ASSESSING AND MITIGATING THE IMPACTS OF CLIMATE CHANGE & HUMAN ACTIVITIES ON GROUNDWATER QUANTITY AND QUALITY OF THE GUARANI AQUIFER IN RIBERAO PRETO, BRAZIL*

RELEVAMIENTO Y MITIGACIÓN DE LOS IMPACTOS DEL CAMBIO CLIMÁTICO Y ACTIVIDADES HUMANAS EN LA CANTIDAD Y CALIDAD DEL AGUA SUBTERRÁNEA DEL ACUÍFERO GUARANI EN RIBEIRÃO PRETO, BRASIL

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Abstract

The Guarani aquifer is one of the largest sources of good quality groundwater in the world, underlying 4 South American countries. In areas such as the city of Ribeirao Preto (Brazil), the aquifer is being used intensively in the last 30 years, which has caused a drawdown of over 60m. Furthermore, many of the aquifer's recharge areas are being used extensively with intensive agriculture, which could lead to groundwater contamination. In addition to these human impacts, there are also the threats of climate change, which could increase the risks to the aquifer's sustainability in the future. The objectives of the present paper were to quantify the present risks to groundwater quantity and quality, and to assess the risks associated with population growth and climate change in the next 50 years. The selected area was a polygon of 2,500 km^2 around the city of Ribeirao Preto, and the scenarios analyzed where those related to the best and worst-case conditions, as well as an intermediary (trend) scenario, for both population and climate. As far as water quantity is concerned, the decreasing groundwater recharge due to climate change and the increasing demand (pumping) in the urban area of Ribeirao Preto could lead to the total depletion of the groundwater around the year 2050. The particular geological setting, reducing the regional groundwater fluxes, contributes to this scenario. However, in 2007 about 65% of the groundwater volume still remained unused, which allows for the implementation of a sustainable groundwater management. As for groundwater quality, a contamination risk analysis, which is function of the area vulnerability and potential of contamination of the agricultural areas, indicates that 90 km^2 of the recharge area present high risk to contamination. Mitigation and adaptation measures were then suggested to the impacts to groundwater quantity and quality. The most viable were the utilization of supplementary water from the Pardo river, and the use of environmentally friendly pesticides, respectively.

Resumen

El acuífero Guaraní es uno de las más grandes fuentes de agua subterránea de buena calidad en el mundo, ubicado en 4 países sudamericanos. En regiones como la ciudad de Ribeirão Preto (Brasil), el acuífero viene siendo utilizado intensamente en los últimos 30 años, lo que ha causado una caída de más de 60 m. Además, muchas áreas de recarga del acuífero vienen siendo utilizadas con agricultura intensiva, la cual podría llevar a su contaminación. Existen también riesgos de cambio climático, que podrían aumentar los riesgos de sostenibilidad del acuífero en el futuro. Los objetivos de este trabajo fueron cuantificar los riesgos actuales a la cantidad y calidad de agua y estimar los riesgos relativos al aumento de la población y cambio climático en los próximos 50 años. El área seleccionada para el estudio fue un polígono de 2.500 km^2 alrededor de la ciudad de Ribeirão Preto, y las condiciones analizadas fueron aquellas relativas al mejor y peor escenario, y un escenario intermedio, para la población y clima. En términos de cantidad de agua, la disminución de la recarga por el cambio climático y por el aumento del bombeo (demanda) en la zona urbana podría llevar a una depleción del agua subterránea en el año 2050. La situación geológica particular del acuífero local, reduciendo el flujo de agua subterránea regional, contribuye a la tendencia de reducción. Entretanto, como el 65% del volumen del agua subterránea no había sido utilizado todavía en 2007, aún es posible manejarla visando su sustentabilidad futura. En términos de calidad del agua, un análisis de riesgo, basado en la vulnerabilidad y el potencial de contaminación de las áreas agrícolas, indicó que 90km^2 del área de recarga presentan alto riesgo de contaminación. Medidas de mitigación y adaptación fueron entonces sugeridas para la gestión del acuífero. Las medidas identificadas como más viables fueron el uso suplementar de agua del río Pardo (cantidad) y el uso de pesticidas de menor impacto (calidad).

INTRODUCTION

The Guarani aquifer is one of the largest sources of groundwater in the world. Although it presents high volumes and water yields, there are risks to its sustainability, particularly when pumping rates are higher than its natural recharge, and unsuitable land uses lye over sensitive recharge areas.

When those two impacts occur simultaneously, the risks increase. Furthermore, there is the potential impact of climate change, which could add even more risk to the aquifer sustainability.

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Those potential impacts exist in the region of Ribeirao Preto (Brazil), where a fast-growing agribusiness-based economy increasingly demands more water, and where sensitive groundwater recharge areas are being intensively farmed with sugar-cane.

In the urban area of Ribeirao Preto, which is supplied exclusively by groundwater from the Guarani aquifer, the overdraft has caused a significant drawdown of the original groundwater level in a period of 50 years (FIPAI, 1996).

The risks of groundwater contamination are also present. The high vulnerability of coarse-textured soils to pesticide and mollasse leaching, and the intensive farming of sugar cane in recharge areas could lead to a serious groundwater contamination in the future.

The objectives of this paper were three-fold: i) to examine the risks of groundwater depletion in the city of Ribeirao Preto, ii) to evaluate the risk of groundwater contamination of the Guarani recharge areas, and iii) to identify adequate adaptation and mitigation measures to reduce those risks.

Different scenarios were analyzed: a) the population and climate trend for the next 50 years, b) the best-case scenario (population & climate), and c) the worst-case scenario.

METHODOLOGY

Description of the Study Area

The study area was a polygon of 2.500 km^2 around the city of Ribeirão Preto (Brazil), which included other 11 small cities. Geologically, the study area is comprised by the sandstones of the Bauru, Botucatu and Piramboia formations (Guarani aquifer), covered by the Serra Geral formation (basalt).

The soils are deep, well drained Oxisols (red latosols) and inceptisols (yellow-red latosos). The groundwater recharge areas are zones where the Botucatu and Piramboia formations surface in the landscape, particularly in the eastern part of the study region. Figures 1 & 2 show the geology and recharge zones of the study area, and Figure 2 shows the main soil classes.

The major land uses in the study area include sugar cane crops (80% or 2.000 km^2) and urban areas 15% or 400 km^2), as seen from Figure 4.

The total population of the study area, including the city of Ribeirão Preto and other 10 smaller cities, was 813.000 inhabitants in 2007, mostly concentrated in the urban areas. The monthly potable water consumption in the study area in 2007 was 7.8 million m^3.

The city of Ribeirão Preto, located in the center of the study area (Figure 2, right), with 572.000 inhabitants in 2007, is totally supplied with groundwater from the Guarani aquifer. There are about 300 deep wells in the urban area, pumping about 10 million m^3/month of groundwater.

The natural groundwater recharge, however, is only about 580.000 m^3/month or about 6% of the water use (COPLAN, 2004), indicating a serious over pumping. Additionally, the city lies in a valley, where the watershed boundary coincides with the groundwater di-

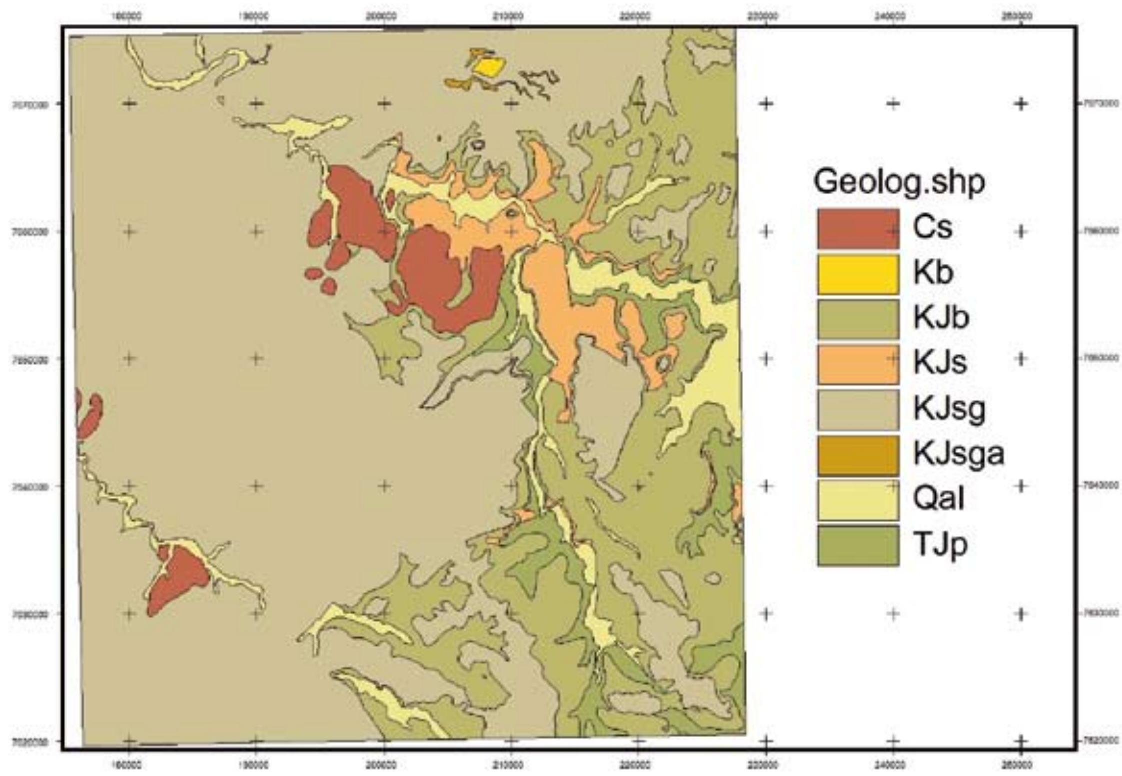

Figure 1. Geology of the study area (Source: Sinelli et al (1973)

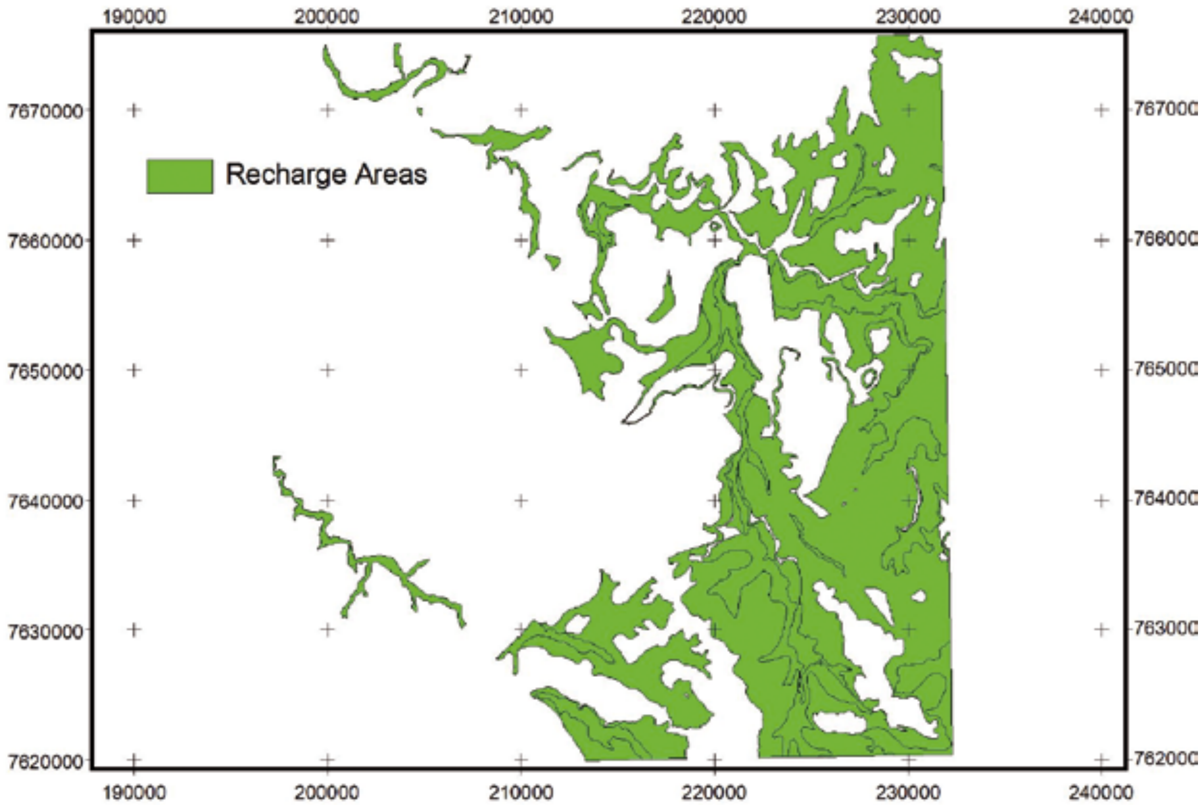

Figure 2. Recharge zones of the study area

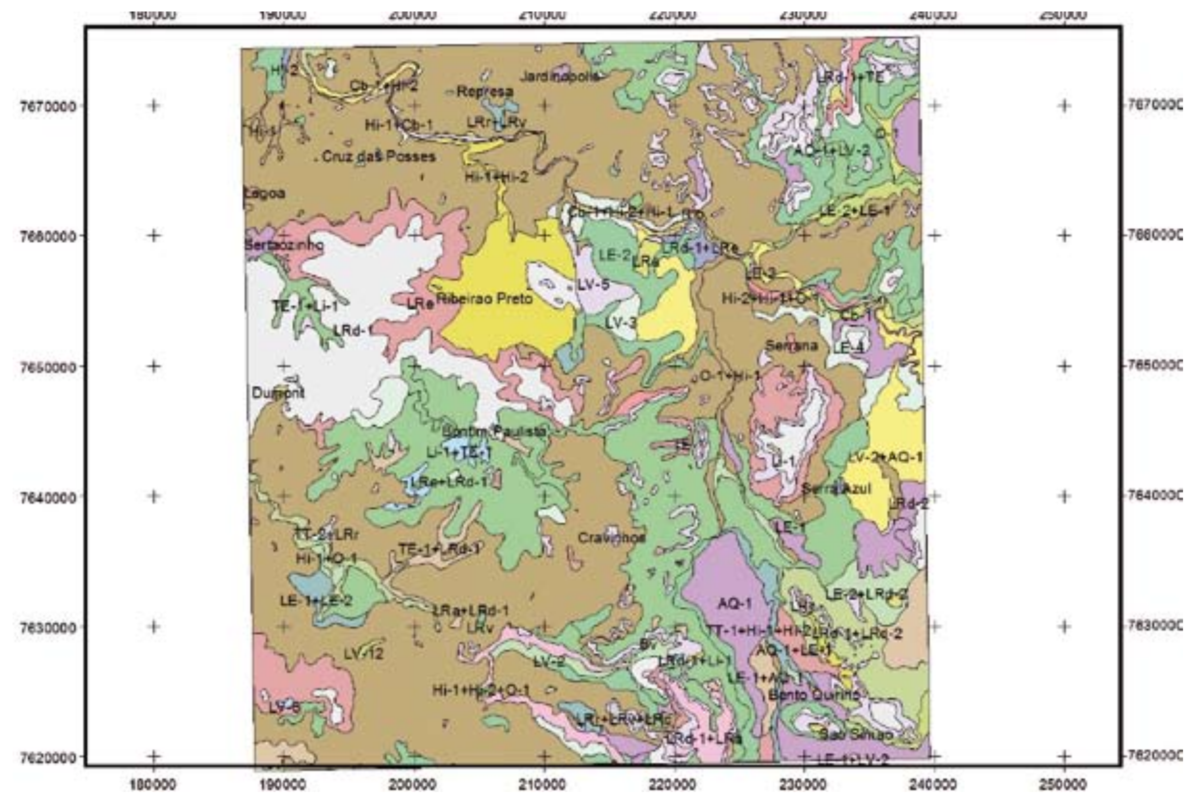

Figure 3. Soils of the study area. Source: Oliveira & Prado (1987)

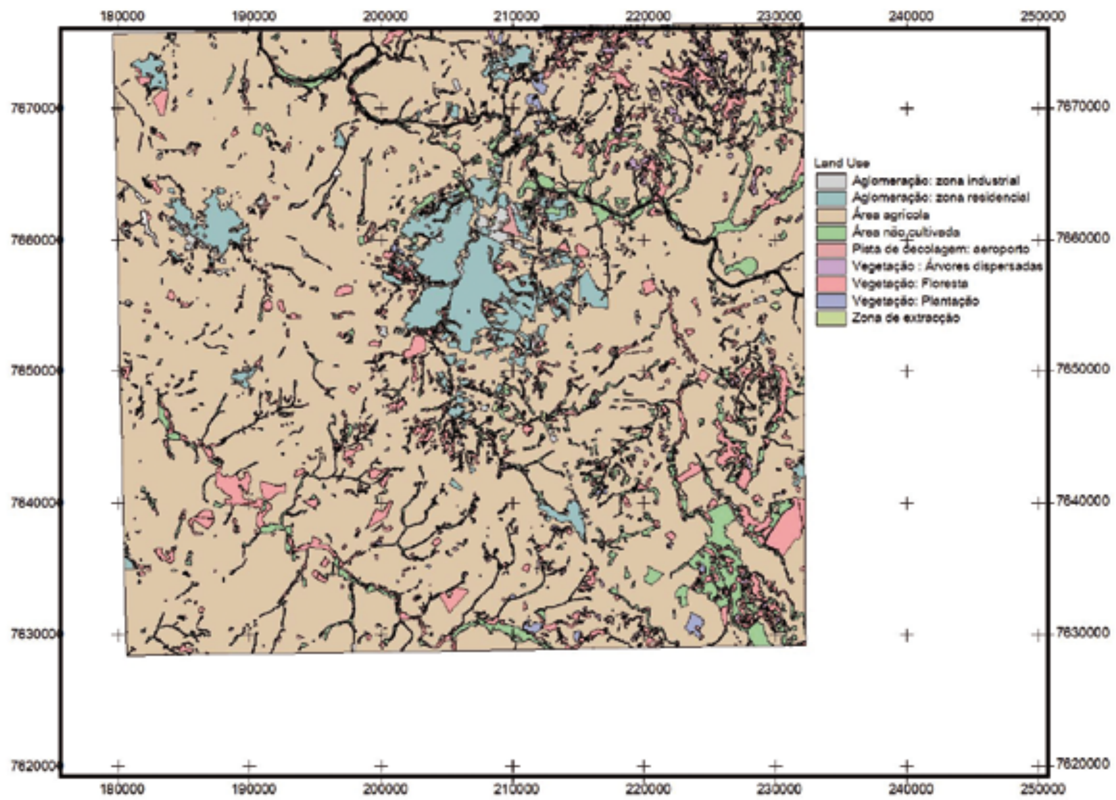

Figure 4. Land use in the study area. Agricultural areas are shown in brown

vide, reducing the lateral fluxes of groundwater from the recharge zones.

Population and Climate Change Scenarios

In order to evaluate the impacts to groundwater quantity and quality in the next 50 years, projections of population growth and climate change were established, considering the present trend, best case, and worst case scenarios.

In the case of the population, the trend obtained in the last 30 years (IBGE, 2008) was extrapolated. The best-case scenario was that of the tendency line less 10%, and the worst-case scenario was the future trend plus 10%. The climate change scenarios were the IPCC's (2008) B2 (best-case), A2 (worst-case), and intermediate (average between A2 and B2) scenarios, respectively.

The temperature increases forecasted by Ambrizzi et al (2007) for the study area in the 3 above mentioned scenarios were then used to compute the water excess curves, using Salatti et al (2007) projections for the nearby city of Piracicaba.

According to Ambrizzi et al (2004), yearly average temperatures are expected to increase by 3^{o}C, 2,5^{o}C and 3,5^{o}C by 2080, in the most probable, best-case, and worst-case scenarios, respectively. Those temperature increases were then applied to the water excess function developed by Salati et al (2007) to estimate the expected change in groundwater recharge in the study area (Figure 5).

According to Figure 3, groundwater recharge in Ribeirao Preto will be reduced by about 17% in 2050, with respect to the year 2000, due mainly to temperature increase.

As for the population and water consumption change between 2000 and 2050, they are presented Figures 6 and 7, for the three selected scenarios. According to those figures, the total population and the water consumption will increase significantly.

Analysis of the Depletion Risk of the Guarani Aquifer in Ribeirao Preto

Due to the confinement of the overlying basalt, and to the eastern and western groundwater divides, the Guarani aquifer under the city of Ribeirao Preto presents a low transmissivity. Consequently, it is subject to depletion, particularly if the pumping rates exceed the groundwater recharge rates.

The risk of depletion of the Guarani aquifer in the city of Ribeirao Preto was estimated with the production frontier approach (Pearce, 1976). This approach allows the estimation of the remaining groundwater volume at the time t+1 based on the estimated based on the initial quantity Q, the pumping rate (p) and the recharge rate (r) (Figure 8).

The initial exploitable volume Q under the city of Ribeirao Preto was estimated to be 10,8 billion m^3 in 1950 (Fipai, 1996), the time when groundwater began to be pumped from the aquifer. The depletion risk was assumed to the tangent of the slope angle

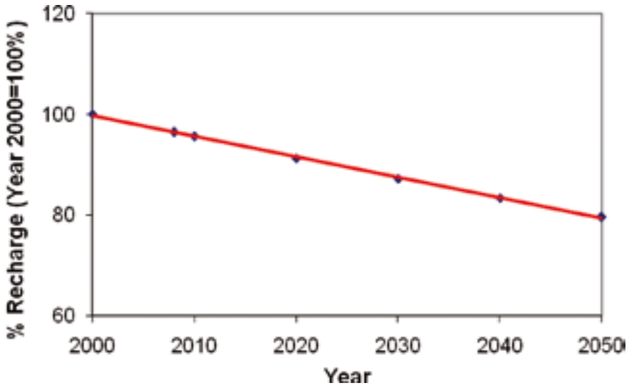

Figure 5. Reduction in groundwater recharge between 2000 and 2050 in the study area (scenario B2)

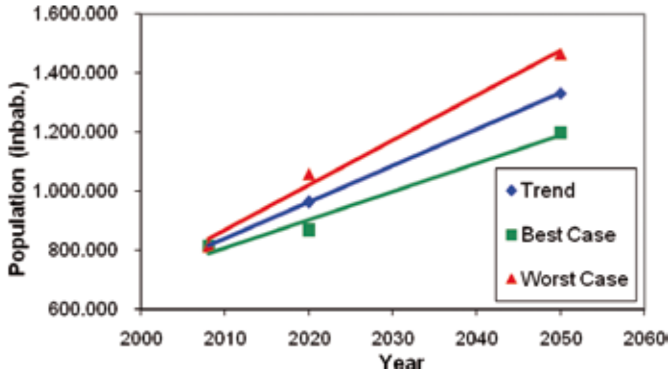

Figure 6. Population trends in the different scenarios, for the study area

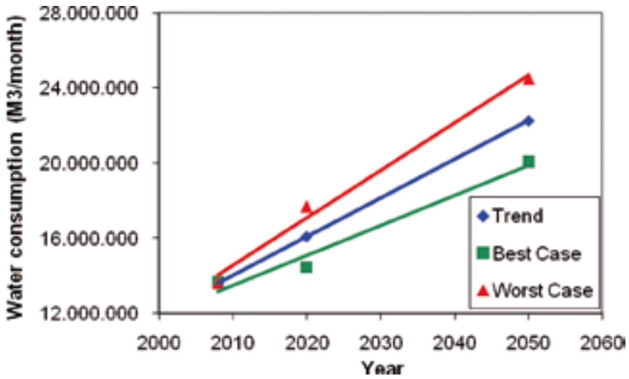

Figure 7. Trends in water consumption in the different scenarios, for the study area

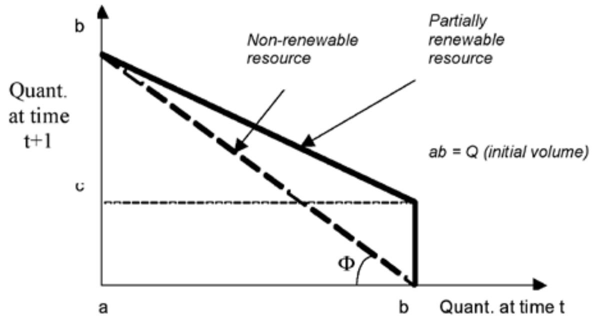

Figure 8. Production frontier of non-renewable resources (Adapted from Pearce, 1976)

(Φ) of the production frontier, as shown in Figure 8. The steeper the slope of the production frontier, the higher the risk, and vice-versa.

Vulnerability and Risk of Contamination of the Guarani Recharge Areas

In addition to the risks of groundwater depletion in the urban zones of the study area, there are risks related to the contamination of the aquifer by pesticides, particularly in the vulnerable recharge areas.

The contamination risk (R_c) was defined as the product of the contamination vulnerability (V), which is a function of the natural soil and geologic conditions, and the contamination potential (C_p), which is related to the characteristics and load of the contaminant (Foster & Hirata (1988):

$$R_c = V \cdot C_p \quad [1]$$

The vulnerability of the recharge area was estimated by the product of the soil clay content (%C), the soil permeability (Perm), and the soil depth (D) (Chaves, 2008):

$$V = \%C \cdot Perm \cdot D \quad [2]$$

Each of the factors of equation 2 varies from 1 to 3, based on their minimum and maximum values, and therefore V varies from 1-27. Tables 1 and 2 present the levels of the factors and vulnerability of equation 2, considering the soils of the study area.

Although equations 1 & 2 are very simple, they are good indicator about the vulnerability of the aquifer recharge areas.

The contamination potential (C_p) was estimated by the product of the pesticide application volume (Vol, in L), the pesticide toxicity (T), with toxicity classes varying from 1-4, established from the pesticide LD_{50} in mice, and the groundwater ubiquity score (GUS), the latter defined by Gustafson (1991):

$$C_p = Vol \cdot T \cdot GUS \quad [3]$$

Where:

$$GUS = \log_{10}(t_{1/2}) \cdot [4 - \log_{10}(K_{oc})] \quad [4]$$

In equation [4], $t_{1/2}$ is the half-life (in days) of the pesticide, and K_{oc} = soil and organic matter adsorption coefficient (l/kg). Equations 3 and 4 were applied to the herbicides, which are the pesticides most used in the study area.

After the numerical product of pesticide *i* in equation 3 is obtained, it was normalized, i.e., $C_p = (Cp_i - Cp_{min})/(Cp_{max} - Cp_{min})$), and divided into 3 classes (low, medium and high contamination potentials), spanning the range of C_p.

The contamination risk (R_c), which is the product of the vulnerability (V) and the contamination potential (C_p) was classified in three levels, namely, low, medium and high (Table 3).

The next step was to map the study area with respect to contamination vulnerability, contamination potential and contamination risk, based on the soils and land use of the recharge zones, as well as equations 1, 2 & 3 and tables 1, 2 & 3.

Mitigating the Impacts to Groundwater Quantity & Quality in the Study Area

In order to mitigate the potential impacts to groundwater quality and quantity in the study area, appropriate measures were identified and evaluated, considering their socioeconomic and environmental feasibility.

The socioeconomic and environmental feasibility F was estimated using a simple optimization approach (see Turban & Aronson, 1998), where the indicators were the environmental risk (R) of the measure, its social impact (S), and its cost (C). The most viable measure was that that minimized the product:

$$F = R \cdot S \cdot C \quad [5]$$

subject to the following constraints:

$$R < \rho,\ S < \sigma,\ C < \chi \quad [6]$$

where ρ, σ, χ are maximum acceptable values for R, S and C, respectively. The details of the optimization model [5, 6] are described in detail in Chaves (2008).

The environmental risk parameter for groundwater quantity was the slope of the groundwater production frontier (tan Φ of Figure 5), the social impact parameter was the reciprocal of Marshall's consumer surplus function, and the cost parameter was the alternative cost, considering implementation, its operation and maintenance.

Among the measures considered for reducing the risk to groundwater depletion in the city of Ribeirao Preto were the use of water from the nearby Pardo river and the use of well fields in the less developed rural areas.

In the case of the reduction of the risks to the contamination of the recharge areas, the measures considered were the protection of vulnerable areas and the use of pesticides with less contamination potential, using the philosophy of the Water Provider Program (Chaves et al, 2004). In that program, the contamination abatement is estimated by the following function:

$$C_a = 100\,[1 - (Cp_1/Cp_0)] \quad [7]$$

where C_a = % of contamination abatement, Cp_1 = contamination potential using BMPs, and Cp_0 = con-

Table 1. Vulnerability factors and values for the soils of the study areas.

Soil Type	%C	Level	Perm.	Level	D	Level	Vuln.	Level
Psaments (Neossolo)	Low	3	High	3	High	1	9	High
Brunizém averm. (Chernossolo)	High	1	Low	1	Medium	2	2	Low
Inceptisol (Cambissolo)	High	1	Low	1	Low	3	3	Medium
Hapludalf (Gleissolo)	Medium	2	Medium	2	Low	3	12	High
Red Oxisol (Latossolo verm. Escuro)	Medium	2	High	3	High	1	6	Medium
Clayey oxisol (eutrof.)	High	1	Medium	2	High	1	2	Low
Yellow-red clayey oxisol (Latossolo verm. amarelo arg.)	High	1	Medium	2	High	1	2	Low
Loamy Oxisol (Latossolo verm. amar. text. méd.)	Medium	2	Medium	2	High	1	4	Medium
Litholic (Neossolo)	Medium	2	Medium	2	Low	3	12	High
Eutrox (terra roxa)	High	1	Medium	2	High	1	2	Low

tamination potential without the BMPs. Cp_0 and Cp_1 are estimated by equation [3], and depend on the volume, toxicity and GUS of the pesticide package used in the farm.

Table 2. Classes of vulnerability to contamination of the recharge areas.

Result	Vulnerability
1-2	Low
3-8	Medium
9-27	High

Table 3. Groundwater contamination risk and its levels.

Cont. Pot. (Cp)	Vulnerabilility (V)		
	Low (1)	Medium (2)	High (3)
Low (1)	Low (1)	Low (2)	Medium (3)
Medium (2)	Medium (2)	Medium (4)	High (6)
High (3)	High (3)	High (6)	High (9)

RESULTS

Analysis of the Depletion Risk of the Guarani aquifer under Ribeirão Preto

The groundwater depletion risk of the Guarani aquifer in the city of Ribeirao Preto was analyzed using the three population and climate change scenarios, as well as the extraction and recharge rates under the same scenarios. Figures 9, 10, and 11 present the groundwater depletion risks, given by *tan* (Φ), for the most probable, best-case and worst-case scenarios, respectively.

As seen from Figures 9, 10 and 11, the expected depletion years for the Guarani aquifer water under Ribeirao Preto were 2052, 2056, and 2048, for the most probable, best-case and worst-case scenarios, respectively, corresponding to the values of 1,48, 1,35 and 1,63 for *tan* Φ, respectively.

In another study, where the climate and population scenarios were not analyzed, it was concluded that the aquifer depletion in the city would occur in 2100 (Fipai, 1996). Another indication of the gravity of the problem is that the drawdown of the aquifer below the city center was over 60 m in 2007, causing the drying if many deep wells (Coplan, 2002).

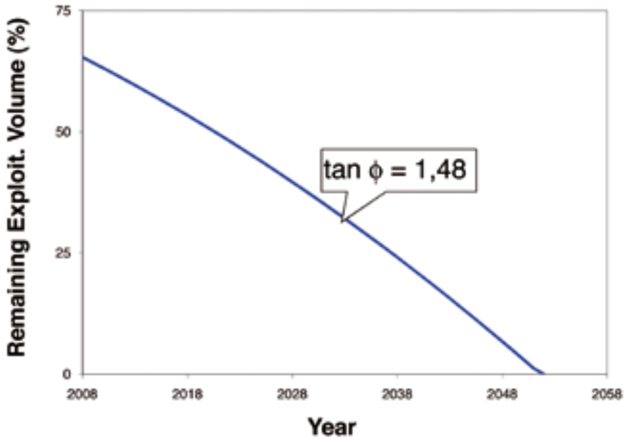

Figure 9. Production frontier for the Guarani aquifer in R. Preto between 2008 and 2050 in the most probable scenario (volume in 1950=100%)

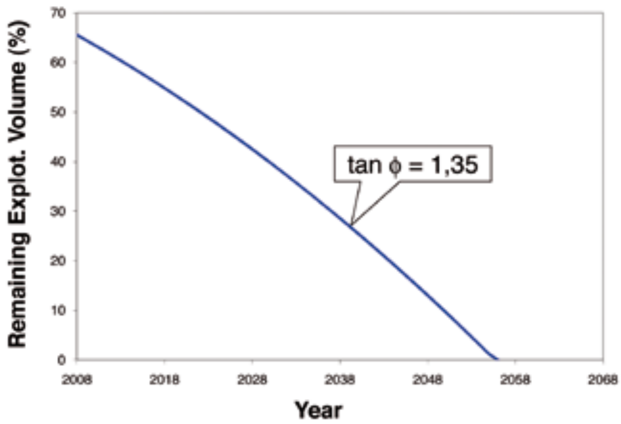

Figure 10. Production frontier for the Guarani aquifer in R. Preto between 2008 and 2050 in the best-case scenario (volume in 1950=100%)

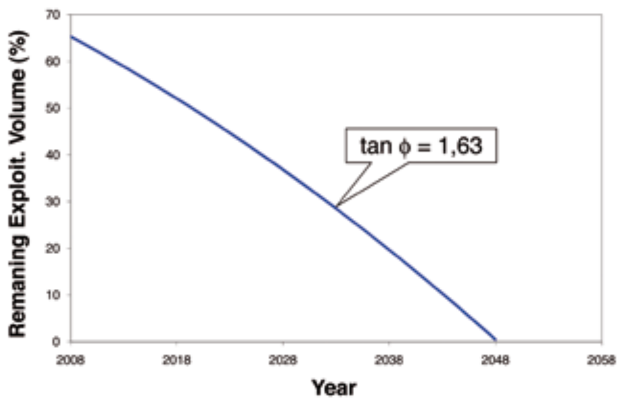

Figure 11. Production frontier for the Guarani aquifer in R. Preto between 2008 and 2050 in the worst-case scenario (volume in 1950=100%)

The good news is that in 2008 more than 65% of the original aquifer volume still remained unexploited, allowing for its conservation in the coming years.

Analysis of the Risk of Contamination of the Recharge Areas

Figure 12 below presents the vulnerability of the recharge zones of the Guarani aquifer in the study area, as estimated by equation 2 and Table 2. In figure 9, 39,5% of the recharge area presented low vulnerability to contamination, 39,2% medium vulnerability, and 29,6% high vulnerability.

The contamination potential (C_p, equation 3 and 4) for the pesticides used in the study area (mostly sugar cane plantations) is presented in Figure 13 below.

According to Figure 10, there are 3 herbicides with high contamination potential (C_p=3), 4 with medium potential (C_p=2) and 5 with low potential (C_p=1). A weighed average of Cp and the number of pesticides in each level yielded an average value of $C_p \approx 2$ for sugar cane.

Overlaying the vulnerability of the recharge zone by the agricultural (dominantly sugar cane) land use, and applying equation 1 and table 3, the map of risk to contamination was obtained, and is presented in Figure 14 below.

In Figure 14, there are 89,2 km^2 of areas with high risk of contamination, 105,6 km^2 of areas with medium risk, and 155,1 km^2 of areas with low risk. The areas of high contamination risk are associated with vulnerable soils and with a medium contamination potential, suggesting that if sugar cane is to be grown in those areas, pesticides with lower C_p are required.

Evaluation of the Feasibility of the Measures to Reduce the Risks to Groundwater Sustainability in the Study Area

In order to reduce the risk of groundwater depletion in the city of Ribeirão Preto, the measures evaluated were the utilization of supplementary water from the Pardo river, water harvesting and utilization in new condominiums, and the establishment of well fields in the rural areas of the city, away from the depression cone area. Table 4 presents the socioeconomic feasibility of the water quantity measures for the city of Ribeirao Preto, and their overall ranking.

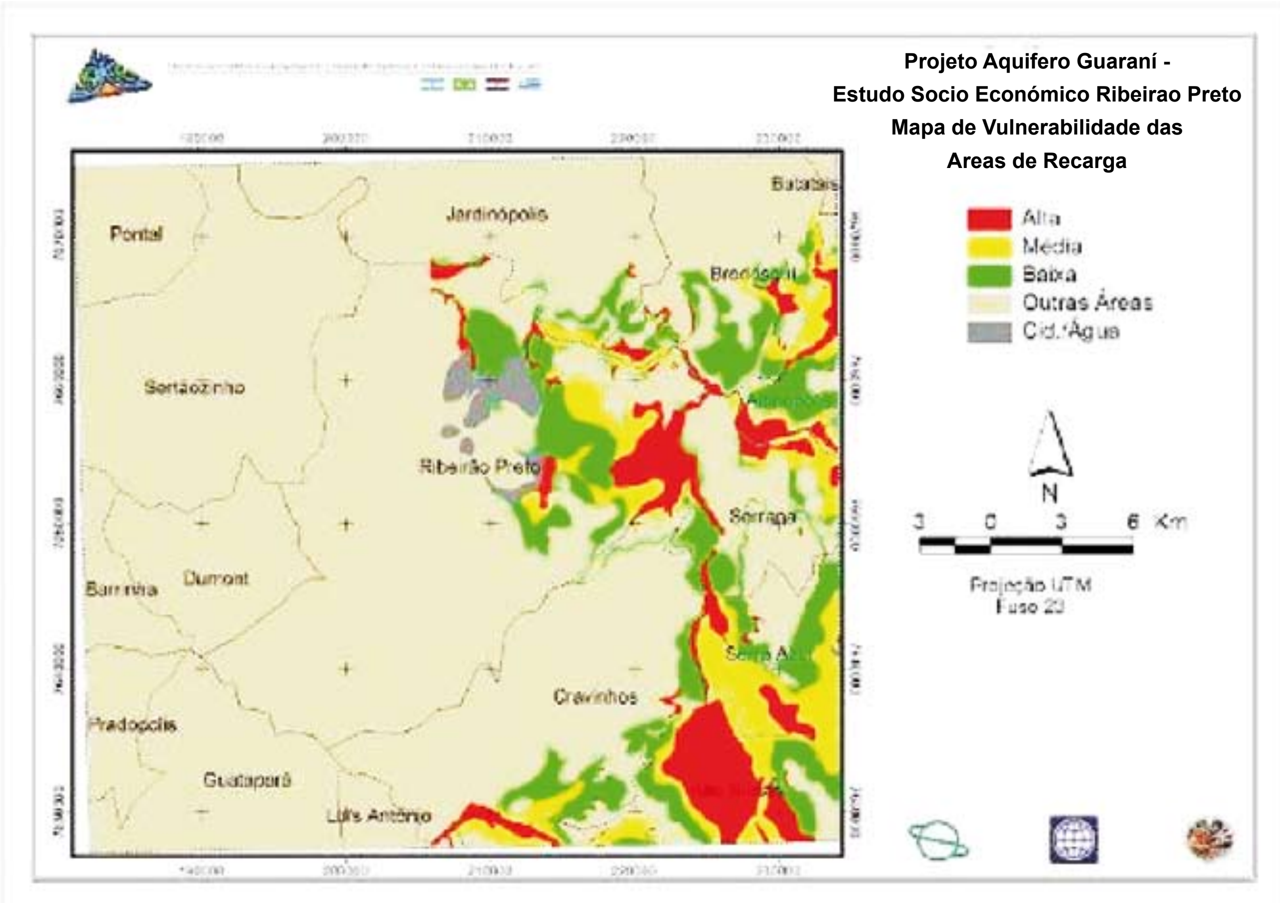

Figure 12. Vulnerability of the recharge zone of the Guarani aquifer in the study area (red=high, yellow=medium, green=low).

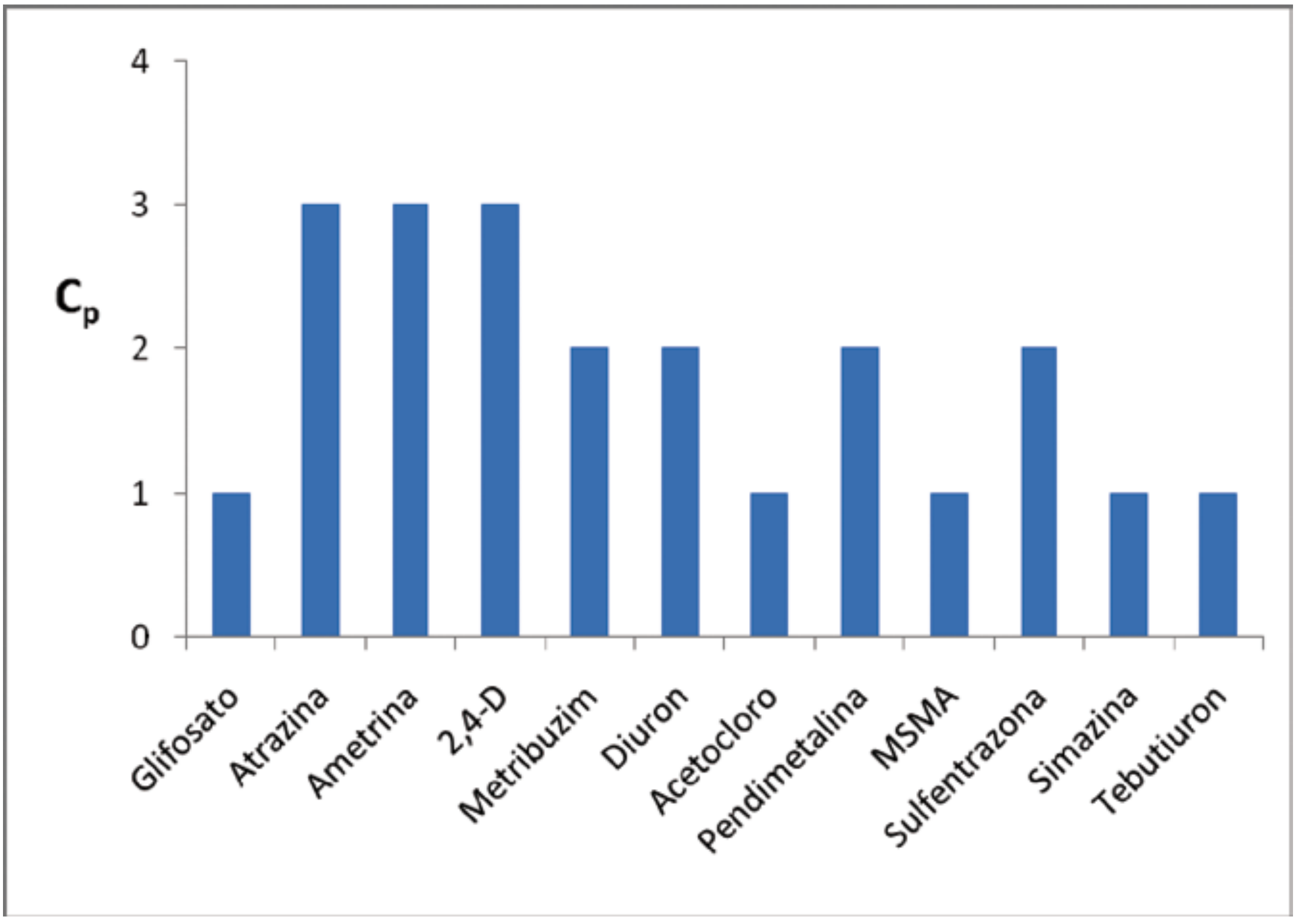

Figure 13. Contamination potential of the pesticides in the study area.

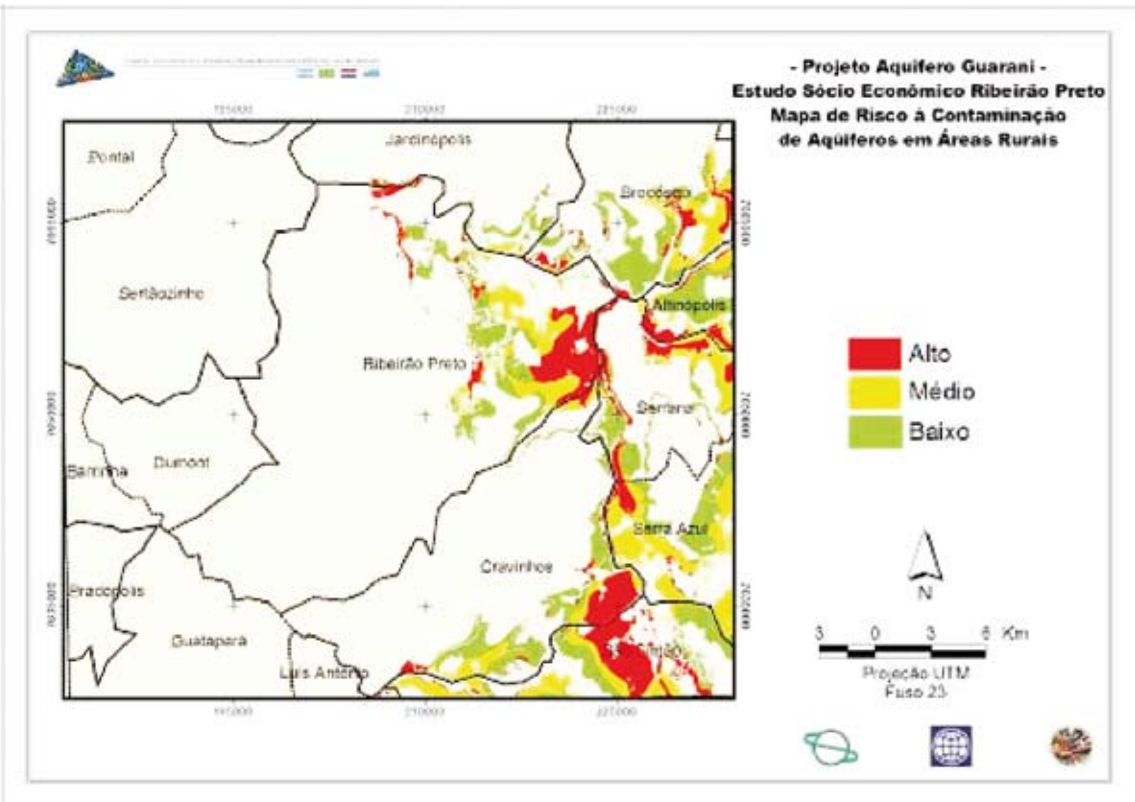

Figure 14. Risk of contamination of the recharge areas by pesticides

Table 4. Socioeconomic feasibility and ranking of alternatives for reducing the risk of groundwater depletion in the city of Ribeirao Preto

Indicator		Alternative		
		Pardo R.	Well Field	Rain Harv.
C	Result	73,5	97,2	199,4
	Normaliz.	0,37	0,49	1,00
R	Result	0,80	0,80	1,39
	Normaliz.	0,58	0,58	1,00
S	Result	-	-	-
	Normaliz.	0,10	0,10	0,43
V	-	0,0215	0,0284	0,430
Rank	-	1st	2nd	3rd

According to Table 4, the normalized product was the lowest for the alternative of supplementary water supply from the Pardo river (V=0,0215), reducing the pumping from the Guarani aquifer in the city of Ribeirao Preto. The rural well field alternative came close (0,0284).

In the case of the groundwater contamination risk from pesticides, a feasible measure was to use herbicides with smaller C_p values. In the case of Figure 14, if only those herbicides with C_p=1 were used, and considering the average of Cp of sugar cane fields in the region is Cp_0= 1,83 (previous condition), the contamination abatement (eq. [7]) would then be:

C_a = 100 [1 - (1,0/1,83)] = 45,4%

Considering that the risks to groundwater quantity and quality would significantly impact the water users in the future, increasing the costs and reducing their reliability, the investments for mitigation measures suggested could be easily amortized. Additionally, financial compensation programs (PES), such as those related to the improvement of the water quality of the Pardo river to meet tolerable levels for urban consumption, and those related to the use of environmentally friendly pesticides, could be implemented in the study area.

CONCLUSIONS

The main conclusions of the present study were the following:

- There risks to the Guarani aquifer sustainability in the study area of 2,500 km^2 around Ribeirao Preto (Brazil) are those related to groundwater depletion under the urban area and the contamination of recharge areas;
- Considering the scenarios of climate change, the groundwater recharge would be reduced by 17% (B2) and by 20% (A2) in 2050;
- Considering that in 2007 about 65% of the original groundwater volume remains unexploited, there is an opportunity for the implementation of appropriate groundwater management measures;
- If groundwater is not managed properly in the city of Ribeirao Preto, there is a high probability that it would be depleted between 2048 and 2056, depending on the climate change scenario;
- 90km^2 of the recharge area the region studied present high risk to contamination by pesticides. Though this area represents only 3,6% of the total area studied, the high permeability rates and the contamination potential of the pesticides could lead to a serious groundwater contamination problem in the future;
- Alternatives to reduce the risk of groundwater depletion in the region included the supplementary supply of water from the nearby Pardo river, installation of well fields in the rural areas, and water harvesting in new urban condominiums;
- The most socioeconomic and environmentally viable of those alternatives was the use of river water, followed by the installation of well fields in the rural areas;
- The enforcement of the use of environmentally friendly pesticides would significantly reduce the risks to groundwater contamination in the recharge areas of the Guarani aquifer.

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