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ORIGINAL PAPER

Groundwater quality assessment in a peri-urban Brazilian semi-arid microbasin

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Abstract

Critical to global water security, aquifers represent a strategic resource that must be rationally exploited to ensure their future availability and to guarantee the socioeconomic and environmental development of a region. This paper assesses the chemistry of groundwater and evaluates its quality status using a hybrid framework that includes the use of a regionalized Groundwater Quality Index (GQI_R) in conjunction with a GIS-based geostatistical tool. The proposed hybrid approach is presented through a case study conducted in a peri-urban microbasin in Northeast Brazil with an unconfined aquifer system as the main source for public water supply. For this purpose, a total of eight wells were sampled during the rainy and dry seasons throughout 2019. Twelve hydrogeochemical parameters were evaluated, of which only phosphorus exceeded the maximum allowable limit in 75% of the cases. The geostatistical distribution maps made it possible to identify the aquifer areas most affected by domestic effluents, agriculture and livestock farming. The water quality parameters are mainly affected in wells located in highly urbanized and agricultural areas (P1–P5). Despite this, the GQI_R ranged from 61.40 to 75.59 (rainy season) and from 55.04 to 72.92 (dry season). Although there was a relative worsening of the water quality in the dry season, in both cases, the water quality can be classified as Good ($51 < GQI_R \leq 79$). This hybrid approach allows water resource managers to prioritize areas in which mitigation and aquifer monitoring actions are most needed.

Keywords Groundwater Quality Index · Peri-urban microbasin · Geostatistical distribution maps · Water management · Hydrogeochemical parameters

Introduction

Groundwater is the main water source for the populations of arid and semi-arid regions and, therefore, the assessment of its quality is a determining factor for their water security (Brhane 2018; Silva et al. 2021). Similar to other regions with water shortages in the world, the availability of good-quality groundwater in the semi-arid region of Northeastern Brazil is directly linked to the region's water security, especially in a context of global climate change affecting rainfall patterns in the region (Hirata et al. 2019; Shubo et al. 2020). We should note that the Brazilian semi-arid region represents about 12% of the country's area and is home to about 28 million people living in urban (62%) and rural (38%) areas, thus representing one of the most populated semi-arid regions in the world (IBGE 2021). In addition to the effects related to global climatic phenomena, groundwater resources in this region are affected as well by regional climate changes, environmental changes caused by increasing anthropogenic pressures, and problems in the management of the sanitation infrastructure. All these factors, when combined, may accentuate the water supply crisis (Getirana et al. 2021; Silva et al. 2021).

In this scenario, a continuous monitoring of groundwater quality is an important management strategy, especially in

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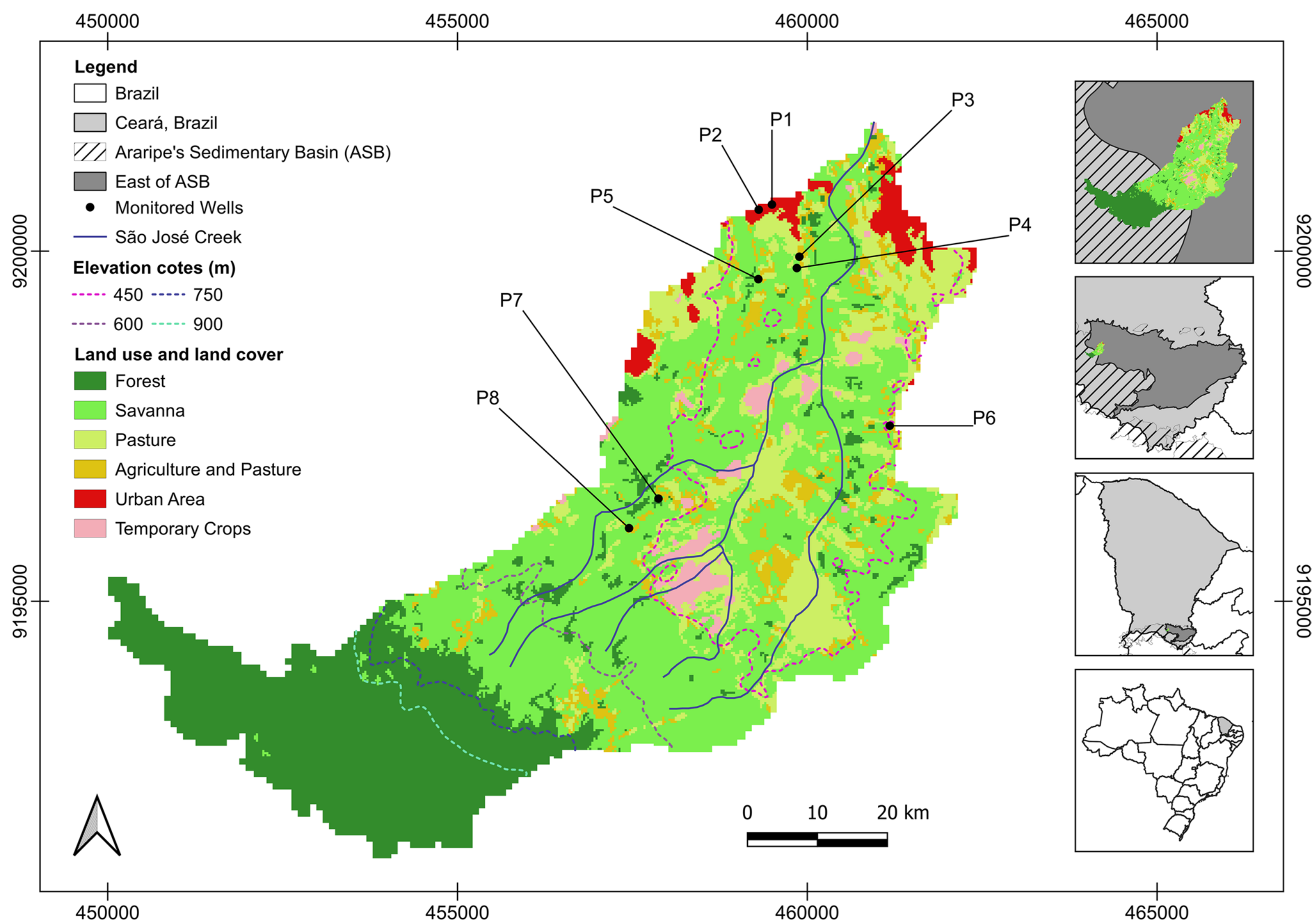

Fig. 1 Location of the monitored wells and land uses in the São José peri-urban microbasin (SJMB)

regions with an arid or semi-arid climate (Maia et al. 2019; Getirana et al. 2021; Silva et al. 2021). In such monitoring, the different water attributes and variables are usually correlated to and under the influence of several factors, making it difficult to tell which variables are most representative when defining the quality of the water (Maia et al. 2019; Getirana et al. 2021). Traditionally, a water quality assessment is made by comparing individual parameters to regulatory allowable values, which may not accurately describe the status of the assessed water (Vadiati et al. 2018; Noori et al. 2019). In developing countries, obtaining a range of parameters that are continuously monitored involves severe restrictions in terms of cost and time. On the other hand, however, the Groundwater Quality Index (GQI) contributes to the water management process and has been widely applied (Badillo-Camacho et al. 2015; Sikder et al. 2015; Benouara et al. 2016; Brhane et al. 2018; Zhang et al. 2020; Silva et al. 2021).

This study aims to evaluate the quality of groundwater in tubular wells in a peri-urban basin located in the Cariri Metropolitan Region (CMR), in the Araripe Sedimentary Basin (ASB) of the Brazilian semi-arid. For this purpose, a hybrid approach using a Geographic Information System (GIS) and a regional Groundwater Quality Index (GQI_R) were used in the São José River microbasin (SJMB).

Materials and methods

Overview of study area

The SJMB covers an area of 49 km^2 inserted in the Eastern sector of the ASB (Fig. 1). The climate is characterized by the scarcity and irregularity of rainfall, associated with high rates of evapotranspiration, making this region susceptible to prolonged droughts. The micro-watershed has three different geomorphological and hydrogeological sections: the plateau (750–900 m), which includes the upper aquifer system, the slope zone (450–600 m) and medium aquifer, and the Pediplain (< 450 m). All monitored wells, which take water from the lower aquifer, are located in the Pediplain. The land use and occupation classes include forest and savanna formations (53%) composed of a mosaic of biomes (Atlantic forest, cerrado, and caatinga), subsistence agriculture and cattle-grazing areas (42%), and urban areas (8%) (northeast and northwest sections). The anthropogenic activities within the SJMB are concentrated above the lower aquifer system, which is predominantly unconfined or phreatic (COGERH 2009). According to Tavares et al. (2009), Pediplain areas in the SJMB have a high permeability and natural porosity, resulting in a significant natural vulnerability to pollutant loads. The use of agrochemicals in crops and pastures, the effluents generated by livestock farming, and the deficient sewage collection and treatment infrastructure are potential sources of groundwater contamination, especially in areas where the vadose zone is thin and the water table is shallow (Silva et al. 2021). Latosols and red clays predominate in the SJMB, characterized by medium- to-fine-grain clayey sandstones and alluvial deposits, mainly in the Pediplain.

Sample collection

For the groundwater quality assessment of the unconfined aquifer system 12 hydrogeochemical parameters were monitored in 8 wells (P1–P8) in different hydrological periods (rainy/dry seasons) throughout 2019 (Supplementary Table 1). The monitored wells were purged at low flow according to standardized sampling protocols. All samples were collected at a depth of 30 m. In the field, multiparametric probes were used to monitor temperature (T), conductivity, pH, dissolved oxygen (DO), turbidity, color, and total dissolved solids (TDS). The biochemical oxygen demand (BOD), nitrate–N ($N - NO_3^-$), ammonia ($N–NH_3$), phosphorus ($P - PO_4^{3-}$) and thermotolerant coliforms (TtC) were tested in the lab (APHA 2018).

Groundwater quality assessment

A GQI adapted to the regional conditions was developed by Silva et al. (2021) through a multivariate statistical analysis of a time series of data from wells monitored in the Araripe sedimentary basin (ASB). The multivariate factorial analysis made it possible to identify the critical parameters for water quality and to propose weights for the regional hydrogeological conditions (Badillo-Camacho et al. 2015; Benouara et al. 2016; Silva et al. 2021). The mathematical formulation is based on the weighted product of the groundwater quality values of the studied variables, raised to the weight defined for each variable according to their importance, according to Eq. (1):

$$GQI_R = \prod_{i=1}^{n} q_i^{w_i}.$$

Table 1 Statistical summary of groundwater hydrogeochemical parameters in the SJMB

Variable	Min–max	Mean ± σ	CV %	MAV[a]
T (°C)	27.60–31.60	30.60 ± 1.56	5.1	–
Conductivity (μS cm^{-1})	0.12–0.89	0.30 ± 0.24	77.5	–
pH	5.27–6.95	6.20 ± 0.41	6.7	6—9.5
DO (mg L^{-1})	0.70–2.23	1.50 ± 0.44	28.8	–
Turbidity (NTU)	0.12–0.80	0.40 ± 0.17	45.5	5
Color (uH)	9.0–11.0	9.9 ± 0.62	6.3	15
TDS (mg L^{-1})	26–232	100.8 ± 76.93	76.3	1000
BOD (mg L^{-1})	0.10–0.89	0.50 ± 0.26	56.1	5
$N–NO_3^-$(mg L^{-1})	0.3–1.04	0.70 ± 0.20	27.4	10
$N–NH_3$ (mg L^{-1})	0.11–1.16	0.30 ± 0.33	109.1	1.5
$P–PO_4^{3-}$ (mg L^{-1})	0.24–2.08	0.90 ± 0.69	74.7	0.03
TtC (MPN/100 mL)	Absent	–	–	Absent

[a]Maximum allowable values in drinking water (MAV) (BRASIL 2008)

The GQI_R has a value between 0 and 100, where (q_i) is the quality rating of the ith parameter, (w_i) is the weight of the ith parameter, and n is the number of variables in the GQI_R calculation. The calibrated weights corresponded to: T ($w_i = 0.08$); pH ($w_i = 0.12$); turbidity ($w_i = 0.11$); TDS ($w_i = 0.11$); DO ($w_i = 0.09$); BOD ($w_i = 0.12$); nitrate–N ($w_i = 0.13$); $P–PO_4^{3-}$ ($w_i = 0.12$); and TtC ($w_i = 0.12$), which are considered to be the critical water quality variables in the ASB (Silva et al. 2021).

Results and discussion

Hydrogeochemical parameters

Table 1 presents a statistical summary and a comparison of water quality standards. The Kolmogorov–Smirnov and Shapiro–Wilk normality tests showed that the electrical conductivity variables, $N - NO_3^-$, $N - NH_3$, TDS and color do not follow a normal distribution pattern ($p < 0.05$). The Wilcoxon non-parametric test was applied, showing no statistically significant differences between the two sampling periods. A similar behavior was seen with the other variables using Student's t test. The relative stability of the hydrogeological conditions in the rainy and dry periods is the result of the longest drought recorded in Northeast Brazil in the last 60 years. Under these conditions, rainfall levels were 50% below the historical average of 600 mm (Cunha et al. 2019), while other studies have shown lower water recharges in the region's aquifers, affecting the quality of its waters (Shubo et al. 2020; Getirana et al. 2021; Silva et al. 2021).

In general, the quality parameters were within the portability standards (MAV). An exception was phosphorus,

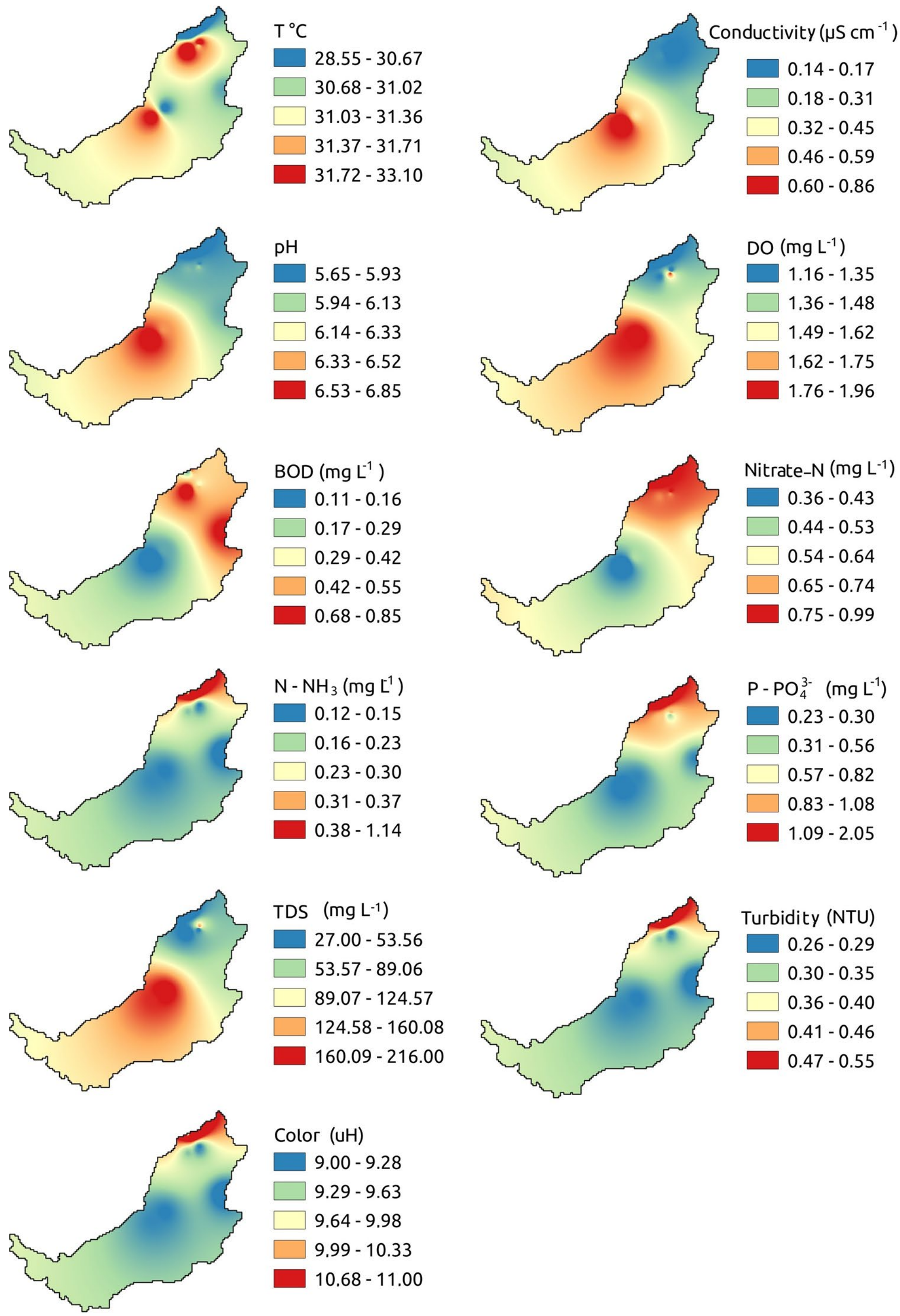

Fig. 2 Spatial behavior of the hydrogeochemical parameters during the monitoring period

which exceeded the allowable limit (0.03 mg L^{-1}) mainly in wells around the most urbanized sectors (P1–P5). Phosphorus was within the allowable concentration in just 25% of the tested samples. Strong correlations were obtained between $P–PO_4^{3-}$ and $N–NO_3^-$ ($r=0.83$) and $N–NH_3$ ($r=0.57$), pointing to a convergence in the hydrogeochemical behavior of these nutrients.

Geostatistical analysis

The geostatistical distribution maps, created using the spatial interpolation of the point values of the concentrations of ten hydrogeochemical parameters, are shown in Fig. 2. The QGIS software (version 3.10.7) was used for this purpose, while the shape files used for the delimitation of the basin were obtained from the Geosciences System of the

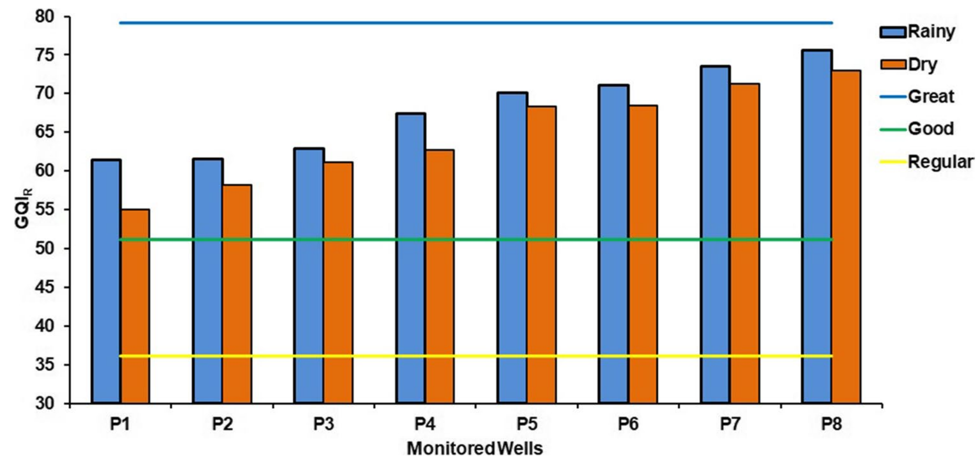

Fig. 3 Spatial variability of the GQI_R during the different hydrological periods

Brazilian Geological Service (CPRM 2021). The location of each well was obtained with a GNSS receiver during the on-site samplings.

The geostatistical distribution maps show well-defined spatial variability trends in the hydrogeochemistry of the wells. In P1 and P2, we observed the lowest average temperatures (29.3 °C and 28.6 °C, respectively), with an increasing trend near the slope zone. A similar behavior was observed for conductivity, as P8 presented a value five times higher than those found in wells located at lower levels of the Pediplain (P1 and P2). This result matches that of TDS, which spatial distribution shows values up to seven times higher in wells located in the upper section of the microbasin. The low conductivity associated with the reduced TDS values (compared to the reference value of < 500) allows us to classify the groundwater as freshwater (BRASIL 2008). The pH's similar behavior is the result of the geogenic sources, caused by the dissolution of natural minerals such as apatite, biotite, cryolite and fluorite found in the region's latosols and rocks.

The spatial behavior of nutrients (nitrate and phosphorus) showed higher concentrations in wells P1–P5, while the highest ammonia readings were in P1 and P2. BOD, color and turbidity also followed the same trend. These results show that in the lower elevations of the SJMB, the free aquifer has been affected by anthropogenic sources. Such poorer hydrogeochemical quality is probably a reflection of the more intensive exploitation of groundwater resources in areas of greater urban density, further boosted by the precarious sanitation found in the area (Badillo-Camacho et al. 2015; Getirana et al. 2021; Silva et al. 2021). Although nutrient concentrations are in general below the MAV, we must consider the influence of pollutant loads found in the domestic effluents of urban areas on the groundwater, as evidenced by the increased turbidity and BOD and the consequent depletion of DO levels. In this section, non-agricultural sources of nutrients include seepage from septic tanks and livestock waste. Inverse correlations were obtained between DO and nitrate–N ($r = 0.68$) and P–PO_4^{3-} ($r = 0.65$), further strengthening the above-mentioned evidence.

Groundwater quality

The groundwater quality behavior in SJMB is presented in Fig. 3. The GQI_R values ranged from 61.40 (P1) to 75.59 (P8) in the rainy season, while in the dry season its values fell, ranging between 55.04 (P1) and 72.92 (P8). Lower quality values were observed in the dry period in wells under greater urban influence (P1–P4), where higher concentrations of nutrients were found (Fig. 2). More pristine areas of the SJMB contribute to maintaining better water quality conditions (P7 and P8) even under low water table recharging conditions. Although the SJMB appears to have areas more vulnerable to contamination, the waters of all the monitored wells are classified as having a good quality ($51 < GQI_R \leq 79$), being suitable for conventional treatment intended for public supply, among other uses (CETESB 2020; BRASIL 2008).

Conclusion

The geostatistical modeling and GQI_R results suggest that the groundwater of the northeast and northwest (urbanized) sections of the SJMB have a poorer quality than that of areas closer to the slope zone, which have a low anthropic impact (pristine). This diagnosis shows the need for the implementation of public policies aimed at reducing organic emissions in these areas, in sight of the high vulnerability of the aquifer. In this particular case, measures should prioritize the implementation of sewage treatment systems and conservation techniques in soil management and in the use of agriculture and livestock farming inputs.

The proposed framework proved to be suitable for assessing the quality of groundwater on a microbasin scale. Due to its simplicity and reduced number of hydrogeological parameters, it can be replicated in other semi-arid areas of developing countries. In this way, it may help to overcome uncertainties in the formulation of public policies and aid decision-making processes involving groundwater resources.

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Author contributions FJPF: conceptualization, funding acquisition, resources, writing—review and editing, project management. MIS: investigation, writing—original draft. MTVL: visualization, formal analysis. CTFC: visualization, writing—review and editing, supervision. PRAF: visualization, formal analysis. JMCM: visualization, methodology. MP: visualization, supervision.

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Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent to participate/consent to publish The authors confirm consent to publication and authorship of the study. Informed consent was obtained from all individual participants included in the manuscript.

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