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GEOSCIENCES - ORIGINAL ARTICLE

Evaluation of the Vulnerability to Contamination of Groundwater in the Central Amazon, Santarém Region

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ABSTRACT

In a context of rapid deforestation and agricultural expansion, the GOD (Groundwater type, Overall lithology of aquifer, and Depth of groundwater) approach can be used to identify areas most susceptible to diffuse contamination of the aquifer. We applied this approach to evaluate the intrinsic vulnerability to pollution of the Alter do Chão Aquifer System, located in the Santarém region (Pará State, Brazil). The parameters G (hydraulic confinement), O (lithology of overlying layers) and D (water table depth) were estimated using data from 41 boreholes from SIAGAS (Sistema de Informações de Águas Subterrâneas) and spatialized with interpolation via kriging. Results reveal predominantly low to moderate vulnerability (79% of the study area), with critical zones near the Tapajós and Amazon rivers (high to extreme vulnerability, 2.2%). The presence of Belterra clay significantly reduces risks in the central plateau. Methodological limitations, associated to data availability, highlight the need for enhanced monitoring networks. This mapping provides a decision-support tool for integrated groundwater management in the Amazon.

KEYWORDS: physical geography; hydrogeology; sustainable groundwater management; confined aquifer; parametric method

Avaliação da vulnerabilidade à contaminação das águas subterrâneas na Amazônia Central, região de Santarém

RESUMO

Em um contexto de rápido desmatamento e expansão agrícola, a abordagem GOD (Ocorrência de água subterrânea ou tipo de aquífero, Litologia geral do aquífero e Profundidade do lençol freático) pode ser utilizada para identificar áreas mais suscetíveis à contaminação difusa do aquífero. Aplicamos essa abordagem para avaliar a vulnerabilidade intrínseca à poluição do Sistema Aquífero Alter do Chão, localizado na região de Santarém (Estado do Pará, Brasil). Os parâmetros G (confinamento hidráulico), O (litologia das camadas sobrejacentes) e D (profundidade do lençol freático) foram estimados utilizando dados de 41 poços do SIAGAS (Sistema de Informações de Águas Subterrâneas) e espacializados por interpolação via krigagem. Os resultados revelam vulnerabilidade predominantemente baixa a moderada (79% da área de estudo), com zonas críticas próximas aos rios Tapajós e Amazonas (vulnerabilidade alta a extrema alta, 2,2%). A presença da argila Belterra reduz significativamente os riscos no planalto central. Limitações metodológicas, associadas à disponibilidade de dados, destacam a necessidade de redes de monitoramento aprimoradas. Este mapeamento fornece uma ferramenta de apoio à tomada de decisões para a gestão integrada das águas subterrâneas na Amazônia.

PALAVRAS-CHAVE: geografia física; hidrogeologia; gestão sustentável das águas subterrâneas; aquífero confinado; método paramétrico

INTRODUCTION

The Amazon River basin holds 16-18% of the world's net freshwater (Latrubesse, 2008). Despite this abundance, these water resources have been threatened by land-use transformation, from natural vegetation to agriculture and mining over the past 50 years (Simon and Garagorry 2005; Nobre and Borma 2009; Müller *et al.* 2016; Souza *et al.* 2020). By 2020, the deforested area in the Amazon Biome had reached 729,781 km², corresponding to 17% of it (INPE 2020). Agricultural expansion causes pollution, particularly by pesticides, whose use is massive and poorly regulated in Brazil, and includes many persistent molecules with deleterious effects on health and the aquatic environment (Mello *et al.* 2020; Morgado *et al.* 2023). This non-point source agricultural pollution contaminates rivers and groundwater.

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Despite the significant health and ecological problems caused by the emission of pollutants in agricultural areas, groundwater pollution in the Amazon remains insufficiently studied. The quantity and quality of groundwater in the Amazon are little known (ANA 2015; Rosário *et al.* 2016). Most of the available knowledge is concentrated in the Alter do Chão Aquifer System (Wahnfried and Soares 2012; Heerspink *et al.* 2020; Azevedo and Campos 2021), particularly in the Manaus and Santarém regions (Tancredi 1996; CPRM 2012; ANA 2015; Silva and Descovi Filho 2023).

Groundwater quality depends on the protective capacity of the pedological and geological environment (the soil-rock complex), and on land use in the aquifer recharge area. Thus, both the occurrence and the spatial distribution of soil and lithology must be considered to predict the polluting potential of a given use, and to design and implement effective management policies.

The concept of vulnerability has been used to express the ease or difficulty with which the physical environment can mitigate potential groundwater contamination by pollutants that infiltrate from the surface (Aller *et al.* 1987). It was coined by the French hydrogeologist Jean Margat (Margat, 1968). Pioneering works to assess groundwater vulnerability were undertaken in the USA by Le Grand (1964) and in France by Albinet (1970).

A significant number of methodologies to map groundwater vulnerability to contamination are available (Aller *et al.* 1987; Bachmat and Collin 1987; Ribeiro 2004). Two key approach types have been proposed to assess groundwater vulnerability and contaminant transfer (Lacroix *et al.* 2006). Both methods provide a fixed range of index values for any parameter considering the impact on groundwater vulnerability. The first type is a quantitative approach based on numerical modelling to replicate pollutant transport in unsaturated and saturated zones by considering the processes that control dispersion, diffusion and attenuation, of which the SWAT model (Arnold *et al.* 1998) or the MikeShe model (Refsgaard *et al.* 1999) are examples. These models are demanding in terms of data, time and expertise. The second type is based on indicators represented by parameters (Aller *et al.* 1987; Foster 1987). An overall assessment resulting from the sum of the parameters is mapped over a given area. The GOD (Foster 1987) and AVI (Stempvoort *et al.* 1993) are unweighted parametric methods. Based on a weighting, different parametric methods use a multiplier value for each parameter to emphasize the importance of a factor to the calculation of the weighted sum. Examples include the DAC, EPIK, DRASTIC and SINTACS methods. The DRASTIC and GOD methods are the most widely used in the world (Sarkar and Pal 2021; Cusano *et al.* 2023).

Based on a few parameters, recognized as determining factors, the GOD method is recommended by UNESCO for the favourable ratio between satisfactory quality of results and perceived ease of use with only three parameters. This paper analyses the suitability of the GOD method to characterize the Alter do Chão Aquifer System in the Santarém region.

MATERIALS AND METHODS

Study area

The research area is located in the state of Pará, central Amazonia (Figure 1), and covers the urban area of Santarém and the region on the right bank of the confluence of the Tapajós and the Amazon rivers. The climate in the region is tropical monsoon, type "Am" according to the Köppen classification. Average annual precipitation measured at the Santarém weather station is 2,150 mm (Climate-Data 2025).

The study area is entirely situated over the Alter do Chão Aquifer System and covers 14,216 km². The Alter do Chão Aquifer System is limited by the Guyana Craton to the north, by the Brazilian Craton to the south, by the Purus Arch (Solimões Basin) to the west, and by the Gurupá Arch (Marajó Basin) to the east, with an extension of 410,000 km² (Souza *et al.* 2013). The aquifer consists of a Cretaceous-Paleogene lithological sequence of fluvial sandy loam, intercalated with clays, conglomerates, and sandstones layers. The Alter do Chão formation is partially covered by more recent layers of duricrust and clay (Figure 2). In a large Amazonian area, Paleogene duricrust cap plateaus are carved by rivers (Rossetti 2004; Laurent *et al.* 2017). In the study area, the duricrust is frequently 5 m thick, and is mainly composed of bauxite, usually found in a nodular or columnar structure. Locally, the "Belterra Clay" covers the duricrust up to 15 m thick (Truckenbrodt *et al.* 1991). The lowlands near the Amazon river are formed by loamy-sand and clay alluvium. These geological characteristics are used to parametrize the GOD method.

The most prevalent soils are Ferralsols. In the study area, soil textures are highly dependent on the nature of the bed rock and the topography (Sombroek 1966): on plateaus covered with Belterra clay, the soil is clayey; on the upper slopes of the valleys, it consists of gravel soils, formed by the dismantling of the duricrust; in the valley lower slopes and bottoms, it is loamy sand.

The Alter do Chão Aquifer System presents a mean thickness of 200 m and an effective porosity of 15-20% (Tancredi 1996; CPRM 2012; CPRM 2023). The hydraulic conductivity tests revealed values ranging from 5.0×10^{-5} to 2.1×10^{-4} m s^{-1} (Tancredi 1996).

A significant portion of the Belterra plateau is used for cultivating grain crops (soybean and maize) and for cattle farming. The west of the plateau and the main part of the Tapajós river border is a protected area, the Floresta Nacional do Tapajós.

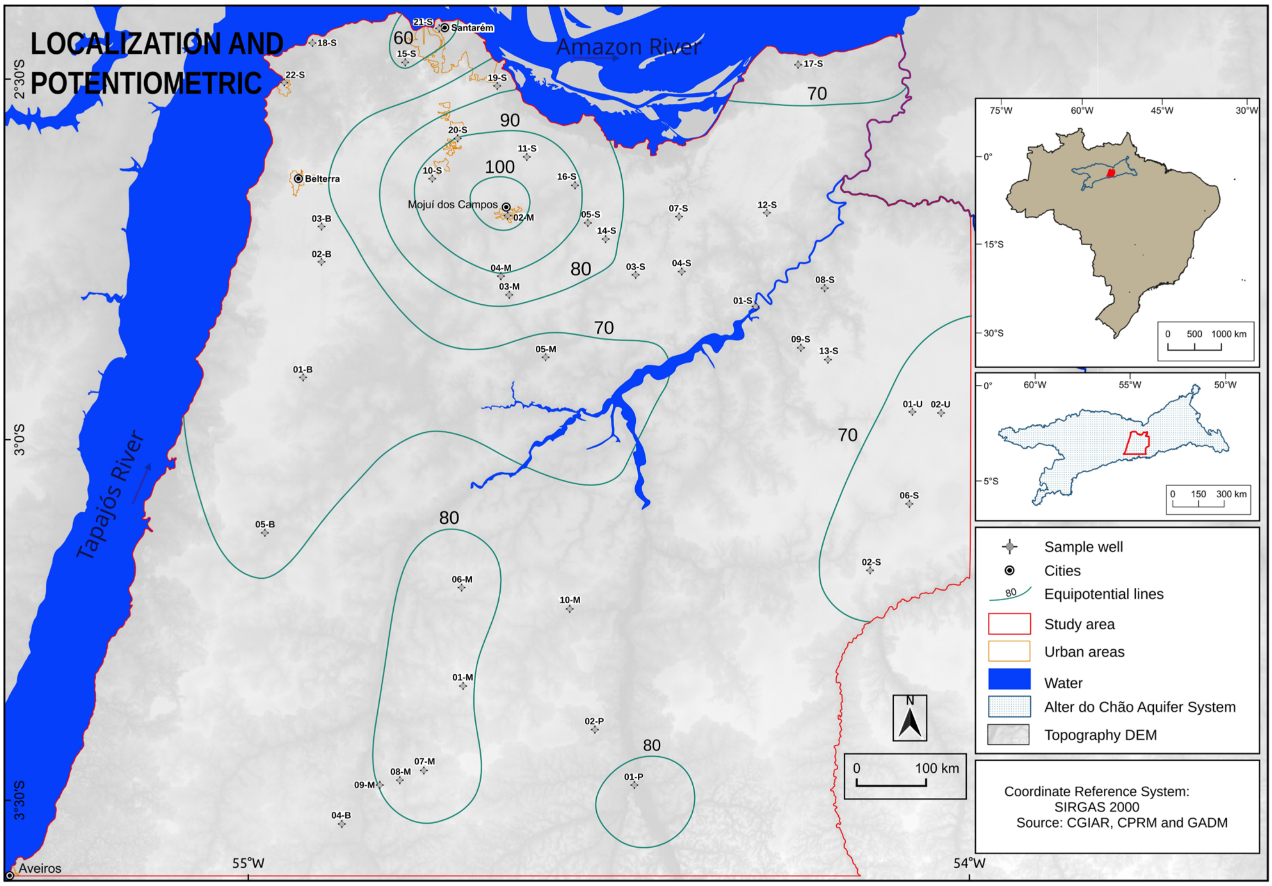

Figure 1. Location map of the study area (Santarém region, central Amazon) with the potentiometric surface of the Alter do Chão Aquifer System.

GOD Method

The GOD method, initially proposed by Foster (1987), was improved by Foster and Hirata (1988), and uses two factors to determine aquifer pollution vulnerability: 1) the level of hydraulic inaccessibility of the saturated zone of the aquifer. It depends on groundwater confinement degree, depth to groundwater table or confined aquifer top and vertical hydraulic conductivity in vadose zone strata; 2) the contaminant attenuation capacity of the strata overlying the saturated aquifer. It depends on the consolidation or fissuring degree of the strata in vadose zone or confining beds and the lithological character of these strata (Foster *et al.* 2002).

The empirical methodology proposed here for the estimation of aquifer pollution vulnerability involved the following stages: 1) identification of the type of groundwater confinement - the G parameter, with ranking of this parameter on a scale of 0 - 1; 2) specification of the strata overlying the aquifer saturated zone - the O parameter, in terms of consolidation degree, presence or absence of fissure permeability, and type of lithology; this leads to a second score on a scale of 0.4 - 1.0; 3) estimation of the depth to groundwater table (of unconfined aquifers) or depth of first major groundwater strike (for confined aquifers) - the D parameter, with a ranking on a scale of 0.6 - 1.0 (Foster *et al.* 2002).

The GOD aquifer vulnerability index results from a multi-criteria sum. It is composed of three criteria: G, O, and D. The effect of each criterion is normalized on a scale of 0 to 1, with each parameter having the same weight in the multiplication. This yields a global vulnerability index representing vulnerabilities ranging from insignificant to very high. This is a qualitative method for interpreting the combination of the three most determining factors of the vulnerability to pollution. The "O" parameter is the most complex. Each well has a pedolithological profile with one or more layers in the unsaturated zone. Scores are assigned to each lithological type according to the logic presented in Figure 3. When two or more layers are present, a weighting is applied to calculate "O" based on their thickness in the unsaturated zone. Layers that attenuate pollutants to varying degrees are analyzed individually, on a case-by-case basis, generating weightings based on the type and thickness of layers in the unsaturated zone, as illustrated in the summary diagram of the GOD method (Figure 3).

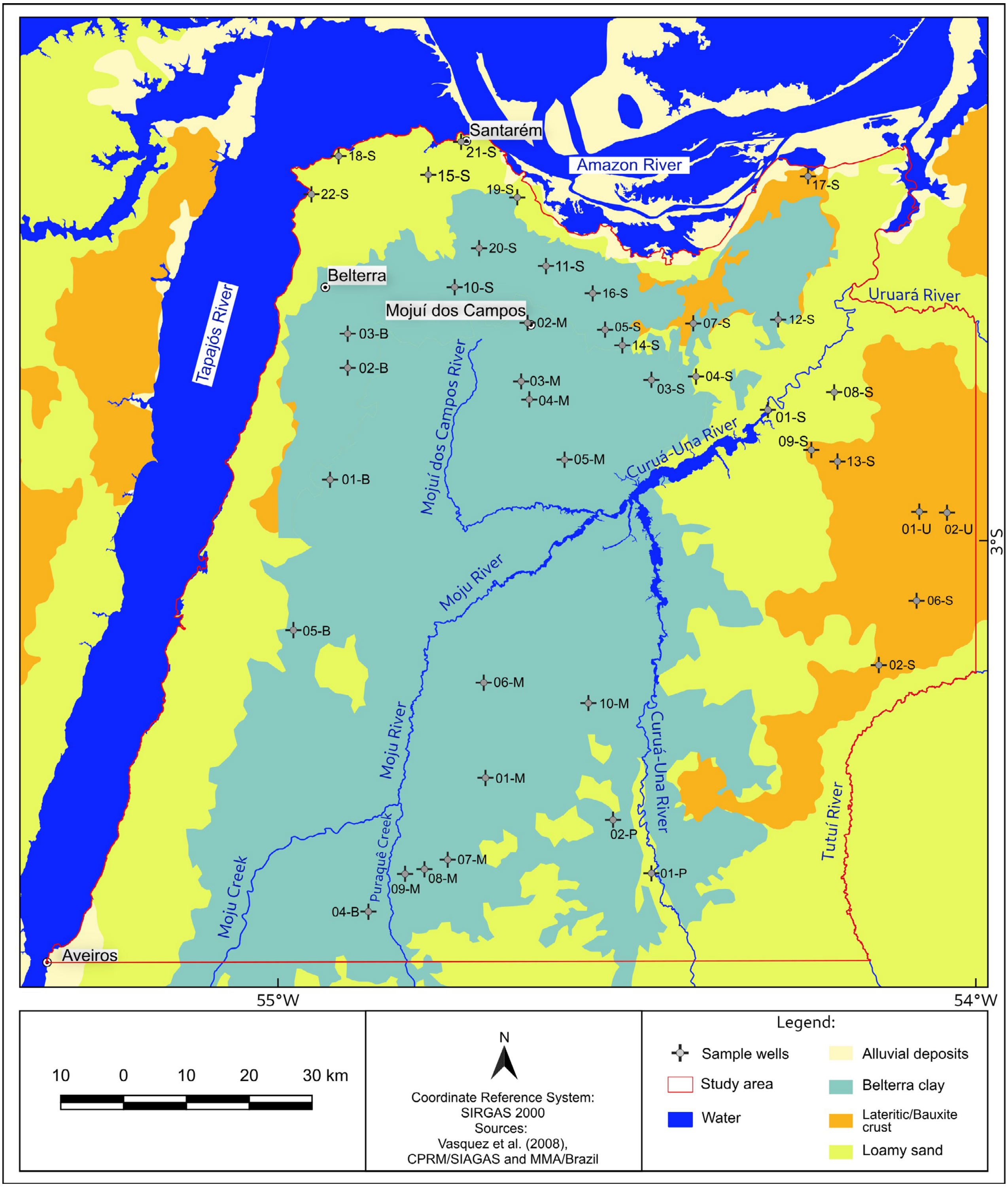

Figure 2. Geology and observation wells. This map shows the geological units and wells found in the Santarém study area. Geological information was obtained from CPRM.

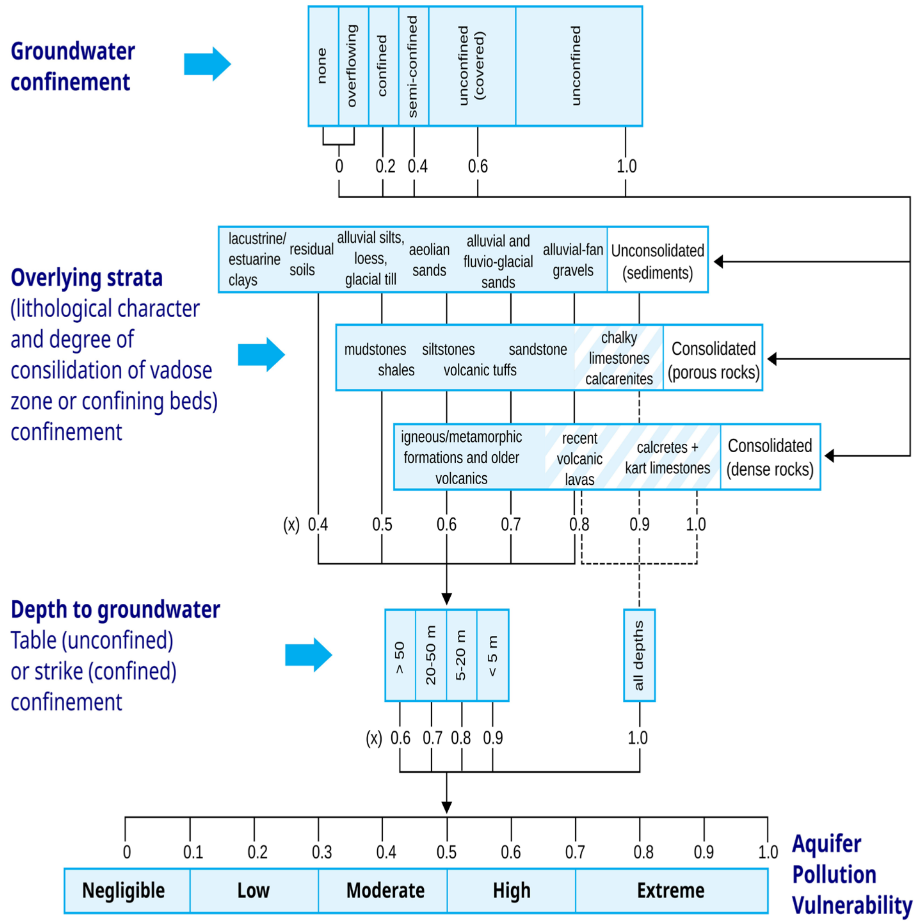

Figure 3. Flowchart illustrating the GOD multicriteria methodology (from Foster *et al.* 2002).

Data

The used data were from a set of sample wells registered in the Groundwater Information System (Sistema de Informações de Águas Subterrâneas - SIAGAS) of the Brazilian Geological Service (CPRM 2023) (Table 1). Wells with water table different from zero that were recognized as upwelling were discarded. Finally, 41 points (Table S1) were chosen due to their reliability in describing the Alter do Chão Aquifer System.

We distinguished the Alter do Chão aquifer system from surface groundwater using data from tube wells (static level and geological profile) which provided representative information of the aquifer system and thus allowed us to keep only the data concerning the Alter do Chão aquifer. Among the available SIAGAS wells, we prioritized a broad and representative spatial distribution of tube wells. For each selected well, the geological profile showing the succession of textures and the measured groundwater depth was used to estimate the GOD parameters. The measurements available in the SIAGAS were acquired on different dates. Thus, seasonal fluctuations can influence the assessment of the piezometric level and thus the depth of water table used in GOD method. These constraints were disregarded in this study.

The Digital Elevation Model SRTM with a spatial resolution of 30 meters (NASA, 2023) was processed to obtain information on terrain altitude. Pre-existing vector data on geology, hydrography and administrative limits were also used (GADM 2023) (Table 1).

Application of the GOD method depends on the interpretation and scoring of each of its parameters. G (degree of hydraulic confinement of the aquifer) and O (type of pedological and lithological cover of the aquifer) were derived (interpreted) directly from each the 41 tube wells, from the observed lithology texture class series; D (Depth to the groundwater table) results from the depth directly measured in the tube well.

The values of the G parameter representing the degree of hydraulic confinement were interpreted based on the lithological profile and the existence and thickness of the impermeable layers, or layers with very low hydraulic conductivity, above the aquifer. When a clay layer two meters or more thick is present in the profile, we interpret that the

Table 1. Databases used for this study and available on the Internet.

Database	Organization	Information	Format	Source
Wells (*Sistema de Informações de Águas Subterrâneas*)	SIAGAS/CPRM	Pumping well	Vector	CPRM 2023
Administrative limits (municipalities)	GADM	Boundaries	Vector	GADM 2023
Digital Elevation Model (Earth Explorer)	EarthExplorer/USGS	SRTM-DEM	Raster	NASA 2023
Geological units (Serviço Geológico Brasileiro)	GeoSGB/CPRM	Lithology Hydrography	Vector	Vasquez *et al.* 2008
Consultative Group on International Agricultural Research - Consortium for Spatial Information	CGIAR-CSI	SRTM-DEM	Raster	Jervis *et al.* 2008

aquifer at the well is "confined". When a clayey-sandy or clayey-silty layer is several meters thick (from 2 meters), we interpret that the aquifer at the well is "semi-confined". When the entire profile was formed of layers of sand, silty sand or clayey sand, and covered by a clayey soil, we interpret that the aquifer at the well is "unconfined (covered)". And when the entire profile was formed of layers of sand, silty sand or clayey sand with a soil of the same nature on top, we interpret that the aquifer at the well is "unconfined".

The values of the O parameter were interpreted from the lithological profile. We preferentially considered the layer with the lower hydraulic conductivity; thus when clay is present over several meters in the lithological profile, the value of O is considered low. The point coverage of G and O was transformed into raster data by ordinary kriging using no nugget, with predefined linear functions.

The potentiometric surface of the aquifer was mapped by kriging (predefined function spherical, cellsize 30 meters) the altitude of the static level observed in the wells and the altitude of the main rivers draining the water table (Amazon, Tapajós, Moju, Curuá-Una, Tutuí, Mojuí dos Campos and Uruará) from the SRTM raster to obtain the raster coverage of the static level. The D parameter raster area coverage was obtained by subtracting the potentiometric surface from the SRTM. Subsequently, each parameter was reclassified according to the correspondence values shown in Figure 4.

Afterwards, the three parameters of the GOD method were mapped using the System for Automated Geoscientific Analyses (SAGA) (Conrad *et al.* 2015) utilizing the ordinary kriging interpolation method. The kriging method is efficient for spatializing hydrogeological data (Kumar and Remadevi 2006). A spatial resolution of 30 meters was used for the raster products considering the resolution of the DEM.

Finally, the GOD vulnerability index was generated by the product G x O x D within QGIS (QGIS, 2025), using Map algebra function. The resulting map was reclassified into the vulnerability intervals proposed by Foster (1987): 0.0 to 0.1 - Negligible; 0.1 to 0.3 - Low; 0.3 to 0.5 - Moderate; 0.5 to 0.7 - High; > 0.7 Extreme.

RESULTS

G - Groundwater hydraulic confinement

Of the 41 surveyed tube wells, 11 were located in an unconfined aquifer, 18 in a confined aquifer, eight were in a semi-confined aquifer, and four in an unconfined covered aquifer (covered by clayey soil). The degree of confinement map produced in this study (Figure 5a) shows a free aquifer along the Tapajós and Amazonas rivers, marking the western and northern boundaries of the study area, with vulnerability index exceeding 0.9. Areas of semi-confined to confined aquifers, with a G parameter less than 0.6, can be seen in the central and eastern parts of the study area.

O - Overlying strata

The spatialization indicates more protective soils and rocks of the vadose zone in the center of Santarém plateau (Figure 5b). In this plateau, the top layer of Belterra clay confers greater protection thanks to the lower hydraulic conductivity of this material, despite the moderate to high macroporosity of the kaolinitic soils (Truckenbrodt *et al.* 1991). In the South-Western part and South-Eastern part, as the Belterra clay is absent or thin, the O parameter is higher.

D - Depth to groundwater table

The region with the deepest groundwater table (up to 142 m), corresponding to a D value equal to 0.6, is the extreme eastern part of the study area (Figure 5c). The areas with the shallowest depth coincide with Tapajós and Amazonas rivers and with Curuá-Una river valley, in the west, north and central areas, respectively, where the aquifer is closest to the surface, directly connecting to the streams and rivers. To better understand the relation between topography and depth to the groundwater table, Figure 5d shows a schematic profile crossing the border of the plateau, until reaching the Amazon River plain, where the level is closer to the surface.

GOD estimates

The variance error analysis on the GOD values by observation well classified by confinement category shows that unconfined wells exhibit the highest mean GOD vulnerability index

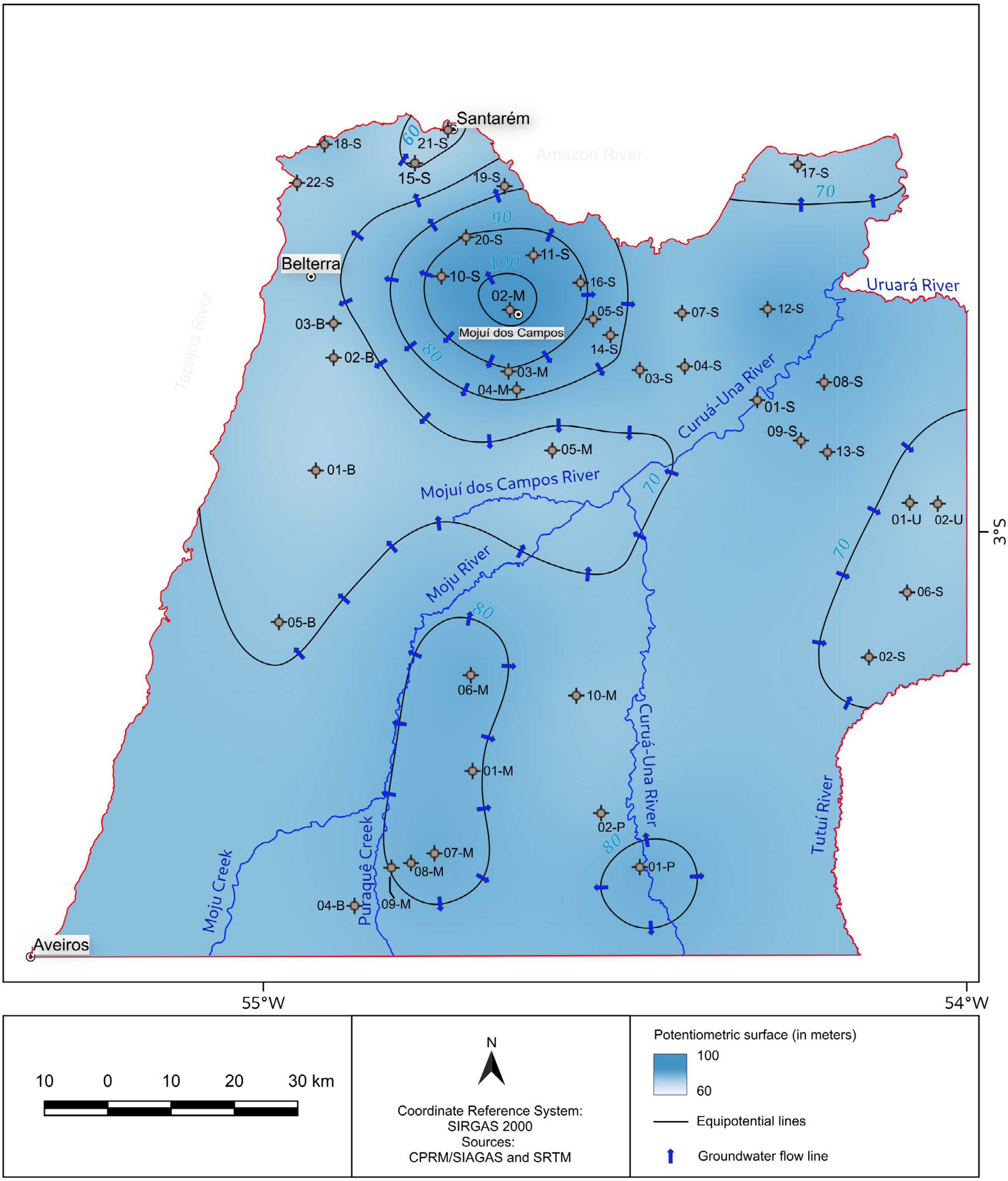

Figure 4. Potentiometric surface and equipotential lines in study area. This map shows the potentiometric surface in raster format and vector lines with the preferred direction of groundwater flows in the Santarém study region. The data were obtained from CPRM and geoprocessed using SAGA and QGIS.

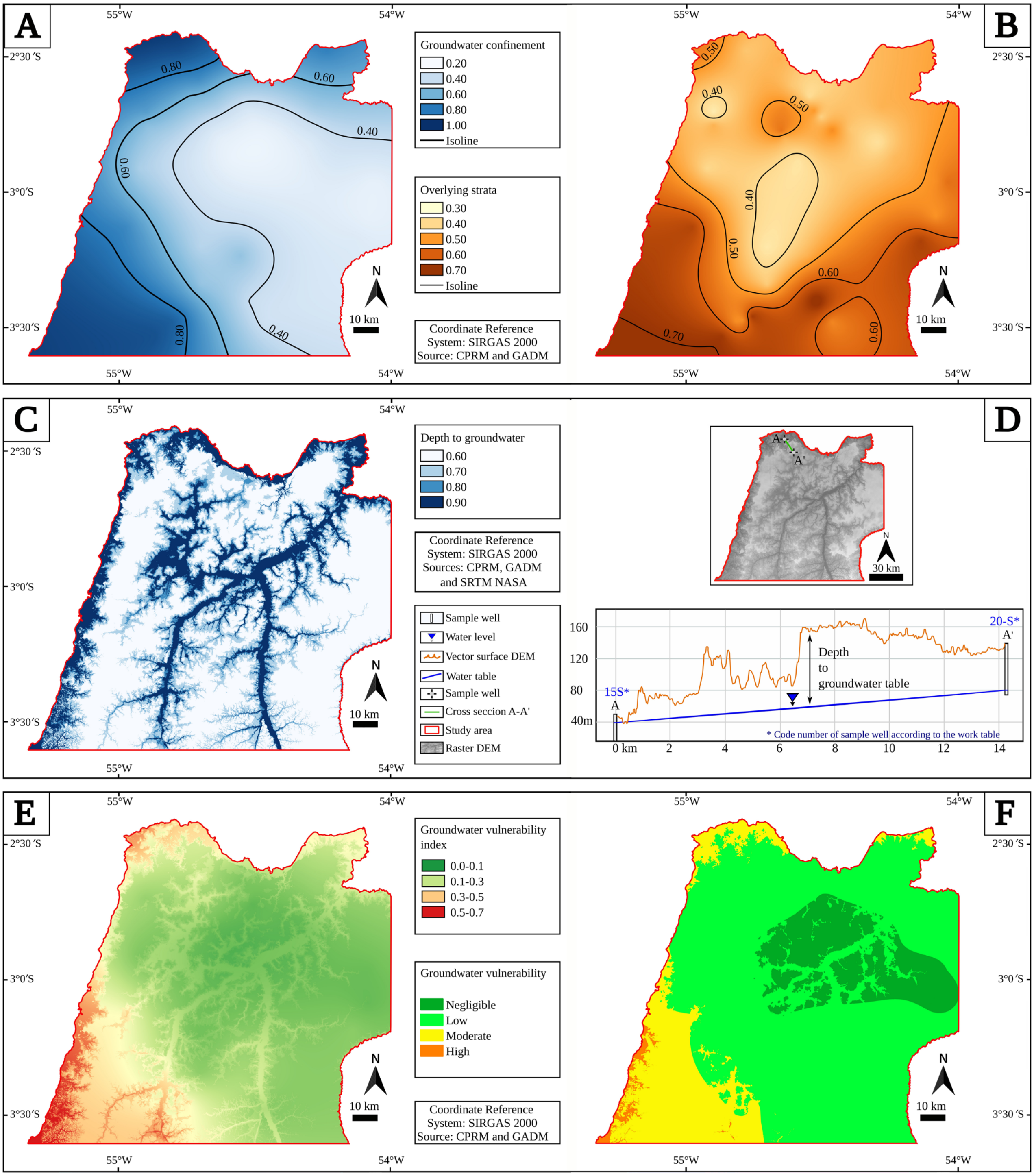

Figure 5. Results of the application of the GOD method to the Alter do Chão Aquifer System in the Santarém region. A - Groundwater hydraulic confinement, estimated as the G parameter. B - Overlying strata, estimated as the O parameter. C - Depth to the groundwater table, estimated as the D parameter. D - Relief and groundwater table based in SRTM/NASA and CPRM. E - Vulnerability according to the GOD method. F - Groundwater pollution vulnerability classes GOD method (Foster 1987) that occur in the study area: 0.0 to 0.1 - Negligible; 0.1 to 0.3 - Low; 0.3 to 0.5 – Moderate and 0.5 to 0.7 - High.

(0.397) and variance (0.0069), which indicates a greater susceptibility to contamination and variability. Confined wells show the lowest mean (0.076) and moderate variance (0.0036), thus reflecting better protection and consistency. Semi-confined and unconfined (covered) categories display intermediate values, with semi-confined having a lower variance (0.0026) compared to unconfined (covered) (0.0036). The Unconfined (covered) category had only four data points, which may skew results.

The GOD maps highlight the marked variability of vulnerability to pollution of the Alter do Chão Aquifer System in our study area, with magnification of – or compensation for – lithological and topographical features (Figures 5 e,f). The areas near the northern and southern banks of the Tapajós river are the most vulnerable. The vulnerability of the southwestern part of the Santarém plateau is moderate, while the central and eastern parts of this plateau are naturally well protected.

The predominance of areas with negligible vulnerability (11%) or low vulnerability (68%) in the study area is caused by the geological and topographical characteristics of a large part of the Santarém plateau, with a deep water table (low D parameter). In this portion of the plateau, the water table is covered in the vadose zone by a series of layers with a predominantly loamy sand composition. Some of them are clayey or clayey-sandy with low or medium hydraulic conductivity, where the plateau is covered with several meters Belterra clay (low O parameter). Also, the water table is frequently confined or semi-confined (low G parameter).

The medium and moderate vulnerability class, which accounts for about 17% of the area, occurs where the water table is not very deep (medium D parameter), the aquifer is semi-confined or not confined (medium to high G parameter) and/or has a thinner or no Belterra clay coverage (medium to high O parameter). The few highly vulnerable portions cover 2.15% of the study area. They appear in valley bottoms, near rivers, where the aquifer is unconfined (high G parameter), is not covered by clay (high O parameter) and the water table is shallow or outcropping (high D parameter).

DISCUSSION

We found a wide variation in the vulnerability of groundwater contamination in the Santarem region. Previous studies demonstrate a certain convergence with the vulnerability assessment carried out in the present study. Mapping results (Silva and Descovi Filho 2023), in a smaller area in the municipality of Santarém (which includes about 20% of the northern part of the area used for this study) are in accordance with the mapping of this study. Their study used a much denser sampling network (393 pumping wells, including 280 located in urban zones) but still the results are mostly in accordance with those found here, attesting to the capacity of the GOD method to provide reliable vulnerability assessments.

However, some limitations of the method should be mentioned. In the SIAGAS database, the potentiometric surface measurements were not conducted during the same season or year. Inaccuracies in the potentiometric map, and subsequently in the D map, may arise from this fact. This is inherent to the use of a public database composed of heterogeneous measurements. However, we presume that the temporal variations of the potentiometric level are still suitable for GOD mapping. First of all, since the Alter do Chão Aquifer System is a deep and large aquifer, seasonal variations in the potentiometric surface are assumed to be low. Second, the GOD method consists of classifying the data into categories; and its sensitivity to seasonal variations is assumed to be low compared to other uncertainties introduced by the classification process. The number of observation wells is insufficient over part of the study area, which makes the estimation of the parameters very uncertain in the south-western and south-eastern parts of the area. As we have previously pointed out, there is a low density of hydrogeological data in the Amazon. The resulting method maps should therefore be considered with caution. However, they present a hierarchy of vulnerability.

The hydrogeological database of wells must be updated, using field measurements, and be expanded to improve representativeness. The human population is quite unevenly distributed in this region, being mostly located in the vicinity of the Amazon and Tapajós rivers, this explains the higher density of wells in these areas. This contrasts with the extensive unpopulated forest and/or sparsely populated agricultural areas, which has few pumping wells with hydrogeological information. This situation limits the assessment of spatial variability vulnerability, whatever the kriging or interpolation method used. Also, field measurements are needed to check the consistency of the information concerning the location, status, lithology series and depth of the water table drilled for wells. Field measurements of potentiometric surface must be carried out during the same season to produce a more robust D-map.

A sensitive stage of the GOD method is the spatialization of point values by kriging. The quality of kriging depends on the method type, density and spatial distribution of measurement points, as well as on the complexity of the systems concerned. The Alter do Chão Aquifer System has been affected by post sedimentary tectonics with faults that separated large blocks (Vasquez *et al.* 2008). The absence or scarcity of data on this tectonic phenomenon may be a source of error in the vulnerability spatialization. Improving the mapping of the "O" (Overlying strata) in the GOD method by inserting geomorphostructures and regional tectonic compartmentalization could be the next step to match the simulations to the geological context.

Other potential issues include the lack of representation of shallow groundwater exploitation. In the study region it is locally exploited, but in the results, the vulnerability of the shallow aquifers is not represented for homogeneity reasons. Only the vulnerability of the Alter do Chão regional Aquifer System was modeled. Further studies are also recommended for a better understanding of the intercommunication between rivers (the Tapajós, Amazon and smaller rivers such as Curuá-Una), quaternary alluvial aquifers and the Alter do Chão Aquifer System.

To assess the aquifer risk to pollution, besides the intrinsic vulnerability, it is necessary to account for activities that involve a risk of contamination. To evaluate this risk, the vulnerability map could be overlaid on a map of pollution pressure associated with land use. The north-western banks of the river are major urbanized zones, in particular the Santarém urban area (population: 357,311; IBGE 2024) and the district of Alter do Chão (6,740 inhabitants). Urban areas have uncontrolled wastewater discharges, receiving both domestic and industrial contaminants. The Santarém plateau, to the south and south-east of the city, is intensively used for cattle breeding, soybean and corn crops. The use of pesticides can contaminate the aquifer, particularly in the valleys in the center of the plateau, which are particularly vulnerable since the depth of the aquifer is shallow, thus connecting groundwater with surface water. The resulting pollution vulnerability map could be used to protect water quality by conserving or restoring forests in the most vulnerable areas. Morgado *et al.* (2023) highlighted pesticide contamination of rivers and shallow groundwater in part of the study area. These pollutants could potentially infiltrate the Alter do Chão aquifer system.

A few other applications of the GOD method in the Amazon show medium to high vulnerability of the aquifers studied. Medium to high vulnerability was reported for the urban area of Belém, also using the SIAGAS database to analyse the vulnerability of shallow groundwater (Lisboa *et al.* 2020). The vulnerability of Rio Branco aquifer, Western Amazon, was assessed with the GOD method as high (Franco and Arcos 2023).

Low to medium vulnerability was found with the GOD method in three hydrogeological units of Abaetetuba, Eastern Amazon, highlighting the contradiction with observed contamination by coliforms in the majority of the wells (Leite *et al.* 2019). Despite its accuracy limitations, GOD remains one of the best spatial multi-criteria overlay methods, being suitable for data-limited regions that require rapid groundwater vulnerability assessment (Goyal *et al.* 2021).

This study represents the first comprehensive application of the GOD method to assess groundwater vulnerability in the Alter do Chão Aquifer System, a critical freshwater resource in the Brazilian Amazon. Our findings demonstrate that approximately 79% of the study area exhibits low to negligible vulnerability, primarily due to the protective combination of deep water tables (>100 m), semi-confined to confined aquifer conditions, and the presence of low-permeability Belterra clay layers. However, the identification of highly vulnerable zones (2.2% of the area) along river valleys and flood areas is increasingly being targeted for agricultural expansion.

The methodological approach proved particularly suitable for data-scarce Amazon environments, although three key limitations that should guide future research were identified: (1) temporal variations in groundwater levels were not captured due to variable monitoring periods. Although the RIMAS system allows this analysis, it would be very localized and could not be generalized to the entire area of study, (2) the spatial distribution of monitoring wells was insufficient to fully characterize hydrogeological heterogeneity, and (3) the assessment did not consider aquifer discontinuities, existence of hydrogeological compartments and other potential contaminant pathways related to tectonic discontinuities.

These results have immediate practical implications for land-use planning in the Santarém region. Three priority actions are recommended: (1) establishment of protection zones in high-vulnerability riparian areas, (2) integration of vulnerability mapping with pesticide use monitoring programs, and (3) expansion of the groundwater monitoring network with seasonal piezometric measurements. Future research should focus on more detailed characterization of the vadose zone hydrodynamics.

CONCLUSIONS

This study establishes a baseline for sustainable groundwater management in the Amazon that balances agricultural development with ecosystem protection. The methodology could be extended to other tropical aquifer systems facing similar pressures from land-use change, due to agricultural expansion. These areas require special attention.

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SUPPLEMENTARY MATERIAL

Descovi Filho & Laurent. Vulnerability to contamination of groundwater in the Santarém region

Table S1. Description of sample wells used in the analysis.

Sample well number	SIAGAS well number 150000+	Sample well code	Municipality	Outcropping Layer	Groundwater confinement	Well depth (m)	*Water table (m)	GOD vulnerability index
1	3331	01-B	Belterra	Loamy sand	Confined	40	40.00	0.06
2	3332	02-B	Belterra	Loamy sand	Confined	126	30.00	0.06
3	3337	03-B	Belterra	Belterra clay	Unconfined	100	36.00	0.25
4	3403	01-S	Santarém	Belterra clay	Confined	90	2.00	0.07
5	3677	02-S	Santarém	Belterra clay	Semi-confined	246	120.00	0.16
6	3692	01-M	Mojuí dos Campos	Belterra clay	Confined	156	56.00	0.05
7	3693		Mojuí dos Campos	Duricrust	Unconfined (Covered)	41	16.10	0.25
8	3696	03-S	Santarém	Belterra clay	Confined	60	20.00	0.08
9	3700	03-M	Mojuí dos Campos	Belterra clay	Confined	40	16.00	0.07
10	3699	04-M	Mojuí dos Campos	Belterra clay	Confined	120	42.00	0.07
11	3713	04-S	Santarém	Belterra clay	Confined	69	36.00	0.06
12	3719	05-M	Mojuí dos Campos	Belterra clay	Confined	144	14.00	0.06
13	3721	01-P	Placas	Belterra clay	Confined	156	7.00	0.08
14	3731	05-S	Santarém	Belterra clay	Confined	140	66.00	0.06
15	3993	01-U	Uruará	Belterra clay	Confined	140	46.00	0.07
16	3996	02-U	Uruará	Belterra clay	Confined	248	142.00	0.07
17	5152	06-M	Mojuí dos Campos	Belterra clay	Confined	204	64.92	0.04
18	5153	02-P	Placas	Loamy sand	Confined	120	21.37	0.10
19	5174	06-S	Santarém	Belterra clay	Confined	246	84.00	0.06
20	5199	07-S	Santarém	Loamy sand	Semi-confined	222	91.33	0.11
21	5219	08-S	Santarém	Belterra clay	Semi-confined	110	32.00	0.13
22	5220	09-S	Santarém	Belterra clay	Semi-confined	80	17.00	0.14
23	5873	10-S	Santarém	Duricrust	Semi-confined	103	61.82	0.11
24	6207	11-S	Santarém	Belterra clay	Semi-confined	90	64.92	0.10
25	7435	12-S	Santarém	Belterra clay	Unconfined (Covered)	130	30.00	0.19
26	7467	13-S	Santarém	Belterra clay	Semi-confined	170	66.00	0.11
27	7660	04-B	Belterra	Belterra clay	Unconfined	40	20.00	0.55
28	7661	07-M	Mojuí dos Campos	Belterra clay	Unconfined	156	78.00	0.41
29	7662	08-M	Mojuí dos Campos	Duricrust	Unconfined	35	20.00	0.42
30	7663	09-M	Mojuí dos Campos	Belterra clay	Unconfined	52	20.00	0.42
31	7664	05-B	Belterra	Duricrust	Unconfined	45	30.00	0.46
32	7677	14-S	Santarém	Belterra clay	Confined	170	84.00	0.05
33	7678	15-S	Santarém	Belterra clay	Confined	132	17.40	0.35
34	7679	16-S	Santarém	Duricrust	Semi-confined	125	30.00	0.11
35	7685	17-S	Santarém	Duricrust	Unconfined (Covered)	130	43.00	0.11
36	7690	18-S	Santarém	Loamy sand	Unconfined (Covered)	106	43.00	0.19
37	7834	19-S	Santarém	Duricrust	Unconfined	38	7.30	0.37
38	7942	20-S	Santarém	Loamy sand	Unconfined	64	12.00	0.37
39	7945	10-M	Mojuí dos Campos	Loamy sand	Unconfined	158	22.00	0.32
40	8002	21-S	Santarém	Loamy sand	Unconfined	36	1.80	0.40
41	8196	22-S	Santarém	Loamy sand	Unconfined	24	12.00	0.42

*Water table: Wells registered in SIAGAS have a water table record. The system's purpose is to register the well; therefore, this value does not represent an average or maximum depth, but rather a unique record, usually obtained during pumping tests for well licensing.