

Article

Removal of Sulphate Ions from Borehole Water Using Nanofiltration and Reverse Osmosis

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Abstract: Consumption of contaminated water poses health hazards to humanity and hence increases the need for treatment. An excessive level of sulphate in borehole water was detected in the drinking water supply of Garpéné village in Burkina Faso. This study aimed to evaluate the performance of nanofiltration and reverse osmosis for the removal of sulphate ions from borehole water. A combined nanofiltration and reverse osmosis pilot was used for the treatment of the raw borehole water and some prepared synthetic solutions. Different experimental conditions were used to evaluate the effects of the pressure, the nature of the solution to be filtered, and the ions accompanying the sulphate. The filtration tests were conducted at transmembrane pressures of 1, 2.5 and 4 bar with a nanofiltration NF270 membrane and at transmembrane pressures of 4, 6 and 8 bar with a reverse osmosis TW30 membrane. The membrane used were a thin-film composite (TFC) membrane from Filmtec. The pilot was fed with real water from the Garpéné borehole and synthetic solutions of calcium sulphate and sodium sulphate at three different concentrations (250, 500 and 1400 mg/L). The results demonstrated that the nanofiltration and reverse osmosis membranes achieved retention rates of sulphate ions ranging from 97.0% to 98.7% and 98.4% to 99.0%, respectively. The results also showed that the operating conditions had a significant effect on the retention of sulphate by reverse osmosis and nanofiltration membranes. With regard to the effect of the counter ion, it was observed that during nanofiltration, the retention rate of sulphate ions in the water to be treated was lower in the presence of calcium ions than that of sodium ions, whereas in reverse osmosis little influence of the counter ion was observed.

Keywords: borehole water; drinking water; nanofiltration; reverse osmosis; sulphate ion removal; water treatment



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1. Introduction

Humans and water constitute an indestructible association. Water is ubiquitous in human daily life mainly for domestic (food, hygiene and sanitation), industrial and agricultural purposes. Globally, groundwater remains the main source of drinking water [1–5]. Grönwall and Danert [6] reported that nearly 2.5 billion people in 2020 solely depended on groundwater to meet their drinking water needs. Generally, the quality and chemical composition of groundwater depend on the geological nature of the rock in contact with the water. For example, water flowing through sandy or granitic subsoils will be acidic and poorly mineralised, whereas water flowing through calcareous soils will be bicarbonate, calcic and often have a high hardness [7,8]. Groundwater has long been considered “clean water”, because in most cases it naturally meets potability standards and therefore does not generally require treatment. However, as groundwater quality varies from place to place [9], some may contain mineral elements in concentrations exceeding potability standards [10–13] and thus requires to be treated before consumption [7,8].

Sulphate ion is a constituent present in the aquatic environment and can be found in almost all natural waters. It plays an important role in biogeochemical cycles and is widely distributed in various environmental compartments. Nonetheless, sulphate is one of the major ions contained in groundwater [14]. The highest concentrations of sulphate are generally of natural origin. Indeed, gypsum is a mineral consisting of hydrated calcium sulphate with low solubility, which is likely to release sulphate upon contact of water with the rock. However, although the chemical composition of groundwater is linked to the geological nature of the aquifer in which it is found, it is recognised that groundwater can be contaminated by anthropogenic activities through industrialisation and urbanisation and thus have its initial quality altered [14,15]. The excessive presence of sulphate in drinking water can alter its taste during its consumption. Furthermore, large doses of sulphate in drinking water can have a laxative effect on the body and cause diarrhea and severe abdominal pain in consumers [16].

The removal of sulphate ions from water can be achieved by chemical or physical processes such as distillation, ion exchanger and membrane technologies. However, among these methods, membrane technologies seem to be the most suitable for high sulphate contents. Membrane technologies developed in the 1970s use the molecular sieving properties of a porous membrane to separate constituents from a mixture in the gas or liquid phase [13]. Thus, membrane technologies such as reverse osmosis and nanofiltration could present an alternative for the treatment of high sulphate concentrations in water [14,17–19]. The literature highlights the performance of reverse osmosis and nanofiltration for the removal of pollutants, but very few associate compliances with WHO potability standards [20–23]. However, it is assumed that NF offers several advantages in comparison to RO such as low operation pressure, high flux, relatively low investment and low operation/maintenance costs [24]. On the other hand, even if reverse osmosis and nanofiltration can lead to a reduction of sulphate ion concentrations in water, a comparison of these techniques should provide the necessary information for the implementation of real solutions to the provision of drinking water while minimising operating costs. However, very few studies have dealt with effects of the pressure on the rejection of main ions and sulphate ion concentration in water and effects of counter ion on sulphate ion retention as well as a comparison analysis of nanofiltration and reverse osmosis treatment. This study, therefore, aims to assess the removal efficiency of nanofiltration and reverse osmosis for the elimination of sulphate ion in a borehole's drinking water through the identification of operating conditions and environmental factors of success.

2. Materials and Methods

2.1. Presentation of Garpéné Village and Samples Collection from a Borehole

The village of Garpéné is located in the rural municipality of Dapélogo, which is in the Province of Ouhritenga in the Plateau Central Region of Burkina Faso (Figure 1). Garpéné village lies with a latitude of 12°38'31" N and a longitude of 1°30'56" W.

The concentration of sulphate ions in the borehole water which serves as the source of drinking water for the village of Garpéné was found at 1400 mg/L. This resulted in the complete abandonment of the borehole and thus demands a better treatment solution. The village of Garpéné has a population of about 3966 [25], where rainfed agriculture is the main economic activity. The soils are shallow with low fertility but are suitable for dry farming. The geology is characterised by crystalline rocks that make up the entire subsoil. The aquifers of the boreholes generally correspond to the fracture zones of altered rocks. The depth of the boreholes is 60 m on average and proportional to the thickness of alteration of the rocks.

The borehole water was sampled for laboratory treatment experimentation. A sterile sampling bottle was used to collect the water samples. A pump submerged in the borehole was switched on, and discharge pipes were disconnected to a reservoir tank to allow the water to flow out for about 5 min before the raw water was collected on a 20 L jerry can with laboratory sanitised standards. The samples were collected before getting to the

reservoir tank (GP tank-overhead tank). The raw water was sent to the laboratory for water characterisation and experiment.

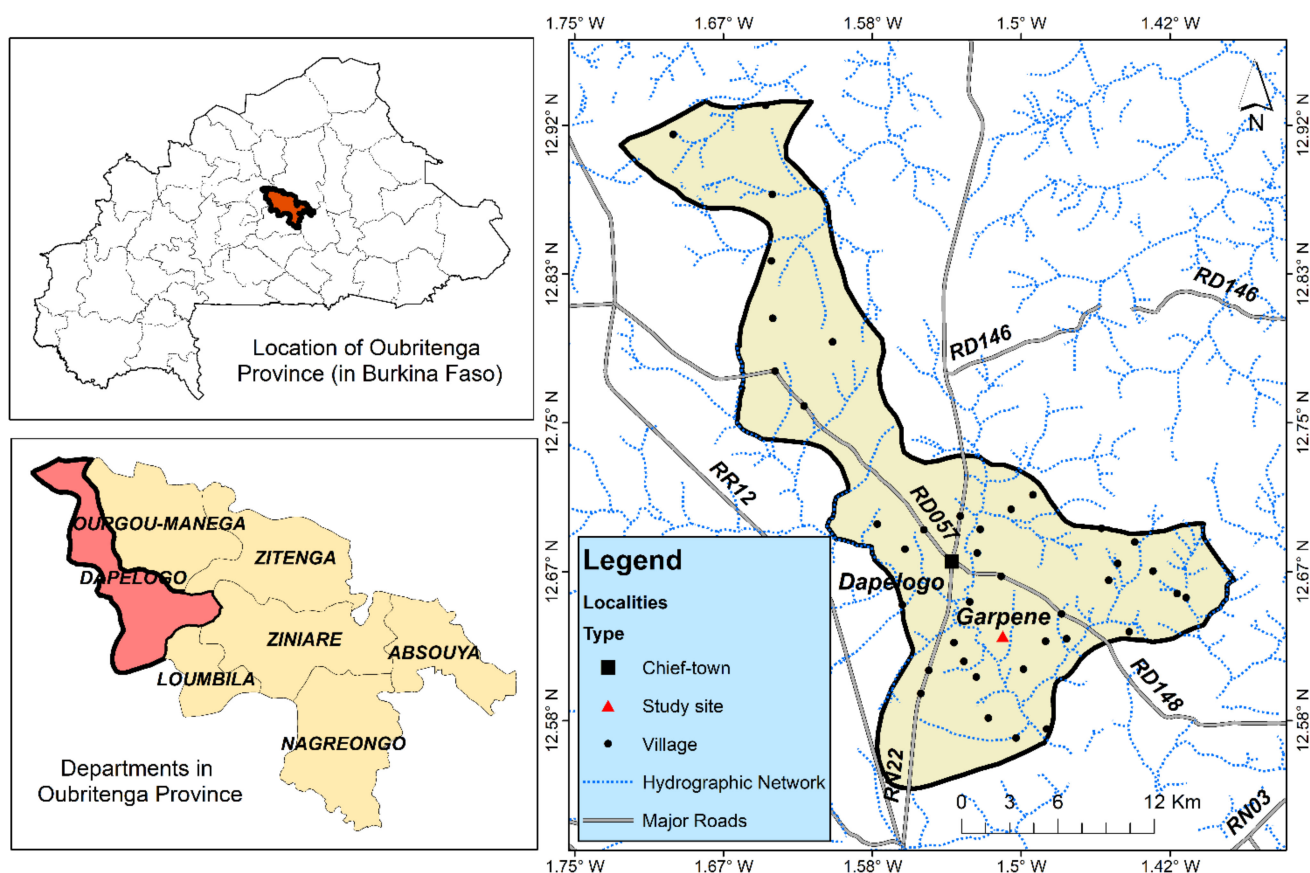


Figure 1. Geographical location of the borehole whose water was used for the tests.

2.2. Design Configuration of the Nanofiltration and Reverse Osmosis Pilot

The experimental pilot consisted of a high-pressure multistage centrifugal pump (16 bar at 800 L/h), which fed a circuit comprising reverse osmosis and nanofiltration cartridges.

Both feed solutions and permeate recovery tanks were made of transparent PVC with capacities of 60 and 18 L, respectively. The feed tank can be filled via a 25 mm filter and an activated carbon filter (5 mm) as well as directly from the feed tank.

The treatment performance of the reverse osmosis or nanofiltration was assessed by two conductivity probes placed in the permeate circuit and the feeding tank. The displays associated with the probes allowed for temperature compensation if desired. Two 0–16 bar pressure sensors were located upstream and downstream of the membranes. Different sets of valves allowed the hydraulic conditions around the cartridges to be varied. The experimental set-up is shown in Figure 2.

2.3. Characteristics of the Membranes Used

Two commercial Filmtec membranes were used in the filtration tests: a nanofiltration membrane (NF270) and a reverse osmosis membrane (TW30). The Filmtec membrane was a thin-film composite (TFC) membrane composed of three layers: a polyester support layer (120 μm), a microporous polysulfone interlayer (40 μm) and an ultra-thin polyamide barrier layer (active layer) on the top surface (0.2 μm). The pure water permeability values of the nanofiltration and reverse osmosis membranes were $12.5 \text{ L}\cdot\text{h}^{-1}\cdot\text{m}^{-2}\cdot\text{bar}^{-1}$ and $5.7 \text{ L}\cdot\text{h}^{-1}\cdot\text{m}^{-2}\cdot\text{bar}^{-1}$, respectively. Both membranes were protected with a plastic cartridge. Table 1 summarises the main characteristics of the membranes studied.

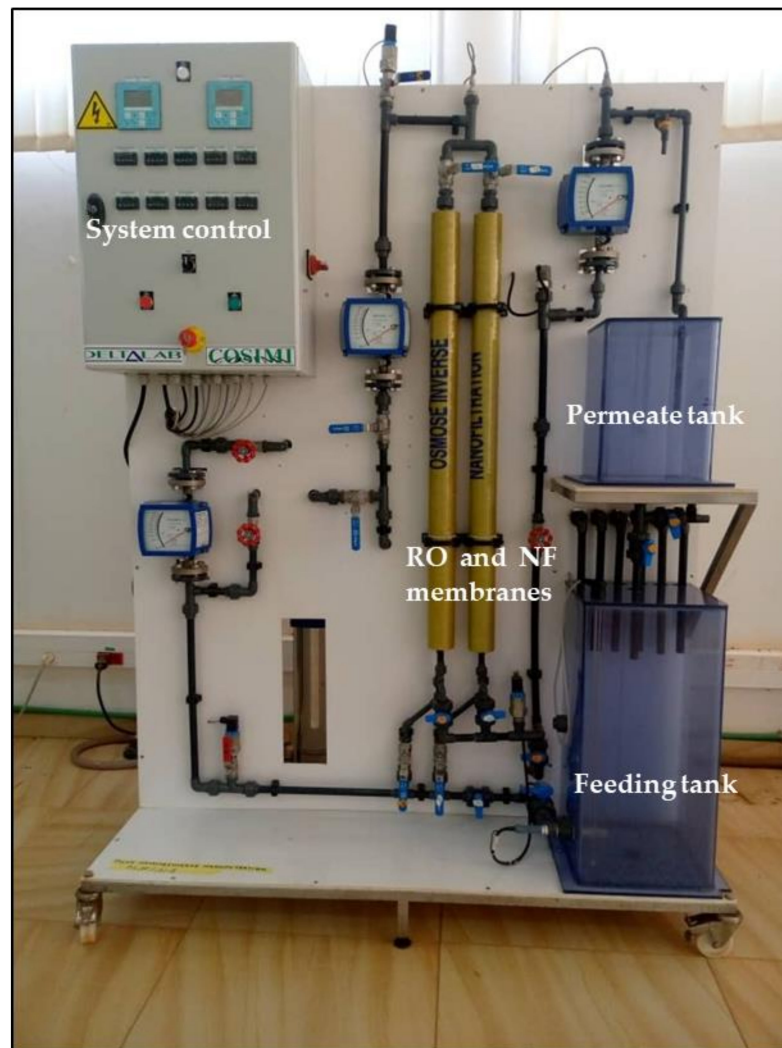


Figure 2. Nanofiltration and reverse osmosis pilot.

Table 1. Membrane characteristics.

Characteristics	NF	RO
Material	Polyamide Thin-film composite	
Type	NF270-2540	TW30-2540
Total filtration area (m ²)	2.6	2.6
Membrane length (mm)	1016	1016
Diameter (mm)	61	61
Pure water permeability (LMH/bar)	12.5	5.7
Pressure (bar)	5	16
Manufacturer	Dow Filmtec	

2.4. Filtration Processes

For each filtration operation, a volume of 40 L of the solution were directly introduced into the feed tank. The pump incorporated in the pilot and then sent these solutions to the membranes according to the chosen circuit (NF or RO). A wash with ultra-pure water was carried out after each test. At each operation, the data communicated by the pilot, i.e., conductivities (feed and permeate), pressures (feed, retentate and permeate), flow rates

(feed, retentate and permeate) and temperatures (feed and permeate), were noted. For each filtered solution, three samples were analysed after 30 min of continuous filtration. These results allowed the retention of the membranes to be studied as a function of the pilot feed pressure, the initial sulphate concentration and the concentration of the sulphate counter ion.

2.5. Evaluation of the Membrane System's Performance

Membrane selectivity and productivity were used to evaluate the performance of the filtration systems: rejection rate and conversion rate. The rejection rate (or retention rate) expressed the degree of selectivity of the process. This was evaluated for sulphate ions and other ions present in the solutions. For each solute i , it was determined by the following equation:

$$R_i = \frac{C_{ai} - C_{pi}}{C_{ai}} \times 100, \quad (1)$$

where C_{pi} and C_{ai} are the concentrations in mg/L of solute i in the permeate and feed, respectively.

The conversion rate (Y) reflected the productivity of the process. It was expressed as a percentage (%) and was determined by the following equation:

$$Y = \frac{Q_p}{Q_a} \times 100, \quad (2)$$

where Q_p and Q_a are the permeate and feed rates, respectively.

2.6. Analytical Methods for Solution Characterisation

Physicochemical analyses were used to characterise the solutions and also to calculate the rates for the evaluation of the performance of the filtration system. Temperature, pH, electrical conductivity and turbidity were monitored. These were measured using a WTW 3310 pH meter, a WTW Cond 3310 conductivity meter and a WTW Turb 430 IR Turbidimeter. The concentrations of ionic species were obtained by ion chromatography using a Dionex chromatograph (Dionex ICS-1000 with an IonPac AS19 column for anions and Dionex ICS-900 with an IonPac CS12A column for cations). Some samples were subjected to suitable dilutions to meet the ranges of the established calibration curves.

2.7. Applied Pressures for Filtration

The pilot used operated at pressures ranging from 1 to 4 bar for nanofiltration and 4 to 8 bar for reverse osmosis. To assess the effect of the pressure on the elimination of sulphate ions, different feed pressures of the pilot were applied. Thus, for each synthetic solution, pressures of 1 and 4 bars in nanofiltration and 4 and 8 bars in reverse osmosis were applied. For the real water, pressures of 1, 2.5 and 4 bar were applied in nanofiltration and 4, 6 and 8 bar were used in reverse osmosis.

2.8. Feed Solutions of the Pilot

For the filtration tests, two types of water were used as feed solutions: synthetic solutions prepared from sulphate ion salts and real borehole water loaded with sulphate ions.

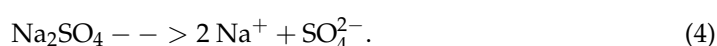
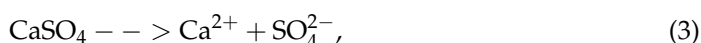
Real water was taken from the borehole, which serves as the source of drinking water for the village of Garpéné. The samples were stored in 20-litre containers and taken to the laboratory for analysis. Characterisation of the water was carried out, before it was used to feed the pilot plant.

The filtration tests conducted on these solutions made it possible to study the effect of the initial concentration and the effect of the counter ion on the retention of sulphate ions.

According to the characteristics of the real water in the drinking water supply system of the village of Garpéné (concentrations around 1400 mg/L for sulphate and 371.2 mg/L for calcium) and the guide value for sulphate in drinking water (250 mg/L for sulphate),

three synthetic solutions with sulphate concentrations of 250, 500 and 1400 mg/L were prepared using calcium sulphate (CaSO_4). The filtration tests on these different concentrations of feed solutions made it possible to evaluate the impact of the initial concentration on the removal of sulphates by the NF270 and TW30 membranes.

In addition, the effect of the type of counter ion (monovalent/bivalent ion) associated with sulphates on sulphate removal was evaluated. For this purpose, two ions of different charges were considered: calcium Ca^{2+} and sodium Na^+ . The same three sulphate concentrations of the synthetic solutions mentioned above (250 mg/L, 500 mg/L and 1400 mg/L) were also prepared from sodium sulphate (Na_2SO_4). For each solution, the necessary mass of calcium sulphate (CaSO_4) or sodium sulphate (Na_2SO_4) to be used was determined from the following dissolution equations:



On the whole, two types of synthetic solutions were prepared (CaSO_4 and Na_2SO_4), with each at three different concentrations and summarised as follows:

- S0: real water from Garpéné borehole;
- S1: solution prepared from CaSO_4 concentrated in sulphate ions to 250 mg/L;
- S2: solution prepared from CaSO_4 concentrated in sulphate ions at 500 mg/L;
- S3: solution prepared from CaSO_4 concentrated in sulphate ions to 1400 mg/L;
- S4: solution prepared from Na_2SO_4 concentrated in sulphate ions to 250 mg/L;
- S5: solution prepared from Na_2SO_4 concentrated in sulphate ions at 500 mg/L;
- S6: solution prepared from Na_2SO_4 concentrated in sulphate ions to 1400 mg/L;
- Pi: the permeate obtained during the filtration of each of these solutions.

3. Results and Discussion

3.1. Characteristics of the Water from the Borehole

Generally, the results obtained revealed that the water from this borehole did not comply with WHO guidelines for drinking water. They showed that the water was highly polluted with sulphate and calcium ions. The average sulphate ion and calcium ion concentrations were 1400 mg/L and 371.2 mg/L in the borehole water, respectively, and exceeded the WHO guidelines limits of 250 and 200 mg/L, respectively [26].

This water was also highly mineralised with an electrical conductivity of 1520 $\mu\text{S}/\text{cm}$, probably due to the high concentrations of ionic species present. Sulphates were, therefore, the major ions contained in the Garpéné borehole water. While it is true that the high concentration of sulphate only has laxative effects on the human organism, it should be recognised that its combination with other ions can introduce discomfort for the consumer (unpleasant taste) and lead to the abandonment of the facility [16]. In addition, the presence of high sulphate content could explain the corrosion of the water storage tank and the high iron concentration obtained. The analyses carried out on the water from neighbouring boreholes showed that they did not have any special characteristics. The sulphate ion content in the water from these boreholes had a maximum value of 15 mg/L. In addition, no immediate anthropic activity that could lead to contamination of the borehole was observed. Geological studies carried out in the area where the borehole was drilled have revealed indications of pyrite [27]. Pyrite is a mineral that can be found in rocks of any nature and geological age, but especially in metamorphic and sedimentary rocks, and is often associated with clay beds. The presence of sulphate ions in borehole water is mainly related to the dissolution of gypsum formations [28,29]. Nonetheless, Porowski et al. [30] reported that favourable conditions can lead to the oxidation of pyrite or aqueous sulphides and result in the formation of sulphate ions (Equations (5) and (6)):





Equation (5) shows that the oxidation reaction of the pyrites releases sulphate ions and ferrous iron, which could justify the high concentration of ferrous ions in the borehole water. It would, therefore, be a transfer of pollutants from the rock to the water. Table 2 summarises the characteristics of the borehole water of Garpéné village.

Table 2. Characteristics of Garpéné's borehole water.

Parameters	Unit	Concentration	WHO Drinking Water Standards [26]
pH		6.9 ± 0.1	6.5–8.5
Turbidité (NTU)	NTU	0.15 ± 0.01	≤ 5
Temperature	°C	27 ± 1	-
Electric conductivity (EC)	$\mu\text{S}/\text{cm}$	1520 ± 4	≤ 1200
Total alkalinity	$\text{mg}/\text{L CaCO}_3$	16 ± 2	-
Total hardness	$\text{mg}/\text{L CaCO}_3$	1220 ± 8	-
Sulfate (SO_4^{2-})	mg/L	1400 ± 28	≤ 250
Calcium (Ca^{2+})	mg/L	371.2 ± 9.3	≤ 100
Sodium (Na^+)	mg/L	138.8 ± 3.7	≤ 200
Potassium (K^+)	mg/L	9.3 ± 0.3	≤ 200
Ammonium (NH_4^+)	mg/L	0.38 ± 0.02	≤ 1.5
Iron (Fe^{2+})	mg/L	0.22 ± 0.03	≤ 0.3
Magnesium (Mg^{2+})	mg/L	70.1 ± 2.8	≤ 50
Nitrite (NO_2^-)	mg/L	0.063 ± 0.001	≤ 3
Nitrate (NO_3^-)	mg/L	9.6 ± 0.3	≤ 50
Orthophosphate (PO_4^{3-})	mg/L	0.11 ± 0.01	-
Chloride (Cl^-)	mg/L	0.028 ± 0.002	250
Sulfide (S^{2-})	mg/L	0.009 ± 0.000	-
Fluoride (F^-)	mg/L	0.40 ± 0.00	≤ 1.5
Bicarbonate (HCO_3^-)	mg/L	19.5 ± 0.9	-

3.2. Performance of Reverse Osmosis and Nanofiltration for the Borehole Water Treatment

Water samples taken from the borehole of the village of Garpéné were used for filtration tests with a nanofiltration membrane and a reverse osmosis membrane. For the nanofiltration membrane, three transmembrane pressures were chosen according to the manufacturer's recommendations (1, 2.5 and 4 bar). The reverse osmosis membrane was also exposed to three increasing transmembrane pressures (4, 6 and 8 bar).

Table 3 shows the characteristics of the borehole water and the permeates obtained after filtration, as well as the removal rates of the different minerals for the maximum pressures chosen for each membrane (4 bar for nanofiltration membrane NF270 and 8 bar for reverse osmosis membrane TW30). The characterisation of the permeates obtained after filtration showed a real decrease in the concentrations of all the ions contained in the water, for the two membranes tested and for the pressures applied (Table 3). Additionally, for all ions in this water, the best rejection rates were obtained with the highest applied pressures. Thus, for the nanofiltration membrane at a 4 bar, retention rates between 32.5% and 98.7% were obtained. The sulphate ion was the best removed ion with a rejection rate of 98.7%, and the fluoride ion was the worst retained with a rejection rate of 32.5%. In general, multivalent ions are better retained by the nanofiltration membrane than monovalent ions. The higher retention of multivalent ions in nanofiltration has already been reported by several authors [31–34]. These results, therefore, confirmed the retention mechanism in nanofiltration based on a combination of electrostatic and steric exclusion effects. The pH values of the solutions used for the filtration tests were between 6.4 and 7.2 (real water and synthetic solutions). Under the experimental conditions implemented, the NF270 and TW30 membranes were negatively charged [32,35]. For the solutions studied, the polarisation of the membrane would, therefore, tend to enhance the removal of sulphate ions.

Table 3. Permeate characteristics and membrane rejection.

Parameters	Unit	Borehole Water	Permeate		Rejection Rate (%)	
			NF	RO	NF	RO
pH		6.9 ± 0.1	7.0	7.0	-	-
Turbidity	NTU	0.15 ± 0.01	0.06	0.01	60.0	93.3
Temperature	°C	27 ± 1	35	35	-	-
Electric conductivity	µS/cm	1520 ± 4	13	10	99.1	99.4
Total alkalinity	mg CaCO ₃ /L	16 ± 2	7	2	56.3	87.5
Total hardness	mg CaCO ₃ /L	1220 ± 8	56	19	95.4	98.4
Sulfate (SO ₄ ²⁻)	mg/L	1400 ± 28	18	14	98.7	99.0
Calcium (Ca ²⁺)	mg/L	371.2 ± 9.3	20	2	94.6	99.5
Sodium (Na ⁺)	mg/L	138.8 ± 3.7	34.2	3.7	75.3	97.3
Potassium (K ⁺)	mg/L	9.3 ± 0.3	2.0	0.0	78.5	100.0
Ammonium (NH ₄ ⁺)	mg/L	0.38 ± 0.02	0.18	0.03	52.6	92.1
Iron (Fe ²⁺)	mg/L	0.22 ± 0.03	0.03	0.02	86.4	90.9
Magnesium (Mg ²⁺)	mg/L	70.1 ± 2.8	1.4	3.4	98.0	95.1
Nitrite (NO ₂ ⁻)	mg/L	0.063 ± 0.001	0.016	0.014	74.6	77.8
Nitrate (NO ₃ ⁻)	mg/L	9.6 ± 0.3	5.0	2.6	47.9	72.9
Orthophosphate (PO ₄ ³⁻)	mg/L	0.11 ± 0.01	0.04	0.01	63.6	90.9
Chloride (Cl ⁻)	mg/L	0.028 ± 0.002	0.0004	0.0003	98.6	98.9
Sulfide (S ²⁻)	mg/L	0.009 ± 0.000	0.003	0.001	66.7	88.9
Fluoride (F ⁻)	mg/L	0.40 ± 0.00	0.27	0.01	32.5	97.5
Bicarbonate (HCO ₃ ⁻)	mg/L	19.5 ± 0.9	8.5	2.4	56.4	87.7

The TW30 reverse osmosis membrane had relatively higher rejection rates than nanofiltration. It, thus, generally presented a higher rejection rate than the NF270 membrane for both divalent and monovalent ions. Indeed, for an applied pressure of 8 bars, the rejection rates of the ions were between 72.9% and 100.0%. In addition, no linear correlation with the ion charge seemed to be evidenced contrary to nanofiltration. Thus, for the reverse osmosis membrane, the passage through the membrane was linked to the solubilisation and diffusion of the compound and therefore depended on the filtration conditions, the characteristics of the membrane and the solution to be filtered. This confirmed the difference in retention mechanism between the porous nanofiltration membrane and the dense reverse osmosis membrane. However, the rejection rates obtained with the NF270 membrane are still high enough to ensure that all permeates obtained after nanofiltration complies with current drinking water standards [26].

3.3. Effect of the Pressure on the Rejection of Main Ions

The selectivity of NF270 and TW30 membranes as a function of the pressure was studied. For this purpose, synthetic solutions prepared from calcium sulphate were filtered under different operating pressures (1, 2.5 and 4 bar in nanofiltration; 4, 6 and 8 bar in reverse osmosis). The same filtration experiments involved solutions prepared from sodium sulphate (Na₂SO₄) at the same sulphate ion concentrations. In addition to sulphate, the three other ions with high concentrations in the borehole water (Na⁺, Ca²⁺ and Mg²⁺) were considered. Figure 3 shows the discharge rates of four selected major ions at different pilot operating pressures.

The treatments applied allowed for a good removal of sulphate ions for both membranes. The rejection rates obtained ranged between 97.0% and 98.7% for the nanofiltration membrane. The results obtained showed that the rejection rates of the ions increased with the pressure. Similarly, the conversion rate increased proportionally with the pressure. Thus, an increase in the conversion rate led to a dilution of the permeate and therefore a decrease in the concentration of the ion in the permeate and might result in an increase in the rejection rate. The optimum point in nanofiltration corresponded to an applied pressure of 4 bar, a conversion rate of 35.7% and rejection rates of 98.7%, 94.6%, 98.0% and 75.3% for sodium, sulphate, calcium and magnesium ions, respectively [36–39]. The results

showed that the sulphate rejection rate seems to converge towards a maximum value for all concentrations of the filtered calcium sulphate solutions [40].

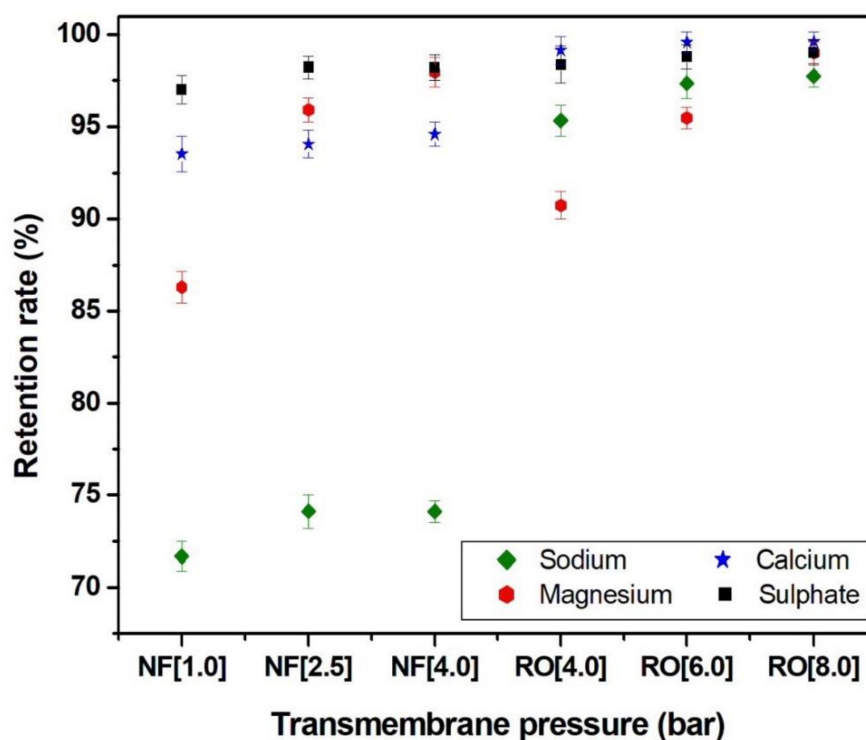


Figure 3. Ion rejection rates for the NF270 and TW30 membranes used.

In reverse osmosis, the pressures applied allowed significant removal of sulphate ions. The results for reverse osmosis were optimum for the applied pressure of 8 bar. This optimum corresponded to a conversion rate of 55.8% and rejection rates of 99.0% for sulphate ions, 99.5% for calcium ions, 95.1% for magnesium ions and 97.3 for sodium ions. For all the filtration tests carried out, the observed sulphate rejection rates varied between 98.4% and 99.0%. In addition, it was found that for all the solutions studied, increasing the feed pressure from 4 to 8 bar resulted in an improvement in the sulphate rejection rates. The greatest variation was observed with solution S3 where the rejection rate increased from 96.6% to 99.3% for a variation of 4 to 8 bars in terms of the pressure [40,41].

In summary, the results showed that all applied pressures resulted in permeates that met drinking water standards (concentration in the permeate less than 250 mg/L). Secondly, it was shown that the feed pressure had a significant impact on the retention of sulphate ions for the different membranes. In both cases, the improvement in retention could be explained by the concentration polarisation phenomenon, which became important at high pressures. This phenomenon, in turn, decreased the permeability of the membrane and therefore increased the retention of sulphates with relatively high molecular weight. In addition to the concentration polarisation phenomena, the increase in the retention rate with the increasing pressure could be explained by the permeate dilution effect.

The results of the filtration test at a pressure of 4 bar showed conversion rates of 29.7% and 35.7% for reverse osmosis and nanofiltration, respectively. At the same pressure, the sulphate rejection rates were 98.2% in reverse osmosis and 98.4% in nanofiltration. It can, therefore, be deduced that at an equal pressure, the NF270 nanofiltration membrane offered a better performance for sulphate removal than the TW30 reverse osmosis membrane for meeting the drinking water standards. However, in terms of the overall rejection of sulphate, calcium, magnesium and sodium, both the NF270 and TW30 membranes were effective in treating the borehole water. As the difference in rejection rates between reverse osmosis and nanofiltration was not huge, several other parameters have to be considered in

order to make a reasonable choice between these two processes such as conversion, capital cost, operating cost, energy requirements and membrane lifespan.

3.4. Effect of Sulphate Ion Concentration in the Feeding Solution on the Rejection Rate

Six solutions of varying sulphate ion concentrations prepared from two different salts were used for filtration tests with the selected membranes (NF270 and TW30). The evolutions of the sulphate ion rejection rates obtained for each membrane are presented in Figures 4 and 5. Both membranes showed a different trend toward the increasing sulphate ion concentration in the feed solutions. For the nanofiltration membrane, an evolution of sulphate ion retention was observed to first decrease and then increase, when the feed concentration increased for both sulphate salts used. The retention rate of sulphate ions decreased from 98.5% to 98.3% and then increased to 99.5% for the calcium sulphate-based solutions. With sodium sulphate solutions, the sulphate ion rejection rate followed the same trend which decreased from 99.3% to 96.5% and subsequently increased to 99.3% [42,43]. The trend for the evolution of sulphate ion rejection rate could be explained by a greater accumulation of sulphate counter ions (calcium or sodium) on the membrane surface for the 500 mg/L solutions. This accumulation partially inhibited the active layer of the membrane and thus reduced the repulsion of sulphate by the active layer due to electrostatic interactions. Abouzaid et al. [43] have previously reported that the increase in the rejection rate observed between 500 and 1400 mg/L could be explained by the very significant accumulation of all the electrolytes (SO_4^{2-} and $\text{Ca}^{2+}/\text{Na}^+$) on the surface (which increases the concentration polarisation phenomena), which reduces the permeability of the membrane and therefore increases the retention of sulphates.

In reverse osmosis for both solutions, the sulphate rejection rates appeared to decrease, as the feed solution concentrations became higher. There were steady decreases in the rejection rate from 99.7% to 99.0% for the calcium sulphate-based solutions and from 99.3% to 98.9% for sodium sulphate solutions. It was, thus, noted that the increase in the concentration of sulphate in the solution resulted in an increase in the density of the ions on the surface of the membrane and therefore a greater competition for solubilisation and diffusion [41]. The results obtained, and particularly the different trends observed, reinforced the difference in ion retention mechanisms by nanofiltration and reverse osmosis membranes.

3.5. Effect of the Counter Ion on Sulphate Ion Retention

The retention of sulphate was studied considering the type of the counter ion in the solution (notably the valence). Solutions prepared from calcium and sodium sulphate were filtered at constant pressures of 4 bar in nanofiltration and 8 bar in reverse osmosis. Figures 6 and 7 show the comparative rejection rates for each solution and the selected membranes. The results varied in the rejection of sulphate ions, depending on the counter ion. Sulphate ions seem to be better eliminated in the presence of sodium ions for the nanofiltration membrane [32,39,43]. For the reverse osmosis membrane, apart from the concentration of 250 mg/L where the retention of sulphate ions was greater in the presence of calcium ions, there was no significant difference between the other two concentrations [13,17]. The results obtained can be explained by the behaviours of sodium and calcium ions towards the membrane and by the charge balance in the permeate. It was indeed shown that the nanofiltration membrane retained fewer sodium ions. As these were found in large quantities in the permeate, the interactions would lead to a greater rejection of sulphate ions for a charge balance in the permeate. In relation to reverse osmosis, the membrane seemed to behave like a molecular sieve. The separation mechanisms of the membranes, therefore, influenced the behaviours of the ions in the solution to be filtered and condition the compositions of the treatment products.

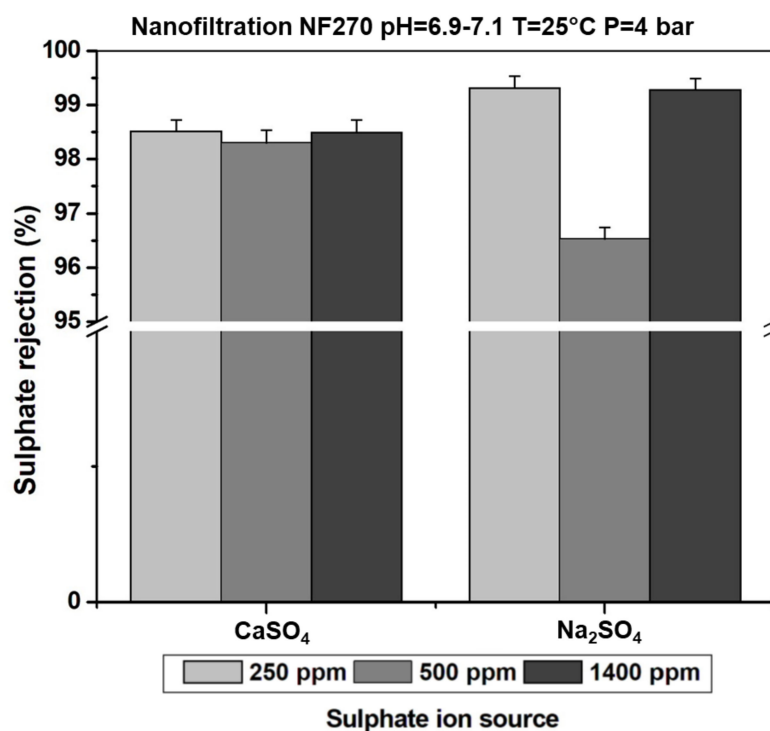


Figure 4. Effect of the sulphate ion concentration in feeding solutions on the rejection rate with the nanofiltration NF270 membrane.

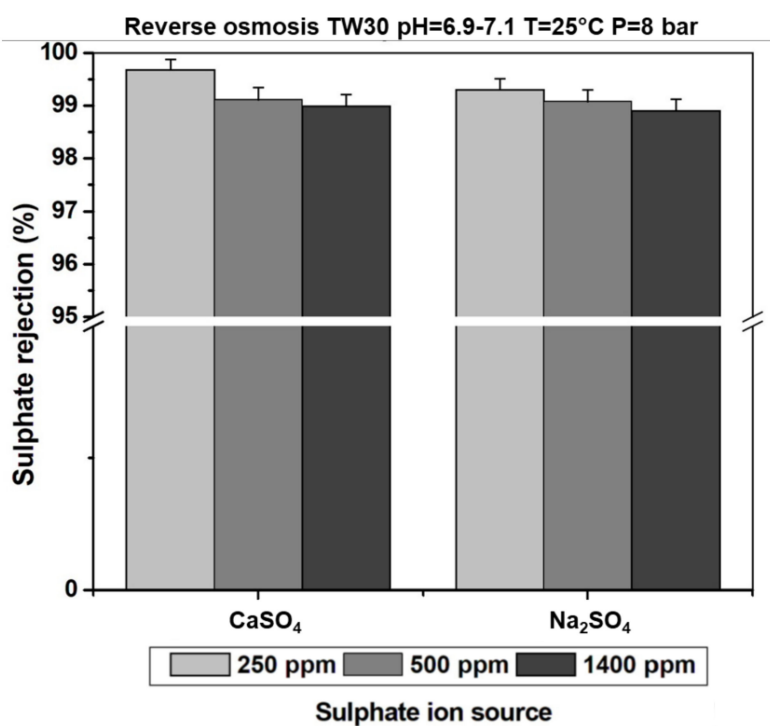


Figure 5. Effect of the sulphate ion concentration in feeding solutions on the rejection rate with the reverse osmosis TW30 membrane.

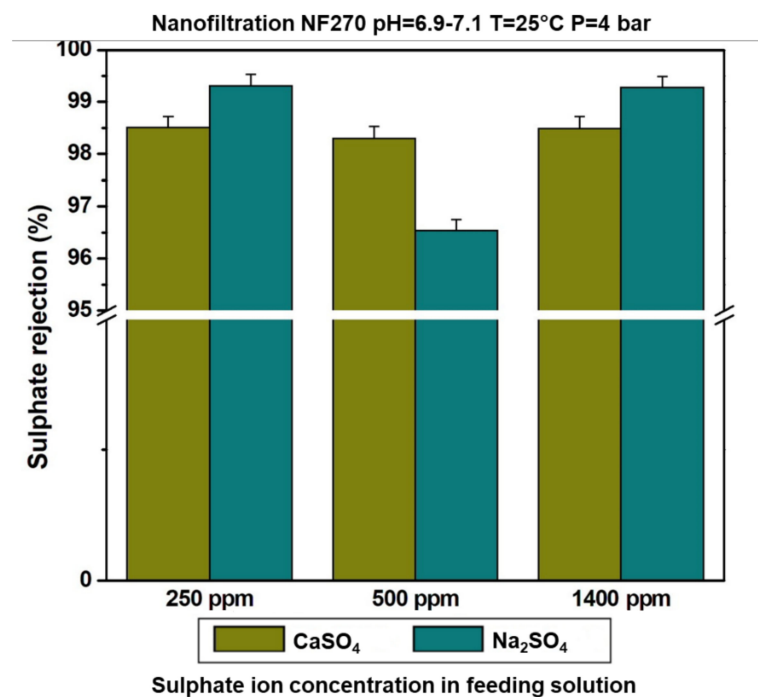


Figure 6. Counter ion effect on sulphate ion rejection with the nanofiltration NF270 membrane.

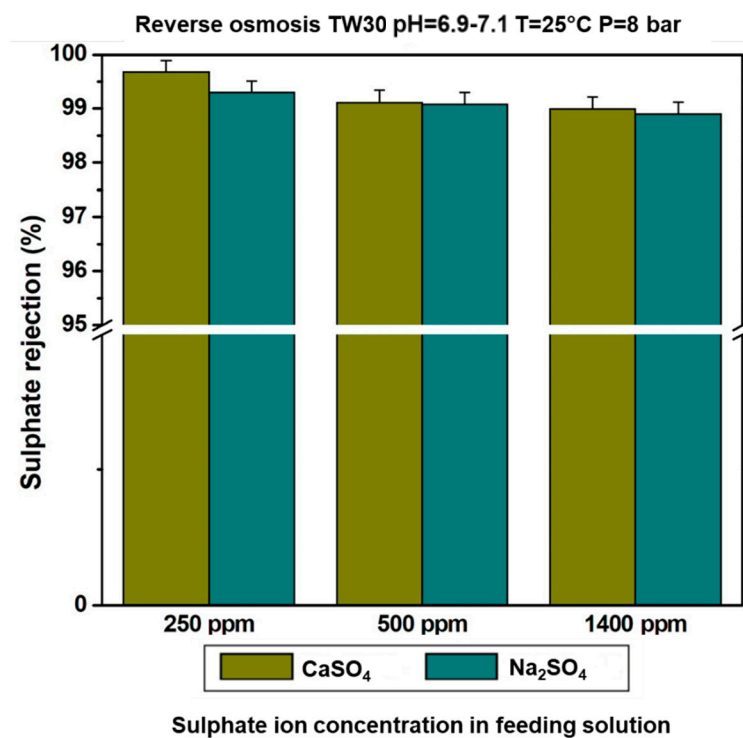


Figure 7. Counter ion effect on sulphate ion rejection with the reverse osmosis TW30 membrane.

4. Conclusions

The study attempted to ascertain the effectiveness of the nanofiltration and reverse osmosis water treatments in the borehole. The NF270 and TW30 membranes enabled remarkable retention of ions to make the water of the Garpéné borehole potable. This study also revealed that during nanofiltration or reverse osmosis operation, the factors of the environment as well as the operating conditions influenced the quality of the permeate obtained after filtration. Specifically, increases in the pilot feed pressure from 1 to 4 bar

for the nanofiltration NF270 membrane and from 4 to 8 bar for the reverse osmosis TW30 led to an increase in the retention of sulphates. For the NF270 nanofiltration membrane, where retention was due to steric hindrance and electrostatic interactions, a decrease in the retention of sulphate ions was observed between 250 and 500 mg/L owing to the modification of the active layer of the membrane by the presence of calcium or sodium counter ions. On the other hand, between 500 and 1400 mg/L, the accumulation of sulphate and calcium and/or sodium ions led to a reduction in permeability and therefore an increase in the retention of sulphate ions. With the TW30 reverse osmosis membrane, an increase in the concentration of sulphate ions in the feed led to a reduction in the retention of sulphate ions, confirming that diffusion is the dominant separation mechanism for this type of process. Nanofiltration and reverse osmosis membranes have different retention mechanisms (steric effect, electrostatic interaction, solubilisation and diffusion) that may influence their performance. For the nanofiltration membrane, sulphate ions were retained slightly more in the presence of sodium ions than in the presence of calcium ions, whereas for the reverse osmosis membrane, the associated counter ion had very little influence on the retention of sulphate ions.

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