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GEOLOGY AND HYDROGEOCHEMICAL ANALYSIS OF GROUNDWATER IN THE PARDO RIVER WATERSHED, SOUTHERN BRAZIL: A CASE STUDY

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ABSTRACT

Groundwater reserves are strategic sources for public water supply. This regional study, accompanied by geomorphologic, geologic, and hydrostratigraphic maps, highlights the importance of stratigraphic and hydrochemical research in preserving water in areas susceptible to contamination, such as aquifer recharge zones. The aquifers were subdivided into the Pre-Guarani Aquifer System (PRE-GAS), the Guarani Aquifer System (GAS), and the Serra Geral Aquifer System (SGAS). This article paper analyzed the hydrogeological characteristics of the Pardo River watershed, focusing on the lithostratigraphic units of the Rosário do Sul Group (PRE-GAS), the Botucatu Formation (GAS), and the Caxias and the Gramado facies of the Serra Geral Formation (SGAS) present in the study area. In terms of hydrogeochemistry, the water from the wells was classified as sodium bicarbonate in the PRE-GAS, and as calcium bicarbonate in the GAS and SGAS. The average specific capacity of the 102 wells analyzed was 0.72 $m^3/h/m$ for the PRE-GAS, 1.76 $m^3/h/m$ for the GAS, and 0.44 $m^3/h/m$ for the SGAS. The use of the public domain SIAGAS database is recommended, but it requires proper validation and standardization. The study reinforces a sustainable approach to ensure the long-term availability of groundwater resources in the region.

Keywords: Hydrogeology. Hydrostratigraphy. PRE-Guarani Aquifer. Guarani Aquifer System. Serra Geral Aquifer System.

GEOLOGIA E ANÁLISE HIDROGEOQUÍMICA DAS ÁGUAS SUBTERRÂNEAS DA BACIA DO RIO PARDO, SUL DO BRASIL: UM ESTUDO DE CASO

RESUMO

As reservas de água subterrânea são fontes estratégicas para o abastecimento público. Este estudo regional com mapas geomorfológico, geológico e hidroestratigráfico destaca a importância das pesquisas estratigráficas e hidroquímicas na preservação da água em áreas suscetíveis à contaminação, como as zonas de recarga dos aquíferos. Os aquíferos foram subdivididos em Pré-Sistema Aquífero Guarani (PRE-SAG), Sistema Aquífero Guaraní (SAG) e Sistema Aquífero Serra Geral (SASG). O artigo analisa as características hidrogeológicas da bacia hidrográfica do rio Pardo, com foco nas unidades litostratigráficas do Grupo Rosário do Sul (PRE-SAG), Formação Botucatu (SAG) e fácies Caxias e Gramado da Formação Serra Geral (SASG), ocorrentes na área de estudo. Em termos hidrogeoquímicos para o Pré-SAG, as águas dos poços são classificadas como bicarbonatadas sódicas e para o SAG e SASG são bicarbonatadas cálcicas. A capacidade específica média de 102 poços analisados é de 0,72 $m^3/h/m$ para o Pré-SAG, 1,76 $m^3/h/m$ para o SAG e 0,44 $m^3/h/m$ para o SASG. O uso do banco de dados SIAGAS de domínio público é recomendado, mas requer validação e padronização adequadas. O estudo reforça uma abordagem sustentável para garantir a disponibilidade a longo prazo dos recursos hídricos subterrâneos na região.

Palavras-chave: Hidrogeologia. Hidroestratigrafia. Pré-sistema Aquífero Guarani. Sistema Aquífero Guarani. Sistema Aquífero Serra Geral.

INTRODUCTION

Groundwater constitutes approximately 0.96% of the Earth's total water volume and 29.9% of available freshwater (Rebouças, 2006). As the global commitment to water quality is on the rise, there has been a significant increase in the demand for groundwater resources in recent decades. Brazil has around 13% of the world's freshwater resources and increasingly uses groundwater (Rebouças, 2006; Veiga; Magrini, 2013). Approximately 39% of Brazilian municipalities rely on groundwater as their water source, with over 500,000 tubular wells drilled (ANA, 2007). The states of São Paulo, Bahia, Rio Grande do Sul, Ceará, and Piauí are the top five in terms of groundwater exploitation in Brazil (ABAS, 2017).

The growing demand for groundwater resources generates a public concern about the water volume, quality, and maintenance for future needs.

Two of the largest groundwater resources on Earth are found in the Paraná and Chaco-Paraná basins, known as the Pre-Guarani Aquifer System (PRE-GAS), Guarani Aquifer System (GAS), and Serra Geral Aquifer System (SGAS), located in central-southern Brazil and parts of Argentina, Paraguay, and Uruguay (Giardin; Faccini, 2004; Rosa Filho *et al*., 2005; OEA/PEA/GEF, 2009).

The geological, structural, stratigraphic, and diagenetic frameworks of the PRE-GAS, GAS, and SGAS produce complex reservoirs in terms of stored volumes, hydrogeochemistry, flow patterns, and flow rates MMA, 2015).

The Pardo River Watershed (PRW), spanning approximately 117 km in length and 50 km in width, covers 1.3% of the area of the state of Rio Grande do Sul State area and 4.3% of the Guaíba Hydrographic Region (COMITÊ PARDO, 2005). The PRW is in southern Brazil, particularly in the central region of the state of Rio Grande do Sul. A substantial part of the population in this area depends on deep tubular wells for water extraction from the PRE-GAS, GAS, and SGAS. In rural areas, where technical or economic limitations hinder water distribution by public systems, a small population depends on shallow wells, springs, and cisterns for their water supply (Foster *et al*., 2000; Foster; Hirata; Andreo, 2013). The expansion of agribusiness and industries related to pig farming, poultry, and tobacco, along with population growth and the trade of mineral water, are the primary drivers behind the increasing demand for groundwater in the PRW. These human activities not only lead to higher demand but also raise the risk of groundwater contamination from solid and liquid waste, particularly in areas lacking effective regulatory control. Consequently, there has been a significant surge in the search for groundwater resources due to the intensification of eutrophication processes and contamination of surface water bodies within the PRW (Lobo; Costa; Kirst, 2000; Wetzel *et al.*, 2002; Lobo *et al*., 2004; Hermany *et al*., 2006; Salles *et al*., 2018).

The sedimentary layers of the Rosário do Sul Group and the Botucatu Formation, as well as the volcanic flows of the Serra Geral Formation, including the Gramado and the Caxias facies, constitute the regional stratigraphic framework in the Pardo River Watershed (PRW). This study evaluated the influence of physicochemical parameters on groundwater in the PRW. The goal was to provide a broader understanding of the groundwater resources in the PRW, with an emphasis on the geographical and geological distribution of wells, physicochemical water parameters, water potential, and their relationships with the PRE-GAS, GAS, and SGAS. The SIAGAS database (Groundwater Information System), developed by CPRM (Brazilian Geological Survey), provides data about deep tubular wells, including geological, hydrostratigraphic, and hydrochemical information (CPRM, 2011). Studies using this database have been carried out by Löbler, Terra and Silvério da Silva (2014), and Nascimento, De Jesus and Gomes (2019).

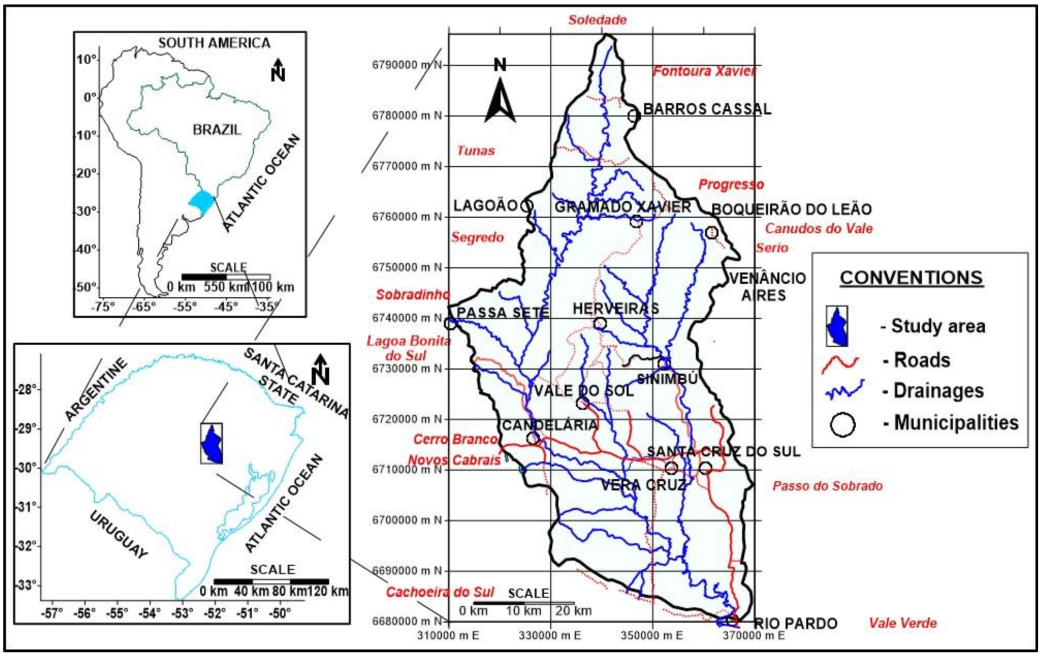
MATERIALS AND METHODS

The PRW serves as a tributary to the Jacuí River and traverses thirteen municipalities in the state of Rio Grande do Sul. It is situated between 28° 50' 00" to 30°"00' 00" S latitude and 52° 15' 00" to 53° 00' 00" W longitude, covering an area of 3,636.8 km² (Figure 1). The watershed area is home to an estimated population of 232,442 inhabitants (IBGE, 2020).

The PRW receives an annual rainfall of approximately 1,600 mm. The monthly average temperature is between 3 °C and 22 °C, with an annual average temperature of 18 °C.

The study involves integrating available georeferenced information with field geological and hydrogeological data. The available information includes the locations of wells, watershed perimeter, area, drainages, municipalities, roads, elevation data, tectonic lineaments, and lithostratigraphic units (1:400,000) from the geological and hydrogeological maps for the state of Rio Grande do Sul (CPRM, 2008; CPRM, 2010), such as the location of the PRE-GAS, GAS, and SGAS and other relevant features. Thematic maps were generated using Surfer 9.11.947 from Golden Software (2010) and QGIS software (version 3.22.0) of the Geographic Information System (GIS). On-site geological analyses were performed, including rock descriptions and structural measurements. Validation of the geological information and, physicochemical groundwater parameters obtained from the SIAGAS database and literature was conducted through visits to multiple wells and their surrounding areas.

Figure 1 - Location map of PRW with municipalities, drainages, and access roads. Adjacent municipalities are shown in red



Source: Prepared by the authors (2022).

Complementary geological and geomorphological data were obtained from 1:750,000 scale maps provided by the Brazilian Geological Survey (SGB-CPRM). The Digital Elevation Model (DEM) and its fundamental local geomorphometric variables were derived from the National Institute for Space Research (INPE) Topodata, which utilized the SRTM data provided by the United States Geological Survey (USGS) through the global computer network (Valeriano, 2008). The Topodata Digital Elevation model was created using the kriging method. It involved the treatment of SRTM images with a spatial resolution of three arc-seconds (approximately 90 meters) processed to one arc-second (approximately 30 meters) (Valeriano; Rossetti, 2010). All the maps generated in the study were converted to the SIRGAS 2000 datum, UTM zone 22S coordinate system, for consistency and standardization.

In the study, groundwater physicochemical parameters (Na, K, Ca, Mg, Cl, CO_3, HCO_3, SO_4, total nitrate - mg/L, EC - micromhos/cm, Turbity - NTU, pH, and T ºC) were assessed using Piper diagrams and the ionic balance modules of the Qualigraf 1.1 software (Möbus, 2010). The evaluation methods were based on previous studies by Garrels; Mackenzie (1967), Custodio; Llamas (1983), Bartarya (1993), Möbus (2010), and Belkhiri; Mouni (2014). The Piper diagram, introduced by Piper (1944), was used to rank groundwater samples into different classes based on the dominant ions present in the waters from the various lithostratigraphic units of the PRW.

To ensure the quality of the analysis, a Water Ionic Balance (WIB) approach was employed. The WIB is based on the principle that the total concentration of positive ions (cations) should be equal to the concentration of negative ions (anions), and any deviation from this equality indicates an error in the analysis. The WIB was calculated using two techniques in the Qualigraf software, both expressing the percentage deviation from the equality, which was based on the analysis's error coefficient (Möbus, 2010). The first technique, known as Practical Error (PE%), based on Electrical Conductivity, calculates the deviation using the values of the water's Electrical Conductivity (EC). The second technique, Practical Error (PE%), is based on ions and calculates the deviation using the values of the individual ions. The equations 1 and 2 for these calculations are as follows:

$$PE\% \text{ based on EC: } PE (\%) = [(\Sigma \text{ cations} - \Sigma \text{ anions}) \div (\Sigma \text{ cations} + \Sigma \text{ anions})] \times 200 \quad (1)$$

$$PE\% \text{ based on ions: } PE (\%) = [(\Sigma \text{ cations} - \Sigma \text{ anions}) \div (\Sigma \text{ cations} + \Sigma \text{ anions})] \times 100 \quad (2)$$

The Total Dissolved Solids (TDS) in groundwater samples were compared to the water quality standards set by the Brazilian National Water Council Resolution 357/2005 (BRASIL, 2005; BRASIL, 2008). According to these resolutions, TDS concentrations are categorized as follows:

- Freshwaters: TDS values ranging from 0 to 500 mg/L.
- Brackish waters: TDS values ranging from 501 to 1,500 mg/L.
- Salty waters: TDS values above 1,500 mg/L.

Furthermore, for drinking water potability standards, the Brazilian Health Ministerial Ordinance (BRASIL, 2011) specifies the largest allowable TDS concentration of 1,000 mg/L. This standard is used to assess the suitability of groundwater for human consumption.

The classification of well productivity was based on the specific capacity, using six class intervals as defined by Oliveira Diniz *et al*. (2012):

- Very high productivity: Specific capacity ≥ 4.0 m^3/h/m.
- High productivity: 2.0 m^3/h/m ≤ Specific capacity < 4.0 m^3/h/m.
- Moderate productivity: 1.0 m^3/h/m ≤ Specific capacity < 2.0 m^3/h/m.
- Low but locally moderate productivity: 0.4 m^3/h/m ≤ Specific capacity < 1.0 m^3/h/m.
- Low but locally very low productivity: 0.04 m^3/h/m ≤ Specific capacity < 0.4 m^3/h/m.
- Non-productive or no aquifer: Specific capacity < 0.04 m^3/h/m.

This classification allows the categorization of wells based on their specific capacity, providing insights into their productivity levels and potential for water supply.

In this study, the physicochemical parameters of groundwater were evaluated concerning the lithostratigraphic units present in the region studied and their relationship with the PRE-GAS, GAS, and SGAS. These analyses aimed to understand how groundwater characteristics vary across different lithostratigraphic units, as well as their connection to the larger aquifer systems.

By examining the physicochemical parameters, such as the Piper diagrams and ionic balance modules, together with the lithostratigraphic units, this study provides insights into the hydrogeochemical patterns and groundwater quality associated with the depth of the specific geological formations. This information helps in understanding the behavior and characteristics of groundwater resources within the region studied and their relation to the PRE-GAS, GAS, and SGAS.

By assessing the parameters in relation to the lithostratigraphic units and their relationship with the aquifer systems, this study contributes to a better understanding of the hydrogeological dynamics and their potential implications for water resource management and planning in the study area.

RESULTS AND DISCUSSIONS

The combined analyses of geomorphology, geology, and hydrogeochemistry supply a better understanding of the Pardo River Watershed (PRW) and its groundwater resources. This integrated approach allows for the assessment of the physical landscape, geological formations, and chemical composition of the water in the region. By examining these factors, researchers can evaluate their potential impacts on water availability, quality, and sustainability.

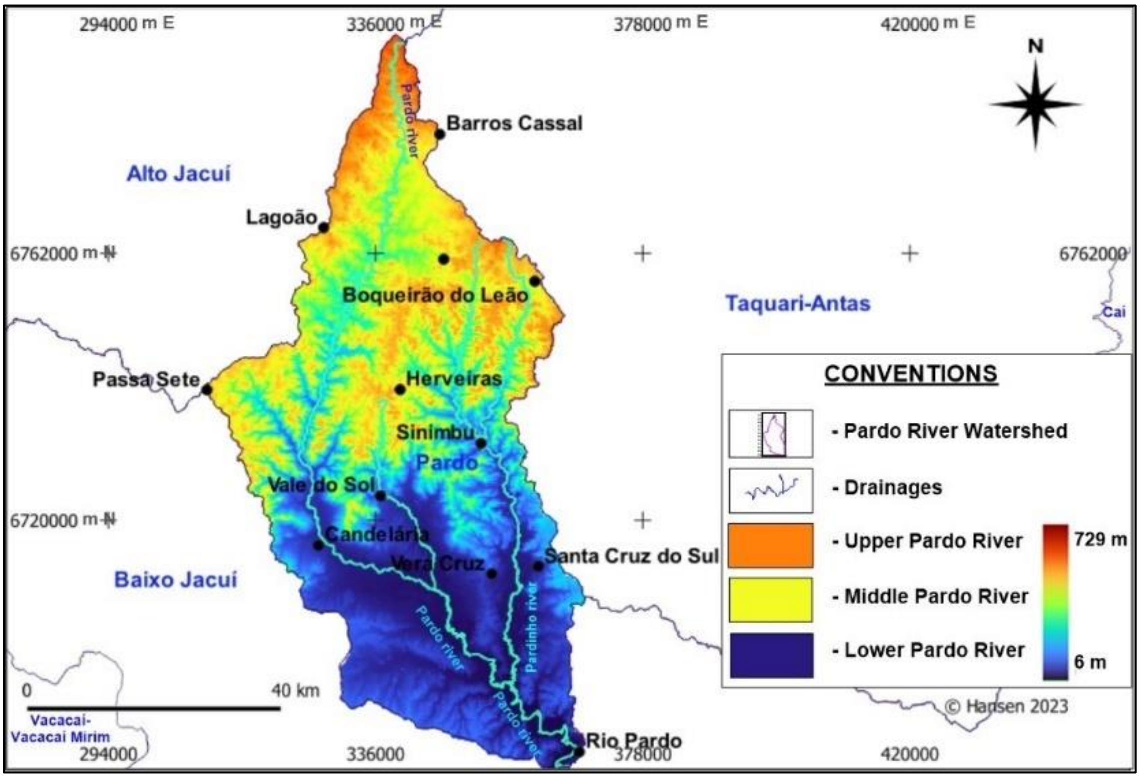
Geomorphology of the PRW

The geomorphological analysis reveals that the Pardo River Watershed (PRW) is situated within the morpho-structural domain of basins and sedimentary covers. It is specifically included in three geomorphological regions: the Geomorphological Region Plateau of the Araucarias, the Geomorphological Unit Plateau of the Serra Geral, and the Peripheral Depression, as classified by Justus; Machado; Franco (1986).

Based on this classification, the PRW can be divided into three distinct sections based on elevation. The Upper Pardo River region encompasses areas situated 400 meters above mean sea level. The Middle Pardo River region includes areas ranging from 400 meters to 200 meters above mean sea level. Lastly, the Lower Pardo River region consists of areas above 200 meters above mean sea level (Figure 2).

These subdivisions provide valuable insights into the elevation variations in the PRW, which can influence the hydrological processes, landforms, and drainage patterns in the watershed. Understanding the geomorphological characteristics of the PRW is essential for assessing the natural features and processes that shape the landscape and influence water flow and storage within the watershed.

Figure 2 - Digital Elevation Model with municipalities, main drainages, and adjacent watersheds, for the Pardo River Watershed: Upper Pardo River (> 400 m); Middle Pardo River (400 m – 200 m); and Lower Pardo River (< 200 m).



Source: INPE Topodata database, Valeriano, 2008, elaborated using QGIS, 2022.
Prepared by the authors (2023).

In the Upper Pardo River region, the springs are in an area known as Coxilha de Rio Pardo, situated northeast of the municipality of Barros Cassal. These springs are located at elevations ranging from 700 to 729 meters above mean sea level. This region is characterized by a residual relief feature of the Serra Geral Plateau, showing the presence of elevated landforms (Figures 3a and 3b).

Figure 3 - Photographs of the Pardo River Watershed: a) Upper Pardo River, Plateau - Springs of the PRW, municipality of Barros Cassal. b) Upper Pardo River, a plateau with residual relief; c) Middle Pardo River, staggered relief with levels and escarpments; and d) Lower Pardo River, Peripheral Depression, Pardo River floodplain.

Source: Prepared by the authors (2022).

The Middle Pardo River region shows significant landscape-shaping processes caused by the action of drainage systems, resulting in the formation of various landforms such as escarpments, and closed valleys. These landforms gradually expand and widen as they extend towards the Peripheral Depression, a lower-lying area of the watershed (Figure 3c).

In contrast, the Lower Pardo River region displays a flatter relief characterized by convex hills, wide gentle hills, and extensive alluvial plains. This area is integrated into the Peripheral Depression, which shows a more level terrain (Figure 3d).

The mouth of the Pardo River Watershed is at the confluence with the Jacuí River, at an elevation of six meters above mean sea level. A substantial number of the analyzed wells is situated in the transitional region between the Middle and Lower Pardo River. This concentration of wells in the transition zone can be attributed to the higher urban population density in that area.

Geological context

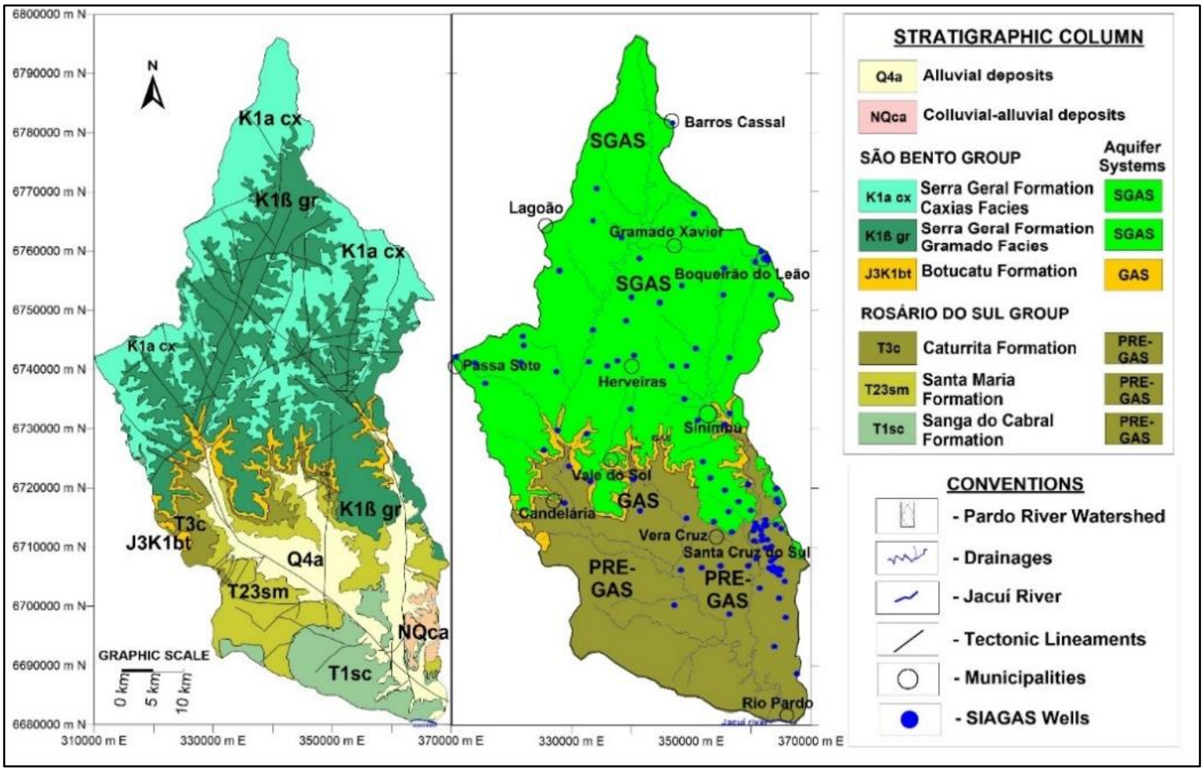
The PRE-GAS, GAS, and SGAS comprise sedimentary rocks of the Rosário do Sul Group, the Botucatu Formation, and volcanic rocks of the São Bento Group in the PRW. The lithostratigraphic units listed in Table 1 have a hydrostratigraphic connotation, which defines their framework in the PRE-GAS, GAS, and SGAS, and influence the storage and migration of groundwater (Figure 4).

Table 1 - Pardo River Watershed lithostratigraphic units

Units	Ages	Main Characteristics
Sedimentary deposits	Holocene Pleistocene	Sedimentary deposits with minimal or absent lithification, slope sediments, riverbed, and floodplain sediments.
São Bento Group		**Upper Jurassic to Lower Cretaceous**
Serra Geral Formation	Upper Cretaceous	Continental volcanism of tholeiitic affinity, encompassing a range from basic to acidic compositions (basalts, andesites, rhyodacites, and rhyolites).
Caxias Facies	132,3 ± 0,5 My Ar-Ar	Rhyodacites, rhyolites, and ignimbrites, exhibiting microgranular to vitric textures, characterized by tabular and columnar disjunction.
Gramado Facies	132,4 ± 1,4 My Ar-Ar	Basalts with vesicles and zeolite geodes, carbonates, apophyllites, and saponites; intercalated with sandstones.
Botucatu Formation	Upper Jurassic	Fine to medium-grained aeolian sandstones, varying in color from yellow to pink, with limonitic or siliceous cements.
Rosário do Sul Group		**Triassic**
Caturrita Formation	Upper Triassic	Sandstones, conglomerates, sandy-silty shales, mudstones, and fluvial deposits are present, indicating a continental environment with lacustrine deltas.
Santa Maria Formation	Middle Triassic	Alemoa Member - Red clayey siltstones and mudstones, representing floodplain, lacustrine, and fluvial channels, with occurrences of carbonate concretions. Passo das Tropas Member - Sandstones to conglomerates dominate, with subordinate occurrences of pelites.
Sanga do Cabral Formation	Lower Triassic	Sandstones, breccias, and conglomerates (tb intraformational), siltstones, subordinate claystones, interlaced fluvial environment, carbonaceous concretions.

Source: Modified from CPRM (2008). Prepared by the authors (2022).

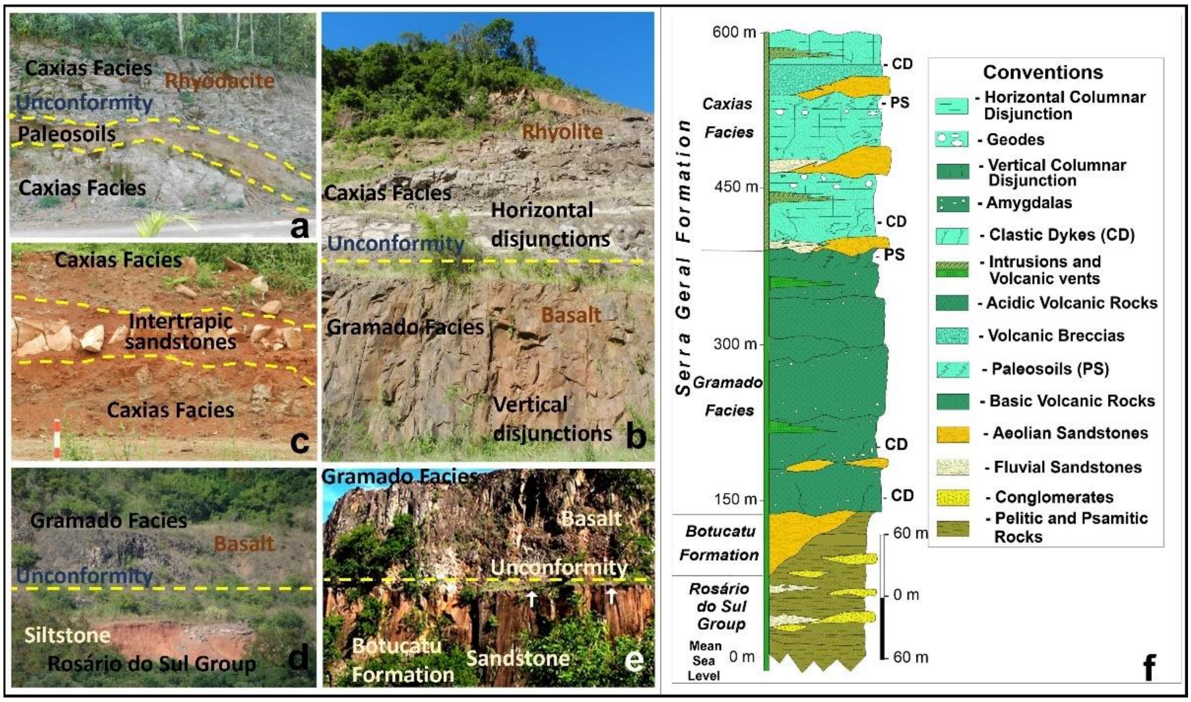
Figure 4 - Geological-structural and aquifer systems maps of the PRE-GAS, GAS, and SGAS with 102 wells in the PRW



Source: Modified from CPRM (2010) using Golden Software (2010).
Prepared by the authors (2023).

The Botucatu Formation is a significant and well-known unit within the GAS. It is characterized by sandstones that have favorable properties for groundwater storage and supply. These sandstones show high porosity, which refers to the number of empty spaces or voids within the rock, and interconnectivity, which allows for the movement of water through the rock matrix (Figure 5). These properties contribute to the capacity to store and transmit groundwater efficiently.

Figure 5 - Pardo River Watershed photographs and composed lithostratigraphic section: a) Caxias Facies with levels of paleosoils; b) Caxias Facies with horizontal disjunctions and Gramado Facies with vertical disjunctions; c) Intertrapic sandstones; d) Lithological unconformity of the Rosário do Sul Group with the Gramado Facies; and e) Lithological unconformity (white arrows) of the Botucatu Formation with the Gramado Facies, and f) Schematic lithostratigraphic section in the PRW



Source: Prepared by the authors (2022).

Many researchers have extensively studied the sedimentary characteristics, depositional environments, and evolutionary history of the Botucatu Formation. These studies include the works of Almeida; Melo (1981); Lavina, Faccini; Ribeiro (1993); Campos (1998); Araújo *et al*. (1999); Faccini (2000); Rosa Filho *et al*. (2005); and Scherer; Lavina (2006).

In addition to the Botucatu Formation, other sedimentary units within the Paraná Basin are also part of the GAS. These include the Pirambóia and Rio do Rastro formations (Upper Permian) in the Passa Dois Group, the Sanga do Cabral (Lower Triassic), Santa Maria (Middle Triassic), and Caturrita formations (Upper Triassic) in the Rosário do Sul Group, and the Guará Formation (Upper Jurassic) in the São Bento Group (CPRM, 2010).

Although these lithostratigraphic units are part of the GAS, variations can occur within a given location in terms of the presence of aquifers (such as sandstones and conglomerates) and aquitards (such as mudstones and muddy sandstones). In some areas of the PRW, including the Botucatu Formation, diagenetic processes such as the precipitation of iron-oxides-hydroxides and silica can lead to the formation of coatings or concretions. Additionally, high-grade diagenesis or low-grade metamorphism can significantly reduce porosity, making the formation unproductive for water accumulation. These variations in diagenetic processes and porosity affect the productivity and water storage capacity of the lithostratigraphic units within the GAS.

The volcanic rocks within the SGAS are represented by the Serra Geral Formation, which encompasses a range of compositions from basic tholeiitic to acidic, including basalt, andesite, rhyodacite, rhyolite, and rheo-ignimbrite (Figure 5a). Within the Serra Geral Formation, groundwater circulation is facilitated by features such as disjunctions, joints, or diaclases (non-tectonic), as well as fractures associated with tectonic activity (geological faults) (Figure 5b). These structural features serve as pathways for groundwater movement, connecting it with meteoric surface waters.

The interaction between meteoric surface waters and groundwater within the SGAS has also been studied in various regions of the Paraná Basin (Fulfaro *et al*., 1982; Milani, 1997; Soares; Soares; Holz, 2008; Squisato *et al*., 2009).

These studies contribute to our understanding of the hydrogeological processes and the role of volcanic rocks, particularly the Serra Geral Formation, in groundwater circulation and storage within the SGAS.

In the PRW, there are significant geofractures of tectonic origin that play a crucial role in the accumulation, supply, and recharge of aquifers. One notable geofracture extends from Boqueirão do Leão to Herveiras in a NE-SW direction, spanning over 54 km in length. This geofracture is part of a larger system that includes other parallel geological faults in the region. Another prominent geofracture extends from the eastern part of Herveiras to the eastern part of Sinimbu, preferentially in the NW-SE direction, with a length exceeding 45 km. This geofracture is also part of a parallel set of geological lineaments in the region (see Figure 4).

These geofractures with groundwater entrances provide pathways for groundwater flow, allowing for the movement and accumulation of water within the aquifers. Their presence and interconnections with other geological features significantly influence the hydrogeological dynamics of the PRW, affecting the distribution and availability of groundwater resources in the area. Understanding the characteristics and behavior of these geofractures is essential to manage and use water resources in the region effectively.

Next to the PRW, there are aeolian sandstones that range from a few decimeters to 15 meters in thickness. These sandstones are laterally discontinuous and found at altitudes ranging from 360 meters to 520 meters above mean sea level, particularly in municipalities such as Boqueirão do Leão, Canudos do Vale, and Sério. Wells that penetrate these interlayered aeolian sandstones and volcanic rocks in the Middle and Upper Pardo River regions can show high water flow rates (Figure 5c).

Besides the aeolian sandstones, siltstone, claystone, and paleosoils deposited in a dissected paleo-relief can also generate aquitards in the Caxias Facies. However, the hydrodynamic behavior in this context reveals confinements and water concentrations in the fractures of the superimposed volcanic unit.

The PRW and its surrounding regions show geological characteristics that significantly influence the subsurface hydrodynamic behavior. In certain areas, the erosion or non-deposition of the Botucatu Formation has resulted in a reduction or complete absence of its thickness in municipalities such as Santa Cruz do Sul, Vera Cruz, and Candelária, as well as adjacent areas. This creates a direct contact between the basalts of the Gramado Facies and the mudstones and sandstones of the Santa Maria or Sanga do Cabral formations (Figure 5d).

This lithological contact concentrates groundwater in the fractures of the lower portions of the Gramado Facies, as the mudstones function as aquitards or subsurface barriers to water flow. In these areas, water sources associated with fractures, joints, and faults show the hydrodynamic mechanism mentioned above. This geological particularity has a considerable influence on groundwater behavior, particularly in the Upper and Middle Pardo River regions.

Another geological feature of great significance for groundwater dynamics in the PRW is the interlayering of sandstones with volcanic rocks of the Serra Geral Formation. This feature is primarily recognized by the presence of aeolian sandstones at the base of the basaltic package in the PRW and adjacent basins like the Botucaraí, Forqueta, and Alto Jacuí river basins. These sandstones occur at higher altitudes compared to other regions in the state of Rio Grande do Sul.

In the PRW, these sandstones are found at the top of the Gramado Facies or interlayered within the Caxias Facies, while, in other regions, they are typically present in the lower lava flows of the Serra Geral Formation. This specific arrangement of sandstones and volcanic rocks has implications for groundwater behavior and can influence the storage, flow, and accessibility of groundwater resources in the region (Figures 5e and f).

Another important aspect of groundwater behavior associated with the SGAS is the presence of open fractures, which can extend for tens of kilometers. These structures play a crucial role in analyzing and evaluating aquifer recharge areas and are excellent sites for groundwater storage. Several studies have highlighted the significance of these open fractures in the hydrogeology of the region (Fulfaro *et al*., 1982; Zalán *et al*., 1991; Scheibe; Hirata, 2008; Soares; Soares; Holz, 2008).

The Hydrogeological Map of the state of Rio Grande do Sul (CPRM, 2010) shows three major fault systems that traverse the state, contributing to the formation of five distinct hydrogeological compartments. These fault systems are known as Jaguari-Mata (NW-SE), Terra de Areia-Posadas (NW-SE), and Dorsal de Canguçú (NE-SW). The PRW region is found within the Canguçú Dorsal Fault System, on the eastern boundary of the northern compartment and the western boundary of the north-eastern compartment (Machado, 2005). The hydrodynamic interactions between these prominent structural alignments of high complexity in the state of Rio Grande do Sul need further research and data collection within the PRW, emphasizing the need for complementary studies as discussed by Machado (2005).

Wells

In the PRW, a total of 267 deep tubular wells were registered in the SIAGAS database. Out of these, 102 wells (38.2%) were selected and evaluated for this study. The remaining 165 wells (61.8%) were discarded for distinct reasons such as missing physicochemical analytical data, inconsistency, or errors in the provided values.

The choice was based on the following criteria:

- Wells that presented all the data requested by the register;
- Wells with complete physicochemical data, and well location, owner, and drilling date;
- Wells with complete geological data, including lithological and stratigraphic data;
- Wells with consistent chemical composition and ionic water balances.

The distribution of the selected wells in the PRW is irregular, with higher densities near populated areas.

The highest wellhead elevation recorded in the database is 650 meters in the municipality of Lagoão, while the lowest is 20 meters in the municipality of Rio Pardo. The depths reached by the wells varied, ranging from 25 meters in the municipality of Vera Cruz to 380 meters in the municipality of Vale do Sol. The average well depth is 123.3 meters (see Figure 4).

Due to the difficulties and inconsistencies met in differentiating and correlating the lithologies of the Caturrita, Santa Maria, and Sanga do Cabral formations in the well's geological profiles, a simplified litho-hydrostratigraphic column was adopted for the PRE-GAS in the PRW. This simplified column includes the undivided Rosário do Sul Group as PRE-GAS, as well as the Botucatu as GAS and Serra Geral formations, specifically the Gramado and the Caxias facies of the São Bento Group as SGAS.

To develop this simplified column, a range of factors were considered, such as the conditions of the wells, which are often macerated and fragmented due to the mechanical action of rotary-pneumatic percussion rock drills. Additionally, different technicians and driller operators may have adopted different stratigraphic columns for the same region, further complicating the correlation of lithologies between wells. Natural variations in the geological record across different regions also contribute to the complexity of litho-hydrostratigraphic correlation, particularly in regional correlations.

Considering these challenges and the inconsistencies in the geological data of many wells, the simplified litho-hydrostratigraphic column was developed based on a combination of factors, including the simplified geological column, local geology, wellhead height, well depth, and descriptions of geological profiles available in the SIAGAS database.

The most considerable number of wells drilled is associated with the Rosário do Sul Group (55 wells), reflecting the higher demographic density of the municipalities of Santa Cruz do Sul and Vera Cruz.

However, only three wells reached the Botucatu Formation. These factors, including the restricted thickness, lateral extent, or absence of the Botucatu Formation in specific areas of the PRW, can be attributed to the limited occurrence of wells that intersect this geological formation. The scarcity of wells intersecting the Botucatu Formation suggests that the presence of this formation may be limited or discontinuous in the PRW.

Table 2 presents the lithostratigraphic units observed in the wells studied, a decision based on the simplified geological column, and the geological data available in the SIAGAS database.

Table 2 - Lithostratigraphic positioning of the wells studied in the Pardo River Watershed

	Lithostratigraphic Units				
Municipalities	Caxias Facies (Upper)	Intertrapic Sandstone	Gramado Facies (Lower)	Botucatu Formation	Rosário do Sul Group
Barros Cassal	2	-	-	-	-
Boqueirão do Leão	5	-	1	-	-
Candelária	-	-	-	1	3
Gramado Xavier	-	-	4	1	-
Herveiras	2	-	3	-	-
Lagoão	2	-	-	-	-
Passa Sete	5	1	-	-	-
Rio Pardo	-	-	-	-	4
Santa Cruz do Sul	-	-	3	1	35
Sinimbu	-	1	9	-	-
Vale do Sol	1	-	4	-	3
Venâncio Aires	1	-	-	-	-
Vera Cruz	-	-	1	-	10
Total	18	2	25	3	55

Source: Prepared by the authors (2023).

Physicochemical Data of PRW Groundwater

Water analysis for the selected wells in the PRW revealed the following:

Total Dissolved Solids (TDS):

- 96.1% of the samples are classified as freshwater;
- Three wells (2.9%) in the municipality of Santa Cruz do Sul have TDS values of 913.1 mg/L, 683.8 mg/L, and 531.5 mg/L. They are classified as brackish water;
- One well (1%) in the municipality of Rio Pardo in the Rosário do Sul Group has a TDS value of 2,275 mg/L. It is classified as salty water;
- The water from the well in the municipality of Rio Pardo is not suitable for human consumption according to the Brazilian Health Ministry Ordinance.

Water Ionic Balance (WIB):

- 49 samples provided satisfactory results for ionic balance;
- 36 samples did not provide conclusive results for ionic balance using techniques 1 and 2;
- Five samples did not meet the ionic balance criteria for technique 1;
- 13 samples did not provide conclusive results for ionic balance using technique 2.

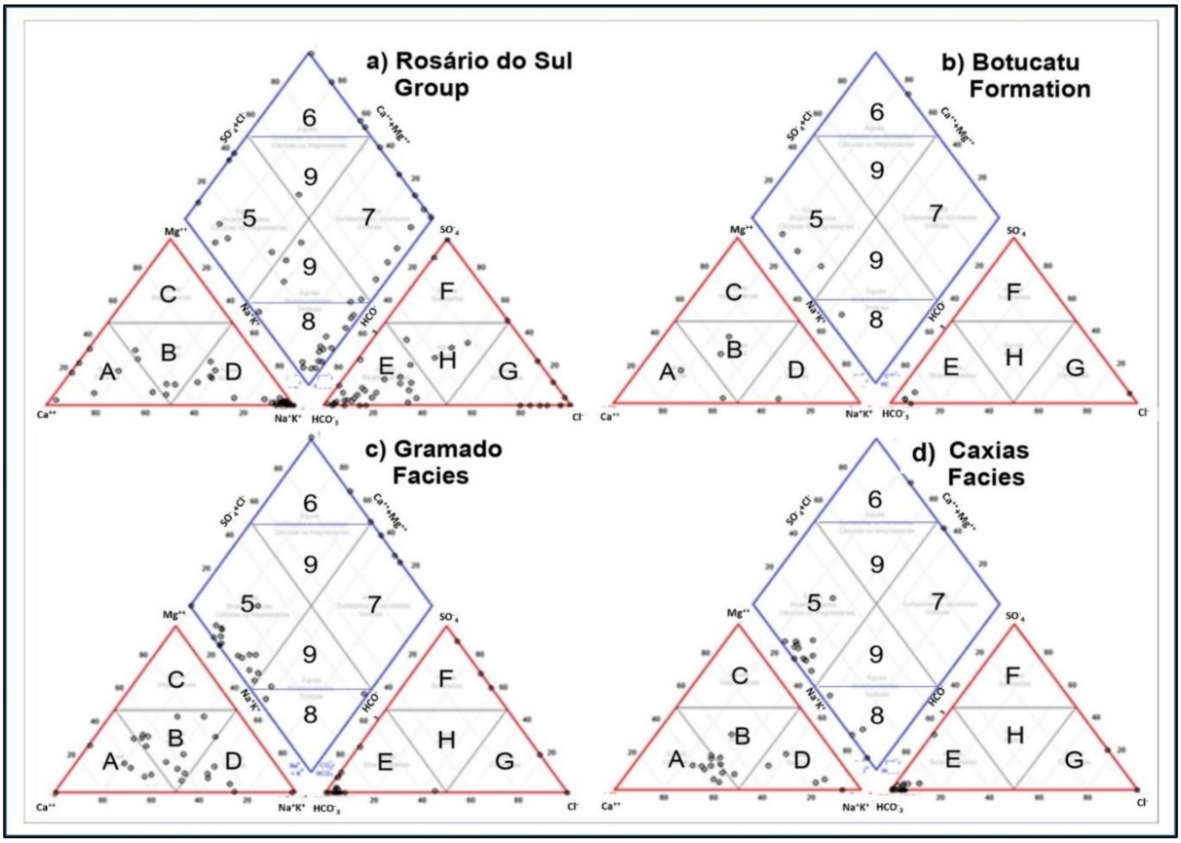
Piper Diagram:

- The dominant anion is bicarbonate (Figure 6, in Piper diagram E);
- The dominant cations are sodium and potassium (Figure 6, in Piper diagram D);
- The groundwater samples are classified as sodium-bicarbonate waters based on the Piper diagrams (Figure 6);
- Samples are classified based on their lithostratigraphic units: Rosário do Sul Group (undivided) (Figure 6a), the Botucatu Formation (Figure 6b), the Gramado (Figure 6c), and the Caxias (Figure 6d) facies of the Serra Geral Formation;
- The Rosário do Sul Group samples mostly consisted of sodium-bicarbonate waters, while the Botucatu Formation and the Gramado and the Caxias facies of the Serra Geral Formation included calcium-bicarbonate waters (Figure 6a).

These findings provide information about the TDS levels, water quality, and ionic balance of the groundwater in the studied wells. While most samples show freshwater characteristics, a small proportion present brackish or saline properties. The Piper diagram analyses indicate the dominance of sodium-bicarbonate waters, with variations between different lithostratigraphic units.

The groundwater quality in the PRW is influenced by several factors, including atmospheric input, anthropogenic activities, mineral weathering, biogeochemical processes, and land use characteristics. Weathering processes, driven by rock-water interactions, play a significant role in controlling the groundwater chemistry. Another likely source of increased salinization in some wells is the mixture of PRE-GAS, GAS, and SGAS groundwater, primarily from the Sanga do Cabral Formation of the Rosário do Sul Group. Major cations such as calcium, magnesium, sodium, and potassium are concentrated through mineral weathering (Garrels; Mackenzie, 1967). As feldspars are highly reactive minerals, they have a significant impact on groundwater quality through their dissolution potential (Bartarya, 1993).

Figure 6 - Classification of groundwater samples by lithostratigraphic units (Figures 6a, b, c, and d) based on the Piper diagram. Classification diagrams for cations and anions as major-ion percentages. Hydrochemical facies: A) Calcium type; B) No Dominant type; C) Magnesium type; D) Sodium and potassium type; E) Bicarbonate type; F) Sulfate type; G) Chloride type; H) No Dominant type; 5) Calcium-Bicarbonate; 6) Calcium-Chloride or Calcium-Sulfate; 7) Sodium-Chloride or Sodium-Sulfate; 8) Sodium-Bicarbonate; 9) Mixed type. Water types are classified according to the domains in which they occur in the diagram segments for the groundwater samples in the PRW, based on the Piper diagram (Piper, 1944)



Source: SIAGAS Database from CPRM (2011). Prepared by the authors (2023).

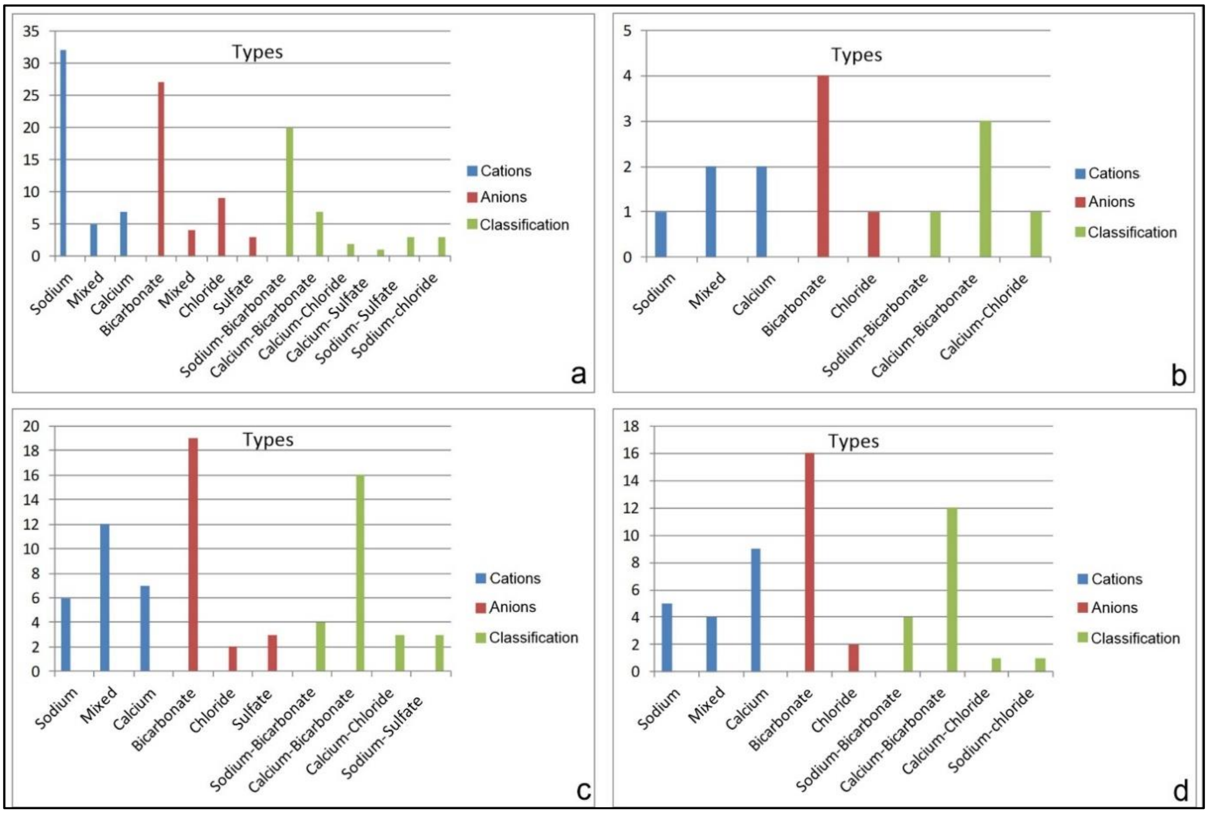
The intensive use of agricultural inputs has led to increased nutrient concentrations and salinization, which can contribute to groundwater contamination (Chen *et al*., 2017; Bekkoussa *et al*., 2018; Gautam *et al*., 2022). Several studies have investigated the hydrochemical characteristics of PRE-GAS, GAS, and SGAS waters, providing insights into this field (Foster; Ventura; Hirata, 1987; Kimmelmann; Forster; Coelho, 1995; Campos; Cerón-Garcia, 1998; Bittencourt *et al*., 2003).

The geological configuration of the PRW and its surrounding regions, which involves the interfingering of sandstones, mudstones, paleosoils, and fractured volcanic rocks, shows a special subsurface hydrodynamic condition related to the recharge of the PRE-GAS, GAS, and SGAS. This hydrodynamic configuration is influenced by the waters present in each stratigraphic unit and the potential dissolution of rocks and minerals during water circulation, leading to chemical reactions. The mixing of waters from different aquifers also plays a role in controlling the hydrodynamic configuration of the PRW. Further analysis is needed to better understand these complex physicochemical water relationships. Complementary analyses can include the use of nuclear tracers to determine the origin of water sources and contributions from different tributaries, assessing groundwater discharge rates, determining water residence times in specific aquifers and their geological ages, studying water-rock interactions, and identifying pollution sources (Hausman, 1966; Plummer; Parkhurst; Thorstenson, 1983; Steelfel; Van Cappellen, 1990; He *et al*., 2022). These analyses can provide valuable insights into the hydrogeological processes and factors influencing groundwater quality in the PRW.

Groundwater in the Rosário do Sul Group

The statistical data from water analyses of the tubular wells in the Rosário do Sul Group (55 wells) show that most samples have freshwater; three samples are classified as brackish water, and one sample as salty water based on Total Dissolved Solids (TDS) from groundwater entrance from the Sanga do Cabral Formation. Out of these samples, only 17 have ionic balance. The dominant cations in the groundwater of this lithostratigraphic unit are sodium, calcium, and mixed cations. For anions, bicarbonate is the predominant ion, followed by chloride, mixed, and sulfate. The classification of water in this unit is primarily sodium-bicarbonate, followed by calcium-bicarbonate, sodium-sulfate, sodium-chloride, calcium-chloride, and calcium-sulfate waters (Figure 7a).

Figure 7 - Histograms corresponding to cations, anions, and groundwater classes for a) Rosário do Sul Group (55 samples); b) Botucatu Formation (5 samples); c) Gramado facies (25 samples); and d) Caxias facies (18 samples) both from the Serra Geral Formation



Source: Prepared by the authors (2023).

These chemical elements in the groundwater of the Rosário do Sul Group have multiple origins, including carbonate concretions, and erosion of marine rocks from the Estrada Nova Subgroup (Upper Permian) in the Paraná Basin, which may contribute to the groundwater composition. The concentration of salts in the water may be due to excessive withdrawals from the aquifer, resulting in mixtures with sodium and making the brackish water non-potable, which needs further investigations (Silvério da Silva *et al*., 2014).

Groundwater in the Botucatu Formation

The statistical data from the water analyses of the tubular wells positioned in the Botucatu Formation (five wells) show that all wells have freshwater. Out of these samples, four samples have the ionic balances. Based on cations, some samples are classified as calcium, mixed cations, and sodium. In terms of anions, the dominant ion is bicarbonate, followed by chloride. The water classification in this unit is primarily calcium-bicarbonate, sodium-bicarbonate, and calcium-chloride (Figure 7b).

The presence of chloride and sodium in the groundwater of the Botucatu Formation can be attributed to GAS-confined aquifers and mixtures of water from PRE-GAS aquifers. Furthermore, the presence of chloride in water can be altered by anthropogenic contamination processes. The minerals contribute to the groundwater chemistry and influence water composition, resulting in the observed prevalence of calcium and bicarbonate ions.

Groundwater in the Gramado Facies

The statistical data from water analyses of the tubular wells in the Gramado Facies (25 wells) show that all wells have freshwater. However, only 16 samples have ionic balance. Based on the types of cations, the samples are mostly classified as mixed cations, with calcium and sodium coming next. Regarding anions, bicarbonate is the most dominant, followed by sulfate and chloride, indicating their origin from a mixture of groundwater. The water classification in this unit includes calcium-bicarbonate, sodium-bicarbonate, calcium-chloride, and sodium-sulfate (Figure 7c).

The presence of mixed cations and bicarbonate as the dominant anion suggests a complex hydrochemical composition influenced by various geological factors in the Gramado Facies. The specific geological characteristics, groundwater mixture, and mineral composition of the formations within the Gramado Facies contribute to the observed water chemistry in these wells.

Groundwater in the Caxias Facies

Analysis of well water in the Caxias Facies (18 wells) shows that all samples have freshwater. However, only 12 samples have the ionic balances. The samples are mainly classified as calcium-based according to the cations, with sodium and mixed cations coming next. Regarding the anions, bicarbonate is the most dominant, followed by chloride, which originates from a mixture of groundwater. The water classification for this unit includes calcium-bicarbonate, sodium-bicarbonate, calcium-chloride, and sodium-chloride (Figure 7d).

The presence of calcium as the dominant cation and bicarbonate as the dominant anion suggests that the water chemistry in the Caxias Facies is influenced by the decomposition of rhyodacite and rhyolite rocks. The weathering of the zeolite mineral group, which includes minerals such as scolecite, natrolite, thomsonite, analcite, stilbite, and heulandite, is also a contributing factor to the water composition. These secondary minerals are commonly found in geodes, amygdales, and fractures, and are associated with past hydrothermal processes. Upward flows of mineralized water may occur along the geological fractures in the region as well.

Differentiation in the classification of groundwater by lithostratigraphic units

The cations, anions, and respective hydrochemical types of the analyzed groundwater in four lithostratigraphic units are different, presenting the predominance order listed in Table 3.

The analyzed anions, particularly bicarbonate and chloride, are consistent in both the Caxias Facies and the Botucatu Formation. However, the other lithostratigraphic units, including the Rosário do Sul Group and the Gramado Facies, present different patterns.

The water classification for the Caxias and the Gramado facies, as well as the Botucatu Formation, follows a similar order: calcium-bicarbonate, sodium-bicarbonate, and calcium-chloride. However, the lower unit (Rosário do Sul Group) includes sodium-chloride waters, which are absent in the other units.

Furthermore, the Rosário do Sul Group shows an additional water classification: calcium-sulfate water, which is not found in the other units.

To summarize, the classification of groundwater in these units varies in terms of the presence of specific ions and their order of prevalence. The Rosário do Sul Group stands out with a distinct classification and the inclusion of calcium-sulfate waters.

Table 3 - Predominance order (PO) for cations, anions, and water classification from lithostratigraphic units of the Pardo River Watershed

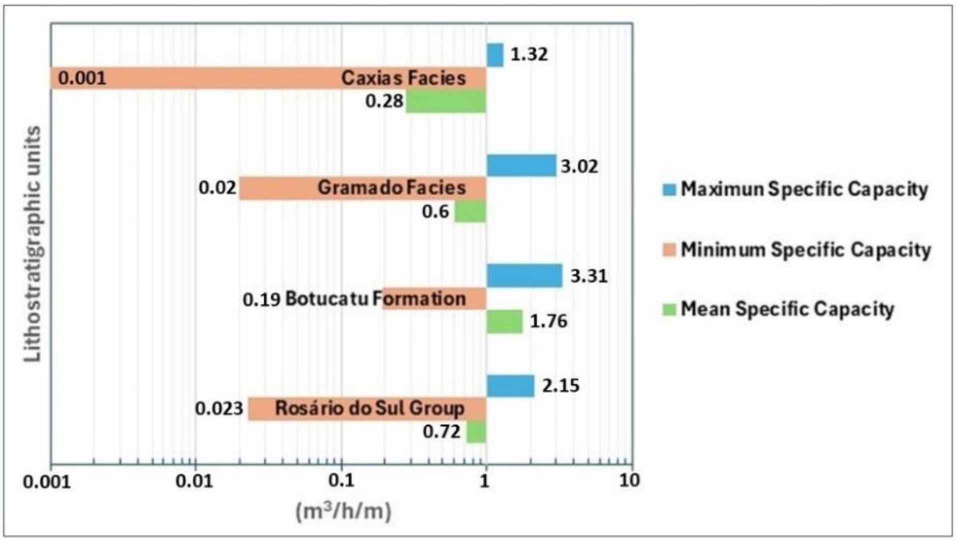
	PO	Rosário do Sul Group	Botucatu Formation	Gramado Facies	Caxias Facies
Cations	1°	Sodium	Calcium	Mixed	Calcium
	2°	Calcium	Mixed	Calcium	Sodium
	3°	Mixed	Sodium	Sodium	Mixed
Anions	1°	Bicarbonate	Bicarbonate	Bicarbonate	Bicarbonate
	2°	Chloride	Chloride	Sulfate	Chloride
	3°	Mixed	-	Chloride	-
	4°	Sulfate	-	-	-
Water classification	1°	Sodium-bicarbonate	Calcium-bicarbonate	Calcium-bicarbonate	Calcium-bicarbonate
	2°	Calcium-bicarbonate	Sodium-bicarbonate	Sodium-bicarbonate	Sodium-bicarbonate
	3°	Sodium-sulfate	Calcium-chloride	Calcium-chloride	Calcium-chloride
	4°	Sodium-chloride	-	Sodium-sulfate	Sodium-chloride
	5°	Calcium-chloride	-	-	-
	6°	Calcium-sulfate	-	-	-

Source: Prepared by the authors (2023).

Flow of wells at PRW

The wells found in the PRW lithostratigraphic units have the following specific capacities ($m^3/h/m$) (Figure 8):

Figure 8 - Maximum, mean, and minimum specific capacities for each lithostratigraphic unit of the Pardo River Watershed



Source: Prepared by the authors (2023).

The wells found in the Caxias Facies show a high mean specific capacity of 0.28 m^3/h/m, showing low but locally very low productivity according to the classification provided by Oliveira Diniz *et al*. (2012). On the other hand, the wells associated with the Gramado Facies have a moderate mean specific capacity of 0.6 m^3/h/m, showing low but locally moderate productivity.

In the case of wells associated with the Botucatu Formation, the mean specific capacity is 1.76 m^3/h/m, showing moderate productivity.

The Rosário do Sul Group, which lacks the presence of the Botucatu Formation and is in direct contact with the first effusive units of volcanic rocks from the Gramado Facies, presents unfavorable conditions for obtaining significant water volumes due to the prevalence of pelitic and psamopelitic lithotypes. Wells associated with the Rosário do Sul Group show a low mean specific capacity of 0.72 m^3/h/m, showing low but locally moderate productivity.

However, in areas near the hydrographic basin, such as in the municipality of Venâncio Aires, the exposure of conglomeratic and conglomeratic sandstone rocks of fluvial origin within the Rosário do Sul Group can provide favorable conditions for water storage and supply in larger volumes. These sedimentary facies, although occurring in a lenticular manner and confined by pelitic lithologies, can be found through geophysical studies or serendipitously during drilling, revealing important water resources in the region.

PRE-GAS, GAS, and SGAS recharge zones

In the state of Rio Grande do Sul, the average annual rainfall ranges from 1,200 mm to 2,000 mm, with the PRW area receiving around 1,600 mm. The analysis of the aquifer recharge zones is based on hydrodynamic relationships between surface waters, soils, rocks, and groundwater (Almeida *et al*., 2000). The assessment of the aquifer recharge zones in the PRE-GAS, GAS, and SGAS at PRW is crucial for urban planning, preservation of environmentally sensitive areas, and land use management. This is particularly important considering the region's significant agricultural activities such as tobacco farming, olive cultivation, and the cultivation of crops like beans and corn, which often involve the use of high volumes of agrochemicals. The evaluation of the potential risk of pollution from agrochemicals and fertilizers is necessary to protect both the free aquifers and the recharge areas (Foster *et al*., 2000). Studies dealing specifically with this study area and other nearby regions have already demonstrated the presence of excessive levels of fluorine, nitrate, and thermotolerant coliforms in well water, showing potential contamination (Costa *et al*., 2010; He *et al*., 2022).

Regarding groundwater recharge in the PRW, areas with significant aeolian sandstone interlayers can be found in the Caxias Facies unit at higher altitudes, particularly in municipalities such as Barros Cassal, Boqueirão do Leão, Herveiras, Lagoão, and Passa Sete. These features can serve as local aquifers with high potential, indirectly recharged through fractures present in the volcanic units of the Caxias Facies. In contrast, direct recharge through surface exposure is minimal in the Botucatu Formation, accounting for less than 1% of the total basin area. Therefore, the Botucatu Formation has limited groundwater potential for public supply in the PRW and surrounding regions, due to its absence or thickness and intense diagenetic processes or low metamorphism that have affected the unit in some areas.

The Rosário do Sul Group, in certain areas, comes into direct contact with the lowermost volcanic strata of the Gramado Facies due to the absence of the Botucatu Formation. However, the formations within the Rosário do Sul Group are unfavorable for obtaining significant water volumes. Exceptions to this are the conglomerates, conglomeratic sandstones, and coarse-grained sandstones associated with this unit, which can serve as indirect recharge areas. In the Peripheral Depression region, these formations can also function as direct recharge areas when exposed. In the northern half of PRW, the group's recharge primarily occurs through water percolation in the thick package of volcanic rocks, interlayered sandstones, and sporadic occurrences of the Botucatu Formation's sandstones.

Concerns arise about the recharge areas of the Rosário do Sul Group due to urban development, particularly in municipalities such as Sinimbu, Vale do Sol, Vera Cruz, Venâncio Aires, Santa Cruz do Sul, and Rio Pardo. Some of the main concerns are the lack or inadequacy of sanitation systems, the exponential increase in drilled tubular wells (some of them illegal and without technical supervision), and the excessive exploitation of aquifers, which leads to water table depletion and impacts surface water bodies. Additionally, urban expansion and the increase in impervious surfaces, as well as the induction of runoff through channels or galleries, further worsen the challenges associated with groundwater management (Tucci, 2006; Heine, 2008; Martinez; Silvério Da Silva; Lopes, 2008).

In addition to these challenges, the significant use of agrochemicals throughout the region further affects the use of PRW's groundwater for consumption. Strategies for water use in this integrated system should prioritize public supply, promoting integrated planning and management of surface and groundwater resources. They should also mobilize the population and civil society organizations to recognize the importance of groundwater and the need for environmental protection of aquifers, encouraging local and regional regulations for land use and groundwater management. Aquifer vulnerability and protection should be incorporated into groundwater management and land use planning, as emphasized by Rebouças (2006); Marsily (1994), and recognized by the National Water Agency (ANA, 2007).

FINAL CONSIDERATIONS

Based on the analyses carried out, the following conclusions are drawn:

Considering the Digital Elevation Model, the PRW was subdivided into Upper Pardo River (> 400 m); Middle Pardo River (400 m – 200 m); and Lower Pardo River (< 200 m).

The hydrogeological characteristics of the Rio Grande do Sul region (PRW), particularly the lithostratigraphic units of the Rosário do Sul Group, the Botucatu Formation, the Caxias Facies, and the Gramado Facies, have significant implications for groundwater resources.

In the SIAGAS database for PRW, 267 wells are registered, and after analysis for data consistency, only 102 wells were selected.

The classification of groundwater by lithostratigraphic unit is complex, influenced by several factors such as rock types, hydrogeological processes, groundwater mixtures, and chemical reactions.

For the Rosário do Sul Group, the sodium-bicarbonate water classes were predominant. The chemical composition of these waters shows higher sodium, bicarbonate, chloride, and low calcium and sulfate, richer in salts. The three wells with brackish water and one with saline water are associated with this stratigraphic unit, mainly the Sanga do Cabral Formation.

The Botucatu Formation presents waters with higher levels of bicarbonate, calcium, and low levels of sodium and chloride in the wells. The water classes are calcium-bicarbonate, originating from the rise of the Rosário do Sul Group water, carrying carbonate layers and concretions.

Regarding the Gramado Facies, there was a predominance of mixed bicarbonate waters, coming from the waters with carbon dioxide, dissolving minerals of basaltic composition, and rich in calcium, silicon, magnesium, bicarbonate, sodium, potassium, and iron. The chemical composition of these waters has higher levels of bicarbonate, calcium, sodium, and low levels of chloride and sulfate. They are associated with the geodes, amygdales, and druse-rich horizons, where zeolites, calcites, apophyllite, and saponites occur and are interspersed with interbedded sandstones, producing different chemical compositions.

The Caxias Facies is classified as calcium-bicarbonate water with influence from interbedded sandstones and the levels of geodes, amygdales, and druses of calcites from the Gramado Facies. The chemical composition of these waters presents higher levels of bicarbonate, calcium, sodium, and low chloride.

We identified wells that collected water from the SGAS (water inlets in volcanic rocks) and sedimentary formations. These wells were more productive because they collected water from more than one type of aquifer (fractured and porous), representing a differentiated hydrochemical response due to the mixing of water from more than one aquifer system.

Integrated management of groundwater resources is essential, taking into account the specific characteristics of different lithostratigraphic units, potential contamination risks, and the need to protect aquifers.

The Caxias and the Gramado facies, together with the Botucatu Formation, present favorable conditions for groundwater availability, with moderate (1.76 $m^3/h/m$) to low, but locally very low (0.28 $m^3/h/m$) productivity. The specific capacity of wells varies throughout the region, indicating the levels of groundwater productivity. These variations in specific capacity have significant implications for both regional and local water supply.

Urbanization and inadequate sanitation systems pose risks to the recharge areas of the Rosário do Sul Group, potentially leading to groundwater contamination. Additionally, the extensive use of agrochemicals in the region raises concerns about water quality and contamination potential.

The use of the SIAGAS database is highlighted as a valuable tool, although it requires careful data validation and standardization.

In conclusion, this study highlights the importance of adopting a comprehensive and sustainable approach to groundwater management in the Rio Grande do Sul region. It emphasizes the need to consider hydrogeological factors, potential contamination risks, and aquifer protection to ensure the long-term availability of safe and reliable water resources.

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