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# GEOLOGICAL AND HYDROGEOLOGICAL REAPPRAISAL OF THE GUARANÍ AQUIFER SYSTEM IN THE URUGUAYAN AREA

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## ABSTRACT

The lack of knowledge of water resources in a region and the absence of obvious symptoms of their deterioration do not favour the establishment of effective management mechanisms for their preservation. This problem is exacerbated in the case of transboundary aquifers such as the "Guaraní Aquifer System" (GAS), a large multi-layered aquifer system in central-eastern South America. We present here a reappraisal of some important aspects that contribute to a better knowledge of the GAS in the Uruguayan area, as for instance an integrated stratigraphic, chronostratigraphic and sedimentological (paleoenvironmental) study of the sequence that encloses their constituent aquifers in order to identify the main hydraulic, hydrochemical and hydrogeological paths that define this fundamental resource. Moreover, we also provide a well-supported re-evaluation of the SAG outline, by including the outcropping areas of the San Gregorio-Tres Islas and the Yaguarí and Cerro Conventos aquifers in the Cerro Largo County. Some hydraulic interconnections between the GAS aquifers has been previously detected but more work needs to be done to evaluate this behaviour within already proposed conceptual flow models. Some evidence for aquifer-river relationships between the GAS and the main rivers such as the Paraná, Uruguay and their tributaries is herein also discussed.

**Keywords:** Geology, Hydrogeology, multilayer Guaraní Aquifer System, aquifers interaction, aquifer-river relationships.

## INTRODUCTION

The "Guaraní Aquifer System" or GAS is a large multi-layered aquifer system that extends for about 2200 km in length, 500 km in width and 200-800 m in thickness (Rebouças and Amore 2002). It encompasses almost the entire Paraná and Chaco-Paraná watersheds, and covers a total area of about 1,100,000 km², with 68-70% in Brazil, 19-21% in Argentina, 6-8% in Paraguay and 3-5% in Uruguay (Secretaría del Ambiente, Asunción, Paraguay 2003; de Rosa Filho et al. 2003; Hirata et al. 2020). This aquifer system was named after the Guaraní Amerindian people who live mainly in the Amazon regions of all the « GAS countries ». The GAS contains from 30 to 57 x $10^{12}$ $m^3$ of water, of which only 2 x $10^{12}$ $m^3$ is economically accessible, taking into account a drawdown of less than 400 m (Kirchheim et al. 2019). Nevertheless, this enormous water reserve is the largest transboundary confined aquifer system and the third largest aquifer system in the world with about 20% of the world's liquid freshwater resources.

Within the GAS area there are about 1500 cities and towns with a total population of 23.5 million, of which about 9-15 million are directly supplied by it (Santa Cruz 2009; Corbo et al. 2012; Walter 2012). About 66-80% of the GAS's water resources are used for urban water supply, 15-16% for industrial processes, 5-13% for thermal tourism and 5% for irrigation (Hussein 2018; Sindico 2018). In some regions, the GAS represents the only source of water supply available for urban, agricultural and industrial uses. It is therefore a strategic water reserve for all four countries (Vives et al. 2011). Due to the unequal distribution of the aquifer under each country and their demographics, 94% of this water is indeed exploited by Brazil (of which about 80% for the state of São Paulo alone), 3% by Uruguay, 2% by Paraguay and 1% by Argentina (Sindico 2018).

For at least two decades, the GAS countries have been experiencing problems related to the very large and unplanned increase in water withdrawals from this aquifer (Rebouças and Amore 2002; Kirchheim et al. 2019). The overexploitation of the GAS water was noted by Gastmans and collaborators as early as 2012, based on the deficient balance estimations of Vives et al (2008). The current exploitation of the GAS water resources exceeds $10^{12}$ $m^3.year^{-1}$ for an estimated recharge of between 0.8 and 1.4 x $10^{12}$ $m^3.year^{-1}$ (Kirchheim et al. 2019). Taking into account the uncertainties, this means that these withdrawals have become more important than the recharge, and that the limit of overexploitation has been reached (Gastmans et al., 2012). This phenomenon could worsen in the coming decades due to human driven climatic disorder, aggravated by ongoing climate change.

However, as early as 2010, the GAS countries drew up the Guarani Aquifer Agreement (GAA), which is one of the first examples of « hydrodiplomacy » linked to groundwater. As the result of a transboundary negotiation process, this agreement seeks to balance national interests and strengthen regional and local cooperative governance of this shared aquifer. Unfortunately, this agreement has so far not been ratified by all the concerned countries, but the debate seems to be opening again (Sindico 2018). As long as the latter country does not ratify it, the GAA cannot enter into force, thus slowing down the momentum that had been developed over a decade to achieve more effective transboundary cooperation around this formidable water reserve. Another problem is that the GAS was arbitrarily restricted to just one geological unit, without any hydrogeological reason. That allowed a misunderstanding of the aquifer system functioning, and thus the governs could not depict a correct management for it. Stratigraphic studies were not prioritized by the GAA, even considering that this issue was in the list of its main contributions to the GAS. It is therefore crucial to have a good understanding of the functioning of this vast aquifer system in order to provide a future basis for concerted plans for sustainable transboundary groundwater management in the hope that the GAA will soon come into force (Vives et al. 2011).

## GEOLOGICAL CONTEXT

### Stratigraphy and lithology

The average thickness of the GAS is 250 m, ranging from 640 m in the centre of the state of Mato Grosso do Sul (Brazil) to only 8 m near the border between Brazil and Argentina (Gastmans et al. 2012). Its main reservoir rocks are eolianites (sandstones) that were deposited from the Jurassic to the Lower Cretaceous (Araújo et al. 1999), although other hypothesis specifical for the Uruguayan region of the GAS will be considered (see below). From top to bottom, these are the Botucatú and Guará formations in Brazil, called Misiones in Paraguay, Tacuarembó and Misiones in Argentina, and Rivera and Tacuarembó in Uruguay. Concerning the stratigraphic equivalence of these formations it is worth to note that the lower section of Tacuarembó is fluvio-lacustrine and has been correlated to Guara (Lavina & Scherer, 1997) whereas the upper section of Tacuarembó and the overlaying Rivera are eolian and so, the entire package has been correlated to the Botucatú (França et al. 1995). Moreover, although former works (i.e. Heinzen et al. 1986) considered the Tacuarembó Formation as the main aquifer of the Uruguayan GAS, Montaño et al (2002, 2007) described it as a poor aquifer compared to the overlying and underlying sandstones (see below).

Other aquifers with variable hydraulic potential are the Triassic sandstones that also participate in the GAS, especially represented in Brazil by the Caturrita, Santa Maria, and Sanga do Cabral formations (Giardin and Faccini 2004) (Table I). Whereas, in Uruguay, the Rivera and the Tacuarembó formations are underlain by Cuchilla de Ombú at the west and Cerro Conventos plus the middle-late Permian Yaguarí-BuenaVista sequence, at the east. All these sandstones constitute what is called in Uruguay as the “Typical GAS” (Montaño et al. 2002, 2006, 2007; Collazo 2006 and Collazo et al. in press) (Figure 1; Table I), underlain by alternating siltstones, fine sandstones and shales of Early Permian (or even older) age. From top to bottom, they correspond to the Paso Aguiar, Mangrullo and Fraile Muerto formations (the Melo Group of Bossi and Navarro, 1991). These formations are referred to as the “Permian GAS” and represent aquitards (Montaño et al. 2002, 2006, 2007) (Figure 1; Table I). The underlying glacio-deltaic San Gregorio-Tres

Islas sequence and the Devonian fluvio-deltaic Durazno Group (including from base to top the Cerrezuelo, Cordobes and La Paloma formations) may represent separated aquifers, although some hydraulic connections with the Typical SAG have been suggested (e.g., Kern et al. 2008; Manzano and Guimareans 2012; Gastmans et al. 2012; Elliot and Bonotto 2017; but see also Sracek and Hirata 2002), depending on the properties of the overlaying aquitards (the Permian GAS of Montaño et al. 2002, or the Pre-SAG according to other authors).

Aquitards represent very important formations in a groundwater flow system; they control recharge and flowing and eventually, they will regulate the migration of chemical and biological contaminants to the deeper aquifers (Cherry et al. 2004). Aquitards recharge from the surface landscapes and they can show a prolonged response to regional groundwater flow changes (Alley et al. 2002). The aquitards of the Permian GAS would show horizontal preferential flow with higher hydraulic conductivity because of stratification, thus would transmit imperceptible amount of water to the underlying aquifer (e.g., San Gregorio-Tres Islas). However, the extensive fracturing and fails observed in the aquitard units will increase the vertical hydraulic conductivity (Cherry et al. 2004) and so, eventual migration of contaminants to the underlying aquifer (and the surrounding wells) could occur.

In northern Brazil, the so-called Pre-GAS underlain the Juro-Cretaceous and Triassic sandstone sequence which is represented by the aeolian Piramboia formation, and the fluvial Middle Permian Rio do Rasto formations followed stratigraphically downwards by the Passa Dois, Guatá and Itararé Groups (Figure 2A). Besides, the Triassic red sandstones represented by the Sanga do Cabral, Santa María and Caturrita formations overlain the Rio do Rasto and the Piramboia formations at the south region, while only the last two are represented at the north. Similarly, Buena Vista in Argentina, and Tacuary and Grupo Independencia in Paraguay are considered as « pre-GAS » aquifers (see for instance Santa Cruz 2009; Vives et al. 2011; Gastmans et al. 2012; Chang et al. 2013; Rodriguez et al. 2013; Mira et al. 2015; Kirchheim et al. 2019; Gonçalves et al. 2020) (Table I).

Furthermore, some of these formations, especially at the Permian roof, can also be locally considered as aquitards (Araujo et al. 1999; Montaño et al. 2006) and the separation between GAS and pre-GAS (or Permian GAS) is based on the evidence of the regional Permo-Triassic discontinuity, which can be observed in geophysical boreholes, especially in Argentina (Mira et al. 2015, Figure 2B; Table I). However, as shown above, it is controversial in Uruguay because there are no Permo-Triassic discontinuities and the Triassic sandstones (i.e., Caturrita, Santa María and Sanga do Cabral formations) were not preserved (Ernesto et al. 2020; Piñeiro et al. in press). In the absence of evidence of hydraulic separation between the Typical GAS and the Permian GAS (Figure 1), it will be considered here as a single aquifer unit simply called GAS.

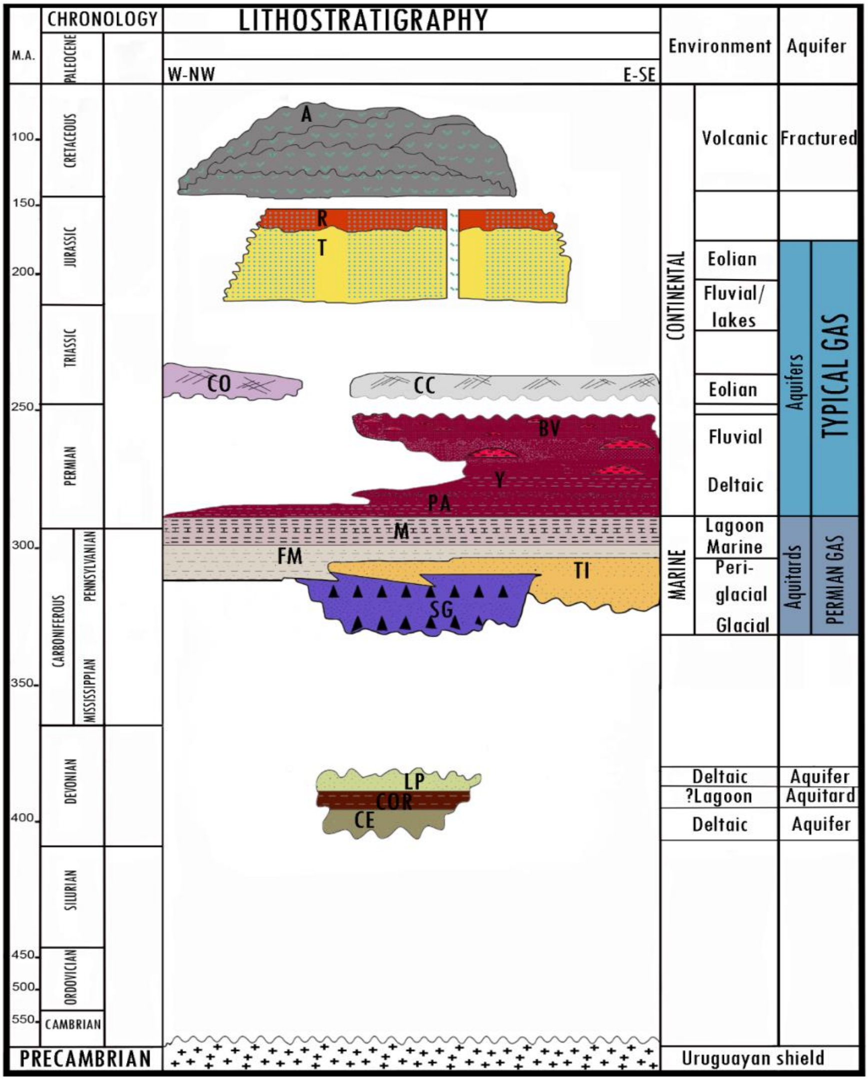


**Figure 1: Stratigraphic and hydrostratigraphic arrangement of the GAS in Uruguay according to paleontological, biostratigraphic, paleoenvironmental, radiometric and paleomagnetic data presented in previous studies** (e.g., Piñeiro et al. 2003; Piñeiro 2006; Piñeiro et al. 2012a,b; Calisto and Piñeiro 2019; Ernesto et al. 2020; Piñeiro et al. 2021) and hydrogeological results provided by Bossi and Schipilof 1998; Montaño et al. 2002, 2006, 2007; Collazo et al. in press). Abbreviations: CE = Cerrezuelo, COR=Cordobes, LP=La Paloma, SG=San Gregorio, TI=Tres Islas, FM=Frayle Muerto, M=Mangrullo; PA=Paso Aguiar; Y=Yaguari, BV=Buena Vista, CO=Cuchilla de Ombú; CC=Cerro Conventos; T=Tacuarembó; R= Rivera; A= Arapey.

At the top, the GAS is suggested to be confined over about 90% of its surface under basaltic outcrops of Early Cretaceous age, which are 1000 to 1500 m thick, but they are fissured and fractured. This formation is known as the Serra Geral in Brazil and Argentina, the Alto Paraná in Paraguay and the Arapey in Uruguay (Table I). It is also responsible for the intrusion of sills and diabase dikes into the underlying sedimentary formations of the basin. These basalts may be locally overlain by sandy-clay sediments of the so-called « Bauru » formation in Brazil, Quebrada Monardes in Argentina, Acaray in Paraguay and Asencio in Uruguay. As the GAS is probably in hydraulic connection with the overlying basaltic layers, they are sometimes referred to as « post-GAS » (Table.1).

**Table 1: Cross-border correlations between the stratigraphic units composing the GAS including the present proposal (adapted from Kirchheim et al. 2019)**

| Sedimentary Basin/Aquifer Unit | Uruguay | Argentina | Paraguay | Brazil | |
|---|---|---|---|---|---|
| | North | Chaco-Paraná | Paraná | Paraná | |
| | | | | South | North |
| ?Post-GAS | Arapey | Serra Geral<br>Posadas/Solari | Alto Paraná | Serra Geral | |
| Typical GAS | Rivera<br>Tacuarembó | Misiones<br>Tacuarembó | Misiones | Guará | Botucatú |
| | Jurassic regional discordance | | | | |
| | | | | Caturrita<br>Santa María<br>Sanga do Cabral | |
| | Permo-Triassic discordance | | | | |
| | Cerro Conventos<br>Buena Vista<br>Yaguarí | Buena Vista | Tacuary<br>Independencia | Piramboia<br>Rio Do Rasto | Corumbataí |
| PERMIAN GAS | Melo | ? Victoriano Rodriguez | | Passa Dois | |
| | San Gregorio<br>Tres Islas | Ordoñez | | Guatá<br>Itararé | |
| | Grupo Durazno | Talacasto | | São Domingos | |
| | Crystalline basement | | | | |

Other aquifers lie below the Typical Gas and even below the Permian GAS. They belong to the Carboniferous San Gregorio-Tres Islas sequence, the Devonian Cerrezuelo, Cordobes and La Paloma sequence and the Precambrian crystalline basement (Table I; Figure 2). The hydraulic relationships between these formations and the GAS are controversial or at least variable from one area to another.

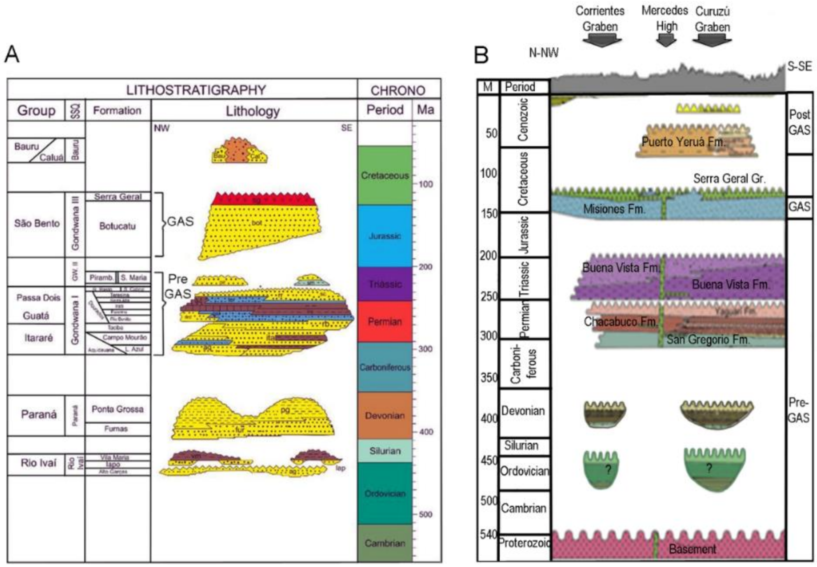


**Figure 2: Stratigraphic columns of the GAS and the surrounding formations in A) Brazil (modified from Teramoto et al. 2020) and B) Argentina (modified from Mira et al. 2015).**

**Boundaries and morphology of the GAS**

The sedimentary formations that contain the GAS are generally bowl-shaped and are occupied, on the surface, by the Paraná and Chacoparaná basins. These formations are bounded to the north, northeast, east and southeast by crystalline basement outcrops that form the Uruguayan shield and to the west by a tectonic structure known as the Asuncion Arch, which is responsible for significant erosion of the upper part of the GAS. Throughout the sedimentary basin, the geometry of the GAS is controlled by other tectonic structures of the same type, the most important of which are the Canastra and São Vicente Arches in the north, the Asunción and Pampeano Arches in the west, and the Rio de la Plata/Rio Grande Arch in the south (Gastmans et al. 2012). However, while the upstream and lateral boundaries of the GAS are well known, those of the southern and southwestern termination of the basin are still poorly defined despite a significant number of wells drilled in this aquifer system (Corbo et al. 2012, **Erreur ! Source du renvoi introuvable.**A). Also, the southeastern boundary should be modified as well as the overall outline of the GAS extending to the northeast, given the hydrostratigraphic model that defines the Yaguarí-Buena Vista and the Cerro Conventos deposits as part of the Typical GAS, whose outcrops into the Cerro Largo County, are important areas of the aquifer recharge (Figure 3B).

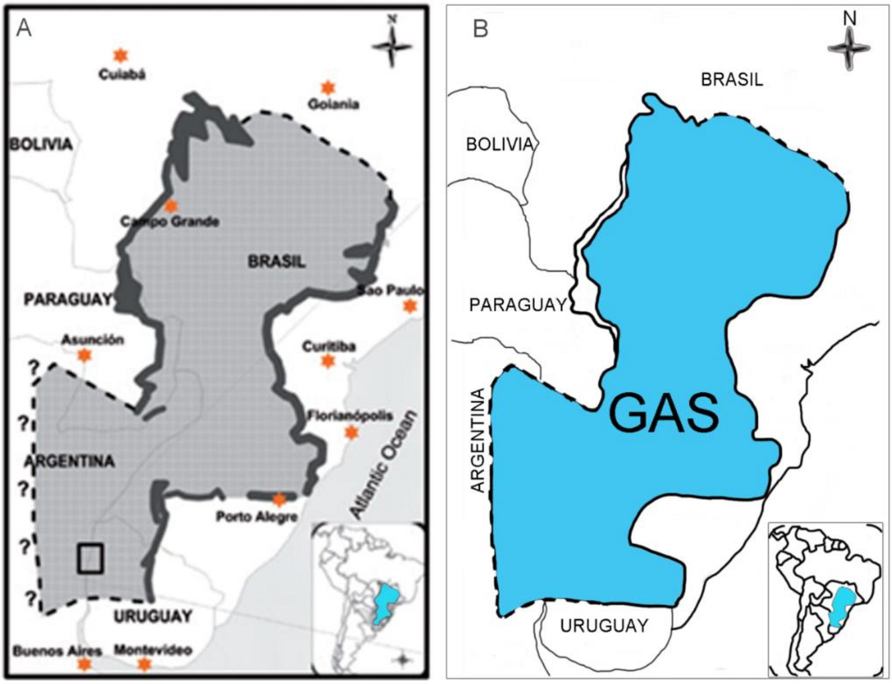


**Figure 3: A) GAS Limits (according to Corbo et al. 2012); B) GAS Limits according to Montaño et al. 2002, Collazo 2006; Collazo et al. (in press), Bossi and Schipilof 1998 and this paper (adapted from Corbo et al. 2012).**

## COMPARTMENTALISATION OF THE AQUIFER SYSTEM

On a global scale, the GAS water flows through a continuous sandstone sedimentary formation, confined between the underlying Carbo-Devonian sediments (or even locally by the basement) and the overlying post-GAS formations, mainly basaltics (Rodriguez et al. 2013). Nevertheless, the GAS sedimentary basin is subdivided into three main domains on either side of two major tectonic structures: the Ponta Grossa Arch in northern Paraná State (Brazil), forces groundwater to flow from east to west, and the Asunción-Rio Grande Arch, which divides the southern part into two semi-independent basins, the Central Paraná and the Lower Chacoparaná (Gastmans et al. 2012). In addition, the presence of numerous diabase dykes plays a fundamental role in the structural compartmentalisation of the GAS, especially in the north-south direction and on both sides of the Ponta Grossa and Rio Grande arches and, probably, also near the Assunção and Campo Grande arches (da Rosa Filho et al. 2003).

In the vertical plane, it has been seen that between the Typical GAS and the Permian GAS there are mostly aquifer formations that allow the GAS as a whole to be considered as a single, multi-layered aquifer system, ranging from the Late Carboniferous to the base of the Cretaceous. Particularly in Uruguay, the Typical GAS is a succession of sandstones which even having different hydraulic properties, they have some kind of hydraulic connection both horizontally and vertically through fractures (see Bossi and Schipilof 1998) (Figure 1, Table I). However, even within the Typical GAS, there may be local hydrogeological disparities: for example, contrary to that occurring Uruguay (see above), the Jurassic sandstones are the best reservoir bedrocks in Brazil, whereas the Triassic sandstones locally have clay content that decreases their porosity and permeability (da Rosa Filho et al. (2003).

On either side of the GAS, there are probably hydraulic connections with its surrounding formations but these have been little studied (Rodriguez et al. 2013). For instance, the base of the GAS is in contact with low-permeability clay formations in the north, more permeable silty-clay formations in the centre, and medium-permeability sandy-silt formations in the south. The matrix of these formations, systematically clayey or silty, means that the extent of vertical flow between the GAS and these underlying sediments can be considered negligible: nevertheless, the draining role of the faults (Bossi and Schipilof 1998), and in particular the dykes, has not been sufficiently studied. At the top, the GAS is in direct contact with the widely fissured and water-bearing basaltic formations, and thus the hydraulic connections seem to be assured. Nevertheless, some authors consider that the connections are poorly known and therefore prefer to neglect them, notably because of the very low permeability of the basalts. However, sandstones levels interlayered within the basaltic layers seem to retain water. That controversy persists basically because some recent conceptual models do not take into account important exchanges (recharge or discharge) at the top and the bottom of the GAS (Gonçalves et al. 2020).

The conceptual model of the GAS has evolved over time from a single homogeneous aquifer to an aquifer divided in two by the Ponta Grossa Arch (Bossi and Schipilof 1998; Kirchheim et al. 2019), and whose hydrogeological behaviour shows strong disparities between the deepest parts where hydraulic gradients are low (0.2‰) and the marginal areas where they are significantly higher (3-5‰) (Chang et al. 2013). The latest data show that the GAS would constitute a continuous but complex aquifer, separated into four domains by the major structural discontinuities of the Paraná Basin but nevertheless retaining a main north-south flow direction (Gastmans et al. 2012; Kirchheim et al. 2019):

- the NE domain, located near São Paulo and Minas Gerais (Brazil); it is characterised by a significant recharge related to the altitude of the eastern outcrop areas; groundwater flows here towards the Paraná River with hydraulic gradients that vary from 3 to 5‰ near the outcrop areas down to about 0.1‰ in the deeper parts of the GAS in the centre of the basin;
- the E domain, located in the Brazilian states of Paraná, Santa Catarina and in the northern part of Rio Grande do Sul; it is separated from the previous domain by

the Ponta Grossa arch; the uplift of the edges and the presence of numerous basaltic dykes can condition a preferential direction of groundwater flow that runs locally from east to west; the hydraulic gradients are moderate and uniform, around 2 to 3‰;

- the W domain, as an almost isolated system with the existence of a groundwater divide and a more fragmented flow through local recharge/discharge systems; the recharge zones are mainly associated with the Brazilian GAS outcrops but also with Paraguayan Misiones formation outcrops (Secretaría del Ambiente, Paraguay, Asunción 2003); the discharge zones are related to the outcrop belt bordering the Pantanal region (Mato Grosso do Sul, Brazil and western Paraguay; hydraulic gradients are low, varying from 1.5-2‰ in the north and west to 0.5-0.8‰ in the east;
- the S domain, located south of the Asunción-Rio Grande arch; groundwater flows east-west from recharge zones associated with submeridian Uruguayan outcrops; in Argentina, in the Corrientes province, the Mercedes area appears to represent a local recharge zone.

Groundwater flow from the three domains Northeast, East and West converges along the central axis of the basin that connects these domains to the Southern one (Kirchheim et al. 2019). In addition, there appears to be a significant artesian zone along this central axis, occupied by the Paraná River.

## HYDROGEOLOGY

### Recharge and discharge areas

The recharge or discharge zones result mostly from the hydraulic connections of the GAS with the overlying formations (basaltic aquifer) and the surface, or with the underlying formations (carbo-devonian aquifers, basement). However, we have seen that these connections are complex and their exact importance is still not known (Araújo et al. 1999; Teramoto et al. 2020). However, we can infer that due to the largely failured condition of the different bedrocks (formations) constituting the Typical GAS, the Upper GAS and the Permian or Pre-GAS the hydraulic connections do exist (Bossi and Schipilof 1998). Moreover, the interaquifer mixing is proved by isotopical signatures (see for instance Manzano and Guimareans 2012; Elliot and Bonotto 2017; Teramoto et al. 2020, among other authors).

Regarding the recharge zones of the GAS, they are mainly located north of the Rio Grande Arch (Araújo et al. 1999), and they consist of outcrops covering about 10% of the total extent of the aquifer, in the form of bands 10-30 km wide with a total cumulative length of 3500 km, as well as leaks from the overlying aquifers (mainly basalts). However, this contribution to the recharge of the GAS appears to be limited: it would be of the order of

1% of annual precipitation, i.e. 10 to 15 mm.year$^{-1}$ for Chang et al. (2013), and 4 to 5% for Rodriguez et al. (2013). There is no evidence of river recharge but Rodriguez et al. (2013) do not rule it out. In the hydrogeological model of Gonçalves et al. (2020), the total calculated recharge is about 0.6 km$^3$.year$^{-1}$, which corresponds to 4.9 mm.year$^{-1}$, with a minimum of 2 to 3 mm.year$^{-1}$ in the north-east and south zones respectively, and a maximum of 6 mm.year$^{-1}$ in the west and east zones. On these data, most authors have based their conclusions that the anthropic water abstraction from the aquifers that comprise the GAS exceeds substantially the annual volume of recharge of them.

Regarding the discharge zones, Araújo et al (1999) consider that they correspond to the hydrographic network of the Paraná River, especially in the area located between the Paraná and Uruguay Rivers, at their middle section basins. In the southern part of the GAS, this would be reflected in the presence of numerous lakes and swamps: however, the role of the large Iberá wetland in Argentina, and of the outcrop areas along the southern and western borders of the GAS, has never been studied according to Chang et al. (2013). Indeed, the lakes and swamps of the Paraná River delta has been almost disappearing in the two last decades because of severe droughts and multiple fires in the area (NASA Earth Observatory 2020). It is possible that the inclusion of the outcrops at the eastern region of Uruguay (i.e. Yaguari-Buena Vista and San Gregorio-Tres Islas formations) extending the outline or distribution of the GAS to the east may support the existence of some north-south flows and recharge areas of the GAS at the eastern region. Indeed, Collazo (2006) found that the main recharging area of the GAS in Uruguay is coincident with the distribution of the outcropping area of the Rivera and Tacuarembó formations (Rivera and Tacuarembó counties) and also with outcrops of the Yaguarí-Buena Vista aquifers. Concerning the discharge of the GAS aquifers, it has been determined that the Tacuarembó aquifer, in the outcropping area, discharges into the Tacuarembó River, not existing enough information yet to assure the flow directions of the discharge zones of the Yaguarí-Buena Vista aquifers, although a regional flow to the west can be considered as the most probable (Collazo 2006; Collazo et al. in press).

In Brazil, in the state of Paraná, the confinement of the GAS under basalts imposes artesian conditions only a few tens of kilometres from the outcrop areas: this leads groundwater to rise to the surface through diabase dykes, and to discharge into the basaltic aquifer of the Serra Geral or directly at the surface, into areas below 400 m a.s.l., i.e. in the valleys of the Paraná, Paranapanema, Iraí, Piquiri, Iguaçu and Uruguay rivers (Araújo et al. 1999; da Rosa Filho et al. 2003). It should also be noted that Rodriguez et al. (2013) consider that the main source of discharge from the GAS is represented by pumped water withdrawals as other sources of discharge are poorly known (leakage to rivers and infiltration to underlying or overlying formations), but they exist as mentioned above.

## Conceptual model and water balance

For da Rosa Filho et al. (2003), the hydrogeological model of the GAS, on which its exploitation should be based, should include the overlying formations (basalts and overlying sediments), and take into account the tectonic structures (arches, dykes) and their relationships with the groundwater recharge and discharge zones. Even though, Gonçalves et al (2020) developed a conceptual model that considers the GAS to be confined between underlying Permian aquitards (called pre-GAS) and overlying aquifer basalts (post-GAS). Nevertheless, the GAS is considered by these authors as a single, fully connected aquifer system (Figure 4). According to the results of dozens of pumping tests, the average hydraulic conductivity is fairly homogeneous around 1 to 6 x $10^{-5}$ $m.s^{-1}$, with extreme values of 2 x $10^{-6}$ $m.s^{-1}$ to 8 x $10^{-5}$ $m.s^{-1}$ (da Rosa Filho et al. 2003; Chang et al. 2013; Gonçalves et al. 2020). These variations result, on the one hand, from the diagenesis that differently affected the pore-filling cement of the sandstones (Gonçalves et al. 2020) and, on the other hand, from the differences between the Jurassic sandstones that are excellent reservoir rocks and the Triassic sandstones that locally have a clay content that decreases their hydrodynamic characteristics (da Rosa Filho et al. 2003).

It has been seen that Gonçalves et al. (2020) prefer to neglect the hydraulic connections between the GAS enclosing formations, but they have nevertheless taken into account some recharge zones along the outcrop areas of the GAS, as well as discharge zones along its western and south-eastern boundaries (see figures 3 and 5 in Gonçalves et al. 2020). If their model's ability to reproduce piezometry and most groundwater ages (see below) is correct, this confirms - according to these authors - that the recharge/discharge volumes of the GAS should not represent a significant fraction of the water flow.

In contrast to the previous authors, Rodriguez et al (2013) carried out a hydrogeological model including discharge and recharge zones. They even consider that recharge flows and relations with rivers are the dominant components of the GAS water balance with 84% of total inflows and 61% of total outflows respectively. Nevertheless, the discharge rates from the GAS to the surface are considered to be low compared to the river flows: for example, they would be 8 $m^3.s^{-1}$ for the whole of the Uruguay River for which the minimum flow is 382 $m^3.s^{-1}$ (Rodriguez et al. 2013, figure 4). The water balance of this model shows that the current exploitation of the GAS in the Uruguay River area does not globally exceed its recharge rate. However, the data on which these authors reach such a conclusion correspond to the period 1931-2001, since there have been an increasing overexploitation of the Rio de la Plata basin rivers, including the Uruguay and the Paraná rivers. Moreover, in areas with high pumping abstraction, there is local overexploitation which would cause the overlying rivers to go from a gain (discharge) to a loss (recharge) situation. The current drying condition observed at the Paraná River Basin may be an example of such a process.

| | | Max | Min | Average | % |
|---|---|---|---|---|---|
| *Inflow* | Recharge | 6470 | 2014 | 3516 | 84,2 |
| | PEF | 1212 | 377 | 659 | 15,8 |
| | Total | 7682 | 2391 | 4175 | 100 |
| *Outflow* | Leakage | 3135 | 2155 | 2512 | 61,4 |
| | PH | 194 | 149 | 164 | 4 |
| | WF | 602 | 485 | 526 | 12,9 |
| | SF | 293 | 191 | 227 | 5,5 |
| | Pumping | 248 | 1024 | 665 | 16,2 |
| | Total | 4472 | 4004 | 4094 | 100 |
| Change in | Storage | 3210 | -1613 | 81 | |

**Figure 4: Hydrogeological modelling of the GAS according to Rodriguez et al. (2013). Here we reproduce their table 4 which shows the mass balance of the model expressed in $hm^3.year^{-1}$ (PEF = Prescribed Eastern Flow, PH = Prescribed Head, WF = Western Flow, SF = Southern Flow).**

**Piezometry**

The different piezometric or potentiometric maps of the GAS, as presented by Chang et al. (2013), show (i) flows that converge from the outcrop areas at the upper edge of the basin (up to 1178 m a.s.l.) towards its axial zone where flows the Paraná River, and (ii) a main flow line that follows this axial zone from north to south (Figure 5). This dual flow pattern is confirmed by Kirchheim et al. (2019). The same scheme is also found south of the Rio Grande Arch, on the Uruguayan side, but not on the Argentine side where a « piezometric bowl » is thought to exist, i.e. a large area of low piezometric level (around 15 m a.s.l.) and probably of low hydraulic gradient. On the other hand, the map issued from the Gonçalves et al. model (2020) gives less prominence to this central north-south flow axis because these authors did not choose to impose significant groundwater-river relationships that would curve the piezometry.

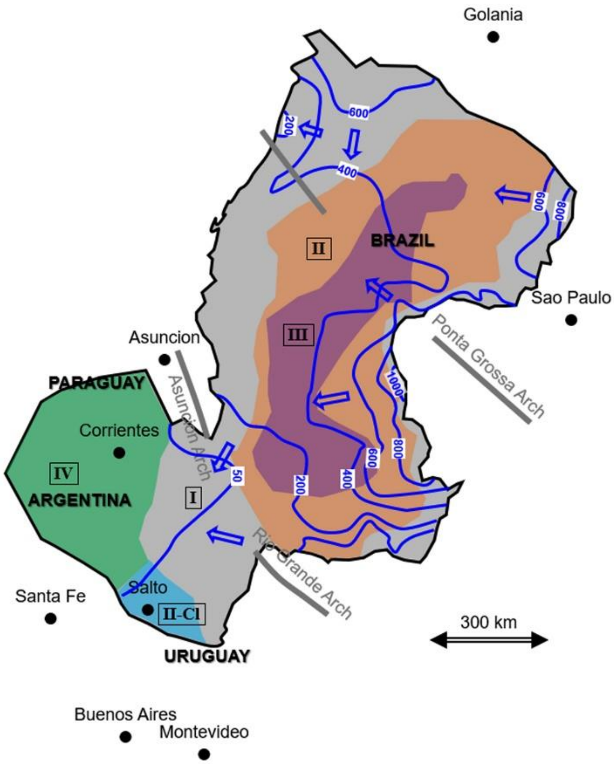


**Figure 5: Piezometric and hydrochemical map of GAS (modified from Gonçalves et al. 2020)**

*Legend: blue lines = isopiezometric level (m ASL), blue arrows = groundwater flow line, coloured shapes = hydrochemistry areas (see text)*

Vives et al (2011) propose a simplified north-south lithological section of the GAS where its piezometric surface has been plotted (Figure 6). It is several hundred metres high in the northern part, i.e. under the thick basaltic formations of the Brazilian area, but it reaches almost the sea level in the southern part (Argentine-western Brazilian border) where it arrives at the surface, especially in the extensive Iberá wetlands, considering these wetlands as an important discharge area for GAS. But as the hydraulic head is closed to the ground surface, it can decrease of a few meters in case of severe drought and consequently the groundwater discharge into the surficial waters can significantly decrease or even cease. This phenomenon could aggravate the extreme low level of streams, as Paraná and Paraguay, as observed since a few decades by several authors in association with an irregular sequence of the El Niño-La Niña Southern oscillation phenomenon (Melo et al. 2016, Sordo-Ward et al. 2017, NASA Earth Observatory 2020, Santos 2021).

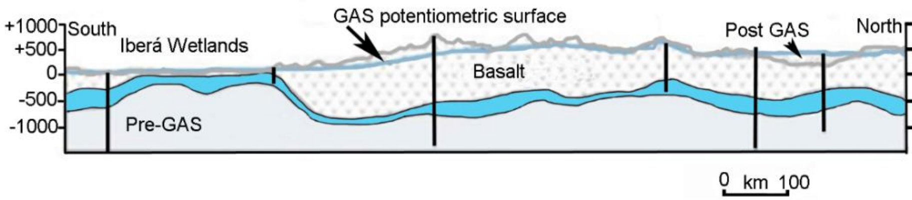


**Figure 6: Simplified longitudinal section of the GAS geology showing its piezometry (modified from Vives et al. 2011)**

## HYDROGEOCHEMISTRY

### Water quality trends

The GAS generally contained freshwater with a low total mineralisation in most areas (Montaño et al., 2002, 2006; Chang et al. 2013). In the state of São Paulo (Brazil), which is the best studied area due to a high density of wells and inhabitants, the total mineralisation is below 250 mg.l$^{-1}$ in 84% of wells with a maximum of 1216 mg.l$^{-1}$ (Araújo et al. 1999). However, in areas of low recharge where the residence time is high (see below), mineralization can be high and the water loaded with fluorides which can make it unfit for human consumption with concentrations of 3.6 to 12 mg.l$^{-1}$ (see also Marczinek, 2005).

In Uruguay, the hydrogeochemical characterization of the GAS was implemented from the study of samples coming from the outcropping area and from the confined aquifers. They were classified as calcic bicarbonate and calcic chloride respectively, and in both areas the water quality was found to be optimal for consumption (Montaño et al. 1998, Collazo 2006; Montaño et al. 2007). From the zone of the outcrops the Ca concentration is higher than that of the sodium, whereas the confined water is richer in Na over the Ca. Moreover, in some cases, the bicarbonate is dominant over the Cl, thus originating bicarbonate calcic waters. Anomalous concentrations of Fe, Mn were not found (Montaño et al. 1998, Montaño et al. 2006) but in some perforations of the western region, close to the Uruguay River, elevated concentrations of fluorides were found in groundwater corresponding to the San Gregorio- Tres Islas aquifer (Montaño et al. 1998, Montaño et al. 2006) and high concentrations (≈88 µg/l) of arsenic was found in the Yaguarí-Buena Vista Aquifer (see below). Such high concentrations of F and As are also mentioned by Marczinek (2005) in the Ciudad del Este region in Paraguay. Moreover, Montaño et al. (2006) also found that concerning the Permian aquitards corresponding to the Melo Group (Bossi and Navarro 1991) the groundwater is sulphate-chlorinated, being considered as not healthy for consumption according to the normative of the Uruguayan State Sanitary Organism (OSE).

Due to the flow of groundwater along the main streamlines, its chemical facies undergoes an evolution that can be attributed to two geochemical processes (Gastmans et al. 2012): (i) the dissolution of carbonates and silicates that occurs at outcrop areas (especially due to recharge by meteoric water rich in dissolved $CO_2$), and (ii) ion exchange processes that are responsible for the evolution of groundwater from calcic bicarbonate facies to sodium bicarbonate facies. Such exchange processes have been confirmed by Sracek and Hirata (2002) in the State of São Paulo in Brazil and by Marczinek (2005) in the deep GAS from the Ciudad del Este region in Paraguay.

In addition, groundwater mixing from the surrounding aquifers occurs locally: Teramoto et al. (2020) showed that the composition of GAS groundwater in the state of São Paulo is modified in recharge areas, by mixing with overlying Cretaceous basalts and/or underlying Permian and Carbo-Devonian aquifers. The latter contain more or less concentrated brines that are responsible for an evolution of the groundwater from a bicarbonate facies to a sulphate or chloride facies.

**Hydrochemical facies**

Four main hydrochemical facies can be identified related to the geochemical evolution of the groundwater from the outcrop areas of the GAS to its deep central parts (Chang et al 2013): (i) facies Ca-Mg-$HCO_3$ in zone I, (ii) facies Na-Ca-$HCO_3$ in zone II (with locally a zone II-Cl characterised by an increase in chlorides), (iii) facies Na-$SO_4$-Cl in zone III and (iv) a very strongly mineralised facies in zone IV, the most downstream part of the GAS (see Figure 5).

The mechanisms responsible for the evolution from facies I to facies II are thought to be internal with the dissolution of feldspars and carbonate cement in the sandstones, followed by ion exchange, which is corroborated by the evolution of $\delta^{13}C$ towards more positive values along the main flow paths. In contrast, the evolution towards facies II and IV would result from the external contribution of brackish or saline water from deeper aquitards (Gastmans et al. 2012; Chang et al. 2013; Kirchheim et al. 2019).

In agreement with isotopic data (see below), Kirchheim et al (2019) think that these different facies reflect the degree of confinement of the GAS from young calcium bicarbonate-rich groundwaters to old sodium chloride/sulphate-rich groundwaters, all influenced by groundwater mixing from underlying formations (Kirchheim et al. 2019). A similar explanation was presented by Gastmans et al. (2012) for the presence of anomalous concentrations of arsenic in thermal waters of the GAS along the Argentinian and Uruguayan frontier border. These authors consider that the arsenic come from the dissolution of the iron coatings covering the sandy clasts from the underlying upper section of the Yaguarí Formation (i.e. the Buena Vista conglomerates). Indeed, the presence of elevated concentrations of arsenic in the Uruguayan aquifers have been discovered for the first time by Rosario Guerequiz (Personal Communication 2006), and then the data were published since 2007 in a series of contributions that recognized the contamination as a serious environmental problem (Guerequiz et al. 2007a,b; Manganelli et al. 2007; Goso et al. 2008). The increased arsenic concentrations were found in the GAS (Buena Vista section) as well as in the Late Cretaceous Mercedes and the Cenozoic Raigón aquifers at the western and southwestern regions respectively and in the Quaternary waters of the SACC (Sistema Acuífero Ciudad de la Costa) at the south of the country (Goso et al. 2008). The origin of the arsenic was interpreted by these authors as derived from bentonitic layers intercalated in Quaternary deposits, although more recent studies suggest that the contamination is of anthropogenic origin, from cumulative application of arsenical pesticides in agriculture crops (Mañay et al. 2013).

Although more studies are necessary to resolve this issue, the different hypotheses presented to explain the origin of the arsenic reveal some interesting aspects that deserve to be mentioned. For instance, the observations from Gastmans et al. (2012) about the upward flows suggest that the GAS is indeed a single interconnected system composed by several types of aquifers that interact each other, producing mixing of waters. Other important conclusion is that the upward flows could have been forced by occasional differences in the hydrostatic pressure of the involved aquifers.

**Isotope analyses**

The stable isotopes ($^{18}O$, $^{2}H$, $^{13}C$) of groundwater and its mineralisation show marked contrasts between different areas of the GAS (Chang et al. 2013). In most recharge areas, the $\delta^{18}O$ and $\delta^{2}H$ isotope ratios of GAS water match those of rainfall, whereas in the confined axial part of the aquifer, several areas show more negative isotope ratios (see figures 3 and 4 of Chang et al. 2013). However, as these unusual values (up to 3‰ in $\delta^{18}O$) are not found in the southern part of the aquifer, they could correspond to the infiltration of water during colder palaeoclimatic conditions: groundwater depleted in $^{18}O$ would have ages greater than 35 kyr where they are correlated with low $^{14}C$ contents (Gastmans et al. 2012). This hypothesis is corroborated by the analysis of unstable isotopes ($^{3}H$, $^{14}C$). For example, in 2013, tritium values in most recharge areas were between 0 and 3 TU, similar to the rainfall levels at the time, while this isotope disappears further downstream (Chang et al. 2013).

Based on $^{14}C$ analyses of the DIC (Dissolved Inorganic Carbon), the presence of recent groundwater in the outcrop areas and its ageing to the confined parts of the GAS, i.e. along the flow path, is confirmed. Most of the deep boreholes in the central part of the GAS have $^{14}C$ activities below the detection limit, implying residence times greater than 50 kyr. Marczinek (2005) cites that $^{14}C$ also revealed groundwater ages of ca. 30 kyr in the Ciudad del Este region in Paraguay. Indeed, new ages using a radiochronology method based on $^{4}He$ concentrations, and Ne/He and $^{3}He/^{4}He$ ratios were found in the north-eastern part of Brazilian's GAS by Aggarwal et al. (2014): about 400 kyr in the groundwater discharge area and 834 kyr in the deep aquifer, confirming that the ages increase with distance from the recharge areas with an average groundwater flow velocity of 0.7 $m.yr^{-1}$. These ages are corroborated by the U isotopes method that reachs at least

45-61 kyr, but two groundwater samples from deep boreholes in very confined areas gave ages of 320 kyr to 1150 kyr using $^{36}C$ analysis (Kirchheim et al. 2019).

Gonçalves et al. (2020) positioned particles in their numerical model at the level of recharge zones and modelled their circulation: they obtained ages ranging from 100 kyr to 500 kyr, and even up to 1 Myr, but it should be remembered that they don't take into account any significative dilution by recent recharge waters.

It is worth to note that the main problem interpreting the data provided by Chang et al. (2013), as well as by the other contributions dealing with isotopic studies is that there is not stratigraphic control of the deposits from which the analysed water is extracted (or at least they are not explicated in the papers). Therefore, identifying the represented lithostratigraphic units will surely help to obtain more accurate results.

### Geothermal

In the southern part of the GAS, in the Norte Basin (Uruguay) as probably in the adjacent regions in Argentina, Morales et al. (2020) found an anomalous geothermal zone with geothermal gradients in the range of 15 to 45°C.km$^{-1}$: groundwater temperature is here between 23°C and 47°C. The large range in geothermal gradients, particularly the lowest ones, points to the presence of a specific heat transfer process due to upward groundwater flow with velocities in the range of $10^{-9}$ to $10^{-8}$ m.s$^{-1}$. In Argentina, recent researches revealed the significant potential of the geothermal resources in the eastern sedimentary basin (Busso 2000; Chiodi et al 2020). They are mainly related with the construction of thermal complexes as Wanda and 2 de Mayo (Misiones Province) or San Roque, Curuzú Cuatiá and Monte Caseros (Corrientes Province). In Brazil, in the central zone of the Paraná Basin, the influence of the depth of GAS formations produces warm groundwaters under the effect of a geothermal gradient that varies from 29 to 55°C.km$^{-1}$ (Gastmans et al. 2012). For this reason, in several regions of Brazil, there are natural emergences of waters with temperatures up to 65ºC that can then be used for thermal tourism (da Rosa Filho et al. 2003): for example, in the state of Paraná (Brazil), the deep confined groundwater of the GAS rises through the numerous diabase dykes that are related to the Ponta Grossa Arch, and that produces springs with water up to 43°C. In Paraguay, the confined part of the Misiones formation determines characteristics of thermalism with groundwater temperatures from 30 to 60°C (Aguas Subterráneas 2003).

## CONCLUSIONS AND LINES OF RESEARCH

The establishment of effective water resource management mechanisms is generally a response to known problems or identified threats. The corollary of this assumption is that the lack of knowledge of the resources and the absence of obvious symptoms of their deterioration do not favour the establishment of such mechanisms. This process is further exacerbated in the case of transboundary aquifers as they require the active participation of political actors from different countries (da Silva, 2008). This is currently the case with the GAS where, after the riparian countries drafted an international agreement in 2010, it has still not entered into force a decade later due to the lack of ratification. This delay has halted the momentum of what was one of the world's first examples of groundwater-related hydrodiplomacy. With anthropogenic climate change underway and its potential effects on this great groundwater resource, it is crucial to understand how it works in order to provide a future basis for effective concerted plans for sustainable transboundary groundwater management, in the hope that the agreement will soon be ratified and come into force. Moreover, considering the current processes of rapid groundwater depletion verified in key food-producing regions (including South America), mainly due to increasing agricultural irrigation (Daling et al. 2017), the future management of the GAS should include an alert for a more rational use of this important non-renewable resource, one of the largest storages of drinking water of the world.

We have revised here some important issues that contribute to a better knowledge of the GAS, as for instance the importance of to count with an integrated stratigraphic, chronostratigraphic and sedimentological (paleoenvironmental) sequence of the constituent aquifer formations in order to identify the main hydraulic, hydrochemical and hydrogeological paths that define this fundamental resource. Moreover, we also provide a well supported reappraisal of the GAS outline, including the outcropping areas of the San Gregorio-Tres Islas and Yaguarí and Cerro Conventos aquifers in the Cerro Largo County, as they are considered to be part of the Permian GAS and the Typical GAS respectively, as was proposed by previous authors. Some hydraulic interconnections between the GAS aquifers appear to be assured, although more work should be done to better understand their relation to the already proposed conceptual flow models.

Therefore, despite each new paper represents a step further in the advance of knowledge, it remains several questions about the GAS, the answers to which should help optimise its management. The main ones are listed below:

- i) Can the GAS be considered as a single, continuous aquifer system from upstream (Brazil) to downstream (Argentina, Uruguay), i.e. over a length of about 2200 km?
- ii) What are the hydraulic connections of the GAS with the surrounding aquifers, i.e. the overlying basalts and the underlying Carbo-Devonian and basement aquifers?
- iii) What is the hydraulic role of the main tectonic structures such as the arches, and in particular of the Rio Grande arch that separates the southern deep sedimentary basins of Paraná and Chacoparaná from the rest of the GAS?
- iv) Which is the downstream limit of extension of the GAS, to the south (Uruguay) and southwest (Argentina)?
- v) What are the aquifer-river relationships between the GAS (or the overlying aquifers in hydraulic connection with it) and the main rivers, the Paraná, Uruguay and their tributaries?

The answers to these questions, for which we present herein some evidence, will make it possible to calculate a more precise GAS water balance in order to propose, for each riparian country, a maximum annual exploitation volume that should not be exceeded to guarantee the long-term sustainability of this very important water resource.

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## CONFLICT OF INTEREST STATEMENT

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

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