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Article

Water Security Assessment of Groundwater Quality in an Anthropized Rural Area from the Atlantic Forest Biome in Brazil

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Abstract: The exploitation of natural resources has grown mainly due to the high rate of population growth that changed over time around the planet. Water is one of the most needed resources essential for survival. Despite all the efforts made to improve water security, an environmental impact related to anthropogenic influence remains of great concern, which is the alteration of surface and groundwater quality. In many regions around the world, there is limited or no access to rural and urban water supply while there is a need to improve sanitation facilities. This work evaluated the spatial distribution of groundwater and surface water quality as well as their changes in wet and dry seasons of the tropical climate in the Atlantic Forest Biome. The study area is under anthropogenic influence, which is in the municipality of Igarassú, Pernambuco State, Brazil. The analysis of the raw water was based on Standard Methods for Examination of Water and Wastewater, as referenced in the Brazilian Ministry of Health Consolidation Ordinance that sets standards for drinking water. The temporal analyses indicated a variation on water quality from the wet to the dry seasons, whereas the spatial results revealed deviations from the Brazilian's Water Supply Standards for some physicochemical parameters. There was an increase in the values of some parameters during the wet season in some hydrological compartments. The anthropized rural area from the Atlantic Forest Biome is affecting the water quality. It is, therefore, necessary to develop environmental policies and put them into practice by implementing engineering projects that guarantee proper treatment for raw water in order to bring the water quality back to a good status in this region.

Keywords: environmental monitoring; water quality; surface water; groundwater; drinking water

1. Introduction

The management of water resources as well as the sustainability of groundwater and surface water systems are topics of great concern [1–3]. Water covers 71% of the Earth's surface, but only 0.3% is available for drinking water [4]. The access to an adequate, reliable, and resilient quantity and quality of water for safe drinking is the main global water security issue related to aquatic ecosystems and human health [5–7] as well as to economic values. The understanding of natural processes and anthropogenic factors [8–10] and their roles for management and sustainability of water security resources require a better comprehension of changes that occur in groundwater and stream water quality [7,11], mainly to develop a governance and an implementation of water and land use policies [12].

Water governance is an excellent alternative for understanding and developing ways for water security [3,13] as well as seeking sustainable ways to exploit the groundwater resource to ensure human development [14] and integrated management [15]. Thus, environmental laws and guidelines are responsible for ensuring groundwater quality standards for consumption [16]. The Brazilian legislation and recommendations related to groundwater and stream quality list the parameters that must meet a certain potability standard directed to human consumption on drinking water [17].

Most of the water in the world goes to irrigation and agriculture, which is estimated at 70%, while industry uses 22%, and domestic use is at 8% [4]. In Brazil, the National Water Agency [18] through the Conjuncture of Water Resources in Brazil estimates that 72% of the country's water is destined for agriculture, 9% is destined for livestock, 6% is meant for industry, and, lastly, 10% is meant for domestic use. Land degradation is also a major source of water pollution related to erosion processes [11,12,19], contamination by heavy metals [20,21], eutrophication [22], and others, which, if unmanaged, can lead to significant economic and environmental costs.

Water quality is influenced by agricultural activities [23,24] and other land uses [11]. However, the consequences for water quality of some activities such as sand extraction or drilling of clandestine wells are still inconclusive or ambiguous. The extraction of sand through dredging is an important activity in the studied area with a need to supply the construction sector. Sand extraction can be an environmental stressor of surface and groundwater quality because the municipality of Igarassu explores a significant number of wells for the supply to local communities [25]. Therefore, the ecosystem integrity is vulnerable to physicochemical, erosive, suspended solid disturbances among others [26].

The Brazilian Northeast faces some inequalities in the access to water resources with certain population groups lacking a water supply system [25,26]. Extensive periods of drought can lead to irreversible socio-environmental impacts, which are related to soil water infiltration, increased runoff, and intensification of erosion. In the state of Pernambuco, the Pernambuco-Paraíba Basin is one of the largest underground water reserves. The Beberibe aquifer is one of the most important public water supplies, and the water company from the state of Pernambuco is responsible for distributing the drinking water to the municipalities of Recife and Igarassú. There are many socioeconomic activities that take advantage of water resources in the region. Additionally, the population in neighborhoods exploit groundwater [26,27].

Igarassú is a municipality of Pernambuco state, Brazil, with an area of 305,560 km^2, located 28 km away from the capital Recife. The climate is defined as Group As (Tropical savanna climate or tropical wet and dry climate), according to the Köppen climate classification. There are two well-defined dry and wet periods [27]: the wet season begins in the fall (May to October) and the dry season starts in the summer (November to April). The average annual rainfall is 1634 mm.

In a developing municipality such as Igarassú, there are densely populated areas with insufficient water supply, incomplete or inexistent sanitation, and ineffective environmental planning [28]. Under these conditions, water can transmit waterborne diseases and degrade environmental quality [28–30]. It is, therefore, important to systematically identify the factors that lead to water quality deterioration and propose solutions that are likely to secure the path of sustainable development [26,30,31].

This study was evaluated through field visits and laboratory analyses, the spatial distribution of groundwater, and surface water quality as well as the changes occurring from the wet to the dry season in the studied area, which aims to identify environmental issues that interfere within the quality of water consumed by rural communities as well as to propose solutions to impacts caused by human action within the framework of water security.

2. Materials and Methods

The study area is in an anthropized rural area from the Atlantic Forest Biome of Brazil, State of Pernambuco, located in the municipality of Igarassú, with central coordinates 7°51′09.5″ S and 34°53′05.4″ W (Figure 1).

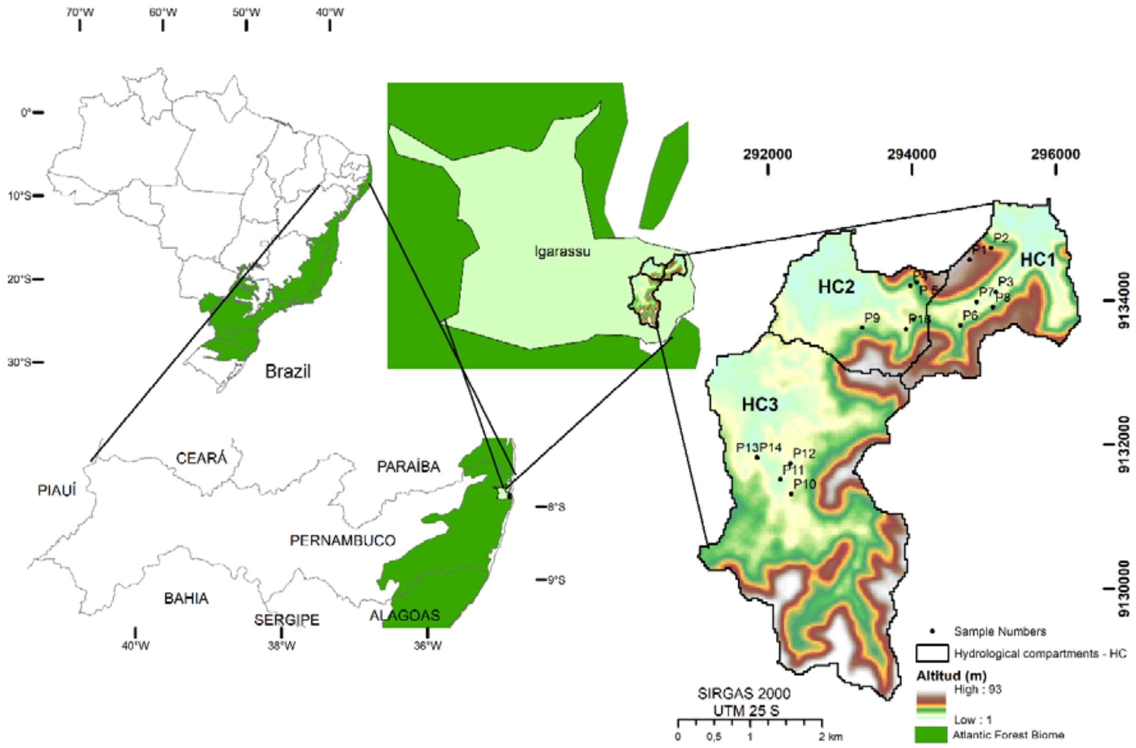

Figure 1. The location of the study area is an anthropized rural area from the Atlantic Forest Biome in Brazil, State of Pernambuco, Igarassú Municipality.

The study area covers approximately 16.1 km^2 with the anthropogenic pressures concentrated in the Northeast portion of the municipality. According to the geological map of the municipality of Igarassú (http://rigeo.cprm.gov.br/xmlui/handle/doc/16272), the area belongs to the Borborema Province where rocks from the Salgadinho Complex, sediments from the Beberibe and Gramame formations, and fluvio-marine and alluvial deposits crop out. Among others, the lithologic types include conglomerate and clay siltstone, sandstone with calcareous cement, and phosphorite interdigitated with calcarenites [29]. Topography is characterized by an undulated relief whereas soils are mostly represented by Yellow Latosols and Yellow Argisols with a sandy texture [27,29].

The water security assessment of groundwater quality was analyzed in three hydrological compartments (HC), as defined in Figure 1. Raw water samples were collected within the HCs and numbered from SN1 to SN16 and geo-referenced (Table 1). The sampling locations were strategically selected, considering the distribution of rural communities and their population. The samples, taken altogether, were representative of the different sources from which drinking water is obtained by the public rural community.

Table 1. Identification (number), source, and geographic coordinates of the water samples.

Sample Number (SN)	Water Source Types Depth (m)	Geographic Coordinate System UTM WGS 84 Longitude Latitude
1	Water well – 117 m	25M 294,802 9,134,568
2	Water well – 15 m	25M 295,100 9,134,730
3	Stream	25M 295,165 9,134,121
4	Cacimba – 8 m	25M 293,980 9,134,207
5	Water well – 128 m	25M 294,066 9,134,254
6	Cacimba – 2 m	25M 294,675 9,133,656
7	Cacimba – 4 m	25M 294,901 9,133,979
8	Cacimba – 4 m	25M 295,126 9,133,906
9	Cacimba – 8 m	25M 293,308 9,133,622
10	Cacimba – 8 m	25M 292,323 9,131,314
11	Water well – 30 m	25M 292,171 9,131,516
12	Dredging Pond – Sand pit	25M 292,313 9,131,739
13	Water well – 15 m	25M 291,853 9,131,820
14	Cacimba - 1.5 m	25M 291,847 9,131,823
15	Water well – 80 m	25M 294,024 9,133,740
16	Cacimba – 8 m	25M 293,919 9,133,606

The sampling of groundwater was conducted in drilled wells from the water table aquifer (SNs 1, 2, 5, 11, 13, and 15) in cacimbas that are small excavations dug near the streams to reach the water table with the purpose to remove water for domestic use or small plantations, which can be lined with a concrete pipe to prevent the collapse of their walls (SNs 4, 6, 7, 8, 9, 10, 14, 16) in the stream (SN 3) and from a dredging pond, which means an area where silt and sand are removed from the bottom of the water bodies (SN 12). The water well depths ranged from 15 m to 128 m, and the cacimbas depths ranged from 2 m to 8 m. The hydrological compartments (HCs) were drawn using a set of 1/10,000 scale contoured orthophoto cards by considering the water divides.

Campaigns for field data collection and raw water sampling in the study area were carried out during the rainy season between the months of March to July, called Wet Season Samples, and during the season without rain from August to February, which is called the Dry Season Samples. The sampling was done by collecting raw water in a 2-L bottle preserved under refrigeration for analysis, according to Standard Methods for the Examination of Water and Wastewater [32]. The samples were taken to the Minerals, Soils, and Water Analysis Laboratory (LAMSA), located at the Department of Chemical Engineering of the Federal University of Pernambuco (UFPE), for processing and conducting physicochemical and microbiological analyzes. The physicochemical analyses were based on specific protocols and assumed as pre-defined standards, described in PRC No. 5 - Annex XX, Chapter III, section V, Art. 22 of the Brazilian Ministry of Health [33] and in American Public Health Association (APHA) [32]. The samples were collected during the day between 6:00 to 18:00 h at the same hour for each sample number at a given site, by following the numbers from SN1 to SN16, during seven consecutive days in each season. The stream (surface water) was sampled at about 7:30 a.m.

Raw water temperature, turbidity, pH, total dissolved solids, dissolved oxygen, ox-redox potential, and electric conductivity were measured in the field during the sampling campaigns using a multiparameter probe called the HORIBA model U-50 (Table 2).

The heavy metal concentrations (lead, copper, total chromium, zinc, and cadmium) were measured by atomic absorption spectrophotometry. UV-VIS spectrometry determined sulfates, nitrate, and nitrite. Flame photometry was used to determine sodium and potassium. Analyses of total hardness and alkalinity (Mohr method) were performed by volumetric analysis. Total iron, aluminum, ammonia, and color were determined using Merck Millipore spectrophotometric analysis, using Merck Millipore PHARO 100 (VIS) and 300 (UV-VIS) spectrophotometers. The method was based on the use of Millipore filters with pores of 0.6 micron. Microbiological analyses of total and thermotolerant (fecal) coliforms and heterotrophic bacterial count were based on the methodology of the Standard Methods for the Examination of Water and Wastewater [32].

Table 2. Parameters measured by the Horiba U-50 model probe and their measurement units and precisions.

Parameter	Measurement Unit	Precision
Temperature	−5 to 55	±0.3 + 0.005
Turbidity	0 to 800 NTU	±1 NTU
pH	0 to 14	±0.1pH
Total dissolved solids	0 to 100 g/L	±5 g/L
Dissolved oxygen	0 to 50 mg/L	0 a 20 mg/L: ±0.2 mg/L 20 a 50 mg/L: ±0.5 mg/L
Oxi-redox potential	−2000 mV to + 2000 mV	±15 mV
Electric conductivity	0.0 µS/cm to 99.9 µS/m	±1%

The analyses were based on Directives 98/83/EC and (EU) 2015/1787, which are methods accepted by PRC No. 5 - Annex XX Chapter III, section V, Art. 22 [33] and by the APHA methodology [32].

Geospatial distribution maps were drawn for the pH, color, turbidity, and total iron parameters within the study area. The Nephelometric Turbidity Units (NTU) varies from 0 to 800 NTU. The Hutchinson's Topo to Raster [34] interpolation method was used. This method allowed the use of contours, basin boundaries, and georeferencing to interpolate data, which highlights the areas where the quality of water is not conforming with the legal standards [33]. The interpolation was performed using the weighted sum of squares in the residuals by the surface elevation data [34,35]. Thus, through this interpolation model, vector data were converted into hydrological land models [34–36].

Radar charts were drawn to display the multivariate water sample observations. Each spoke in the chart represents one variable. The length of a spoke is proportional for the magnitude of the variable. Radar charts were drawn for every data point (SN1 to SN16) and were represented in a multi-plot format.

3. Results and Discussion

3.1. Water Parameters' Interaction at the Sample Number and Hydrological Compartments

The specific studied area was divided in three hydrological compartments (HC) considering the altitude of land that drains the water downslope to the lowest point (HC1, HC2, and HC3) and the anthropized rural area from the Atlantic Forest Biome in Brazil.

Identification of seasonal trends (wet and dry) in raw water-quality constituents was especially important because high or low rates of each parameter have such a substantial effect on analyses of an anthropized rural area [9]. Surrogates monitored on a continuous basis provide resource managers with real-time information on sample number properties that showed different water characteristics and specific land uses as well as distinct reliefs [9,10]. The maximum, minimum, average, and stand deviation measured values at each compartment are shown in the Supplementary Material.

HC1 and HC2 stand out as areas of low dense community occupation within small planting areas, animal husbandry, drinking water, and multiple uses of water. HC3, in turn, represents an area where there are sand extraction sample numbers, a small aerodrome, and coconut processing industries for oil production.

The geospatial distribution of the physicochemical parameters showed that some of the SNs are not in line with the Brazilian Ministry of Health Consolidation Ordinance.

3.1.1. pH

The pH is a measure of the hydrogen concentration of the water, which is controlled by chemical reactions and the balance of ions present. According to the pH data, acidic waters are observed in the research sites. The raw water was measured in each Sample Number (SN) by the pH to show how acidic, neutral, or basic is the site. pHs of less than 7 indicate an acidic nature, whereas a pH of greater than 7 indicates an alkaline water, and it is a very important measurement concerning water quality. As the range moves from 0 to 14, with 7 being neutral, the PRC No. 5 recommends that the pH of water for the human supply stays around 6.0 to 9.0 [33].

As shown on sites, the raw water is changing chemically, and the measured sites (SNs) that showed relative acidic water (4.2 to 6.9) have a higher amount of free hydrogen. Yet, the sites where the raw water had more free hydroxyl ions were considered as basic samples (7.1 to 8.4) (Figure 2).

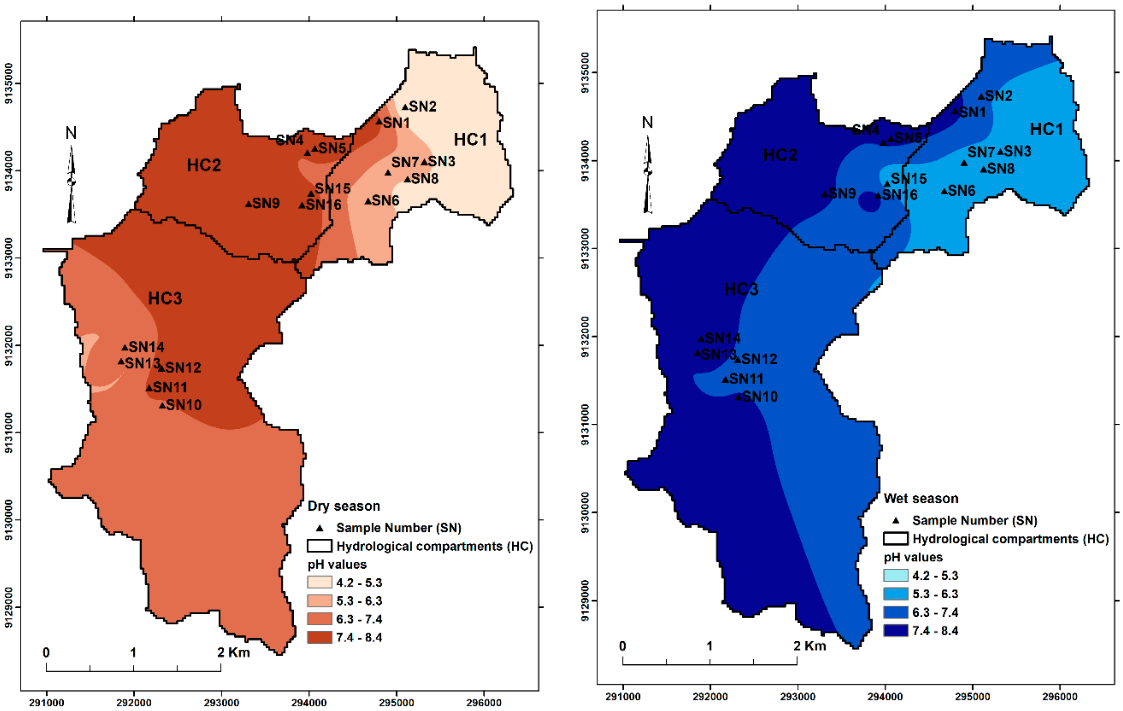

Figure 2. Spatial distribution of pH on the dry and wet seasons in the three hydrological compartments.

The pH represents a unit related to the activities of H + ions, which indicates in its expression's indices of neutrality, acidity or alkalinity. When comparing this parameter in the three hydrological compartments in the two climatic periods (wet and dry), there is a predominance of acidic pH in the hydrological compartment 1 (HC1), while the hydrological compartment 2 (HC2) presented an index of alkalinity in the studied period, which is similar to work conducted on groundwater as an alternative source to an irregular surface water in Namaqualand, South Africa [3].

The pH of groundwater is influenced by salts, acids, and bases present in the environment. In the studied area, the pH may result from natural geologic-soil-water interactions, or trace the environment's quality, which includes the water source, land degradation, or deforestation [2,3,6], among other factors that occur in the region. In the environment, aquatic systems showing low pH values may be related to weathering processes [3]. Some lithological structures, when weathered, contribute by releasing acid-forming elements [6].

The minimum values of pHs < 6 listed in the Supplementary Material were shown to be more prominent on sites SNs at HC1 during the dry season (Figure 2). In addition, one of the reasons for pH values stays less than 6 and is the higher concentration of clay minerals, which dissolve releasing silica and aluminum in the waters [6]. This parameter directly influences the distribution of elements and chemical compounds in their free and ionized forms, which gives water an ability to increase or reduce its potential solubility relative to substances, including those with a degree of toxicity [1]. One of the factors that also contribute to acidic pH indices in water is the concentration of organic acids from dissolution resulting from the decomposition of organic matter, which may be happening in the hydrological compartment 1 (HC1), where there is a stream with visible contribution of organic matter. Additionally, the pH of rain varies between 5.0 and 6.0, but also "acid rain" may reach pH values as low as 4.3 [1,33]. The highest pH values (e.g., <7.5) are most likely related to weathering of the carbonate rocks that are represented in the study area [29].

pH is a very sensitive component to changes and variations in water resources, and may oscillate, according to the dissolution of salts, decomposed organic matter, leaching processes, lithological soil types [29,37], and, above all, due to temperature [6,38].

3.1.2. Turbidity

The appearance of water with a turbidity less than 5 NTU is acceptable by the Brazilian Standards. The turbidity can be caused by particulate matter that may be present in the water source by resuspension of sediment along the flow path, or by the presence of inorganic particulate matter in groundwater [39,40]. Observing the turbidity in water (Figure 3) in both climatic periods (values in the Supplementary Material), there is an average value as a high turbidity during the dry season in SN 2, 7, 8 (HC1), 4, 9 (HC2), and 11, 13 (HC3) and on wet season in SN 10, 11, and 13 (HC3). The higher values of the parameter during the dry season may be related to the permanence of the suspended material that confers water turbidity through the lower rainfall of the dry season. Usually, clastic suspended sediments, such as sand and silt, give high turbidity in the waters [39–41], which are characteristic of the region where the study area is inserted.

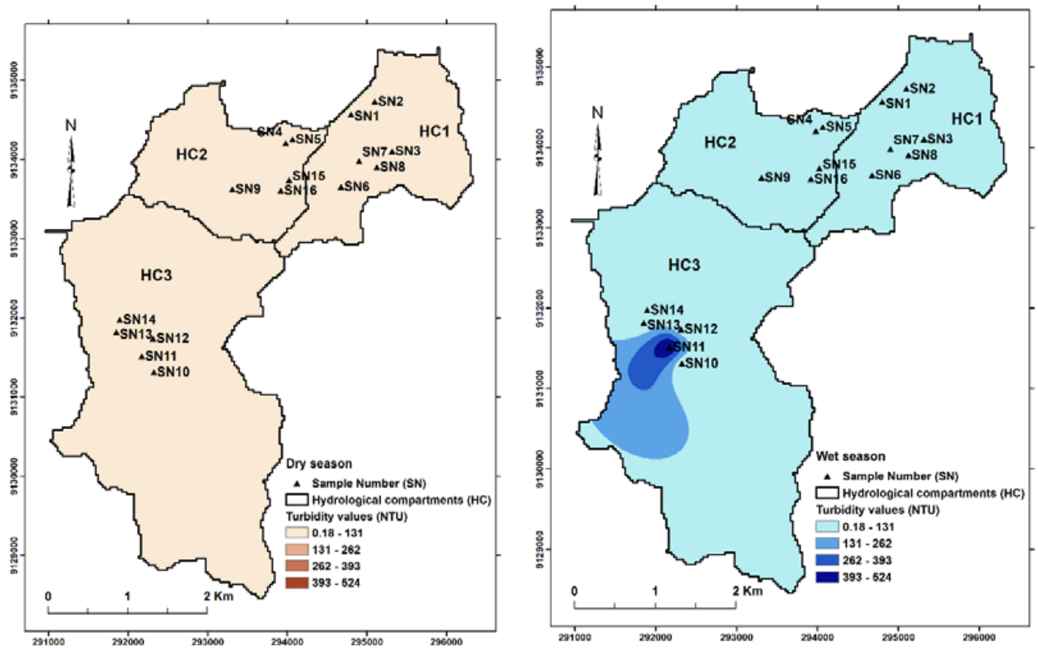

Figure 3. Spatial distribution of turbidity in the dry and wet seasons in the three hydrological compartments.

Considering the maximum values observed, the turbidity was higher than 5 NTU in almost all sites evaluated in both seasons except on SN 15 and SN 16 (HC2) during the dry season and SN9 (HC2) during the wet season (Supplementary Material). Anthropic actions have a direct relationship under high turbidity rates (SN11 and SN12) (Figure 3). Leaching and hauling of particles from soil exposed by mining activities, such as sand extraction, provoke upturning, which increases the availability of suspended particles. Environments where turbidity values are high are difficult for light to penetrate in water, which impairs the action of photosynthetic organisms. Some microorganisms are physically protected by the turbidity particles, which reduces the efficiency of water treatment [39–42]. Microbes and other colloidal particles can be physically removed from water by various processes. The sizes of the microbes are especially important for their removal by sedimentation and filtration. Such methods are described in report APHA methodology [32].

3.1.3. Color

The color in water can be caused by dissolved and/or suspended materials, and a brown shade often comes from rust in the water pipes. The physico-chemical characterization of color of sampling sites that exceeded the thresholds of PRC n°5, with color > 100 UH, were SN 3, SN 11, and SN 13 during the wet season and SN 3 and SN11 with color 67 UH and 80.9 UH, respectively, during the dry season. Studies refer that the presence of organic matter, metals, and other chemical and biological components can cause changes in color values in surface water and in groundwater [43]. To understand color, it is important to deepen the characterization of sampling sites where the anomalous values occurred.

The characteristics of site 3 are illustrated in Figure 4a. There is vegetation on the banks and a substantial amount of decomposing organic matter is suspended in the stream surface. The site number 11 (Figure 4b) is a lagoon where massive sand exploration occurs, and high turbidity occurred. Sample number 13 (Figure 4c) is a shallow cacimba without any fence and is situated in a contaminated area in a sanitation-free community surrounded by vegetation. Water is used for multiple uses and there is a makeshift toilet and laundry facility located within meters.

Figure 4. Sampling sites with anomalous color: (**a**) in the creek (SN3), (**b**) in the drainage pond of an area with sand exploration (SN 11), and (**c**) in an open cacimba (SN13).

According to Figure 5, the hydrological compartments HC1 and HC3 possibly presented the highest color indices, which is above what is allowed by the comparison norms (PRCn.5 threshold > B15UH). The results indicate that a probable source of color in these compartments is, as well as turbidity, responsible for the dissolution of organic substances that confer color and natural pigmentation.

Color as well as turbidity is a parameter influenced by natural factors such as decaying organic matter and substances dissolved in water. By analyzing the geospatial distribution of this parameter in the three hydrological compartments, it was shown that a similar profile in the two climatic periods occurred and was analyzed (Figure 5).

At the same sampling sites that showed color values outside the Brazilian Standards, turbidity was also out of the standard range. High turbidity was measured at the SN11 (> 100 UT), where sand extraction occurred for years. The emerging issue of sand extraction and solutions to address potential environmental impact is of great concern. Some authors discuss environmental stressors related to the exploitation of sand in which one of them is the alteration of the surface and groundwater quality since this activity is capable of dissolving, suspending, and transporting organic and inorganic substances, which changes several quality parameters [41–43]. Turbidity is one of the most affected parameters, and very little attention has been given to this parameter related to sand extraction.

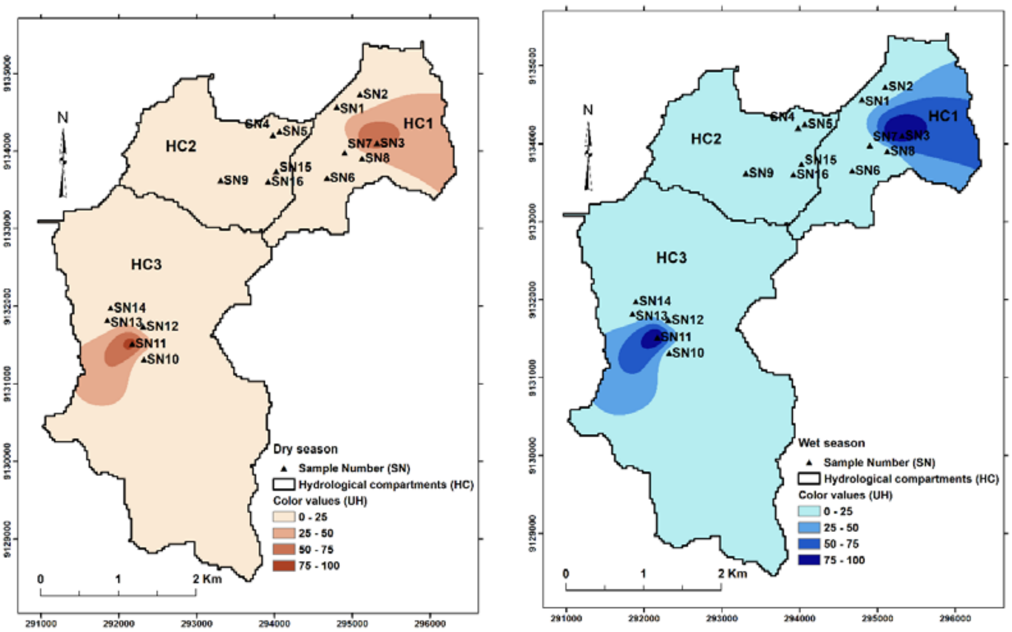

Figure 5. Spatial distribution of color on the dry and wet seasons in the three hydrological compartments.

3.1.4. Total Iron

Total iron was non-standard in four sampling sites. During the dry season, iron values were above the legal thresholds in sample numbers 1, 3, and 11 while, during the wet season, the affected sample numbers were SN3 and SN10. The SN1 presented relatively high values of iron where the soil and geology may be an influencing factor when considering the highest value of the well depth [6,43]. During the dry season, SN3 presented iron values of 4.5 mg/L and a pH of 5.41. It is common in waters that present this kind of pH values that the occurrence of Fe^{2}+ iron indicates that water with a certain acidity presents high iron concentrations [38,44,45]. Iron in groundwater may contain ferrous iron at concentrations up to several milligrams per liter without discoloration or turbidity in the water when directly pumped from a well [45]. On exposure to the atmosphere, however, the ferrous iron oxidizes to ferric iron, which gives a reddish-brown color to the water. At levels above 0.3 mg/liter (SN1, SN3, and SN11), iron stains laundry and plumbing fixtures. There is usually no noticeable taste at iron concentrations below 0.3 mg/l even though turbidity and color may develop [24].

The physico-chemical characterization of total iron of sampling sites that exceeded the thresholds of PRC n°5, > 0.3 mg/L were SN3 (0.6 mg/L) and SN 10 (0.53 mg/L) during the wet season, and SN1 (0.44 mg/L), SN3 (4.5 mg/L), and SN 11 (0.61 mg/L).

Observing the values of the total iron in both wet and dry seasons (Figure 6), an increase in concentration during the dry season is noticeable, especially in the SN 3, in hydrological compartments of HC1. In this compartment, sample number 10 showed values that did not comply with the compared norms. Hydrological compartments HC2 and HC3 did not show a significant change in iron concentrations in both climatic periods even though this element is not in accordance with the Brazilian Ministry of Health ordinance [33].

Iron can also arise from corrosion of ferrous pipework and chemicals used in treatment processes (coagulation). Iron suspensions cause aesthetic problems including metallic taste and discoloration of water fittings and laundry. The Brazilian drinking water quality regulations include national standards for iron (0.3 mg/L), which can be removed from water by filtration, oxidation, coagulation, and sedimentation [32,33].

Generally, in groundwater, iron levels derive from minerals and sediments that can be present in particulate or dissolved forms [1,38]. In surface waters, iron levels increase in the wet season as a result of soil runoff and erosion due to higher precipitation. Iron dissolved in water sets color, odor, and taste.

Iron concentrations in the dry season are higher than during the wet season, mainly in HC1. In both seasons, most of the area is higher than 0.3 mg/L (standard value for drinking water), but, during the dry season, much higher concentrations (up to 0.58 mg/L) can be encountered in groundwater from water wells, cacimbas, and surface water.

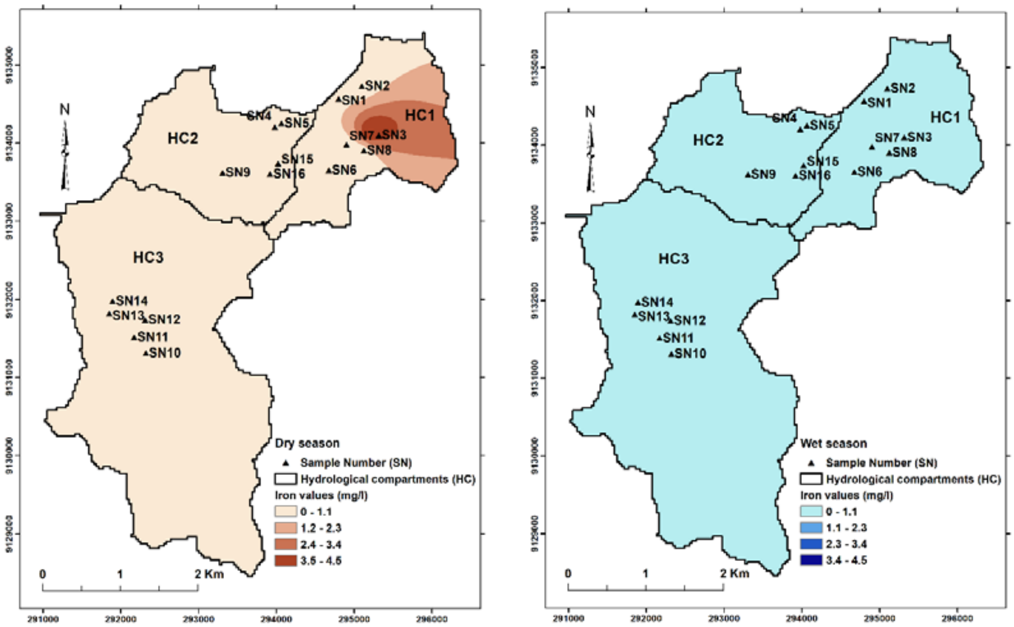

Figure 6. Spatial distribution of total iron during the dry and wet seasons in the three hydrological compartments.

The sample number SN3 during the wet season (0.6 mg/L) and the sample numbers SN3 (4.5 mg/L) and SN11 (0.61 mg/L) during the dry season showed a common phenomenon where high iron levels that occurred showed high color concentrations [38]. It is usually possible to find high levels of iron in groundwater whose pH has acidity, and, in surface water, that has organic matter [44,45].

With this distribution, a higher concentration of acidity pH in the hydrological compartment 1 (HC1) is present (Figure 2). This same compartment presented levels of turbidity, color, and total iron out of the PRC threshold [33] (Supplementary Material and Figures 3, 5 and 6).

3.1.5. Correlation Analysis

The chart on 7, 8, and 9 contains the star plots of seven water parameters. The variable list for the sample star plot is Total Dissolved Solids (TDS), Temperature (Temp), pH, Oxi-redox potential (ORP), Electric Conductivity (Cond), Turbidity (Turb), and Dissolved Oxygen (OD). The plots were analyzed individually to identify clusters of the water parameters with similar features. The star plot of the water quality parameters compares the variables during dry and wet seasons at the three hydrological compartments (HC1, HC2, and HC3). The star plot in Figure 7 predicts the concentration of the parameters in HC1 and their comparison with drinking water standards in each sample number. In the hydrological compartment 1 (HC1), there is a significant correlation in STD and Cond in SN1 and SN2. The SN3 was higher during the dry season than during the wet season.

The dissolved oxygen (OD) was higher on SN1, SN3, SN6, and SN8 during the wet season. This is likely a consequence of gas exchange with the atmosphere, agitation, rainwater recharge, and increased movement of the water stream, which improves the aeration capacity of this ecosystem. Dissolved oxygen concentration is one of the most important factors for maintaining biodiversity in surface waters [46] such as rivers and streams.

A constant relationship in HC1, regardless of the season, is Total Dissolved Solids (TDS) with Electrical Conductivity (Cond). There is a similar response of both parameters, and, when this does not occur, a significant reduction in turbidity is noted. This can be explained as described in water quality manuals where the dissolution of salts in water can result in electrolytes capable of conducting certain electrical current [23,46,47]. The temperature increase corresponds to a gradual increase in conductivity with a proportionality relationship [47]. All sample numbers (SN) show similar ecosystem performance, especially during the dry season. During the wet season, the correlation of the dissolved solids and conductivity became more evident.

In hydrological compartment HC2 (Figure 8), in general, the correlated comportment between dissolved solids and conductivity was similar for both wet and dry seasons. The parameters showed the similar concentration mainly during the wet season.

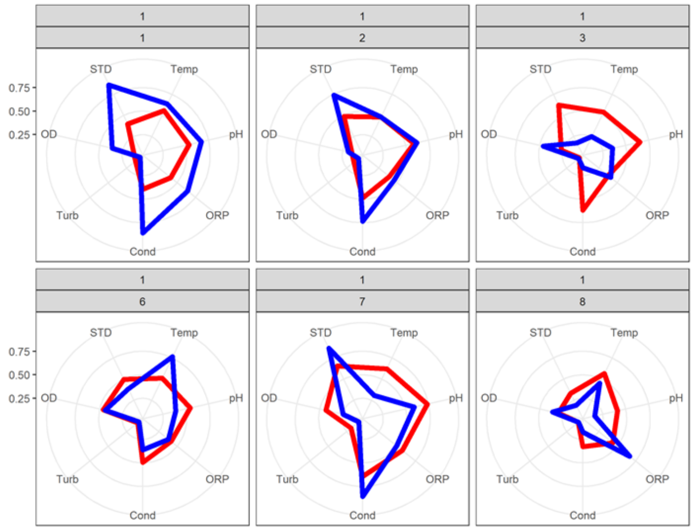

Figure 7. Correlation of water quality parameters during the wet and dry seasons in the hydrological compartment (HC) 1. Red line (dry season), blue line (wet season).

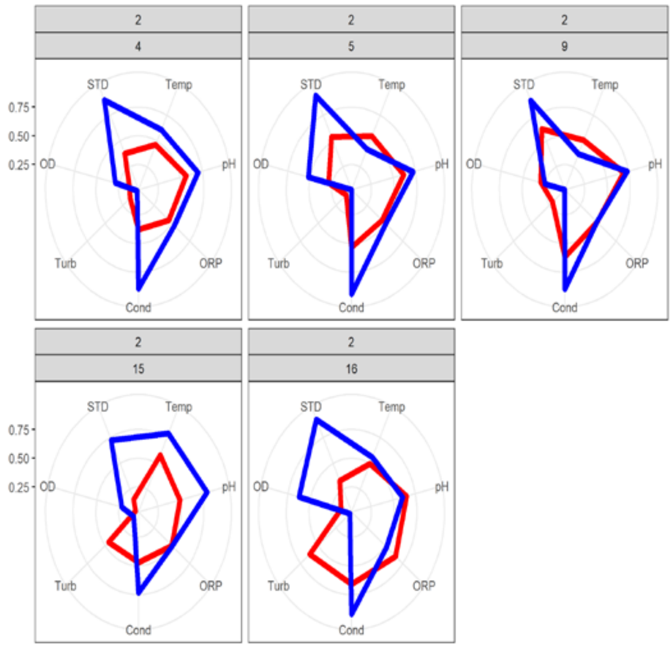

Figure 8. Correlation of water quality parameters during wet and dry seasons in a hydrological compartment (HC) 2. Red line (dry season), blue line (wet season).

The pH at all sample numbers from HC2 remained in the same ranges. However, the Oxi-Redox water Potential (ORP) had a different value when compared to HC1. The potential for oxir-reduction with the tendency of substances to receive electrons can be evaluated, and it is possible to determine the potential by the possibility of the microorganisms grown in the area by the values of the redox potential, as shown on research on ORP in environmental research [48]. The ORP values in this compartment were similar to the values studied [48], within this premise, in a sample of natural water at a pH of 7. Oxygen should be the main electron receptor when the measured redox potential is close to (and above) + 400 mV. When the ORP value is between +100 and +300 mV, all oxygen must have been consumed and the main electron receptors will be NO_3^- and Mn, respectively, with the most abundant products being nitrogen and ammonia in addition to solubilizing manganese in the form of Mn^{2+}. In more drastic anoxic conditions, ranging from 0 to –300 mV, the electron receptors will be Fe^{3+}, then SO_4, and, finally, organic matter and CO_2, which are generated as reduction products iron (II), sulfide, and methane, respectively. It can be characterized as stable for both seasons [44,48]. Where there is a greater availability of dissolved oxygen (OD), there is an increase of ORP, which is a clear correlation in both climatic periods in this compartment.

In hydrological compartment 3 (HC3) (Figure 9), there is a similar result of the correlations that occurred on HC1 and HC2. All sample numbers have a low correlation to turbidity except on sample number 11, which is a lagoon from which sand has been extracted for years. At this point, it is possible to notice what differs from all the sample points, with low correlation on turbidity (Turb) and high correlation during the wet season for STD and pH. Similar results were found in a natural water reservoir [49,50].

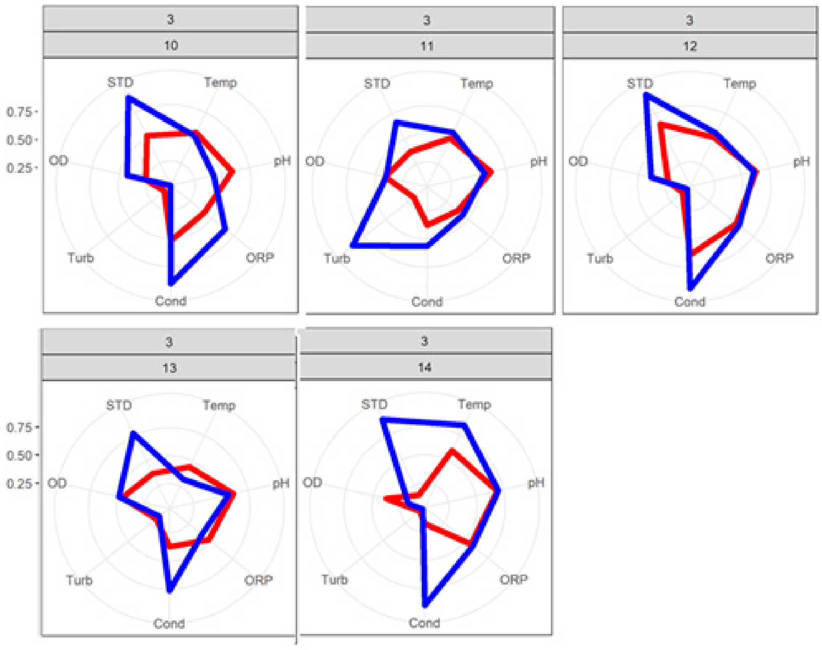

Figure 9. Correlation of water quality parameters during wet and dry seasons in the hydrological compartment (HC) 3. Red line (dry season) and blue line (wet season).

In all three hydrological compartments, there was a correlation between STD, pH, Cond and OD, mainly during the wet season. Similar results were verified in natural and anthropic influences on groundwater quality of public wells in São Paulo State, Brazil [28,47,50]. It was observed in all studied sample numbers an increase of the concentrations of the parameters evaluated, mainly during the wet season. In the summer, there is a shorter dwell time of water in the water table [50,51]. This is explained by the lower percolation of rainwater. Thus, it is understandable to increase the values of the physicochemical parameters evaluated during the wet season.

Considering all the parameters evaluated, the inequalities in access to water is verified and should aggregate contextual aspects of the ecosystem during dry and wet seasons and in the demographic perspectives, which reflect the intrinsic characteristics of the Atlantic Forest Biome dynamics and the relationships that are established daily in the water resource use and anthropized rural area. The view toward increasing inequalities in the access to water and the concentration of the deficit in certain rural communities corroborates the research in the Brazilian northeast area in underground flows of nutrients and trace metals [21,26,43].

The water supply system in the area must improve, mainly in treatment for drinking water, and from the aquifer [52]. Considering the inequalities in accessing better quality drinking water, the water security assessment is not present and significant progress is expected from the government to determine the vulnerability to water access [7,18,23]. Assessments involving the treatment of water or a better land use management [53,54] to ensure better water quality is necessary to include basic services such as the water supply for multiple uses.

The contributions of the paper results in (1) providing further evidence on similar investigations by water monitoring those rural communities and by an environmental education service, (2) the paper introduces the land use problems of the anthropized rural areas in the Atlantic Forest Biome, (3) the results show an improvement on the performance measurements of a set of water parameter results and should encourage the view that the subsequent water quality mapping that is necessary for a water security system.

For instance, the Pernambuco government must be alert of the boundaries between unconfined/confined aquifers that mark the interfaces for recharge and, thereby, contaminants that must be included in a study of hydro chemical investigation of the aquifers to determine the trace and minor element anomalies and possibly delineation of the interfaces and its vulnerability [52,53].

The anthropogenic activities from the rural area at the Atlantic Forest Biome in Pernambuco contribute significantly to groundwater contamination and to a water security assessment of groundwater quality. The government must investigate the influences from anthropogenic activities on deep groundwater (SN11) reflected in two possible scenarios: mixing with deep geological features and vertical leakage of shallow groundwater. Additionally, intensive groundwater contamination treatment must be done and controlled by water supply companies. The public drinking-water supply using groundwater should be tested prior to being used for general consumption.

3.2. Microbiological Analyses

3.2.1. Coliforms

Presence/absence tests were performed for total and thermotolerant (fecal) coliforms in all samples studied in the established climatic seasonal periods. Ministry of Health Consolidation Ordinance No. 5 establishes water as unfit for human consumption in the presence of coliforms, which requires a maximum permissible (MPN)/100 mL of thermotolerant coliforms [33]. All studied sample numbers (SN1–SN16) presented fecal coliforms in their waters, which make them unsuitable for direct human consumption. The waters studied in this region should only be used for drinking water after a previous disinfection water treatment.

Although water does not naturally provide conditions for the proliferation of pathogenic organisms, they survive long enough in the environment to occur in the water transmission [55]. Therefore, the presence of pathogenic microorganisms in water comes from the contamination by the anthropized area [55,56] from animal or human feces, which results from infiltration and wastewater among others [10].

The studied region does not have basic sanitation structures in the area of influence of this study. The study area receives impacts with the exploitation of sand. The population uses septic tanks as a sewage system including many without adopting the safe distances for the installation of such systems.

It is also emphasized that, in areas near the collection sampling sites, there is livestock breeding, and, in some of them, there is no proper sealing of the wells.

The contamination of water in an anthropized rural area from the Atlantic Forest Biome is not favorable since, in the studied area, risks of contamination can occur from the reservoirs or even in the distribution networks created by the residents since the urban supply system does not reach these areas [55–57]. Thus, it is common for distinct sources of contamination to occur [57].

Pathogenic agents have several properties that distinguish them from other drinking water contaminants. If infection is established, pathogens multiply in their host. Certain pathogenic bacteria are also able to multiply in food or beverages, and, thereby, perpetuate or even increase the chances of infection. The water studied must have a water quality verification that complements operational monitoring and assessments of contamination risks such as through auditing of treatment works and evaluating the process control and sanitary inspection. Water intended for human consumption should contain no indicator organisms. In most cases, monitoring for indicator bacteria provides a high degree of safety because of their large numbers in polluted waters [55–57].

3.2.2. Heterotrophic Bacterial Count

The Brazilian Ministry of Health Consolidation Ordinance No. 5 performed bacterial counting test analyses, which established a maximum permitted number of less than 500 CFU/mL [33]. From all sample numbers, six presented adequate values within the potability standards. They are the sample number 1, 6, 7, 8, 10, and 15. All other sample numbers presented inadequate values for human consumption. This is an important result because contaminants indicate a high probability of pathogenic microorganisms occurring in water [55]. Microorganisms responsible for gastroenteritis may occur, which are infections that have diarrhea as their main symptom.

3.3. Heavy Metals

Heavy metals are harmful for freshwater ecosystems such as fish communities, and, therefore, can also be harmful to humans if they enter the food chain through the fish [53,54]. The Brazilian Standards for drinking water are established in the maximum permissible physicochemical parameter's concentrations [33]. Based on those values of the analyzed sample numbers (SN 1 to SN16), the heavy metal (Lead (0.01 mg/L^{-1}), copper (2.00 mg/L), total chromium (0.05 mg/L), zinc (5.00 mg/L), cadmium (0.005 mg/L)), sulfates (250.00 mg/L), nitrate (10.00 mg/L), nitrite (1.00 mg/L), total hardness (500.0 mg/L), aluminum (0.20 mg/L), and ammonia (1.5 mg/L) had established an acceptable range for drinking water [21,33].

4. Conclusions

The water quality in all studied sample numbers and hydrological compartments was not according to drinking water standards related to the parameters established by the PRC n°5.

Drinking water sources in the rural area are contaminated, which can cause sickness and disease from pathogens. The presence of fecal coliforms is the most serious alteration in the quality of these waters since it configures contamination by pathogens that can lead to gastrointestinal diseases.

Drinking water sources are subject to contamination and require appropriate treatment to provide safe drinking water for their communities.

The color, pH, turbidity, and total iron parameters are the physicochemical parameters that classify, together with the microbiological ones, the waters studied as unfit for human consumption.

None of the collection sample numbers presented alterations for the analyzed heavy metals.

There was a significant change in water quality between the dry and wet seasons, which comes with a similar quality pattern throughout the year. There was an increase in the values of some of the specific physicochemical parameters during the wet season.

In all three hydrological compartments, there was a concentration of different chemicals of interest not suitable for drinking water. Assessing water quality must involve monitoring the chemical concentrations in a government baseline concentration in a guideline established to protect human health or ecological communities.

The anthropized rural area from the Atlantic Forest Biome affects water quality. The Pernambuco water supply system must implement a regional simplified water treatment, so that people in the rural area can have access to better quality water. This would solve many of the water quality changes assessed in this paper.

For a water security assessment of groundwater quality, practices can be adopted for effective improvement of water quality evaluated in this research regarding the development of environmental public policies that monitor the quality of water used by the population in the region or the increase of the water and sanitation distribution network. Environmental education and the regulation of wells and cacimbas used by communities in the area are also key practices to ensure water quality within the parameters.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/3/623/s1, Table S1: Raw water maximum, minimum, average, and stand deviation measured values at each compartment (HC).

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