

**HYDROLOGICAL AND
ANTHROPOGENIC
CONTROLS ON
GROUNDWATER LEVEL
VARIABILITY IN THE
CAUAMÉ RIVER BASIN,
BRAZILIAN AMAZONIAN
SAVANNA**

**CONTROLES HIDROLÓGICOS E ANTROPOGÊNICOS DA VARIABILIDADE
DO NÍVEL DAS ÁGUAS SUBTERRÂNEAS NA BACIA DO RIO CAUAMÉ,
SAVANA AMAZÔNICA BRASILEIRA**

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ABSTRACT

Groundwater plays a crucial role in supplying environmental sustainability, particularly in regions subject to increasing anthropic pressure. The study analyzed the hydrological and anthropogenic controls in the variation of the water level in the Boa Vista Aquifer (ABV), in the Cauamé River Hydrographic Basin (BHRC), Roraima, Brazil. The equipped approach combined groundwater data (static and dynamic levels) of 80 wells, obtained from the data bank of the Underground Water Information System (SIAGAS, 1982-2014), precipitation data from the National Institute of Meteorology (INMET, 1999-2024) and land use of the MapBiomas platform (1985-2022). Linear regression models applied to evaluate the relationships between the static level (NE), the dynamic level (ND) and the NE/ND ratio and the predictive variables (latitude, longitude, altitude, precipitation and time). The results reveal explanatory power ($R^2 \leq 30\%$), reflecting the intrinsic complexity of the ABV system. Precipitation has a statistically significant influence on dynamic levels ($p < 0.05$), highlighting its role in groundwater recharge processes. In contrast, spatial variations exhibit limited explanatory capacity. A temporal analysis indicated a marginal decline in dynamic water levels and a significant increase in the NE/ND ratio over time. Since land use changes have not been incorporated into statistical models, the expansion of agricultural and urban areas suggests increasing pressure on groundwater. This work contributes to a better understanding of groundwater dynamics in Amazonian savanna environments and provides a basis for future research and water resource management in the BHRC.

Keywords: Boa Vista Aquifer; Land Use; Groundwater Resources; Multivariate Statistics.

RESUMO

As águas subterrâneas desempenham papel crucial no abastecimento e na sustentabilidade ambiental, particularmente em regiões sujeitas a crescente pressão antrópica. O estudo analisou os controles hidrológicos e antropogênicos na variação do nível d'água no Aquífero Boa Vista (ABV), na bacia hidrográfica do rio Cauamé (BHRC), Roraima, Brasil. A abordagem adotada, combinou dados de águas subterrâneas (níveis estáticos e dinâmicos) de 80 poços, obtidos no banco de dados do Sistema de Informações de Águas Subterrâneas (SIAGAS, 1982-2014), dados de precipitação do Instituto Nacional de Meteorologia (INMET, 1999-2024) e do uso da terra da plataforma MapBiomas (1985-2022). Modelos de regressão linear foram aplicados para avaliar as relações entre os níveis estático (NE), nível dinâmico (ND) e a razão NE/ND e as variáveis preditoras (latitude, longitude, altitude, precipitação e tempo). Os resultados revelaram poder explicativo ($R^2 \leq 30\%$), refletindo a complexidade intrínseca do sistema ABV. A precipitação apresentou influência estatisticamente significativa nos níveis dinâmicos ($p < 0,05$), destacando seu papel nos processos de recarga do aquífero. Em contraste, as variáveis espaciais exibiram capacidade explicativa limitada. A análise temporal indicou um declínio marginal nos níveis dinâmicos d'água e um aumento significativo na razão NE/ND ao longo do tempo. Embora as mudanças no uso da terra não tenham sido incorporadas aos modelos estatísticos, a expansão das áreas agrícolas e urbanas sugere uma crescente pressão sobre as águas subterrâneas. Este trabalho contribui para uma melhor compreensão da dinâmica das águas subterrâneas em ambientes de savana amazônica e fornece uma base para pesquisas futuras e gestão de recursos hídricos na BHRC.

Palavras-chave: Aquífero Boa Vista; Uso da Terra; Recursos Hídricos Subterrâneos; Estatística Multivariada.

1. INTRODUCTION

Groundwater is a critical component of global water resources, playing a fundamental role in urban and rural water supply, the sustainability of agricultural production, and ecosystem services, particularly in regions where surface water availability is limited or highly variable due to climate variability and change (Jasechko et al., 2024). As a strategic reserve, groundwater becomes especially important during extreme events such as prolonged droughts (Santos et al., 2018; 2022).

At the global scale, pressure on groundwater reservoirs has intensified due to surface water degradation, pollution, overexploitation through excessive pumping, and various anthropogenic activities, posing significant challenges to current and future water availability (Silva et al., 2021; Jasechko et al., 2024; ODS, 2024; ANA, 2024; MapBiomas, 2024).

In Brazil, and particularly in Amazonian savanna regions, these challenges are even more complex due to the region's physical, climatic, and socioeconomic characteristics.

Understanding the factors that influence groundwater level variation in aquifers is essential for the sustainable management of these resources, especially in a context of population growth, land-use expansion, increasing water demand, and climate instability (Brito et al., 2022).

However, the increasing exploitation of groundwater for urban, rural, and agricultural uses has raised concerns regarding aquifer depletion and contamination, particularly in developing regions

where monitoring and management mechanisms are still limited (Wankler et al., 2022).

In recent decades, the intensification of anthropogenic pressures—combined with climate variability—has significantly affected groundwater systems worldwide (Jasechko et al., 2024). Excessive extraction, land-use changes, and vegetation removal have altered recharge processes and groundwater dynamics, leading to declining water levels in many regions (Jasechko et al., 2024).

These challenges have reinforced the need for integrated groundwater management strategies, as highlighted in international policies focused on water security and sustainable resource use (ANA, 2024). In this context, understanding the interactions between hydrological processes and human activities is essential to ensure long-term water availability, both in quantity and quality (ODS, 2024).

Despite advances in groundwater research, there is still a limited number of studies addressing these interactions in tropical savanna regions, particularly in northern Brazil. The Cauamé River Hydrographic Basin (BHRC), located in the municipalities of Alto Alegre and Boa Vista (state of Roraima), represents a strategic case study due to its growing socioeconomic importance and increasing pressure on water resources. Groundwater in this basin, mainly stored in the Boa Vista Aquifer, is widely used for public supply, agriculture, and industrial activities. It is estimated that approximately 70% of the population of Boa Vista depends on groundwater extracted from tubular wells, highlighting the critical role of this resource in regional water security (Wankler et al., 2022).

The region has experienced significant demographic growth in recent decades, driven mainly by migration processes (IBGE, 2024), which, combined with a 177% expansion (2022–2025) in areas occupied by agricultural, livestock, and industrial activities, has resulted in increased demand for groundwater (ANA, 2024; MapBiomas, 2024a; SIAGAS, 2024). These changes have also led to the progressive degradation of native savanna vegetation, potentially affecting infiltration rates, recharge processes, and overall aquifer dynamics (Carvalho et al., 2022; Eloy et al., 2023).

At the same time, extreme climate events associated with global warming—such as severe droughts, floods, and heatwaves—have become more frequent and intense in the Amazon region, impacting ecosystem stability and groundwater availability (Salazar et al., 2015; Eloy et al., 2023; Falcão; Souza, 2022; Sander et al., 2024). Consequently, the relationship between land-use change and groundwater behavior remains a key issue requiring further investigation. Although previous studies have addressed aspects of groundwater variability and land-use dynamics, there is still a lack of integrative analyses that quantitatively assess the combined effects of hydrological and anthropogenic variables on groundwater level fluctuations over time in the Cauamé River Hydrographic Basin (BHRC).

Moreover, the implications of these interactions for groundwater management and future sustainability scenarios remain insufficiently explored. In this context, the present study seeks to address the following research questions: (1) How do human activities (urban and agricultural expansion) and climate variability influence groundwater level fluctuations and availability in the BHRC? (2) How do hydrological variables—such as precipitation,

infiltration, evapotranspiration, and surface runoff—affect groundwater dynamics in the basin? (3) How have these factors influenced changes in aquifer storage over time (1982–2014)?

To answer these questions, this study integrates hydrological and anthropogenic variables to evaluate their influence on groundwater level variation in the Boa Vista Aquifer. The analysis includes long-term precipitation data obtained from the Boa Vista station, provided by the National Institute of Meteorology (INMET, 2024), covering the period from 1999 to 2024; land-use data from 1985 to 2022; groundwater level indicators (static and dynamic levels) and their ratio as an indicator of system response to environmental changes, obtained from the Groundwater Information System (SIAGAS, 2024), considering the period from 1982 to 2014, which encompasses significant socio-environmental transformations in the region, including demographic expansion, agricultural intensification, and institutional changes that may have influenced groundwater dynamics.

Therefore, the objective of this study was to investigate the hydrological and anthropogenic controls on groundwater level variation in the Boa Vista Aquifer, within the Cauamé River Hydrographic Basin, over the period from 1982 to 2014, contributing to a better understanding of groundwater behavior in Amazonian savanna environments and supporting future water resource management strategies.

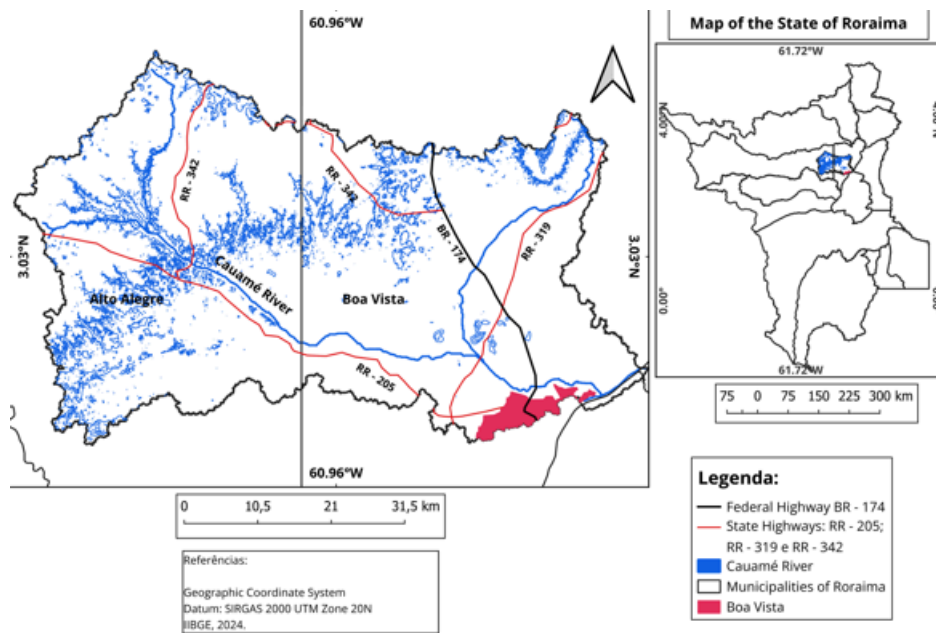
2. THEORETICAL FRAMEWORK

2.1. Study Area Characterization

The Cauamé River Hydrographic Basin (BHRC) is located in the north-northeastern portion of the state of Roraima, above the Equator, within the geological domain of the Guiana Shield (Reis; Alamy Filho, 2018; Galdino, 2018). The basin covers an area of approximately 3,159 km² and includes the municipalities of Alto Alegre and Boa Vista (the state capital), extending to the urban perimeter of Boa Vista (Wankler et al., 2022).

The drainage network is highly diverse, consisting of approximately 1,942 channels and a main river (the Cauamé River) with about 120 km in length. The region is accessible through several state highways (RR-205, RR-319, RR-342, among others) and the federal highway BR-174, which plays a fundamental role in regional economic dynamics and land-use expansion (Galdino, 2018; Wankler et al., 2022). Figure 1 shows the location of the Cauamé River Hydrographic Basin (BHRC) along with its main state highways, which are responsible for the transport of people, goods, fruits, among others, while BR-174 is responsible for connecting Roraima's electrical energy system to the national power grid.

Figure 1: Location of the Cauamé River Basin showing its road network and the Cauamé River Hydrographic Basin (BHRC).



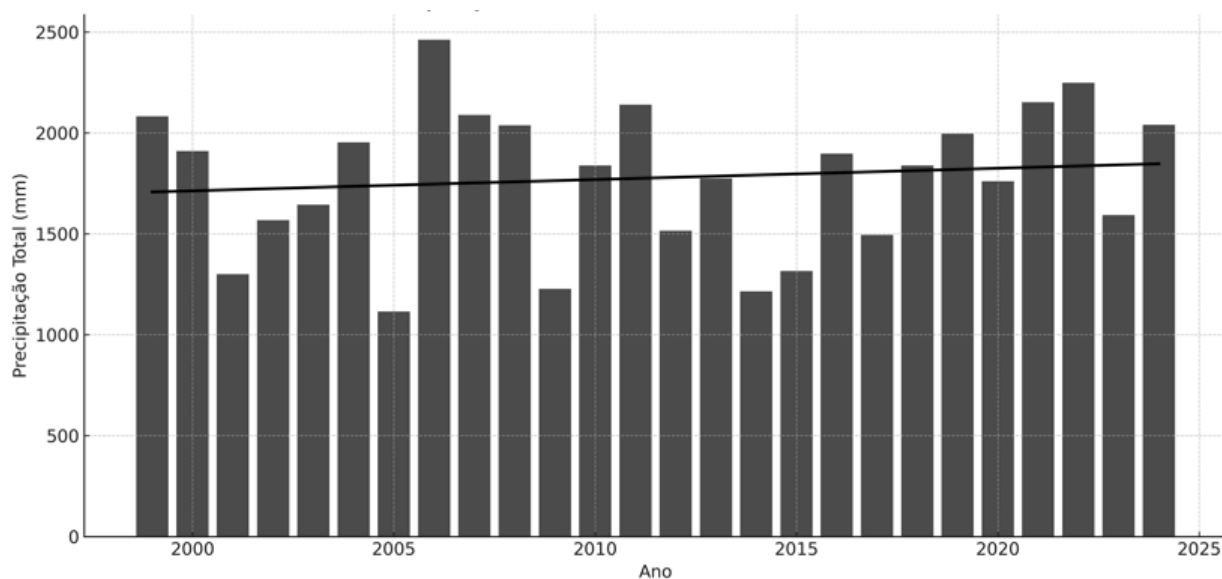
Source: adapted by the author from IBGE (2024).

Geologically, the basin is characterized by volcanic rocks of the Apoteri Formation and sedimentary deposits of the Boa Vista Formation, predominantly composed of unconsolidated sandy materials (Wankler et al., 2022). The relief ranges from flat to gently undulating, with elevations between 60 and 400 m; however, more than 70% of the basin lies at low elevations (60–90 m) with very gentle slopes (~ 0.00276 m), favoring infiltration processes (Carvalho et al., 2016; Oliveira et al., 2021). Geomorphologically, the area is classified as a pediplain, with flat surfaces developed over sedimentary substrates.

The regional climate is classified as Am (tropical monsoon) and represents a hot and humid transitional zone, characterized by high temperatures throughout the year ($>20^{\circ}\text{C}$) and two well-defined seasons: a rainy season (April–September) and a dry season (October–March). The average annual precipitation ranges from 1,600 to 1,800 mm, with peak rainfall occurring between May and July, and mean temperatures around 29°C (Araújo et al., 2024; Sander et al., 2025). Figure 2 presents the total annual precipitation (mm) for the region, obtained from the Boa Vista station and

provided by INMET (2024), covering the period from 1999 to 2024, ensuring temporal consistency among the climatic datasets over a long-term period.

Figure 2: Total annual precipitation (1999–2024).



Source: adapted by the author from INMET (2024).

Analyzing the previous figure, a slight increasing trend in precipitation can be observed over the years. The most critical year in terms of climatic variability was 2005 (1,100 mm), while the year with the highest precipitation was 2006 (~2,400 mm).

The basin is located within the *lavrado* domain (Amazonian savanna), characterized by a mosaic of grasslands, shrub vegetation, and forest islands (Figure 3). Vegetation plays an important role in regulating hydrological processes, particularly infiltration and recharge of the Boa Vista Aquifer (BVA), due to deep root systems adapted to seasonal water availability (Santos et al., 2022; Wankler et al., 2022; Sander et al., 2024; 2025).

Figure 3: Savanna vegetation area and a soybean cultivation area.



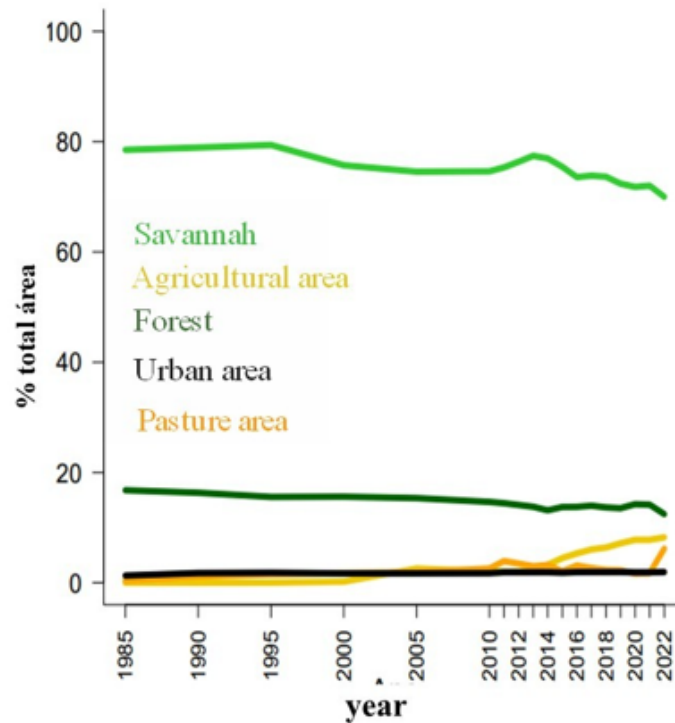
Source: Authors (2025)

Land use and land cover data (Figure 4) were obtained from the MapBiomas platform (2024) for the period from 1985 to 2022. Although this dataset extends beyond the groundwater time series, it was used to provide contextual support for long-term anthropogenic changes in the basin. Temporal differences between datasets are acknowledged and discussed as a limitation.

According to data from the MapBiomas platform (2024), the replacement of native vegetation (savanna) by pasturelands, agricultural areas, and urban expansion has driven significant landscape transformations in the Cauamé River Basin (CRB), leading to changes in the natural water balance. Analysis of Figure 4 indicates that savanna, which was the dominant land cover type in the basin, accounted for 78.51% of the total area in 1985. By 2022, this proportion had decreased to 69.99%, representing a reduction of 8.52% over the analyzed period (1985–2022). This decline reflects the

progressive conversion of native vegetation into anthropogenic land uses.

Figure 4: Land use and land cover classes in the CRB (% of total area) from 1985 to 2022.



Source: adapted by the author from MapBiomass (2024).

Similarly, natural forest areas also showed a reduction, decreasing from 16.77% in 1985 to 12.44% in 2022, corresponding to a loss of 4.33% of the basin area. This reduction is associated with the expansion of agricultural activities, particularly mechanized cropping systems for grain production.

In contrast, pasture areas exhibited a substantial increase. In 1985, pastures occupied only 0.41% of the basin; however, this value increased continuously, reaching 6.17% in 2022, corresponding to an expansion of 5.76% over the study period. This growth reflects the intensification of livestock activities in the region.

Agricultural land use showed the most significant proportional increase. In 1985, agricultural areas represented less than 0.02% of the basin, whereas by 2022 this value had increased to 8.23%. This expansion is mainly associated with the development of mechanized agriculture, particularly irrigated soybean cultivation, which has become one of the main drivers of land-use change in the region.

Urban areas also expanded during the analyzed period, although on a smaller scale compared to agricultural and pasture areas. The urban area increased from 1.29% in 1985 to 1.93% in 2022, representing a growth of 0.64%. This expansion is closely linked to population growth, largely influenced by migration processes in recent decades (IBGE, 2024; MapBiomas, 2024; 2024a; Eloy et al., 2023; Veras et al., 2023).

Overall, these land-use changes demonstrate a clear trend of anthropogenic pressure on the basin, characterized by the reduction of native vegetation and the expansion of productive and urban areas. Such transformations have important implications for hydrological processes, particularly aquifer recharge, infiltration capacity, and evapotranspiration dynamics, reinforcing the need for integrated land and water management strategies.

Thus, the Cauamé River Hydrographic Basin (BHRC) can be understood as a geographic space resulting from the dynamic interaction between society and nature, continuously transformed by human actions and natural processes. In this sense, hydrogeological systems do not constitute isolated physical elements but are part of a constantly reorganizing space, in which

land use and occupation directly influence infiltration processes and water storage.

Therefore, understanding the interaction between anthropogenic and natural factors is essential to identify patterns of groundwater level variation and to propose mitigation strategies. This study is justified by the need to produce updated scientific knowledge on the mechanisms that regulate groundwater level fluctuations in the BHRC. Such understanding is fundamental to guide public policies and support technical decision-making in territorial planning, ensuring the rational use of resources. Furthermore, this research shows strong alignment with the United Nations 2030 Agenda, directly contributing to Sustainable Development Goals (SDGs) 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), 13 (Climate Action), 15 (Life on Land), and 17 (Partnerships for the Goals) (ODS, 2024).

3. METHODOLOGY

The methodological approach adopted in this study was exploratory and qualitative in nature. The exploratory approach was carried out through a systematic literature review, aiming to understand how groundwater level variation in the aquifer relates to hydrogeological parameters. In the quantitative approach, data were collected from public sources to identify the hydrological characteristics that influence groundwater level variation in the Cauamé River Hydrographic Basin, Roraima.

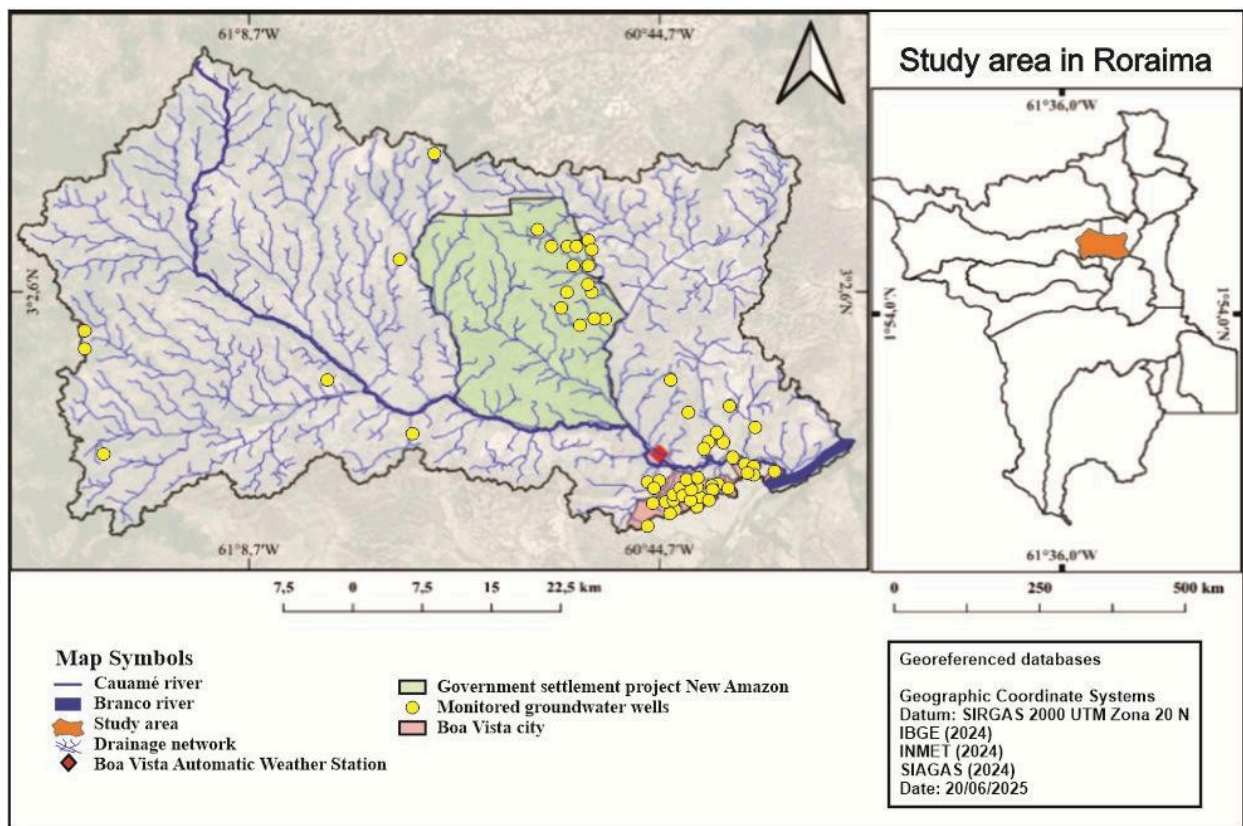
Thus, the spatial dynamics of land use and land cover between 1985 and 2022 were analyzed using data from the MapBiomas platform (2024), along with precipitation data from the Boa Vista

meteorological station (INMET, 2024) for the period 1999–2024. The response variables—static water level (SWL), dynamic water level (DWL), and the SWL/DWL ratio—were analyzed for the period 1982–2014, based on a sample of 80 tubular wells registered in the Groundwater Information System (SIAGAS, 2024). For data analysis and interpretation, multivariate statistical methods were applied using RStudio software (R Project, 2023), enabling the generation of regression graphs.

3.1. Data Sources And Selection Criteria

This study adopted an integrative approach, combining hydrological and anthropogenic variables. Groundwater data, including static water level (SWL) and dynamic water level (DWL), were obtained from the Groundwater Information System (SIAGAS, 1982–2014). A total of 80 monitored tubular wells, registered in SIAGAS and located within the Cauamé River Hydrographic Basin (BHRC), were selected for the analysis.

Figure 5: Tubular wells registered in SIAGAS within the BHRC and selected for analysis, along with the drainage network and the Cauamé River Hydrographic Basin (BHRC).



Source: adapted by the author from SIAGAS (2024).

The selection of wells followed the following criteria: (I) availability of consistent historical records between 1982 and 2014; (II) complete geographic information (latitude, longitude, and altitude); (III) presence of both static and dynamic water level measurements; and (IV) spatial distribution covering both urban and rural areas of the basin. Wells with incomplete records, inconsistent measurements, or missing key variables were excluded to ensure data reliability.

3.2. Data Processing And GIS Analysis

Spatial data processing and map generation were carried out using QGIS software (version 3.34.12). The geographic distribution of the 80 tubular wells, the drainage network, and the boundaries of the river basin were mapped and analyzed. The groundwater dataset was organized and preprocessed using Microsoft Excel, including: (a) verification of missing values; (b) removal of inconsistent records; and (c) standardization of units and variables.

The final dataset, including dependent and independent variables, was then imported into RStudio (version 4.4.2) for statistical analysis.

3.3. Statistical Analysis

To evaluate the relationships between groundwater levels (static and dynamic) in the 80 tubular wells (Table 1) and environmental variables, multiple linear regression models were applied. The dependent variables analyzed were: static water level (SWL), dynamic water level (DWL), and the SWL/DWL ratio. The independent variables included: latitude, longitude, altitude, precipitation, and time (year).

The general form of the model is expressed as:

SWL, DWL, or SWL/DWL Ratio = $\beta_0 + \beta_1(\text{Lat}) + \beta_2(\text{Long}) + \beta_3(\text{Alt}) + \beta_4(\text{Prec}) + \beta_5(\text{Time}) + \varepsilon$, where β_0 is the intercept; β_1 – β_5 are the regression coefficients; and ε represents the error term. To evaluate model performance, the coefficient of determination (R^2) was used, indicating the proportion of variance explained by the predictors. In addition, diagnostic analyses were conducted to assess: residual distribution, multicollinearity among predictors, and the statistical significance of coefficients ($p < 0.05$).

It is important to note that groundwater systems are inherently complex, and relatively low R^2 values are expected due to the influence of multiple unobserved variables (e.g., pumping rates, soil properties, and aquifer characteristics). Therefore, results should be interpreted with caution, emphasizing trends rather than deterministic relationships.

Table 1: Summary of 15 regression models tested, with five predictor combinations for each dependent variable.

Hydrological Characteristics	R ² (%)	Predictor	Coefficient	P
Static Level vs. Predictors	26	Intercept	-4,463.10 ²	-
		Latitude	7,226.10 ¹	0,0232
		Longitude	-3,916.10 ⁰	0,8414
		Altitude	1,068.10 ⁻¹	0,5589
		Precipitation	4,272.10 ⁻³	0,1958
		Date	-1,717.10 ⁻⁵	0,8969
Dynamic Level vs. Predictors	22	Intercept	-2,650.10 ³	-
		Latitude	1,028.10 ²	0,1676
		Longitude	-3,888.10 ¹	0,4034
		Altitude	2,154.10 ⁻¹	0,6190
		Precipitation	2,257.10 ⁻²	0,0049
		Date	-6,128.10 ⁻⁴	0,0546
Static Level Ratio: Dynamic vs. Predictors	30	Intercept	-1,498.10 ⁰	-
		Latitude	2,309.10 ⁰	0,0901
		Longitude	7,496.10 ⁻²	0,9294
		Altitude	-4,189.10 ⁻³	0,5956
		Precipitation	-1,134.10 ⁻⁴	0,4247
		Date	1,933.10 ⁻⁵	0,0012

Source: adapted by the author from SIAGAS (2024).

3.4. Methodological Limitations

Some limitations should be acknowledged, such as: the absence of direct data on groundwater extraction rates; limited integration of land-use variables into the statistical models; and temporal mismatches between groundwater and land-use datasets.

Despite these limitations, the adopted approach provides a relevant initial assessment of groundwater dynamics in the Cauamé River Hydrographic Basin and establishes a foundation for more complex modeling approaches in future studies.

4. RESULTS AND DISCUSSION

The results indicated that groundwater level variability in the Cauamé River Hydrographic Basin (BHRC) is influenced by a combination of hydrological and anthropogenic factors; however, the strength of these relationships varies and is generally moderate to low. The coefficients of determination (R²) obtained (22–30%) suggest that the selected variables explain only part of the observed variability, indicating that groundwater dynamics in the study area

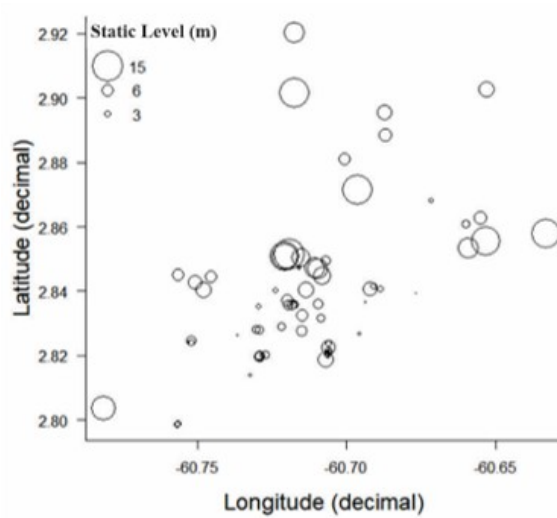
are controlled by multiple interacting processes that are not fully captured by the models.

This behavior is consistent with previous studies in similar hydrogeological contexts, where groundwater systems exhibit complex responses due to the combined influence of climate variability, land-use change, and subsurface heterogeneity (Tucci et al., 2000; Tucci, 2009; Manzione et al., 2020; 2021; Sander et al., 2024). In tropical and savanna environments, such as northern Brazil, groundwater recharge and storage are strongly influenced by seasonal precipitation patterns, soil properties, and vegetation dynamics, which may not be fully represented by simplified statistical models (Salazar et al., 2015; Santos et al., 2022; Jasechko et al., 2024; Eloy et al., 2023; MapBiomass, 2024; 2024a).

4.1. Spatial Distribution Of The Analyzed Wells

In Figure 6, the spatial distribution of the 80 analyzed tubular wells is shown, plotted using geographic coordinates in decimal degrees of latitude and longitude. The study area is located between 2.80 and 2.92° N latitude and -60.75 to -60.65° W longitude. The wells exhibit a heterogeneous spatial distribution, with concentrations in two distinct areas (urban and rural zones).

Figure 6: Spatial distribution of latitude (decimal degrees) versus longitude (decimal degrees) of the 80 wells registered in SIAGAS within the BHRC, during the period 1982–2014.



Source: adapted by the authors from SIAGAS (2024).

The area with the highest concentration of wells is situated in a highly permeable aquifer. This reservoir, which is part of the Boa Vista Formation, is characterized by homogeneous, unconsolidated, and uniform sandy sediments (Wankler et al., 2021; 2022). The selected wells reach depths of up to 40 meters, within a savanna landscape with elevations ranging from 60 to 80 meters above sea level. Spatial statistical analysis of these data suggests positive spatial dependence, where nearby wells tend to share similar hydrogeological characteristics, such as stable groundwater levels and homogeneous hydraulic conductivity (SIAGAS, 2024).

However, spatial variables such as latitude and longitude did not show consistent statistical significance across the models. Although some trends were observed, their explanatory power was limited, indicating that spatial gradients alone are insufficient to explain groundwater variability in the Cauamé River Hydrographic Basin (BHRC). This suggests that local-scale factors, including land-use practices and specific well characteristics, may play a more significant role than regional spatial positioning.

4.2. Static Water Level Vs. Predictor Variables

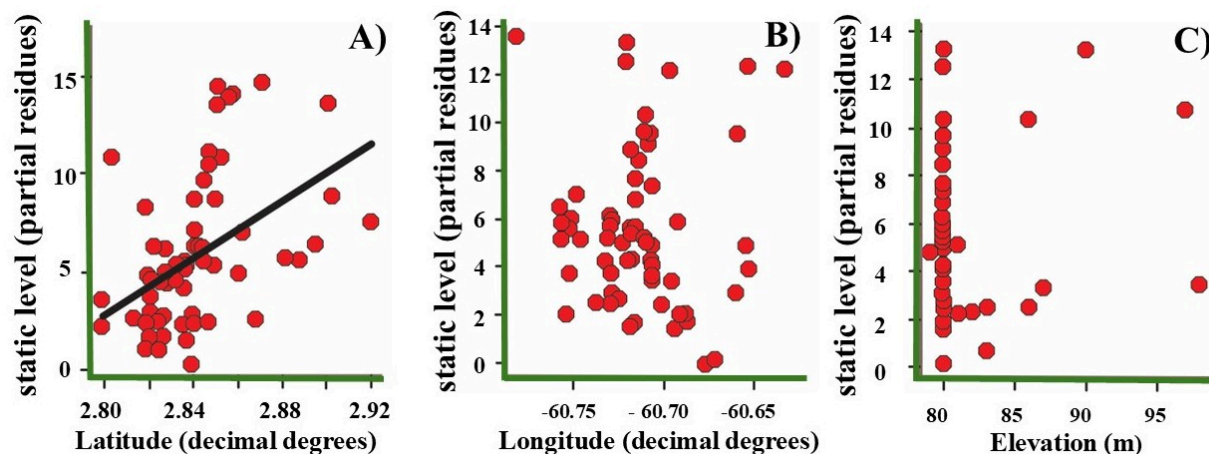
The analysis of Figures 7A, 7B, and 7C, together with Figures 8A and 8B—which relate static water level (SWL) to the predictor variables (latitude, longitude, altitude, precipitation, and time) — indicates generally weak linear relationships between the dependent and independent variables. For the static water level, the linear regression model explains only 26% of the observed variance ($R^2 = 0.26$), indicating low explanatory power (Table 1). This result suggests that additional variables not included in the model—such as groundwater extraction rates, soil properties, and aquifer characteristics—may play a more significant role in controlling groundwater levels.

In the relationship between SWL and latitude (in decimal degrees), a weak positive trend is observed, indicating a potential spatial variation in groundwater levels. However, this relationship is not statistically significant ($p > 0.05$) and should therefore be interpreted with caution. As shown in Figure 7A, a slightly stronger alignment between the variables can be observed within the depth range of 4 to 6 m; however, this pattern is not consistent across the entire dataset.

Additionally, a decrease in well density is observed with increasing latitude, which may influence the apparent spatial pattern. Although there is a trend of variation in static water levels along the latitudinal gradient, the lack of statistical significance limits the robustness of this interpretation.

Figure 7 (A–C): Linear regression plots showing the relationship between static water level (m) and the predictor variables—(A) latitude, (B) longitude, and (C) altitude—based on a dataset of 80 wells obtained from the SIAGAS database. The analysis covers the

period from 1982 to 2014 in the Cauamé River Hydrographic Basin (BHRC).



Source: adapted by the authors from SIAGAS (2024).

Regarding the correlation between static water level and longitude (Figure 7B), no clear or consistent relationship is observed. The regression model shows low explanatory power ($R^2 = 0.26$), and the associated p-values indicate non-significant relationships between the variables (Table 1). This result suggests that longitudinal variation does not play a significant role in explaining groundwater level variability in the study area.

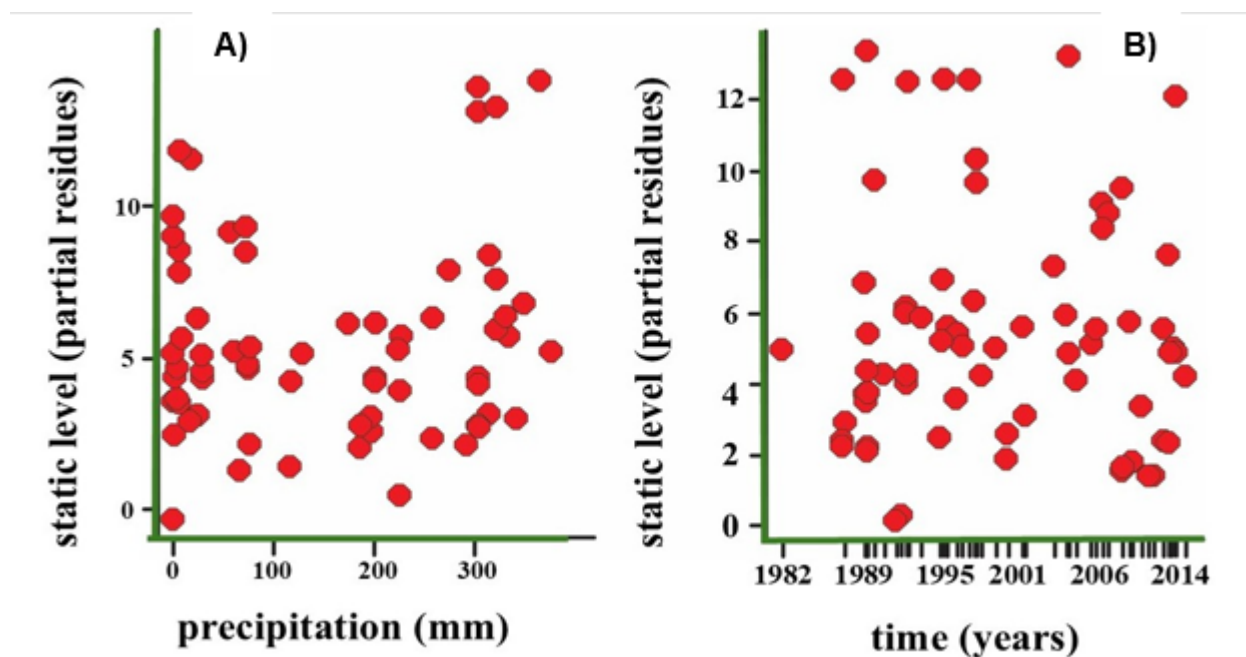
The static water level ranges from 0 to 14 m in depth, with most wells concentrated between 2 and 7 m. A slight decrease in both well density and static groundwater levels is observed with decreasing longitude; however, as with latitude, this pattern lacks statistical support and should not be overinterpreted.

As shown in Figure 7C, which relates static water level (m) to altitude (m), no correlation is observed between the variables. Although the correlation coefficient is positive (1.068×10^{-1}), the p-value ($p = 0.5589$) indicates a lack of statistical significance. The static water

level ranges from 0 to 14 m in depth, while altitude is predominantly concentrated around 80 m.

Overall, the results indicate that spatial variables alone are insufficient to explain the variability of static groundwater levels in the BHRC, reinforcing the need to incorporate additional hydrological and anthropogenic factors into the analysis.

Figure 8 (A–B): Linear regression plots showing the relationship between static water level (m) and the predictor variables—(A) precipitation and (B) time (years)—based on data from 80 wells obtained from the SIAGAS database. The analysis covers the period from 1982 to 2014 in the Cauamé River Hydrographic Basin (BHRC).



Source: adapted by the authors from SIAGAS (2024).

Analyzing Figure 8A, which relates static water level (SWL) to monthly precipitation (mm), no correlation is observed between the variables. SWL ranges from 0 to 12 m in depth, while precipitation varies between 0 and 400 mm per month.

The graph also reveals three distinct intervals with different patterns of groundwater level variation: the first, within the precipitation range of 0 to 100 mm, where groundwater levels show a wide amplitude, ranging from 0 to 12 m in depth; the second, between 100 and 200 mm, where SWL exhibits a narrower range, from 1 to 6 m in depth; and the third, with precipitation above 200 mm, where SWL varies from 1 to 15 m, with the highest concentration occurring between 3 and 8 m in depth.

The relationship between static water level (SWL) and time (years) does not show statistical significance ($p = 0.8969$), indicating the absence of a temporal trend in the dataset. The regression coefficient is negative (-1.717×10^{-5}), but its magnitude is negligible and not statistically significant (Table 1).

As illustrated in Figure 8B, SWL values range from 0 to 14 m in depth, with maximum values observed in 1989 and 2007. Most wells are concentrated within the depth interval of 1 to 7 m. Despite the long temporal coverage (1982–2014), the distribution of values does not indicate a consistent increase or decrease in static water levels over time.

4.3. Dynamic Water Level Vs. Predictor Variables

The analysis of Figures 9A, 9B, and 9C, together with Figures 10A and 10B—which relate dynamic water level (DWL) to the predictor variables (latitude, longitude, altitude, precipitation, and time) — indicates generally weak linear relationships between the dependent and independent variables.

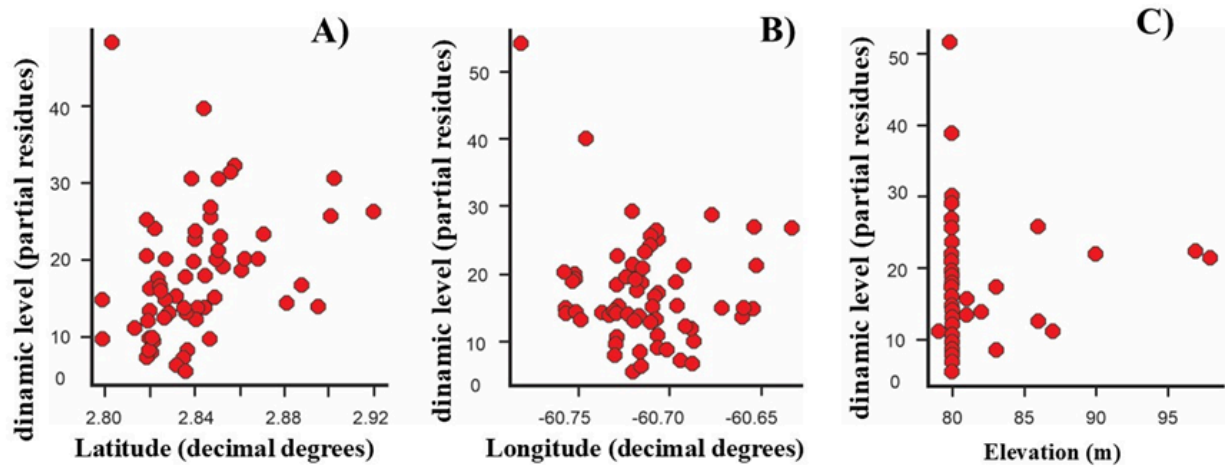
The multiple linear regression model explains only 22% of the observed variance in DWL ($R^2 = 0.22$), indicating low explanatory

power (Table 1). This suggests that additional variables not included in the model—such as groundwater extraction rates, aquifer properties, and soil characteristics—may exert a stronger influence on dynamic groundwater levels.

Regarding the relationship between DWL and latitude (Figure 9A), no statistically significant correlation was observed ($p > 0.05$). Most wells are distributed within the latitude range of 2.80 to 2.92 decimal degrees, with DWL values generally below 33 m. A concentration of wells is observed between latitudes 2.82 and 2.86 (decimal degrees), where DWL values (water depth levels) are predominantly around 20 m.

A slight decrease in both DWL and well density is observed with increasing latitude; however, this pattern is not statistically significant and should be interpreted with caution. Some outliers are present, including wells with depths of 40 m and 50 m.

Figure 9 (A–C): Linear regression plots showing the relationship between dynamic water level (m) and the predictor variables—(A) latitude, (B) longitude, and (C) altitude—based on data from 80 wells obtained from the SIAGAS database. The analysis covers the period from 1982 to 2014 in the Cauamé River Hydrographic Basin (BHRC).



Source: adapted by the authors from SIAGAS (2024).

Similarly, the relationship between DWL and longitude (Figure 9B) does not show a statistically significant correlation ($p > 0.05$). Most wells are concentrated within the longitude range of -60.75 to -60.68 decimal degrees, where DWL values generally reach up to 28 m in depth. Although a slight decreasing trend in both DWL and well density is observed with decreasing longitude, this pattern lacks statistical support. Higher isolated values (up to 55 m) are observed in a small number of wells, indicating local variability.

Regarding altitude (Figure 9C), no statistically significant relationship was identified with dynamic water level (DWL) ($p = 0.6190$), despite a positive regression coefficient (2.154×10^{-1}). Most wells are located at approximately 80 m of altitude, where DWL values are typically below 30 m. A general decrease in both DWL and well frequency is observed with increasing altitude; however, this trend is weak and not statistically supported. A single well with a DWL of 52 m represents a potential anomaly, possibly associated with localized hydrogeological conditions, such as fractured zones in the underlying bedrock.

Overall, although a slight downward trend is suggested, the results do not provide robust statistical evidence of a consistent decline in

dynamic water levels during the analyzed period.

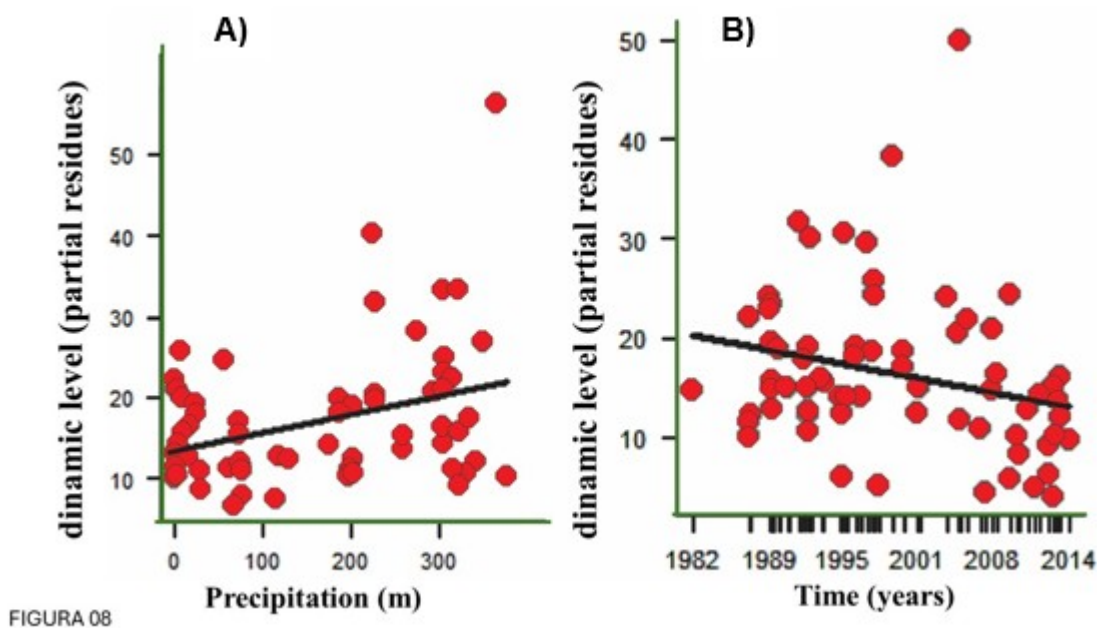
In contrast, the relationship between DWL and precipitation (Figure 10A) shows a statistically significant positive correlation ($p = 0.0049$), although the strength of the relationship remains weak. The positive coefficient (2.257×10^{-2}) indicates that higher precipitation levels are associated with increases in dynamic water levels, reflecting the influence of recharge processes. Most wells exhibit DWL values (water depth levels) around 28 m, with slight increases under higher precipitation conditions. Notably, within the precipitation range of 250–400 mm, some wells display higher DWL values (up to 40 m and 60 m), suggesting localized responses to intense rainfall events.

The analysis of Figure 10B, which relates dynamic water level (DWL) to time (years), indicates a slight negative trend over the period from 1982 to 2014. The regression coefficient is negative (-6.128×10^{-4}), suggesting a slight decrease in DWL over time; however, this relationship is only marginally significant ($p = 0.0546$) and should therefore be interpreted with caution, as with the previous results.

Most wells show maximum dynamic water level (DWL) values of up to 30 m, with the majority of observations concentrated at shallower depths. The average DWL is approximately 8 m. A small number of wells exhibit higher values, including depths of 40 m and 50 m recorded in 2001 and 2008, respectively, which represent isolated observations rather than a consistent temporal pattern.

Figure 10 (A–B): Linear regression plots showing the relationship between dynamic water level (m) and the predictor variables—(A) precipitation and (B) time (years)—based on data from 80 wells

obtained from the SIAGAS database. The analysis covers the period from 1982 to 2014 in the Cauamé River Hydrographic Basin (BHRC).



Source: adapted by the authors from SIAGAS (2024).

Overall, the results indicate that, among the predictors analyzed, precipitation is the only variable that shows a statistically significant relationship with DWL. Spatial variables (latitude, longitude, and altitude) and temporal variation exhibit limited explanatory power, reinforcing the complexity of groundwater dynamics and the influence of additional unmeasured factors.

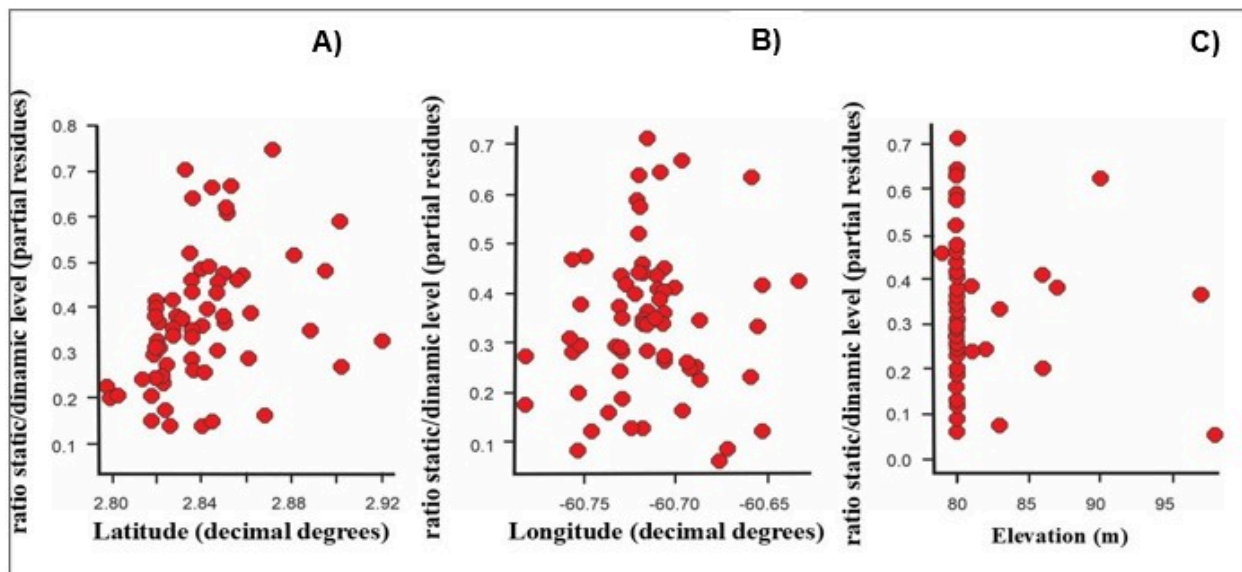
4.4. Ratio Between Static And Dynamic Water Levels Vs. Predictor Variables

The analysis of Figures 11A, 11B, and 11C, together with Figures 12A and 12B—which relate the ratio between static and dynamic water levels (SWL/DWL) to the predictor variables (latitude, longitude, altitude, precipitation, and time) — indicates generally weak to moderate relationships between the dependent and independent variables.

The multiple linear regression model explains approximately 30% of the observed variance ($R^2 = 0.30$), representing a modest explanatory capacity (Table 1). Although this value is higher than those obtained for static and dynamic water levels individually, it still indicates that a substantial portion of the variability is controlled by factors not included in the model.

Regarding spatial variables, no statistically significant relationships were identified. The relationship between the SWL/DWL ratio and latitude (Figure 11A) does not show a clear correlation, with values ranging from 0.0 to 0.7 across a latitude range of 2.80 to 2.92 decimal degrees. Most wells are concentrated between latitudes 2.82 and 2.85 decimal degrees, where SWL/DWL values are generally around 0.5. A slight decrease in both the ratio and well density is observed with increasing latitude; however, this pattern lacks statistical support.

Figure 11 (A–C): Linear regression plots showing the relationship between the ratio of static to dynamic water levels (m) and the spatial predictor variables—(A) latitude, (B) longitude, and (C) altitude—based on data from 80 wells obtained from the SIAGAS database. The analysis covers the period from 1982 to 2014 in the Cauamé River Hydrographic Basin (BHRC).



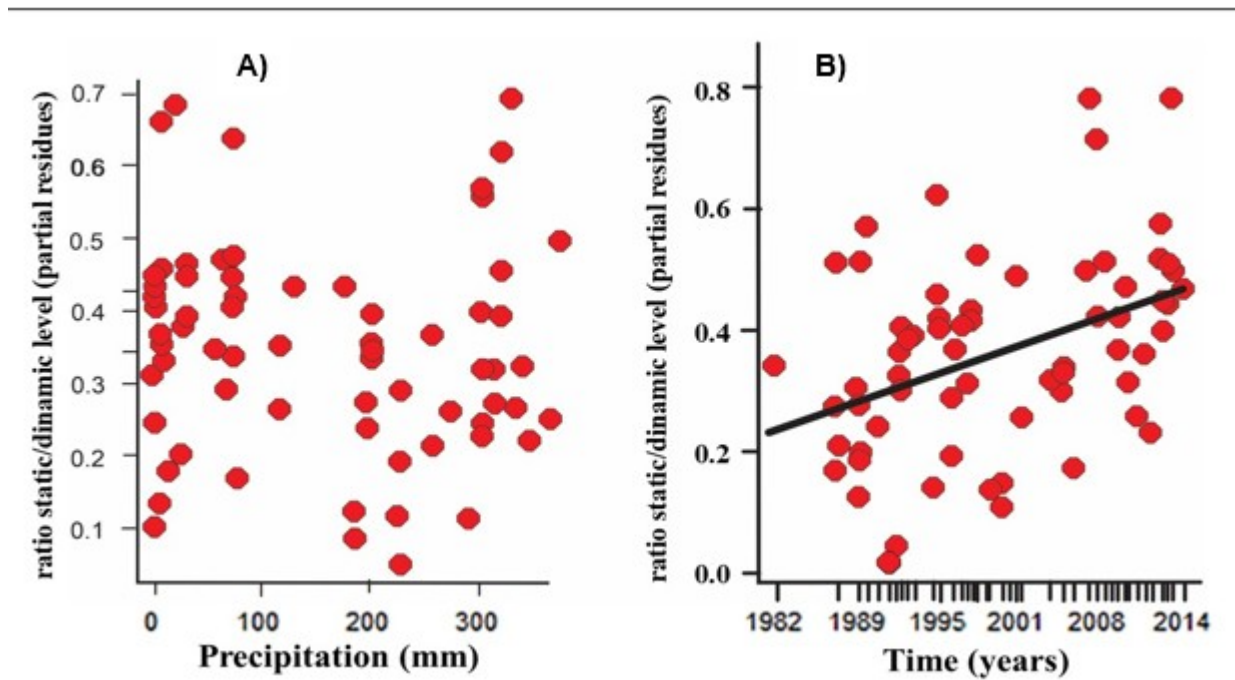
Source: adapted by the authors from SIAGAS (2024).

Similarly, the relationship between the SWL/DWL ratio and longitude (Figure 11B) does not show a statistically significant correlation. The ratio ranges from 0.0 to 0.7, with most wells concentrated between -60.75 and -60.68 decimal degrees, where values typically range from 0.1 to 0.5. Although a decrease in both the ratio and well density is observed along the longitudinal gradient, this trend lacks statistical significance.

Regarding altitude (Figure 11C), no statistically significant association was observed with the SWL/DWL ratio. Most wells are located at approximately 80 m of altitude, where the ratio is typically around 0.5. A reduction in well density is observed at higher elevations (82–100 m), accompanied by a slight decrease in the ratio; however, this pattern is weak and not statistically supported.

The relationship between the SWL/DWL ratio and precipitation (Figure 12A) also does not show a statistically significant correlation. Most wells exhibit values close to 0.5, with the maximum ratio reaching approximately 0.7 under precipitation conditions ranging from 0 to 400 mm. Small variations are observed across different precipitation intervals; however, no consistent pattern is identified.

Figure 12 (A–B): Linear regression plots showing the relationship between the ratio of static to dynamic water levels (m) and the predictor variables—(A) precipitation and (B) time (years)—based on the same dataset of 80 wells from SIAGAS, covering the period from 1982 to 2014 in the Cauamé River Hydrographic Basin (BHRC).



Source: adapted by the authors from SIAGAS (2024).

In contrast, the relationship between the SWL/DWL ratio and time (Figure 12B) shows a statistically significant positive trend ($p = 0.0012$). The regression coefficient (1.933×10^{-5}) indicates a gradual increase in the ratio over the analyzed period (1982–2014). Most wells present values around 0.5, with higher values (up to 0.8) observed in more recent years (2008–2014).

This temporal increase may reflect changes in the aquifer system's response to groundwater extraction and recharge processes. However, considering the moderate explanatory power of the model and the absence of direct data on pumping rates and aquifer properties, this interpretation should be regarded as indicative rather than conclusive. Overall, the results suggest that temporal variation plays a more relevant role in explaining changes in the

SWL/DWL ratio than spatial or climatic variables, although the complexity of groundwater systems limits the robustness of these inferences.

Thus, the results indicate that groundwater level variability in the Cauamé River Basin (CRB) is controlled by multiple hydrological and anthropogenic factors, exhibiting low to moderate statistical relationships (R^2 between 22% and 30%). Precipitation proved to be significant for dynamic water levels, confirming its role in aquifer recharge. In contrast, spatial variables showed low influence, indicating that local factors are more relevant. The ratio between static and dynamic levels showed limited explanatory capacity and should be interpreted with caution as an indicator of system resilience. The low R^2 values reflect the complexity of aquifer systems, which are often influenced by unmeasured variables such as pumping rates and soil properties. Although not directly incorporated into the models, land use changes indicate increasing anthropogenic pressure, particularly due to agricultural and urban expansion.

Among the predictors analyzed, precipitation showed a statistically significant relationship with dynamic water level ($p < 0.05$), reinforcing its role as the main driver of short-term groundwater fluctuations. This finding is consistent with expected hydrological behavior, in which increased precipitation enhances infiltration and contributes to aquifer recharge. However, the absence of strong relationships between precipitation and static water level suggests that long-term groundwater storage is influenced by additional factors, such as aquifer properties and extraction rates, which were not directly included in this study.

5. CONCLUSIONS

This study investigated the effects of hydrological and anthropogenic variables on groundwater level variation in the Cauamé River Hydrographic Basin (BHRC) over the period 1982 to 2014, based on publicly available datasets, including static and dynamic groundwater levels (SIAGAS), precipitation (INMET), and land use (MapBiomas).

The results show that the CRB experienced significant land use changes between 1985 and 2022, characterized by a reduction in native vegetation (natural savanna and forest) driven by the expansion of agricultural, pasture, and urban areas. These transformations reflect increasing anthropogenic pressure on the basin and have important implications for hydrological processes, particularly influencing groundwater recharge and the regulation of the water balance. In this context, the findings highlight the need for integrated water resource and land-use management strategies aimed at reconciling economic development with environmental sustainability.

Statistical analyses revealed limited explanatory power of the regression models ($R^2 \leq 0.30$), indicating that the selected variables explain only a small proportion of groundwater variability. Spatial predictors (latitude, longitude, and altitude) did not show statistically significant relationships with groundwater levels, suggesting that spatial variation alone is insufficient to explain aquifer dynamics in the study area.

Among the analyzed variables, precipitation was the only factor significantly associated with dynamic water level ($p = 0.0049$),

confirming its role as a key driver of aquifer recharge. In contrast, the temporal variable showed a marginally significant negative trend for dynamic water levels ($p = 0.0546$), indicating a possible, though inconclusive, decrease over time.

For the ratio between static and dynamic water levels, a statistically significant positive temporal trend was identified ($p = 0.0012$), suggesting changes in aquifer response over the analyzed period. However, given the moderate explanatory capacity of the models and the absence of key variables—such as groundwater extraction rates and hydrogeological parameters—these results should be interpreted with caution.

Overall, the findings indicate that groundwater dynamics in the BHRC are influenced by a combination of climatic variability and increasing anthropogenic pressure, although system complexity limits the ability of simplified models to fully capture these interactions.

Future research should incorporate additional variables, including pumping rates, soil properties, and aquifer characteristics, as well as more advanced statistical and spatial modeling approaches. Such efforts are essential to improve the understanding of groundwater behavior and to support more effective water resource management strategies in the region.

The results do not provide sufficient statistical support to robustly characterize system resilience, highlighting the need for more comprehensive indicators and datasets. The relatively moderate R^2 values observed across all models do not necessarily invalidate the

results but rather reflect the intrinsic complexity of groundwater systems.

Regarding anthropogenic influences, although land use and land cover changes were not directly incorporated into the statistical models, their potential impact on groundwater dynamics is supported by the literature. The expansion of agricultural activities, vegetation removal, and urban growth in the Cauamé River Hydrographic Basin (BHRC) may affect infiltration rates and recharge processes. However, due to the lack of direct quantitative integration, these relationships are discussed qualitatively and should be further investigated in future studies.

The temporal scope of the analysis (1982–2014) encompasses a period of significant socio-environmental transformations in the region, including population growth, infrastructure development, and agricultural expansion. These processes likely contributed to increased groundwater demand and may have influenced the observed trends in water levels. However, the absence of direct data on groundwater extraction limits the ability to establish causal relationships between human activities and groundwater level decline.

From a methodological perspective, the use of multiple linear regression provided a useful initial framework for evaluating relationships between variables. However, given the non-linear and spatially heterogeneous nature of groundwater systems, alternative approaches—such as non-linear models, spatial statistics, or integrated hydrological modeling—may provide more robust insights in future research.

Finally, the conclusions of this study have important implications for groundwater management in the Cauamé River Hydrographic Basin. The observed sensitivity of groundwater levels to precipitation highlights the system's potential vulnerability to climatic variability. In addition, increasing anthropogenic pressure in the region underscores the need for improved monitoring, regulation of groundwater extraction, and the integration of land-use planning into water resource management strategies.

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