Revista Brasileira de Ciência, Tecnologia e Inovação

DOI: https://doi.org/10.18554/rbcti.v9i2.8090

Research paper

Analysis of the Distribution and Management of Tubular Wells in the Urban Area of Cuiabá, Mato Grosso

Análise da Distribuição e Gestão dos Poços Tubulares na Área Urbana de Cuiabá, Mato Grosso

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ABSTRACT: Groundwater exploitation in Cuiabá faces significant challenges due to the hydrogeological complexity of fractured rocks and accelerated urban growth. This study aimed to analyze the distribution and concentration of tubular wells in the urban area to identify the overexploitation of water resources. Spatial density and Inverse Distance Weighting (IDW) interpolation techniques were applied to data on geographic coordinates, flow rates, and pumping regimes to map and assess the situation. The results revealed the presence of 1,886 tubular wells, with 74.3% operating illegally and an average density of 7.4 wells/km². The Centro-Leste Regional Administration exhibited the highest concentration of illegal wells, highlighting uncontrolled exploitation. The analysis showed that 81.4% of the wells are intended for supply and sanitation. Variations in well characteristics, such as flow rates and water levels, reflect the geological diversity and pressure on resources. The high incidence of illegal wells and the discrepancy between regulated and unregulated wells indicate deficiencies in the monitoring and management of groundwater resources. Implementing more strict monitoring policies and effective regulation is essential to ensure the sustainability of water resources and water quality in Cuiabá.

Keywords: Water vulnerability, groundwater exploitation, illegal wells, water resource management.

RESUMO: *A explotação de água subterrânea em Cuiabá enfrenta desafios significativos devido à complexidade hidrogeológica das rochas fraturadas e ao crescimento urbano acelerado. Este estudo teve como objetivo analisar a distribuição e a concentração dos poços tubulares na área urbana para identificar superexplotação dos recursos hídricos. Utilizando dados sobre coordenadas geográficas, vazão e regime de bombeamento, foram aplicadas técnicas de densidade espacial e interpolação por Distância Inversa Ponderada (IDW) para mapear e avaliar a situação. Os resultados mostraram a presença de 1.886 poços tubulares, com 74,3% operando de forma clandestina e uma densidade média de 7,4 poços/km². A Administração Regional Centro-Leste apresentou a maior concentração de poços clandestinos, evidenciando a explotação descontrolada. A análise revelou que 81,4% dos poços são destinados a abastecimento e saneamento. A variação nas características dos poços, como vazão e níveis de água, reflete a diversidade geológica e a pressão sobre os recursos. Conclui-se que a alta incidência de poços clandestinos e a discrepância entre poços regulamentados e não regulamentados indicam deficiências na fiscalização e gestão dos recursos hídricos subterrâneos. A implementação de políticas de monitoramento mais rigorosas e a regulamentação efetiva são essenciais para garantir a sustentabilidade dos recursos hídricos e a qualidade da água em Cuiabá.*

Palavras-chave: *Vulnerabilidade hídrica, explotação de água subterrânea, poços clandestinos e gestão de recursos hídricos.*

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INTRODUCTION

Groundwater exploitation in urban areas presents complex challenges, especially when dealing with hydrogeology in fractured rocks. Rock fractures significantly alter the flow and distribution of groundwater, resulting in an unpredictable geological structure that complicates the management and monitoring of groundwater resources (Read *et al.*, 2013; Troeger; Chambel, 2021) in urban areas and has presented complex challenges. In urban environments, where the water demand is high, this geological complexity can aggravate problems such as scarcity, contamination, and soil subsidence (Ciampittiello; Marchetto; Boggero, 2024).

The municipality of Cuiabá, located in Central-West Brazil, faces challenges in exploiting groundwater due to its unique hydrogeological structure. The region is characterized by fractured metasediments, including phyllite, conglomeratic phyllite, and metadiamictite, interbedded with metarcose and metarenite. The presence of these fractures and the associated geological complexity significantly influence the flow and distribution of groundwater, thereby complicating management and monitoring strategies. Given the rising urban growth and increasing demand for water resources, it becomes essential to understand these dynamics to ensure the sustainable availability and quality of water in the region (Read *et al.*, 2013).

Population and urban growth in Cuiabá has led to an increase in the number of wells, both authorized and illegal (Nicochelli *et al.*, 2009; Rocha; Campos, 2014). Clandestine wells, operating outside of regulations, can cause contamination and compromise the management of water resources. These challenges can be addressed by mapping all wells, including unregulated ones, to identify areas with greater overexploitation and monitor the impact of water abstraction (Conicelli *et al.*, 2021; Ndoziya; Hoko; Gumindoga, 2019). This mapping allows for more effective control of water resources and facilitates the implementation of measures to prevent aquifer depletion.

This study aimed to analyze and evaluate the concentration and distribution of tubular wells in the urban area of the municipality of Cuiabá to identify areas of overexploitation of water resources. The research focuses on assessing the spatial distribution and density of wells through the processing of collected data, which include geographic coordinates, purpose of use, flow rate, and pumping regime, organized in a database. For spatial analysis, techniques such as spatial density and Inverse Distance Weighted (IDW) were used to estimate the distribution of wells and their characteristics in unsampled areas.

Study Area

The study area is located in the municipality of Cuiabá, capital of the state of Mato Grosso, Brazil. It is situated in the Pantanal Basin and over the Guarani Aquifer, one of the largest transboundary aquifers in South America. The city covers an urban area of around 160.59 km² within a municipality with a total area of approximately 4,327 km². The estimated population is 650,912 in urban and rural areas (CUIABÁ; IPDU, 2007; Oliveira, 2016).

Groundwater resources in the area are predominantly supplied by the Cuiabá Group, a geological unit of regional importance located in the Inner Paraguay Fold Belt. Specifically, the Coxipó Formation, which outcrops in the southern portion of Cuiabá, is a lithological unit relevant to the local hydrogeological context. This formation is subdivided into two main

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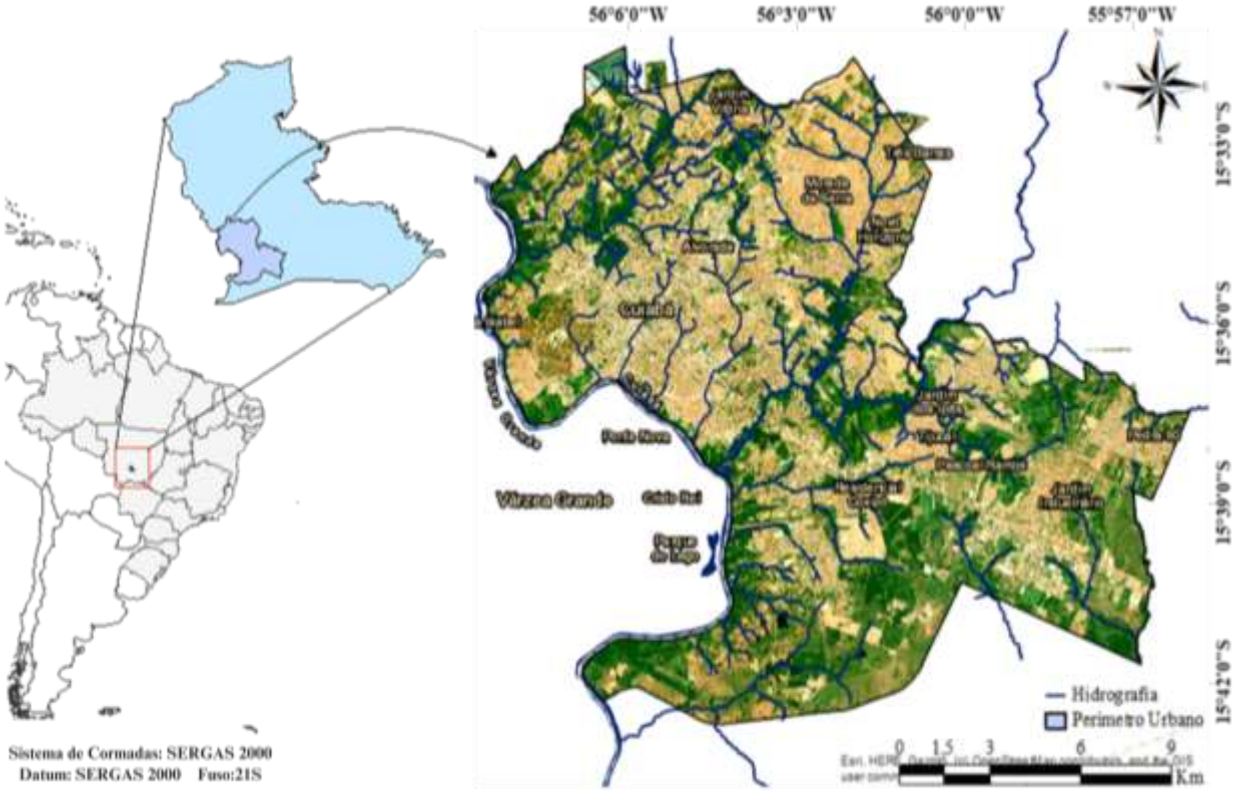
lithological units. Unit I is composed of metadiamictites with a clayey matrix and intercalated by quartz metarenites, and Unit II comprises metadiamictites with a sandy matrix (Gomes; Migliorini, 2019).

The water supply system of Cuiabá is based on the abstraction of surface water at five sites on the Cuiabá and Coxipó rivers. The collected water is directed to eight treatment plants in the urban area, with emphasis on the Ribeirão do Lipa WTP and the Tijucal WTP, which are responsible for supplying most of the water to the neighborhoods. Preserving the quality and sustainable availability of water resources is paramount, requiring the preservation of the banks of water bodies and suitable effluent treatment. **Figure 1** illustrates the geographic location of Cuiabá and its urban perimeter.

Figure 1. Location of the study area in the municipality of Cuiabá, state of Mato Grosso, Central-West Brazil.



METHODOLOGICAL PROCEDURES

The methodology of this study involved the collection and analysis of data on groundwater resources in Cuiabá. Legal documents, such as Laws, Decrees, and Resolutions, were accessed through the federal government website and the State Secretariat for the Environment (SEMA-MT), establishing the normative basis for using these resources.

Technical information about the tubular wells, including geographic coordinates, intended use, flow rate, and pumping regime, was gathered and organized in an Excel spreadsheet. Data on unregistered wells were requested from the concessionaire Águas

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Cuiabá until August 2021, allowing the identification of illegal wells and estimation of their consumption.

The collected data were spatially processed for a detailed analysis of groundwater resources. Construction and lithological profiles of the wells, provided by SEMA-MT in 2019, in addition to historical and monitoring data, were incorporated to assess variations in water levels.

Data Consistency and Verification Processes

Strict consistency and verification procedures were adopted to ensure the accuracy and integrity of data on tube wells in the urban area of Cuiabá. Initially, duplicate records were deleted using specialized tools in Microsoft Excel to guarantee the uniqueness of each entry. Then, the Intersect tool of ArcGIS 10.5 was used to detect overlaps between the tube wells, creating a spatial layer that revealed the intersection between records. The choice of this tool was motivated by the lack of chronological data in the available records, which made the identification of critical events difficult, such as changes in the corporate name of the wells. Overlay analysis was crucial to identify and correct inconsistencies, which ensured data accuracy for groundwater resource analysis (Longley *et al.*, 2012; Smith; Goodchild; Longley, 2018).

Spatial interpolation methods

The spatial density technique was used for the spatial analysis of the concentration of tubular wells in the urban area of Cuiabá, which allowed for estimating the number of wells in a specific area. The formula used to calculate spatial density is given by Equation 1:

$$D = \frac{N}{A} \qquad (1)$$

Where D represents the spatial density of wells, N is the total number of wells located within the area of interest, and A is the total area of the analyzed region (Cressie, 2015). The Inverse Distance Weighted (IDW) method was adopted for spatial interpolation of data on wells. It is a technique commonly adopted to estimate values at unsampled locations based on known spatial data. The IDW formula was expressed by Equation 2 (Chang, 2019).

$$Z_p = \frac{\sum_{i=1}^{n} \left(\frac{1}{d_p^i} * z_i\right)}{\sum_{i=1}^{n} \left(\frac{1}{d_i^p}\right)} \qquad (2)$$

In this formula, Z_p is the estimated value for point *p*, *zi* is the attribute value at sampling point *i*, d_i is the distance between point *p* and sampling point *i* and *p* is the exponent that controls the influence of distance, usually set to 2 to give better weight to closer points. The number n indicates the total number of sampling points considered in the interpolation (Shepard, 1968). The IDW method adjusted the estimate based on the proximity of data points, allowing the creation of a continuous surface that represented the spatial distribution of wells.

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These methodologies were used to analyze the spatial distribution of tubular wells and associated variables, such as Required Flow, Static Level, Dynamic Level, Groundwater Potential, and Potentiometric Quotas (m). Spatial density analysis helped identify areas with a high concentration of wells and facilitated the assessment of the distribution of groundwater resources in Cuiabá. Spatial interpolation with the Inverse Distance Kriging (IDW) method provided detailed variable estimates at unsampled locations. These methods also made it possible to identify areas with the greatest water exploitation, highlighting regions with significant changes in the aquifer flow pattern for water abstraction works.

RESULTS AND DISCUSSIONS

A discrepancy was detected between legally authorized and clandestine wells. In total, 1,886 tubular wells were found, with a density of 7.4 wells/km², of which only 148 (7.8%) had a permit, evidencing the regularization of their use. Most wells, totaling 1,401 (74.3%), operated clandestinely, with an average density of approximately 5.49 wells/km². The high concentration of clandestine wells suggests uncontrolled and unauthorized exploitation of underground water resources (**Figure 2A**).

The data collected allowed the identification of the distribution of tubular wells registered with the State Secretariat for the Environment (SEMA) in the urban area of Cuiabá. The regional analysis showed that the Central-East Regional Administration had 148 tubular wells, representing 30.52%. The Midwest Regional Administration presented 176 tubular wells, corresponding to 36.29%. The North Regional Administration had 27 tubular wells (5.57%). Finally, the Southeast Regional Administration had 134 tubular wells, representing 27.63%. **Figure 3A** details the distribution of tubular wells in the different regions of Cuiabá and shows the density of the wells registered with SEMA.

The distribution of clandestine wells among the various administrative regions was as follows: The Central-East Regional Administration had 425 clandestine wells, accounting for 30.36% of the total. The Midwest Regional Administration had 350 clandestine wells, making up 25.00%. The Northern Regional Administration had 160 clandestine wells, which constitutes 11.43% of the total, while the South-East Regional Administration had 465 clandestine wells, amounting to 33.21%. This information is illustrated in **Figure 3B**.

In general, the results indicated that the Central-East Regional Administration contains the highest proportion of clandestine tubular wells compared to the total, with 30.36%, as shown in **Figure 3C**. The high incidence of clandestine wells in this region suggests a greater vulnerability of the underground aquifer to uncontrolled and unauthorized exploitation of groundwater (Govea, 2014).

Our analysis revealed that 81.4% of tubular wells were intended for supply and sanitation, highlighting their importance for the supply of drinking water and basic services. Wells intended for other purposes represented 14%, while those for irrigation and industrial use were less frequent, with 0.4% and 3.91%, respectively, as shown in **Figure 2B**. The predominance of wells for supply and sanitation reflected the need to meet the demands of a growing and urbanized population (Yadav, 2023).

Out of the 1,401 clandestine wells identified, 308 were active, 93 were inactive, and 1,000 were considered non-existent or illegal. In the residential category, 781 wells were registered, of which 195 were active and 535 were non-existent. The commercial category had 94 active wells, 38 canceled, and 402 non-existent (**Figure 2C**). The industrial and

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public categories presented smaller numbers, with three active wells, two canceled and 33 non-existent in the industrial category, and 16 active wells, two canceled, and 30 non-existent in the public category, as shown in **Figure 2D** (Araújo, 2012; Hirata; Zoby; Oliveira, 2010).

Figure 2. Location of deep tubular wells in Cuiabá (A); purpose of requests for tubular wells to the environmental agency in the urban area of Cuiabá (B); location of clandestine tubular wells according to the connection type (C); location of clandestine tubular wells of the existing connection type (D)

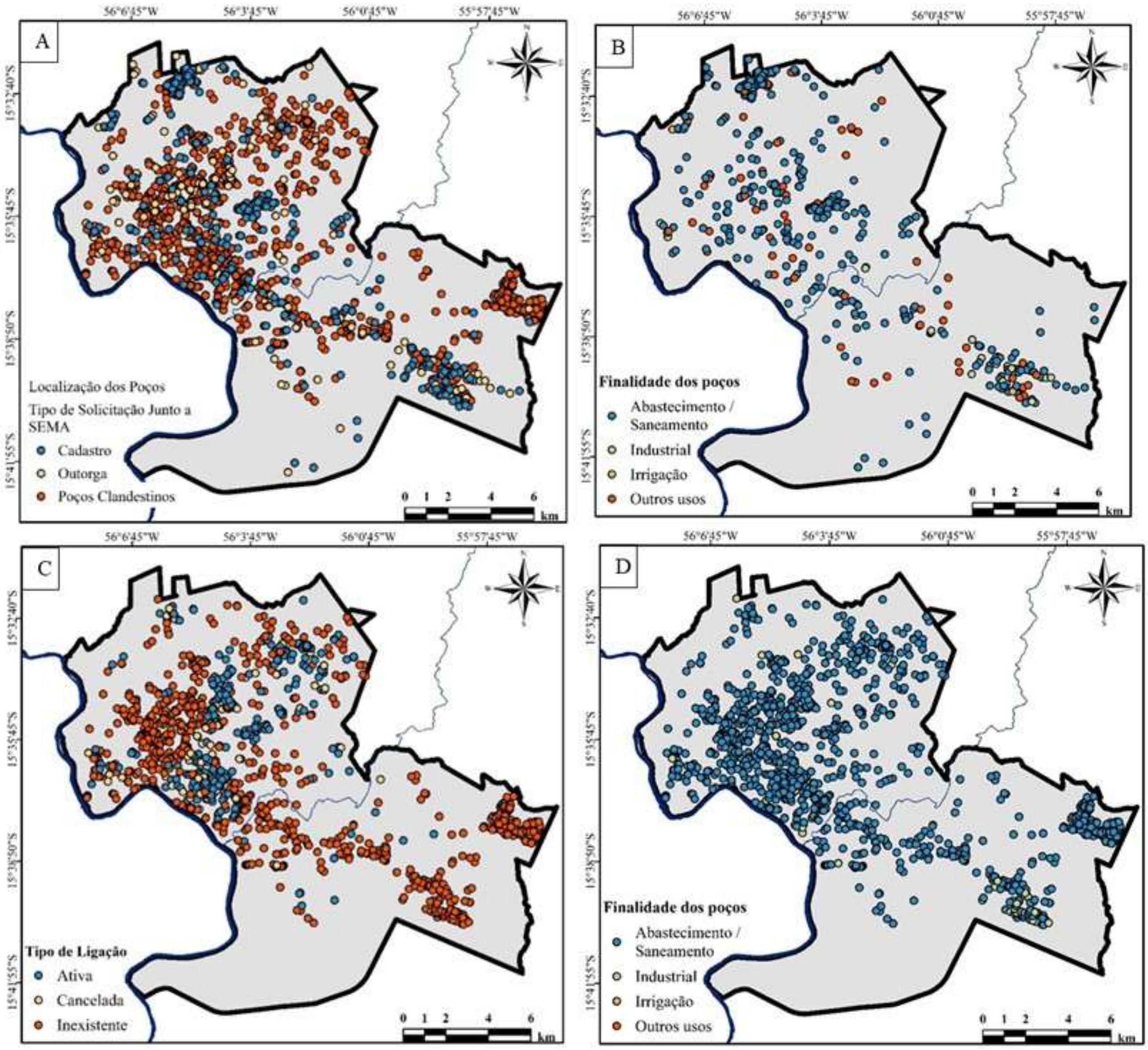

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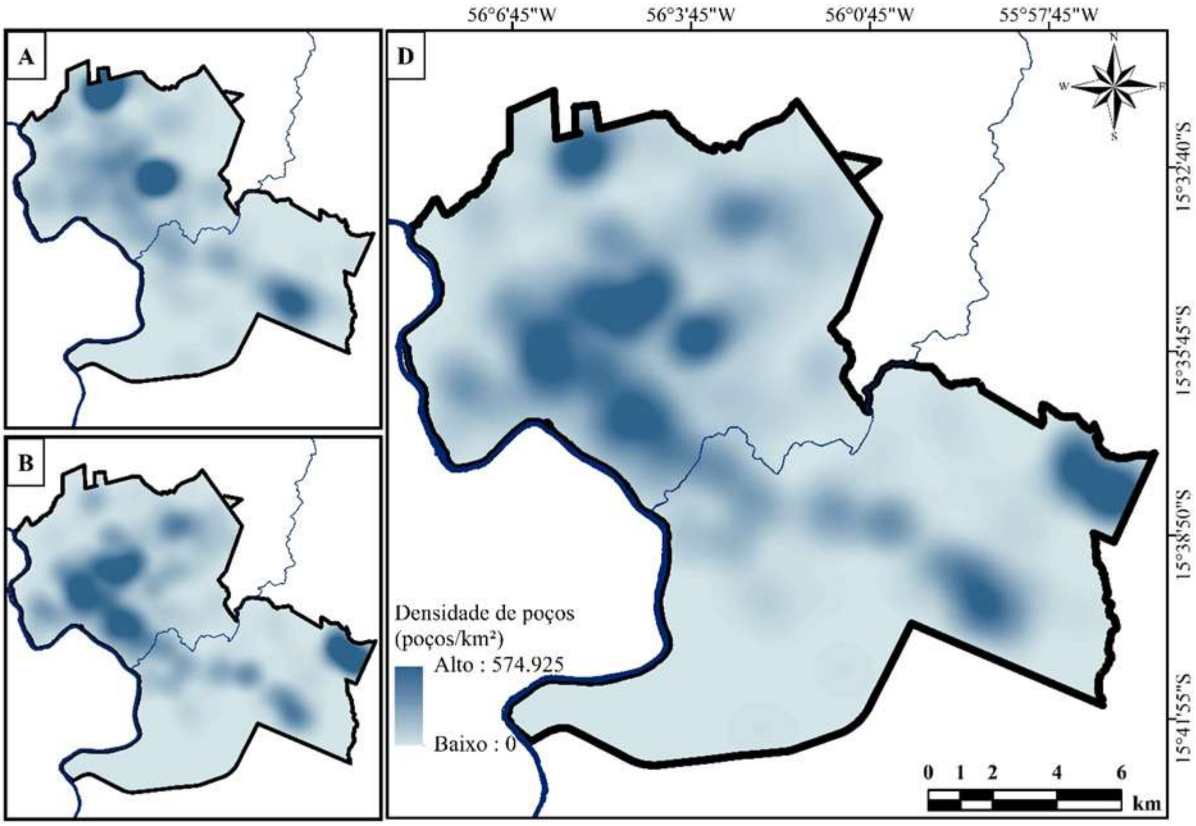
Figure 3. Density of tubular wells duly registered with the State Secretariat for the Environment (SEMA) (A); Density of clandestine tubular wells (B); total density of tubular wells, covering clandestine and regularized/granted wells and those granted/registered in the urban area of Cuiabá (C)



The growth in demand for water in the urban area of Cuiabá, driven by urbanization, is associated with an escalation in groundwater abstraction, which could result in the depletion of these resources. The significant presence of clandestine wells, many operating without proper regulation, was directly linked to the lack of adequate sanitation infrastructure and the unmet pressure on water resources. More strict and effective management of these resources is essential to ensure the sustainability and adequacy of the water supply for various uses (Yadav, 2023).

Analysis of Water Demand in Authorized Tubular Wells

In this study, 485 tubular wells were analyzed, with the information obtained undergoing a detailed screening process. The water demand showed an average required flow rate of 17.05 m³/day and a median of 8.00 m³/day, with values ranging from a minimum of 0.45 m³/day to a maximum of 162.00 m³/day. The total demand amounted to 9,090.41 m³/day (equivalent to 105.21 L/s), indicating the presence of wells with very high demands, possibly associated with intensive uses such as agricultural irrigation or public water supply. Static levels ranged from 0.05 to 40.10 meters, with a mean of 11.99 meters and a median of 10.16 meters. The dynamic level showed an average of 48.22 meters and a median of

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37.45 meters, with values from 4.45 to 204.00 meters, revealing hydrogeological heterogeneity in the area, with wells abstracting water at different depths, as listed in **Table 1**.

Table 1. Statistical Parameters of the Characteristics of Tubular Wells

Statistical Parameters	Required Flow Rate (m^3/d)	Static Level (m)	Dynamic Level (m)	Groundwater Potential ($m^3/h/m$)	Potentiometric quotas (m)
Mean	17.05	11.99	48.22	0.03	183.08
Median	8.00	10.16	37.45	0.01	182.70
Minimum	0.45	0.05	4.45	0.0009	132.00
Maximum	162.00	40.10	204.00	0.15	236.00
Third Quartile	17.00	16.00	63.00	0.03	194.21
Standard Deviation	25.09	7.99	33.86	0.03	17.28
Range	161.55	40.05	199.55	0.15	104.00

The analysis of the groundwater hydrological variables in the Cuiabá region, using the inverse distance interpolation (IDW) method, showed the following estimates: for the Required Flow, the average was 17.03 m^3/d, with a median of 8.54 m^3/d, and variation between 1.34 m^3/d and 159.33 m^3/d. The standard deviation was 23.42 m^3/d, indicating a wide dispersion. The positive skewness of 3.06 and kurtosis of 11.18 pointed to a leptokurtic distribution with a long right tail. The coefficient of determination (R^2) was 0.92, and the correlation coefficient (R) was 0.96, suggesting a strong linear relationship between the measured and estimated values (**Figure 4A**).

The distribution of clandestine wells in the different administrative regions was as follows: the Central-East Regional Administration had 425 clandestine wells (30.36%), the Midwest Regional Administration had 350 clandestine wells (25.00%), the North Regional Administration had 160 clandestine wells (11.43%), and the South-East Regional Administration had 465 clandestine wells (33.21%), as illustrated in **Figure 3B**.

In general, the Central-East Regional Administration presented the highest proportion of clandestine tubular wells compared to the total analyzed, accounting for 30.36%, as shown in **Figure 3C**. The prevalence of unauthorized wells in this region suggests a higher risk of uncontrolled and unregulated groundwater exploitation (Govea, 2014).

Analysis of tubular wells revealed that 81.4% were intended for supply and sanitation, highlighting their importance for the supply of drinking water and basic services. Wells intended for other purposes represented 14%, while those for irrigation and industrial use were less frequent, with 0.4% and 3.91%, respectively, as shown in **Figure 2B**. The predominance of wells for supply and sanitation reflected the need to meet the demands of a growing and urbanized population (Yadav, 2023).

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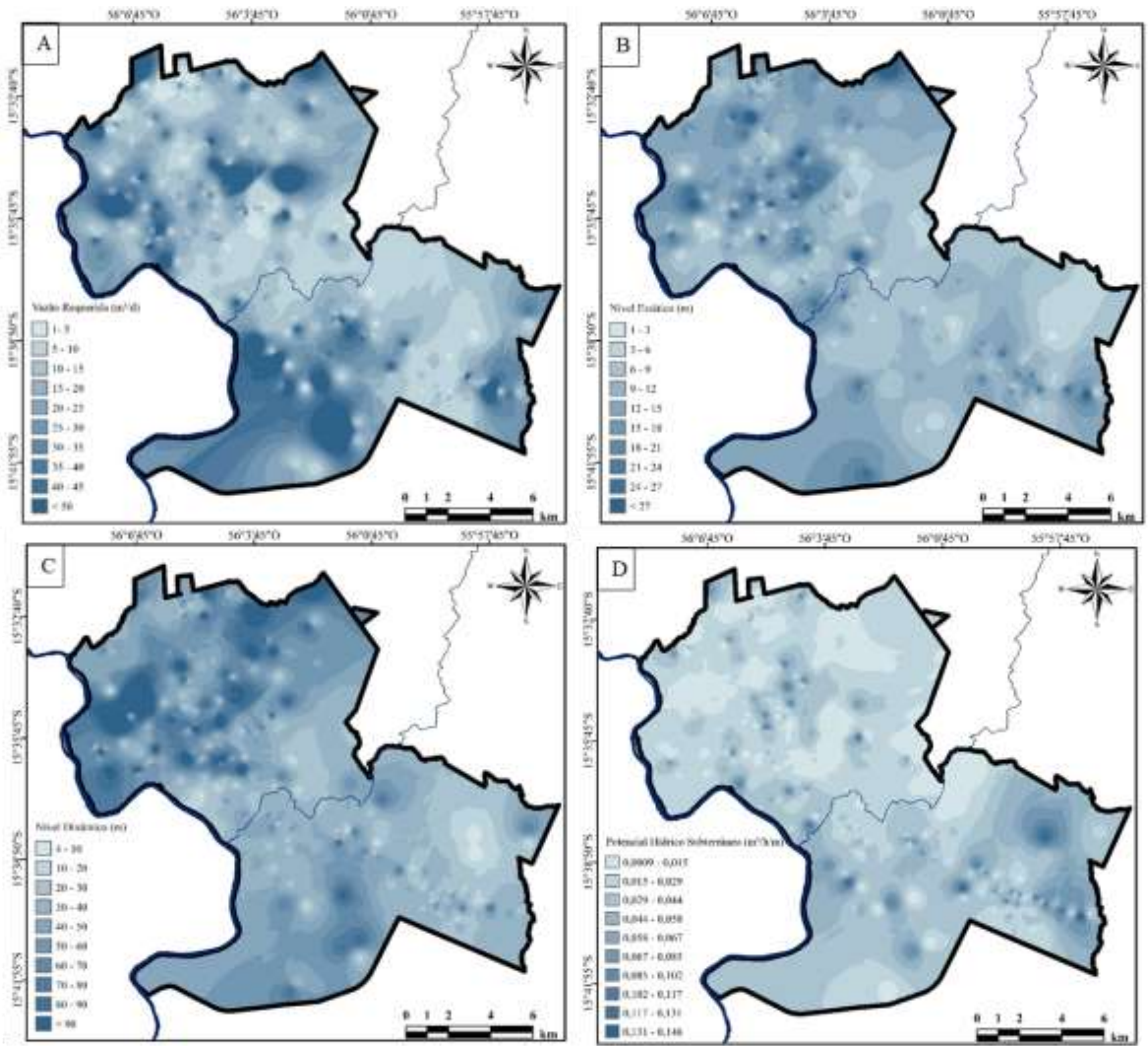
Figure 4 – Inverse-Distance Weighted Interpolation Maps for (A) Water Flow Distribution; (B) Static Level Distribution; and (C) Dynamic Level Distribution



For Potentiometric Quotas, the average was 183.04 m, with a median of 182.63 m. The values varied from 133.61 m to 235.72 m. The standard deviation was 16.88 m, with a total range of 102.11 m. The skewness was close to zero, and the kurtosis of 0.11 indicated a nearly symmetric and platykurtic distribution. The R² and R values were 0.98 and 0.99, respectively, indicating an excellent linear correlation, as observed in **Figure 5**.

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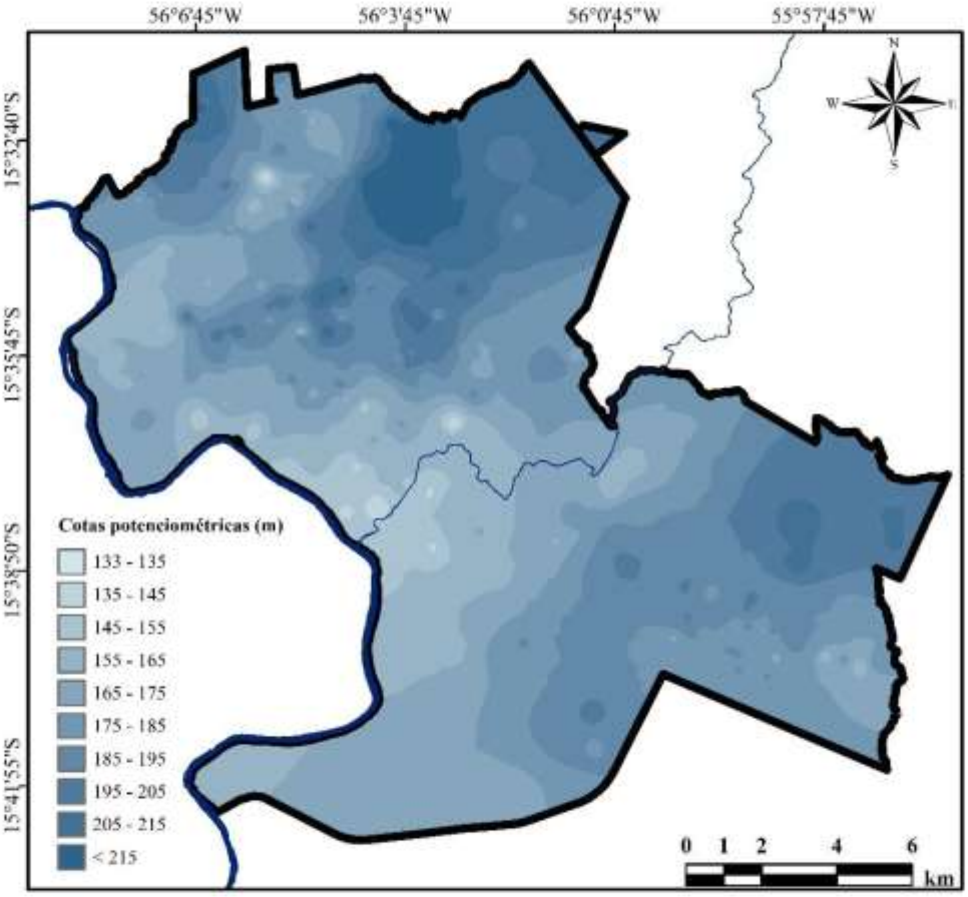
Figure 5 - Distribution of Groundwater Potential



The Nash-Sutcliffe efficiency coefficients (NSE) were 0.923 for Required Flow, 0.907 for Static Level, 0.937 for Dynamic Level, 0.879 for Groundwater Potential, and 0.978 for Potentiometric Levels, reflecting a very good fit between the estimates and the observed data. These results confirm the effectiveness of the IDW method in estimating groundwater hydrological variables, demonstrating a robust correlation between estimates and real observations (Krause *et al.*, 2005; Nash; Sutcliffe, 1970).

CONCLUSIONS

The analysis of authorized tubular wells in Cuiabá shows a wide variability in hydraulic characteristics. The average required flow rate is 17.05 m³/day, with a standard deviation of 25.09 m³/day, indicating a wide range of water demands. The average static level is 11.99 meters, with a standard deviation of 7.99 meters, demonstrating significant differences in well depths. The dynamic level, with an average of 48.22 meters and a standard deviation of 33.86 meters, reflects substantial variations in water depth. The groundwater potential has an average of 0.03 m³/h/m and low variation, and the potentiometric levels average 183.08 meters with an amplitude of 104 meters, indicating a considerable dispersion in the levels.

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The spatial distribution of tubular wells in the different administrative regions of Cuiabá reveals a significant concentration of clandestine wells in the Central-East Regional Administration, making up 30.36% of the total. This high proportion suggests a higher vulnerability of this region to uncontrolled exploitation of groundwater resources. The predominance of wells intended for supply and sanitation (81.4%) highlights the importance of these wells for the supply of drinking water and the provision of basic sanitation services, indicating the need for priority management focused on this purpose.

Data on inactive and non-existent wells highlight persistent challenges in regulation and control, particularly in the residential and commercial categories. The discrepancy between the total number of wells and those with permits points to gaps in inspection practices, which may compromise the sustainable management of water resources. The temporal analysis of the records indicates an increase in authorizations until 2015, followed by a sharp decline in 2018, which stresses the need for more strict monitoring and enhanced management policies to ensure the sustainability of groundwater resources.

The results reveal a significant discrepancy between authorized and illegal wells. Only 7.8% of wells are properly regulated, while a staggering 74.3% operate without proper authorization. This highlights the urgent need to enhance the monitoring and regulation of groundwater resources. There are notable variations in the distribution of wells across different administrative regions: the Midwest Regional Administration has the highest number of wells, whereas the North Regional Administration has the fewest. In addition, the Central-East Regional Administration has the largest proportion of unregistered (clandestine) wells and requires targeted strategies to address this issue.

The high number of clandestine wells evidences deficiencies in regulation and inspection, which can lead to groundwater depletion and soil contamination, emphasizing the need for enhancing regulation and inspection of wells. The analysis of their characteristics, including required flow, static level, dynamic level, groundwater potential, and potentiometric quotas, reveals significant variations, reflecting the diversity of geological and drilling conditions. These variations must be considered in water resources management. The application of the Inverse Distance Weighting (IDW) interpolation method indicates that the data dispersion is proportionally associated with the density of wells, except for potentiometric quotas, which present an inverse dispersion. This suggests that the spatial distribution of wells influences hydraulic characteristics and should be taken into account in the analysis of water resources.

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Received on: 2024/10/29
Approved on: 2024/12/12