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Vulnerability Assessment of Guarani Aquifer Using PESTICIDE-DRASTIC-LU Model: Insights from Brotas Municipality, Brazil

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Abstract: Free aquifers have become an important water supply option for underdeveloped and developing countries, due to the resource quality and relatively low extraction prices. However, overexploitation and the lack of territorial planning guidelines in these areas endanger groundwater availability and quality. In this context, this study aimed to analyze the vulnerability to groundwater contamination and contribute to the conservation of the ecosystem services, provided by the Guarani aquifer in Brotas, Brazil, by applying the PESTICIDE-DRASTIC-LU model. The application of this model allowed the identification of priority conservation areas within the context of ecosystem services that groundwater provides to local inhabitants. To this end, we collected, treated, and analyzed seven different hydrogeological data to understand the environmental dynamics of the system and to identify which areas are most vulnerable to aquifer contamination. The results pointed out that 64% of the study area presents zones of high and very high vulnerability to contamination, due to the local hydrogeological characteristics (sandy soils and rocks) and the various anthropogenic activities, mainly with large plantations of sugar cane and eucalyptus. In addition, the mapping allowed the spatial demonstration of the places that should be considered a priority for the conservation of ecosystem services provided by local groundwater. Thus, our results can serve as a baseline to define public action strategies for the preservation and sustainable management of the Guarani aquifer areas.

Keywords: groundwater; guarani aquifer; environmental dynamics; GIS; sustainable management

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Citation: Guerrero, J.V.; Gomes, A.; Lorandi, R.; Di Lollo, J.A.; Mataveli, G.; Moschini, L.E. Vulnerability Assessment of Guarani Aquifer Using PESTICIDE-DRASTIC-LU Model: Insights from Brotas Municipality, Brazil. *Water* **2024**, *16*, 1748. https://doi.org/10.3390/w16121748

Academic Editor: Juan José Durán

Received: 17 May 2024
Revised: 14 June 2024
Accepted: 16 June 2024
Published: 20 June 2024

1. Introduction

Groundwater constitutes a critical component of the Earth's hydrologic cycle. As surface water resources become increasingly susceptible to contamination, the importance of groundwater for contemporary societies intensifies [1]. This is due to the crucial role groundwater plays in supplying water for strategic sectors, including domestic use, agriculture, industry, environmental sustainability, and in mitigating the impacts of droughts and floods [2–4].

A prime example of the importance of groundwater resources is evident in Brazil, which possesses several vast aquifers noted for their exceptional water quality [5]. Among these, the Guarani Aquifer System (GAS, Sistema Aquífero Guarani, in Portuguese) stands out as a crucial freshwater resource [6]. Comprised of a sequence of Triassic-Jurassic age sedimentary layers primarily composed of sands deposited in continental, fluvial, lagoonal, and aeolian environments, the Guarani Aquifer System is capped by a thick Cretaceous basalt layer [7]. Occupying an extensive area of approximately 1,087,000 km^2 within the South American Paraná Basin [1], this transboundary aquifer system holds an estimated volume of 37,000 km^3 of freshwater and underlies portions of Brazil, Argentina, Paraguay, and Uruguay [8,9].

The Guarani Aquifer System stretches across eight Brazilian states, acting as a critical source of water for essential services like human supply, industry, and agriculture [10]. In São Paulo, Brazil's richest and most industrialized state, a staggering 70% of water use relies on the GAS [8]. However, this heavy reliance on the aquifer for agriculture, drinking water, and industry comes with growing concerns. As pressure on this resource increases, so do worries about the impact on the GAS's ability to provide vital ecosystem services [11]. While most of the GAS still have their natural quality preserved, recent studies reveal worrisome signs of contamination from intensive agriculture and urban activities [1,12].

High anthropogenic interventions in GAS areas along the São Paulo state and alarming signs of contamination in the Guarani Aquifer System, reinforce the necessity to develop research based on scientific methods to support the decision-making process by public managers to protect this unique aquifer [6]. In the current scenario of GAS water quality declining, and the lack of conservation guidelines in the legal strategies of territorial planning of the Brazilian municipalities, public managers must set up strategies to organize and minimize the anthropogenic activities that impact this aquifer based on technical studies that assess their intrinsic vulnerability [13,14].

Research about the intrinsic vulnerability of groundwater resources to contamination and their provided ecosystem services is an effective tool to control their quality and contribute to their protection [15–17]. Additionally, an aquifer's vulnerability can be defined as its intrinsic susceptibility to the harmful effects of a human-made contaminant load. This helps public managers make decisions in environmental planning [18].

In recent years, several studies have been dedicated to mapping vulnerability to contamination, such as [19–24], among others. This research reflects growing concerns about protecting the valuable ecosystem services provided by groundwater [11,25,26] aligning with recommendations from the United Nations [27]. The achieved results demonstrate the viability and significance of incorporating ecosystem services into environmental modeling for territorial planning, thereby promoting sustainable development in diverse global contexts.

Given that pesticide contamination from intensive agricultural uses is currently a major concern for the provision of local ecosystem services, particularly in the GAS recharge zones [28,29], it is necessary to develop a geoenvironmental vulnerability assessment model that considers the relationship between groundwater and land use.

Thus, the methodology proposed by Aller et al. [30] called PESTICIDE-DRASTIC stands out for its capacity to analyze multiple hydrogeological parameters to identify natural vulnerability to contamination by pesticides, supported by geographic information systems. The extensive use of the PESTICIDE-DRASTIC method in studies on this subject, such as in [31–34], demonstrates its effectiveness. However, the land use parameter was not originally considered in the DRASTIC/PESTICIDE-DRASTIC model, and its inclusion was proposed by Allam et al. [35], which the authors named the DRASTIC-LU model.

In this context, the objectives of this research are as follows: (1) develop a methodological integration based on PESTICIDE-DRASTIC and DRASTIC-LU, known as PESTICIDE-DRASTIC-LU, a model that integrates the dangerousness of an area with extensive pesticide use and the influence of local land use types; (2) identify areas where the relationship between geoenvironmental structure and human occupation patterns most threatens groundwater ecosystem services; and (3) apply an environmental mapping method to identify areas with varying degrees of vulnerability to groundwater contamination and consequent loss of essential ecosystem services. The resulting chart will be an instrument capable of identifying priority conservation areas where the essential ecosystem services provided by this resource are vulnerable, allowing for the most effective planning and land management actions for each area.

The municipality of Brotas, Brazil, situated in the Guarani Aquifer System was chosen to test this methodology for three reasons: (1) the GAS integrates the entire municipality's area; (2) a significant portion of the agricultural area employs intensive agrochemical-based agricultural practices; and (3) the aquifer plays a crucial role in maintaining ecosystem services. Furthermore, [8] reports that outcrop areas occupy 85% of the Brotas territory over this aquifer, which, due to its predominantly sandy characteristics and greater porosity, strongly suggests the need for conservation to ensure the provision of ecosystem services by the GAS.

2. Study Area

The GAS is the largest underground freshwater resource in the world, with an extension of 1.2 million km^2 and an estimated cumulative volume of 37,000 km^3 [8,9]. Figure 1 shows where GAS occurs in South America, covering Brazil, Argentina, Paraguay, and Uruguay [8]. The aquifer is made up of sedimentary rocks from the Mesozoic that lie within the Paraná and Chacoparanaense basins, a complex geological area [36]. Basically, the hydrogeological structure is made up of a series of sandy layers from the Pirambóia Formation of the Triassic age and the Botucatu Formation of the Jurassic [9].

The sandstones of the Botucatu Formation stand out for storing large quantities of groundwater since they are of eolian origin, which means they have a greater water capacity than the sandstones of the Pirambóia Formation. The latter derive from fluvial-lacustrine and eolian sedimentation, implying that they have a greater amount of clay, which reduces their hydraulic efficiency [9,37]. In addition to the sandstones mentioned above, the GAS also includes rocks from the Cretaceous, called the Serra Geral Formation [38]. This formation, composed of basaltic spills located above the sandy layers, gives the aquifer a certain degree of confinement and protection in approximately 80% of its total area.

The remaining 20% of the total surface area of the GAS represents places where the aquifer outcrops correspond to direct recharge areas, i.e., where vulnerability to contamination is more favorable [8,36]. Considering the state of São Paulo alone, these areas occupy around 16,000 km^2 located in the peripheral depression (Figure 1.b), which demonstrates the importance of preserving the system in that state [8].

Far beyond the provision of water for supply, GAS acts as an essential component in promoting various ecosystem services essential to the well-being of human and non-human communities, such as climate regulation, provision of habitats, regulation of water resources in rivers and smaller aquifers, the promotion of tourism and recreation activities, among others [39,40].

Brotas, the study area, is a Brazilian municipality located in the central region of São Paulo State, southeast Brazil (Figure 1.c). Concerning groundwater, the municipality is completely inside the GAS, and 85% of its territory corresponds to an outcrop. According to Salis [41], the climate in the region of Brotas corresponds to the characteristics of the Cwa climate, which is described according to the Köppen climate classification as subtropical with humid summers (temperatures above 22 °C) and dry winters (temperatures below 18 °C) (Beck et al., 2018). The rainfall data from the meteorological stations provided by CEMADEN [42] show that there are two areas with different rainfall in the municipality [43]. The first is located in the far north, with an average annual rainfall of 1600 to 1800 mm. In the southern portion, average annual rainfall ranges from 1300 to 1600 mm (Figure 1.d).

The Geomorphological Map of the State of São Paulo [44] shows that, as a reflection of the sedimentary basin of Paraná, the study area is located in the morphoscultural units of São Paulo's western plateau and unconsolidated sediments (Figure 1.e).

At a local scale, Moraes et al. [45] proposed the occurrence of 11 relief forms in the municipality of Brotas: low dissected plateaus, plateaus, hills, degraded scarps/structural steps/erosive edges, inselbergs, water bodies, lithostructural levels, flood plains, alluvium-colluvium ramps, colluvium ramps/talus deposit and embedded valleys (Figure 1.e). Studies by the Geological Institute of the State of São Paulo identified six rock units in the study area [46], with a predominance of the Botucatu and Pirambóia formations (GAS formers), as shown in Figure 1.c. The characterization of these units is shown in Table 1.

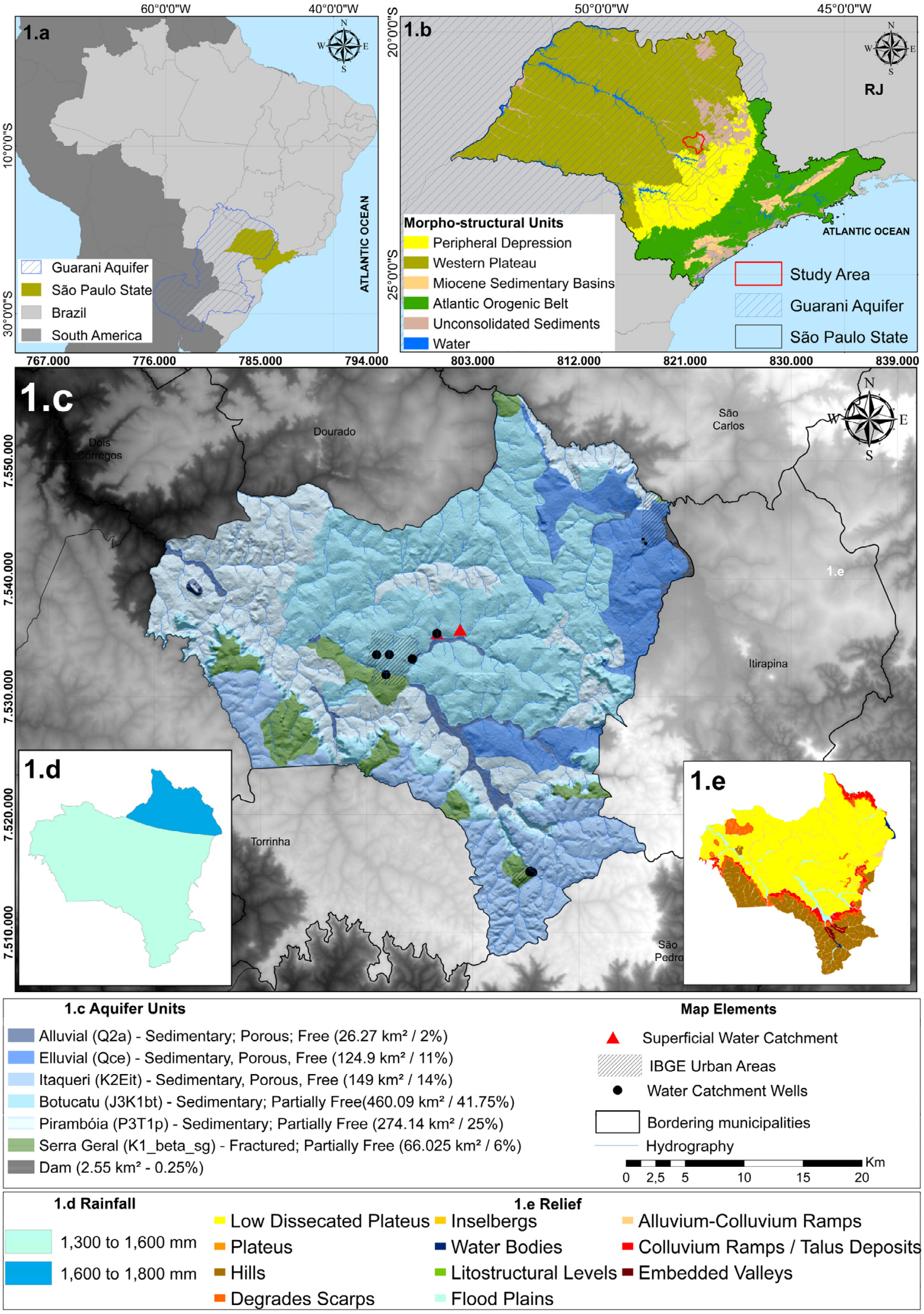

Figure 1. Study Area Location. (**1.a**) Location in Brazil; (**1.b**) Location in São Paulo State; (**1.c**) Study area and its Aquifer Units; (**1.d**) Rainfall average in the study area; (**1.e**) Relief Patterns in the study area.

Table 1. Rock units description.

Rock Unit	Description	(%)
Botucatu Formation	Formed predominantly by fine- to coarse-grained sandstones, with rounded clasts and with great sphericity and reddish and matte coloration. Refers to past sub-environments of a climate desert of increasing aridity.	42
Pirambóia Formation	It consists of eolian sediments and a fluvial-eolian formation deposited in areas of a desert environment, corresponding to the evolution of a wind dunes field. Characterized by thick reddish, yellowish, and whitish sandstones, with fine to medium sand size.	25
Serra Geral Formation	Set of basaltic spills, including sandstones of the Botucatu Formation, forming the so-called Serra Geral Basin.	6
Itaqueri Formation	Sandstones and conglomerates that present silicification and stratification essentially form it. It comprises rudaceous deposits from alluvial fans located geographically in the Itaqueri, Cuscuzeiro, São Carlos, and São Pedro mountains, thus comprising the southern region of the municipality of Brotas.	14
Alluvial deposits	Alluvial deposits are derived from the weathering of the bedrock and thus are formed primarily by transported and deposited sandy sediments. Located along plains and allocated in the valley bottoms and surrounding areas.	11
Eluvial deposits	Eluvial deposits are considered chaotic and poorly selected sediments ranging from blocks and fragments to clays. Such deposits are the result of the mechanical breakdown of rocks and slopes. The transport and deposition of this eroded material occur by the action of gravity or flow current.	2

3. Materials and Methods

The United States Environmental Protection Agency developed the DRASTIC and PESTICIDE-DRASTIC models [30]. These models consist of GIS methods, based on the subjective attribution of relative weights in hydrogeological parameters relevant to the aquifer vulnerability process, which have been proven efficient for analyzing both porous aquifers and fractured aquifers [47].

Both methods allows systematic assessment of vulnerability to groundwater contamination using two main structures: hydrogeological parameter mapping and overlapping the proposed classification system [30]. The main difference between the models is that giving parameter weights to PESTICIDE-DRASTIC makes the possible interactions between hydrogeological dynamics and pesticides stand out. In order to deepen the DRASTIC model, Alam et al. [35] proposed the DRASTIC-LU, seeking to combine hydrogeological parameters with land use to understand in an integrated manner the complexity of vulnerability to contamination.

Taking into account that the study area is essentially rural and that, consequently, there is a greater risk of contamination vectors, we proposed a methodological integration between the PESTICIDE-DRASTIC and DRASTIC-LU models, giving rise to PESTICIDE-DRASTIC-LU, which aims to allow analysis of integrating the risk of pesticide contamination with local land use patterns.

The PESTICIDE-DRASTIC-LU methodology was applied on the basis of three main procedures: data collection, geographic information processing, and hydrogeological modeling in a GIS environment. Figure 2 illustrates this methodological procedure.

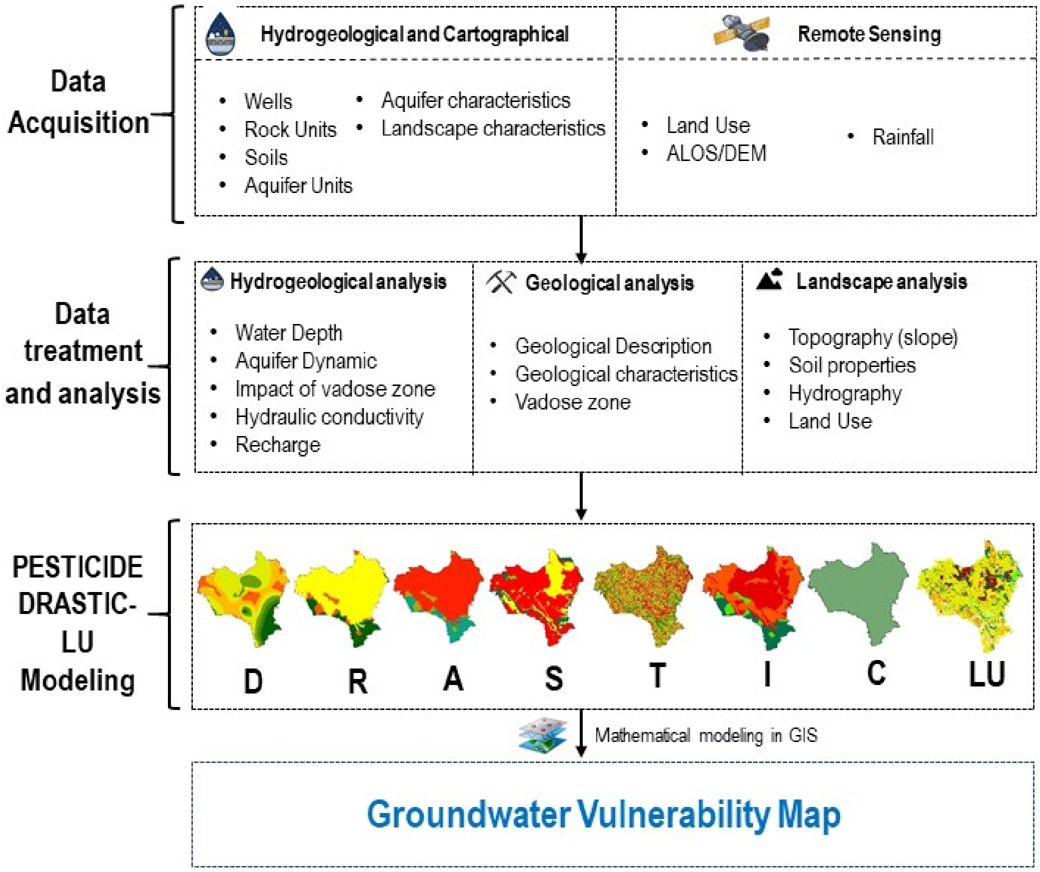

Figure 2. Workflow presenting the method for assessing the vulnerability of groundwater ecosystem services.

3.1. Data Collection and Treatment and Parameters' Characterization

As DRASTIC-LU and PESTICIDE-DRASTIC-LU are hydrogeological models processed using geographic information systems (GIS), a variety of geospatial information was acquired and processed. After acquisition and characterization, the data were prepared for insertion into the GIS hydrogeological model. This preparation consisted of assigning values to the attributes of each variable used and assigning index values to the following parameters:

- Depth of the water table (D): This parameter refers to the level of the water table, which is of great importance as it quantifies the thickness of soil or rock that a pesticide or pollutant has to pass through until it meets the water table [35]. Based on CPRM [48] deep well data available, we obtained this parameter by interpolating information on the position of the hydrostatic level to generate an estimate of the water depth for the entire study area.
- Net recharge (R): The net recharge refers to the amount of water that infiltrates the soil layers and reaches the aquifer [30]. This infiltrated water is the main vehicle for transporting pollutants that degrade aquifer systems [33]. The recharge values used in this work are taken from studies conducted in the Guarani aquifer, such as Rabelo [37]. We assigned the values based on the geological materials present in the area and reclassified them from the original DRASTIC methodology values.
- Aquifer media (A): Aquifer media evaluates the characteristics of the materials that constitute the aquifer, classifying their capacity to attenuate or aggravate the contamination of groundwater [49]. We obtained this information by analyzing the geological map of the state of São Paulo [46] and the deep well data [48].

- Soil media (S): Soil media refers to the superficial layer that overlies the vadose zone and presents great biological activity. The surface soil can attenuate, accelerate, or aggravate the contamination of groundwater, depending on characteristics, such as permeability, and elements that constitute sand, clay, and organic matter [50]. In general, the protection capacity of the aquifer increases the extent to which there is clay material in the soil [51]. We used the Pedological Map of the State of São Paulo [52] to analyze the soil characteristics mentioned.
- Topography (T): Topography is particularly important for assessing groundwater contamination because it directly affects aspects of runoff and infiltration, indicating the dynamics of the accumulation or dispersion of fluids along slopes. To analyze this parameter, we produced the slope chart using the ALOS-PALSAR Digital Elevation Model.
- Impact of vadose zone media (I): The impact of vadose zone media represents the influence that the constituent materials of the region between the superficial soil and the water table infer from the contamination of the underground water resources. This information comes from the deep well lithology data analysis [48].
- Hydraulic conductivity (C): According to Aller et al. [30], hydraulic conductivity is the ability of the aquifer's constituent materials to transmit underground water, controlled by a hydraulic gradient. As a result, the higher the material's hydraulic conductivity, the greater the aquifer's vulnerability to contamination. Based on a review of the literature and the values suggested in CPRM [48] and Tanajura and Leite [53], the hydraulic conductivity values used in this study come from an analysis of the aquifer's materials.
- Land use (LU): The groundwater quality of the study area has been deteriorating mainly due to the uncontrolled use of pesticides in monocultures, especially sugar cane. To assess the relationship between hydrogeological parameters and the pattern of land use, it is essential to indicate the most vulnerable areas to contamination. We derived the land use data from the MapBiomas project [54]. We adapted the assigned vulnerability values from Alam et al. [35], taking into account the Brazilian scenario.

3.2. Values Assigned to Hydrogeological Parameters

In Table 2, we present the values assigned to each attribute of the eight parameters of the model, according to the PESTICIDE-DRASTIC-LU methodology, adapted to the study area's characteristics, with the help of experts on the subject and in related studies, such as those of [24,55–57].

Table 2. Values assigned to hydrogeological parameters.

Value	Hydrogeological Parameters							
	D	R	A	S	T	I	C	LU
1	>30.5	Itaqueri	--	Red Nitisols Loamy Ultisols	>18	Confining Layer	<4.1	Natural formations, Water
2	22.9–30.5	--	Serra Geral	Red Oxisols;	--		--	Pasture
3	15.22–22.9	--	--	--	12–18	-- Basalt	--	--
4	--	--	Itaqueri	Sandy Ultisols	--	--	--	--
5	9.1–15.2	--	--	--	6–12	--	--	--
6	--	--	--	--	--	--	--	Forestry
7	4.6–9.1	--	--	Red-Yellow Oxisols	--	--	--	Annual Crops

Table 2. *Cont.*

Value	Hydrogeological Parameters							
	D	R	A	S	T	I	C	LU
8	--	Serra Geral	--	Lithic Entisols	--	--	--	Sugar Cane
9	1.5–4.6	Pirambóia Botucatu Alluvium Colluvium	Alluvium Colluvium	Quartzipsamments Entisols Alfisols	2–6	Sand (1)	--	Urban
10	<1.5	--	Botucatu Pirambóia	--	<2	Sand (2)	--	Bare Soil

3.3. Parameters' Index Values

The parameter index is the value (weight) assigned to each of the eight input data for executing PESTICIDE-DRASTIC-LU. Those values (Table 3) represent the relative importance of the analyzed parameters, determined from the adaptation of Saha and Alam [58].

Table 3. Parameters' index values.

	Parameters' Index Values							
	D	R	A	S	T	I	C	LU
PESTICIDE DRASTIC-LU	5	4	3	5	3	4	2	5

3.4. Ranges of DRASTIC-LU Index

The parameters for the application of PESTICIDE-DRASTIC-LU are depth to water (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone media (I), hydraulic conductivity of the aquifer (C) and land use (LU), which are based on Aller et al. [30] and Alam et al. [35]. The systematization of the model occurs from the following equation, adapted from Saha and Alam [58] and Alam et al. [35], and applied with the "raster calculator" tool in ArcGis 10.6:

$$\text{Vulnerability} = D(p) \times D(i) + R(p) \times R(i) + A(p) \times A(i) + S(p) \times S(i) + T(p) \times T(i) + I(p) \times (i) + C(p) \times C(i) + LU(p) \times LU(i)$$

where (p) are PESTICIDE-DRASTIC-LU parameters weights values and (i) are the index values for each parameter

The values resulting from the application of the PESTICIDE-DRASTIC-LU model were classified into four classes of contamination vulnerability, as shown in Table 4. We adapted the ranges of the original PESTICIDE-DRASTIC-LU indices to make this method compatible with the reality of Brazilian landscapes.

Table 4. Ranges of DRASTIC-LU index.

PDRASTIC-LU Index	PDRASTIC-LU Value	Color in the Map
Low	<120	Green
Moderate	120–160	Yellow
High	160–200	Orange
Very High	>200	Red

The resulting map of this methodology presents four zones of vulnerability. These zones spatially indicate priority areas for the conservation of groundwater ecosystem services in the municipality of Brotas.

4. Results

4.1. PESTICIDE-DRASTIC-LU Parameters

The eight hydrogeological variables that served as the input data for PESTICIDE-DRASTIC-LU's execution were the first products to be produced following the application of the methodological model. For the municipality of Brotas, Brazil, Figure 3 displays the parameters that have already been reclassified using the values suggested by Aller et al. [30] and Alam et al. [35].

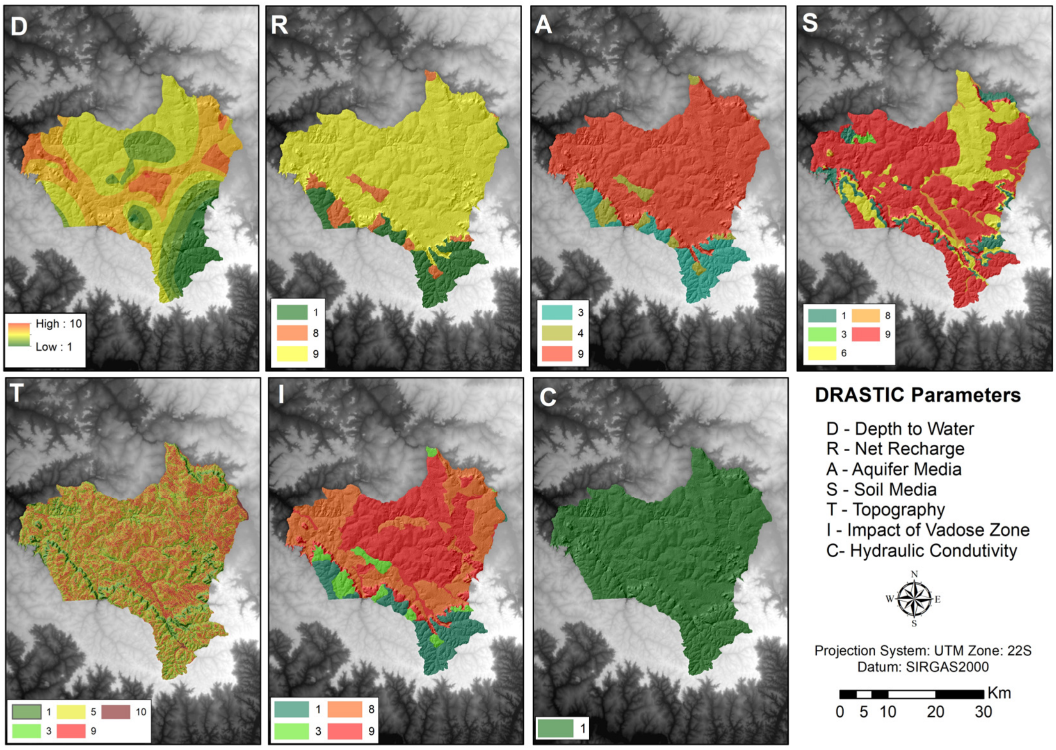

Figure 3. PESTICIDE-DRASTIC-LU parameters.

Through local geological dynamics, observable through the recharge map, we observe that 67% of the territory is occupied by the Botucatu and Pirambóia geological formations, i.e., the main structure of the Guarani aquifer, which includes sandstones formed in a desert environment [59,60]. Soils, as a reflection of geological processes, present favorable conditions for infiltration in more than 70% of the territory, with the main emphasis on lithic entisols, quartzipsamments entisols, and sandy ultisols. This geological and pedological makeup has a direct effect on the aquifer media, soil media, impact on the vadose zone, and recharge. This means that the aquifer can be very naturally vulnerable [37]. Another factor that increases local vulnerability is the topography since 41% of the area represents flat relief (slope < 6%), which favors soil infiltration. On the other hand, 59% of the land has steeper slopes (between 6 and 100%), which are places with more runoff and less chance of contamination.

Land use reveals a significant anthropogenic intervention, which directly affects the stability of the landscape dynamics, including ecosystem services provided by groundwater [58]. Brotas' land use reflects Brazil's history of producing agricultural commodities, meeting the current pattern of appropriation of rural areas in the State of São Paulo with the vast production of sugar cane. The current occupation demonstrates that the municipality has undergone an intense process of alterations in recent decades, substituting natural formations of Cerrado for crops and pastures [61,62].

4.2. Groundwater Vulnerability—PESTICIDE-DRASTIC-LU Model

After overlapping the basic parameters, the application of the Pesticide-DRASTIC-LU resulted in a cartographic product (Figure 4.a), which spatially demonstrates four zones according to the degree of the aquifer's vulnerability to contamination. The modeling of these areas aimed to identify which parts of the territory are less or more susceptible to the loss of groundwater ecosystem services, mainly the provision of quality water for human supply and crop maintenance.

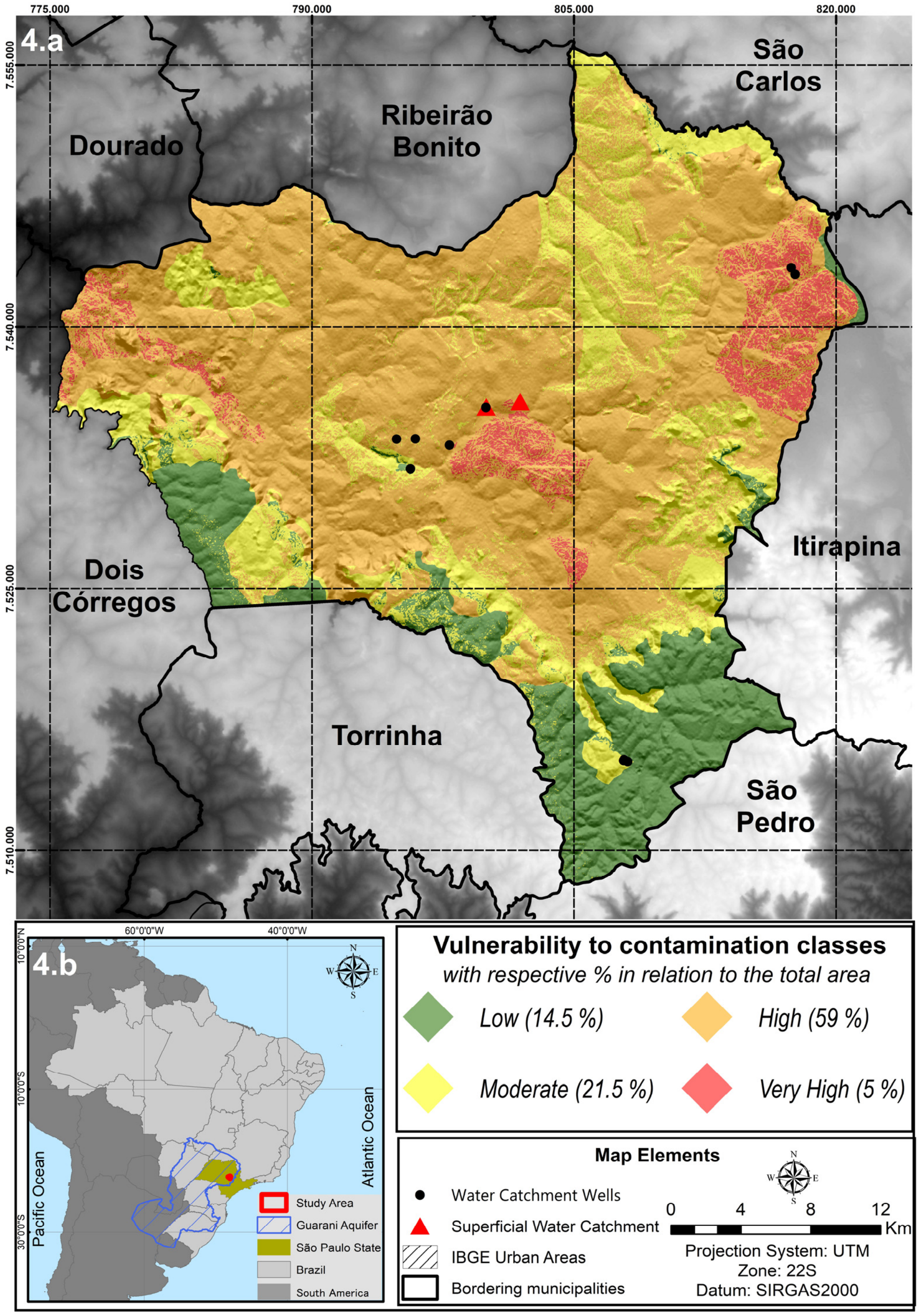

Figure 4. PESTICIDE-DRASTIC-LU chart. (**4.a**) PESTICIDE-DRASTIC-LU classes in Brotas, SP, Brazil. (**4.b**) Study area location in relation to South America, Brazil, GAS and the state of São Paulo.

4.2.1. Low Vulnerability

Areas of low vulnerability occupy only 14.5% of the territory and indicate the places where the probability of aquifer contamination is lower, resulting in greater protection for ecosystem services provided by groundwater. Hydrogeological parameters related to geology and soils directly influence these areas, as basaltic outcrops prevent pollutants from infiltrating, thereby enhancing aquifer protection. In addition, the resulting model output demonstrated a significant correlation with the presence of preserved forests, reinforcing the need for territorial planning to include reforestation programs to maintain the ecological balance of this type of land occupation.

In summary, these areas represent sectors of stability and protection for ecosystem services, allowing municipal managers to direct essential activities with greater degrading action, such as heavy industries and crops. Although we consider encouraging sustainable development as an essential factor for Brazilian landscapes, we cannot neglect the national history of producing agricultural and industrial commodities. Therefore, it is crucial to implement activities of greater degradation with a technical understanding of the territory, ensuring they pose the least possible risk to ecosystem services provided by natural resources.

4.2.2. Moderate Vulnerability

The moderate vulnerability class represents 21.5% of the Brotas landscape, being a transition zone between areas of low vulnerability and regions with a greater chance of aquifer contamination occurring. This region contains a strong spatial correlation with the topographic thresholds, where the larger slopes increase the runoff and contribute to the protection against contamination. Furthermore, several forest remnants are observed, which, in addition to their importance in providing ecosystem services on the surface, directly contribute to less vulnerability.

Our results also show that these areas occupy the transition between the geological formations Itaqueri and Botucatu/Pirambóia as well as some sparse areas where there is a slightly steeper slope. Despite the steeper slope, these areas are already better suited to certain types of anthropogenic use without major groundwater contamination risks.

Even if it represents a relatively greater security for the aquifer, it is imperative that, due to the landscape structure, land use be regulated to limit uses with a high degree of degradation to prevent these areas from shifting to high vulnerability.

4.2.3. High Vulnerability

The fact that 59% of the study area has a high vulnerability to pesticide contamination highlights the concern about the conflicting relationship between monocultures and aquifers. This class demonstrates that, spatially, the aquifer media, soil media, recharge, and impact of vadose zone parameters have a high correlation with the vulnerability index. These areas consist of the sandy geological formations of the Botucatu and Pirambóia formations, which, due to their sandy structure and porosity, imply a dichotomy: a high infiltration capacity to recharge the aquifer, while improper land uses directly correlate to an increased vulnerability to contamination. Corroborating these results are analyses promoted by Reporter Brasil [63], who, using Brazilian Ministry of Health data, diagnosed 27 pesticides in water and soil in the municipality of Brotas, most of them related to monocultures such as sugarcane.

4.2.4. Very High Vulnerability

Locations mapped as having a very high vulnerability represent 5% of the study area and reveal where the landscape is under more pressure due to the relationship between the natural dynamics of the physical environment and anthropogenic activities. This analysis is based on the argument that local ecosystem services may suffer a decrease in quality and quantity, harming local society, the environment, and the economy.

These highly vulnerable zones indicate that the relationships between internal and external geodynamics intervene negatively in aquifers, causing ecodynamic instability. Thus, the local geoenvironmental structure is highly susceptible to anthropogenic changes promoted in the surface, lacking agricultural practices and/or territorial planning aimed at sustainable use of the territory to promote the conservation of essential ecosystem services provided.

To provide an overview of the local environment concerning the mapped vulnerability classes, Figure 5 depicts regions of significance within the municipality of Brotas.

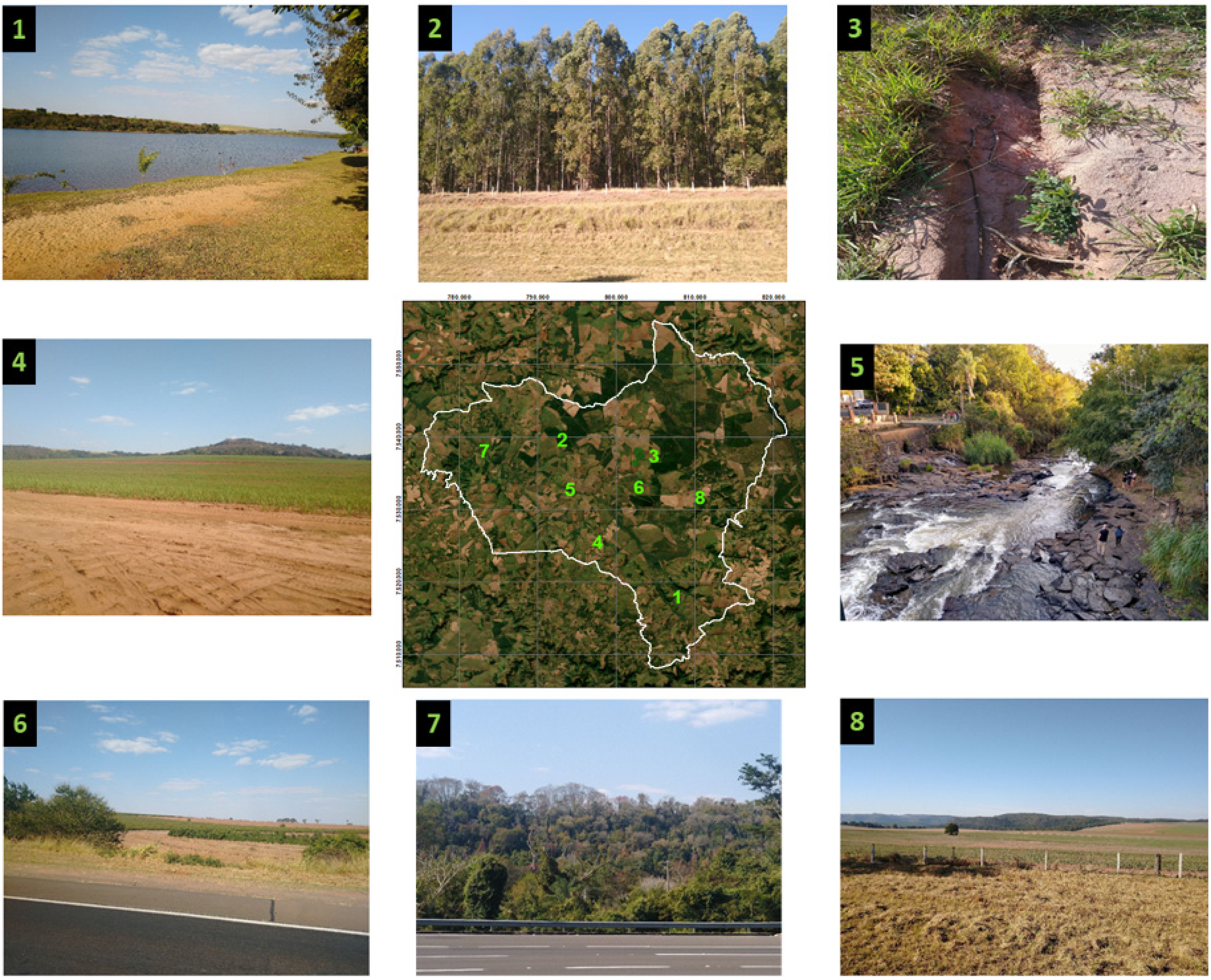

Figure 5. Landscapes that illustrate the mapped vulnerability classes in the municipality of Brotas: (1) Patrimonio Dam, over the Itaqueri formation; (2) eucalyptus silviculture, on the Botucatu formation; (3) example of sandy soil from the Botucatu formation; (4) sandy soil from the Pirambóia Formation, with the Itaqueri mountain range in the background; (5) Jacaré Pepira River; (6) mosaic containing sugarcane and coffee farming, and remnants of natural vegetation, demonstrating the heterogeneity of the landscape; (7) dense remnant of natural vegetation; (8) flat area (Pirambóia and Botucatu Formations) in contact with the Itaqueri Formation (area with higher altitude, in the background.

5. Discussion

The originally proposed DRASTIC methodology seeks to assess the natural vulnerability of territories to aquifer contamination [30,51]. However, the Guarani aquifer's great concern over the relationship between groundwater and anthropogenic activities, particularly agricultural ones, justifies the application of the PESTICIDE-DRASTIC-LU variation by Alam et al. [35], which aims to incorporate land use into the hydrogeological analysis.

Our model results also indicate that the topographic factor has a strong relationship with the areas of greatest vulnerability, since infiltration over the lower slopes exceeds runoff and contributes directly to their vulnerability. The study by Trevisan et al. [62] in a Tunisian aquifer also obtained similar results. In addition to this, there is a greater probability of the implementation of mechanized monocultures in flatter terrains, which contribute to the degradation of groundwater ecosystem services [63].

Currently, land use in the most vulnerable areas shows a high degree of anthropogenic activity, mainly sugarcane, annual crops (orange and coffee), forestry, and pastures [54]. We also see vegetation in the floodplains of the largest rivers that cross these areas. Due to its high degree of ecodynamic instability and risk to the ecosystem services provided, this zone is very unsuitable for anthropogenic use when it comes to aquifer protection. Thus, it demands emergency actions for protection, conservation, and remediation, as well as the restriction of any anthropogenic land use.

The advance of sugarcane planting in vulnerable areas is corroborated by information released by IBGE [64], which presents that sugarcane production in Brotas experienced a notable surge, rising from 480,000 tonnes in 1994 to 2640 tonnes in 2018. In twenty-four years, this represents a 550% increase in the planted area, proving that the expansion of commodity agriculture is a major force transforming the local landscape.

Considering that the Guarani aquifer recharge zones make up 85% of Brotas [8], the indiscriminate use of pesticides in crops, particularly sugarcane, is a growing concern. According to Valadares et al. [65], Brotas is part of a group of municipalities that registered a significant increase in the use of pesticides in the period from 2006 to 2017. Among these pesticides, 2.4D and Tebuconazole stand out due to their extensive use in the sugar and alcohol industry [63], indicating the conflicting relationship between groundwater and land use.

Upon analyzing the vulnerability outputs, it becomes evident that 64% of the municipality corresponds to high or very high vulnerability areas, which exacerbates these concerns. The susceptibility of the hydrogeological materials due to their sandy characteristics also exposes the 'high' and 'very high' zones to various geo-environmental landscape risks, making it a challenge to integrate economic development based on the production of agricultural commodities with the maintenance of the ecosystem services that the GSA provides [66].

Given the impossibility of removing sugarcane crops from the entire study area, it is suggested that the planting approach be rethought, leading to proposals with a sustainable bias. As examples, we can mention agroecological techniques [67], analysis of soil productivity [68], using natural resource management interventions [69], and investing in sustainable agriculture strategies [70,71].

Comparably, in relation to the interaction between human activity and nature, several authors discuss the impact of inadequate land use on aquifers, indicating a negative effect of increased anthropogenic landscapes on groundwater quality around the world [69,72,73]. In the municipality of Brotas, systematic mapping data from MapBiomas [54] present a scenario of intense land use conversion in the last 30 years, with the advance of sugarcane over areas that once represented remnants of the Brazilian Cerrado [74].

When comparing the current land use with the geoenvironmental aspects analyzed during the mapping, it is possible to affirm the need for instruments that legally control land use in the municipality of Brotas. We can cite efficient sustainable instruments such as environmental zoning, as proposed by Guerrero et al. [75,76], and MMA [77], and the insertion of sustainable laws in the municipal master plan, which is one of Brazil's main urban management tools.

We also emphasize that in areas of very high vulnerability, the local government must restrict all anthropogenic uses to protect the aquifer's quality. Transforming these areas into integral conservation units using reforestation projects is an alternative that can be efficient in reframing the landscape in favor of the preservation of ecosystem services assured by the Guarani aquifer.

Finally, the results from the vulnerability analysis highlight the importance of the Guarani aquifer to public authorities' considering areas of high and very high vulnerability as a priority for the preservation of ecosystem services in their territorial planning projects. As proposed by Costanza et al. [78], the integration of ecosystem services in planning processes provides an appropriate approach for a better balance of ecological and socio-economic aspects within the context of sustainable development.

6. Conclusions

Assessing vulnerability to groundwater contamination is an indispensable tool in land planning and management projects, especially when it has a cartographic character, since it allows identifying the most vulnerable areas spatially and those that require greater attention from the public authorities.

Strategic environmental planning is particularly interested in the Brotas territory, a Brazilian municipality, due to its 100% integration into the vast Guarani aquifer system and the 85% of its territory that serves as recharge areas.

The research indicated four vulnerability zones for the PESTICIDE-DRASTIC-LU model. The analysis also demonstrated a strong relationship between the Guarani aquifer sandstones and their vulnerability to contamination. The study area's low forest presence and high spatial representativeness of crops exacerbate this factor.

The PESTICIDE-DRASTIC-LU model proved to be an efficient alternative for the conservation of groundwater ecosystem services in areas where crops predominate in the landscape. When considering the dynamics of both pesticides and the local geoenvironmental structure, it was possible to indicate that 64% of the study area has high or very high vulnerabilities, spatially determining that such areas are a priority for conservation.

For the environmental, social, and economic sustainability of the Guarani aquifer areas, it is critical to reconsider landscape management practices in light of the territory's limitations and opportunities. This is particularly true for managers, who are tasked with implementing sustainable development-based programs and techniques to ensure the continuity of groundwater ecosystem services.

Therefore, it can be concluded that the use of the PESTICIDE-DRASTIC-LU framework generates indispensable technical reports for public administrators. It is possible to direct territorial planning actions based on scientific and technical advice using the final charts, which provide managers with an integrated information base consisting of diagnoses and solutions to the presented problems.

Although this was not one of the objectives of this study, we can point out the lack of comparison with field contamination data as a limitation. In this sense, it is worth highlighting the current limitations in the availability of contamination data in Brazilian territory in terms of spatial and temporal coverage.

Based on the definition of vulnerability zones proposed in this study, it is recommended that studies be carried out to evaluate the quality of groundwater, especially where there is concomitance between zones of high vulnerability and land uses focused on sugarcane and urban and industrial activities.

Author Contributions: Conceptualization, J.V.G., A.G., J.A.D.L. and R.L.; methodology, J.V.G. and A.G.; formal analysis, J.V.G., A.G., L.E.M., G.M., R.L., J.A.D.L. and L.E.M.; investigation, J.V.G. and A.G.; resources, J.V.G. and L.E.M.; data curation, J.V.G., A.G. and L.E.M.; writing—original draft preparation, J.V.G. and A.G.; writing—review and editing, J.V.G., A.G., L.E.M., G.M., R.L., J.A.D.L.

and L.E.M.; supervision, L.E.M.; project administration L.E.M.; funding acquisition, J.V.G., A.G. and L.E.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by São Paulo Research Foundation—FAPESP, Grants 2016/19020-0 (João Guerrero), 2019/25701-8 and 2023/03206-0 (Guilherme Mataveli), and by the Foundation for Science and Technology by FEDER funding through the COMPETE 2020 programme and framed within the activities of UIDB/04084/2020—CEGOT financed through the European Regional Development Fund (COMPETE 2020), with ref. POCI-01-0145-FEDER-006891. (Alberto Gomes).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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