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Economic assessment of the desalination of the Guarani Aquifer System by reverse osmosis to produce potable water in southern Brazil

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ABSTRACT

Brazil, contrary to what many people believe, is a country that is suffering from water shortage. The inland regions of the country have experienced drought periods and must be prepared for this reality. Brackish groundwater from the Guarani Aquifer System treated by reverse osmosis (RO) could be used for the water supply, but the cost of the produced water must be competitive. We designed a RO facility for supplying water to a small city and made an economic assessment using different scenarios. The predicted cost of the water was in the range of 0.25–0.39 US$/m^3.

Keywords: Brackish; Brazil; Groundwater; Drinking water

1. Introduction

The water in the inland regions is poorly distributed across the Brazilian territory [1]. The northern region (where the Amazon flows) concentrates 80% of this volume and only 8% of the population. In contrast, the largest Brazilian city (São Paulo) has been experiencing its worst water supply crisis, which has affected approximately 11 million people. In southern Brazil, although some regions have abundant water, other microregions endure local drought spells. In 2012, Rio Grande do Sul state experienced its worst drought period in the last 50 years. Thus, in addition to regulated, conservative use, other water sources must be sought in preparation for drought conditions.

An alternative for southern Brazil could be the use of groundwater from the Guarani Aquifer [2]. The Guarani Aquifer System (GAS) is a cluster of hydrostratigraphic units that form a large groundwater reservoir [3]. Its area totals 1,194,000 km^2 [4] and is distributed across the territories of Brazil, Argentina, Uruguay, and Paraguay [5], as shown in Fig. 1(a). In Brazil, the southern region covers the largest area of the GAS [6]. However, in most of its extension, the confined deep waters are classified as brackish [5]. Thus, the GAS is a large groundwater reservoir, but the physicochemical quality of the water is uneven, and in some areas (such as in the southern region), the water is unfit for human consumption [7,8].

The desalination of saline and brackish waters by reverse osmosis (RO) is growing as an alternative technology for producing water for human consumption or industrial use [9,10]. Thus, RO is a possible solution for inland regions where no or inadequate superficial water is available [11]. Nonetheless, the

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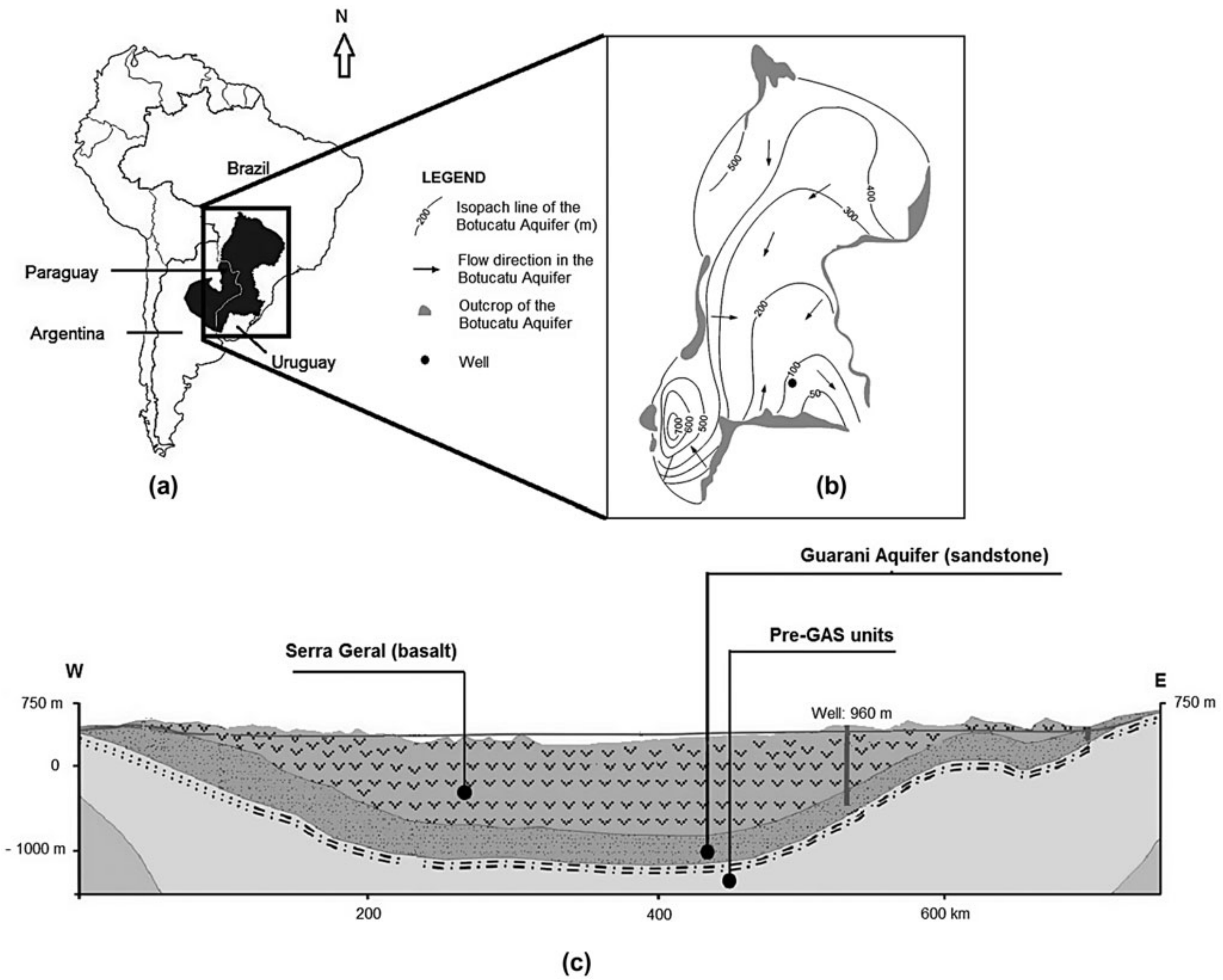

Fig. 1. Hydrogeological location of the GAS (Adapted from [2,7,30]).

desalination of brackish water from the Guarani Aquifer could be an alternative source of water for the population because droughts have been far more frequent in this region [2]. Furthermore, in Brazil, the counties are responsible for the water supply, and most cities in southern Brazil have fewer than 10,000 inhabitants. Thus, a water supply of good quality is becoming a challenge for small counties in the inland regions.

Brião et al. [2] showed that RO could be a good technical alternative to produce drinking water from the water of the GAS in southern Brazil. The RO membrane reached rejections higher than 95% (approximately 98% for TDS, 97% for sulfate, and 100% for fluoride), and the recovery was 93%. However, aside from the technical barriers, the water produced by RO must show an attractive economical value because surface water and shallow groundwater are the conventional sources of drinking water in Brazil.

Though there are many reports on the economic value of desalination in other regions of the world [12–24], records in specialized journals about the value of desalination in Brazil or even in South America are scarce. Thus, this article is a follow-up to the study of Brião et al. [2] and proposes a provisional estimate of the economic value of the drinking water produced by RO from the GAS to supply small cities in southern Brazil.

2. Water from the GAS

The GAS is located in mid-eastern South America (Fig. 1(a)). It is located in a sandstone formation (the Botucatu Formation) and is confined by basalt rock (the Serra Geral Formation). The overall recharge zones of the GAS are associated with outcrop areas [7], as shown in Fig. 1(b). The extraction of water from the aquifer requires wells with depths ranging from 200 to 1,000 m.

The water quality from the GAS is variable and depends on the location of the harvesting. In general, low concentrations of TDS (lower than 500 mg L^{-1}) and low salinity and hardness occur in the shallower regions [7], and the TDS tends to be lower near the outcrop region. In some areas of Uruguay and Argentina, groundwater from the Guarani Aquifer has 8,000 mg L^{-1} of total dissolved solids (TDS), 1,200 mg L^{-1} of sulfates, and 3.1 mg L^{-1} of fluorides and is used only for thermal baths due to the high salt content [25].

In a great area near the Brazil/Uruguay/Argentina border and in southern Brazil, there are confined regions of the GAS with high salt concentrations. The hydrochemical evolution of the water in the Guarani Aquifer is determined by the flow direction, residence time, and confinement conditions [26], and different types of water can be found in the GAS because of free or confined zones. The temperature, pH, HCO_3^- concentration, and EC tend to increase in the direction of the flow, and these parameters are higher in confinement conditions [6].

In the specific location where groundwater was extracted for this study (a well 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′′), the water is slightly saline (1,000 < TDS < 3,000 mg/L), as shown in Table 1.

The high EC and TDS indicate that the water from the GAS is in confined conditions [6]. In general, deep aquifers that are highly confined are old, and the water quality is typically stable. The deep region of the GAS has a high volume of confined water, and thus, the salinity is high. Therefore, this study could be representative of a large area of the GAS where the water is confined, including a great area of the states of Rio Grande do Sul, Santa Catarina, and western São Paulo. Thus, we considered other scenarios in the study to assess the sensitivity of the costs regarding the water quality.

The main cations in Table 1 are Na^+ and Ca^{2+}, and the main anions present are SO_4^{2-}, Cl^-, and HCO_3^-. The TDS and the concentration of scaling substances (Ca, Si, Mg, Fe, HCO_3^-) are not high; therefore, the most common forms of fouling can either be prevented by adjusting the pH or adding an antiscalant or be controlled by not exceeding the Volume Reduction Rate (VRR) such that the TDS does not exceed 5 g L^{-1}. In addition, the concentration of total suspended solids is below 10 mg L^{-1}, which indicates a low level of suspended/colloidal matter [2].

However, Table 1 reveals that SO_4^{2-}, F^-, and TDS do not comply with the WHO [27] guidelines and Brazilian regulations [28] for potability. No health-based guideline values have been developed for TDS and sulfate concentrations, but both chemical parameters can influence the acceptability of drinking water to consumers. A fluoride concentration of approximately 1 mg L^{-1} in drinking water may prevent dental cavities without harmful effects on health [30], but the regular consumption of fluoridated water with more than 1.5 mg L^{-1} could seriously damage the teeth or even the skeletal structure [29].

Reverse osmosis can be a good technical treatment for adjusting the physicochemical quality of water. The main goal is to remove sulfates, TDS, and fluoride ions. Brião et al. [2] carried out a study to adjust the quality of groundwater by considering fluoride as the critical constituent, and this work is a follow-up to this previous research.

Softening membranes could also be used to adjust the physicochemical quality of the water, but we think that a mix of groundwater and permeate can result in a better recovery because the salt concentration is lower in the permeate obtained by RO than by NF. Furthermore, this is a first study regarding the subject, and softening membranes will be tested in a next step.

3. Materials and methods

3.1. Steps of the method

The economic assessment was carried out in three steps:

(a) Most cities in southern Brazil contain fewer than 10,000 inhabitants, and each city is responsible for its own water supply. Thus, we designed a RO facility for the desalination of water from the GAS to produce drinking water for a small city of 10,000 inhabitants.
(b) We predicted the variable and fixed costs with real values in Brazil; they comprise the installation costs (starting costs of civil work and equipment), and operation and maintenance (i.e. labor, chemicals, power).
(c) The costs were compared with those of other desalination facilities used worldwide to assess whether desalting groundwater from the GAS could be useful for the Brazilian reality. We then tested other scenarios with different water qualities to evaluate the cost of the produced drinking water.

Table 1
Physicochemical composition of the water from the drilled well in the Guarani Aquifer in southern Brazil (adapted from [2])

Physicochemical parameters	Water from GAS	WHO recommendation	Brazilian Standard[a]
TDS (mg L^{-1})	1,059–1,321	1,000	1,000
TSS (mg L^{-1})	6	–	–
pH	8.53–8.82	6.5 ≤ pH ≤ 8.5	6.0 ≤ pH ≤ 9.5
Color (Hz)	0	15	15
Turbidity (NTU)	0	1.0	1.0
Electrical conductivity (μS cm^{-1})	1,702–1846	–	–
Zn (mg L^{-1})	0.03	4	5
Na (mg L^{-1})	159–192	200	200
K (mg L^{-1})	10	–	–
Hardness ($CaCO_3$) (mg L^{-1})	43	500	500
Ca^{2+} (mg L^{-1})	29	–	–
Mg^{2+} (mg L^{-1})	14	–	–
Mn (mg L^{-1})	0.1	0.1	0.1
Total Fe (mg L^{-1})	0.1	0.3	0.3
Total Cr (mg L^{-1})	ND	0.05	0.05
Cu (mg L^{-1})	ND	2	20
Pb (mg L^{-1})	ND	–	0.01
Cd (μg L^{-1})	ND	3	5
Al (mg L^{-1})	ND	0.1	0.2
SiO_2 (mg L^{-1})	14		
Sr (mg L^{-1})	0.18	–[b]	–
NH_4^+ (mg L^{-1})	ND	1.5	1.5
NO_2^- (mg L^{-1})	ND	3	1
NO_3^- (mg L^{-1})	0.65	50	10
Cl^- (mg L^{-1})	98	250	250
Alkalinity ($CaCO_3$) (mg L^{-1})	3.4	–	–
Alkalinity (HCO_3^-) (mg L^{-1})	68.3	–	
SO_4^{2-} (mg L^{-1})	285–346	250	250
F^- (mg L^{-a})	1.91–2.25	1.5	1.5

Notes: ND: Not detected by the analytical method.
[a]Ordinance 2,914/2012 issued by the Brazilian Ministry of Health.
[b]There are no guidelines for strontium concentrations, but there is a radiation guidance level of 10 Bq/L of strontium[90].

3.2. Design of the RO facility

The information regarding the technical evaluation for installing a RO system is found in the work of Brião et al. [2]. The basic assumption comprises filtering only 30% of the water pumped from the Guarani Aquifer and mixing the permeate with the groundwater (Fig. 2) to adjust the fluoride concentration (critical compound) to 1.5 mg/L (the maximum concentration suggested by the World Health Organization [27]). The main advantage of this configuration is that a membrane with a smaller area is required. The brine is sent to disposal, and the permeate is mixed with water from the well.

The water from the GAS in the southern region of Brazil has a low salinity (Table 1). However, we used other mixing ratios to evaluate their effect on the final cost of the water.

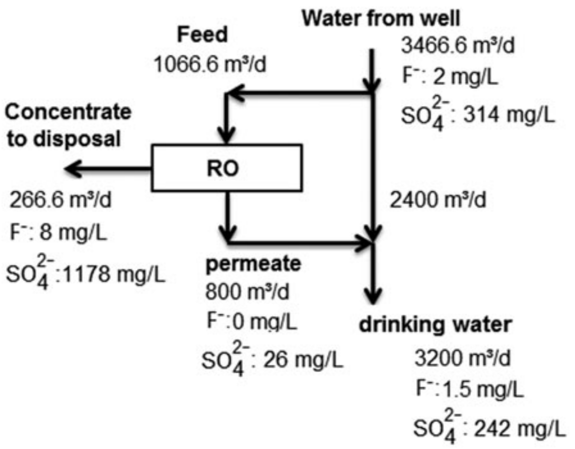

Fig. 2. Schematic of the mixing of groundwater from the GAS and the permeate to produce drinking water.

We chose to design a small RO facility because most cities in South Brazil include fewer than 10,000 inhabitants. Thus, this perspective can be useful for several cities that could extract water from the Guarani Aquifer.

The following assumptions were made:

(a) We predicted a high water demand of 320 L/d person, as reported in a study by the Water National Agency [30]. The household water consumption is 150 L/d person, but that in public infrastructures (such as schools and hospitals) and other activities (such as commerce) is 320 L/d person. Thus, for a total of 10,000 inhabitants, the required amount of drinking water is 3,200 m^3/d.

(b) A fourfold VRR was adopted, producing 75% permeate and 25% concentrate. The RO was designed as a two-pass system to achieve this VRR.

(c) The mixing ratio in Fig. 2 (groundwater/permeate) is equal to three. Once fluoride has been added by the groundwater, no further addition to the drinking water will be required; this rate will yield a fluoride concentration of 1.5 mg L^{-1} in the drinking water. Furthermore, the mixing between the groundwater and permeate adds alkalinity, and no post-treatment will be necessary [23], except for the addition of chlorine.

(d) The required permeate rate is 800 m^3/d, and the total groundwater pumped is 3,466 m^3/d. Thus, 266.6 m^3/d of concentrate must be sent to disposal. We propose to dilute the concentrate in the municipal wastewater treatment system, as discussed by Brião et al. [2], in a dilution ratio of 1/20. The wastewater plant (hypothetically) has the capacity to treat the total volume of sewage of the city (approximately the same volume of drinking water ~3,200 $m^3\,d^{-1}$).

(e) The typical permeate flux for brackish RO desalination plants is in the range of 12–45 L/m^2 h [23]. We used a permeate flux of 35 L $m^{-2}\,h^{-1}$ [2] to predict the permeation area. The required area is calculated from Eq. (1):

$$A = \frac{P}{J} = \frac{\frac{800,000\ \text{L/d}}{24\,\text{h/d}}}{35\,\frac{\text{L}}{\text{h m}^2}} = 952.4\,\text{m}^2 \quad (1)$$

where A is the required area (m^2), P is the permeate flow rate (L h^{-1}), and J is the permeate flux (L h^{-1} m^{-2}).

Thus, the required filtration area is 952.4 m^2. The selected membrane (Koch Membrane Systems-8038 HR-NYV) has a useful area of 34.5 m^2, and 27 membranes can thus be used. We designed the system with 32 membranes and a total filtration area of 1,104 m^2. We chose to use two membranes inside each vessel. Thus, 16 vessels are necessary. Filter cartridges (5 μm) are installed to remove possible colloidal and suspended matter.

(f) The designed facility has two buffering tanks (built in fiberglass) with a volume of 25 m^3 for the storage of the raw water for a short time (approximately 20 min); the produced drinking water is sent to the municipal reservoir.

(g) A civil construction of 50 m^2 is large enough to house the RO system and a small laboratory and for a possible expansion of the water treatment plant.

(h) The required power is calculated from Eq. (2). The feed flow rate (Q) is 1,066 $m^3\,d^{-1}$ (1.23 exp 5 $m^3\,s^{-1}$). The transmembrane pressure (ΔP) is 20 bar (20 exp5 Pa) [2]. The estimated pressure drop is 0.5 bar per vessel and the pump efficiency (η) is 0.7.

$$\text{Power} = \frac{Q \times \Delta P}{\eta} = \frac{1.23 \times 10^{-5}\text{m}^3\text{s}^1 \times 20.5 \times 10^5\,\text{Pa}}{0.7} = 35.1\,\text{kW} = 47\text{HP} \quad (2)$$

Thus, the power required is 50 HP for the RO process and 100 HP to pump groundwater from a depth of 960 m.

3.3. Predicting the fixed and variable costs

The costs were predicted with real budgets or estimates used by specialized companies. We divided the costs into “installation” (capital costs, calculating the annual depreciation) and “operating and maintenance,” as suggested by Younos [24]. The budgets were made using “reais” (R$), and we used the average exchange rate of September 2015: US$1 = R$4.0.

(a) The installation costs are the civil construction, well drilling, well equipment (pump, pipes, valves, instrumentation, and controls), buffering tanks, and RO system.

(b) For the capital costs, the annual depreciation is constant; this estimation is based on the straight-line method by Al-Wazzan et al. [13], as shown in Eq. (3). The lifespan used is 25 years.

$$D_t = \frac{I - H}{n} \quad (3)$$

where D_t is the annual depreciation, I is the investment, and H is the residual value after the life span. We chose H to be zero (no residual value).

(c) The well facility was composed of two sections: drilling and facilities. The facilities include a 100 HP submerged pump, pipelines, valves, and controls.
(d) The RO system includes vessels, valves, controls, a 50 HP pump, flowmeters, and other accessories.
(e) Regarding the civil construction, a good approximation used by civil engineers in Brazil is R$1,600/m^2 for rustic constructions; thus, US$ 400/m^2.
(f) The operating costs are the maintenance, membrane and cartridge filter replacements, labor, electricity, membranes, chemicals, and concentrate disposal in the municipal wastewater treatment system.
(g) Intake facilities (well maintenance) and RO maintenance: we used an annual value of 2% of the capital for spare parts and pump maintenance, as suggested by Talaat et al. [21] and Poullikas [22].
(h) Membranes will be replaced every 5 years. Thus, 32 membranes * US$1,600/5 years = US $10,240/year.
(i) The groundwater from the Guarani Aquifer contains less than 10 mg/L of suspend solids. Thus, cartridge filters will be replaced every 6 months (2 replacements per year). Replacing the 5-μm filter cartridges requires 80 high flow rate polypropylene filters: R$100/cartridge × 30 cartridge × 2 replacements/year = R$6,000 (US $1,500)/year.
(j) The cost of the maintenance of the civil construction is predicted to be 10% of the investment per year.
(k) The extracted water does not require pre-treatment, and the produced water does not require any post-treatment except for chlorination. Thus, the only necessary chemicals are an anti-scaling agent (to prevent fouling), NaOCl (for chlorination), sodium hydroxide, citric acid (for cleaning), and a biocide to prevent microbiological scaling. An amount of US $ 24,000 seems to be a good estimate.
(l) The labor consists of four operators to supervise the system 24–7. They can also conduct chemical analyses. The individual monthly pay is R$1,000 (US$250). It must be noted that the minimum salary in Brazil is R$788/month.
(m) We included a chemist (as the technical responsible party) in the operating costs with a monthly payment of R$2500.00 (US$625).
(n) Labor charges in Brazil are 62% over the salary, but can be higher.
(o) The power consumption was divided between the well (intake) and the RO process. The cost of electricity is US$0.12/kW h in the Rio Grande do Sul State.
(p) The concentrate will be sent to the municipal wastewater treatment plant. The dilution rate is approximately 1/20, and there is no need for pre-treatment. Thus, this cost will be part of the total cost of the municipal sewage treatment. Some cities charge the cost of sewage at 75% of the price of tap water. In Rio Grande do Sul, the cost of tap water is R$4.0/m^3 (US $1.0/m^3). Thus, the cost of the brine treatment will be US$0.75/m^3.
(q) The Load Factor is 349 d per year, as suggested by Moch et al. [31], i.e. 1 d/month for cleaning and 4 d/year for maintenance.

4. Results and discussion

Fig. 3 shows a sketch of the RO system designed to produce 3,200 m^3/d of drinking water from groundwater from the GAS. This figure does not show the details (e.g. pumps, pipelines, valves, controls), but we can estimate that 50 m^2 will be sufficient to house the RO facilities. Furthermore, there is sufficient surface area for a possible expansion of the treatment plant, and we reserve a location for a small laboratory for routine analysis. The tanks will be used to equalize the flow, and the main reservoir will be the depot of the distribution network.

Table 2 shows the predicted costs for the desalination of water from the GAS according the scheme laid out in Fig. 2, which was assembled in the facility depicted in Fig. 3. The volume of drinking water produced per year is 1.11 Mm^3, and the annual costs amount to over US$ 282,000.

The US$ 0.25/m^3 cost of produced drinking water is a competitive value. However, only 30% of the water harvested from the GAS is fed to the RO plant, and the annual permeate volume is 279,200 m^3. If this volume is considered, the cost to obtain the permeate is US$ 1.01/m^3, which is a relatively high mark. Thus, mixing the permeate and groundwater is a good alternative to decrease the cost of water production. The

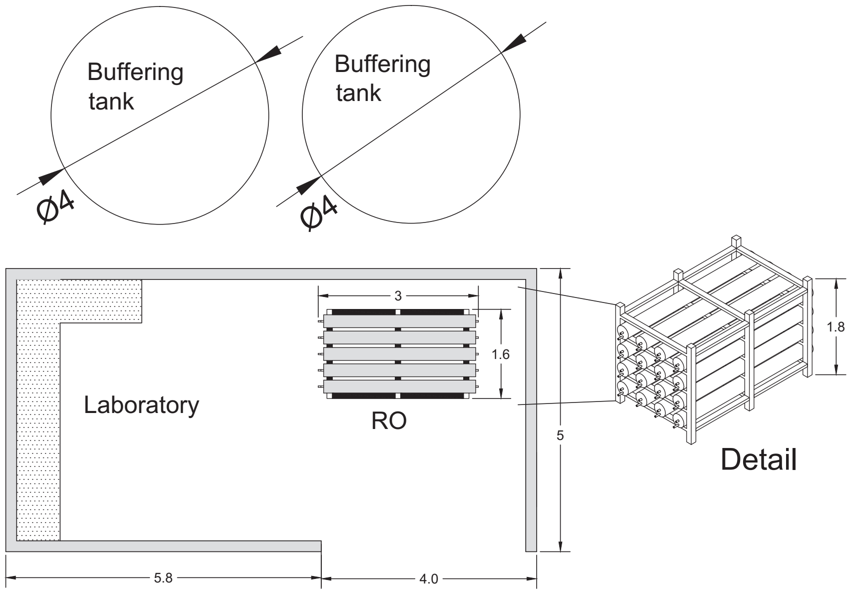

Fig. 3. Sketch of the designed area for housing the RO system to produce drinking water from the GAS (dimensions in meters).

Table 2
Predicted costs for the desalination of water from the GAS to produce drinking water in southern Brazil

Item	Life span (year)	Investment (US$)	Annual depreciation (US$)	% of annual costs
Capital Costs		489,250.00	19,570.00	6.92
Well drilling	25	138,250.00	5,530.00	1.96
Well facilities	25	125,000.00	5,000.00	1.77
Reverse osmosis	25	200,000.00	8,000.00	2.83
Buffering tank	25	3,000.00	120.00	0.04
Buffering tank	25	3,000.00	120.00	0.04
Civil work	25	20,000.00	800.00	0.28
Operating costs			263,084.15	93.08
Well maintenance	Annual	–	2,500.00	0.88
Reverse osmosis maintenance	Annual	–	4,000.00	1.42
Membrane replacement	Annual	–	10,240.00	3.62
Cartridges filter replacement	Annual		1,500.00	0.53
Civil construction maintenance	Annual	–	2,000.00	0.71
Chemical products	Annual	–	24,000.00	8.49
Manpower	Annual	–	12,000.00	4.25
Chemist	Annual	–	7,500.00	2.65
Labor charges	Annual	–	12,090.00	4.28
Electricity for intake	Annual	–	78,314.40	27.71
Electricity for RO	Annual	–	39,157.20	13.85
Concentrate disposal	Annual	–	69,782.55	24.69
Total			282,654.15	100.00
Annual drink water produced (m^3)			1,116,800	
Water cost (US$/$m^3$)			0.25	

costs to produce desalinated water from brackish sources are more difficult to predict because the water quality and quantity changes from site to site [32]; however, Ghaffour et al. [16] showed that the costs are in the range of US\$0.2–0.4/m^3 for BWRO, and our predicted cost thus seems to be a good estimate. In contrast, the same authors report that the capital investment for a BWRO process is in the range of US \$300–1,200/m^3/d, and our budgets indicated a ratio of US\$ 153/m^3/d. If the investment in the RO system was twice the predicted value (US\$400,000), this ratio would be US\$ 215/m^3/d, and only a small impact can be observed on the water cost (US\$ 0.26/m^3) because the biggest contribution is the variable cost. In fact, the operating and maintenance costs are very high, and they amounted to over 93% of the total cost; however, our values (US\$0.23/m^3) are within the same order (US\$0.26/m^3) as the values given in a report regarding the 10-year operation of a BWRO system located in Saudi Arabia [33]. However, this facility is a large RO plant that produces approximately 84,000 $m^3\,d^{-1}$ (TDS ~500 mg L^{-1}) by blending pre-treated raw water with permeate.

Our predicted intake costs are 32% (well drilling + well facilities + well maintenance + power to pump the groundwater). However, there is a decaying trend in the intake costs when new approaches are used to extract the raw water [16]. Note that the electrical cost for the intake is 28% (0.558 kW h/m^3), and the electrical cost for RO is only 14% (0.279 kW h/m^3). Reports have shown that the ratio for pumping groundwater can be over 2 kW h/m^3 (for a vertical distance of 600 m) [28], and the intake costs can be in the range of 17–33% [18].

The power consumption is 0.83 kW h/m^3. We predicted that the energy consumption would be 41% of the total cost. In fact, this expenditure can contribute anywhere between 25 and 50% [19]. This value depends on the TDS of the groundwater and can be in the range of 0.3–1.4 kW h/m^3 [34] or 0.5–2.5 kW h/m^3, but the total power consumption tends to decrease when large-scale desalination plants are installed [16]. Thus, our predicted power consumption is a relatively low value, but it must be noted that the TDS in the well drilled in the GAS in southern Brazil is only 1,300 mg/L and that the cost tends to increase when the TDS is high [22].

Chemical costs can be variable. They depend on the required pre-/post-treatment of the water, but we can find papers reporting that they comprise 14% [14] or 6% [35] of the total costs. Thus, we think that 8% (US\$24,000 per year) is a good estimate.

Another important point related to the costs of desalination is membrane replacement, which can represent 15–20% of the capital or 10% of the water production [22]. This expenditure can be in the range of €0.02–€0.29/m^3 [14,15]. However, new membranes with high permeability have been developed, thus lowering this cost. Our estimate is a good value (approximately US\$0.01/m^3) and has been adapted to the Brazilian reality.

Labor-related costs tend to be higher in small RO facilities, for example, reaching US\$0.037/m^3 in Kuwait [13]. In fact, this value is very close to our estimate (US\$0.03/m^3), amounting to 11% (Manpower + Chemist + Labor charges) to the total cost.

Regarding the concentrate disposal, we understand that it is overestimated (25% of the total cost). However, finding an adequate final destination for wastewater is a worldwide challenge [23,36,37], and the already high costs are further increased depending on the strategy adopted for brine waste disposal [24]. Furthermore, there are few records on this subject in Brazil. In northeast Brazil, there are a great number of small RO facilities, but the problem related to concentrate disposal has been neglected. Local solutions have been proposed, such as temporary storage ponds, diluting the concentrate to fish farming ponds, or even seeding aquatic plants [38], but Brazil still does not have a systematic solution for the problem. We will approach this subject in the next paragraphs.

The cost of the surface water treatment to produce drinking water is variable, but was predicted to be US \$0.10/m^3 by Mierzwa et al. [39]. In fact, the current value is close to this number. Thus, the cost of desalinated water (US\$ 0.25/m^3) is twice this value, but the price of tap water in southern Brazil is US \$ 1.0/m^3. In simulations made by Campos [40] in northeast Brazil, the cost of desalinated water reached US\$1.8/m^3. However, similar to other locations around the world, the transport and inefficient distribution of water in networks and other infrastructures can constitute the largest contribution to the cost of tap water [19,22,41]. Moreover, as more desalination plants are installed around the world, the cost of desalinated water tends to decrease and stabilizes at approximately US\$0.5/m^3 [16].

4.1. Other scenarios

The water from the Guarani Aquifer is stable in confined areas. However, if the water quality is poor, the mixing ratio between the permeate and raw water will change, and the costs will change. We simulated two more scenarios by raising the fluoride concentration (critical constituent) of groundwater from the GAS to 2.5 and 3.0 mg L^{-1}. Fig. 4 shows a generic

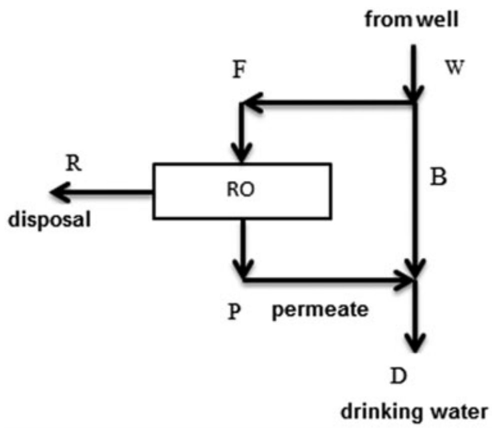

Fig. 4. Generic mass balance in the mixing between the groundwater from the Guarani Aquifer and the permeate from the RO process.

mass balance of the system, and Table 3 shows the flow rates of the simulated scenarios.

The fluoride rejection is 100% for VRR = 4 [2]. Thus, for an even higher salinity, no fluoride is found in the permeate. If the F^- concentration in the water from the GAS increases, the mixing ratios between the groundwater and permeate (B/P) change to 3:1, 1.66:1, and 1:1 to adjust the water quality. The new scenarios could be useful for other regions of the GAS, where other parameters are critical and different mixing ratios must be used.

The worse the quality of the groundwater is, the lower the mixing ratio between the groundwater and the permeate (B/P) is. This will have several consequences as follows: a higher extraction flow rate (7% higher); a lower recovery; a higher volume of concentrate (*R*); a higher permeation area because a higher permeate flow rate is required; higher electricity consumption. The new costs are given in Table 4.

The new prices increased by US$ 0.33/m^3 and US $ 0.39/m^3 (32 and 56%, respectively) with the increase in fluoride concentration. Nevertheless, the cost is still lower than the estimates from the simulations run by Téllez et al. [12] ($5.00/m^3) for the desalination of brackish water by a Linear Fresnel System Evaporator and injection of the brine in a deep well.

The decrease of groundwater in the groundwater/permeate mixture (low B/P ratio) allowed for some observations:

(a) The increase in groundwater extraction was only 7% for B/P = 1. The 100 HP pump is powerful enough for this increased flow rate. Thus, the intake costs were not changed.
(b) We considered a linear increase of the costs with the membranes and RO facilities (including electricity) because the volume of permeate increases in the same proportion.
(c) Some capital costs were kept constant for the new scenarios, such as the civil work, water harvesting, and some operating costs such as labor.
(d) However, there was an increase of 30 and 56% for the operating costs for the new B/P ratios (1.66 and 1, respectively) when a lower volume of groundwater was added in the groundwater/permeate mixture.
(e) We previously commented on the high costs for the concentrate disposal in the first scenario. As the fluoride concentration in the water from the GAS increases, a higher volume of concentrate is sent for disposal, and there is a linear increase in this cost. Some notes are as follows:

Table 3
Different mixing ratios between the groundwater (B) and permeate (P) with different fluoride concentrations in the water from the GAS

Fluoride (mg L^{-1}) in water from GAS	2	2.5	3.0
Mixing ratio (B/P)	3	1.66	1
Flow rates (m^3 d^{-1})			
W (water from well)	3,466.6	3,601	3,733.3
F (RO Feed)	1,066.6	1,604	2,133.3
R (Concentrate)	266.6	401	533.3
P (Permeate)	800	1,203	1,600
B (By pass from well)	2,400	1997	1,600
D (Drinking water)	3,200	3,200	3,200
Recovery (%)	92.31	88.86	85.71

Table 4
Sensitivity Analysis of the costs for desalting water from the Guarani Aquifer with different mixing ratios of raw water and permeate

Item	Life span (year)	Raw water/permeate (B/P) = 3			Raw water/permeate (B/P) = 1.66			Raw water/permeate (B/P) = 1		
		Investment (US$)	Annual depreciation (US$)	% of total costs	Investment (US$)	Annual depreciation (US$)	% of total costs	Investment (US$)	Annual depreciation (US$)	% of total costs
Capital costs		489,250.00	19,570.00	6.92	621,250.00	24,850.00	6.78	689,250.00	27,570.00	6.27
Well drilling	25	138,250.00	5,530.00	1.96	138,250.00	5,530.00	1.51	138,250.00	5,530.00	1.26
Well facilities	25	125,000.00	5,000.00	1.77	125,000.00	5,000.00	1.36	125,000.00	5,000.00	1.14
Reverse osmosis	25	200,000.00	8,000.00	2.83	332,000.00	13,280.00	3.62	400,000.00	16,000.00	3.64
Buffering tank	25	3,000.00	120.00	0.04	3,000.00	120.00	0.03	3,000.00	120.00	0.03
Buffering tank	25	3,000.00	120.00	0.04	3,000.00	120.00	0.03	3,000.00	120.00	0.03
Civil work	25	20,000.00	800.00	0.28	20,000.00	800.00	0.22	20,000.00	800.00	0.18
Operating costs			263,084.15	93.08		341,495.63	93.22		411,797.93	93.73
Well maintenance	Annual	–	2,500.00	0.88	–	2,500.00	0.68	–	2,500.00	0.57
RO maintenance	Annual	–	4,000.00	1.42	–	6,640.00	1.81	–	8,000.00	1.82
Membrane replacement	Annual	–	10,240.00	3.62	–	16,998.40	4.64	–	20,480.00	4.66
Cartridges filter replacement	Annual		1,500.00	0.53		2,490.00	0.68		3,000.00	0.68
Civil Construction maintenance	Annual	–	2,000.00	0.71	–	2,000.00	0.55	–	2,000.00	0.46
Chemical products	Annual	–	24,000.00	8.49	–	39,840.00	10.87	–	48,000.00	10.92
Manpower	Annual	–	12,000.00	4.25	–	12,000.00	3.28	–	12,000.00	2.73
Chemist	Annual	–	7,500.00	2.65	–	7,500.00	2.05	–	7,500.00	1.71
Labor charges	Annual	–	12,090.00	4.28	–	12,090.00	3.30	–	12,090.00	2.75
Electricity for intake	Annual	–	78,314.40	27.71	–	78,314.40	21.38	–	78,314.40	17.82
Electricity for RO	Annual	–	39,157.20	13.85	–	56,161.08	15.33	–	78,314.40	17.82
Concentrate disposal	Annual	–	69,782.55	24.69	–	104,961.75	28.65	–	139,599.13	31.77
Total			282,654.15	100.00		366,345.63	100.00		439,367.93	100.00
Annual drink water produced (m^3)			1,116,800		1,116,800			1,116,800		
Watercost (US$/$m^3$)			0.25			0.33			0.39	

(i) Commercial prices (i.e. for the treatment of the wastewater generated by private companies) were taken into account for this calculation. However, in general, the water supply and the sewage treatment are provided by the same sanitation company. Moreover, water supply is a public service, and we believe that the costs for concentrate disposal should be limited to the manufacturing expenses.

(ii) Deep well injection into the recharge zones of the GAS could be an alternative for concentrate disposal. This practice is not common in Brazil, but it could be applied to this specific situation. The GAS contains deep zones of high TDS concentrations with sufficient permeability such that the concentrate will not alter the characteristics of the groundwater [2]. However, Schijven et al. [42] suggested that the deep well injection site must be extensively studied to assess its injection capacity and to investigate factors that affect this capacity. Furthermore, Téllez et al. [12] noted that in the case of inland operations, the disposal of rejected water is reflected in the cost of the produced water. Thus, specific studies must be performed before considering this option for concentrate disposal.

Finally, the price of drinking water obtained by desalination is higher than that of drinking water obtained by the treatment of surface water sources. However, note that 86% of the cities in Brazil use only one source of water supply: either groundwater or surface water. The extraction of water from both sources is a practice that is only carried out in the large cities where the water harvest is beyond the edge of the county [30]. This study does not aim for the substitution of surface water, but we are suggesting an integrated point of view because some microregions have local drought spells, and other water sources must therefore be sought in preparation for drought conditions [2].

5. Conclusion

Brazil must be prepared for water shortage, and we showed that the desalination of water from the Guarani Aquifer could be an economical alternative for supplying drinking water in southern Brazil.

Mixing permeate with groundwater is a good strategy to make the water production cheaper. The predicted cost of drinking water treated by RO from the Guarani Aquifer depending upon this mixing, and the cost was in the range of US\$ 0.32/m^3–0.49 US\$/m^3.

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