Guarani Aquifer System – The Strategical Water Source In South America

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Introduction

Guarani Aquifer System (SAG) is the formal denomination for a transboundary aquifer underlying four countries (Argentina, Brazil, Paraguay and Uruguay) in South America. Due to its strategic importance, a joint research project aiming for sustainable management and preservation of the aquifer was initiated by the four neighbour countries together. In this work, an overview of hydro-geological characteristics as well as basic information on availability, quality and management efforts are presented.

Historically, the main attention concerning water resources regarded the superficial water like rivers and lakes (blue water flow), while the underground water (gray water flow), was comparatively ignored. On the other hand, underground water is generally considered of good quality due to the filtering and protection characteristics of the aquifer, while blue water loses each quality due to anthropogenic activity. Generally, when the population density around a superficial water reserve is low, the residues can be degraded by microorganisms, in a natural cleaning process. In highly populated centers this capacity is exceeded. Many pollutants contaminate rivers and lakes through punctual sources, as sewers canalizations, or diffuse sources, as the case of draining waters (runoff) that carry pesticides and fertilizers. In Brazil, 92 % of the sewers are launched in the rivers and 8 7% of the wastes are deposited under rain influence. Under these conditions, the use of superficial water (rivers, dams and lagoons) only becomes viable in the absence of groundwater sources. The filtration processes and bio-geochemical reactions that take place in subsurface assure a good quality to groundwater, which is naturally protected against the pollution that reach rivers and lakes.

The Guarani Aquifer System (SAG, in Portuguese) is situated in the eastern and south central portion of South America, extending from the Paraná Sedimentary Basin in the East to the Chaco-Paraná Basin in the West (figure 1). This aquifer got attention due to its extension and stored volume of water, being considered one of the biggest transboundary underground water source in the world. It underlies parts of Argentina (225,500 km^2), Brazil (839,800 km^2), Paraguay (71,700 km^2), and Uruguay (58,500 km^2), covering an area of approximately 1.2 million km^2. The SAG appears to be a sandstone formation, predominantly confined (approx. 90 % of the area) by a huge spill of volcanic rocks. Due to its hydro-geologic characteristics, extension and localization, near to regions of great social-economic importance for the four countries, the aquifer is recognized as a strategic source.

However, at the aquifer's current rate of use, and considering the growing use of groundwater for human consumption, it is easy to foresee an increasing threat of pollution and depletion in a not to distant future. Uncontrolled use, without rules or regulation, can alter the status of the Guarani Aquifer System from a strategic drinking water reserve to a degraded water-body that is the source of conflict among the countries. According to the UNESCO/PHI (2003) report, there are 261 transboundary water basins in the world, being shared by 145 countries. Approximately one third of these basins pertain to more than two countries. Considering the strategic importance of water for life, the management of such resources became in many regions a potential source of political conflicts.

This facts motivated the Governments of these countries to search international financial support with the objective to develop a joint project aiming for the management and preservation of the SAG for the current and future generations.

Figure 1: Simplified South America map showing the Guarani Aquifer System.

Geology and Hydrogeology

The geology of SAG includes rocks of Cretaceous, Jurassic, and Triassic periods. The Guarani Aquifer is composed by sandstones comprising two formations (Triassic and Jurassic periods). The older Triassic sandstone formation of humid fluvial origin presents higher clay portion, compromising its hydraulic efficiency. The sandstone of the Jurassic period, formed under dry conditions (eolian origin) presents higher porosity and hydraulic conductivity, consisting in the best reservoirs of the basins (CAMPOS, 1999).

The sedimentary rocks below the aquifer (of Permo-Triassic period) present low permeability and are characterized as aquitard. Above, the Guarani Aquifer is confined by successive layers of basaltic spill, originated from volcanic activity in the Cretaceous period. These consolidated rocks are characterized in part as aquitard and part as aquifer, depending on the fractures density.

Overlying this formations are Cretaceous sandstones of the Bauru Group, which form another sedimentary free aquifer. According to table 1, the Formations have different names in each country. In Brazil, the Triassic Formation is known as Pirambóia or Rosario do Sul Formations, while the Jurassic sandstone receives the name Botucatu. The Cretaceous Formations receive the denomination Serra Geral Formation, for the basalts, and Bauru Group for the younger sandstones (ARAÚJO et al. 1999).

Table 1: Hydro-stratigraphy of the SAG (adapted from ARAÚJO et al., 1999)

Hydro-stratigraphic unit	Period	Formation			
		Brazil	Argentina	Paraguay	Uruguay
Upper Aquifer	Cretaceous	Bauru Group	Quebrada Monardes	Acaray	Ascencio
Aquitard / aquifer	Cretaceous	Serra Geral	Serra Geral	Alto Paraná	Arapey
Guarani Aquifer	Jurassic Triassic	Botucatu Pirambóia / Rosário do Sul	Taquarembó Buena Vista	Misiones Misiones	Tacuarembó Buena Vista
Aquitard	Permo-Triassic	Rio do Rasto	Victorino Rodrigues	Unnamed	Yaguary

The Guarani Aquifer System has an estimated average thickness of 250 meters, varying from lenses of a few meters at the borders of the basin to about 800 m in its central parts (northern parts of the States of São Paulo and Paraná, and southern parts of Mato Grosso do Sul, in Brazil). The depth below land surface varies from zero in outcropping areas in Brazil to more than 1.800 meters in Argentina. Figure 2 shows a typical geologic section of the geologic stratification.

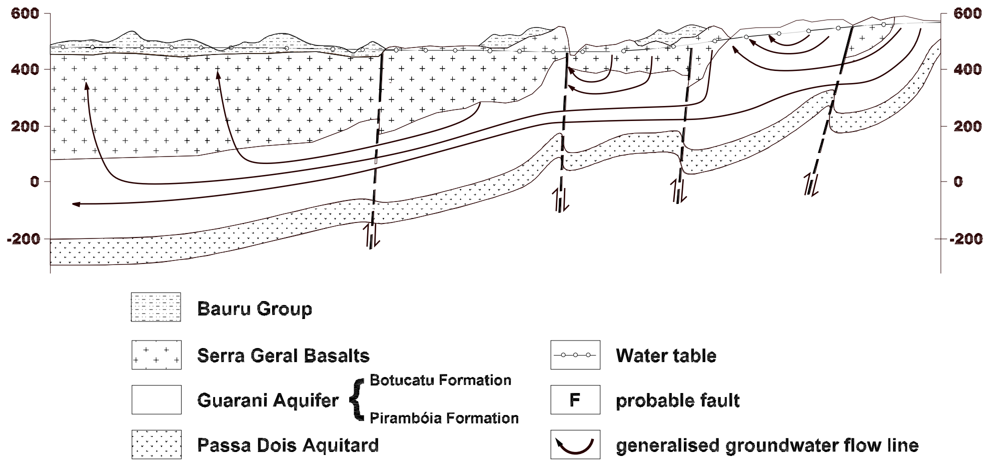
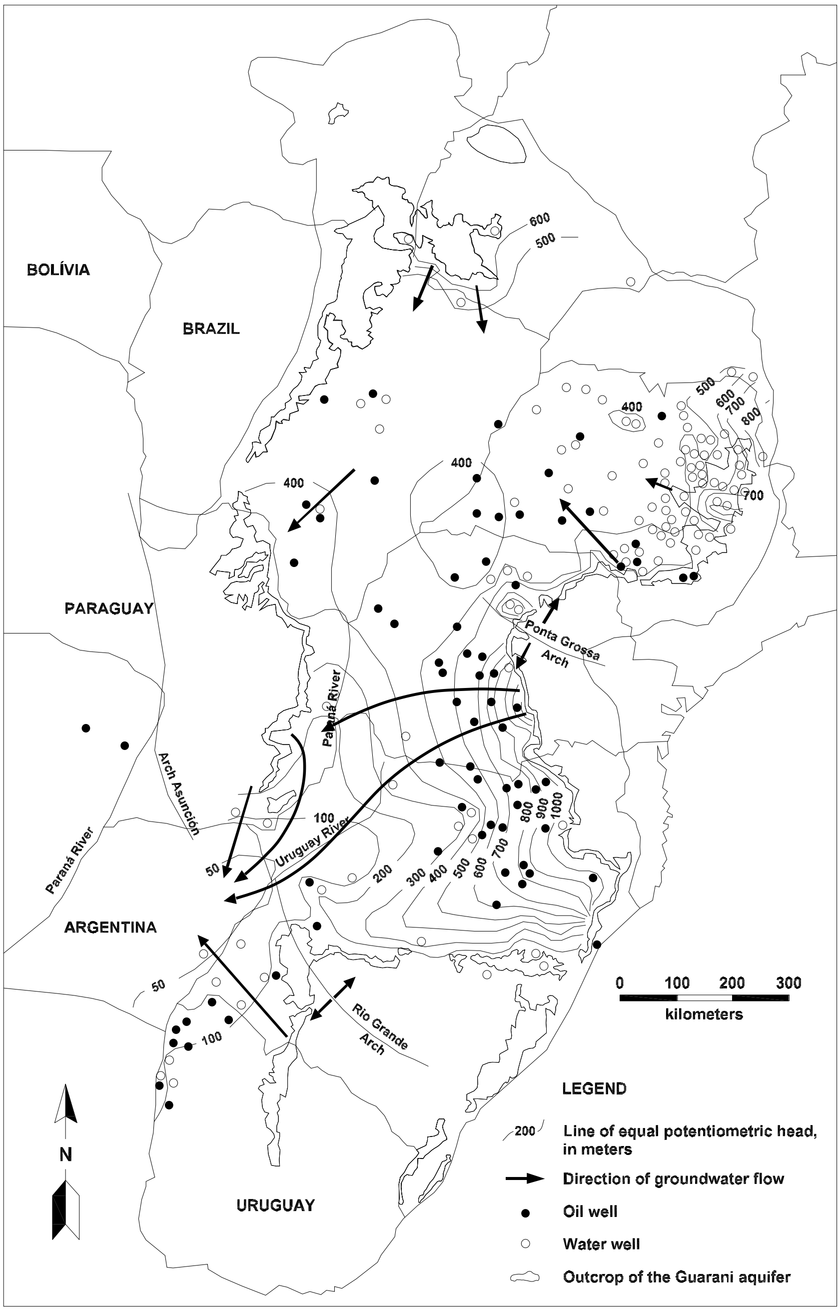


Figure 2: Schematic representation of the SAG in a geologic section across São Paulo State, Brazil

Groundwater recharge in the Guarani Aquifer is supposed to occur based on two main mechanisms:

a) by direct infiltration, through the outcrop zones in the Brazilian states (São Paulo, Goiás, Mato Grosso do Sul, Paraná and Santa Catarina), eastern Paraguay and North Uruguay;
b) indirectly, through the overlapping formations that include the fractured basalts of the Serra Geral Formation. In fact, the water-bearing basalt zones can be seen as a prolongation of the sedimentary overlying sandstones (Bauru Group). According to ROSA FILHO et al. (2003) locally, where the basalt thickness become small or the fracture system reach the top of the Guarani Aquifer, infiltration due to leakage may be determining for recharge. Depending on the hydraulic head in the Guarani Aquifer and in the Serra Geral Formation, ascending or descending vertical flow is possible. Viewing the observed potential surface in many places, the basaltic rocks of Serra Geral Formation function sometimes as reservoir and as semi-permeable, beyond its character of hydraulic barrier.

These characteristics confer a high water potentiality to the SAG, at the same time, however, it establishes a stronger complexity of the flow system and ways of contamination. In this sense, solutes originating from industrial, agricultural and domestic activities developed at the surface may reach the reservoir from the outcrop zones as well as through the Serra Geral Formation.



Three main structural arcs (Arco de Assunção, Arco de Ponta Grossa e Arco de Rio Grande), resulting from basal lifting, together with the localization of the recharge zones, inclination of the Guarani Aquifer and thickness variations, determine the flow behaviour in the SAG (figure 3).

The regional potential surface, derived from water level measurements in diverse wells, indicates the main flow direction. Flow is pre-ferentially directed to the Paraná River, which crosses the basin from NE to SW and configures the main drainage of base discharge in the basin. Apparently, the main areas of groundwater discharge are situated in Argentina between the Paraná and Uruguay rivers, west from Arco de Rio Grande.

Figure 3: Flow system and hydraulic head in the SAG based on well measurements (adapted from ARAÚJO et al., 1999)

However, understanding the flow behavior in the SAG is still matter of research (GEF, 2003) and no affirmation is definitive. Due to the presence of dikes and sills originated during the volcanic activity, the sandstone formations present many compartments, which are not well understood up to now.

Climate

A great variation of climatic characteristics is observed in the considered region, following the long length, extending over approximately 20° of latitude or 2200 km. Climate in the region varies from subtropical in the North to semi-arid in the southern part. The average temperatures vary between 11° C in the South and 29° C in the North, while the annual mean precipitations vary between 1000 mm and 1800 mm in the SW and NE regions, respectively (DNM, 1992). The potential evapotranspiration, strongly associated to the rain occurrence, indicates annual values of 980 mm in regions with precipitation of around 1400 mm in Brazil (BRAGA et al., 1991). Additional to the climatic aspects, geometry, hydraulic parameters and recharge and discharge conditions of the aquifer determine the amount of flowing groundwater. At the outcrop zones, the direct infiltration in the system is estimated to 15 % of the precipitation (REBOUÇAS, 1976), while the indirect infiltrations are of difficult quantification.

Water availability and demand

Knowledge on water availability is essential for the management of aquifers. Availability is defined by estimates of active or regulating reserves, which correspond to the portion subjected to fluctuations of the water level, and by the permanent reserves, which correspond to the volume of water situated below the fluctuation zone. ROCHA (1997) presents an evaluation for the whole aquifer area, finding values of 37.000 km³ for permanent reserves and 160 km³/a for active reserves. The estimation is based on an average precipitation of 1.500 mm/a, recharge area of 150.000 km², confined area of 1.000.000 km², average thickness of 250 m, effective porosity of 15 % and storage coefficient of 10^{-4}. In the work, the value of 25 % was adopted as index of active reserve, justified as the necessity of rational use planning, reducing the corresponding volume for the active reserve.

The volume of freshwater reserves stored is estimated as around 40.000 km³ that is equivalent, for example, to the totality of water in the Paraná River with a discharge of about 10.000 m³/s during 127 years. According to a technical report by the World Bank (GEF, 2002), fifteen million people live in the aquifer's area of influence. Sustainable exploration is estimated to be able to attend the water demand of a population of 360 million people, considering a per capita use of 300 l/ha/day. Based on spatial, hydro-geologic and hydrologic data, ROCHA (1970) founds out that such potential would correspond to around 30 times the total water demand of the 15 million inhabitants of the region, in which the water reserves are found.

Despite large surface water reserves, drinking water supply in heavily populated regions is increasingly dependent on groundwater. Thus, future problems may occur, if exploration does not take place in a sustainable manner, or if waters are polluted. In São Paulo State in Brazil, estimates indicate that 60.5 % of urban centers are served totally or partially by groundwater sources, supplying 5.5 million people. The use of the Guarani Aquifer System's water has increased significantly in the last decades, as consequence of the extreme urbanization pattern of some areas on the one hand and developments in large scale of agriculture schemes on the other. In some areas of the aquifer system there is a high concentration of wells whose water is used for different purposes. Estimates indicate that 77 % of these sources are for domestic use, while the remaining are equally divided between the industrial and agricultural use (GEF, 2002). Forecasts for the future are of growing demand of groundwater following the demographic growth and the economic expansion. Due to the bad distribution of demand related to high consumption of water resources in regions of population concentration, supply problems can already be observed. Some of the conflicts related to water quantity are already well identified. These include, among others, the reduction of potentiometric and phreatic levels, and the interference between wells experienced in the highly urbanized areas around Ribeirão Preto and Bauru, in São Paulo State (Brazil) and the transboundary thermal sites between Uruguay and Argentina, particularly in the area of Salto (Uruguay) and Concordia (Argentina). In Ribeirão Preto, recent works evaluated the recharge of the Guarani Aquifer, obtaining values between 200 and 250 mm/a in the outcrop zone and between 100 and 50 mm/a in confined areas, for a precipitation of 1.413 mm/a (SMA, 2004).

However, it is likely that this is exceeded by the abstraction since, over a large area across the city, groundwater levels have fallen since the 1970s by an estimated 15-25 m. In this area, the Guarani Aquifer is exploited by some 2000 wells. In some regions, approximately 800 m lateral distance is maintained between production wells, which have a potential maximum yield of about 3.700 l/s and an estimated actual production of around 65 Mm^3/a. However, there is a significant degree of uncertainty about the total level of actual groundwater abstraction (GEF, 2003). In Brazil, where approximately 2/3 of the total SAG area is found, São Paulo State is responsible for about 77 % of water exploited by the Brazilian states supplied by the system (CHANG, 2001). Preliminary studies estimated that water abstractions in the Brazilian states of Minas Gerais, São Paulo and Paraná – if not managed – will surpass the aquifer's local recharge rates by 2025. Some regions in Argentina and Paraguay, where the aquifer's potential has only recently been discovered, are now undergoing groundwater exploitation with an increasing number of wells being drilled. The actual number of wells tapping the aquifer system in those regions is still unknown.

Aspects on water quality and thermal potential

Water quality analysis of diverse wells indicates that about 90 % of the 40.000 km^3 water available in the SAG is of good quality for human consumption. Locally, the quality is reduced due to salinity and to higher Fluor content (affecting less than 10 % of the volume).

However, the countries' legal frameworks for managing and monitoring groundwater use have not accompanied the rates of extraction and expansion of groundwater use. Missing control on wells design and closure seems to have caused wells to act, in some cases, as open channels for surface contamination. In regions of the aquifer system, where water quality is being monitored systematically (like in CETESB's well-functioning monitoring network in São Paulo State), inorganic contamination (high nitrate content) and anomalous pesticide traces have been detected. This is also assumed to be occurring in other regions of the Aquifer, particularly in outcrop areas, showing high natural vulnerability, and in semi-confined areas, showing an effective connection with overlying unconfined and contaminated aquifers.

Recently, in the central west region of Santa Catarina State, Brazil, hydro-geochemical investigations detected pollution in deep wells in the Serra Geral Aquifer system, representing local contamination risk for the Guarani System through fractures in the basalt formation. The analyses indicated the presence of phosphate and nitrate in levels above the accepted for human consumption, being attributed to intense practical of swine farming and extensive agriculture, especially soy and maize (ALMEIDA, 2004).

Beyond the good quality of SAG water, another characteristic appears to be relevant for the sustained exploitation of this underground source: the warm water pumped from deep wells. The geothermal heat transmitted to SAG water is conserved by the confinement due to the basaltic rocks of the Serra Geral Formation, which reduces the heat transport by convection. Preliminary data and estimates of the geothermal potentiality have been presented by ARAÚJO et al. (1999) and ROSA FILHO et al. (2001). The observed average value for the geothermal gradient lies between 2 and 3 ° C/100 m. This value is considered low, being attributed to many points of cold water recharge. Extreme values, around 5.5 ° C/100 m, are found in north of Paraná State, Brazil. Water with temperatures of up to 68 ° C is found in President Prudente, Brazil. Existing deep wells in the SAG allow, in average, a production of up to 100.000 l/h with temperatures between 30 and 45 ° C.

With low temperature reservoirs and low thermal gradients, the production of electric energy from the SAG is almost impossible. However, a variety of other uses may be devised, ranging from district heating and provision of warm tap water to thermal tourism (already highly important in northwestern Uruguay) to industrial and agribusiness uses, substituting non-renewable energy in the area.

Vulnerability and sustainable development

Research concerning vulnerability and risk mapping of the SAG is being done since the 1970's, in Brazil, by the Department of Waters and Electric Energy of the São Paulo State (DAEE) and Geologic Institute (IG); in Argentina, by the Universidad de Buenos Aires and the National Institute of Water; in Uruguay, by the Universidad de la Republic; in Paraguay, by the Environmental System of Eastern Region. Currently the concept of aquifer vulnerability includes factors as the degree of protection against contaminants by the overlying layers, groundwater flow conditions, climatic conditions and contamination risks related to soil use and occupation. These factors include the so called anthropogenic and natural or specific vulnerability. Crossing the information contained in the map of natural vulnerability with anthropogenic evolution factors results in a map of aquifer risk or danger. These maps are important instruments for decisions making aiming to the protection and sustainable use of water resources.

The recognition of the SAG potential was mainly intensified by increasing research and technical works developed in the four countries, by academic and governmental institutions together. In 1996, an international cooperation to develop jointly the transboundary SAG was formalized. This agreement originated a mutual long period project with the objective to support the four countries to implement technical, legal and institutional frameworks for management and preservation of the SAG. The project is supported by diverse international organisms with financial assistance by the GEF/BIRD, currently in progress. One of the most important tasks is the definition of critical zones according to standards of vulnerability, risk and over-exploration. These zones should be representative for the conditions found in diverse other regions of the SAG. Four critical areas are identified: the area of Rivera/Santana do Livramento, at the Uruguay/Brazil border, with one of the largest urban concentrations in the southern aquifer outcropping area (around 200.000 inhabitants), is a case where water supply relies almost entirely on groundwater, extracted from about 160 tube wells with depths between 40 m and 160 m. Here, the aquifer faces the threats of lacking sanitation infrastructure (60 % of the population is served by inadequate sanitation schemes – septic tanks and drains*)*, increasing use of pesticides and fertilizers in agriculture and industrial activities. A similar situation is observed in Eastern Paraguay (Ciudad del Este – Encarnación – Caaguazú), where a vulnerable non-confined aquifer experiences booming urban and agricultural expansion. Concordia/Salto, in the border between Argentina and Uruguay, characterizes a region with high exploitation and geothermal use. Ribeirão Preto, in Brazil, is a city with around 500.000 inhabitants mainly using Guarani Aquifer water. About 12 % of water users do not have access to sewerage system, generating a potential nitrate load of 200.000 tons per year, which is considered rather elevated (GEF, 2002).

For each of these zones, projects with participation of official institutions, universities, technical-scientific associations and non-governmental organizations are being developed. The objective is to share the positive results and to establish a model of management for the SAG, through a program of strategic actions including common scientific, institutional, financial and legal aspects in the four countries. The main goal is the protection and sustainable use of the Guarani Aquifer System, justifying its condition as strategic source in South America.

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