QJEGH
Review article
Quarterly Journal of Engineering Geology and Hydrogeology
Published Online First
https://doi.org/10.1144/qjegh2020-091

The Guarani Aquifer System – from regional reserves to local use

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Abstract: The Guarani Aquifer System is a massive groundwater body underlying large areas of Brazil, Paraguay, Uruguay and Argentina, with a thickness of 50–600 m (averaging about 250 m). It is one of the world's largest sandstone aquifers. The mainly weakly-cemented sandstones were formed by aeolian, fluvial and lacustrine continental deposition during the Triassic–Jurassic period and are overlain by extensive Cretaceous basalt lava-flows. The system is totally storage-dominated, with recharge amounting to only about 0.2% of the estimated 30 000 km^3 of water stored. Using ^{14}C and^{81}Kr techniques, it was possible to confirm extremely slow flow rates, with groundwater older than 730 000 years BP in some parts of São Paulo State, Brazil. The vast regional freshwater storage contrasts sharply with localized active flow systems of recharge areas, which are strongly impacted by land-use change. The aquifer is the best known and most exploited in São Paulo State (80% of total extraction) and the experience of groundwater use for the supply of Ribeirão Preto and São José do Rio Preto (both with populations of over 0.5 million), together with one transboundary urban area, will be summarized.

Thematic collection: This article is part of the Hydrogeology of Sandstone collection available at: https://www.lyellcollection.org/cc/hydrogeology-of-sandstone

Received 2 May 2020; **revised** 7 July 2020; **accepted** 8 July 2020

Hydrogeological characteristics of the aquifer system

The Guarani Aquifer is a huge hydrogeological system that underlies an area of about 1 100 000 km^2, mainly in the Paraná River Basin of Brazil (with about 62% of its known area), Paraguay, Uruguay and Argentina (Fig. 1). It has an average thickness of about 250 m (varying from about 50 to >600 m) and reaches depths of over 1000 m (Fig. 2). The total volume of freshwater it contains in storage is estimated to be around 30 000 km^3 – equivalent to 100 years' cumulative flow in the Paraná River. The aquifer extends across international political boundaries, as well as those of many individual states of Brazil and provinces of Argentina, which are federal countries with groundwater resources essentially under state/provincial-level jurisdiction.

The Guarani Aquifer System comprises a sequence of mainly weakly-cemented sandstone beds of Triassic–Jurassic age (Hirata *et al.* 2011), which were formed by the aeolian, fluvial and lacustrine processes of continental deposition on a Permo-Triassic regional erosion surface (dated at 250 Ma BP). They are overlain by Cretaceous basalt flows (dated at 145–130 Ma BP), which are almost equally-extensive and exceed 1000 m thickness in some areas.

The first regional hydrogeological study (Silva 1983) was informed by limited deep drilling, but the geostratigraphic equivalence of these sandstones was only recognized in the 1990s, following oil exploration well-drilling and subsequent stratigraphic interpretation by academic researchers (Araujo *et al.* 1999; Campos 2000). The associated aquifer system was named the 'Guarani' in recognition of the indigenous population that inhabited approximately the same area. The geological formations comprising the Guarani Aquifer System (SAG from the Spanish and Portuguese abbreviation), whose nomenclature pre-dates this, are thus known by different names in different areas.

The aquifer occurs in three main 'hydrogeological domains' delimited by two geological structures that have exerted control on aquifer thickness and depth, and today influence regional groundwater flow:

- the Ponta Grossa Arch (in the north of Paraná State), which forces groundwater to flow from east to west in São Paulo State;
- the Asunción–Rio Grande Arch, which divides the portion south of the Ponta Grossa Arch into two semi-independent sedimentary basins.

The SAG is also affected by many tectonic structures and crossed by numerous volcanic dykes, but, despite these significant discontinuities at the local scale, it is considered to be a 'continuous groundwater body' across the entire region.

Current status and future drivers of resource utilization

The GEF Guarani Aquifer Program of 2003–08 (Foster *et al.* 2009) completed a full inventory of production boreholes in the SAG which indicated that resource exploitation totalled 1.04 km^3 a^{-1}, with 94% in Brazil (of which 80% is in São Paulo State), 3% in Uruguay, 2% in Paraguay and 1% in Argentina. Some 80% of the total is used for public water-supply, 15% for industrial processes and 5% by geothermal spas. There were estimated to be around 2000 operating deep production boreholes, with some capable of producing more than 500 m^3 h^{-1}, although as regards average abstraction, only 20% of the total were producing more than 100 m^3 h^{-1}.

The extensive area underlain by the SAG has a present population of about 15 million (although including large cities in its proximity this figure increases to about 90 million), a mainly sub-tropical climate and abundant (but often polluted) surface water resources

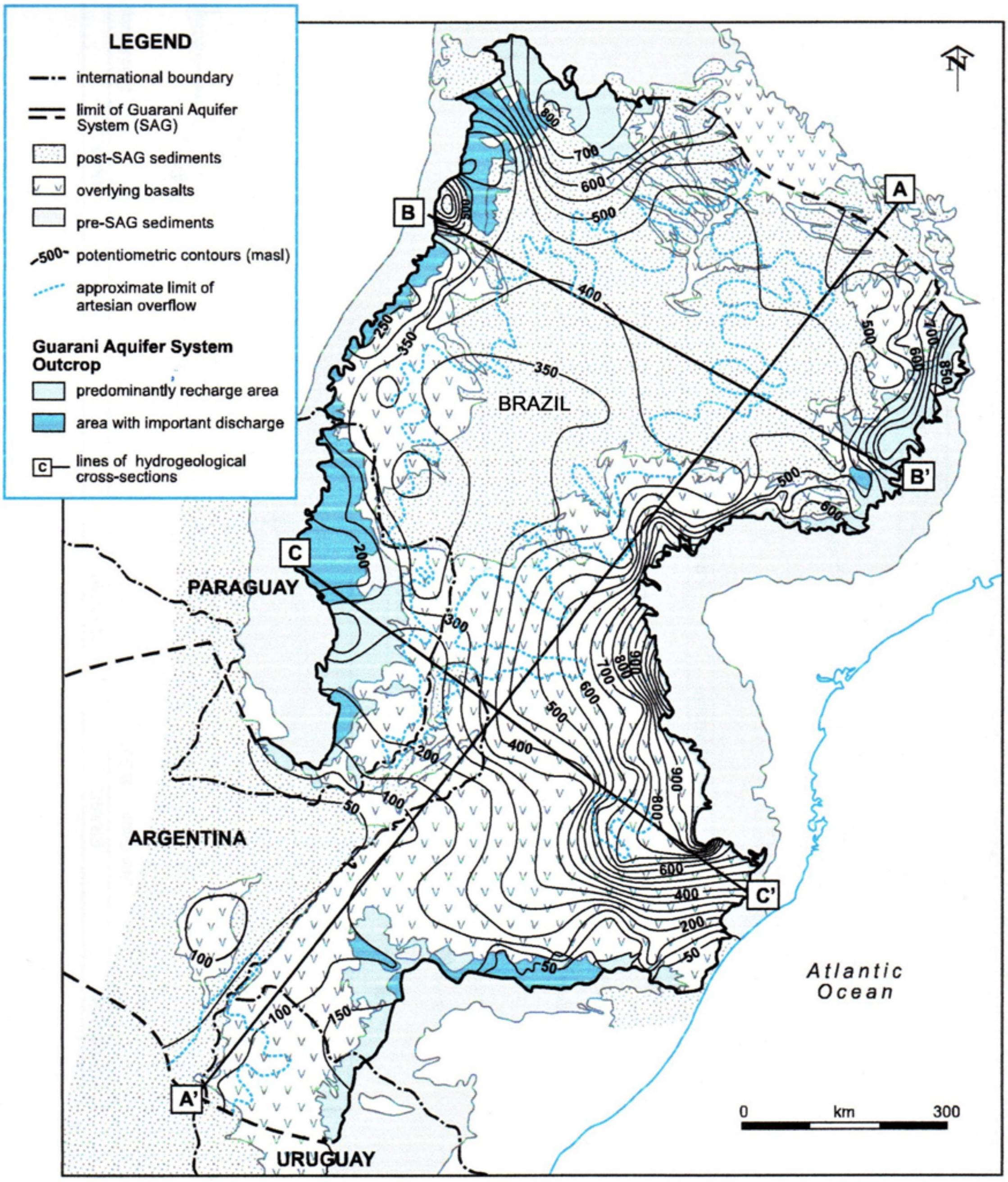

Fig. 1. Schematic hydrogeological map of the Guarani Aquifer System (Foster *et al.* 2009).

which experience occasional droughts. Thus, the need for reliable potable water-supply sources and industrial supplies (of low-treatment cost) is likely to grow significantly, especially in some climate-change scenarios. Potentially increasing importance of the SAG for the potable water-supply of many towns with populations of 50 000–250 000 must be emphasized – examples include Tacuarembo and Rivera in Uruguay, Caaguazu and Ciudad del Este in Paraguay and, in Brazil, Santana do Livramento and Caxias do Sul in Rio Grande do Sul, Londrina in Paraná, Uberaba and Uberlândia in Minas Gerais, and Campo Grande in Mato Grosso do Sul.

The SAG also represents a major low-enthalpy geothermal resource (often with overflowing artesian head) of pervasive distribution (Fig. 1), which has potential for future expansion of:

- spa facilities in northwestern Uruguay, neighbouring parts of Argentina and further north in the Iguazu international tourist area;
- numerous industrial applications and potential agro-industrial processes, but groundwater temperatures are too low for conventional electric-power generation.

However, preliminary agro-economic assessment suggests that the use of SAG groundwater for supplementary irrigation (as an insurance against crop yield reduction caused by short-duration drought) is not yet generally economical, except in recharge areas with a shallow water-table.

Groundwater storage and flow regime

The 'active flow system' in recharge areas

Replenishment of the SAG occurs by direct infiltration of excess rainfall and streamflow along the length of the aquifer outcrop area (Fig. 1), and in adjacent zones with a limited thickness of well-fractured basalt and via 'windows' in the basalt from overlying local groundwater bodies in Tertiary sedimentary formations.

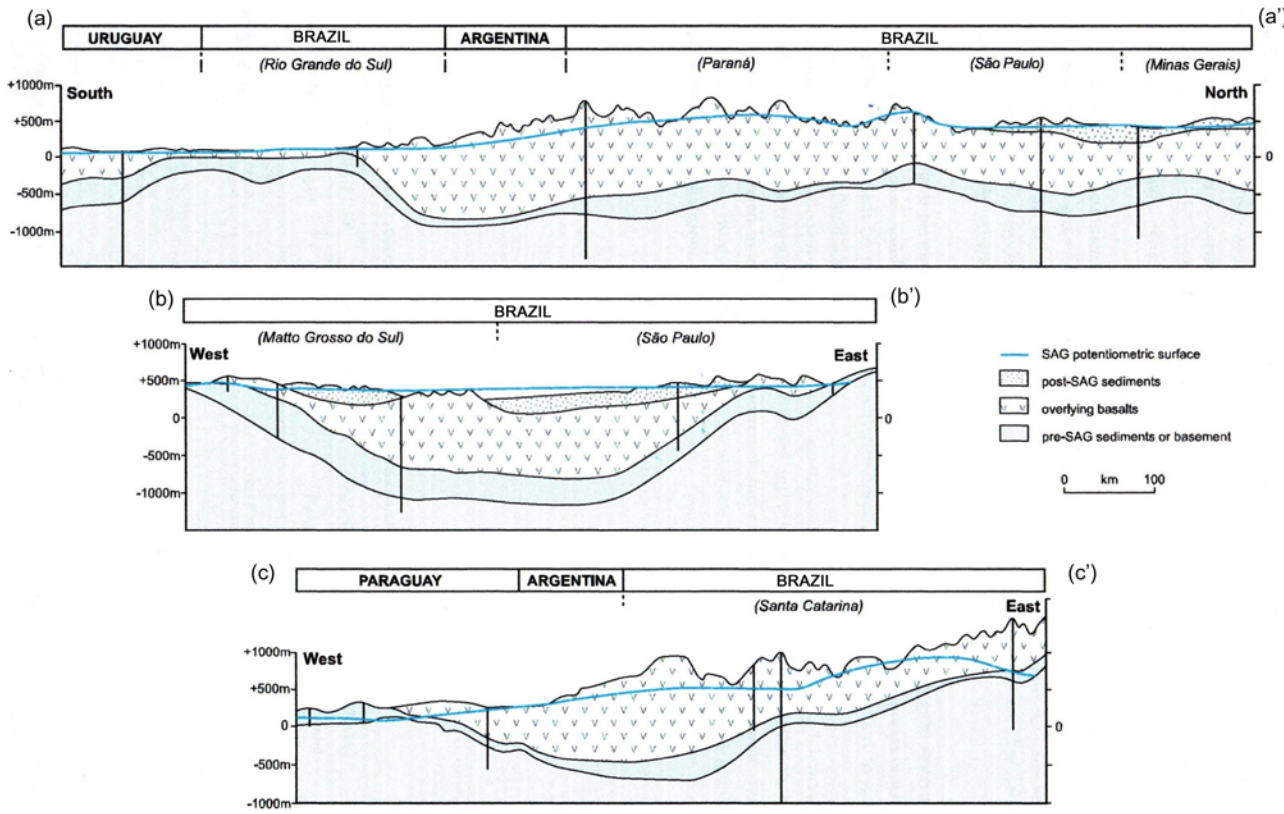

Fig. 2. Hydrogeological cross-sections of the Guarani Aquifer System. See Figure 1 for locations.

The high average rainfall across most of the SAG recharge area (1000–2000 mm a^{-1}) results in potentially elevated rates of aquifer recharge (300–400 and 500–600 mm a^{-1} in the northern and southern regions, respectively) (Wendland *et al.* 2015). Although some may be 'rejected' because of inadequate infiltration capacity or high water-table, most of this potential recharge infiltrates forming local flow cells, which discharge nearby as baseflow to rivers crossing the SAG outcrop. In these areas, groundwater hydraulic gradients are up to 3–5 m km^{-1}, and actual flow velocities are over 5 m a^{-1}.

There are, however, substantial differences in detail between the recharge areas (Fig. 1) on the 'northwestern flank' of the main basin (Paraguay to Mato Grosso do Sul-Brasil) and on the 'northeastern flank' (Santa Catarina to São Paulo State in Brazil), where reduced formation thickness and steeper dip result in a much narrower outcrop area, a smaller zone where recharge through the basalt cover is favoured and much more restricted aquifer discharge areas (Fig. 1).

Estimation of the overall current rate of SAG recharge is not straightforward because of uncertainties not only in the spatial variation of average potential recharge rates but also over the proportion of SAG outcrop area that permits recharge and the extent of recharge in basalt-covered areas. But the total SAG recharge area is only a minor proportion of the known aquifer extension (Fig. 1) and, using best estimates for the above factors, a value in the range of 45–55 km^3 a^{-1} appears reasonable, which is less than 0.2% of the estimated freshwater storage. The SAG is thus unquestionably a totally 'storage-dominated' groundwater system.

Groundwater resources extracted from the 'active flow zone' (and the closely adjacent area of thin basalt cover) will be fully renewable up to a level equivalent to somewhere in the range 300–600 mm a^{-1} natural recharge over the local area concerned (depending on location). Indeed, there may be potential to induce additional recharge as the water-table becomes depressed. However, the aquifer is significantly vulnerable to pollution from land-surface activities, and for potable and other supplies where quality is a premium, a focused campaign of aquifer or source protection measures should be implemented. The main impact of intensive groundwater abstraction will be reducing the baseflow of local rivers. For this reason, it may be convenient to regard only a proportion of the total recharge as 'available for extraction' – although if groundwater use is not significantly consumptive, the baseflow reduction can be compensated by effluent returns (albeit with some river-water quality implications).

The contrasting picture of 'regional storage'

The groundwater potentiometric map (Fig. 1) indicates some regional flow from the main recharge areas into the deeper structural basins, and subsequent southward flow parallel to the general axis of the Paraná Catchment. Towards the centre of structural basins, the SAG groundwater becomes progressively more confined by increasing thickness of overlying basalts and exhibits overflowing artesian head in deep water-wells over extensive areas.

The SAG has a relatively high hydraulic conductivity (K_h of 5–10 m d^{-1}) and a mean estimated transmissivity of about 300 m^2 d^{-1} (range 50–1200 m^2 d^{-1}). Nevertheless, the flat terrain and low hydraulic gradients into the confined aquifer (about 0.1–0.3 m km^{-1}) imply very low groundwater flow velocities (less than 0.5 m a^{-1}). Aquifer numerical modelling suggests that the active groundwater flow into the deep confined aquifer is very limited, probably equivalent to 10–15 mm a^{-1} of vertical infiltration in the recharge area (only about 1–2% of the annual rainfall). With increasing depth and confinement, the groundwater temperature also increases substantially (as a result of normal geothermal gradients), such that it forms a low-enthalpy hydrothermal resource with temperatures widely exceeding 40°C and locally reaching 60°C.

Some natural discharge from the regional flow regime undoubtedly occurs, although it is not yet quantified due to difficulty in detecting and measuring small groundwater upwellings in areas with large river flows. But there are often small springs with a chemical composition similar to that of confined SAG groundwater in areas with volcanic dykes. Other potential discharge zones include sections of the Paraná River (along the Paraguay frontier) and the Pelotas and Uruguay River (in Rio Grande do Sul and Santa Catarina States – Brazil), and the Esteros de Iberá (Argentina) and Ñeembacú (Paraguay) wetlands.

An extensive study of environmental isotopes in SAG groundwater has proved very useful for corroboration of this regional flow model (Foster *et al.* 2009). Groundwater associated with the aquifer recharge area generally has $\delta^{18}O/\delta^{2}H$ values matching those of present-day rainfall (exceeding –7.5‰ in $\delta^{18}O$). Moreover, the presence of ^{3}H up to 3 TU and ^{14}C activity close to 100 pmC confirm the presence of recently recharged water, including below some ‘windows’ in areas with thicker basalts. The rapid decline of ^{14}C activity along groundwater flow paths towards the highly confined SAG is commensurate with extremely slow circulation – with most deep boreholes recording ^{14}C below the detection limit (probably water recharged more than 35 000 years BP). Subsequently, it proved possible, using ^{14}C and ^{81}Kr techniques (Aggarwal *et al.* 2015), to confirm the extremely slow flow rates (0.3–0.7 m a^{-1}) with groundwater older than 730–830 000 years BP at 250–560 km from the outcrop in São Paulo State, Brazil. However, these water ages are not compatible with the results of Darcy Law approach, suggesting that there may be older water mixtures coming from pre-SAG formations. In addition, the $\delta^{18}O$ content of groundwater in some confined SAG areas (e.g. in São Paulo State, Brazil) is at first sight anomalous, given a more negative stable isotope composition than present-day rainfall ($\delta^{18}O$ of −8 to −9.5‰; Gastmans *et al.* 2012).

Natural groundwater quality regime

Natural SAG groundwater quality is generally very good with low mineralization in most areas. A hydrogeochemical evolution is seen as recharging waters from outcrop areas flow slowly into the deeper confined aquifer (Table 1) with the dissolution of carbonates (confirmed by $\delta^{13}C$ content of dissolved inorganic carbon), ion exchange processes (notably Na replacing Ca), rising pH from 6.8 to 9.5 and marked temperature increases (Sracek and Hirata 2002; Manzano and Guimaraens 2012).

The hydrochemical and isotopic data show that formations underlying parts of the SAG (mostly saline aquitards) contribute to observed salinity and significant trace element increases (especially F and more locally As) in certain areas, but that this contribution is not substantial in terms of associated groundwater flow volumes. There are also much more marked and general down-dip increases in groundwater salinity in the extreme SW of the SAG in Argentina, which effectively marks the limit of the potentially useful aquifer system. There have also been some concerns that the deep confined groundwater might locally contain significant levels of the soluble U isotopes, radium and radon gas (Bonotto and Bueno 2008).

Table 1. *Typical changes in groundwater chemistry in the Guarani Aquifer System when traced westwards down-dip in São Paulo State, Brazil*

Parameter (units)	Outcrop boreholes	Down-dip boreholes (distance from outcrop, km) 30	150
Temperature (°C)	24	25	42
pH	6.5	8.5	9.5
Calcium (Ca mg l^{-1})	30	20	2
Sodium (Na mg l^{-1})	1	5	90
Bicarbonate (HCO_3 mg l^{-1})	15	75	160
Chloride (Cl mg l^{-1})	1	2	10
Fluoride (F mg l^{-1})	<0.1	0.2	>1.0
Silica (SiO_2 mg l^{-1})	15	20	30

Sracek and Hirata (2002)

Aquifer pollution vulnerability and land-use issues

The only parts of the SAG that exhibit significant vulnerability to groundwater pollution from anthropogenic activities on the land surface are the main recharge area – comprising the aquifer outcrop and adjacent regions where the basalts are highly fractured, or ‘windows’ through the basalt exist. The degree of groundwater pollution vulnerability here will vary with water-table depth and the degree of consolidation of the sandstone units or fracturing of the overlying basalts and, although not ‘extreme’, is likely to be in the ‘moderate to high range’. At some distance from the SAG outcrop below basalt cover, the ‘relatively old groundwater ages’ deduced from isotopic analyses indicate minimal pollution vulnerability. Potential threats to the naturally excellent groundwater quality of the SAG in its recharge areas include:

- urbanization and the disposal of domestic urban wastewaters;
- industrial premises and their potentially inadequate storage and handling of hazardous chemicals, and disposal of liquid and solid effluents;
- intensification of agricultural crop cultivation and forestry.

As a result of the latter, rural land-use in parts of the SAG recharge area has witnessed enormous changes over the past 30 years (Fig. 3) or so including:

- clearing of humid subtropical forests to exploit their timber resources and make way for cattle ranching pastures (in Brazil and Paraguay);
- ploughing-in pastureland for the introduction of intensive agriculture – soya-sunflower/soya-maize rotations and sugar-cane (in Brazil, Paraguay and Argentina), in part for biofuel production, and citrus fruits (Brazil);
- forestation of some natural rough pastureland with eucalyptus for paper-pulp or pines for timber production (in Uruguay).

Since much better soil profiles are developed on the basalts than the sandstones, the introduction of intensive soya-bean rotations within the SAG recharge zone tends to be concentrated in the areas with thin basalt cover. The impact of these significant large-scale changes on the quality and rate of SAG recharge has not yet been adequately researched and requires further attention.

International agreement on aquifer management

The Guarani Aquifer Agreement, which was signed by Argentina, Brazil, Paraguay and Uruguay at a meeting in San Juan, Argentina on 2 August 2010 was hailed by some as a ‘new paradigm’ of international transboundary groundwater management (Villar and Ribeiro 2011), in the sense that it was characterized by an absence of water-use conflicts and was precautionary in character. However, doubts have subsequently been cast about its effectiveness in the sense that the period 2010–17 was marked by a slowdown of international co-operation and only sporadic and limited cross-border projects (Leite and Ribeiro 2018; Sindico *et al.* 2018). Moreover, in this period only Argentina and Uruguay ratified the agreement, although it is now possible that Brazil and Paraguay will soon follow suit.

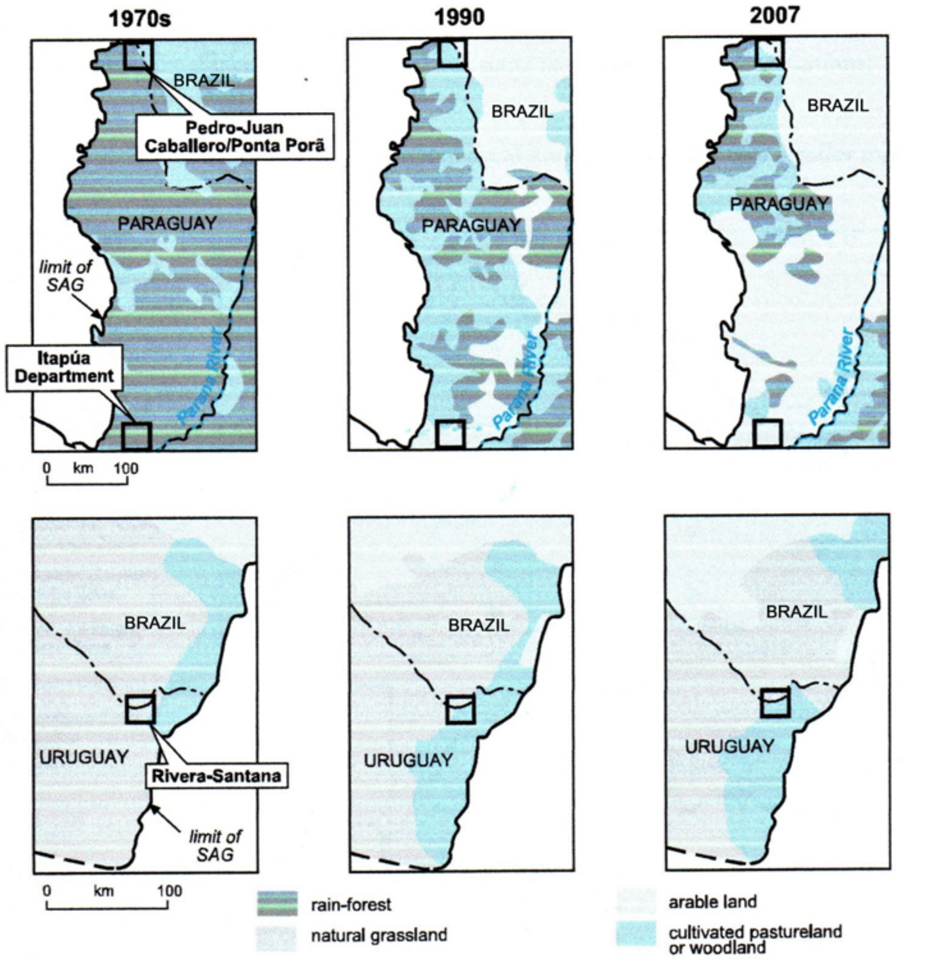

Fig. 3. Land-use changes during 1970–2007 above the Guarani Aquifer System (Foster *et al.* 2009).

Local groundwater supply development

Ribeirão Preto (Brazil)

Ribeirão Preto is a city in the northeastern part of São Paulo State with a population of about 590 000 and an area of 652 km^2 (including 137 km^2 of SAG outcrop) and spreading across the overlying Serra Geral Basalts. If neighbouring municipalities are included, the population is about 800 000, which according to government projections, will double by the year 2045. The area is one of major agricultural production, with sugarcane (for sugar refining and alcohol distillation), coffee and oranges (for fruit juice production) being the dominant crops. The city is also a major industrial centre – with important fuel-alcohol distilling, and agro-industrial products and services.

Groundwater recharge occurs when rainfall excess on the sandstone outcrop infiltrates during November–March at rates believed to be around 250 mm a^{-1}. Very detailed studies in this area concluded that little recharge to the SAG occurs through the Serra Geral Basalt of over 30 m thickness (Fernandes *et al.* 2016). The SAG is exploited by more than 1000 water-wells – with the Departamento de Águas e Esgotos (DAERP) having 117 active with a production of 127 Mm^3 a^{-1}. However, there is significant uncertainty about the total level of groundwater abstraction – which is estimated to have grown from 45 Mm^3 a^{-1} in 1976, to 96 Mm^3 a^{-1} in 1996 and to 133 Mm^3 a^{-1} in 2007. For the entire area (including adjacent municipalities), the extraction reached 186 Mm^3 a^{-1} in 2007. Groundwater development and water-table lowering have largely eliminated natural groundwater discharge to streamflow (and replaced it by wastewater discharge). Contemporary groundwater recharge is exceeded by abstraction and, over a large area across the city, groundwater levels have fallen by an estimated 30–40 m since 1970, with increases in operational water-supply costs and previously effluent watercourses becoming influent.

Groundwater quality from the DAERP water-wells (in the part of the aquifer protected by basalt cover) is reported to be fair, with excellent microbiology, very low total salinity (EC = 60 µS cm^{-1}), slightly acidic pH (5.5–7.0) and nitrate not exceeding 10 mg l^{-1} NO_3-N. Mobile herbicides (such as tebuthiuron, diuron and ametrine) are widely applied to sugarcane but have not yet been detected in groundwater samples, nor any of the chlorinated solvents used in some industries. Elsewhere, in the more vulnerable outcrop area, the vadose zone is generally thick (30–60 m) and increasing as a result of falling water-tables, and thus groundwater pollution by persistent contaminants from sanitation practices, industrial effluents and agricultural cultivation may not yet have percolated down to the deep water-well screen-intakes, although not many studies have been conducted in this area

The pressing issues that need to be addressed are:

- promotion of land-use planning on the SAG recharge zone compatible with its primary function as a source of potable municipal water-supply and based on aquifer vulnerability mapping and groundwater supply protection area delineation;
- appraisal of the risks to existing municipal groundwater sources posed by current urban sanitation measures, industrial activities and agricultural practices, and promoting action to manage any significant identified risk;
- constraint on the demand for groundwater abstraction, since current average water production is very high (350 l d^{-1} per capita);

- possible development of municipal groundwater production from wellfields situated in the protected SAG confined area, in part to replace any existing source at great risk of pollution and to reduce intense hydraulic interference in the downtown area.

Some important advances that have already been promoted include:

- strong time-based constraints on water-well drilling and replacement within Ribeirão Preto until the definition of a management policy between DAEE (Departamento de Águas e Energia Elétrica-São Paulo State) and the Municipal Government;
- the Comitê da Bacia Hidrográfica do Pardo (CBHP) promoting actions to constrain urban water demand.

São José do Rio Preto (Brazil)

São José do Rio Preto is a city of about 460 000 inhabitants, located in the interior of São Paulo State, whose water services are provided by a municipally owned company SEMAE. The SAG is located at considerable depth below the city, beneath the Bauru Aquifer and Serra Geral Basalts.

The urban water-supply of about 50 $Mm^3\ a^{-1}$ is provided from the Preto River (17%), public water-wells in the unconfined Bauru Aquifer (27%) and the deep confined Guarani Aquifer (22%), and some 1700 private water-wells in the Bauru Aquifer (33%), of which 80% are not yet licensed. Although there is intense competition between the water-utility and private abstractors, private water-wells cannot be closed without causing severe problems for the public supply (Wendland *et al.* 2013). Thus, SEMAE has taken various measures to impose some order on private groundwater use, which is mainly by residential condominiums and industrial premises:

- mapping and metering of all private water-wells (licensed or otherwise), as the basis for charging for sewerage discharge;
- commissioning a study of all private water-wells to improve groundwater management for the Bauru Aquifer, based on the identification of areas of intense exploitation – the technique consisted of dividing the urbanized area into 500 m squares, mapping all known water-wells, classifying them according to well density (4–10, 11–30 and >30) and total abstraction (<0.36, 0.36–0.72 and >0.72 $Mm^3\ a^{-1}$) and providing actions for the guidance of the regulatory agency to limit or to permit expansion of groundwater use.

Groundwater quality investigations have revealed that the upper 30–40 m of the unconfined Bauru Aquifer (which exceeds 150 m in total thickness) have significant nitrate contamination, from both sewerage losses and *in situ* sanitation, and this problem is now having to be confronted.

Rivera (Uruguay)/Santana do Livramento (Brazil)

The towns of Rivera and Santana do Livramento straddle the Uruguay–Brazil (Rio Grande do Sul State) border and have a total population of about 190 000. In many ways they act as a continuous urban area (with single electricity supply and emergency services). Economic activity is based largely upon agriculture, with cattle and sheep for leather, meat and wool production, maize and increasingly soybean cultivation and, on the Uruguayan side, forestation for wood and pulp.

The SAG outcrops across much of the area and elsewhere are covered by a thin capping of basalts, with the frontier following a low but hilly surface water-divide. The groundwater table occurs at shallow depth, with natural groundwater flow in a northeasterly direction and concentrated at 40–80 m depth in the most permeable aquifer horizons. However, this has been modified by groundwater abstraction depressing levels by 5–10 m. The SAG is the principal source of water supply, with about 300 water-wells, including those of Obras Sanitarias del Estado (OSE) in Rivera and the Departamento de Aguas e Esgotos (DAE) in Santana do Livramento providing some 7 and 9 $Mm^3\ a^{-1}$ (100% of the corresponding totals) respectively in 2015. Mains water-supply coverage is more than 95% by population, but multi-residential buildings and larger family residences also operate private boreholes to mitigate against discontinuity of mains service and/or to reduce the overall cost of water-supply.

Natural groundwater quality is excellent, with low $CaHCO_3$ (80 mg l^{-1}) mineralization and average values of Cl = 33 mg l^{-1}, SO_4 = 4 mg l^{-1} and Na = 6 mg l^{-1}, although pH is low (less than 6.0) and NO_3 concentrations are elevated (some over 10 mg l^{-1} NO_3-N). The main groundwater management problem relates to the lack of mains sewerage, which results in a substantial load of wastewater to an aquifer of significant pollution vulnerability either directly from cesspits or indirectly from polluted streams. The history of land tipping of solid municipal waste, the infiltration of some industrial effluents (from timber-processing yards and livestock slaughterhouses), and the presence of a substantial number of poorly-maintained gasoline filling stations represent further hazards to groundwater quality. Main sewerage coverage is restricted to about 40% of both the Rivera and Santana do Livramento populations, and there is also an overflow of *in situ* sanitation units in certain areas (due to improper construction and insufficient space for soakaway construction). Both towns are striving to amplify their mains sewerage system, but the process is complicated by a number of factors:

- hummocky terrain which necessitates many local sub-stations for pumping sewage and causes escalating capital cost and operational problems;
- low population density in outer urban areas considerably increasing the unit cost of sewerage provision;
- unwillingness of part of the population to meet the capital cost of linking properties to the main sewer when provided and/or to pay the annual charge for mains sewerage provision once connected;
- illegal connections of roof and patio drainage from residential properties to the main sewers, causing system overload, heavy sediment load and treatment plant by-pass during frequent episodes of intense rainfall.

It is thus uncertain whether increased investment will result in better aquifer protection.

Both OSE and DAE have high-yielding (>100 $m^3\ h^{-1}$) SAG water-wells in restricted areas west of the city, close to the prominent basalt escarpment where the full thickness and most permeable horizons are present. The supply derived from these areas already appears to represent more than 30% of the total, and these locations (which are at or beyond the current limit of urbanization) are suited to the construction of public water-supply wellfields and the establishment of special groundwater protection areas. This approach would provide a more secure urban water-supply, reducing dependence on the numerous wells dispersed throughout the urban area. A question arises as to where the legal and institutional powers lie for a possible declaration of potable groundwater supply protection areas of significant extension, for which numerous land-use constraints would apply. Against a background of a past international agreement ('Acuerdo sobre Cooperación Brasil-Uruguay en Materia Ambiental de 1992'), the Comisión Transfronteriza del Acuífero Guaraní (COTRAGUA, which ceased to function soon after the completion of the GEF

Guarani Aquifer Programme in 2008), with representation of 5 stakeholder organizations on each side (including local government offices, corresponding water utilities, water-well drillers, NGOs, agricultural, hydrological and public health organizations), was formed with the functions of:

- assisting in the collation of relevant technical, economic and legal materials;
- serving as a focal point for social survey and participation in groundwater management, such as denouncing illegal well construction and polluting discharges;
- co-ordinating local efforts for capacity building amongst stakeholders.

Concluding remarks

The strategic importance of the SAG is based on the fact that it is a vast aquifer, located in one of the most important economic regions in South America. Currently, more than 1.1 km^3 a^{-1} of groundwater are exploited mainly in São Paulo State (80%), which have an economic value of about US$ 600 million a^{-1}. The exploitation in São Paulo State arises not only because of its high water demand and capacity to drill deep water-wells (some to more than 1000 m and costing more than US$ 1 million), but also because the SAG has its high transmissivity (up to 1200 m^2 d^{-1}) here, resulting in large water-well production.

There are local problems where intense exploitation has required water-well drilling restriction, as in Ribeirão Preto. However, it is evident that the SAG is still an underutilized system. In this regard, one should distinguish areas where the SAG is unconfined, and low water-well drilling costs combined with high aquifer productivity have driven development mainly by the private sector. The government agency responsible for water resource management has little control over these wells, and it is estimated that more than 70% are not licensed. In these areas the water is young and sustainable exploitation is limited to a fraction of aquifer recharge, but a greater concern is the high vulnerability of the aquifer to pollution. In its confined part, water-well drilling is better controlled and the number of clandestine wells is low. In this area, groundwater is very old and the risk lies in extracting fossil water without a strategy to assess the gradual lowering of hydraulic heads. Thus far there is no regulation, or recognition, of this problem even in the State of São Paulo.

Studies have shown that the SAG, previously understood as a monolithic system with high and homogeneous production capacity, is instead a heterogeneous and complex aquifer. Local characteristic is still only partially understood and exploited inefficiently. An aquifer of ‘continental dimension’ requires a system for sharing hydrogeological knowledge and management experience.

Acknowledgements This paper represents a concise summary and full update of the extensive investigations of the Guarani Aquifer System undertaken by the World Bank GW-MATe during 2004–08 and reported more fully in GW-MATe Case Profile Collection 9 (of 2009/see References). The second author directed the GW-MATe Programme during 2001–11, and the first author served as a Senior Consultant throughout the work. The authors would like to acknowledge valuable discussions with World Bank and GW-MATe colleagues, groundwater specialists from the Guarani countries (Brazil, Paraguay, Uruguay and Argentina), and of the Universidade de São Paulo in developing the concepts and information on which this paper is based.

Author contributions **RH**: data curation (lead), investigation (lead), writing – original draft (equal); **SF**: data curation (supporting), investigation (supporting), writing – original draft (equal)

Funding During 2004-08 the work was funded by a Global Environment Facility (GEF) Project administered and supervized by the World Bank –Latin America & Caribbean Department, and subsequent work in São Paulo State was undertaken as part of the programme of the Universidade de São Paulo –Groundwater \research Centre.

Data availability statement All data generated or analysed during this study are included in this published article (and its supplementary information files).

Scientific editing by Jonathan Smith

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