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How much do we know about the groundwater quality and its impact on Brazilian society today?

Quanto sabemos da qualidade das águas subterrâneas e seu impacto na sociedade brasileira nos dias de hoje?

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Abstract: Groundwater is an essential resource for society and the environment in Brazil. More than 557 m^3/s (17.5 km^3/y) are extracted through 2.5 million wells to meet demand in cities and the countryside, generating an economy of R$ 56 billion per year (US$ 14 billion/year). The aquifer has a remarkable function in the hydrological cycle because its large storage regulates the perenniality of rivers, lakes and preserves mangroves, marshes, and vegetation in dry periods. Aquifer discharges maintain between 24% (annual average) and 49% (dry season) of the flow of these surface water bodies. Although studies on groundwater quality are still restricted, it is known that most aquifers still preserve their excellent natural quality. Nevertheless, over the past years, there has been a growing increase in cases of contamination associated with: (i) natural geochemical anomalies (iron, manganese, and fluorine, secondarily, chromium, and barium, and rarely arsenic) due to the dissolution of specific minerals; and (ii) human contaminant activities, related to urban areas without sewage network, or with industrial activities, storage of hazardous products, and solid waste facilities. Among the anthropic compounds commonly handled, the most problematic are the chlorinated organic solvents and heavy metals, and in non-sewage areas, nitrate. The precarious knowledge of aquifer-quality, especially in cities, demonstrates the need to invest in regular and systematic hydrogeological research and mapping projects that drive to the improvement of the practices on aquifer quality protection.

Keywords: water resource; hydrogeochemical anomalies; anthropic contamination.

Resumo: As águas subterrâneas são um recurso imprescindível para a sociedade e o meio ambiente no Brasil. Mais de 557 m^3/s (17.5 km^3/a) são extraídos através de 2.5 milhões de poços para atender a demanda nas cidades e no campo, gerando uma economia de R$ 56 bilhões ao ano (US$ 14 bilhões/ano). O aquífero tem função impar no ciclo hidrológico, pois seu gigantesco armazenamento regula a perenidade de rios, lagos e mantém mangues, pântanos e a vegetação em épocas secas. Mais de 24% (média anual) a 49% (período de estiagem) da vazão desses corpos hídricos é mantida pela descarga de aquíferos. Embora os estudos sobre a qualidade de suas águas seja ainda restrita, sabe-se que a maior parte dos aquíferos ainda preserva sua excelente qualidade natural. Mais recentemente, tem-se visto o crescente aumento dos casos de contaminação, associadas a: (i) anomalias naturais geoquímicas (ferro, manganês, flúor e, secundariamente, cromo, bário e arsênico), devido à dissolução de minerais específicos; e (ii) atividades humanas contaminantes, relacionadas a áreas urbanas sem rede de esgoto ou com atividades industriais, armazenamento de produtos perigosos e deposição de resíduos sólidos. Dentre os compostos antrópicos comumente manipulados, os mais problemáticos correspondem aos solventes organoclorados e metais pesados e, para áreas sem rede

de esgoto, o nitrato. O precário conhecimento da situação da qualidade dos aquíferos, sobretudo em cidades, demonstra a necessidade de se investir em projetos de pesquisa e mapeamento hidrogeológicos permanentes e sistemáticos, que levem à melhoria das práticas de proteção da qualidade das águas subterrâneas.

Palavras-chave: recurso hídrico; anomalias hidrogeoquímicas; contaminação antrópica.

1. Introduction

Groundwater is a valuable water resource for both public and private supply in Brazil. With groundwater extractions over 557 m^3/s (17.5 km^3/y), through more than 2.5 million tubular wells, this resource is fundamental for the economy (value of R$ 56 billion per year), and population health, whether in the countryside or cities (Hirata et al., 2019).

As part of the hydrological cycle, groundwater also plays a crucial role in maintaining ecosystems. The discharge of this water into rivers, lakes, and swamps maintains their constancy in the dry season, as well as in the equilibrium between fresh and saline water in coastal aquifers and mangroves. Moreover, plants and trees extract groundwater to meet their needs during the dry period, including maintaining soil moisture, which is necessary for other species to survive (Figure 1).

Aquifers are also large reservoirs, where more than 90% of all water naturally stored in the country is found. Due to this large storage, its extraction is very little affected by long drought periods, which allows balancing the water supply in cities and countryside. Therefore, groundwater has been claimed as one of the most important solutions to address the problems of rainfall irregularity associated with global climate changes (Hirata & Conicelli, 2012). Nevertheless, the existing knowledge of groundwater in Brazil is still very incipient. It is known that aquifers generally offer water of excellent natural quality, most of the time suitable to be directly consumed by the populations. However, the aquifer contamination caused by anthropic activities has been reported increasingly in the last decades, especially in urban centers. Less frequent but not less important is the natural aquifer contamination, caused by the presence of soluble minerals that end up releasing toxic inorganic substances to groundwater.

This study presents a critical evaluation of the water quality situation in Brazilian aquifers and its relation with natural and anthropic contamination, although it is also recognized that there are occurrences: (i) induced by the lack of control in groundwater extractions, which brings intrusion of saline or low-quality water to the aquifer; and (ii) associated with poor design, construction and/or maintenance of supply wells.

2. The Groundwater in Brazil

2.1. The potential of Brazilian aquifers

The renewable reserves of groundwater in Brazil, that is, its effective recharge, reach 42,289 m^3/s (1,334 km^3/y) and correspond to 24% of the river discharge (baseflow; annual average of

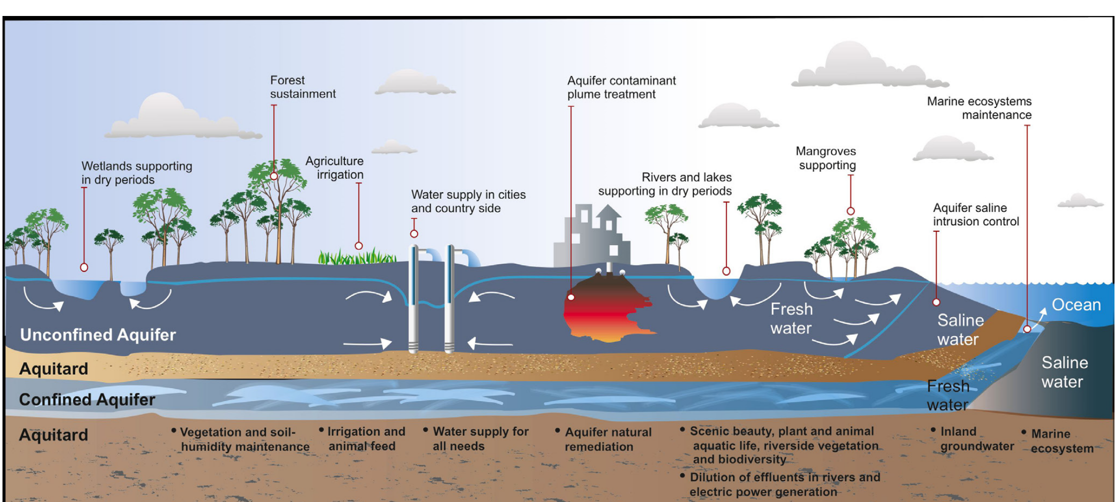

Figure 1. Services performed by groundwater and aquifers (Hirata et al., 2019).

179,433 m³/s) and 49% in a dry season (baseflow with 95% permanence). This massive flow of water is distributed, in a simplified way, into two large groups of aquifers, namely (ANA 2005a, b; Hirata et al., 2006, 2010):

- **Sedimentary aquifers:** sedimentary terrain occupies about 4.13 million km², that is, 48.5% of the area of the country, associated with the large Proterozoic/Paleozoic, Proterozoic/Mesozoic-Paleozoic sedimentary basins and to the Mesozoic and Cenozoic basins (Figure 2, Table 1). There are 27 regional sedimentary aquifer systems with granular porosity and, secondarily, karst and fractured areas, with a total recharge area (rocks outcrops) of 2.76 million km² (32% of Brazilian territory) and effective recharge of 20,473 m³/s. It is also important to mention the extent of karst aquifers that comprise between 5-7% of the Brazilian territory (425,000-600,000 km²) (Auler & Farrant, 1996), and they are characterized by carbonates with permeability associated with the chemical dissolution of rocks. (tertiary porosity). The remaining area of 16.5% is occupied by local aquifers, which although of less potentiality, they are underneath many of the largest Brazilian cities.
- **Fractured crystalline aquifers:** Precambrian crystalline terrains, which behave as typical fractured aquifers, occupy an area of about 4.38 million km² (approximately 51.5% of Brazilian territory) and coincide, in large part, with the Amazon Craton and the Neoproterozoic folding belts, including part of the basement of the São Francisco Craton (Figure 2, Table 2). These geological units, together with the areas of volcanism within sedimentary basins, represent the main fractured aquifer systems in the country.

2.2. Natural composition of groundwater and geochemical anomalies

In general, Brazilian aquifers have water with excellent natural quality. Natural chemistry is primarily controlled by the mineralogical composition of rocks and sediments present in the aquifer and by the climate in the recharge area. Hydrogeological units in the northern region, for example, where rainfall is abundant, present acidic and bicarbonated waters with low mineralization. The crystalline rocks are characterized by calcium-bicarbonated and calcium-magnesian water. The aquifers near the coastal region are, as

Figure 2. Recharge areas of the main Brazilian Aquifer Systems. In light yellow, fractured aquifer systems or not described sedimentary aquifers (ANA, 2005b).

Table 1. General features and aquifer yield of the main Brazilian Sedimentary Aquifer Systems grouped by sedimentary basins.

GENERAL FEATURES				WELL PRODUCTIVITY							
				UNCONFINED AQUIFER				CONFINED AQUIFER			
BASIN	AQUIFER SYSTEM	TYPE OF AQUIFER	LITHOLOGY	Depth (m)	Q (m^3/h)	Q/s ($m^3/h/m$)	#wells	Depth (m)	Q (m^3/h)	Q/s ($m^3/h/m$)	#wells
AMAZONAS (Paleozoic)	Boa Vista	PP/Uc	Sands, lateritic concretions & conglomeratic layers	33-40 (34)	19.8-40.0 (30)	2.41-8.89 (3.15)	9				
	Solimões	PP/Uc	Siltstone & sandstone banks	38-62 (45)	10.2-36.7 (24.5)	0.97-5.22 (1.63)	36				
	Alter Do Chão	PP/Uc	Argillaceous & silty sandstones	85-189 (140)	9.4-68.0 (26.4)	0.35-2.26 (0.94)	145				
PARECIS (Paleozoic)	Parecis	PP/Uc	Medium to fine sandstones, levels of conglomerates and siltstone lens	100-112 (104)	72.0-283.0 (128.4)	5.76-15.36 (9.1)	8				
MESOZOIC/ CENOZOIC	Barreiras	PP/Uc & Co	Argillaceous sandstones and siltstones	20-51 (33)	4.0-18.0 (9.3)	0.31-4.83 (2.11)	140	37-66 (50)	2.6-10.6 (5.0)	0.16-1.35 (0.56)	167
	Beberibe	PP/Uc & Co	Sandstones with intercalations of siltstone	162-220 (200)	23.3-36.8 (26.0)	0.96-1.42 (1.10)	4	81-302 (250)	31.7-113.1 (72.0)	1.36-3.87 (2.59)	21
	Jandaíra	Karst-fract	Limestones with intercalation of siltstone, argillaceous limonites	72-120 (100)	2.2-7.2 (4.5)	0.07-2.46 (0.29)	180				
	Açu	PP & Co	Fine sandstones with argillaceous-siltstones					59-535 (289)	6.4-32.2 (11.0)	0.65-4.78 (1.24)	16
	Marizal	PP/Uc & Co	Coarse to conglomerate sandstones with argillaceous and limestone layers	98-150 (118)	6.8-22.6 (12.7)	0.53-3.27 (1.35)	43	96-178 (142)	7.4-21.2 (13.5)	0.52-2.78 (0.95)	42
	São Sebastião	PP/Uc & Co	Medium to coarse sandstones with siltstone and clays	83-152 (119)	10.0-26.8 (16.5)	0.46-3.72 (2.06)	59	106-203 (164)	13.6-44.0 (24.0)	0.62-2.95 (1.38)	109
	Inajá	PP/Uc & Co	Medium to fine sandstones with clay and silt layers	83-136 (118)	2.1-4.0 (3.3)	0.13-0.35 (0.24)	30	157-227 (187)	7.1-15.8 (10.2)	0.26-1.47 (0.77)	7
	Tacaratu	PP/Uc	Coarse to fine sandstones with conglomerate layers	50-134 (73)	2.5-7.0 (5.0)	0.21-0.62 (0.47)	27				
	Missão Velha	PP & Co	Fine to argillaceous sandstones with levels of siltstone	76-83 (80)	4.2-8.6 (5.1)	0.43-0.85 (0.57)	3	53-84 (73)	4.1-19.0 (12.0)	0.29-2.57 (1.38)	15
	São Paulo	PP, SCo	Sandstone, conglomerates, siltstone	100-175 (134)	5.8-26.4 (13.0)	0.18-1.76 (0.5)	165				
	Tubaté	PP, SCo	Sandstone, conglomerates, siltstone	124-175 (150)	16.1-58.0 (30.0)	0.59-6.00 (2.1)	111				

Interval values are 25% and 75% quartiles and median is presented between parentheses. PP = Primary Porosity; Uc = Unconfined; Co = Confined; SCo = semi-confined; Karst-fract = karstic-fractured; Q/s = specific capacity; Q = discharge rate; #wells (number of wells) that were considered in the statistic calculation. Source: Modified from Hirata et al. (2010).

Table 1. Continued...

GENERAL FEATURES				WELL PRODUCTIVITY							
				UNCONFINED AQUIFER				CONFINED AQUIFER			
PARANÁ (Paleozoic/ Mesozoic)	Bauru	PP/Uc	Fine to medium sandstone with intercalation of silts	101-160 (140)	8.0-20.7 (14.4)	0.22-0.96 (0.43)	119				
	Guarani	PP/Uc & Co	Medium to fine sandstones	85-136 (103)	5.4-18.7 (10.2)	0.25-0.99 (0.49)	87	111-242 (154)	18.4-60.0 (35.7)	0.87-2.91 (1.82)	69
	Tubarão	PP/Uc & SCo	Medium to fine sandstone, diamectites	117-201 (151)	3-13.2 (6.8)	0.06-0.31 (0.12)	831				
	Ponta Grossa	PP/Uc	Clay with intercalation of fine sandstones	118-192 (135)	1.2-6.0 (2.4)	0.02-0.12 (0.06)	9				
	Furnas	PP/Uc & Co	Medium sandstones	85-150 (115)	9.3-27.0 (11.6)	0.54-1.94 (1.20)	21	135-265 (175)	12.0-23.4 (15.4)	0.73-1.22 (0.94)	6
PARNAÍBA (Paleozoic)	Itapecuru	PP/Uc	Fine to conglomerated sandstone with clay layers	60-100 (79)	5.1-16.0 (9.1)	0.25-2.35 (1.03)	116				
	Corda	PP/Uc & Co	Medium to conglomerate sandstones	72-112 (84)	4.0-18.0 (8.0)	0.40-1.87 (1.07)	35	147-250 (170)	7.2-20.0 (12.0)	0.29-1.14 (0.47)	47
	Motuca	PP/Uc	Medium to fine sandstone	63-122 (80)	3.6-11.8 (6.1)	0.49-2.91 (1.90)	22				
	Poti-Piauí	PP/Uc & Co	Medium to fine sandstones with layers of clays and limonite	93-157 (122)	6.0-18.0 (10.0)	0.34-1.46 (0.59)	49	111-346 (159)	13.4-40.3 (31.5)	0.92-2.91 (1.12)	10
	Cabeças	PP/Uc & Co	Fine to coarse sandstones with claystones	79-130 (100)	4.0-13.1 (6.0)	0.49-2.16 (1.00)	87	153-399 (233)	8.3-53.8 (26.4)	1.01-10.08 (4.37)	34
	Serra Grande	PP/Uc & Co	Fine to medium sandstone with conglomerate layers	107-200 (170)	2.0-6.0 (3.2)	0.06-0.33 (0.13)	111	120-180 (150)	5.9-21.0 (9.8)	0.63-2.42 (1.29)	111
SÃO FRANCISCO (Proterozoic)	Urucuia-Areado	PP/Uc	Medium to fine sandstones and siltstone and conglomerates	50-117 (86)	5.5-14.7 (7.8)	0.19-1.15 (0.53)	28				
	Bambuí	Karst-fract	Meta-limestone, marl, meta-limonites e meta-claystones	60-100 (80)	3.3-15.7 (8.8)	0.10-3.17 (0.51)	159				

Interval values are 25% and 75% quartiles and median is presented between parentheses. PP = Primary Porosity; Uc = Unconfined; Co = Confined; SCo = semi-confined; Karst-fract = karstic-fractured; Q/s = specific capacity; Q = discharge rate; #wells (number of wells) that were considered in the statistic calculation. Source: Modified from Hirata et al. (2010).

Table 2. Hydrodynamic characteristics of main Precambrian and Eocretacic fractured aquifers.

GEOLOGIC UNIT	STATE, REGION OR AQUIFER SYSTEM	Well Productivity			
		Depth (m)	Q (m^3/h)	Q/s (m3/h/m)	#wells
NEOPROTEROZOIC FOLDING BELTS AND SÃO FRANCISCO CRATON	Northeast region	48-70 (59)	0.8-5.1 (2.1)	0.03-0.38 (0.10)	8329
	Minas Gerais State	-	1.1-5.0 (2.8)	0.03-0.35 (0.13)	128
	Rio de Janeiro State	57-102 (80)	4.0-11.5 (7.0)	0.12-0.64 (0.28)	110
	São Paulo State	110-198 (150)	2.6-12.1 (6.0)	0.03-0.30 (0.09)	1201
PARANÁ BASIN	Serra Geral – Basalt	100-163 (127)	7.1-35.0 (15.3)	0.21-2.12 (0.63)	278
	Serra Geral –Diabase	90-157 (121)	1.8-11.0 (5.5)	0.02-0.40 (0.13)	49

Interval values are 25% and 75% quartiles and median is presented between parentheses. #wells (number of wells) that were considered in the statistic calculation. Source: Modified from Hirata et al. (2010).

opposed to the inland water, more abundant in chloride and sodium ions (Hirata et al., 2006).

Regionally it is possible to identify problems associated with the excess of some ions (Zoby, 2008):

- Limestone areas where groundwater has high hardness and/or high dissolved solids content, such as the Bambuí and Jandaíra aquifer systems;
- Aquifer systems located in more confined portions of some sedimentary basins where, under conditions of slow circulation, mineral salt enrichment in depth can create restrictions on the use of water by total salinity, as observed in the Açu and Serra Grande and Guarani (in some places of Paraná and Rio Grande do Sul states) aquifer systems;
- Aquifers whose hydrogeochemical conditions favor the localized dissolution of certain minerals that release ions in the groundwater at concentrations above the drinking standard. This is the case of dissolved iron and manganese in the aquifer systems of Alter do Chão, Missão Velha, Barreiras and Cenozoic continental and coastal deposits; and fluorine in fractured aquifer systems (Martins et al., 2018) Bambuí, Guarani and Serra Geral. It is also known the occurrence of high levels of chromium and barium in the Bauru-Caiuá Aquifer System in the State of São Paulo (Bertolo et al., 2011; Tavares et al., 2015);
- Crystalline terrains located in arid and semi-arid regions, such as in the Brazilian northeast, where high salinity affects the natural quality of groundwater. The salinization occurs due to intense evaporation of the water presents in the soil or infiltrated at a shallow depth. The origin of many ions, particularly chloride and some of the sodium, comes from the humidity brought from the Atlantic Ocean.

2.3. Anthropic contamination

One can state that most aquifers still have their natural quality preserved. This is a perception based on the nature of anthropic contamination events, which usually create plumes of small area and volume, controlled by the hydrodynamic dispersion and natural degradation. Some exceptions occur in areas of multipoint or disperse sources, such as cesspits and septic tanks or agricultural activities, which generally impact larger regions (Table 3).

However, reports of quality impacts on groundwater have been increasing, as observed in the State of São Paulo, which has a government-pioneering program to manage contaminated areas (CETESB, 2019). An analysis of these data shows that: (i) the more one searches for contaminated areas, the more they are found, evidencing the need for permanent attention; (ii) there is a clear underestimation of the number of contaminated sites, with at least ten times more than those currently identified and studied; and (iii) the adopted strategy has focused on the contaminant activity, but little attention is given to the protection of the water resource as a whole.

The groundwater monitoring program itself, which surveys a little more than 0.1% of the São Paulo state territory (thus insignificant to address

Table 3. Anthropic activities, types of contaminants and their frequency of occurrence in contamination of Brazilian aquifers.

ACTIVITY	POLLUTANT LOAD CHARACTERISTICS				
	Type	Main type of pollutant	Rel. hydraulic surcharge	Frequency in Brazil	Relative area of occurrence
Urbanization					
Unsewered sanitation	u/r P-MP	n f o	+	***	****
Leaking sewers	u MP	o f n	+	***	****
Sewage oxidation lagoons	u/r P	o f n	++	**	**
Leaching refuse landfill/tips	u/r P	o s h		***	**
Fuel storage tanks (incl. gas station)	u/r P	o		***	*
Industrial					
Leaking tanks/pipelines	u P (D)	o h		*	**
Accidental spillages	u P (D)	o h	+	**	*
Process water/effluent lagoons	u P	o h s	++	***	**
Effluent land discharge	u P (D)	o h s	+	**	**
Leaching residue tips	u/r P	o h s		**	**
Soak away drainage	u D	o h	++	**	**
Agricultural					
a. Soil cultivation					
- with agrochemicals	r D	n o		**	****
- and with irrigation	r D	n o s	+	**	****
- with sludge/slurry	r D	n o s		*	***
- with wastewater irrigation (sugar cane vinasse)	r D	n o s f	+	**	****
b. Livestock rearing/crop processing	r P				
- unlined effluent lagoons	r P/D	f o n	++	*	**
- effluent land discharge	r P-D	n s o f		*	**
Mineral extraction					
Hydraulic disturbance	r/u P-D	s h		*	****
Drainage water discharge	r/u P-D	h s	++	*	***
Unlined process water/sludge lagoons	r/u P	h s	++	**	**
Leaching residue tips	r/u P	s h		**	**

u = urban; r = rural; P = punctual; MP = multipunctual; D = diffuse; n = nutrient compounds; f = fecal pathogens; o = micro-organic compounds and/or organic load (including VOC and semi-VOC); s = salinity; h = heavy metals; + > ++ > +++ increase intensity; * > ** > *** frequency of cases or area of occurrence.

to the quality of the aquifers), has shown a growing contamination from domestic sewage (especially nitrate), either by the lack of public network or by leaking of sewer pipes poorly maintained (Hirata et al., 2006, 2019). The total amount of sewage infiltrated in the soils is 4,911 Mm^3/y, which makes this source the one that generates the most significant contamination volume in Brazil (Hirata et al., 2019). In cities, especially in areas with active or abandoned industries, the main concern is the chlorine organic solvents, which are very common in the production chain. These compounds, besides being very common, present high toxicity and great persistence in the aquifers. When there is a free phase of these substances (i.e., immiscible pools of the pure product inside the aquifer), they can infiltrate to great depths, including accessing fractures in crystalline aquifers. In that case, remediation is almost impossible. Agricultural contamination, despite very common in Europe and North America, is a wholly neglected subject in Brazil, and there are so far no detailed studies that clearly show the relationship between the activity and the aquifer degradation by fertilizers and other agrochemicals.

3. Conclusions and Recommendations

The current use of the groundwater in Brazil is made by 2.5 million tubular wells that extract more than 557 m^3/s (17.5 km^3/y). Such extraction represents only 2% of the effective recharge of 42,289 m^3/s (1,334 km^3/y), demonstrating its great potential to meet future demands in the countryside and cities. Therefore, an increase in groundwater extraction should be sought to improve the water security of human activities throughout the country, as long as they are well managed to avoid problems of localized aquifer overexploitation or its induced contamination.

Groundwater presents a natural quality that is generally good to excellent, being mostly potable or with minor organoleptic concerns caused by dissolved iron and manganese. There are local geochemical anomalies, which can compromise the water potability, usually associated with fluorine, chromium, barium, and rarely arsenic. As these anomalies are directly dependent on the type of rock, it is recommended that hydrogeological mapping give special attention to the type and composition of the rocks.

Groundwater contamination by anthropic activities, although increasing throughout the country, is still restricted to areas where the occupation of the territory is most intense, such as urban areas, especially those without sewage network, or situated close to industrial districts and in storage areas of dangerous products or solid waste disposal. Thus, it is recommended the implementation of regular programs to identify critical or vulnerable areas, where there is a higher risk of aquifer degradation. In these critical areas, detailed studies should be carried out, aiming at the protection of the aquifer or public supply wells.

Finally, it should be recognized that one of the main problems in hydrogeology is the lack of information on aquifers, about their quality and the risks that may drive them to contamination. Such scarcity of data has affected and limited the proper and efficient management of groundwater resources. Thus, it is crucial to introduce monitoring programs that encourage wells registration throughout the country, to instill efficiency in resource management, and bring benefits to the whole society.

References

AGÊNCIA NACIONAL DE ÁGUAS – ANA. *Panorama da qualidade das águas subterrâneas no Brasil* [online]. Brasília: ANA, 2005a [viewed 1 Mar. 2019]. Available from: http://www.ana.gov.br/sprtew/recursoshidricos.asp

AGÊNCIA NACIONAL DE ÁGUAS – ANA. *Disponibilidade e demandas de recursos hídricos no Brasil* [online]. Brasília: ANA, 2005b [viewed 1 Mar. 2019]. Available from: http://www.ana.gov.br/sprtew/recursoshidricos.asp

AULER, A. and FARRANT, A. A brief introduction to karst and caves in Brazil. *Proceedings of the University of Bristol Spelaeological Society*, 1996, 20(3), 187-200.

BERTOLO, R., BOUROTTE, C., MARCOLAN, L., OLIVEIRA, S.B. and HIRATA, R. Anomalous content of chromium in a Cretaceous sandstone aquifer of the Bauru Basin, state of São Paulo, Brazil. *Journal of South American Earth Sciences*, 2011, 31(1), 69-80. http://dx.doi.org/10.1016/j.jsames.2010.10.002.

COMPANHIA DE TECNOLOGIA DE SANEAMENTO AMBIENTAL – CETESB. Áreas contaminadas [online]. São Paulo: CETESB, 2019 [viewed 1 Mar. 2019]. Available from: https://cetesb.sp.gov.br/areas-contaminadas/

HIRATA, R. and CONICELLI, B. Groundwater resources in Brazil: a review of possible impacts caused by climate change. *Anais da Academia Brasileira de Ciências*, 2012, 84(2), 297-312. http://dx.doi.org/10.1590/S0001-37652012005000037. PMid:22634744.

HIRATA, R., SUHOGUSOFF, A., MARCELLINI, S., VILLAR, P. and MARCELLINI, L. *As águas subterrâneas e sua importância ambiental e socioeconômica para o Brasil*. São Paulo: Instituto de Geociências, Universidade de São Paulo, Instituto Trata Brasil, CEPAS|USP, 2019. 64 p.

HIRATA, R., ZOBBI, J.L., FERNANDES, A. and BERTOLO, R. Hidrogeología del Brasil: Una breve crónica de las potencialidades, problemática y perspectivas. *Boletín Geológico y Minero*, 2006, 217(1), 25-36.

HIRATA, R., ZOBY, J.L.G. and OLIVEIRA, F.R. Águas subterrâneas: reserva estratégica ou emergencial. In: C.E. BICUDO, J.G. TUNDISI and M. SCHEUENSTUHL, eds. Águas do Brasil: análises estratégicas. 1. ed. São Paulo: Instituto de Botânica, 2010, pp. 149-164. vol. 1.

MARTINS, V., PINO, D., BERTOLO, R., HIRATA, R., BABINSKI, M., PACHECO, D. and RIOS, A.P. Who to blame for groundwater fluoride anomaly in São Paulo, Brazil? Hydrogeochemistry and isotopic evidence. *Applied Geochemistry*, 2018, 90, 25-38. http://dx.doi.org/10.1016/j.apgeochem.2017.12.020.

TAVARES, T., BERTOLO, R.A., FIUME, B., CRESPI, A., MARTINS, V. and HIRATA, R. Hydrochemical investigation of barium in the public water supply wells of Sao Paulo state, southern Brazil. *Environmental Earth Sciences*, 2015, 74(9), 100-115. http://dx.doi.org/10.1007/s12665-015-4661-7.

ZOBY, J.L.G. Panorama da qualidade das águas subterrâneas no Brasil. In: *Anais do 15º Congresso Brasileiro de Águas Subterrâneas*. Natal: ABAS, 2008. CD-ROM.

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