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Reverse osmosis for desalination of water from the Guarani Aquifer System to produce drinking water in southern Brazil

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HIGHLIGHTS

- Water from the Guarani Aquifer revealed excess F^-, SO_4^{2-} and TDS.
- RO was used to desalinate this water varying cross-flow velocity and pressure.
- A mix between groundwater and permeate allowed for a recovery of 93%.
- There is a potential for the desalination of this water to supply small cities.

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ABSTRACT

Like other regions around the world, southern Brazil has experienced periods of drought, having to find alternative water resources for producing drinking water during these times. The deep wells drilled in the Guarani Aquifer could help with this water imbalance, but the water, in some places, is brackish. This work is an exploratory study of the use of the brackish water from the Guarani Aquifer as an alternative supply for drinking water, using reverse osmosis to reduce the content of F^-, SO_4^{2-} and TDS (Total Dissolved Solids). The desalinated water obtained from reverse osmosis at a pressure of 2 MPa and a cross-flow velocity of 1.61 $m.s^{-1}$ showed rejections of approximately 94% for SO_4^{2-}, 97% for TDS and 100% for F^-. Blended water, produced by mixing groundwater and permeate, was proposed to optimize the produced drinking water with a recovery rate of 93%. Reverse osmosis is an excellent alternative for the supply of water in southern Brazil.

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1. Introduction

Brazil, contrary to what many people believe, is a country assailed by water shortage. Although the country has a large volume of superficial water, such water is poorly distributed across the Brazilian territory [1]. In southern Brazil, while some regions have abundant water, other microregions have endemic drought spells, and the rains are poorly distributed throughout the year. This indicates that inhabitants of Brazil must be prepared for dire water supply shortages. In addition to regulated, conservative use, other water sources must be sought as a preparation for drought conditions. An alternative would be the use of groundwater from the Guarani Aquifer.

The Guarani Aquifer System (GAS) is a cluster of hydrostratigraphic units, forming a large groundwater reservoir [2]. It is located in mid-eastern South America, as shown in Fig. 1. Its area corresponds to 1,194,000 km^2 [3] distributed across the territories of Brazil, Argentina, Uruguay, and Paraguay [4]. In Brazil, the southern region contains the largest area of the GAS [5].

The continental dimensions of the GAS have a large water storage potential; however, in most of its extension, the waters are classified as brackish [4]. A study coordinated by the Water Resources Agencies from Brazil, Uruguay, Paraguay and Argentina found that salinity is low/medium in the GAS, but the southern Brazilian region may have a higher salinity [6]. Thus, the GAS is a large groundwater reservoir, but the physicochemical quality is discontinuous, and in some areas the water is unfit for human consumption [6,7]. In some regions of Uruguay and Argentina, groundwater from the Guarani Aquifer has 8000 $mg \cdot L^{-1}$ of total dissolved solids, 1200 $mg \cdot L^{-1}$ of sulfates and 3.1 $mg \cdot L^{-1}$ of fluorides and is used only for thermal baths due to excess salt content [8].

Desalination of saline and brackish waters has expanded as an alternative technology for the production of water for human consumption and for industrial use [9]. Desalination by reverse osmosis is widely used for the production of drinking water [10] and is the main unconventional way to obtain drinking water in several countries, especially

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Fig. 1. Location of the Guarani Aquifer.

in those countries that suffer from a seasonal or continuous lack of natural fresh water resources [11]. Moreover, if fresh water must be pumped over long distances, it can become just as expensive as desalinated water, depending on the distances involved and on the amount of pumping required [12]. Thus, reverse osmosis is a possible solution for inland regions where there is no or inadequate superficial water available [13].

Reverse osmosis is a pressure-driven process whereby a semi-permeable membrane rejects dissolved constituents present in the feed solution. Size exclusion, charge exclusion and physicochemical interactions between solute, solvent, and membrane are the main mechanisms that facilitate the separation of permeate and reject in reverse osmosis [14].

We have seen many reports of desalination of brackish water by reverse osmosis in arid regions around the world, such as in the Middle East [15–29] and in Australia [30,31]. In addition, desalination has been largely used in the United States, which desalinates the third largest quantity of brackish or saline water of any country in the world [9]. In Brazil, desalination has gained momentum in the northeastern region, where there is a continuous shortage of superficial water, and where a large quantity of the supply is obtained from brackish groundwater [32]. In southern Brazil, however, desalination of groundwater has been used only for industrial applications, such as the production of boiler feed water. Nonetheless, desalination of water from the Guarani Aquifer could produce an alternative supply of water to the population, given that droughts have been far more frequent in this region.

The efficiency of reverse osmosis depends on operating parameters and on membrane and feed water properties [14]. Desalination of water by reverse osmosis should ideally occur under operating conditions that allow for the maximum rejection of salts by the membrane, yielding permeate with a lower salt content. The operating pressure has a direct impact on permeate flux, whereas cross-flow velocity minimizes the concentration polarization in the retentate stream, having an impact on both permeate flux and on the efficiency of separation. Thus, cross-flow velocity and pressure can have a direct effect on membrane rejection and permeate flux in water desalination.

The aim of this work is to study the groundwater from the Guarani Aquifer as an alternative water resource, adjusting the physicochemical parameters of this water through reverse osmosis to produce drinking water.

2. Water characterization

The GAS is located in a sandstone formation (the Botucatu Formation) and is confined by basalt rock (the Serra Geral Formation) on the top side (Fig. 2). The overall recharge zones of GAS are associated with the outcrop areas [6], as shown in Fig. 2. The extraction of water from the aquifer requires wells with depths ranging from 200 m to 1000 m, depending on the location.

Fig. 3 shows a schematic of a groundwater well, which is 8 in. in diameter, and uses a 100 HP submersible pump to maintain a water extraction flow rate of approximately 100 $m^3 \cdot h^{-1}$. The well was drilled to a depth of 960 m in the Guarani Aquifer in the town of Tapejara (state of Rio Grande do Sul) in southern Brazil (coordinates −28°3′19″, −51°59′49″). Table 1 shows the physicochemical properties of the water from the Guarani Aquifer. The water temperature at time of extraction was approximately 42 °C.

Previous studies performed in different regions of the GAS have demonstrated that, in general, the groundwater is good quality water, with a TDS concentration lower than 500 $mg \cdot L^{-1}$, low salinity and low hardness in shallower regions [6,33]. However, in deep wells drilled into confined regions of the GAS there is often higher salt concentrations. The hydrochemical evolution in the Guarani Aquifer is determinate by the flow direction, residence time and confinement conditions [54]. In fact, different water types can be found in the GAS due the free or confined zones [57]. The temperature, pH, HCO_3^- concentration and EC have the tendency to rise in the flow direction and these parameters are higher in confined conditions. Sulfate is added in the water from GAS by meteoric waters or by dissolution of the basement of the Pirambóia formation. Fluoride is not common. Some evidences suggest that F^- is inserted by leaching of the basement formed before GAS, and in some deep confined zones from GAS this compound is found in higher concentrations (western region of the State of São Paulo and Santa Catarina) [54,55,57].

In the specific location where groundwater was extracted for this study, the water is slightly saline ($1000 < TDS < 3000$ $mg \cdot L^{-1}$). An electrical balance including the major ions (sample 2) shows −1.1%, and, in general, analytical errors less than ±5% are acceptable.

The main cations (Sample 2) present are Na^+ and Ca^{2+}, while the main anions present are SO_4^{2-}, Cl^- and HCO_3^-. The high EC (and TDS) could indicate that the water was mineralized by the contact with soil/rocks. Beside, high TDS indicates that the water from GAS is in confined conditions [57]. The presence of sulfate, sodium and chloride as dominant species leads us to think that this water was extracted from a discharge area [56]. $Na^+ > Ca^+ > Mg^{2+}$ (sample 2) and the molar ratios Na^+/Ca^{2+}, Cl^-/HCO_3^- and SO_4^{2-}/Cl^- are higher than 1.0. This is typical for more confined water from the GAS [3]. In general, deep aquifers that are highly confined are old, and water quality is typically stable.

The Total Dissolved Solids (TDS) and the concentration of scaling substances (Ca, Si, Mg, Fe, and HCO_3^-) are not high; therefore, most common forms of fouling can be prevented by pH adjustment or the addition of an antiscalant or can be controlled by not exceeding the volume reduction rate (VRR) so that the TDS does not exceed 5 $g \cdot L^{-1}$. In addition, the total suspended solids concentration is below 10 $mg \cdot L^{-1}$ (sample 2), indicating a low level of suspended/colloidal matter.

However, Table 1 reveals that SO_4^{2-}, F^- and TDS do not comply with WHO [34] guidelines and Brazilian regulations [35] for potability. No

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