



Thirty years of geothic conflicts between natural groundwater vulnerability and land use in a southeastern Brazilian municipality

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Received: 13 August 2022 / Accepted: 4 January 2023 / Published online: 18 January 2023
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Abstract

Geothics is the research and reflection about values, behaviors, and best practices to adopt in areas where human activities interact with the earth system. Considering that groundwater is one of the most vital natural resources for human survival and that the enormous increase in human pressures on ecosystems poses an imminent threat to its quality, it may be stated that there is a geoethical issue on a worldwide scale. In this context, the present study aimed to analyse the geoethical conflicts between the increase in human activities and the natural vulnerability of aquifers over the past 3 decades in a Brazilian municipality located in the Guarani Aquifer System, one of the world's largest freshwater reservoirs. For this purpose, we utilized geoenvironmental mapping techniques, treated and handled hydrogeological data (geology, soils, depth) from the GODS vulnerability model, and cross-referenced this information with 30 years of local land use data. The results indicated a considerable rise in geoethical conflicts in the region, with high-conflict zones increasing by 800% between 1989 and 2019, primarily as a result of the expansion of sugarcane monocultures and forests over natural environments. This evolution demonstrates that the process of changing land use has occurred without taking into account the potential and limitations of the local environment, endangering the quality and accessibility of drinking water.

Keywords Geoethic conflicts · Groundwater · GIS · Environmental planning · Geoenvironmental cartography

Introduction

Globally, groundwater is crucial for the dynamics of life on earth, whether it is used to support aquatic life or to provide a variety of ecosystem services, or the advantages that people derive from natural ecosystems (De Groot et al. 2002; Grizzetti et al. 2016; Bertolo et al. 2019). Given the significance of aquifers to Brazil's regional hydrological cycle,

society and the environment place an even larger value on this resource, as the yearly discharge of aquifers maintains 24% of the flow of the main watersheds (Hirata and Suhogusoff 2019).

The Guarani Aquifer System (GAS) is one of the world's greatest freshwater reservoirs, with an extension covering 1,088,000 km² of South America's southeast, including Brazil, Argentina, Paraguay, and Uruguay (Sindico et al. 2018; Santarosa et al. 2021). The structure of the GAS is made up of a series of Triassic–Jurassic sandstone layers that were deposited on an erosional surface and covered with a layer of Cretaceous basalts, presenting as a relevant hydrological characteristic in Brazil, the geological units Botucatu, Pirambóia, Caturrita and Santamaria that are hydraulically connected (Sindico et al. 2018).

Several studies show that the aquifer has been degrading due to overexploitation and contamination by anthropogenic agents in its most vulnerable areas, primarily due to impacting land uses, such as contamination of septic tanks and agricultural pesticides, despite the natural protection

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provided by the overlying basalt layer (Manzano and Guimaraens 2012; Sindico et al. 2018; Ferrari et al. 2019).

Geoscience researchers must comprehend, analyze, and diagnose geoethical conflicts that jeopardize the ecosystem services offered by aquifers to contribute to more effective territorial planning in the quest for the sustainable development of territories. According to Guerrero et al. (2020b), the concurrent spatial relationship between naturally vulnerable areas and potentially impacting land use is given conflict status. In the case of the relationship between anthropogenic elements and the earth system, this conflict can be inserted in the context of geoethics.

Geoethics can be defined by the study and promotion of the evaluation and protection of the geosphere, focusing on the ethical debate on some of the main current environmental emergencies and on the main social, environmental, cultural and economic consequences of activities related to geosciences (Peppoloni and Di Capua 2022; Manzione and Siva 2022). The rise of geoethics as an essential branch that deals with the ethical implications of Earth sciences brings even greater importance to the work and studies of geoscientists as it reinforces the repercussions that their choices can have on society (Di Capua et al. 2021; Peppoloni and Di Capua 2022).

In Brazil, geoethics has gained increasing attention in recent years as the country faces a range of environmental and social challenges related to resource extraction, land use, and climate change. Some of the key issues that have been the focus of geoethics in Brazil includes:

- Deforestation and land use: Brazil is home to a significant portion of the Amazon rainforest, which is facing increasing pressure from logging, mining, and agriculture (Mataveli et al. 2022). The destruction of the forest has significant impacts on the environment and local communities, and raises ethical questions about the balance between economic development and the conservation of natural resources.
- Water resources: Brazil has a number of major rivers and a large network of dams and reservoirs, which provide important sources of water for irrigation, hydroelectric power, and other uses. However, the management of these resources is often controversial, with competing interests and conflicting priorities (Guerrero et al. 2020a, b, c). Geoethics can help to identify and address the ethical dimensions of these issues.
- Climate change: Brazil is one of the world's largest emitters of greenhouse gases, and is vulnerable to the impacts of climate change, including rising sea levels, more frequent and intense storms, and changes in precipitation patterns. Geoethics can help to identify and address the ethical implications of climate change for Brazil and the wider region.

Overall, the practice of geoethics in Brazil is still in its early stages, and there is a need for more research, education, and dialogue on these and other issues (Imbernon et al. 2021). However, the growing awareness of the ethical dimensions of the Earth sciences is an important step towards more sustainable and responsible development in the country.

Due to its vast territory, Brazil offers particularly difficult institutional challenges when attempting to execute integrated planning initiatives on its territory, highlighting the importance of taking local-scale initiatives. Given that they have clearly defined scales of activity, Brazilian municipalities are important agents in the adoption of integrated territorial planning strategies. Additionally, Articles 1 and 18 of the Brazilian Federal Constitution (Brasil 1988), which encourage municipalities' autonomy for the protection of the environment and its natural resources, provide support for Brazilian municipalities' capacity to actively participate in the environmental planning process.

In this context, this study set out to find and examine 30 years' worth of geoethical conflicts—reflections about the negative results of the interaction of anthropic activities with the geosphere (Peppoloni and Capua 2015)—between the groundwater's intrinsic vulnerability and the land use change in the Brotas municipality, SP, Brazil. Groundwater research is particularly interesting in Brotas, since 85 percent of its territory are included on the Guarani aquifer (CETESB 2018), given a special interest regarding the protection of this huge aquifer. Since these areas control how much water enters the system and are more prone to contamination, these locations are highly important to ecological and geoenvironmental planning.

Still regarding the concerns related to groundwater, it is noted that the history of territorial occupation of Brotas occurred without land use planning processes in accordance with the regional strengths and weaknesses, which motivated a great expansion of agricultural activities (mainly sugarcane-de-sugar, pastures, orange, coffee and forestry), activities that until today consist of the main source of municipal income (Guerrero et al. 2020c; Martins and Madureira 2019; Manzione and Silva 2022).

This history of occupation focused on the intense exploitation of agricultural commodities represented (and still represents) geoethical conflicts between a territory with unique characteristics in the region (ecotourism potential in a context of environmental weaknesses) and a disorderly occupation that did not favor the conservation of natural resources, such as aquifers.

However, in recent years, the municipality has tended to value privileged local environmental characteristics to introduce ecotourism as an important profit-making strategy allied with nature conservation. Thus, several projects have been implemented to redefine landscapes that were once

degraded or used exclusively for agriculture and livestock in favor of landscape enhancement to attract tourists. Even with these more sustainable bias incentives, studies such as those by Barrocas (2005), Ribeiro and Amaral (2016) and Guerrero et al. (2018, 2020a, b, c) demonstrate that the degradation of the territory/ecosystem services caused by poor management still occurs on worrying scales, reinforcing the need for studies in geosciences that indicate the potentialities and local restrictions to contribute with the idea that only a sustainable planning based on technical and scientific studies that spatially assess the potentialities and geoenvironmental restrictions of the constituent elements of the landscape can reconcile the geoethical conflicts of this and other areas that present similar characteristics or problems.

Based on information from the Map Biomas project (MapBiomas 2019), an GIS approach was used to map the natural vulnerability to contamination using the GODS method (Foster and Hirata 1988; Foster et al. 2002) in the multitemporal mapping of land use on four dates—1989, 1999, 2019, and 2019. Four conflict maps encompassing 30 years of the investigation were produced by the spatial integration of natural vulnerability and land usage.

The following inquiries served as the study's guiding principles: in the past 30 years, how has the municipality of Brotas' occupation pattern changed? What traits and locations do the regional geoenvironmental context identify higher levels of natural vulnerability to pollutants entering the system? What causes and where are the greatest geoethical tensions between human occupation and natural vulnerability? Therefore, it is anticipated that the responses to these inquiries will aid future territorial planning efforts in the municipality of Brotas and all other municipalities located near the Guarani Aquifer.

Materials and method

Study area

Brotas is a municipality in southeastern Brazil located in the central region of the state of São Paulo (Fig. 1), 150 km away from the city of São Paulo, the most populous in Brazil. Despite being close to this important urban center, the municipality of Brotas has a rural population matrix with 24,636 residents in 1101.373 km² (IBGE 2018).

Regarding groundwater, the geological and hydrogeological environment of Brotas makes it unique. Data from CETESB (2018) show that the Guarani aquifer, the greatest source of cross-border freshwater in the world, overlaps with the municipality in its entirety, and approx. 85% are outcrop zones (Hirata and Foster 2020). Additionally, the aquifer recharge zones are represented by the subsurface of the sandstone formations Botucatu and Pirambóia (Fig. 1). These

areas are crucial for storing, recharging, and supporting all aquifer groundwater uses and are particularly sensitive.

Brotas municipality's anthropic occupation is historically linked with agricultural production—primarily coffee monoculture—which peaked around 1920–1930. (Brotas 2018). Beginning in the 1980s, the Brazilian government provided fiscal and financial incentives (such as PROALCOOL), and the strong increase in demand from the international market drove local economic activity toward the production of sugarcane (Rodrigues and Ross 2020). According to the IBGE (2018), Brotas' economy still depends on agriculture, with a sizable portion of its land used to cultivate sugarcane, oranges, coffee, and forestry.

As a country's epicenter for ecotourism in recent years, Brotas has distinguished itself thanks to its breathtaking scenery, as presented in Fig. 1.2, including waterfalls, look-out sites, and navigable rivers. From a sustainable perspective, only with a certain level of environmental protection, which affects all local ecosystems, can this sustainable enterprise flourish (Guerrero et al. 2020b).

Data used

Two types of spatial data were needed for the cartographic study of the conflicts between land use and natural groundwater vulnerability: multitemporal land use data and hydrogeological data. The data used, its sources of acquisition, and its original format are shown in Table 1.

Method

Three primary steps make up the conflict analysis methodology suggested in this article (Fig. 2): (i) groundwater vulnerability is mapped using the GODS approach (Foster and Hirata 1988; Foster et al. 2002); (ii) territorial occupation patterns for 30 years are obtained from Mapbiomas project (MapBiomas 2019); (iii) analysis of land use data and conflicts between natural groundwater vulnerability and land use are mapped.

Natural groundwater vulnerability map

The aquifer's natural vulnerability was analyzed using the GODS method (Foster et al. 2002), a conceptual adaptation—with the insertion of the parameter soils—of the GOD method (Foster and Hirata 1988).

This approach takes into account the following parameters as analysis factors: (1) The level of hydraulic inaccessibility of the saturated zone of the aquifer, (2) The attenuation capacity of the cover strata of the saturated portion of the aquifer using the level of hydraulic confinement of the groundwater as parameters, (3) The covering characteristic in terms of hydrogeological characteristics, (4) The

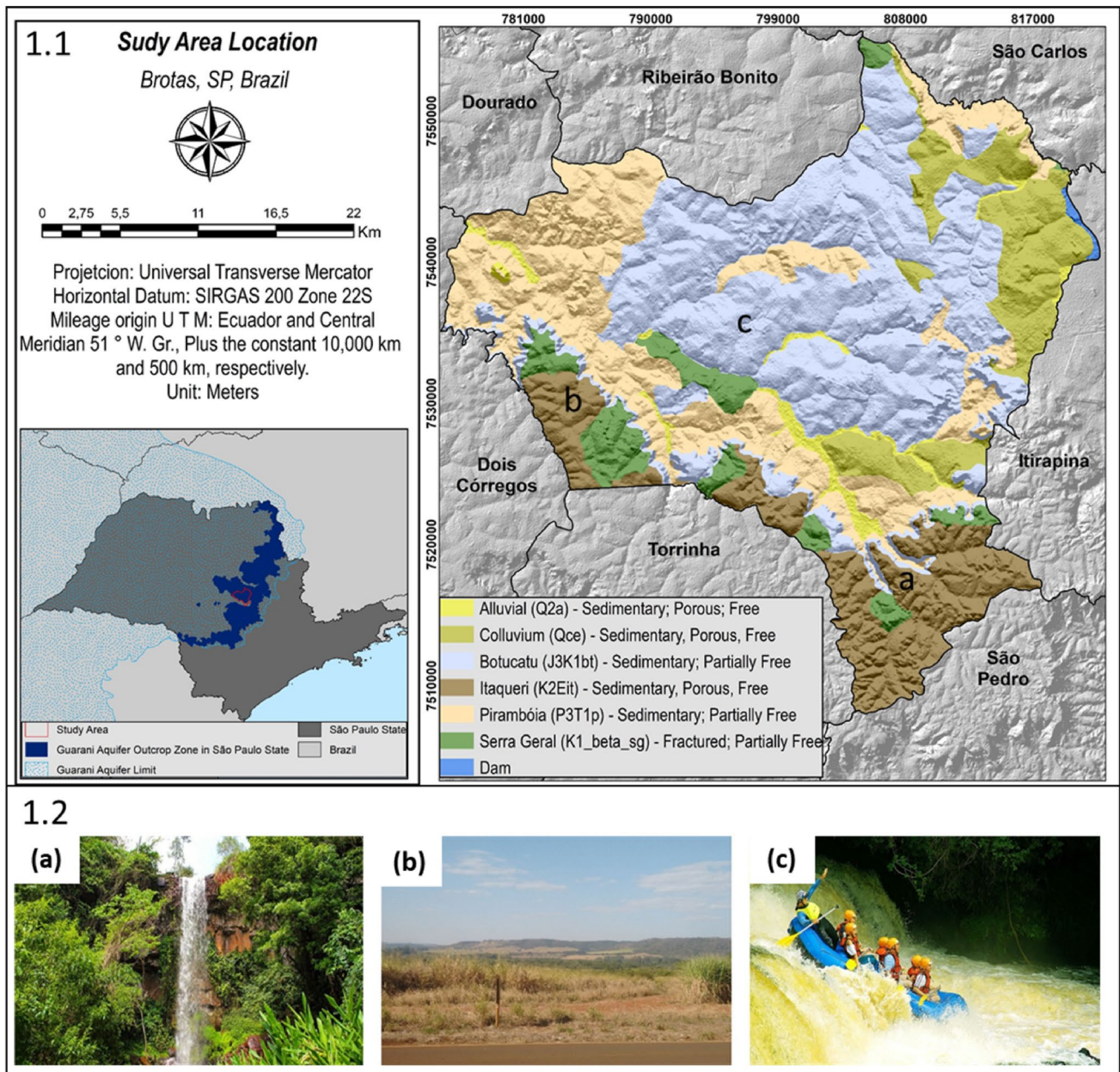


Fig. 1 Overview of the study area—(1.1) Study Area Location; (1.2) Landscapes of interest in Brotas: **a** 3 Quedas waterfall (Brotas 2018); **b** Lookout site—Authors photo; **c** Rafting in the navigable river (Brotas 2018)

Table 1 Data used in the study, sources and formats

Data type	Data	Source	Format
Land use	2019 Land Use map – Collection 5	MapBiomias (2020)	.tiff
	2009 Land Use map – Collection 5	MapBiomias (2020)	.tiff
	1999 Land Use map – Collection 5	MapBiomias (2020)	.tiff
	1989 Land Use map – Collection 5	MapBiomias (2020)	.tiff
Hydrogeology	Geological units	SSIG (2014)	.shp
	Geological characterisation	Authors	Descriptive
	Wells	SIAGAS/CPRM (2019)	Geoinformation
	Aquifer units	Guerrero et al. (2019)	.shp
	Soil types	CAI (1981)	.shp

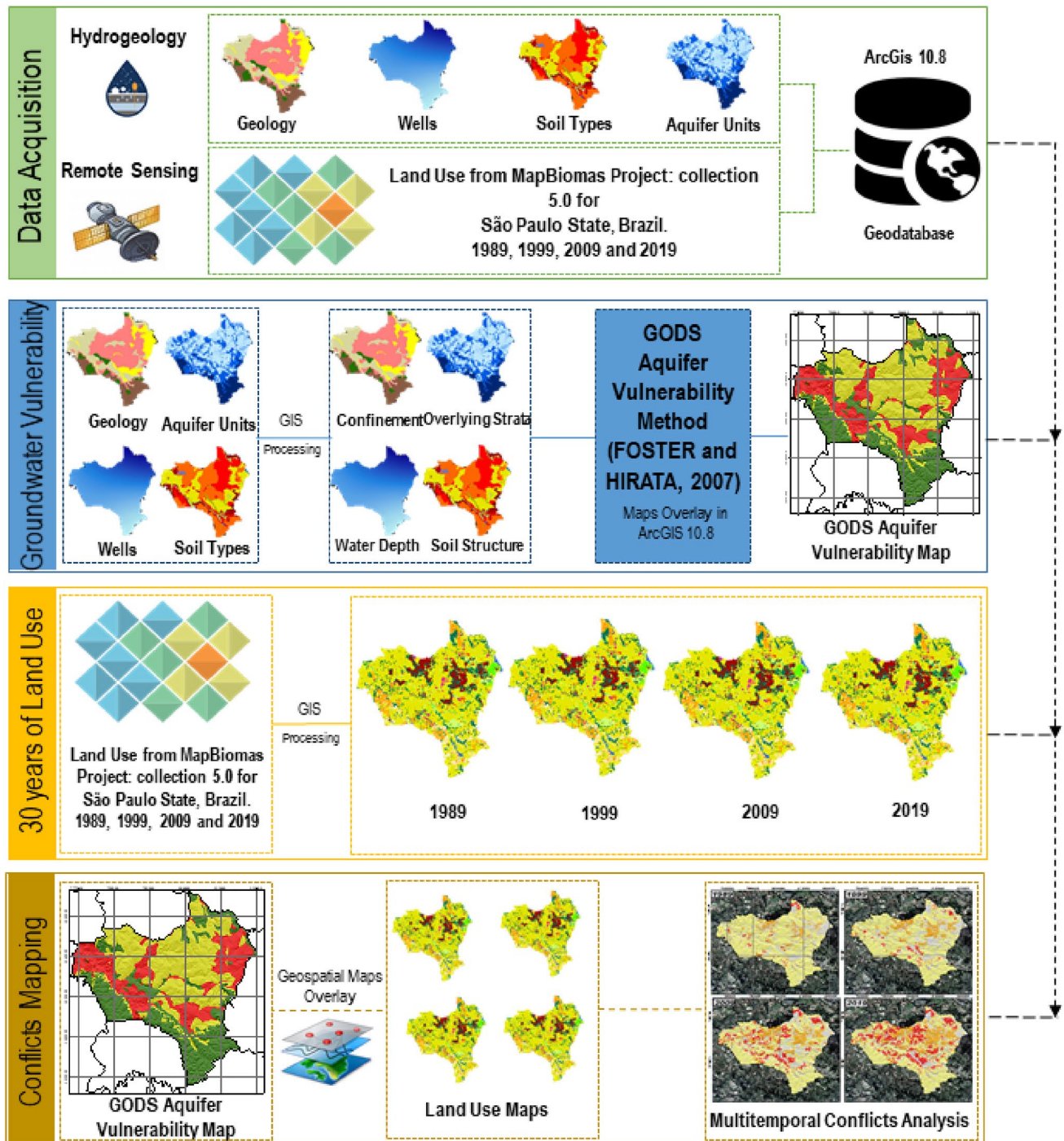


Fig. 2 Methodological procedures and steps of this study

level of soil and geological consolidation that determines its capacity to attenuate the contaminant and the depth to the water table.

The first step in implementing the GODS natural vulnerability is assigning vulnerability values to each of the four fundamental parameters:

(G)= Groundwater Confinement—The analysis of the site’s aquifer units’ degree of confinement (Guerrero et al. 2018).

(O)= Overlying Strata—The analysis of the local geological and vadose zone parameters regarding their capacity to reduce contaminants infiltration.

(D) = Depth to groundwater—Wells Kriggage Analysis (CPRM 2019) considers that the aquifer’s level of protection increases with depth.
(S) = Soil Structure—The analysis of the soil properties (IAC 1981), considering their capacity to favor more infiltration or runoff.

The values assigned to the constituent elements of each analyzed parameter are presented in Table 2:

Finally, we used the weighted sum spatial function to overlay the maps. The resulting values, as shown in Table 3, illustrated the various levels of natural vulnerability to aquifer contamination in the municipality of Brotas (Foster et al. 2002).

LULC multitemporal analysis

For the investigation of territorial conflicts, mapping land use is a crucial component. These geographic representations show how the human appropriation of the landscape, that is, the patterns of anthropic occupation, currently exists and interacts with the environment.

We used geodata from the Mapbiomas project database (MapBiomas 2019). Mapbiomas is a scientific endeavor to provide annual land use for all Brazilian biomes at a spatial resolution of 30 m for the period 1985–2021, based on the

Table 3 Distribution of the resulting values according to the GODS vulnerability

0.00–0.33	0.33–0.66	0.66–1
Low	Moderate	High

automatic pixel-by-pixel classification of the time series of images collected by the satellites of the Landsat constellation and processed with the machine learning algorithm “Random Forest” in the Google Earth Engine environment (Mapbiomas 2019).

The products generated in Collection 6 are available at three different levels of detail, with level 3 (the most extensive and the one utilized in this study) providing 34 classes and subclasses of LULC with the detail necessary to identify the exact types of changes induced in the studied area. In the municipality of Brotas, 13 types of land use were identified, described in Table 4:

The complete methodological description of the classification models applied in the MapBiomas project is presented in the project’s reference article of Souza et al. (2020) and on its website (www.mapbiomas.org).

To diagnose the spatio-temporal evolution of the landscape dynamics, the processing of the Mapbiomas data required the download of LULC products for the years 1989, 1999, 2009 and 2019 (covering 30 years of anthropogenic alterations produced in the landscape), the clipping of scenes

Table 2 The vulnerability values for each parameter’s attribute for the GIS modeling

GODS parameters	Ranges/attributes	GODS rating	
Groundwater confinement (G)	Itaqueri— <i>Granular, sedimentary, porous, free</i>	0.4	
	Serra Geral— <i>Fractured, partially free</i>	0.1	
	Pirambóia— <i>Granular, sedimentary, partially free</i>	0.8	
	Botucatu— <i>Granular, sedimentary, partially free</i>	0.8	
	Colluvium— <i>Granular, sedimentary, porous, free</i>	0.9	
	Alluvium— <i>Granular, sedimentary, porous, free</i>	0.9	
	Overlying strata (O)	Itaqueri	0.1
		Serra Geral	0.3
		Pirambóia	0.8
Botucatu		0.8	
Colluvium		0.9	
Alluvium		0.9	
Depth to groundwater (D)	> 50 m	0.6	
	20–50 m	0.7	
	5–20 m	0.8	
	< 5 m	0.9	
Soil structure (S)	Red Nitisols	0.1	
	Loamy Acrisols	0.1	
	Red Ferralsols	0.2	
	Sandy Acrisols	0.4	
	Red-Yellow Ferralsols	0.7	
	Lithic Gleysols	0.8	
	Quartzipsamments Entisols	0.9	

Table 4 Description of the MapBiomass' land use types

Land use/description	Land use/description
1. Forests —represents all natural forest compositions present in the area	8. Savannah —Savanna formation: also known as cerrado areas
2. Forest Plantation —All kinds of forestry, like eucalyptus, pine	9. Grassland —Natural grasses without anthropic use
3. Pasture —Grasses prepared for cattle feed	10. Sugarcane —Type of temporary crop aimed at producing sugar and ethanol
4. Mosaic of Agriculture and Pasture —Transition areas between agriculture and pasture, without well-defined boundaries	11. Urban —Urbanized areas
5. Non-vegetated —Bare lands	12. Water —Water bodies
6. Perennial Crops —Agricultural types maintained throughout the cycles, such as coffee and oranges	13. Soybean —Type of temporary crop
7. Other Temporary Crops —Agricultural areas with defined cycles that need replanting, such as corn	

Table 5 Values assigned to groundwater vulnerability cluster

GODS vulnerability	ID number
Low	100
Moderate	200
High	300

using the official boundary of the study area provided by IBGE (2018), and the calculation of the areas represented by each type of use over the years studied.

Conflicts map

The theoretical concepts established by Brown and Raymond (2014), which were arranged by map algebra in ArcGis 10.8, served as the foundation for this mapping. Based on the intersection (or geographic inference) between the groundwater vulnerability maps and the Land Use maps, locations of greater or lesser geoethical conflict can be identified. The classification process started from the concept that higher conflicts result from the spatial correlation of highly vulnerable areas (identified by the GODS method) and uses that have the greatest potential for degradation.

To establish and allow the identification and classification of the values resulting from the intersection of the maps, we assigned ID numbers to the elements of each input map, where the sum of the values could be associated with a conflict class.

The values for the groundwater cluster are shown in Table 5 according to a vulnerable degree:

Table 6, on the other hand, presents the identification numbers assigned to the classes of land use types, according to the potential hazard that each one poses to local aquifers.

The map algebra results—which served as the weighted sum between the layers representing groundwater risk and land use—was reclassified with the aforementioned updated control values. Finally, we classified the values resulting

Table 6 ID numbers assigned to land use types cluster, according to their groundwater hazard impact

Land use type	Impact on groundwater	ID number
Forests	Minimum	1
Savannah	Minimum	2
Grassland	Minimum	3
Water	Minimum	4
Pasture	Moderate	5
Other temporary crops (OTC)	Moderate	6
Non-vegetated	Moderate	7
Forestry	Moderate	8
Crops Mosaic	High	9
Urban	High	10
Perennial crops	High	11
Sugarcane	High	12
Soybean	High	13

from this operation into conflict classes according to the relationships between land use types and degrees of vulnerability, as shown in the geoethical conflicts identification matrix presented on Fig. 3.

Results and discussion

Land use changes in Brotas over the last 30 years

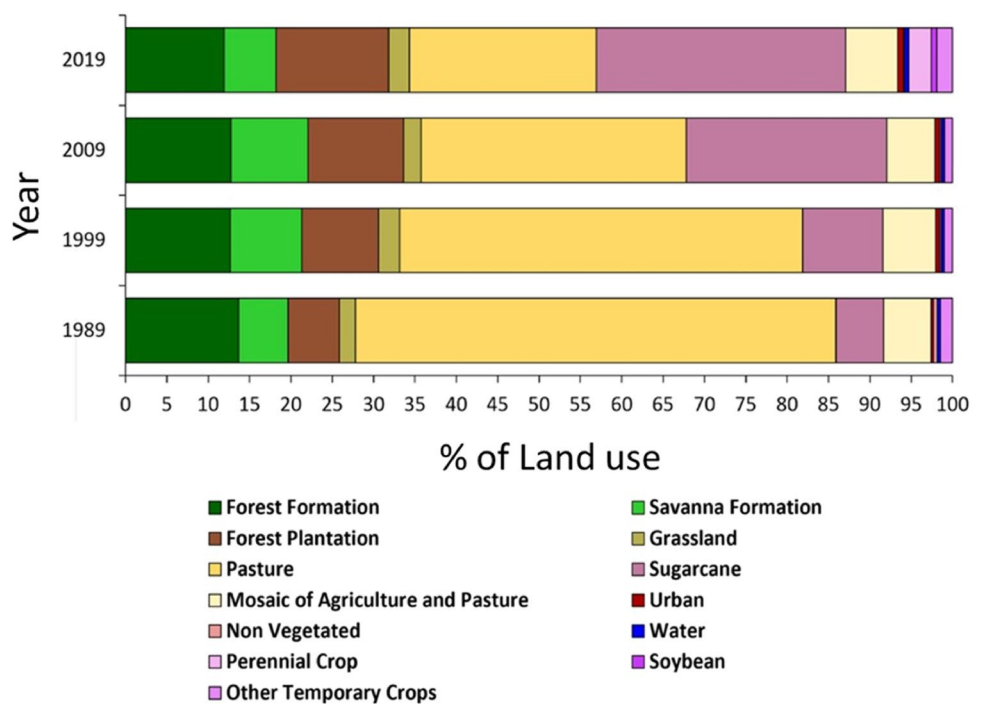
The variations in the percentage of land use (LU) classes in Brotas over the past 30 years (1989, 1999, 2009, and 2019) show that the municipality's landscape has undergone significant changes (Fig. 4).

The Forest Formation, Savana Formation, and Grasslands LUs (natural vegetation areas) did not exhibit significant declines between 1989 and 2019. In 1989 (238.51 km²), they made up 21.62% of Brotas' total area and 20.72% in

Fig. 3 Identification matrix for geothetical conflicts based on the values derived from the intersection of the vulnerability map and land use types

Conflicts between GW vulnerability and land use		Land Use Impact on Groundwater												
		Forests	Savannah	Grassland	Water	Pasture	OTC	Non Vegetated	Forestry	Crops Mosaic	Urban	Perennial Crops	Sugar Cane	Soybean
Vulnerability	Low	101	102	103	104	105	106	107	108	109	110	111	112	113
	Moderate	201	202	203	204	205	206	207	208	209	210	211	212	213
	High	301	302	303	304	305	306	307	308	309	310	311	312	313

Fig. 4 Distribution of land use types over the studied years



2019 (228.69 km²). In contrast to places where Land Use Changes (LUC) are dominant over naturally occurring vegetation, such as the Brazilian Amazon (Guerrero et al. 2020a; Mataveli et al. 2021), LUC predominated over previously non-natural areas in Brotas. The pasture was the primary LU in Brotas in 1989 (640.90 km², or 58.10% of the total area). However, in 2019 this LU grew to become the second main LU of Brotas and only covered 22.61% of the study area (249.45 km²). The majority of the pasturelands were transformed into sugarcane and forest plantations. LU maps for 1989, 1999, 2009, and 2019 (Fig. 5) demonstrate this change. The conversion of pasture into sugarcane may be seen in this figure centered in the southern and

south-western parts of Brotas. In contrast, the Central and Central-Northern regions of the Brotas experienced a higher rate of pasture conversion to eucalyptus forestry.

In 1989, sugarcane LU made up 5.77% of Brotas; this percentage increased substantially between 1999 and 2009 (9.70% and 24.25%, respectively); in 2019, it made up 30.17% of the municipality (332.79 km²). In the São Paulo State, where Brotas is located, (Rudorff et al. 2010) noted a significant development of sugarcane farms for ethanol production after 2003. In Brotas, Forest Plantation LU doubled in size between 1989 and 2019, from 68.22 to 150.10 km². Throughout the 30 years of analysis, no other LUs demonstrated appreciable modifications.

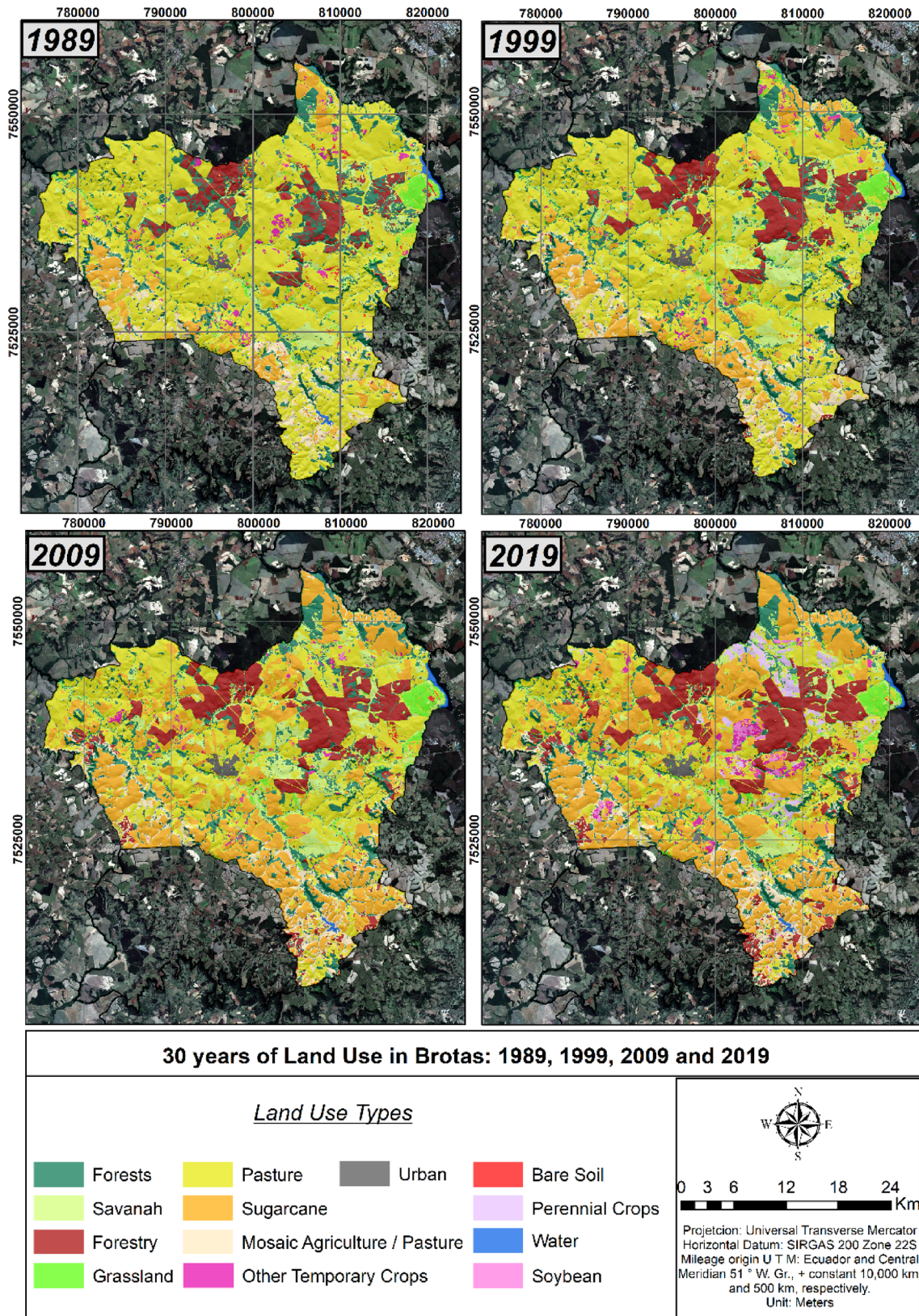


Fig. 5 Land use maps over the studied years

Natural groundwater vulnerability

As an outcome of using the GODS approach, the natural groundwater vulnerability map (Fig. 6) shows three levels of vulnerability—Low, Moderate, and High—taking into consideration the natural components of the research area (Foster and Hirata 1988; Foster et al. 2002).

As a result of the protection provided by natural conditioners, low vulnerability zones, which make up 30.5% of the research area, are placed with a low likelihood of groundwater pollution. These regions have basaltic geological structures (Itaqueri and the Serra Geral), clayey soils, and a deep water table that avoids groundwater contamination.

Other studies in the same region, such as those by Santos et al. (2014) and Tanajura and Leite (2016), support the identification of places with low natural vulnerability. They also determined that, along with the Itaqueri and the Serra Geral formations, the Guarani Aquifer is better protected due to the confining layers' deeper depth and geological features.

Moderate vulnerability, shown in yellow on the map, represents transitional areas between safety and risk for local groundwater contamination, accounting for 43% of

the territory. The middle class begins with contact between the Itaqueri and Pirambóia/Botucatu formations, guaranteeing high declivity and lower infiltration rates. It is primarily located in the municipality's central-north portion. This middle class continues towards the center in sandstone areas (Botucatu and Piramboia), which are already in Guarani Aquifer outcrop zones.

Despite being a sensitive area for the Guarani aquifer's composing outcrop zones, the local soils can at least slow the contamination process there. According to Paes (2014) and Manzione et al. (2021), soils directly impact recharge dynamics and vulnerability. The Red Oxisols, which are less vulnerable, because they are mineral-rich, uniform, deep, and well-drained, are the mitigating soils, according to IAC (2014).

High natural vulnerability areas cover 26.5% of Brotas. They are distinguished by low slopes, sandy soils with a granular texture, low rates of confinement due to the vadose zone's structure, and the water table's location at shallow depths. However, these characteristics also represent aquifer recharge zones, which are particularly

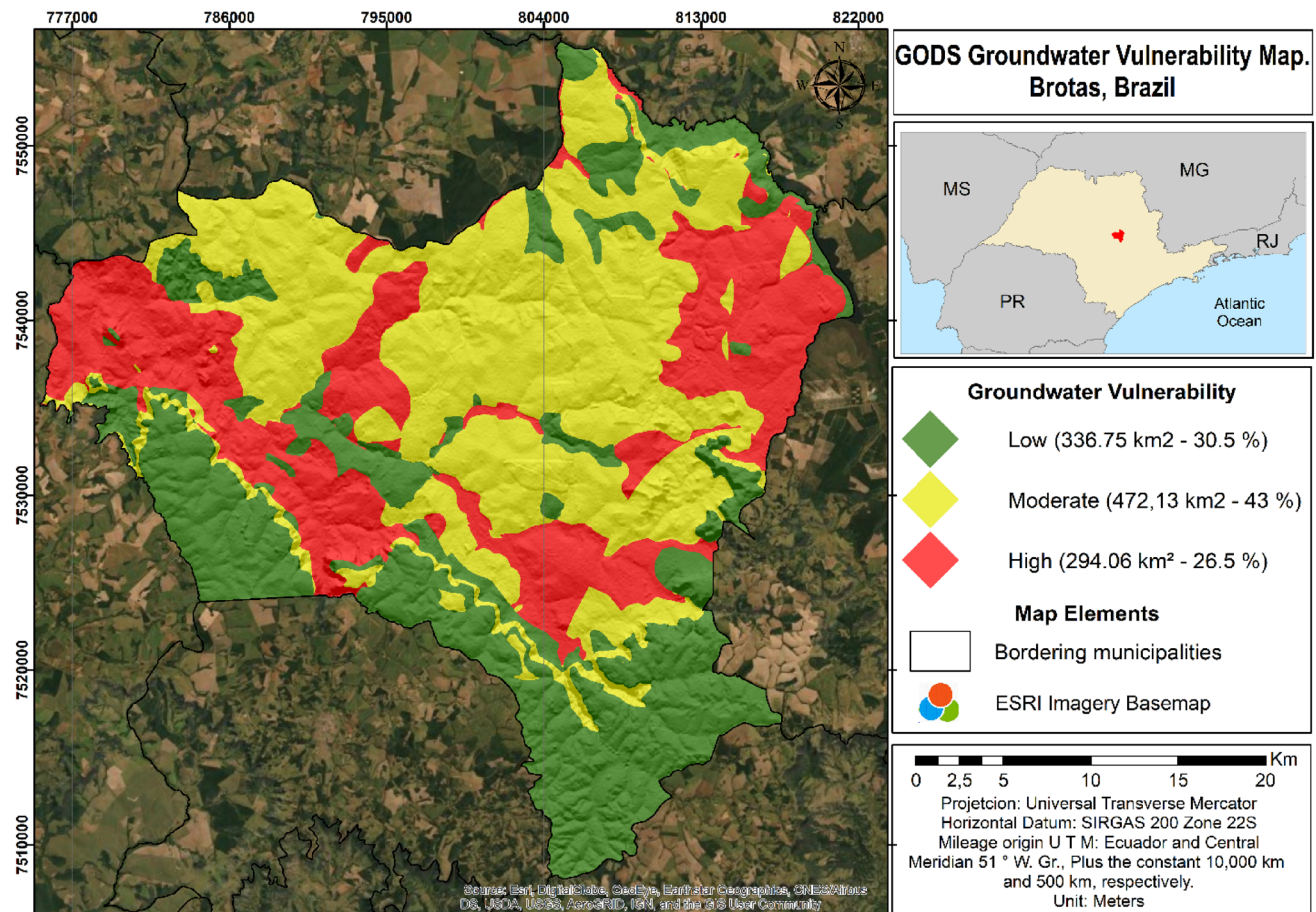


Fig. 6 GODS groundwater vulnerability map for Brotas

sensitive and important regarding water quality and availability dynamics at a regional scale.

Conflicts map

Vasconcelos et al. (2020) proposed that geoethical conflicts consist of non-responsible relationships between human interaction and the terrestrial system. They are reflected in the case of groundwater in the municipality of Brotas by allocating potential land uses over areas that are naturally vulnerable to contamination of local aquifers. The conflict maps (Fig. 7) spatially identified the places where, over time, the relationship between natural aquifer vulnerability and current land use resulted in geoethical conflicts. In other words, this conflict refers to the spatial correlation between areas potentially vulnerable to contamination of aquifers with types of use with potentially degrading potential, such as sugarcane and its pesticides, and urban areas and their various contaminating sources, for example.

The quantitative variation of each class across the four investigated dates (1989, 1999, 2009, and 2019) reveals the dynamics of the municipality's significant geoethical conflict changes (Fig. 8).

The mappings revealed that the percentage of areas devoid of geoethical conflicts did not change significantly over 3 decades (21% in 1989 to 22% in 2019, with minor variations between periods), indicating that, according to an analysis of the sites' past occupations, they have been environmentally preserved and that it is difficult to conduct significant human activities there due to legal restrictions or other natural barriers, which also reduces vulnerabilities.

Lower conflict areas have shown consistent declines over time, with a 66% increase from 1989 to 2019. It was feasible to notice a diverse distribution of this class throughout the municipality between 1989 and 1999. However, according to the 2009 mapping, this class has been replaced by high and very high conflicts, covering the southernmost area (with less natural vulnerability due to the geoenvironmental framework) and portions of the center-north where there are greater slopes.

In contrast, high-conflict regions showed growth across all research dates, with an 800% rise in 2019 compared to 1989. Significant land use changes, such as the replacement of grasslands and fields with intensive agriculture, were predominantly observed in the municipality's northern regions. When evaluating the period between 1989 and 2019, the areas with the highest conflict showed an increase of 225%, highlighting the flatter areas on the Botucatu and Pirambóia aquifer Units in the central-north of the study area (Guerrero et al. 2018).

According to Lerner and Harris (2009), groundwater quality is highly vulnerable to anthropogenic land surface activities, particularly those having the potential to degrade

the system by leaking contaminants into it. According to this finding, the increase in conflicts identified over the 3 decades studied leads to a shift in the pattern of occupation toward land uses with higher degrading potential. In a rural municipality such as Brotas, this results in an increase in pesticide use, which threatens vulnerable areas such as the Guarani aquifer recharge zones (in the central portion of the study area).

Nonetheless, the main changes in conflict patterns occurred precisely in the central part of Brotas. This idea is supported by studies evaluating land use in Brotas conducted by Abreu et al. (2020) and Guerrero et al. (2020b), which indicate that sugarcane is the primary driving force for landscape transformation.

Sugarcane development in Brotas is remarkable. Sugarcane production in the municipality increased from 1,275,000 tons in 2004 to 2,722,400 tons in 2019, according to data from the Systematic Survey of Agricultural Production (IBGE 2018). The planted area increased from 15,000 ha in 2004 to 33,200 ha in 2019, confirming this study's multitemporal land use map.

Brotas became Brazil's 55th largest sugarcane producer due to this significant productive reconfiguration, which was accompanied by the extensive use of pesticides that contaminated local surface groundwater resources. The study of RepórterBrasil (2020), which used data from the Ministry of Health of Brazil, refers to the presence of 27 pesticides in the municipality's water. Eleven are linked to chronic diseases like cancer, congenital disabilities, and endocrine disorders.

As Stanley and Reading (2020) proposed, applying these pesticides in potentially contaminated areas must be of particular concern. The transport of dissolved nitrogen in the form of nitrates, which are byproducts of pesticides used in sugarcane, can cause large-scale environmental and social imbalances, raising geoethical conflicts in the municipality.

Due to the rise of geoethical conflicts between land use changes and aquifer-vulnerable places, more sustainable territorial planning projects capable of regulating anthropogenic advances on the territory are required. Respect for landscape support capacity should be prioritized on a technical and scientific basis (Ross 1994; Massa and Ross 2012), emphasizing environmental, agricultural, and agroecological zoning (Guerrero et al. 2016; Lerner and Harris 2009; Manzatto et al. 2009). This can be used to spatially identify locations of more geoethical conflict so that public authorities can mitigate problems and mediate conflicts more effectively.

By relating the understanding of geoethical conflict as reflections on the negative results of the interaction of anthropic activities with the geosphere (Peppoloni and Capua 2015) with the increase in conflicts between land use and groundwater vulnerability diagnosed in this study, it is possible to state that, despite efforts to implement more

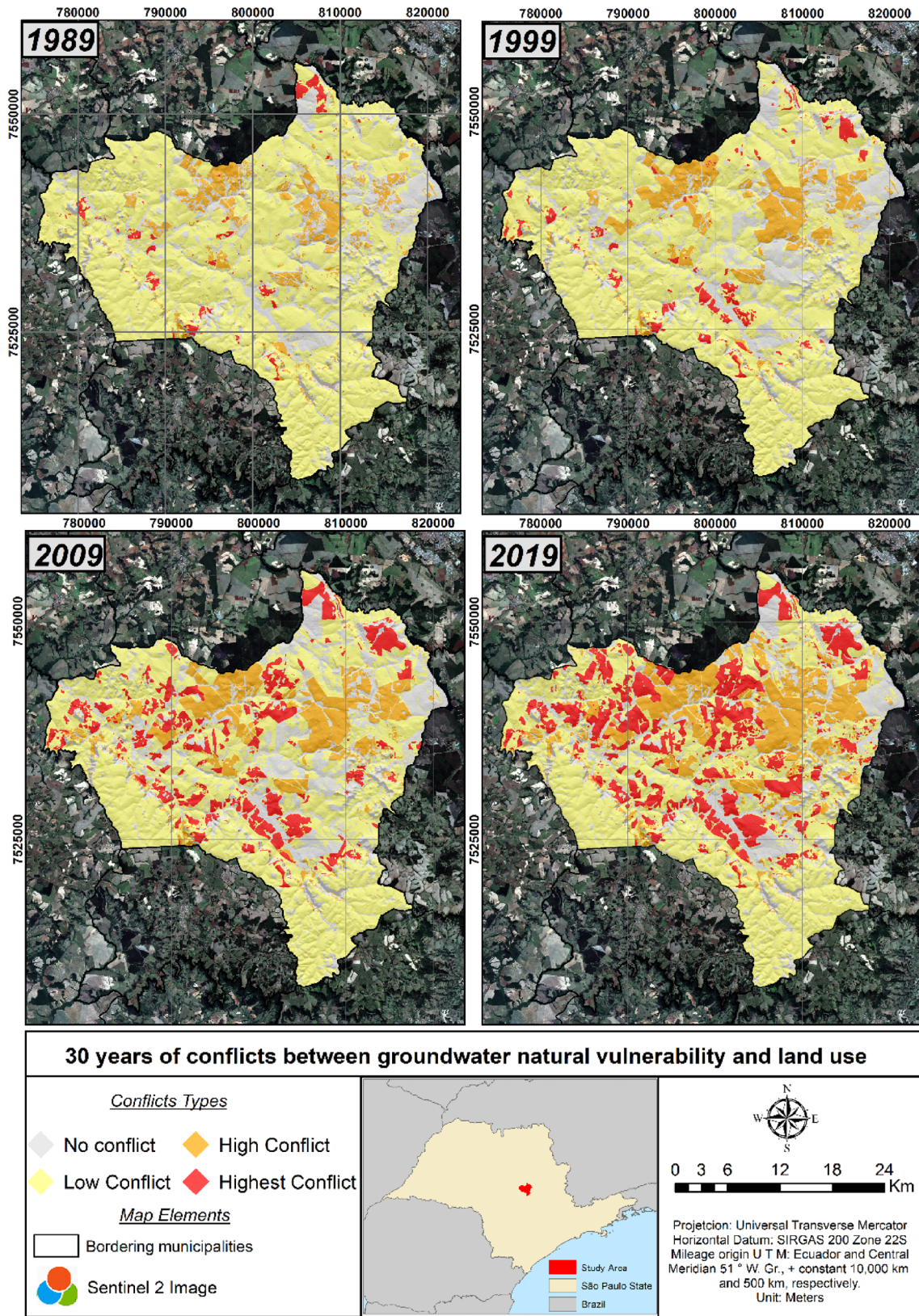
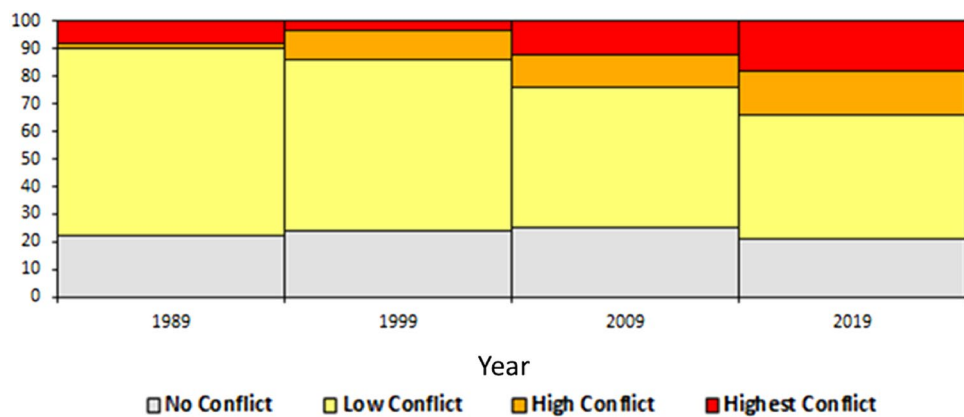


Fig. 7 Geothetical conflicts between the natural vulnerability of aquifers and the types of land use

Fig. 8 Total percentage of each type of conflict identified over the years studied



sustainable activities (Martins and Madureira 2019), geoethical conflicts are still a challenge to be overcome in Brotas' territorial management.

As a suggestion, we can indicate the incentive to sustainable ecotourism as an ALTERNATIVE to agricultural production, mainly in areas with greater groundwater vulnerability, a factor that tends to substantially reduce geoethical conflicts in the landscape, as proposed by Guerrero et al. (2020a, b, c), and Martins and Madureira (2019). Despite appearing to be a drastic action, the recovery and re-signification of areas vulnerable to contamination is essential for the prosperity of the ecosystem services provided by the Guarani aquifer to the municipality, and if immediate action is not taken, the damage could be irreversible.

Several studies, such as those by Manzione and Silva (2022), Castro et al. (2018), and Imbernon et al. (2021) demonstrate that geoethical conflicts between territory vulnerabilities and land use without proper planning are not exclusive to Brotas, but also occur in Brazil as a whole and with high severity scales. Such data reinforce the need to implement geoethical concepts in the territorial planning and management processes themselves, based on technical and scientific studies carried out by geoscientists, aiming to reduce the social, environmental, economic, and cultural impacts arising from these conflicts based on the dynamic balance between the inevitable need to use the territory and its potentialities and restrictions.

Conclusions

This study uses 30 years of land use mapping (1989–2019) and geoenvironmental cartographic principles to identify the geoethical conflicts between human activities and the naturally occurring vulnerability of groundwater in the municipality of Brotas.

We discovered that throughout time, the land use coverage pattern of Brotas dramatically evolved in favor of more damaging uses, as evidenced by the region's significant

increase in sugarcane crops, as well as forestry, citrus, and coffee, particularly in the last two dates examined.

Regarding the study area's natural vulnerability to aquifer contamination, mapping using the GODS method revealed that 69.5% of it has a moderate or high vulnerability, raising concerns about where these areas are located given that they make up the majority of the GAS recharge areas in the municipality's central region.

The four final maps showed the development of geoethical conflicts in the Brotas municipality and revealed that the locations with the greatest influencing activities were those where the local aquifers were most naturally vulnerable. This claim is supported by the fact that, in 2019, high or very high conflicts affected 34% of the area, compared to 10% in 1989. Due to the significant conflicts in the municipality's center region, specifically in the GAS outcrop zone, the spatial arrangement study of geoethical conflicts revealed that the case is even more severe.

This study aimed to show that an effective planning tool could be created using readily available data and a reasonably straightforward application procedure. The outcomes supported the value of mapping geoethical issues in locating regions that require further involvement. It is anticipated that public authorities will be able to direct their measures to safeguard the GAS more effectively for both Brotas and the other accountable municipalities after results have been spatially shown.

The results obtained and lessons learned during this study also demonstrated the importance and urgent need for geoethical dilemmas (Peppoloni and Di Capua 2022) to be better disseminated and implemented in territorial management and planning processes in Brazil, aiming, as proposed by Manzione and Silva (2022) to anticipate issues, create scenarios, and guide the decision-making processes, enhancing water governance.

In conclusion, it is hoped that the ideas and methods presented in this paper will inspire and encourage the conduct of additional research on the conservation of the Guarani Aquifer based on geoethical assumptions and more sustainable

use of groundwater in Brazil. In addition, the perception was reinforced that the geoethical approach in studies on the topic of groundwater conservation is an extremely efficient tool for the achievement of several components of the United Nations' sustainable development goals, due to its ability to contribute not only to the specific context of geosciences but also in the socio-environmental and economic aspects that surround them towards more sustainable management and with greater capacity to maintain the ecosystem services provided by aquifers.

Acknowledgements Alberto Gomes and José Teixeira received support from the Centre of Studies in Geography and Spatial Planning (CEGOT) (Grant 2016/19020-0), funded by national funds through the Foundation for Science and Technology (FCT) under the reference UIDB/04084/2020. Guilherme Mataveli thanks the São Paulo Research Foundation (FAPESP, grant 2019/25701-8) for financial support. The authors would like to thank all the reviewers who took the time to provide valuable feedback on our paper. Your comments and suggestions have helped us refine our work and improve its quality. We are deeply grateful for your time and expertise.

Data availability Data will be made available on reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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