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Characterisation of the aquifer and river-aquifer interaction in an agricultural area of the lower Natuba River sub-basin – Pernambuco, Brazil

Caracterização do aquífero e da interação rio-aquífero em região agrícola localizada na sub-bacia do baixo rio Natuba - Pernambuco

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Abstract: Aquifers play a fundamental role in the hydrological cycle and in the maintenance of surface water sources. However, excessive groundwater abstraction for agricultural irrigation can reduce their groundwater levels. This study aimed to characterise the unconfined aquifer of an agricultural region in Vitória de Santo Antão-PE and its interaction with the local river, through field monitoring conducted between June 2023 and May 2024. Eight monitoring wells, each 4 m deep, were installed and the following were performed: (a) slug tests to estimate hydraulic conductivity and effective porosity; (b) weekly measurements of water table levels; (c) estimation of aquifer recharge; and (d) evaluation of the vertical hydraulic conductivity of the riverbed. The average hydraulic conductivity was 8.69 x 10^{-6} m/s, ranging from 10^{-5} to 10^{-8} m/s, reflecting the heterogeneous grain-size distribution of the area, with an average effective porosity of 13.62%. Variations in hydraulic head indicated significant ecovery of groundwater levels following rainfall events. The estimated average recharge was 27.10%. Infiltration into the riverbed was 3.72 x 10^{-6} m/s in winter and 1.74 x 10^{-6} m/s in summer. Groundwater flow predominantly occurred from the aquifer toward the river, evidencing that excessive pumping can shift the river from gaining to losing conditions due to the decrease in hydraulic load.

Keywords: Hyporrheic zone; Vertical flow; Capibaribe River basin.

Resumo: Os aquíferos têm papel fundamental no ciclo hidrológico e na manutenção de mananciais superficiais. Entretanto, o uso excessivo para irrigação agrícola pode reduzir seus níveis potenciométricos. Este estudo teve como objetivo caracterizar o aquífero livre de uma região agrícola em Vitória de Santo Antão-PE e sua interação com o rio local, por meio de monitoramento entre junho/2023 e maio/2024. Foram instalados 8 poços de 4 m de profundidade e realizados: (a) ensaios de slug test, para estimar condutividade hidráulica e porosidade efetiva; (b) medições semanais dos níveis estáticos; (c) estimativa da recarga do aquífero; e (d) avaliação da condutividade hidráulica vertical do leito do rio. A condutividade hidráulica média foi de 8,69 x 10^{-6} m/s, variando de 10^{-5} a 10^{-8} m/s, refletindo a granulometria heterogênea da área, com porosidade drenável média de 13,62%. As variações nas cargas hidráulicas indicaram boa recuperação dos níveis devido às chuvas. A recarga média estimada foi de 27,10%. A infiltração no leito do rio foi de 3,72 x 10^{-6} m/s no inverno e 1,74 x 10^{-6} m/s no verão. O fluxo predominante foi do aquífero para o rio, evidenciando que o bombeamento excessivo pode tornar o rio efluente, através do decréscimo de carga hidráulica.

Palavras-chave: Zona hiporreica; Fluxo vertical; Bacia hidrográfica do rio Capibaribe.

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1. Introduction

The hydrological cycle, which maintains water circulation on Earth, involves several mechanisms such as evaporation, precipitation, percolation in the soil to aquifers, surface runoff to rivers, among others. Among these processes, interactions between unconfined aquifers and surface water bodies are particularly important, as they regulate water exchange driven by hydraulic head gradients between the surface water and groundwater systems.

Veras (2011), Albuquerque (2015) and Veras *et al*. (2016a, 2016b) have highlighted the importance of this exchange of water between surface and groundwater sources, including natural attenuation processes. These same studies conducted infiltration tests in riverbeds to characterise the infiltration rate and provide insights into this relationship, which is essential for the sustainable management of water resources.

In this context, studies that provide a better understanding of the hydrological connectivity between water bodies are essential, as they can support environmental management of these areas and help maintain water quantity and quality for their predominant uses.

In view of the above, the Natuba River basin, entirely located within the Tapacurá River basin, still lacks studies aimed at a better assessment of certain hydrological parameters of the local unconfined aquifer, as well as its interaction with the river system, particularly because it is situated in a predominantly agricultural region subjected to continuous water exploitation. On the other hand, studies with similar objectives have been conducted in the Beberibe River basin (VERAS, 2011; ALBUQUERQUE, 2015; VERAS, 2016a; 2016b) and in the Capibaribe River basin (CARVALHO FILHO, 2019; SILVA, 2019; SILVA FILHO, 2024), both located in the Metropolitan Region of Pernambuco.

Accordingly, this study aimed to characterise the unconfined aquifer in the lower Natuba River sub-basin and its hydrological interaction with the associated surface water body, thereby contributing to a better understanding of the local hydrological dynamics.

2. Methodology

2.1 Study area delineation

The Natuba River originates in the municipality of Pombos, in the upper Natuba region (UTM coordinates 0237280 E and 9090994 N), and flows into Vitória de Santo Antão (BRAGA; SILVA, 2009), where it joins the Tapacurá River. The Natuba basin is part of Water Resources Planning Unit 2 (UP2), corresponding to the Capibaribe River basin, located in the western portion of the state of Pernambuco and subdivided into upper, middle, and lower sections (PERNAMBUCO, 2022) (Figure 1).

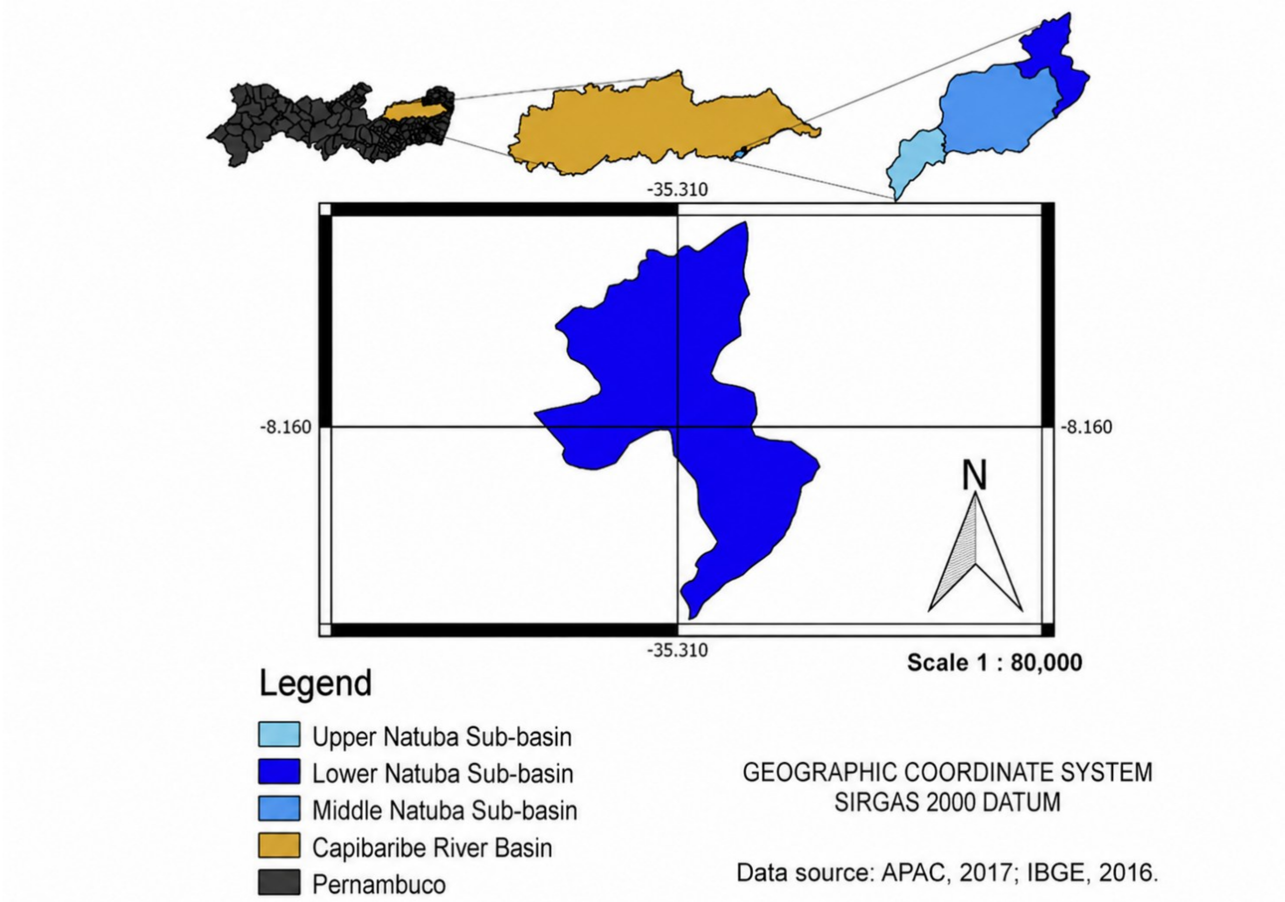

Figure 1 – Delineation of the area of interest within the Natuba River sub-basin.
Legend: Upper, middle, and lower Natuba sub-basins, from left to right.
Source: Authors (2025).

This is an important basin within the hydrological context of the Pernambuco state due to its role in sustaining irrigation activities in the horticultural production area located along its margins, as well as the discharge it contributes to the Tapacurá Reservoir (ALBUQUERQUE, 2010; MARQUES, 2017), which supplies part of the Recife Metropolitan Region. Within the lower Natuba River region, the study focused on a 3-hectare pilot area entirely situated within a smallholder farming setting, where water is extracted from the Natuba River in an unregulated manner.

It should be noted that this agricultural pattern, characterised by proximity to water sources used for public water supply, is recurrent in several agricultural regions in Brazil and worldwide, making the present study relevant for broader inferences beyond the currently investigated area.

2.2 Hydrological tests

To characterise the aquifer and its interaction with the Natuba River in the studied stream section, eight wells were installed, each with a depth of 4 meters and a screened interval located in the lower middle third (Figure 2).

Figure 2 – Location of the monitoring wells in the Lower Natuba River sub-basin.
Source: Authors (2025).

Additionally, granulometric analysis (TEIXEIRA *et al*., 2017) was performed on the lithological profile of the eight wells at 20 cm intervals, resulting in 20 samples per well, totalling 160 samples. Subsequently, the samples were averaged for each meter of the profile and subjected to statistical analysis using the Scott-Knott test (SCOTT; KNOTT, 1974) at a 5% significance level to group treatments with statistically homogeneous values among the 20 treatments (depths within the soil profile).

2.2.1 Aquifer hydraulic conductivity

The aquifer hydraulic conductivity was estimated between July 1 and 3, 2024, through duplicate Slug tests conducted in the eight wells of the study area. The test consisted of stabilising the static water level, instantaneously displacing the water column with a known volume, and monitoring its recovery using a HOBO datalogger that recorded water level recovery at 1-second intervals. The data were analysed using the AQTESOLV software, applying the Bouwer-Rice (1976) method, which is suitable for unconfined aquifers.

The effective porosity was estimated using the equation proposed by Poulsen *et al*. (1999) (Equation 1), considering that higher hydraulic conductivity corresponds to higher effective porosity (positive correlation) (RIBEIRO, 2008).

$$\mu = 10[(\log K - 4{,}3)/2{,}8] \quad (1)$$

Where μ is the effective porosity (dimensionless), and K is the hydraulic conductivity ($cm.day^{-1}$).

2.2.2 Water table levels of the Natuba unconfined aquifer

Water table levels were measured weekly over a 12-month period (June 2023 to May 2024) in monitoring wells, totalling 52 measurements using a manual KLL meter (50 m, Seba Hydrometrie). The data, referenced by elevation, allowed the evaluation of shallow aquifer fluctuations and the identification of statistically significant differences among the months ($p < 0.0001$). Based on these results, the Water Table Fluctuation (WTF) method (HEALY; COOK, 2002) was applied to estimate recharge rate, a widely validated technique in international studies for unconfined aquifers.

The equation used for this estimation was:

$$R = Sy \cdot \Delta h / \Delta t \quad (2)$$

Where: R is the estimated aquifer recharge rate ($mm.day^{-1}$); Sy is the specific yield; Δh is the water level variation (mm), calculated between the peak water-level rise and the extrapolated antecedent recession; and Δt is the elapsed time interval (days).

2.2.3 Vertical hydraulic conductivity of the riverbed

Given the interaction between surface water bodies and aquifers, the relationship between the Natuba River and these bodies was investigated, as it is important for the recovery of potentiometric levels. To estimate the infiltration rate or vertical hydraulic conductivity of the riverbed, the method proposed by Veras (2011) was applied, which uses an acrylic cylinder coupled to a plastic bag (Figure 3).

Figure 3 – Estimation of the vertical hydraulic conductivity of the riverbed using a cylinder.
Source: Authors (2025).

The method adapted from Lee (1977) and used by GRH/UFPE consisted of an acrylic cylinder (314 cm²) coupled to a 2 L hospital bag, sealed within the hyporheic zone of the river. After weighing the bag and removing air bubbles, a 30-minute test was conducted, after which the bag was weighed again to calculate the infiltrated or received volume, converted into mm³. The water was collected directly from the river, thereby avoiding changes in density and temperature.

Six tests were carried out during the winter (July 2023) and six during the summer (January 2024), with two repetitions per sampling point, except for point 3 (summer), which was replaced by a triplicate at Point 1 (Figure 4). The data were analysed using Equation 3, with a standard time of 1,800 s adopted from the study by Veras (2011). Additionally, the Mann-Whitney U test (MANN; WHITNEY, 1947) was performed to compare infiltration data between winter and summer.

$$I = V/t.A \qquad (3)$$

Where: I is the infiltration rate ($mm.s^{-1}$); V is the infiltrated water volume (mm^3); t is the elapsed observation time (s); and A is the cylinder area (mm^2).

Figure 4 – Spatial distribution of the analysis points for the vertical hydraulic conductivity of the riverbed.
Source: Authors (2025).

Additionally, sediment samples were collected from the river for physical analysis at the 0–25 cm and 25–50 cm profiles, enabling more robust inferences about the infiltration results.

3. Results and discussion

The granulometric characterisation of the eight wells' profilesis presented in Table 1.

Table 1 – Mean (per meter) percentage of the textural class of the wells.

Test well	Soil profile (cm)	Total sand (%)	Silt (%)	Clay (%)	Textural classification (Shepard)	Textural classification (USDA)
P01	0 ⊢100	79.32%	8.04%	12.64%	Sand	Sandy loam
	100 ⊢200	64.40%	15.95%	19.65%	Clayey sand	Sandy loam
	200 ⊢300	59.68%	17.27%	23.05%	Clayey sand	Sandy clay loam
	300 ⊢400	42.44%	22.08%	35.48%	Sandy silty clay	Clay loam
P02	0 ⊢100	54.40%	24.54%	21.06%	Sandy silty clay	Sandy clay loam
	100 ⊢200	80.54%	7.43%	12.03%	Sand	Sandy loam
	200 ⊢300	79.82%	5.70%	14.48%	Sand	Sandy loam
	300 ⊢400	31.37%	31.36%	37.27%	Sandy silty clay	Clay loam
P03	0 ⊢100	63.22%	19.76%	17.02%	Silty sand	Sandy loam
	100 ⊢200	64.84%	18.61%	16.55%	Silty sand	Sandy loam
	200 ⊢300	78.79%	12.01%	9.20%	Sand	Sandy loam
	300 ⊢400	77.34%	8.23%	14.43%	Sand	Sandy loam
P04	0 ⊢100	43.66%	29.67%	26.67%	Sandy silty clay	Loam
	100 ⊢200	42.98%	26.99%	30.03%	Sandy silty clay	Clay loam
	200 ⊢300	53.72%	20.63%	25.65%	Sandy silty clay	Sandy clay loam
	300 ⊢400	49.23%	27.66%	23.11%	Sandy silty clay	Sandy clay loam
P05	0 ⊢100	62.97%	19.25%	17.78%	Silty sand	Sandy loam
	100 ⊢200	37.23%	30.60%	32.17%	Sandy silty clay	Clay loam
	200 ⊢300	56.05%	18.41%	25.54%	Areia argilosa	Sandy clay loam
	300 ⊢400	49.13%	23.77%	27.10%	Sandy silty clay	Sandy clay loam
P06	0 ⊢100	53.98%	25.35%	20.67%	Sandy silty clay	Sandy clay loam
	100 ⊢200	50.92%	23.14%	25.94%	Sandy silty clay	Sandy clay loam
	200 ⊢300	51.54%	23.81%	24.65%	Sandy silty clay	Sandy clay loam
	300 ⊢400	41.74%	26.30%	31.96%	Sandy silty clay	Clay loam
P07	0 ⊢100	76.31%	11.72%	11.97%	Sand	Sandy loam
	100 ⊢200	60.80%	21.89%	17.31%	Silty sand	Sandy loam
	200 ⊢300	75.13%	11.22%	13.65%	Sand	Sandy loam
	300 ⊢400	36.95%	30.43%	32.62%	Sandy silty clay	Clay loam
P08	0 ⊢100	45.40%	30.91%	23.69%	Sandy silty clay	Loam
	100 ⊢200	26.27%	39.12%	34.61%	Sandy silty clay	Clay loam
	200 ⊢300	25.62%	36.08%	38.30%	Sandy silty clay	Clay loam
	300 ⊢400	20.40%	38.63%	40.97%	Sandy silty clay	Clay

Source: Authors (2025).

In the region, the predominant soil type is fluvic neosol, characterised by wide variation in granulometric composition (clay, silt, and coarse and fine sand fractions). Statistical analysis allowed the grouping of the 20 treatments into homogeneous sets for each soil fraction. Table 2 presents these groupings, which indicate that the clay percentage showed a significant difference between the 0–300 cm range ($G1_{arg}$) and the 300–400 cm range ($G2_{arg}$); silt formed a single group ($G1_{s}$); and fine sand differed between 0–280 cm ($G1_{af}$) and 280–400 cm ($G2_{af}$). Coarse sand was the only variable that did not group exclusively into continuous profile sections: homogeneity was observed at 0–60 cm and 240–340 cm ($G1_{ag}$), and between 60–240 cm and 340–400 cm ($G2_{ag}$).

Table 2 – Statistical grouping into homogeneous groups (Scott-Knott) according to soil profile depth.

Depth	(%)	Group.	Depth	(%)	Group.	Depth	(%)	Group.	Depth	(%)	Group.

Coarse sand			Fine sand			Silt			Clay		
0⊢20	13.88	$G1_{ag}$	220⊢240	56.65	$G1_{af}$	380⊢400	29.3	$G1_{s}$	380⊢400	32.2	$G1_{arg}$
280⊢300	13.69	$G1_{ag}$	240⊢260	55.95	$G1_{af}$	360⊢380	26.2	$G1_{s}$	360⊢380	30.9	$G1_{arg}$
20⊢40	10.90	$G1_{ag}$	260⊢280	55.88	$G1_{af}$	340⊢360	25.5	$G1_{s}$	340⊢360	29.8	$G1_{arg}$
300⊢320	10.07	$G1_{ag}$	200⊢220	54.00	$G1_{af}$	300⊢320	24.8	$G1_{s}$	300⊢320	29.6	$G1_{arg}$
40⊢60	9.04	$G1_{ag}$	60⊢80	53.67	$G1_{af}$	120⊢140	24.6	$G1_{s}$	320⊢340	29.5	$G1_{arg}$
260⊢280	8.70	$G1_{ag}$	20⊢40	53.37	$G1_{af}$	320⊢340	24.4	$G1_{s}$	100⊢120	25.1	$G2_{arg}$
320⊢340	8.09	$G1_{ag}$	180⊢200	53.35	$G1_{af}$	100⊢120	24.2	$G1_{s}$	80⊢100	24.6	$G2_{arg}$
240⊢260	7.60	$G1_{ag}$	0⊢20	51.53	$G1_{af}$	80⊢100	23.8	$G1_{s}$	280⊢300	24.6	$G2_{arg}$
60⊢80	5.64	$G2_{ag}$	160⊢180	51.28	$G1_{af}$	160⊢180	22.7	$G1_{s}$	120⊢140	24.6	$G2_{arg}$
340⊢360	5.59	$G2_{ag}$	140⊢160	50.85	$G1_{af}$	180⊢200	21.8	$G1_{s}$	140⊢160	23.9	$G2_{arg}$
80⊢100	4.44	$G2_{ag}$	40⊢60	49.89	$G1_{af}$	40⊢60	21.6	$G1_{s}$	180⊢200	22.8	$G2_{arg}$
160⊢180	4.33	$G2_{ag}$	120⊢140	47.83	$G1_{af}$	140⊢160	21.6	$G1_{s}$	200⊢220	22.1	$G2_{arg}$
100⊢120	4.30	$G2_{ag}$	80⊢100	47.18	$G1_{af}$	200⊢220	21.1	$G1_{s}$	160⊢180	21.7	$G2_{arg}$
140⊢160	3.66	$G2_{ag}$	100⊢120	46.39	$G1_{af}$	0⊢20	20.7	$G1_{s}$	220⊢240	21.6	$G2_{arg}$
220⊢240	3.09	$G2_{ag}$	280⊢300	41.81	$G2_{af}$	60⊢80	20.1	$G1_{s}$	60⊢80	20.6	$G2_{arg}$
120⊢140	2.96	$G2_{ag}$	360⊢380	40.62	$G2_{af}$	280⊢300	19.9	$G1_{s}$	260⊢280	20.4	$G2_{arg}$
200⊢220	2.86	$G2_{ag}$	340⊢360	39.19	$G2_{af}$	20⊢40	19.6	$G1_{s}$	240⊢260	20.3	$G2_{arg}$
380⊢400	2.32	$G2_{ag}$	320⊢340	37.97	$G2_{af}$	220⊢240	18.6	$G1_{s}$	40⊢60	19.4	$G2_{arg}$
360⊢380	2.28	$G2_{ag}$	380⊢400	36.24	$G2_{af}$	240⊢260	16.1	$G1_{s}$	20⊢40	16.2	$G2_{arg}$
180⊢200	2.13	$G2_{ag}$	300⊢320	35.51	$G2_{af}$	260⊢280	15.0	$G1_{s}$	0⊢20	13.9	$G2_{arg}$

Legend: Group. – Grouping.
Source: Authors (2025).

Corroborating the analysis presented above, Cunha Filho (2013) and Nascimento (2013) indicate that, in the lower Natuba region, there is an increase in clay content and a gradual decrease in sand content from the most superficial layer to the deepest layer.

3.1 Aquifer hydraulic conductivity

The tests were conducted, and the estimated horizontal hydraulic conductivity values for the aquifer (Table 3) were similar between duplicate samples from the same well. According to Freeze and Cherry (2017), the variation observed among wells (10^{-5} to 10^{-8}) is typical of differences between clean sand, silty sand, and silt/clay, and is generally consistent with the diverse grain-size distribution observed in the well profiles.

Table 3 – Estimated hydraulic conductivity values for the wells installed in the Lower Natuba sub-basin.

Well	Hydraulic conductivity (m/s)		
	Replication 1	**Replication 2**	**Mean**
1	1.99×10^{-06}	2.35×10^{-06}	2.17×10^{-06}
2	1.06×10^{-06}	1.07×10^{-06}	1.07×10^{-06}
3	1.15×10^{-05}	9.41×10^{-06}	1.05×10^{-05}
4	9.52×10^{-07}	2.06×10^{-06}	1.51×10^{-06}
5	1.47×10^{-06}	1.84×10^{-06}	1.65×10^{-06}
6	1.59×10^{-08}	1.55×10^{-08}	1.57×10^{-08}
7	8.48×10^{-07}	9.79×10^{-07}	9.14×10^{-07}
8	4.96×10^{-05}	5.38×10^{-05}	5.17×10^{-05}
Mean			$\mathbf{8.69 \times 10^{-06}}$

Source: Authors (2025).

Hydraulic conductivity values were generally consistent across the wells, despite variation in total sand percentage. Wells 3 and 8 showed the highest hydraulic conductivity values. The higher conductivity observed in well 3 can be explained by the fact that it presented the highest percentage of total sand in the deepest meters of the profile (78.06%)

among the constructed wells, approaching the value estimated by Paiva (2009) for the unconfined aquifer region of the Beberibe River (1.5×10^{-5} m/s), where a similar sand percentage was observed at the depth corresponding to the screened interval.

Well 8, in turn, despite exhibiting good hydraulic conductivity, shows the highest percentage of clay and silt among to the others. This behavior may be associated not only with the textural class influencing this variable, but also with the way the material is structurally arranged, as noted by Gonçalves and Libardi (2013). Oliveira, Gonçalves, and Martins (2010) corroborate this statement in their study when comparing a sandy clay loam soil (red latosol) and a clayey soil (rhodic ferralsol), observing higher hydraulic conductivity in the clayey profile. In that case, cracks associated with clay swelling and shrinkage were identified, which enhanced water percolation.

Effective porosity was estimated at 13.62%, based on the average hydraulic conductivity of the analysed wells. This result is consistent, as it falls within the reference ranges established by Johnson (1967): 3–12% for sandy clay soils and 15–32% for medium sand. Additionally, it is also within the expected range for silty soils (3–19%) and fine sand (10–28%).

3.2 Water table levels of the Natuba unconfined aquifer

The results of measurements of water table levels in the eight wells over a hydrological year (June 2023 to May 2024), along with their relationship with precipitation, are shown in Figure 5. It is worth noting that the accumulated precipitation data were obtained from APAC for the automatic station "488 – Vitória de Santo Antão (PCD)", located at the Agronomic Institute of Pernambuco (IPA), approximately 3 km from the study area.

It is known that the hydraulic head difference between two points in an aquifer, driven by variations in topographic elevation, generates a hydraulic gradient that governs groundwater flow, moving from higher to lower elevations, according to Darcy's Law (SAHYA *et al.*, 2023). This behavior is observed in the lower Natuba (Figure 6) in the potentiometric map, obtained from a groundwater flow simulation using a previously calibrated model for the area (R^2 = 0.997).

The Natuba unconfined aquifer exhibited a strong hydrological response to precipitation events, with water levels rising proportionally with rainfall intensity. This behavior has also been reported by several authors in different aquifers (MONTEIRO; MONTENEGRO; MONTENEGRO, 2014; BARBOSA, 2020; PASINI *et al.*, 2022).

According to Barbosa (2020), the rainfall–water table relationship in unconfined aquifers may be influenced by several factors, including soil lithology, thickness of the unsaturated zone, specific yield of the well, soil type and land use/land cover, and the presence of nearby pumping. In general, thinner and sandier unsaturated zones tend to promote faster groundwater responses to rainfall, resulting in faster rainfall-driven changes in water table levels, which was also observed in Natuba.

Furthermore, multivariate analysis of variance ($p < 0.0001$) of the water table levels for the eight wells over the 12-month evaluation period indicates that there are statistically significant differences between seasons for each well. Table 4 summarises that these differences are mainly related to June and July, corroborating what is shown in Figure 4, where approximately 37% of the total annual precipitation occurs during this two-month period. The identification of significant differences in other months is also consistent, as hydraulic head varies among wells inresponse to rainfall events.

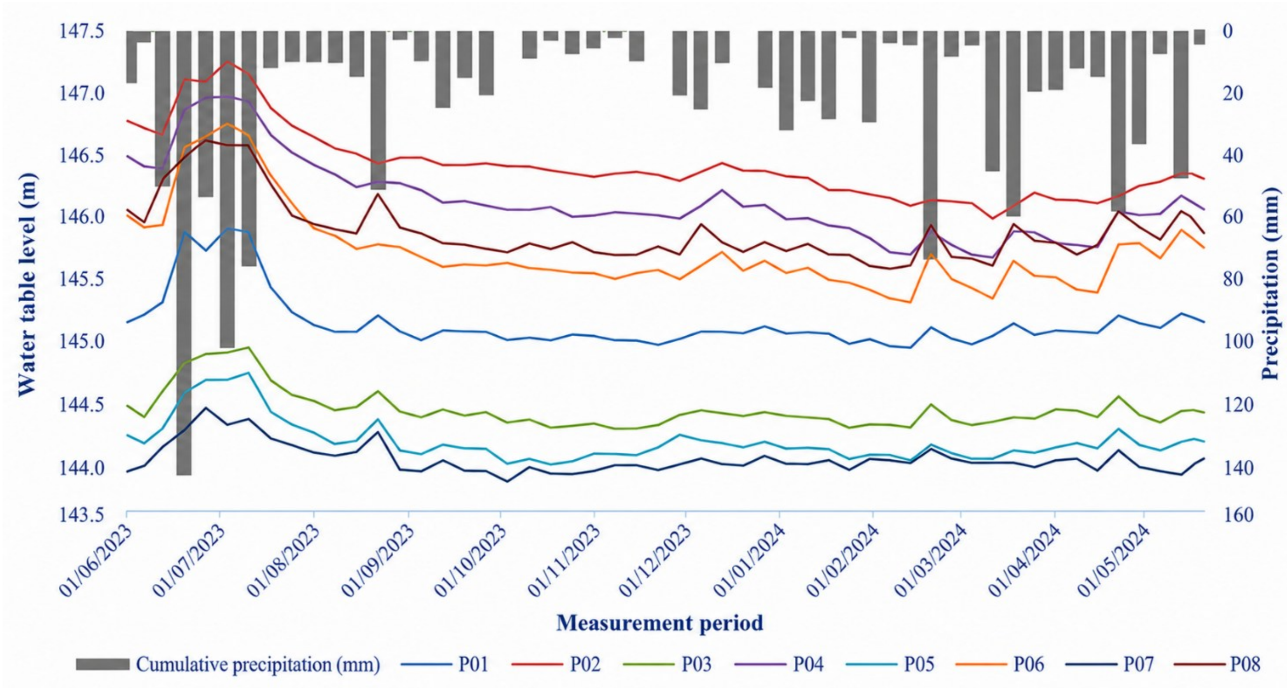

Figure 5 – Variation in water table level from June 2023 to May 2024 in the eight wells located in the lower Natuba River community, municipality of Vitória de Santo Antão, Pernambuco.
Source: Authors (2025).

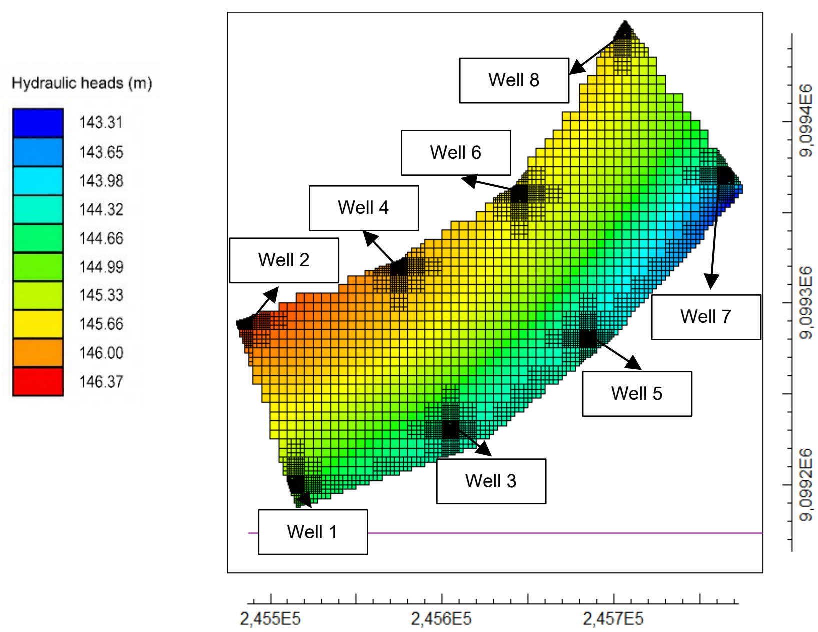

Figure 6 – Potentiometric map of the study area located in the lower Natuba River, municipality of Vitória de Santo Antão, Pernambuco.
Source: Authors (2025).

Table 4 – Analysis of differences in water table levels during the hydrological cycle: June 2023 to May 2024.

Months with significant differences	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
	Difference between means (95% CI)							
June / August	-	0.38 (0.11-0.65)	-	0.34 (0.02-0.65)	-	-	-	-
June / September	0.39 (0.03-0.76)	0.43 (0.16-0.7)	-	0.48 (0.16-0.79)	0.27 (0.01-0.52)	0.58 (0.15-10.22)	-	0.49 (0.12-0.86)
June / October	0.42 (0.08-0.77)	0.5 (0.24-0.75)	0.3 (0.07-0.52)	0.57 (0.28-0.87)	0.36 (0.12-0.59)	0.63 (0.22-10.4)	0.23 (0.03-0.43)	0.53 (0.18-0.88)
June / November	0.45 (0.09-0.81)	0.53 (0.26-0.8)	0.3 (0.06-0.54)	0.6 (0.28-0.91)	0.26 (0.01-0.51)	0.67 (0.24-11.12)	-	0.57 (0.19-0.94)
June / December	0.37 (0.01-0.73)	0.48 (0.21-0.75)	-	0.49 (0.18-0.8)	-	0.57 (0.13-10.09)	-	0.46 (0.09-0.83)
June / January	0.41 (0.07-0.76)	0.61 (0.36-0.87)	0.27 (0.05-0.5)	0.68 (0.39-0.98)	0.28 (0.05-0.52)	0.7 (0.29-11.12)	-	0.57 (0.22-0.92)
June / February	0.44 (0.08-0.81)	0.74 (0.47-100.48)	0.26 (0.02-0.5)	0.84 (0.53-115.33)	0.3 (0.05-0.55)	0.73 (0.29-11.69)	-	0.58 (0.21-0.95)
June / March	0.4 (0.03-0.76)	0.77 (0.5-104.23)	0.27 (0.04-0.51)	0.83 (0.51-113.83)	0.31 (0.06-0.56)	0.72 (0.28-11.59)	-	0.52 (0.15-0.89)
June / April	-	0.7 (0.45-0.96)	-	0.73 (0.44-102.9)	-	0.63 (0.21-10.38)	-	0.43 (0.08-0.78)
June / May	-	0.54 (0.27-0.8)	-	0.52 (0.21-0.83)	-	0.46 (0.02-0.89)	-	0.37 (0-0.74)
July / August	0.41 (0.04-0.77)	0.44 (0.17-0.71)	-	0.42 (0.1-0.73)	0.27 (0.02-0.52)	0.57 (0.13-10.04)	-	-
July / September	0.45 (0.09-0.82)	0.5 (0.23-0.77)	0.31 (0.07-0.54)	0.56 (0.24-0.87)	0.35 (0.1-0.6)	0.72 (0.29-11.62)	0.25 (0.04-0.46)	0.48 (0.11-0.85)
July / October	0.48 (0.14-0.83)	0.56 (0.31-0.81)	0.38 (0.16-0.61)	0.65 (0.36-0.95)	0.44 (0.21-0.68)	0.77 (0.36-11.8)	0.29 (0.1-0.49)	0.51 (0.16-0.86)
July / November	0.51 (0.15-0.87)	0.6 (0.33-0.86)	0.39 (0.15-0.62)	0.68 (0.36-0.99)	0.35 (0.09-0.6)	0.81 (0.38-12.52)	0.24 (0.03-0.44)	0.55 (0.18-0.93)
July / December	0.43 (0.07-0.79)	0.55 (0.28-0.82)	0.3 (0.06-0.53)	0.57 (0.26-0.89)	0.31 (0.06-0.56)	0.71 (0.27-11.49)	-	0.45 (0.08-0.82)
July / January	0.47 (0.13-0.82)	0.68 (0.42-0.93)	0.36 (0.14-0.58)	0.76 (0.47-105.9)	0.37 (0.14-0.61)	0.84 (0.43-12.52)	0.21 (0.02-0.41)	0.56 (0.21-0.91)
July / February	0.5 (0.14-0.87)	0.8 (0.53-106.88)	0.35 (0.11-0.58)	0.92 (0.61-123.53)	0.39 (0.13-0.64)	0.87 (0.43-13.09)	-	0.57 (0.2-0.94)
July / March	0.46 (0.09-0.82)	0.84 (0.57-110.63)	0.36 (0.12-0.6)	0.91 (0.59-122.03)	0.4 (0.15-0.65)	0.86 (0.42-12.99)	0.22 (0.01-0.42)	0.51 (0.14-0.88)
July / April	0.4 (0.05-0.74)	0.77 (0.51-102.14)	0.27 (0.05-0.49)	0.82 (0.52-111.1)	0.3 (0.07-0.54)	0.77 (0.35-11.78)	0.2 (0-0.4)	0.42 (0.07-0.77)
July / May	-	0.6 (0.33-0.87)	0.32 (0.08-0.55)	0.6 (0.29-0.91)	0.32 (0.07-0.57)	0.6 (0.16-10.34)	0.26 (0.05-0.46)	-

August / January	-	-	-	0.35 (0.03-0.66)	-	-	-	-
August / February	-	0.36 (0.07-0.64)	-	0.51 (0.18-0.83)	-	-	-	-
August / March	-	0.4 (0.11-0.68)	-	0.49 (0,16-0,82)	-	-	-	-
August / April	-	0.33 (0.06-0.59)	-	0.40 (0.09-0.71)	-	-	-	-
September / February	-	0.3 (0.02-0.59)	-	0.37 (0.04-0.69)	-	-	-	-
September / March	-	0.34 (0.06-0.62)	-	0.35 (0.02-0.68)	-	-	-	-
September / April	-	0.27 (0-0.54)	-	-	-	-	-	-
October / March	-	0.28 (0.01-0.55)	-	-	-	-	-	-
December / February	-	-	-	0.35 (0.02-0.68)	-	-	-	-
December / March	-	0.29 (0.01-0.57)	-	0.34 (0.01-0.66)	-	-	-	-

Source: Authors (2025).

Based on this information on water-level variations over one hydrological year (2023/2024), the recharge rate was estimated using the Water Table Fluctuation (WTF) method (Table 5), yielding an average of 27.10%. In other words, it is estimated that 337.03 mm, out of a total of 1243.6 mm precipitated during the analyzed period, infiltrated into the soil.

Table 5 – Estimated recharge values for the eight wells installed in the Natuba community, municipality of Vitória de Santo Antão, Pernambuco.

Well	Annual recharge value (m)	Annual recharge value (mm)	Annual precipitation (mm) (2023-2024)	Recharge percentage (%)
1	0.31	308.90	1243.60	24.84
2	0.26	262.87		21.14
3	0.32	315.58		25.38
4	0.28	275.53		22.16
5	0.34	344.31		27.69
6	0.36	361.20		29.04
7	0.31	305.63		24.58
8	0.52	522.19		41.99
Mean	**0.34**	**337.03**		**27.10**
Maximum	0.52	522.19		41.99
Minimum	0.26	262.87		21.14

Source: Authors (2025).

Although variations in this percentage may occur among different aquifers due to the specific characteristics of each environment/region, the estimated values obtained here are consistent and agree with those reported by authors who applied the same method: 21–40% in a coastal alluvial aquifer in Rio Grande do Sul (TROIAN *et al.*, 2017), 8–34% in aquifers located in São Carlos, São Paulo (MAZIERO; WENDLAND, 2005), and 32–36% in the sedimentary basin of Araripe, Ceará (MELATI *et al.,* 2017).

3.3 Vertical hydraulic conductivity of the riverbed

The infiltration values, and the granulometric analysis results for the studied section of the Natuba River, are presented in Tables 6 and 7, respectively.

Table 6 – Vertical infiltration values in the bed of the Natuba River, municipality of Vitória de Santo Antão, Pernambuco.

Point	Replication	Value (m/s)	
		Winter	Summer
Point 1	1	-0.00000694	-0.00000536
Point 1	2	-0.00001037	0.00000076
Point 1	3	-	0.00000042
Point 2	1	0.00000035	0.00000357
Point 2	2	0.00000119	0.00000021
Point 3	1	0.00000310	0.00000011
Point 3	2	0.00000039	-

Source: Authors (2025).

Table 7 – Granulometric percentages for the locations where infiltration tests were conducted in the bed of the Natuba River.

Test location	Soil profile (cm)	Period	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Textural classification (Shepard)
1	00-25	Inverno	63.00	35.26	0.03	1.71	Sand
	00-25	Verão	36.80	60.64	0.27	2.29	Sand
	25-50	Inverno	48.66	50.14	0.06	1.14	Sand
	25-50	Verão	45.40	53.08	0.11	1.41	Sand
2	00-25	Inverno	15.90	82.42	0.04	1.64	Sand
	00-25	Verão	17.16	79.08	0.12	3.64	Sand
	25-50	Inverno	49.30	49.58	0.06	1.06	Sand
	25-50	Verão	20.52	75.80	0.04	3.64	Sand
3	00-25	Inverno	22.96	75.06	0.12	1.86	Sand
	00-25	Verão	28.86	64.22	2.78	4.14	Sand
	25-50	Inverno	10.04	87.08	0.66	2.22	Sand
	25-50	Verão	23.88	69.52	0.46	6.14	Sand

Source: Authors (2025).

Negative results are possible in infiltration tests (VERAS, 2011; FREITAS, 2018) and, in the present study, it is likely that local farmers had begun river water pumping while some of the tests at Point 1 were being conducted. This may have influenced the lowering of the hydraulic head of the water body and consequently induced a temporary reversal from losing stream (supplying water to the aquifer) to gaining stream (receiving water from the aquifer) hydraulic conditions at that specific moment.

The Mann–Whitney U test (MANN; WHITNEY, 1947) indicates that there is no statistically significant difference in infiltration rate between winter and summer conditions (Table 8).

Table 8 – Mann–Whitney U test and descriptive statistics for the infiltration test dataset.

Applied test	Statistic	p-value
Mann–Whitney U test	16	0.818

Descriptive statistics				
Group	**n**	**Median**	**Q1**	**Q3**
WINTER	6	3.15E-07	1.35E-07	6.75E-07
SUMMER	6	3.70E-07	-5.12E-06	9.90E-07

Source: Authors (2025).

Freitas (2018) reported a higher proportion of silt/clay in the months immediately following winter (summer) than in the actual winter months, suggesting the "settling" of finer particles after winter-induced disturbance, a phenomenon also observed in the present study (Table 8). It is possible that clogging by these fine particles occurred, which may have led to a slightly lower average infiltration rate in summer than in winter. However, riverbed grain-size distribution did not show significant differences in the percentages of coarse sand, fine sand, silt, and clay between the analysed depths (0–25 and 25–50 cm) or between the winter and summer periods, according to the analysis of variance performed.

Furthermore, it was observed that the balance, or difference, between the infiltration test values in the riverbed indicating flow in the aquifer-to-river and river-to-aquifer directions resulted in a residual infiltration of 1.23×10^{-5} m/s and 2.8×10^{-7} m/s toward the aquifer-to-river direction during winter and summer, respectively. These results support the hypothesis that excessive river pumping generates an additional flow in this direction.

Therefore, these initial tests represent a starting point for further and more comprehensive studies aimed at identifying zones of greater aquifer recharge, or vice versa, thereby enabling the integrated and sustainable management of the region's water resources (whether surface and/or groundwater), ensuring the preservation of water quantity and quality.

4. Final considerations

The river–aquifer interaction in Natuba may occur in both the river-to-aquifer and the aquifer-to-river directions, depending on local hydraulic gradients. The infiltration rate, among other factors, depends on the aggregation of river sediments and the season of the year (rainfall regime). Thus, infiltration in the riverbed presented average values of 3.72×10^{-6} m/s and 1.74×10^{-6} m/s during winter and summer, respectively, with lower values observed in summer, likely due to increased fine sediment deposition and partial pore clogging.

Monitoring of the water table levels in the local unconfined aquifer indicated a decline in groundwater levels after one year of measurements, despite the aquifer exhibiting good hydraulic conductivity (8.69×10^{-6}) and a satisfactory recharge rate (27.10%). This behavior is explained by the agricultural region in the lower Natuba River basin, which shows uncontrolled surface water abstraction from the Natuba River. This process reduces the river hydraulic head and induces a predominant groundwater flow toward the aquifer-to-river direction, as confirmed by the infiltration tests conducted in the riverbed of the surface water body, which generated additional residual flow in this direction (1.23×10^{-5} m/s and 2.8×10^{-7} m/s during winter and summer, respectively). Therefore, the need for monitoring aquifer exploitation is emphasised, directly associated with groundwater level monitoring and the evaluation of water quality and possible contamination, given the region's agricultural characteristics.

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