# Groundwater Vulnerability and Cemetery Urbanization Areas

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# Groundwater Vulnerability and Cemetery Urbanization Areas

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**Abstract**

Water analysis and hydrological and geotechnical investigations were carried out in order to evaluate the influence of the decomposition of human bodies buried in a cemetery on aquifer vulnerability. Data collection on the unconfined aquifer from 2007 to 2018 took place at three monitoring wells built inside the cemetery area. Water quality monitoring through these years was evaluated for 25 analytical parameters (20 physicochemicals and 5 microbiologicals). Lab reports from neighboring cisterns located outside the cemetery area and carried out by the local sewage water company were also included in this work. Multivariate analyses from the water data showed a strong correlation between both iron contents and turbidity and the rainfall indicating a direct consequence of leaching from the soil (oxisol). According to the physical characterization data of the soil the unsaturated area above the aquifer favors the absorption of the body residuals by the soil, preventing it from reaching the aquifer. This work also found that collected water in areas outside the cemeteries and surrounding dwelling areas do not comply with federal norms for drinking water. In a conclusion, the water samples collected inside cemetery wells present low vulnerability to both subsurface and underground contamination.

**Keywords:** aquifer, water analysis, oxisol, multivariate analysis, human remains

# 1 Introduction

The accumulation of corpses buried in cemeteries is a common practice in various cultures. As the population and cities have been growing, some urban areas have become closer to cemeteries. On top of that, the increase in the number of bodies buried is also a consequence of the demographic growth.

Biological, physical, and chemical agents promote the decomposition of the matter of the buried bodies in the cemeteries; this process derives from a series of composites that are potentially polluting (Żychowski and Bryndal, 2014). Therefore, they represent an environmental risk to the ground and aquifers located in their area of influence which are then vulnerable to pollution due to the transport processes (Reddy et al, 1981) and also to the storage of a high quantity of decomposing bodies (Neckel et al, 2017).

In Brazil, the population growth reached 0.7% from 2016 to 2017. In 2018, we add one person to the population, in average, at each 19 seconds. This steady increase of the population, the residential, commercial, and industrial areas are occupying new areas, including those surrounding regions close to cemeteries. Such an aspect from the territorial engineering has called the attention of the scientific society that has been carrying out studies around cemeteries, pointing out the urban expansion standards and the changes in the processes of contemporary cities under the perspective of the ground and underground water contamination (Alnsour, 2016; Zhang et al, 2016).

This is the scenario found in the area around the Jardim Metropolitano Cemetery localted in the city of Valparaíso de Goiás, GO, Brazil in which there was an expansion of its surrounding residential area from 2008 (Figure 1a) to 2019 (Figure 1b).

In general, the aquifers, whether at a deeper or shallower level, Figure 2, can be affected by the way in which the ground is used and occupied (Silva et al, 2017). Such interferences can contribute to alter the quantity of the water they can store and/or it can impact on the quality of the water (Marengoa et al, 2008).

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

Human activity on the surface can alter and induce new mechanisms of aquifer recharge, altering the quality, frequency and groundwater recharge rate (Costa et al, 2019). For this reason cemeteries, like any other premises that can affect the natural conditions of underground waters and of the soil, are classified as activities that present a risk of environmental contamination (Lahr and Kooistra, 2010).

The vulnerability to the water table contamination around the cemetery was evaluated by means of physicochemical and microbiological water quality analyses between 2008 and 2018. Monitoring wells were built inside the cemetery area for water sampling. Geotechnical investigation was also performed to obtain the physical characterization of the soil, so as to contrast the results of the quality of the water found in the aquifer with the features of the soil, which is the main filter for the aquifer polluting contaminants in the region. Water quality data from home cisterns located around the cemetery collected by the local water and wastewater treatment company was also analyzed in order to compare it to the ones collected in the monitoring wells inside the cemetery. Hydrological investigations were also carried out aiming to diagnose and delimit the watershed that includes the cemetery.

Therefore, this article aims to characterize the vulnerability of underground waters in the areas influenced by a cemetery. Both physicochemical and microbiological parameter data collected along 11 years were analyzed to assess the potential impact of the body residuals to pollute the groundwater. The studies were also supported by hydrological and geotechnical investigations of the Fundo river watershed and complementary water analysis from neighbors cisterns located nearby the cemetery.

# 2 Material and methods

This research was divided into four steps: a) on site water sample collection; b) physicochemical and microbiological water analyses; c) data analysis; and d) hydrological and geotechnical investigations.

## 2.1 The cemetery

The Jardim Metropolitano Cemetery and Crematorium of Valparaíso de Goiás is located at the outskirts of Brasília DC, Brazil, in an area of 300,000 $m^2$, Figure 1. It presents an average of 40 burials per month, with records showing around 10,000 burials since its opening in 1998 (pandemic covid-19 data is not included).

## 2.2 Water sample collection

To assure the quality of the underground water three monitoring wells (MW01, MW02, and MW03), Figure 3, were built following Brazilian standards (ABNT NBR 15495-1, 2007) inside the cemetery. Wells MW01 and MW02, 10 m depth and 122 m apart from each other, were built near the ground burial area. A reference well (MW03, 40 m depth) was built outside the area of influence of the cemetery's contamination 780 m apart from MW02.

In the overall, 115 water samples were collected and analyzed between 2007 and 2018 but the final data set contains the results for 104 samples. Results from samples collected in 2007 (4 samples) and 2017 (7 samples) were considered outliers due to contamination from the well drilling and ants, respectively.

In order to compare the quality of water in the vicinity of the cemetery with data collected from monitoring wells inside the cemetery the data for a set of 10 samples collected in 2017 in 10 home cisterns located nearby the cemetery location by the local water and wastewater treatment company (SANEAGO) was also analyzed.

## 2.3 Physicochemical and microbiological water analyses

After collection, water samples were kept between 2 and 6 °C at the QUINOSAN Chemical Analysis Laboratory Ltd (QUINOSAN). Water quality monitoring was evaluated for 25 analytical parameters (20 physicochemicals and 5 microbiologicals) following Brazilian standards (Ministry of Environment of Brazil, 2005, 2008). Table 1 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 $L^{-1}$.

Physicochemical analyses were performed following Instituto Adolfo Lutz (2008) standards but biological oxygen demand (BOD) analyses followed the Standard Methods for the Examination of Water and Wastewater (Rice et al, 2017). Microbiological analyzes were based on Siqueira (1995).

## 2.4 Soil Analysis

Soil liquid and plastic limits followed regulation norm ABNT NBR 6459 (2016). Soil plasticity index followed ABNT NBR 7180 (2016) and grain size analysis followed ABNT NBR 7181 (2016). The specific gravity of soil samples was measured from a dry sample taking the weight-volume ratio and soil-water retention curves were obtained using a WP4C Dewpoint Potentiometer from Decagon Devices.

## 2.5 Data analysis

The water analysis data set contains the results of 20 physicochemical and 5 microbiological parameters for 104 samples collected in the 3 monitoring wells. The water analyses from the home cisterns data set contains the results

**Table 1**: Maximum contaminant level (MCL) established for drinking water quality according to Brazilian standards[1] and its respective limit of detection (LoD).

| Physicochemical parameter | MCL | LoD |
|---|---|---|
| Alkalinity[2] | 500 | 0.1 |
| pH | 6.0[9] - 9.0 | 0.001 |
| Phosphorous[2] | 0.025 | 0.01 |
| Conductivity[3] | not specified | 0.01 |
| Manganese[2] | 0.1 | 0.01 |
| Hardness[2] | 0.5 | 0.1 |
| Iron[2] | 0.3 | 0.01 |
| Chromium[2] | 0.05 | 0.001 |
| Ammonia[2] | 1.5 | 0.001 |
| Nitrite[2] | 1 | 0.001 |
| Nitrate[2] | 10 | 0.0001 |
| Lead[2] | 0.01 | 0.0001 |
| Mercury[2] | 0.001 | 0.001 |
| Silver[2] | 0.1 | 0.001 |
| Cadmium[2] | 0.005 | 0.001 |
| TDS[2],4 | 1000 | 0.01 |
| COD[2],5 | 3.69 | 0.1 |
| BOD[2],6 | 3 | 0.1 |
| Turbidity[7] | 5 | 0.01 |
| Microbiological parameter[8] | | |
| Mesophyll | 500 | 3.0 |
| Thermotolerant coliforms | 0 | 0 |
| Total coliforms | 0 | 0 |
| Clostridium | 0 | 0 |
| Escherichia coli | 0 | 0 |

[1]references Ministry of Health of Brazil (2011); Ministry of Environment of Brazil (2005, 2008)

[2]mg $L^{-1}$

[3]$\mu S\ cm^{-1}$

[4]total dissolved solids

[5]chemical oxygen demand

[6]biological oxygen demand

[7]FTU

[8]CFU $mL^{-1}$

[9]*minimum* level

of 10 samples. 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 redundant (RDA) and principal component data analyses (PCA).

## 2.6 Hydrological and geotechnical investigations

The hydrological investigations included the diagnosis and delimitation of the watershed that includes the cemetery. This represents the Fundo river watershed (Figure 3) for the evaluation of the drainage network, in addition to the verification, delimitation, and understanding of the underground aquifer and its possible influence on percolative behavior . In addition, both topographic profile and soil surface hypsometry were also evaluated to support the elaboration, verification, and evaluation of the land use map, according to slope classes proposed by the Brazilian Agricultural Research Corporation (EMBRAPA, 1979).

Rain data was collected from the rainfall station closest to the study area, covering the years 1963 to 2018 (National Institute of Meteorology of Brazil, 2022) to assess the influence of percolation and other hydrological (infiltration and runoff) and geotechnical (erosion) processes.

A Digital Elevation Model (DEM) from *Topodata* (Valeriano and Rossetti, 2008) was employed 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 the 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 automatically processed by the Qgis software, version 3.10, using SIRGAS 2000 datum and geographic-type cartographic projection.

Map of land use was manually generated based on a satellite image made available free of charge by Google Earth, year 2019, and validated with in 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 the scale of 1:1,000,000.

Geotechnical investigations carried out physical characterization of the soil and the determination of hydraulic conductivity and soil-water retention curve (SWRC). This step is divided into two phases. Phase 01 included collection of deformed and undisturbed samples near the monitoring wells MW1 and MW3 (see Figure 3 for wells location) to carry out the laboratory geotechnical 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 carried out for deformed samples; while density, SWRC and hydraulic conductivity tests were carried out for undisturbed samples. The results of the suction tests relied on the use of shaft translation equipment,

**Table 2**: Statistical data distribution for the aquifer water samples collected in the monitoring wells located at the Jardim Metropolitano Cemetery of Valparaíso de Goiás, Brazil, from 2008 to 2016, and 2018.

| Analysis | Statistics[8] | | | | | | |
|---|---|---|---|---|---|---|---|
| | min | Q1 | med | mean | Q3 | max | sd |
| Alkalinity[1] | 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[1] | 0.12 | 4.05 | 4.88 | 4.98 | 6.03 | 9.98 | 1.62 |
| Conductivity[2] | 6.69 | 17.06 | 23.75 | 24.74 | 30.60 | 70.50 | 11.02 |
| Hardness[1] | 3.79 | 8.16 | 8.16 | 10.55 | 12.24 | 40.82 | 6.33 |
| Turbidity[6] | 0.02 | 0.19 | 0.51 | 5.62 | 2.90 | 54.10 | 12.30 |
| Iron[1] | 0.06 | 0.22 | 0.36 | 0.72 | 0.70 | 7.89 | 1.17 |
| TDS[1,3] | 6.10 | 14.54 | 20.42 | 20.83 | 26.00 | 51.30 | 8.50 |
| COD[1,4] | 1.37 | 4.00 | 5.36 | 5.51 | 6.48 | 21.00 | 2.58 |
| BOD[1,5] | 0.00 | 2.90 | 3.40 | 3.82 | 4.57 | 13.95 | 1.90 |
| Mesophyll[7] | 0.00 | 14.50 | 29.50 | 46.08 | 58.25 | 422.00 | 56.60 |

[1]mg $L^{-1}$

[2]$\mu$S $cm^{-1}$

[3]total dissolved solids

[4]chemical oxygen demand

[5]biological oxygen demand

[6]FTU

[7]CFU $mL^{-1}$

[8]min, max = minimum and maximum; Q1 and Q3 = 1st and 3rd quartils; med = median; sd = standard deviation

Fredlund cell model (low suction up to 500 kPa) and Dewpoint Water Potentiometer model WP4C from Decagon Devices Inc. (high suction, from 500 to $10^5$ kPa).

# 3 Results and Discussion

## 3.1 Water quality from the monitoring wells located inside the cemetery area

Ten out of twenty physicochemical parameters (phosphorous, manganese, chromium, ammonia, nitrite, nitrate, lead, mercury, silver, and cadmium) were find below LoD (Table 1) for all samples. For the microbiological parameters, only one (mesophyll) out of five was detected. In the end, 11 parameters (10 physicochemicals and 1 microbiological) presented values above LoD. Table 2 summarizes the statistical data distribution for all 11 analytical parameters having statistical significance measured in the three monitoring wells.

Alkalinity, hardness, TDS, and mesophyll levels (Table 2) were always find below MCL according to Brazilian standards for drinking water quality, Table 1, for all three monitoring wells. As a result, 7 out 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 (cubic polynomial) functions and are presented in Figure 4.

Some pH values in Figure 4a are below the minimum recommended level (pH = 6.0, horizontal dashed line) and they are related to the intense leaching of the laterite soil (Dwevedi et al, 2017). This soil becomes acid due to the tropical climate and its mineralogy composition. The major composites such as Ca, Mg, K, and P are leachate for years due to rainfall in such a way that those components of lower geochemical mobility such as Fe and Al (oxy-hydroxides) are more abundant (de Carvalho et al, 2012). The profiles for all three monitoring wells are very similar and they are strongly correlated to each other indicating that the pH is not influenced by the cemetery activity.

Most of the results obtained for the dissolved oxygen (Figure 4b) are lower than 6.0 mg $L^{-1}$ (horizontal dashed line). When compared to surface waters the oxygen level in underground water is expected to be lower (Mendes et al, 2019) since the aquifer is constrained from the dynamic of exchanging oxygen with the atmospheric air (Figure 2). The results for MW01 and MW02 indicate a similar pattern. On the other hand, MW03 oxygen levels seem to be uncorrelated with 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 correlation found between MW01 and MW02 dissolved oxygen data and the respective no correlation with MW03 was also found for conductivity (Figure 4c), turbidity (Figure 4d), and iron (Figure 4e) values. Plus, the result found for turbidity strongly indicates that there is no influence of the cemetery on the aquifer. Turbidity values were, in general, below MCL for MW01 and MW02 (Figure 4d).

Many samples presented iron contents above MCL (Figure 4e). However, this result is not related to the influence of the cemetery since the iron level in the human body is ca. 9 mg $kg^{-1}$ (Cook et al, 2003). Thus, the main source of iron that may be affecting both the analyzed iron contents and the turbidity comes from the oxisol, a tropical red earth which have a relatively high content of iron oxides (Hasiotis et al, 2007).

Most COD and BOD (Figures 4f and 4g, respectively) results are above the MCL. However, COD and BOD values for both MW01 and MW02 are highly correlated with the ones for the reference well, MW03, indicating that the cemetery is not influencing the aquifer.

Through the analysis carried out up to this point it is possible to realize that, according to the Brazilian standards, the aquifer was not being contaminated by the cemetery.

### 3.1.1 Multivariate analysis

Multivariate data analysis applied to the aquifer data included monthly precipitation data collected from the INMET database (National Institute of Meteorology of Brazil, 2022). The data matrix of 104 observations/samples by

10 variables (being 7 variables from Table 2, 1 for the monitoring wells, 1 for the year, and 1 for the 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%. Which means that the aquifer data set is not structured by the two explanatory variables *monitoring wells* and *year*. The biplot of the PCA can be visualized in Figure 5 and the correlation of the factors iron, turbidity, and rainfall strongly supports the fact that both iron and turbidity are influenced by the intense leaching of the soil due to the rainfall.

## 3.2 Water quality from the cemetery's neighborhood

To assess whether there were other sources of water pollution used by the population the local water and wastewater treatment company (SANEAGO) collected water samples in 2017 in neighboring cisterns around the cemetery. The summary of laboratory reports can be seen on Table 3.

All alkalinity, manganese, nitrite, and TDS values were find below MCL in Table 3 and six samples presented pH values below 6. Despite the fact that MCL for conductivity is not specified by the Brazilian standards (see Table 1) its values for 8 samples were above the maximum value of 70.50 $\mu$S cm$^{-1}$ found for the monitoring wells analyzed inside the cemetery (Table 2). Only two samples presented iron values above MCL and only one presented nitrate content above MCL.

As it can be realized, physicochemical data collected from the cisterns in the neighborhood of the cemetery present some differences. But the major impact on the water quality originates from the two microbiological parameters *Total coliforms* and *Escherichia coli*. As a consequence, when comparing the results in Tables 2 and 3 it indicates that this contamination can not be related to the cemetery activity since these two microbiological parameters were reported absent in *all* samples collected inside the cemetery.

## 3.3 Hydrological and geotechnical investigations

### 3.3.1 Hydrological investigations

The Fundo river watershed in which the cemetery is located comprises an area 8.42 km$^2$ and a perimeter of 14.27 km, with a large part of its area in urban or modified environment with some fragments of vegetation (Figure 6).

Figure 7 shows the physical characteristics of the existing relief in the Fundo river watershed such as slope (Figure 7a), hypsometry (Figure 7b), and land use (Figure 7c).

From a topographic (slope and hypsometry) and hydrogeological point of view, the locations of the monitoring points were strategically chosen (located) in an attempt to better understand the percolation behavior of water and its transported compounds and their possible interference in groundwater.

**Table 3**: Water quality analysis from 10 samples collected[1] in home cisterns located outside the cemetery area.

| Analytes | Home cisterns | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | I | J |
| Alkalinity[2] | 10 | 21 | 12 | 10 | 3.89 | 80 | 13 | 40 | 50 | 30 |
| pH | 5.71 | 5.66 | 5.7 | 5.61 | 3.89 | 6.15 | 5.85 | 6.12 | 6.37 | 6.98 |
| Conductivity[3] | 16.19 | 99.8 | 162.2 | 100.71 | 83.6 | 148.7 | 23.24 | 98.2 | 155.8 | 135.6 |
| Iron[2] | 0.5 | 0.2 | 0.03 | 0.01 | 0.12 | 0.02 | 0.00 | 0.27 | 0.12 | 0.33 |
| TDS[2] | 8.9 | 54.89 | 89.21 | 55.39 | 45.98 | 81.79 | 12.78 | 54.01 | 85.69 | 74.58 |
| Nitrite[2] | 0.002 | 0.000 | 0.012 | 0.003 | 0.000 | 0.000 | 0.0016 | 0.004 | 0.012 | 0.009 |
| Nitrate[2] | 0.6 | 6.7 | 6.1 | 7.1 | 25.6 | 0.4 | 0.8 | 2.2 | 4.5 | 3.6 |
| Manganese[2] | 0.024 | 0.031 | 0.025 | 0.015 | 0.020 | 0.020 | 0.028 | 0.031 | 0.022 | 0.336 |
| Total coliforms[4] | P | P | P | P | P | P | P | P | P | P |
| Escherichia coli[4] | A | P | P | P | A | P | P | P | P | P |

[1]source: SANEAGO (local state water and wastewater treatment company)

[2]mg $L^{-1}$

[3]$\mu$S $cm^{-1}$

[4]P = present; A = absent.

**Table 4**: Relief classes[1] and areas in relation to the slope of the watershed in which the Jardim Metropolitano cemetery is located.

| Slope (%) | Relief | Area km$^2$ | Area % |
|---|---|---|---|
| 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 |
| 45.0 - 75.0 | mountainous | 0.00 | 0.00 |
| > 75.0 | strong-mountainous | 0.00 | 0.00 |
| | Total area (km$^2$) | 8.42 | |

[1]following reference EMBRAPA (1979).

Figure 7a presents the slope of the terrain which complements and supports the hypsometry (Figure 7b). It is noticed that the drainage networks that make up the watershed of the Fundo river, mainly in the main channel of this river, have a higher percentage of declivity ranging from 3.0 to 20.0%. On the watershed boundaries the declivity ranges from 20.0 to 45.0%; and on the stretches upstream from 0.0 to 3.0% (Figure 7b and Table 4). Thus, based on the physical characteristics of the land in the study area, Figure 7, the location of the MW03 well is very representative for monitoring both surface and underground water flow. 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 MW03.

Thus, significant changes in the water quality parameters of the monitoring well MW03 in relation to the other two (MW01 and MW02) can result from both the flow and the decomposition of the cemetery leachate towards the watercourse, which was not noticed in this study over the monitoring time.

Analyzing the hypsometry (topography), which measures the elevation and depth of a terrain, the watershed area has a maximum altitude of 1,102 m (watershed boundary) and a minimum of 891 m (the mouth of the Fundo river) representing 211 m of total difference in elevation, while the height of the water source of the Fundo river is 1010 m. Thus, it is inferred that almost half of the total unevenness of the watershed comprises the stretch of maximum altitude and the location of the cemetery.

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

Regarding land use, it is clear that the cemetery is strongly influenced by runoff from part of the rains that cannot infiltrate into the soil in the highest part of the Fundo river watershed. It happens because it is where most of the waterproofing of this watershed is located.

Thus, the land use map enabled the identification and demonstrated little variability of the surface soil in the area and vicinity of the cemetery. This allowed us to carry out a smaller number of samples to identify the soil hydraulic conductivity, $k_{sat}$, 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 be performed 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).

### 3.3.2 Geotechnical investigations

Seven undisturbed samples of the soil cemetery (study site) having 0.4 $m^3$ were collected at different locations (three near the graveyard, one between MW01 and MW02, and three near MW03) at three depths (0.3, 1.0, and 2.0 m). All samples were wrapped in paraffin preserving their original characteristics. Based on physical indexes (specific gravity, plastic and liquid limits, plasticity index, soil moisture, and hygroscopic water) and Atterberg limits (results not shown) 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 soil classification with and without the use of SHMP indicates that this soil is lateritic, highly porous, and has a bimodal porous behavior.

Two types of soils were characterized based on SWRC (Supplementary Information, Figure A1) and particle-size distribution plots (Supplementary Information, Figure B2): clayey and silty with bimodal structural behavior, i.e. macro- and micropores.

The clayey graveyard soil does not fit into the description of a typical clayey soil due to its structural characteristics like hydraulic conductivity and soil percolation. There are cementations and a high content of both iron and aluminum oxides (red or yellow oxisols) which are characteristics of highly weathered soils.

The saturated hydraulic conductivity of $4.1 \times 10^{-5}$ $ms^{-1}$ indicates a weathered tropical soil similar to fine sands since typical clayey soils present values between $10^{-10}$ and $10^{-6}$ $ms^{-1}$ (Kardena et al, 2014). Even when considering a clay percentage greater than 50% the conductivity value is similar to a sandy soil (Araki, 1997) having 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 sands and gravels are not indicated for the superficial layers of the cemetery. These type of soils present high hydraulic conductivity and low retention capacity of contaminants so that the human body remains would percolate all the way down to the aquifer. And that was not the soil found in the Jardim Metropolitano cemetery.

On the other hand, anaerobic conditions prevail in thin soils such as clays since their hydraulic conductivity are very low hindering the gradual human decomposition process. Again, that is not the cemetery soil since it presents a good draining capacity for suction under natural field conditions (up to 100 kPa, Supplementary Information, Figure A1) due to presence of micro and macropores. Thus, the soils found in the cemetery can be considered suitable for this type of activity in face of the physical, granulometric, and flow characteristics (hydraulic conductivity, $k$).

Even when compacted or when a large amount of water is present (heavy precipitation) the cemetery soils still exhibit the same hydromechanical behavior, i.e. high hydraulic conductivity and porosity. As an example, for the soil sampled at MW01 (0.30 m) when in the state of optimum compaction (optimum soil moisture of 28% and compacted dry specific mass of 1.51 g $cm^{-3}$) it still has a porosity of approximately 45%. It represents a reduction of only 10% of porosity when related to its natural state (uncompacted).

## 4 Conclusion

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

Collected water samples in areas outside the cemetery do not comply with Brazilian norms for drinking water. Since two microbiological parameters (Total coliforms and Escherichia coli) were reported absent in all samples collected inside the cemetery this contamination can not be related to the 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 of bimodal behavior. This soil has a great capacity of retention of the contaminants and for suction above natural field conditions (up to 100 kPa) it presents a very low hydraulic conductivity. As a consequence, the unsaturated area above the aquifer favors the absorption of the body residuals from the soil, preventing it from reaching the aquifer. In the overall, the favorable topographic and hydromechanical behavior of the soil favor the low environmental impact of the cemetery.

In the end, this multidisciplinary study concludes that the water samples collected inside the cemetery wells present low vulnerability to both subsurface and underground contamination.

**Supplementary information.** Soil-water retention curves (SWRC) and particle-size distribution plots can be visualized in Figures A1 and B2, respectively.

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Material preparation, data collection and analysis were performed by E.D. Saba. The first draft of the manuscript was written by A.E. de Oliveira and all authors commented on further versions of the manuscript. All authors read and approved the final manuscript.

# Appendix A Soil-water retention curves

# Appendix B Particle-size distribution plots

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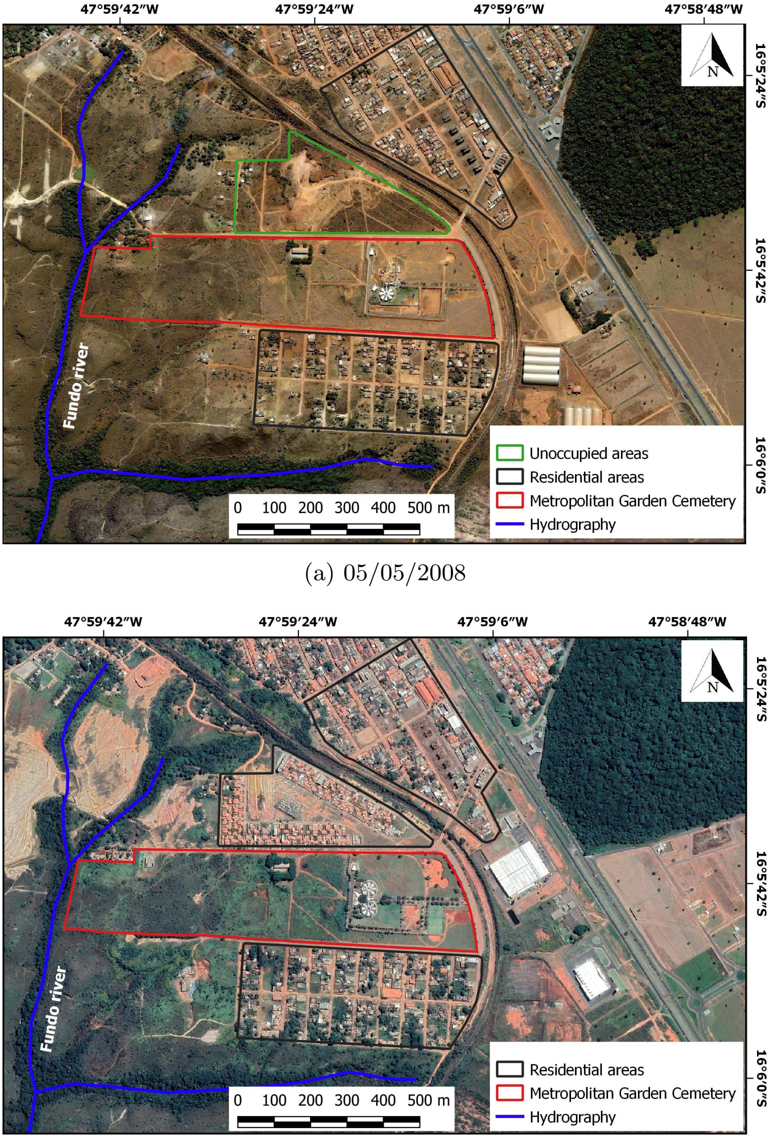



(a) 05/05/2008



(b) 08/05/2019

**Fig. 1**: Satellite images of the Jardim Metropolitano Cemetery of Valparaíso de Goiás, GO, Brazil, taken a) 05/05/2008 and b) 08/05/2019.

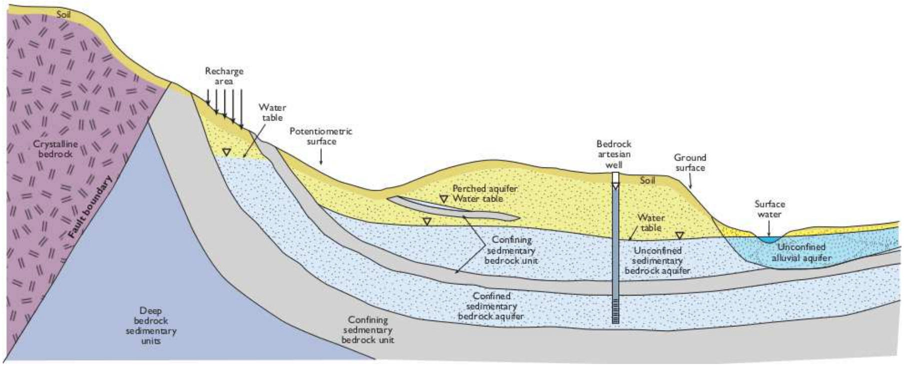



**Fig. 2**: Illustration of the main types of aquifers (Barkmann et al, 2020).


**Fig. 3**: Fundo river watershed (bordered in pink) including the Jardim Metropolitano cemetery (bordered in red) and the monitoring wells MW01, MW02, and MW03 (green bullets).

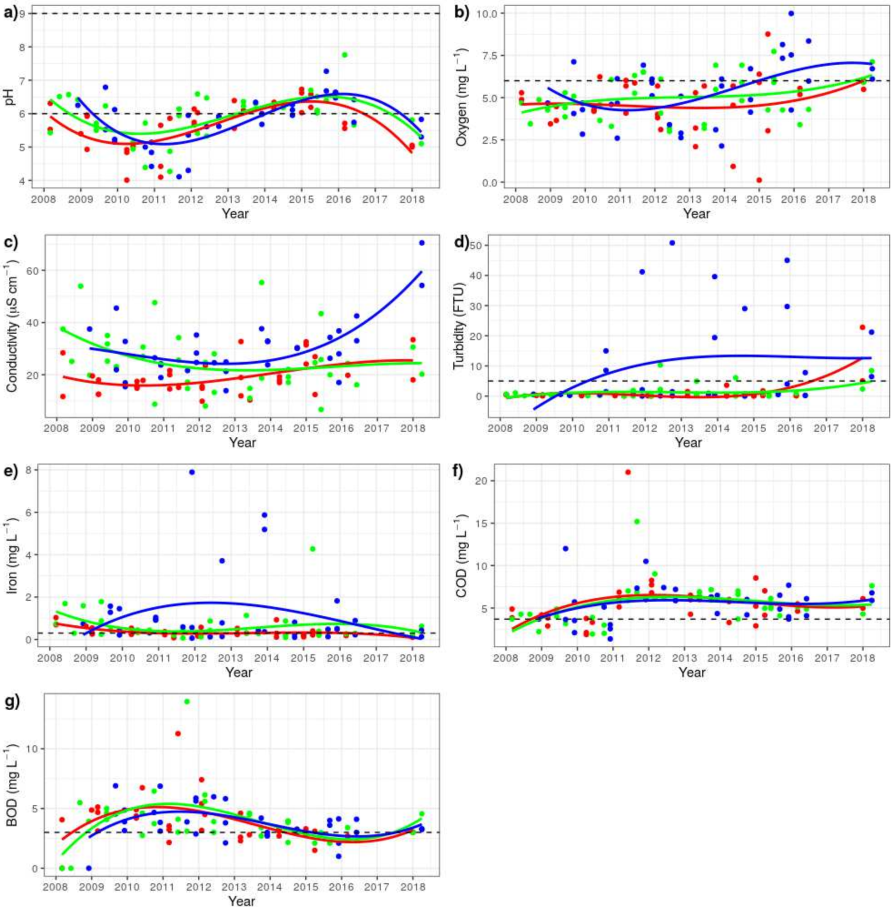



**Fig. 4**: Water quality parameters measured over the years for the three monitoring wells (• MW01; • MW02; • MW03): a) pH, b) oxygen, c) conductivity, d) turbidity, e) iron, f) COD, and g) BOD; Horizontal dashed lines indicate Brazilian standards (see Table 1) and continuous lines represent smoothed conditional means.

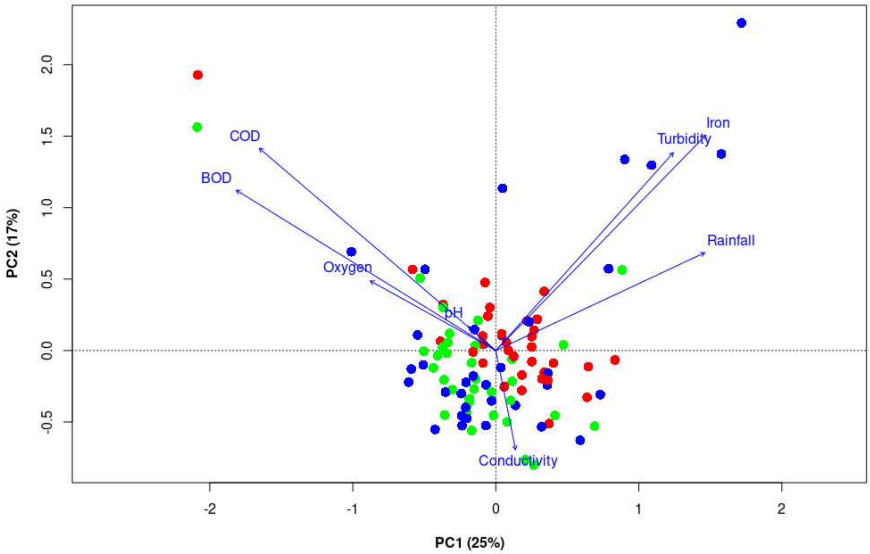



**Fig. 5**: Biplot of the principal component analysis of the aquifer data. Colored points represent monitoring wells (• MW01, • MW02, and • MW03). This plot explains 42% of the data variance.

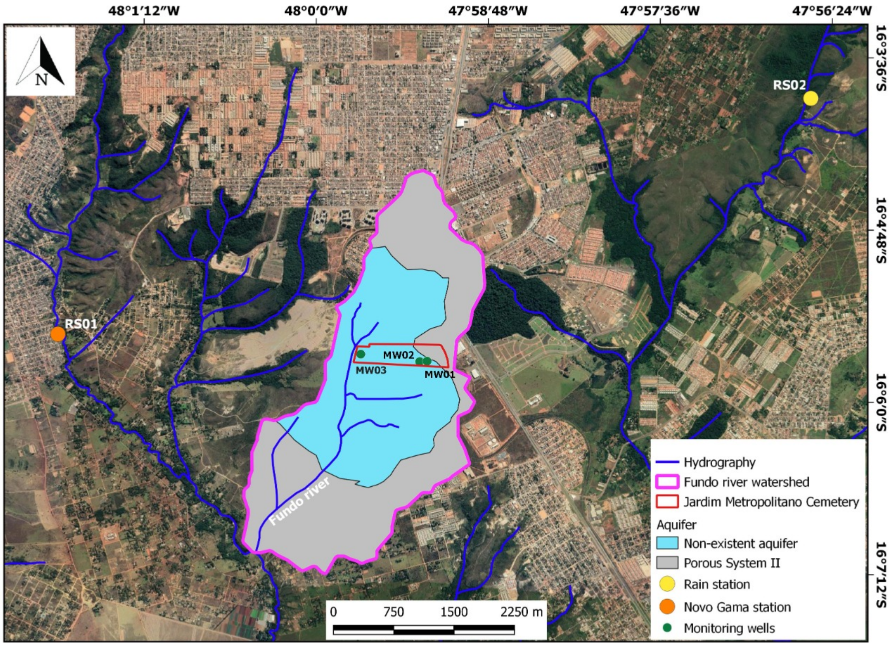
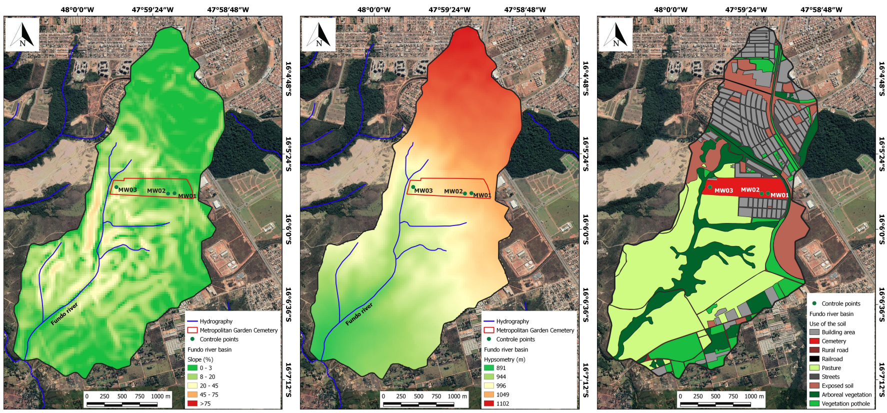
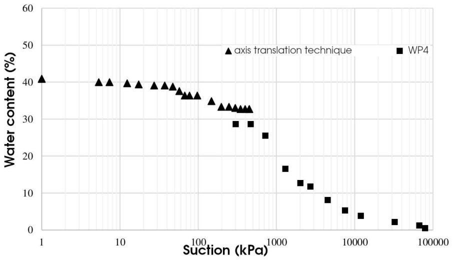



**Fig. 6**: Fundo river watershed including rain stations RS01 (orange bullet on the left) and RS02 (yellow bullet on the top right).

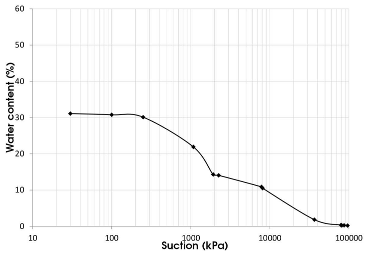



(a) Slope. (b) Hypsometry. (c) Land use.

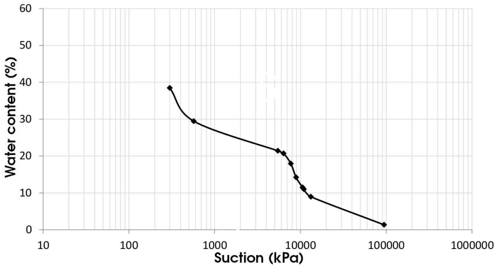
**Fig. 7**: Physical characteristics of the Fundo river watershed: a) slope; b) hypsometry; and c) land use.



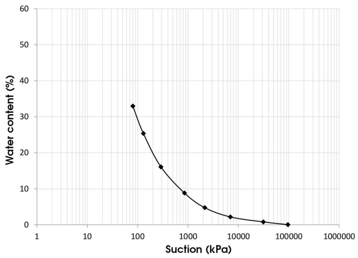

(a)




(b)

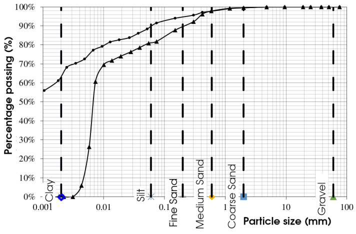



(c)

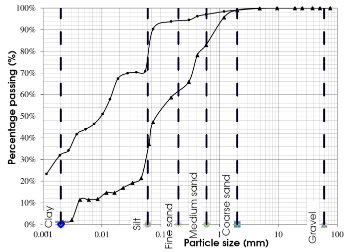



(d)

**Fig. A1**: Soil-water retention curves from samples collected at three different locations and depths: a) Graveyard at 0.30 m; b) MW01 at 1.0 m; c) MW01 at 2.0 m; and d) MW03 at 1.0 m.




(a)

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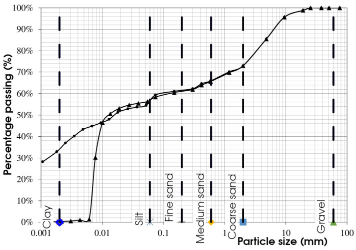
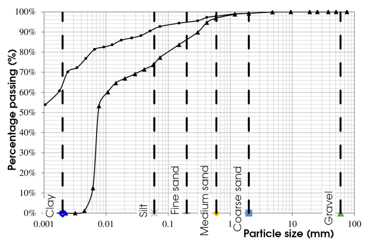
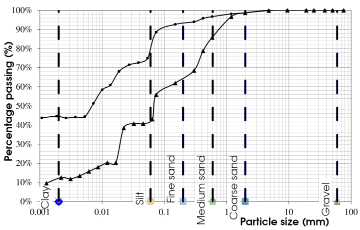


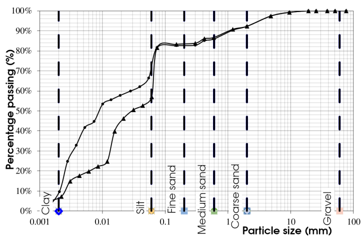

(c)



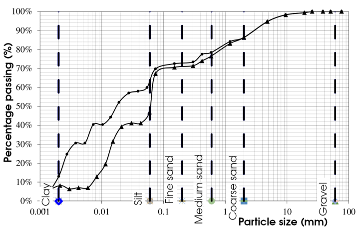

(d)




(e)




(f)




(g)

**Fig. B2**: Particle-size distribution plots for untreated (▲) and treated with SHMP samples (●) collected at three different locations and depths: a) Graveyard at 0.30 m; b) Graveyard at 1.0 m; c) Graveyard at 2.0 m; d) MW01 at 1.0 m; e) MW01 at 2.0 m; f) MW03 at 1.0 m; and g) MW02 at 2.0 m.