



Characteristics and impacts on the groundwater of the Guriri beach resort, São Mateus, ES, Brazil

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Abstract

Water abstraction from phreatic aquifers allows easy access at low cost. However, these waters' direct consumption can be harmful, especially in unsewered areas where domestic effluents are discharged into cesspits. This study assesses the quality of the groundwater explored by the Guriri beach resort residents. Samples from 35 residential wells were characterized, considering physicochemical and microbiological parameters. The water balance (rainfall–evapotranspiration), proximity to the shoreline, and separation between the well and the cesspit were taken into account in the interpretations. The evaluation with statistical tests (mean and correlation), graphs (Piper and Gibbs), and multivariate techniques (PCA and HCA) allowed the separation of two chemically distinct groups of waters. One from shallow wells (3 to 4 m depth) with lower electrical conductivity (EC) and acidic characteristics and the other gathering the deeper wells (11 to 13 m) with higher EC and neutral pH. All samples were classified as freshwater (TDS < 1 g/L), but its quality was compromised by permissible values infractions for pH, Fe_T, Cl⁻, HCO₃⁻ and by the presence of thermotolerant coliforms and *E. Coli*, in 50 and 20% of the wells, respectively. The participating residents were instructed on how to treat the waters by filtration and chlorination techniques. The effects of marine intrusion were absent. Moreover, the alternation between months with negative and positive water balance explains the groundwater EC values variation due to the accumulation and leaching of salts to the aquifer. The study revealed the aquifer vulnerability and the need for higher protection of this vital water source.

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1 Introduction

Water is an essential resource for all living beings, whose quality is one of the most important indicators of a population's well-being or vulnerability (Minayo et al. 2000). The availability of drinking water sources is decisive for society's sustainability (WHO 2017).

In coastal areas, as well as in arid and semiarid regions, fresh surface waters are scarce or of low quality, which leads to the exploitation of aquifers, due to their less seasonal variability and ease of abstraction (Kumar et al. 2011; Amiri et al. 2016; Karunanidhi et al. 2020; Liu et al. 2020). In Brazil, groundwater accounts for 50% of the public water supply (ANA 2017). The underground reserves exploration was further intensified to overcome the surface water crisis resulting from the rainfall shortage over the period 2015–2016 (Marengo et al. 2017, 2018). The drilling of residential wells in São Mateus, ES, increased substantially after the collapse of the public supply, which relies on capturing the waters of the São Mateus River (Decree N° 9.319/2017 2020).

Compared to deep aquifers, phreatic groundwater is a lot easier to capture. Moreover, generally, it has good quality, given the recharge from precipitation and rivers (Naik and Awasthi 2003; Belkhir and Mouni 2012; Tubau et al. 2017). In urban areas, the topmost aquifers have undeniable strategic importance in developing peripheral neighborhoods (Peixoto et al. 2020). The groundwater composition is mainly controlled by the mineralogical composition of the watershed and aquifer layers, rainfall regime, residence time, and aerosol deposition (Schot and Der Wal 1992; Islam et al. 2019). The alteration of these natural processes by anthropic activities, such as excessive abstraction, seepage of cesspits, and application of fertilizers and pesticides, compromises water quality (Chae et al. 2008; Prasanth et al. 2012; Affum et al. 2015; Rao et al. 2017; Gharbi et al. 2019; Akhtar et al. 2019; Mielke et al. 2020; Gaikwad et al. 2020; Costall et al. 2020).

The disordered growth of many Brazilian cities with precarious or nonexistent sanitation infrastructure has forced isolated populations or those from peripheral neighborhoods to resort to alternative water collection systems and to dispose of the domestic sewage in rudimentary cesspits or directly into water bodies (Silva 2003; Hirata et al. 2007, 2016; Malheiros et al. 2009; Oliveira and von Sperling 2011; Withers et al. 2013; Huang et al. 2013; Cotta et al. 2017; Marras et al. 2020). The contamination of an urban aquifer of Fortaleza city due to its sewage collection system's precariousness was recently demonstrated by Peixoto et al. (2020). The influence of socioeconomic factors, local sanitation infrastructure, and water quality was evidenced by Pacata et al. (2020) and Ducci et al. (2020).

There are many cases of aquifer contamination by disease-causing bacteria, infectious viruses, and household chemicals in locations lacking a sewage system in Brazil (Gomes et al. 2011; Capp et al. 2012; Kronemberger 2013; Suhogusoff et al. 2013; Cavalcante 2014; Hirata et al. 2015; Oliveira et al. 2015; Neto et al. 2017; Varnier et al. 2017; Sabino et al. 2020). According to Hirata et al. (2019), pathogens' contamination can spread from the water table to as depth as 60 m.

The presence of thermotolerant coliforms (TC) and *Escherichia coli* (*E. Coli*) in water is a reliable indicator of fecal contamination (WHO 2017). Mazhar et al. (2019) reported that about 30% of Pakistan's deaths are related to groundwater consumption contaminated by pathogens given the absence of basic sanitation. Domiciles supplied with groundwater captured with shallow wells are subject to waterborne diseases, since, generally, no treatment

technique is used before consumption (Neto et al. 2017). Besides, the lack of monitoring of these sources, the population's unfamiliarity of the causes, and problems associated with groundwater contamination contribute to a higher incidence of diseases. The present study focused on evaluating the physicochemical characteristics and the microbiological contamination of the groundwater used by residents of Guriri, São Mateus—ES (Brazil), a coastal resort region devoid of a sewage system and without studies on the potability of its waters. The study has involved high school students in alerting the local population about the risks associated with these waters' consumption.

2 Methodology

2.1 Study area

The city of São Mateus ($18^{\circ}43'09''$ S; $39^{\circ}51'09''$ W) is 221 km from Vitória, capital of Espírito Santo (ES) State (Fig. 1). The neighborhood of Guriri, São Mateus, has grown at an accelerated pace. Officially, there are about 10,000 inhabitants (IBGE 2010), but more recent estimates indicate a population of 20,000 (Lira and Cavatti 2016). Due to the beauty of its warm water beaches, the beach resort receives a large number of tourists during the summer (between 100 and 150 thousand people), especially during new year's and Carnival festivities (CHSM 2019).

Despite the economic and tourist development, Guriri does not have a sewage collection system. Therefore, all households discharge their domestic effluents into cesspits. Besides that, many houses are not connected to the public water supply system. Even the

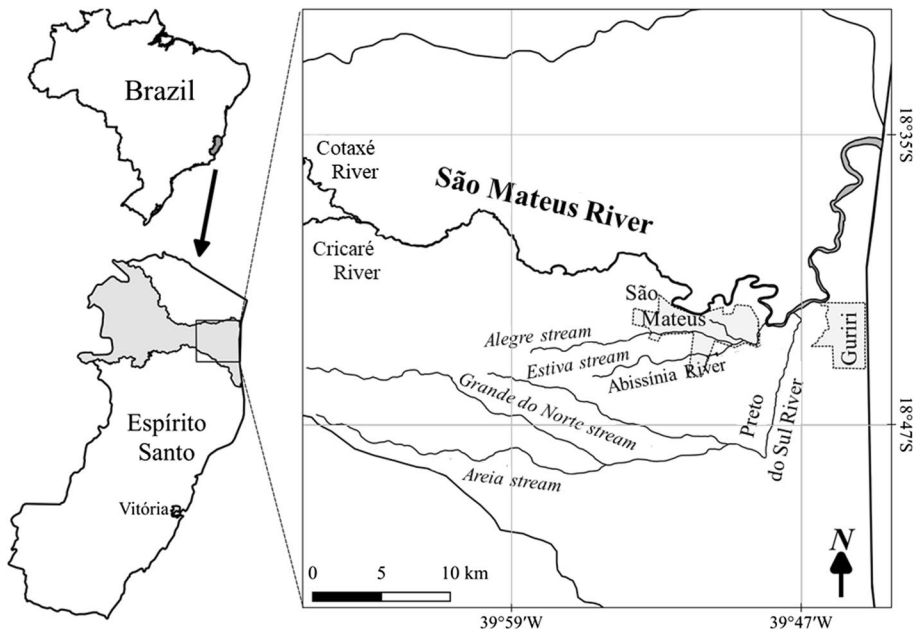


Fig. 1 Study area location

ones assisted by it also appeal to shallow wells' drilling to complement their provision in periods of high demand and irregular public supply (summer season). Thus, most homes, hotels, and other businesses have a well as an individual water supply solution. A movement intensified since the 2015–2016 hydric crisis (Alvalá et al. 2019), in which even the central neighborhoods of São Mateus city were under a water rationing (Decree N° 9.319/2017 2020), as a consequence of the marine intrusion in the São Mateus River during a period of low discharge.

The climate in northern ES is tropical (Am) with hot and rainy summers, with 31 to 34 °C and 70% of the annual rainfall of 1100 mm·year⁻¹ concentrated between October and March, and dry winters, 13 to 18 °C (Ramos et al. 2016). The standardized precipitation index (SPI) classifies northern ES as susceptible to severe droughts between November and January (Uliana et al. 2017). This period coincides with the festivities and an increase of up to 500% in Guriri's population, which intensifies groundwater exploration.

The study area, circumscribed by the 35 sampled wells, is 15 km² (Fig. 2a). Its relief is flat, with an altitude of about 5 m above sea level.

This fluvic–alluvium plain can be considered as a multilayer system with high permeability. In the unconfined aquifer, the water table appears between 2 and 3 m deep in a substrate initially composed of layers (grayish, yellowish, and reddish) of sandstone with about 2 m of thickness up to 5 m. Then, there are layers of reddish clay up to 8 m and whitish clay up to 16 m deep, encompassing the greater quantity of water abstractions with PVC tubular wells (Ø 100 mm). The quaternary sediments consist of medium- to fine-grained quartz sands, with feldspars and micas dispersed between silty clay and clay interleaving, mostly related to floodplains of the Barreiras Formation (Albino et al. 2006).

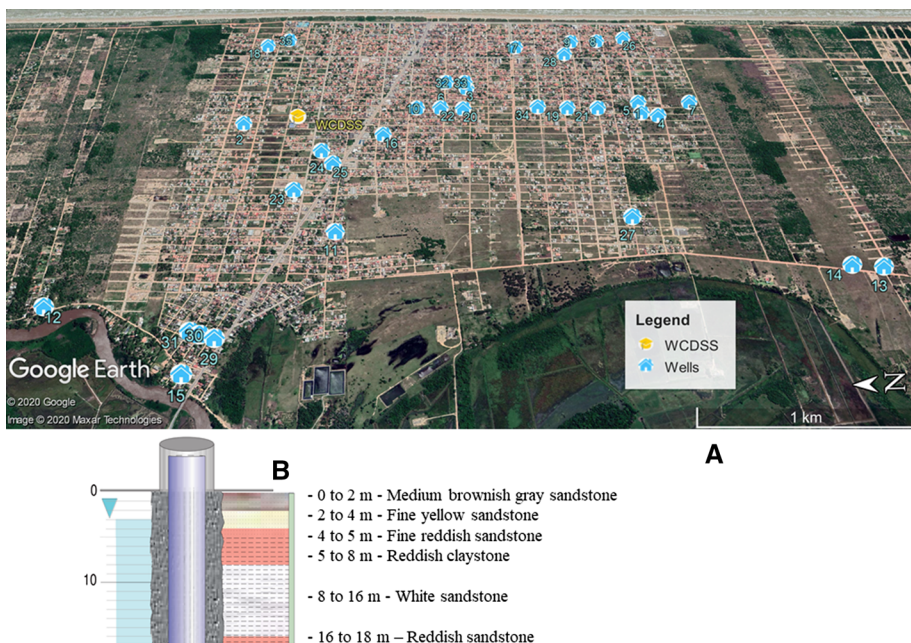


Fig. 2 Sampling points. **a** Location of the 35 wells and the Wallace Castelo Dutra State School (WCDS) in Guriri, São Mateus, ES. **b** Subsoil profile

2.2 Groundwater sampling, characterization, and results representation

High school students from the Wallace Castello Dutra State School (WCDSS) were trained on the techniques for collecting samples (NBR 9898 1987) and performing the hydro-chemical characterization (APHA 1998). Sampling was performed after 2 min of pumping, using sterilized and decontaminated glass vials (1L), and analysis took place on the same day. The students registered the wells and recorded the depth and the distance between the well and the cesspit. They assisted in the measurements of pH and EC with portable sensors (KR20 and KR31, AKROM), and during the determinations of alkalinity (HCO_3^-), total hardness ($\text{Ca}^{+2} + \text{Mg}^{+2}$, both expressed as mg/L of CaCO_3) and chloride (Cl^-) by volumetric techniques.

The concentrations of sodium (Na^+) and potassium (K^+) by flame photometry (Q498M2, Quimis), sulfate (SO_4^{2-}) by turbidimetry (ITEST—IDLT-WV), and total soluble iron ($\text{Fe}_T = \text{Fe}^{+2} + \text{Fe}^{+3}$) by colorimetry (Genesys 10S, Thermo) were determined in the CEUNES/UFES laboratories, using standard procedures (APHA 1998). Thermotolerant coliform (TC) and *E. coli* were quantified using Colipaper®, with incubation for 15 h at 36 °C (Thermobac, Alfakit). The content of total dissolved solids (TDS) was estimated considering: $\text{TDS} = \text{EC}^{1.0878} \times 466.5$, with EC in mS/cm. Ammonia (NH_4^+) was determined with a selective HANNA electrode (HI 4101). The error in ion balance (Hounslow 1995) usually does not exceed $\pm 10\%$.

Five sampling campaigns were carried out (Table 1). The daily rainfall series (1971–2019), minimum, maximum, and mean temperatures of INMET (National Institute of Meteorology) stations 83,550 and A616, installed in São Mateus, were used to estimate surface evapotranspiration (ET), by the Hargreaves method with correction coefficient, $Kc=0.7$ (AWWA 1993; Yates and Strzepek 1994). Accumulated rainfall (Rain), ET, and the water balance (Rain–ET) were calculated for 30 days before each sampling campaign. It indicates that the water balance was negative for the first four campaigns and positive only in the last. When considering the monthly averages, the water balance was negative only in September 2016 (first campaign). In the other months, the rains were concentrated in the days after the samples collection (Table 1). In general, the year of 2016 had a negative water balance (–312 mm), and 2017 a positive balance (+299 mm). It is well recognized that shallow aquifers (with water tables less than 3.5 m) may experience significant

Table 1 Number of samples collected in each campaign, accumulated rainfall (Rain), evapotranspiration (ET), and water balance (Rain–ET)

Samples	09/17/16	11/12/16	03/25/17	05/13/17	07/01/17
	16	14	20	11	8
Rain, ET, and water balance in the 30 days before sampling, in mm					
Rain	2	81	59	41	102
ET	93	103	115	81	58
Water balance	–91	–22	–56	–40	+44
Rain, ET, and water balance in the month of the campaign, in mm					
Rain	31	218	129	200	103
ET	90	82	104	62	61
Water balance	–59	+136	+25	+138	+42

evapotranspiration losses (Naik and Awasthi 2003). The complete records for 2016 and 2017 are available as Online Resource 1 (Table 1S).

According to the wells registration data, 31 of them are of the tubular kind, presenting depths from 11 to 13 m, and capturing waters from the whitish clay substrate, while the other four wells are hand-dug, 3 to 4 m deep, thus representing the water table in the fine yellowish sandstone substrate (vadose zone). Unfortunately, there are no monitoring wells in the area to record the water table fluctuations or pumping test results to estimate aquifer recharge (Türker et al. 2013). Additionally, the input associated with the volume of water supplied to residents by the public system (abstracted from a deep aquifer), or the groundwater output due to domestic needs, and residential well's operation scheme (pumping rate, how many hours/day, and days/year) are highly variable (or unknown), preventing local groundwater budgeting.

In Brazil, Resolution CONAMA No. 396 (2008) provides environmental guidelines for the classification, prevention, and control of water bodies pollution. The Ordinance 2914 (2011) sets the drinking water standards. Internationally, the World Health Organization (WHO) guidelines are considered to ensure public health (WHO 2017). The maximum permitted values (MPV) of these references were used to assess the samples' potability. For phosphorus, the limit of 0.10 mg/L, CONAMA n° 357 (2005) was used to complement the MPV.

Location maps and for infractions to MPV were generated with Google Earth Pro (Google Earth 2020). The diagrams of Piper and Gibbs were prepared with an electronic spreadsheet (USGS 2005) and with the Origin software (OriginLab 2018), according to Marandi and Shand (2018), to establish the compositional pattern of the waters and to identify the most impacting process on its development.

Principal component analysis (PCA) and hierarchical clustering analysis (HCA) were performed with free Chemoface software (Nunes et al. 2012), with self-scaled data (Lever et al. 2017) to investigate the similarities between variables and wells. Maps representing the spatial distribution of the physicochemical dataset obtained with the tubular wells were prepared using the inverse distance weighted (IDW) interpolation method (Zolekar et al. 2020) in QGIS software (QGIS.org 2020).

A Spearman's rank-order correlation was used to evaluate the behavior of the variables and to test whether the separation between the well and the beach (D_{beach}) or the setback between the well and cesspit (D_{cesspit}) influences water quality. Kolmogorov–Smirnov normality test, linear regression, ANOVA, Pearson's (r), and Spearman's correlation coefficients (r_s), Student's T test, and F test were performed with the Origin software (OriginLab 2018), at the 5% probability.

3 Results and discussion

3.1 Assessment of potability

The results obtained with 69 samples from the 35 wells are summarized in Table 2. The Kolmogorov–Smirnov normality test (K–S test) indicates that most results have a normal distribution ($\alpha=0.05$); those parameters with rejected normality generally present elevated concentrations in individual wells. The complete dataset is available as Online Resource 1 (Table 2S).

Table 2 Compilation of results and infractions to the maximum permitted value (MPV)

	Min	Max	Mean \pm SD	K-S test	MPV	Infractions (%)
pH	5.44	7.89	7.20 \pm 0.60	Normal	6.5–8.5 ^c	8
CE (μ S/cm)	129	1.603	873 \pm 344	Normal		
TDS (mg/L)	50	779	410 \pm 174	Normal	< 500 ^{b,c}	26
Na ⁺ (mg/L)	15	135	75 \pm 27	Normal	< 200 ^{a,c}	0
Ca ²⁺ (mg/L)	4.2	99	48 \pm 20	Normal	< 200 ^c	0
Mg ²⁺ (mg/L)	< 0.01	93	26 \pm 16	Normal	< 150 ^c	0
Hardness (mg/L)	24.1	480	226 \pm 84	Reject	< 500 ^{a,c}	0
Cl ⁻ (mg/L)	24	338	114 \pm 58	Normal	< 250 ^{a,c}	8
HCO ₃ ⁻ (mg/L)	27	655	389 \pm 158	Normal	< 500 ^c	19
SO ₄ ²⁻ (mg/L)	< 0.01	0.50	0.09 \pm 0.10	Reject	< 250 ^{a,c}	0
Fe _T (mg/L)	< 0.01	4.2	0.50 \pm 0.45	Reject	< 0.30 ^{a,b}	70
PO ₄ ³⁻ (mg/L)	< 0.01	0.88	0.07 \pm 0.14	Reject	< 0.10 ^d	11
TC (CFU/100 mL)	< 80	5.600	1.052 \pm 1.353	Reject	Absent	43

TC=thermotolerant coliforms. ^a=Ordinance 2914 (2011); ^b=Class I, CONAMA Resolution n° 396 (2008); ^c=WHO (2017); ^d=CONAMA Resolution n° 357 (2005). SD=standard deviation of the mean. Alkalinity (HCO₃⁻) and total hardness (Ca²⁺ + Mg²⁺), both expressed as mg/L of CaCO₃. CFU=colony-forming unit

To Ordinance 2914 (2011) and WHO (2017), the pH of potable water must be within 6 and 9 or 6.5 and 8.5, respectively. The pH of most samples (average 7.20 \pm 0.60) meets the most restrictive WHO (2017) standard, except the four hand-dug wells (numbers 12, 29, 30, and 31) with slightly acidic water (pH 5.47 to 5.87). These wells also present low EC values, indicating waters with distinctive characteristics from those of tubular wells, whose pH values (between 6.78 and 7.89) agree with the drinking water standard.

In natural waters, pH is generally a function of the acid–base balance established by the carbon dioxide–carbonate system, in which an increase in the concentration of CO₂ implies a reduction in the pH (Hem 1985; Butler 1991). Thus, the acidity of the waters in the hand-dug wells probably results from the oxidation of organic matter present in the upper layers of the soil and the consequent increase in CO₂ close to the vadose zone, which explains the lower pH values of the shallower wells. Even disagreeing with the ideal range, the pH verified in these wells does not preclude waters use, since extreme values (pH < 4 or pH > 10) capable of irritating eyes, skin, gastrointestinal system, and mucous membranes (WHO 2012) were not recorded in any sample.

In Figs. 3, 4, and 5, the results are represented on a color scale. The infractions to MPV are highlighted in red. The datasets of pH, TDS, and EC are represented in Fig. 3. The EC values are distributed in three classes arbitrarily established because there is no MPV for EC.

The TDS values (50 to 779 mg/L) indicate waters with low to medium salinity, with 11 wells exceeding 500 mg/L. According to CONAMA Resolution No. 396 (2008), all samples are classified as freshwater, as TDS < 1000 mg/L. None sample exceeded the limit of 500 mg/L for total hardness. Other parameters (Na⁺, Ca²⁺, Mg²⁺, and SO₄²⁻) also meet the respective MPV listed in Table 2.

Iron is an omnipresent element in groundwater (Edmunds and Shand 2008), whose results ranged from below the detection limit to 4.2 mg/L, making iron the parameter with the highest infraction index (70%) (Fig. 4). At this level, it is not harmful to health, but its



Fig. 3 Map of infractions for pH and TDS against MPV and distribution of EC values

precipitation may produce taste and color in the water, incrustations in pumps and filters, as well as stained clothes and toilet parts (Di Bernardo 1993).

Values higher than the MPV for alkalinity and chloride were found in 19 and 8% of the samples, respectively. For phosphate, the highest values were recorded in wells 32 and 33 (located in the central region of Guriri), and its origin may be associated with the use of fertilizers in gardens. The contamination from the cesspits is unlikely given the absence of TC in the samples of these wells.

According to Hirata et al. (2015), the deficiency of sanitation infrastructure causes aquifer contamination due to sewage destination in cesspits. In the present study, 43% of the samples (from 17 of the 35 wells) contained TC between 80 and 5,600 CFU/100 mL. Additionally, 20% of the wells also presented *E.coli*, revealing the population's exposure to dangerous pathogens.

The loads and high percentage of contaminated wells verified in this study probably stems from the elevated density of cesspits (1000 to 2000 units/km²) in the neighborhood (Lira and Cavatti 2016), which exceeds the recommended limit of 1000 units/km² (NBR 13969 1997). Besides, most of the units were built in disagreement with the technical parameters for septic tanks, generating an influx of sewer waters that contaminates the aquifer.

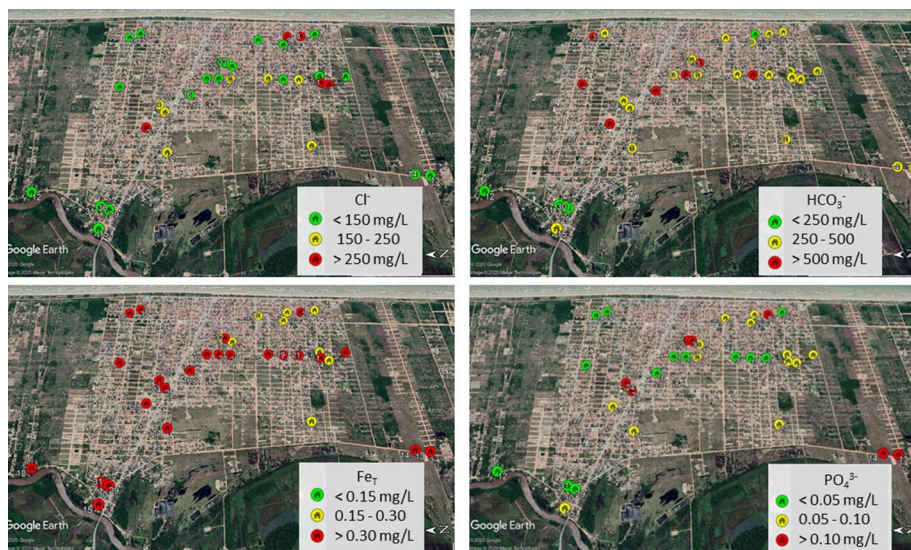


Fig. 4 Map of infractions for chloride, alkalinity, iron, and phosphate

Nitrogen compounds may impose a risk to human health (Oliveira and Von Sperling 2011). Wells 7, 13, 20, 28, and 35 were analyzed for ammonia, and results (2.5 to 4.5 mg/L) exceeded the MPV of 1.5 mg/L (Ordinance 2914, 2011). It is noteworthy that these wells also presented TC, indicating that both contaminants originate from the effluents of the cesspits and are dispersed by the groundwater flow. The occurrence of elevated concentrations of ammonia in concert with TC in groundwater was also reported by Chae et al. (2008). Peixoto et al. (2020) correlated the ammonia concentrations (0.1 to 3.0 mg/L) of an urban aquifer with the area’s precariousness of basic sanitation. These studies demonstrate the general decline in water quality in unsewered regions.

According to Fig. 5, the wells with the highest number of violations to the MPV (with two or more infractions) are concentrated in the Guriri beach resort’s central part, coinciding with the population density. Among all of them, the wells 8 and 23 had a higher infraction number. Hence, the residents were recommended to implement both filtration and chlorination systems to reduce iron and pathogens.

Samples from well 17 were collected and analyzed on two occasions, with none infraction perceived. The setback distance to the home’s cesspit is considerable (20 m), and the well is on a corner (between a street and an avenue), diminishing the number of cesspits around it and the chance of the water’s bacteriological contamination. The public water system assists this region. So, most homes only use groundwater during shortage periods with insufficient public supply, which diminishes the transport of cesspit effluents in the well’s direction.

In retribution to water samples donation, each contributing family received a report, alerting for infractions to potability standards. Also, they were instructed to proceed with water treatment before consumption. The construction and installation of the home-made chlorinator, model EMBRAPA (2014), were recommended and exemplified for the WCDSS students. That way, they can act as disseminators of information about the risks of using untreated water and as promoters of the disinfection technique.

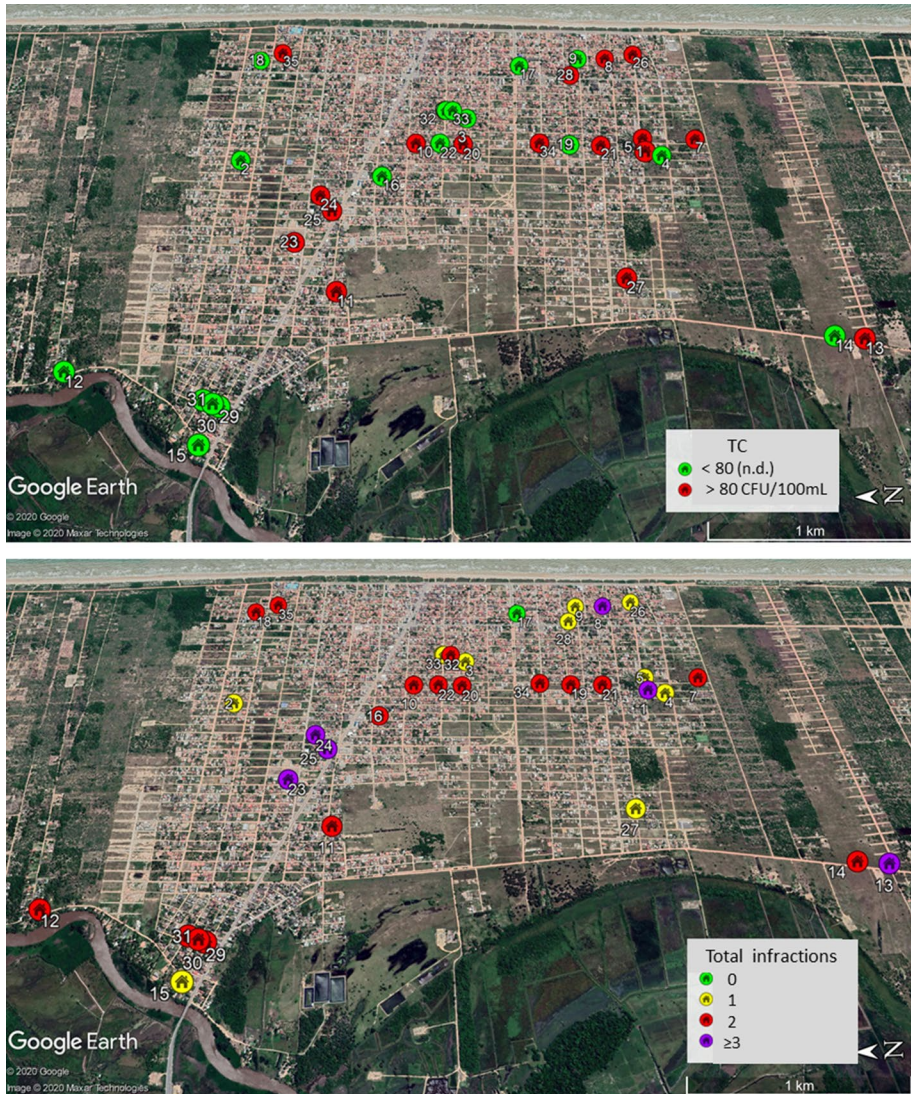


Fig. 5 Map of infractions for thermotolerant coliforms (TC) and the total of infractions. n.d. = not detected

3.2 Hydrochemical assessment and correlations

In the Piper diagram, the combination of ternaries, one for cations and another for anions, and its projection on a central diamond allow the hydrochemical classification (Hounslow 1995). As shown in Fig. 6a, the waters of the hand-dug wells (12, 29, 30, and 31) are predominantly chlorinated, while the others are mixed bicarbonate-chlorinated, all with low sulfate content. On average, the composition follows the order $\text{HCO}_3^- > \text{Cl}^- > \text{SO}_4^{2-}$ (53, 47, and $< 0.1\%$ in milliequivalent (mEq)). For cations, the waters are sodium type, with similar proportions of calcium and magnesium, in the order $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+}$ (42, 30,

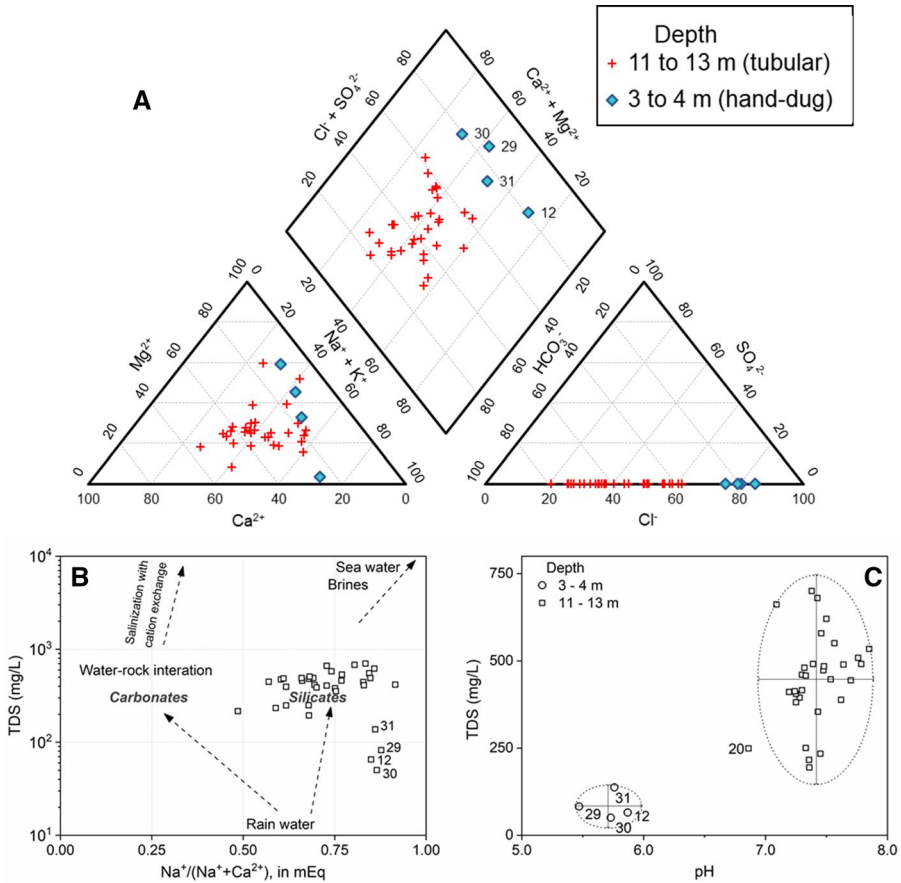


Fig. 6 Diagrams of Piper (a), Gibbs (b), and TDS versus pH graph with 95% confidence intervals for both types of wells (c)

and 28% in mEq). A similar hydrochemical pattern was observed in the São Mateus River and reservoirs in the northern region of ES (Cotta et al. 2017; Favero et al. 2020).

With the Gibbs diagram, it is possible to infer about the natural processes that contribute to the elevation of the TDS of the waters from its meteoric composition. The interaction of water with carbonates is signaled by low values in the $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ ratio, and with silicates by high quantities (Marandi and Shand 2018). Figure 6b shows that the four hand-dug wells have the lowest TDS values and are aligned between the meteoric composition and the field of water interacting with silicates, in which the tubular wells plot.

According to Hounslow (1995), a reduction in the $\text{Na}^+ / \text{Cl}^-$ ratio with an increase in TDS may indicate the exchange of Na^+ for Ca^{2+} or Mg^{2+} , while $\text{Na}^+ / \text{Cl}^-$ values close to 1 reflect the dissolution of halite ($\text{NaCl}_{(s)}$). However, ratios greater than 1 indicate the weathering of silicates as a source of Na^+ for groundwater. The $\text{Na}^+ / \text{Cl}^-$ results of this study ranged from 0.43 to 2.59, with a mean of 1.15 (regardless of TDS, $r=0.30$), indicating that the weathering of silicates is the leading source of minerals for the waters, as also pointed by the Gibbs diagram of Fig. 6b. Wu and Wang (2014) demonstrated that the hydrolysis of silicates is the principal process responsible for the hydrochemical evolution of water from

shallow wells (<30 m) in the Datong region, China. Rao et al. (2017) and Gharbi et al. (2019) used the Gibbs diagram and ratios between constituents (Na^+/Cl^- and $\text{Na}^+/\text{HCO}_3^-$) to relate the compositional changes recorded in groundwater from Andhra Pradesh region (India) and Sidi Bouzid aquifer (Tunisia), respectively, with silicate weathering.

Assuming that the aquifer is homogeneous in the area of the present study, it is proposed that the waters of the hand-dug wells are younger, being the direct result of the rainwater infiltration through the vadose zone. This process explains their lower TDS values and the slight compositional change. The waters of the tubular wells, on the other hand, are older and more chemically evolved, as they experience longer residence time and, therefore, present higher TDS and distinct compositional alteration after interacting with the subsequent aquifer layers.

The pH versus EC diagram (Fig. 6c) also presents the separation into two groups with its characteristics, one having low pH and EC values, gathering the four hand-dug wells, and the group of tubular wells with waters of higher pH and EC values. The pH and EC values were evaluated by the F and t tests, revealing that the differences between the means are statistically significant, which probably reflects the fact that these wells capture water from different layers of the aquifer. Several other parameters (TDS, Na^+ , Ca^{+2} , Mg^{+2} , HCO_3^- , Cl^- , and TC) also showed significant differences between the two types of wells, confirming the compositional contrast (Table 3). Maps representing the spatial distribution of the groundwater's physicochemical characteristics captured by the 31 tubular wells are presented in Fig. 1S (Online Resource 1). Most parameters' spatial distribution shows a division between the north and south sides of the neighborhood, while some present higher concentration in the central region.

The PCA and HCA were applied to the parameters' mean values (Fig. 7a, b). The principal components (PC), PC1 and PC2, explain 40.28 and 13.48% of the original data, and only these two were used in HCA. The number of groups highlighted in the HCA was established based on a visual examination of the dendrogram, allowing the recognition of two main groups. One composed by the hand-dug wells (12, 29, 30 and 31) and the other

Table 3 Mean values and standard deviation of hand-dug and tubular wells, and probability (*p*) associated with Student's *t* test

	Hand-dug	Tubular	<i>p</i>
pH	5.7 ± 0.2	7.4 ± 0.2 ^a	1.6 × 10 ⁻⁵
CE (µS/cm)	205 ± 85	959 ± 258 ^a	1.7 × 10 ⁻⁸
TDS (mg/L)	84 ± 38	439 ± 129 ^a	2.3 × 10 ⁻⁹
Na^+ (mg/L)	28 ± 10	81 ± 22 ^a	3.0 × 10 ⁻⁵
Ca^{2+} (mg/L)	8 ± 4	53 ± 15 ^a	1.1 × 10 ⁻¹²
Mg^{2+} (mg/L)	10 ± 6	28 ± 16 ^a	1.0 × 10 ⁻³
Hardness (mg/L)	62 ± 20	247 ± 63 ^a	7.1 × 10 ⁻⁹
Cl^- (mg/L)	55 ± 21	122 ± 57 ^a	1.6 × 10 ⁻⁵
HCO_3^- (mg/L)	41 ± 25	433 ± 101 ^a	3.9 × 10 ⁻¹⁴
SO_4^{2-} (mg/L)	0.03 ± 0.05	0.09 ± 0.11	0.053
Fe_T (mg/L)	0.7 ± 0.3	0.5 ± 0.5	0.13
PO_4^{3-} (mg/L)	0.04 ± 0.01	0.07 ± 0.15	0.11
TC (CFU/100 ml)	< 80	684 ± 817 ^a	1.7 × 10 ⁻³

TC = thermotolerant coliforms. CFU = colony-forming unit

^aMean value is statistically different from the mean of the hand-dug wells ($\alpha = 5\%$)

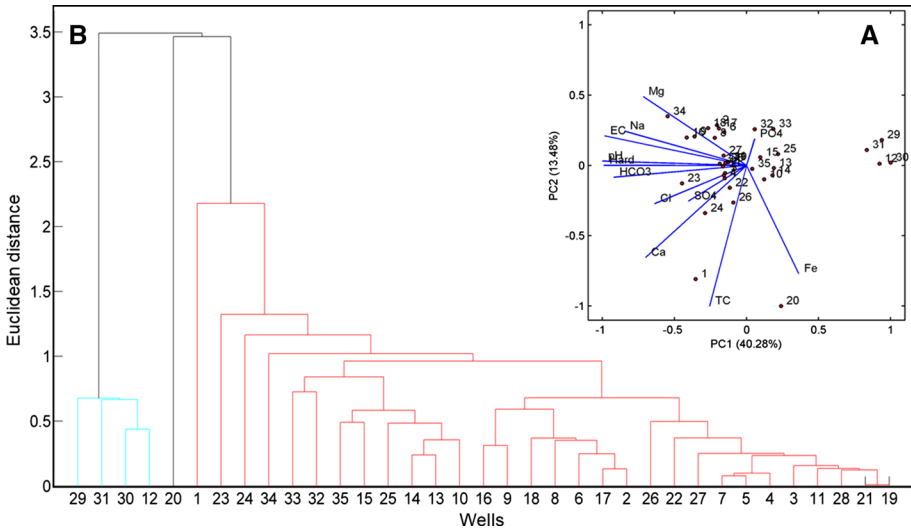


Fig. 7 (a) PCA biplot diagram with main components, PC1 versus PC2, (b) HCA dendrogram

by the deeper tubular wells. Among them is the well 20, whose waters (analyzed on two occasions, $n = 2$) presented an intermediate composition, probably as a result of an intense groundwater extraction rate, which promotes the infiltration and mixing with the waters of the upper layers.

In the PCA biplot diagram (Fig. 7a), the larger the vector of a variable on a PC axis, the higher the loading on that PC. The shallow wells stand out from the others, with the separation occurring on the horizontal axis of PC1, due to the high loads of pH, CE, Na^+ , HCO_3^- , and total hardness (Hard) on PC1. In the vertical axis, TC and Fe_T have the highest projections on PC2, which contributes to the distinction of wells 1 and 20, which presented the highest TC and Fe_T values, respectively.

Islam et al. (2019), using PCA and HCA, were able to differentiate three distinct groups of water, due to anthropogenic and natural controls of a multilayer aquifer in the Bengal delta, Bangladesh. Gharbi et al. (2019) differentiated five distinct types of waters (with a significant overlap in the Piper and Gibbs diagrams) from the Sidi Bouzid aquifer (Tunisia). Islam et al. (2019) and Gharbi et al. (2019) used three PCs in the HCA, which increase the segregation power of the analysis. In our study, just two PCs were used, since PC3 represented only 10.26% of the data variation, with low eigenvalue and inflection in the scree plot. Gomes et al. (2020) also employed only two PCs at HCA, which were sufficient to classify the groundwater of Boquira, BA (Brazil), into three groups.

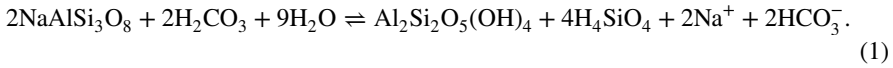
The correlation matrix is presented in Table 4, detaching the highest values ($r_s \geq 0.6$). EC and pH are strongly correlated with Na^+ , Ca^{+2} , and HCO_3^- contents since these are the major constituents of these waters. The dissolution and weathering of minerals such as carbonates (CaCO_3) and silicates, as albite ($\text{NaAlSi}_3\text{O}_8$), Eq. (1), explain the correlations between Na^+ , Ca^{+2} , HCO_3^- , and pH, since such processes contribute together, to raise the values of these parameters, mainly in the tubular wells that capture slightly alkaline waters below the vadose zone. Similar correlations and weathering processes described the hydrochemical composition of the waters of 20 shallow wells (from 5 to 30 m) studied by Bouderbala and Gharbi (2017) in another alluvial aquifer.

Table 4 Spearman's correlation matrix between the mean values for the 35 wells

	pH	EC	Na ⁺	Ca ²⁺	Mg ²⁺	Hardness	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	Fe _T	PO ₄ ³⁻	TC	D _{cesspit}	D _{beach}
pH	1.00													
EC	0.73*	1.00												
Na ⁺	0.60*	0.81*	1.00											
Ca ²⁺	0.63*	0.40*	0.23	1.00										
Mg ²⁺	0.50*	0.49*	0.33	0.01	1.00									
Hardness	0.74*	0.64*	0.41*	0.58*	0.78*	1.00								
HCO ₃ ⁻	0.70*	0.60*	0.70*	0.60*	0.35*	0.63*	1.00							
Cl ⁻	0.36*	0.45*	0.48*	0.29	0.28	0.41*	0.34*	1.00						
SO ₄ ²⁻	0.17	0.25	0.13	0.14	0.25	0.29	0.30	0.08	1.00					
Fe _T	-0.30	-0.39*	-0.16	0.00	-0.33	-0.26	-0.06	-0.03	-0.14	1.00				
PO ₃ ³⁻	0.02	0.01	-0.07	0.03	-0.07	-0.02	-0.10	0.05	-0.16	-0.10	1.00			
TC	0.14	0.03	-0.22	0.41*	-0.17	0.22	-0.02	0.44	0.31	0.21	0.08	1.00		
D _{cesspit}	-0.17	0.14	-0.13	0.02	-0.19	-0.14	-0.16	-0.11	0.18	-0.17	0.16	0.16	1.00	
D _{beach}	-0.49*	-0.58*	-0.52*	-0.23	-0.34*	-0.41*	-0.32	-0.33	-0.16	0.10	-0.07	-0.13	-0.06	1.00

Strong correlations ($r \geq /0.6/$) are highlighted in bold

*Correlation is significant at the 0.05 level, 2-tailed test



The data obtained during the wells' registration revealed that they are drilled close to the cesspit of the residence (D_{cesspit}). The separation ranged from 5.2 to 25 m, with an average spacing of 15 m. The absence of a significant correlation between TC counts and D_{cesspit} revealed that pathogens' contamination is not strictly related to the setback distance (Fig. 8). The presence of TC in half of the studied wells probably arises from the high permeability of the aquifer layers, enabling the dispersion of pathogens. The vadose zone's insufficient filtering action also facilitates the diffusion of pathogens, as exemplified by Voisin et al. (2018), to a shallow aquifer constituted by glaciofluvial sediments.

There is no consensus on the minimum D_{cesspit} capable of preventing groundwater contamination (Vaughn et al. 1983; Yates et al. 1986). Lauthartte et al. (2016) recorded the presence of coliforms in 100% of the 82 residential wells (8.2 to 17 m depth) studied; such a scenario was attributed to the small separation (from 4 to 66 m) between the wells and the cesspits. Elisante and Muzuka (2016) verified the presence of TC and *E. coli* in groundwater, even in samples taken 50 m away from a pit source. In Guriri home lots, the higher setback possible is limited to 25 m, and the correlation between TC and the D_{cesspit} registered in our study was low, as shown in Table 4. Considering these facts, we propose that residents cannot be secure that there will not be contamination of their well, having a cesspit inside their residential plot. Therefore, any improvement in groundwater quality depends on the construction of the sewage collection system or replacing of the current cesspits by septic tank capable of providing the necessary sanitary protection (Withers et al. 2013).

The exploration of coastal aquifers requires specific abstraction strategies to prevent seawater intrusion (Mondal et al. 2011; Ma et al. 2020). Salinization in freshwater pumping areas can occur through the migration of brackish or seawater (Gad and Khalaf 2015; Costall et al. 2020; Liu et al. 2020). The absence of strong correlations between the distance from the well to the beach (D_{beach}) with Na^+ or Cl^- or SO_4^{2-} or EC (Table 4) indicates that the seawater intrusion does not reach the well's capture zone.

Almeida and Junior (2007) used the decrease in the values of EC and Cl^- , from the coast, to study the marine intrusion in the aquifer of Maricá, RJ (Brazil). As presented

Fig. 8 Thermotolerant coliforms (TC) counts with lateral setback distance from cesspit to residential drinking water wells. Wells are identified by number; those that tested positive to *E. coli* are highlighted in red

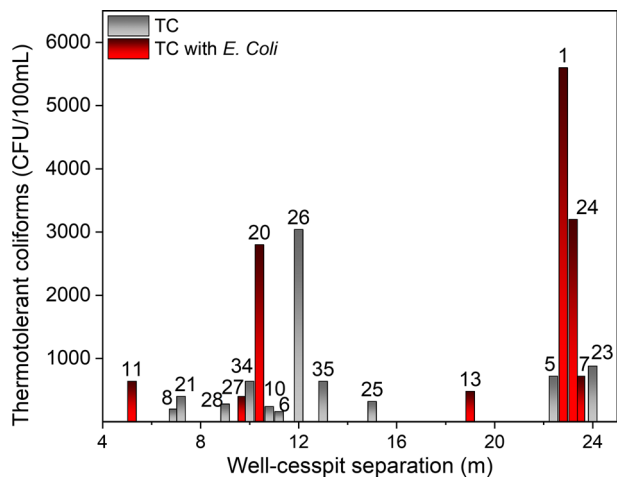


Fig. 9 Mean values of chloride and electrical conductivity (EC) of the 31 tubular wells

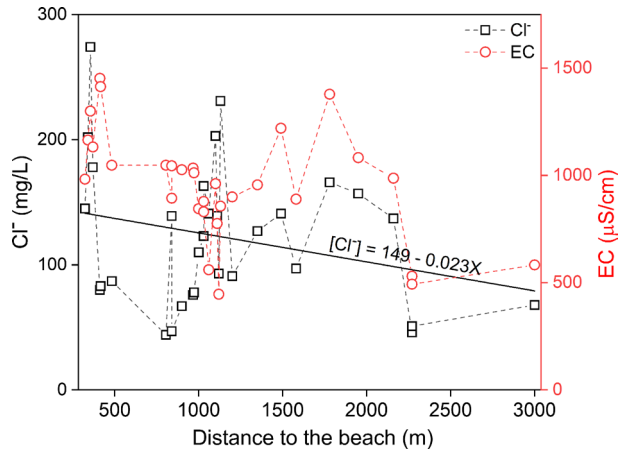
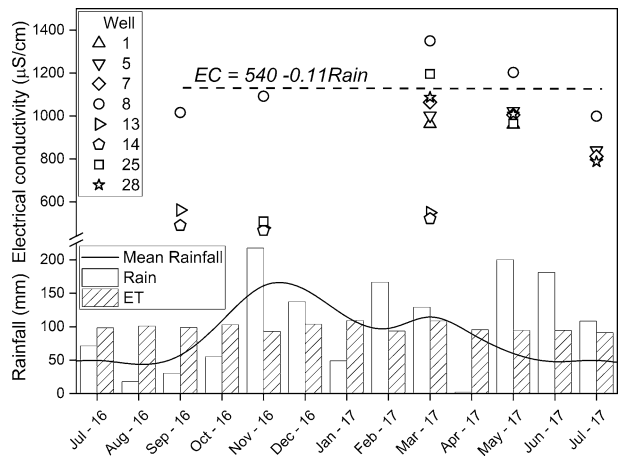


Fig. 10 Electrical conductivity of water, average (1971–2019) of the rainfall series (mean rainfall), monthly rainfall (Rain), and evapotranspiration (ET), over the study period. The dashed line represents the function adjusted to the EC data of the well 8 with the accumulated rainfall of 30 days before sampling



in Fig. 9, there is no systematic reduction in the values of Cl⁻ and CE with the distance from the beach (the slope of the fittings is not significantly different from zero, $\alpha=0.05$), indicating that the wells are not affected by the marine intrusion under current pumping conditions.

Figure 10 shows the EC value for wells with three or more samples analyzed, along with the average of the rainfall series (mean rainfall), the monthly records (Rain), and evapotranspiration (ET) during the monitoring period. In general, the EC values did not show a single trend of behavior, while some wells presented constant values (e.g., 13 and 14), others showed some variation. A function was adjusted to the EC data, and the rainfall accumulated in the 30 days before each sampling campaign, using the well 8 as an example. The low slope of the linear regression (dashed line) indicates that the EC variation does not correlate with the rainfall ($r=0.35$, the slope is not significantly different from zero, at 0.05 level).

The highest EC values were recorded in the third campaign (March 2017), preceded by months (December 2016 and January 2017) with small or negative water balance, allowing the accumulation of marine aerosols in the region’s soil. In the sequence, the intense

rainfall of February 2017 produced a positive water balance. Therefore, the infiltration of rainwater transported the accumulated salts to the aquifer, increasing the water's EC. A detailed assessment of the recharge process on Indian groundwater resources was made by Naik and Awasthi (2003), demonstrating the ruling contribution of rainfall to a shallow aquifer's replenishment.

In 2017, the rainfall regime was atypical, with records from May to July exceeding the historical series' double (Fig. 10). The reduction in EC recorded in the fourth and fifth campaigns indicates that the rains from this period overcame the ET index, promoting the aquifer's recharge and dilution of dissolved salts. The reduction in EC is fast due to the intercommunication between the surface and the aquifer's subsequent layers. Peixoto et al. (2020) and Amiri et al. (2016) reported similar behavior in different coastal aquifers. Troudi et al. (2020) also attributed the variation in EC and TDS values recorded in a shallow aquifer (Guenniche plain, Tunisia) to oscillations of the rainfall regime, and its effect over the piezometric level, the accumulation and the leaching of salts from the topsoil to the groundwater.

4 Conclusions

The physicochemical and bacteriological contamination parameters evaluation for groundwater samples from 35 residential wells revealed violations of drinking water standards. All samples were classified as freshwater, but pH, chloride, and alkalinity in some of them exceeded the desirable limits. Iron presented the highest number of infractions, but at levels that did not compromise groundwater use.

The hydrochemical classification and multivariate techniques revealed the existence of two distinct groups of water. Differences in pH, EC, Na^+ , hardness, and HCO_3^- values were identified as the main responsible for the discrimination. The samples from deeper wells presented higher mineral constituents concentration than shallower wells, revealing the hydrochemical evolution through aquifer layers. The weathering of silicates was identified as the main factor for the development of the $\text{Na}^+ - \text{HCO}_3^-$ pattern.

Locally, there is no control over groundwater exploitation. Due to the lack of inspection, residential wells are drilled without a minimum setback distance from the cesspits. The leniency of the public administration to this situation results in the contamination of half of the wells. Considering the widespread of TC in the wells, we propose that groundwater quality improvement depends on the replacement of the cesspits by septic tanks or that the construction of new ones becomes prohibited. Meanwhile, water disinfection is necessary, and the tablet chlorinator was recommended to all residences.

The salts accumulation in months with low rainfall and their dissolution and leaching processes during months with positive water balance control the groundwater's EC values. In turn, this reveals the high permeability of the aquifer layers and its vulnerability to the assimilation of pollutants. Further studies are necessary to assess the recharge and withdrawal processes to establish a management strategy. Our investigation alerts the urgent need to protect this natural resource, vital for the resort's social and economic development.

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References

- Affum, A. O., Osaé, S. D., Nyarko, B. J. B., et al. (2015). Total coliforms, arsenic and cadmium exposure through drinking water in the Western Region of Ghana: Application of multivariate statistical technique to groundwater quality. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-014-4167-x>
- Akhtar, S., Fatima, R., Soomro, Z. A., et al. (2019). Bacteriological quality assessment of water supply schemes (WSS) of Mianwali, Punjab, Pakistan. *Environmental Earth Science*. <https://doi.org/10.1007/s12665-019-8455-1>
- Albino, J., Girardi, G., & Nascimento, K. A. (2006). Erosão e progradação do litoral brasileiro—Espírito Santo, 48 p. https://www.mma.gov.br/estruturas/sqa_sigercom/_arquivos/es_erosao.pdf. Accessed 10 January, 2017.
- Almeida, G. M., & Junior, G. C. S. (2007). Fatores hidrogeológicos no estudo da intrusão salina em aquíferos costeiros da região litorânea do município de Maricá-RJ. *Anuário do Instituto de Geociências - UFRJ*, 30, 104–117.
- Alvalá, R. C. S., Cunha, A. P. M. A., Brito, S. S. B., et al. (2019). Drought monitoring in the Brazilian Semiarid region. *Anais da Academia Brasileira de Ciências*. <https://doi.org/10.1590/0001-3765201720170209>
- Amiri, V., Nakhaei, M., Lak, R., et al. (2016). Investigating the salinization and freshening processes of coastal groundwater resources in Urmia aquifer, NW Iran. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-016-5231-5>
- ANA (2017). Conjuntura dos recursos hídricos no Brasil 2017: Relatório pleno, 2017. <https://www.snirh.gov.br/portal/snirh/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/relatorio-conjuntura-2017.pdf>. Accessed 01 february 2019.
- APHA. (1998). *Standard Methods for the examination of water and wastewater* (20th ed.). New York: United Book.
- AWWA. (1993). *American water works association. Water-efficient landscape—guidelines*. Colorado: Denver.
- Belkhir, L., & Mouni, L. (2012). Hydrochemical analysis and evaluation of groundwater quality in El Eulma area, Algeria. *Applied Water Science*. <https://doi.org/10.1007/s13201-012-0033-6>
- Bouderbala, A., & Gharbi, B. Y. (2017). Hydrogeochemical characterization and groundwater quality assessment in the intensive agricultural zone of the Upper Cheliff Plain, Algeria. *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-017-7067-x>
- Butler, J. N. (1991). *Carbon dioxide equilibria and their applications* (1st ed.). Michigan: CRC Press.
- Capp, N., Ayach, L. R., Santos, T. M. B., & Guimarães, S. T. L. (2012). Qualidade da água e fatores de contaminação de poços raso na área urbana de Anastácio (MS). *Geografia Ensino & Pesquisa*. <https://doi.org/10.5902/223649947581>
- Cavalcante, R. B. L. (2014). Ocorrência de *Escherichia coli* em fontes de água e pontos de consumo em uma comunidade rural. *Revista Ambiente & Água*. <https://doi.org/10.4136/ambi-agua.1301>
- Chae, G., Yun, S. T., Choi, B. Y., et al. (2008). Hydrochemistry of urban groundwater, Seoul, Korea: The impact of subway tunnels on groundwater quality. *Journal of Contaminant Hydrology*. <https://doi.org/10.1016/j.jconhyd.2008.07.008>
- CHSM (2019). Guia turístico da prefeitura municipal de São Mateus, 2019. <https://www.saomateus.es.gov.br/guia-turistico/praias>. Accessed 01 January 2020.
- CONAMA N° 357 (2005). Resolution of the Environment National Council. <https://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=459>. Accessed 31 March 2020.
- CONAMA N° 396 (2008). Resolution of the Environment National Council. <https://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=562>. Accessed 31 Mar 2020.
- Costall, A. R., Harris, B. D., Teo, B., et al. (2020). Groundwater throughflow and seawater intrusion in high quality coastal aquifers. *Scientific Reports*. <https://doi.org/10.1038/s41598-020-66516-6>
- Cotta, A. J. B., Duboc, L. F., & De Jesus, H. C. (2017). Impacts of urban wastewater and hydrogeochemistry of the São Mateus River, Espírito Santo, Brazil. *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-017-6658-x>
- Decree N° 9319/2017. City Hall of São Mateus-ES, Brazil. https://www.saomateus.es.gov.br/uploads/legislacao/Decretos_2017_9319_8b3ffe9-da2e-442f-9927-732205ebb01f.pdf Accessed 15 January 2020.
- Di Bernardo, L. (1993). *Métodos e técnicas de tratamento de água*. Rio de Janeiro: Associação Brasileira de Engenharia Sanitária.

- Ducci, D., Morte, R. D., Mottola, A., Onorati, G., & Pugliano, G. (2020). Evaluating upward trends in groundwater nitrate concentrations: an example in an alluvial plain of the Campania region (Southern Italy). *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-020-09062-8>
- Edmunds, M., & Shand, P. (2008). *Natural groundwater quality* (1st ed.). Hoboken: Wiley-Blackwell. <https://doi.org/10.1002/9781444300345>
- Elisante, E., & Muzuka, A. N. N. (2016). Sources and seasonal variation of coliform bacteria abundance in groundwater around the slopes of Mount Meru, Arusha, Tanzania. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/S10661-016-5384-2>
- EMBRAPA (2014). Como montar e usar o clorador de pastilhas em residências rurais. <https://ainfo.cnptia.embrapa.br/digital/bitstream/item/116736/1/Cnpgl-2014-Cartilha-Clorador-completa.pdf>. Accessed 07 June 2020.
- Favero, D., Cotta, A. J. B., & Bonomo, R. (2020). Characterization and suitability of water for irrigation in new and old reservoirs in northern Espírito Santo, Brazil. *Environment, Development and Sustainability*, (in press), 2020.
- Gad, M. I., & Khalaf, S. (2015). Management of groundwater resources in arid areas case study: North Sinai, Egypt. *Water Resources*. <https://doi.org/10.1134/S0097807815040053>
- Gaikwad, S., Gaikwad, S., Meshram, D., et al. (2020). Geochemical mobility of ions in groundwater from the tropical western coast of Maharashtra, India: Implication to groundwater quality. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-019-00312-9>
- Gharbi, A., Ali, Z. I., & Zairi, M. (2019). Groundwater suitability for drinking and agriculture purposes using irrigation water quality index and multivariate analysis: Case of Sidi Bouzid aquifer, central Tunisia. *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-019-8733-y>
- Gomes, M. C. R. L., Souza, J. B., & Fujinaga, C. I. (2011). Estudo de caso das condições de abastecimento de água e esgotamento sanitário dos moradores da estação ecológica de Fernandes Pinheiro (PR). *Ambiência*. <https://doi.org/10.5777/ambiencia.2011.01.02>
- Gomes, M. C. R., Anjos, J. A. S. A., & Daltro, R. R. (2020). Multivariate statistical analysis applied to the evaluation of groundwater quality in the central-southern portion of the state of Bahia—Brazil. *Revista Ambiente & Água*. <https://doi.org/10.4136/ambi-agua.2408>
- Google Earth 7.3.3. 04/07/2020. Guriri, São Mateus-ES, Brazil (18° 44' 2S; 39° 45' 3W).
- Hem, J. D. (1985). *Study and interpretation of the chemical characteristics of natural water*. Washington: US Geological Survey.
- Hirata, R., Fernandes, A. J., & Bertolo, R. (2016). As águas subterrâneas: longe dos olhos, longe do coração e das ações para sua proteção. *Acta Paulista de Enfermagem*. <https://doi.org/10.1590/1982-019401600084>
- Hirata, R., Foster, S., & Oliveira, F. (2015). *Águas Subterrâneas Urbanas no Brasil: avaliação para uma gestão sustentável* (1st ed.). São Paulo: Instituto de Geociências e FAPESP.
- Hirata, R., Suhogusoff, A. V., & Fernandes, A. (2007). Groundwater resources in the State of São Paulo (Brazil): The application of indicators. *Anais da Academia Brasileira de Ciências*. <https://doi.org/10.1590/S0001-37652007000100016>
- Hirata, R., Suhogusoff, A. V., Marcellini, S. S., Villar, P. C., & Marcellini, L. (2019). *A revolução silenciosa das águas subterrâneas no Brasil: uma análise da importância do recurso e os riscos pela falta de saneamento*. Instituto Trata Brasil: São Paulo.
- Hounslow, A. W. (1995). *Water quality data: Analysis and interpretation*. New York: CRC Lewis Publishers.
- Huang, G., Sun, J., Zongyu, Y. Z., & Liu, C. F. (2013). Impact of anthropogenic and natural processes on the evolution of groundwater chemistry in a rapidly urbanized coastal area, South China. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2013.05.078>
- IBGE (2010). Censo Demográfico 2010. São Mateus-ES. Código: 3204906. <https://cidades.ibge.gov.br/brasileis/sao-mateus/panorama> Accessed 15 May 2020.
- Islam, M. M., Marandi, A., Fatema, S., et al. (2019). *The evolution of the groundwater quality in the alluvial aquifers of the south western part of Bengal Basin*. Bangladesh: Environmental Earth Sciences. <https://doi.org/10.1007/s12665-019-8714-1>
- Karunanidhi, D., Aravinthasamy, P., Deepalib, M., et al. (2020). The effects of geochemical processes on groundwater chemistry and the health risks associated with fluoride intake in a semi-arid region of South India. *RSC Advances*. <https://doi.org/10.1039/C9RA10332E>
- Kronemberger, D. (2013). Análise dos impactos na saúde e no Sistema Único de Saúde decorrentes de agravos relacionados a um esgotamento sanitário inadequado dos 100 maiores municípios brasileiros no período 2008–2011. Relatório Final. 2013. <https://www.tratabrasil.org.br/datafiles/uploads/drsai/Relatorio-Final-Trata-Brasil-Denise-Versao-FINAL.pdf>. Accessed 01 February 2019.

- Kumar, P. J. S., Jegathambal, P., & James, E. J. (2011). Multivariate and geostatistical analysis of groundwater quality in Palar river basin. *International Journal of Geology*, 5(4), 108–119.
- Lauthartte, L. C., Holanda, I. B. B., Luz, C. C., et al. (2016). Avaliação da qualidade da água subterrânea para consumo humano: estudo de caso no distrito de Jaci-Paraná, Porto Velho-RO. *Águas Subterrâneas*. <https://doi.org/10.14295/ras.v30i2.28547>
- Lever, J., Krzywinski, M., & Altman, N. (2017). Principal component analysis. *Nature Methods*. <https://doi.org/10.1038/nmeth.4346>
- Lira, P., & Cavatti, C. (2016). *O estado do Espírito Santo no Censo 2010*. Instituto Jones dos Santos Neves – IJSN.
- Liu, J., Gao, Z., Wang, Z., et al. (2020). Hydrogeochemical processes and suitability assessment of groundwater in the Jiaodong Peninsula, China. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-020-08356-5>
- Ma, C., Li, Y., Li, X., & Gao, L. (2020). Evaluation of groundwater sustainable development considering seawater intrusion in Beihai City, China. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-019-07311-3>
- Malheiros, P. S., Schäfer, D. F., Herbert, I. M., et al. (2009). Contaminação bacteriológica de águas subterrâneas da região oeste de Santa Catarina, Brasil. *Revista do Instituto Adolfo Lutz*, 68(2), 305–308.
- Marandi, A., & Shand, P. (2018). Groundwater chemistry and the Gibbs Diagram. *Applied Geochemistry*. <https://doi.org/10.1016/j.apgeochem.2018.07.009>
- Marengo, J. A., Alves, L. M., Alvares, R. C. S., et al. (2018). Climatic characteristics of the 2010–2016 drought in the semiarid Northeast Brazil region. *Anais da Academia Brasileira de Ciências*. <https://doi.org/10.1590/0001-3765201720170206>
- Marengo, J. A., Torres, R. R., & Alves, L. M. (2017). Drought in Northeast Brazil—past, present, and future. *Theoretical and Applied Climatology*. <https://doi.org/10.1007/s00704-016-1840-8>
- Marras, L., Bertolino, G., Sanna, A., et al. (2020). Potential issues of well water in domestic use in a retrospective study from 2014 to 2018. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-020-08388-x>
- Mazhar, I., Hamid, A., & Afzal, S. (2019). Groundwater quality assessment and human health risks in Gujranwala District, Pakistan. *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-019-8644-y>
- Mielke, K. C., Bertuani, R. R., Pires, F. R., et al. (2020). Does Canavalia ensiformis inoculation with *Bradyrhizobium* sp. enhance phytoremediation of sulfentrazone-contaminated soil? *Chemosphere*. <https://doi.org/10.1016/j.chemosphere.2020.127033>
- Minayo, M. C. S., Hartz, Z. M. A., & Buss, P. M. (2000). Qualidade de vida e saúde: Um debate necessário. *Ciência & saúde coletiva*. <https://doi.org/10.1590/S1413-8123200000100002>
- Mondal, N. C., Singh, V. P., Singh, S., et al. (2011). Hydrochemical characteristic of coastal aquifer from Tuticorin, Tamil Nadu, India. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-010-1549-6>
- Naik, P. K., & Awasthi, A. K. (2003). Groundwater resources assessment of the Koyna River basin, India. *Hydrogeology Journal*. <https://doi.org/10.1007/s10040-003-0273-5>
- NBR 13969. (1997). *Tanques sépticos—Unidades de tratamento complementar e disposição final dos efluentes líquidos—Projeto, construção e operação*. São Paulo: ABNT - Associação Brasileira de Normas Técnicas.
- NBR 9898. (1987). *Preservação e técnicas de amostragem de afluente líquidos e corpos receptores - Procedimento*. São Paulo: ABNT - Associação Brasileira de Normas Técnicas.
- Neto, W. R. N., Pereira, D. C. A., Santos, J. R. N., et al. (2017). Análise da potabilidade das águas dos poços rasos escavados da comunidade do Taim em São Luís—Maranhão. *Águas Subterrâneas*. <https://doi.org/10.14295/ras.v31i3.28869>
- Nunes, C. A., Freitas, M. P., Pinheiro, A. C. M., & Bastos, S. C. (2012). Chemoface: a novel free user-friendly interface for chemometrics. *Journal of the Brazilian Chemical Society*. <https://doi.org/10.1590/S0103-50532012005000073>
- Oliveira, G. A., Nascimento, E. L., Rosa, A. L. B., et al. (2015). Avaliação da qualidade da água subterrânea: estudo de caso de Vilhena-RO. *Águas Subterrâneas*. <https://doi.org/10.14295/ras.v29i2.28399>
- Oliveira, S. M. A. C., & Von Sperling, M. (2011). Potenciais Impactos de Sistemas Estáticos de Esgotamento Sanitário na Água Subterrânea - Revisão de literatura. *Revista Brasileira de Recursos Hídricos*. <https://doi.org/10.21168/rbrh.v16n4.p95-107>
- Ordinance n° 2.914 (2011). Brazilian Ministry of Health. https://bvsms.saude.gov.br/bvs/saudelegis/gm/2011/prt2914_12_12_2011.html. Accessed 30 March 2018.
- OriginLab. (2018). *OriginLab Corporation* (p. 2018). Northampton, MA: USA, v.

- Pacata, L. C. M., Pedrosa, M. A. F., Zolnikov, T. R., & Mol, M. P. G. (2020). Water quality index and sanitary and socioeconomic indicators in Minas Gerais, Brazil. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-020-08425-9>
- Peixoto, F. S., Cavalcante, I. N., & Gomes, D. F. (2020). Influence of land use and sanitation issues on water quality of an urban aquifer. *Water Resources Management*. <https://doi.org/10.1007/s11269-019-02467-6>
- Prasanth, S. S., Magesh, N. S., Jitheshlal, K. V., et al. (2012). Evaluation of groundwater quality and its suitability for drinking and agricultural use in the coastal stretch of Alappuzha District, Kerala, India. *Applied Water Science*. <https://doi.org/10.1007/s13201-018-0795-6>
- QGIS.org (2020) QGIS Geographic Information System. Open Source Geospatial Foundation Project. <https://qgis.org>
- Ramos, H. E. A., Silva, B. F. P., Brito, T. T., et al. (2016). A estiagem no ano hidrológico 2014–2015 no Espírito Santo. *Incaper em Revista*, 7, 6–25.
- Rao, N. S., Marghade, D., Dinakar, A., et al. (2017). Geochemical characteristics and controlling factors of chemical composition of groundwater in a part of Guntur district, Andhra Pradesh, India. *Environmental Earth Science*. <https://doi.org/10.1007/s12665-017-7093-8>
- Sabino, H., Menezes, J., & Lima, L. A. (2020). Indexing the groundwater quality index for human consumption (GWQIHC) for urban coastal aquifer assessment. *Environmental Earth Science*. <https://doi.org/10.1007/s12665-020-8882-z>
- Schot, P. P., & Van Der Wal, J. (1992). Human impact on regional groundwater composition through intervention in natural flow patterns and changes in land use. *Journal of Hydrology*. [https://doi.org/10.1016/0022-1694\(92\)90040-3](https://doi.org/10.1016/0022-1694(92)90040-3)
- Silva, R. B. G. (2003). *Águas subterrâneas: Um valioso recurso que requer proteção*. DAEE: São Paulo.
- Suhogusoff, A. V., Hirata, R., & Ferrari, L. C. K. M. (2013). Water quality and risk assessment of dug wells: a case study for a poor community in the city of São Paulo, Brazil. *Environmental Earth Sciences*. <https://doi.org/10.1007/s12665-012-1971-x>
- Troudi, N., Hamzaoui-Azaza, F., Tzoraki, O., et al. (2020). Assessment of groundwater quality for drinking purpose with special emphasis on salinity and nitrate contamination in the shallow aquifer of Guenniche (Northern Tunisia). *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-020-08584-9>
- Tubau, I., Vasquez-Sunê, E., Carrera, J., et al. (2017). Quantification of groundwater recharge in urban environments. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2017.03.118>
- Türker, U., Alsababi, B. S., & Rızza, T. (2013). Water table fluctuation analyses and associated empirical approach to predict spatial distribution of water table at Yeşilköy/AgiosAndronikos aquifer. *Environmental Earth Science*. <https://doi.org/10.1007/s12665-012-1934-2>
- Uliana, E. M., Mendes, M., Almeida, F. T., et al. (2017). Standardized precipitation index: a case study on the northwestern region of Espírito Santo state, Brazil. *Pesquisas Agrárias e Ambientais*. <https://doi.org/10.5935/2318-7670.v05n05a05>
- USGS (2005). Excel for Hydrology (WaterQualityTools\PiperPlot-QW.XLS). <https://nevada.usgs.gov/tech/excellforhydrology/WaterQualityTools/PiperPlot-QW.XLS>. 2005. Accessed 20 February 2019.
- Varnier, C., Hirata, R., & Aravena, R. (2017). Examining nitrogen dynamics in the unsaturated zone under an inactive cesspit using chemical tracers and environmental isotopes. *Applied Geochemistry*. <https://doi.org/10.1016/j.apgeochem.2016.12.022>
- Vaughn, J. M., Landry, E. F., & Mcharrell, T. Z. (1983). Entrainment of viruses from septic tank leach fields through a shallow, sandy soil aquifer. *Applied and Environmental Microbiology*. <https://doi.org/10.1128/AEM.45.5.1474-1480.1983>
- Voisin, J., Cournoyer, B., Vienney, A., & Mermillod-Blondin, F. (2018). Aquifer recharge with storm-water runoff in urban areas: Influence of vadose zone thickness on nutrient and bacterial transfers from the surface of infiltration basins to groundwater. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2018.05.094>
- WHO (2012). World Health Organization. pH in Drinking-water. https://www.who.int/water_sanitation_health/dwq/chemicals/ph_revised_2007_clean_version.pdf?ua=1. Accessed 10 October 2019.
- WHO (2017). World Health Organization. Guidelines for drinking-water quality fourth edition incorporating the first addendum, Switzerland.
- Withers, P. J. A., Jordan, P., May, L., et al. (2013). Do septic tank systems pose a hidden threat to water quality? *Frontiers in Ecology and the Environment*. <https://doi.org/10.1890/130131>
- Wu, Y., & Wang, Y. (2014). Geochemical evolution of groundwater salinity at basin scale: A case study from Datong basin, northern China. *Environmental Science Processes & Impacts*. <https://doi.org/10.1039/c4em00019f>.

- Yates, D. & Strzepek, K. (1994). Potential evapotranspiration methods and their impact on the assessment of river basin runoff under climate change. *International Institute for Applied Systems Analysis*, A-2361, Laxenburg, Austria.
- Yates, M. V., Yates, S. R., Warrick, A. W., & Gerba, C. P. (1986). Use of geostatistics to predict virus decay rates for determination of septic tank setback distances. *Applied and Environmental Microbiology*, 52(3), 479–483.
- Zolekar, R. B., Todmal, R. S., Bhagat, V. S., et al. (2020). Hydro-chemical characterization and geospatial analysis of groundwater for drinking and agricultural usage in Nashik district in Maharashtra, India. *Environment Development and Sustainability*. <https://doi.org/10.1007/s10668-020-00782-2>

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