. (2013). Continuous field soil moisture content mapping by means of apparent electrical conductivity (eca) measurement. *Journal of Hydrology and Hydromechanics*, 61(4), 305–312. <https://doi.org/10.2478/johh-2013-0039>
- Neckel, A., Costa, C., Mario, D. N., Sabadin, C. E. G., & Bodah, E. T. (2017). Environmental damage and public health threat caused by cemeteries: A proposal of ideal cemeteries for the growing urban sprawl. *Brazilian Journal of Urban Management*, 9, 216–230.
- Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlenn, D., Minchin, P. R., O'Hara, R. B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, E., & Wagner, H. (2020). *vegan: Community Ecology Package*. R package version 2.5–7. <https://CRAN.R-project.org/package=vegan>.
- Perotti, D. A., Gitirana, G. F. N., Jr., Mendes, T. A., & Fredlund, M. D. (2022). Numerical analysis of cover systems for mining waste in tropical regions. *International Journal of Mining, Reclamation and Environment*, 36(7), 492–511. <https://doi.org/10.1080/17480930.2022.2069915>
- QUINOSAN. (2022). Retrieved October 20, 2022, from <http://www.quinosan.com.br>
- R Core Team. (2021). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, version 4.0.4. <https://www.R-project.org>
- Reddy, K. R., Khaleel, R., & Overcash, M. R. (1981). Behavior and transport of microbial pathogens and indicator organisms in soils treated with organic wastes. *Journal of Environmental Quality*, 10(3), 255–266. <https://doi.org/10.2134/jeq1981.00472425001000030001x>
- Rice, E. W., Baird, R. B., & Eaton, A. D. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). American Public Health Association.
- SANEAGO. (2022). Goiás state water and sewage treatment company. Retrieved October 20, 2022, from <https://www.saneago.com.br>
- SIEG. (2022). Goiás state geoinformation system. Retrieved October 20, 2022, from https://www.imb.go.gov.br/index.php?option=com_sppagebuilder&view=page&id=8&Itemid=130
- Silva, M. M. V. G., Gomes, E. M. C., & Isaías, M., Azevedo, J.M.M. & Zeferino, B. (2017). Spatial and seasonal variations of surface and groundwater quality in a fast-growing city: Lubango, angola. *Environmental Earth Sciences*, 76(23), 790. <https://doi.org/10.1007/s12665-017-7149-9>
- Siqueira, R. S. (1995). *Manual de microbiologia de alimentos*. EMBRAPA.
- SRTM. (2022). *Shuttle Radar Topography Mission*. Retrieved October 20, 2022, from <https://www2.jpl.nasa.gov/srtm>
- USGS. (2022). *US Geological Survey*. Retrieved October 20, 2022, from <https://www.usgs.gov>
- Uzielli, M. (2008). Statistical analysis of geotechnical data. In A. B. Huang, & P. W. Mayne (Eds.), *Geotechnical and geophysical site characterization* (pp. 173–193). London: CRC Press. <https://doi.org/10.1201/9780203883198>
- Valeriano, M. M., & Rossetti, D. F. T. (2008). *Topodata: seleção de coeficientes geoestatísticos para o refinamento unificado de dados srtm*. Retrieved October 20, 2022, from <http://www.dpi.inpe.br/topodata/documentos.php>
- Varmuza, K., & Filzmoser, P. (2008). *Introduction to multivariate statistical analysis in chemometrics*. CRC Press.
- Zhang, H., Merrett, D. C., Jing, Z., Jigen, T., Yuling, H., Hongbin, Y., Zhanwei, Y., & Dongya, Y. (2016). Osteoarchaeological studies of human systemic stress of early urbanization in late Shang at Anyang China. *PLoS One*, 11(4), 1–25. <https://doi.org/10.1371/journal.pone.0151854>
- Zenebon, O., Pascuet, N. S., & Tiglea, P. (2008). *Métodos físico-químicos para análise de alimentos*. Instituto Adolfo Lutz.
- Żychowski, J., & Bryndal, T. (2014). Impact of cemeteries on groundwater contamination by bacteria and viruses – A review. *Journal of Water and Health*, 13(2), 285–301. <https://doi.org/10.2166/wh.2014.119>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.