Study and Proposal for a Hyperfluorinated Brackish Water Treatment System in the Fatick Region, Case of Diouroup (Senegal)

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Abstract

Groundwater is the main resource for human consumption in many countries, especially in developing countries. This groundwater is often brackish and hyperfluorinated, which leads to diseases such as dental and bone fluorosis, etc. The water from the Diouroup water drainage facilities, like those from many other water drainage facilities in the regions of Fatick, Kaolack, Diourbel and the area of Touba, is facing this problem. To solve these problems, several physicochemical and membrane methods have been implemented. In this work we have briefly outlined some of these methods and we have chosen one of them, low pressure reverse osmosis. In addition, this technique is very simple to operate and maintain. Reverse osmosis provides good quality water in a single step, without the need for additional sterilization or remineralization treatments. We then carried out simulations with the Reverse Osmosis System Analysis (ROSA) software. For reasonable operating parameters, we have noticed a low feed pressure of 11.58 bars, a good average flow of raw water of 27.79 L/m²/h and a recovery rate of the first pass of 75.01%. The results obtained also showed a good quality of the permeate which respects the recommendations of the World Health Organization (WHO) on drinking water. The fluorides of 0.59 mg/L have a recovery rate of 90.8% while the chlorides of 59.09 mg/L have a recovery rate of 92.12% as for the Total Dissolved Solids of 184.90 mg/L for an abatement of 92%. Finally, the low energy consumption of the process makes it possible to consider it in coupling with an electric supply by photovoltaic solar collectors for isolated sites.

Keywords

Brackish Water, Drinking Water, Fluoride, Reverse Osmosis, Diouroup

1. Introduction

Today, more than one billion people in the world lack access to clean water and half of the population in the developing world suffers from diseases due to water contamination [1]. High quantities of fluorides are often found in groundwater from the captive aquifers of phosphate-producing countries. Fluoride poses public health problems, for example in India, where research with CEFIRES [2] [3] is available, but also in Senegal, China, Russia, the United States, etc. In countries, such as the United States, the Commonwealth of Independent States, North Africa and West Africa, including Senegal, the fluorides attributed to fluorine ores (fluoroapatite) are generally due to the presence of phosphates (hydroxyapatite). Fluoride concentrations in these regions can reach values of 5 to 15 mg/L, whereas the potability standards are 1.5 mg/L [4]. Water quality monitoring data collected over the past decade in urban drinking water systems call for a re-evaluation of water and health issues in developed countries [5].

The consumption of hyperfluorinated brackish water is the cause of serious poisoning. Consumed at low levels, fluorides are necessary and beneficial for the body such as protection against tooth decay. However, at high concentrations, above 1.5 mg/L, they are toxic and lead to dental and bone fluorescence. This fluoride poisoning in some regions is serious and is a real public health problem [6].

Studies have been conducted to better understand the origin and transport of fluorides in water [7] [8] [9]. In Senegal, this hyperfluorinated water is generally brackish and their salinity can sometimes exceed 2.5 g/L. The populations of the central zone of Senegal (Fatick, Kaolack, Diourbel) who consume these water are confronted with dental and bone fluorescence. To face the health problems caused by the consumption of these hyperfluorinated brines, a treatment is necessary [10].

The aim of this study is to propose a method of treatment of brackish and fluoridated water in Senegal, more precisely in Diouroup, in the region of Fatick. The chosen method is the reverse osmosis at low pressure.

2. Materials and Methods

The region of Fatick was born from the partition of the former region of Sine Saloum in 1984. It is limited to the East by the Kaolack region, to the West by the Atlantic Ocean, to the North by the Diourbel region, to the North-West by the Thiès region, to the South by the Gambia. Figure 1 shows the administrative map of the Fatick region. Figure 2 shows the Diouroup location.

2.1. Characterization of Fluorides and Chlorides

Fluorine which is one of the most abundant elements in the earth's crust occurs in the form of fluorite (CaF_2), biotite ($(Mg, Fe)_2 Al_2(K, H)(SiO_4)_2$), cryolite ($Na_3(AlF_6)$) and fluoro-apatite ($Ca_{10}F_2(PO_4)_6$) [11] [12] [13].
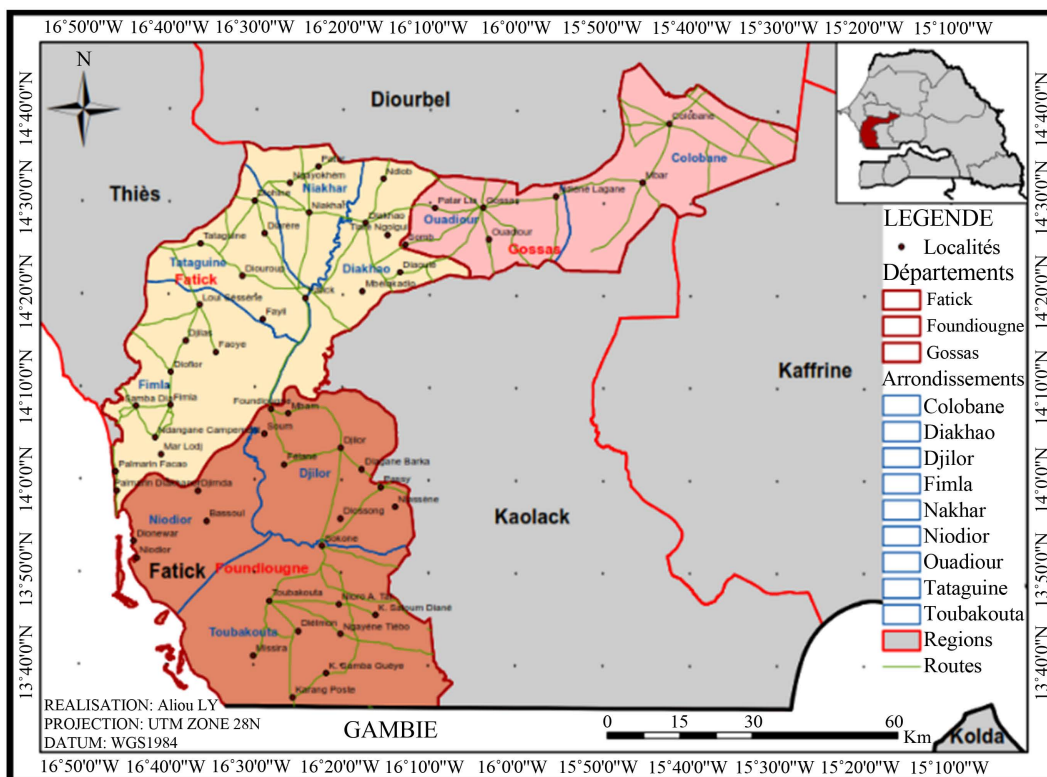
Figure 1. Administrative map of the Fatick region.
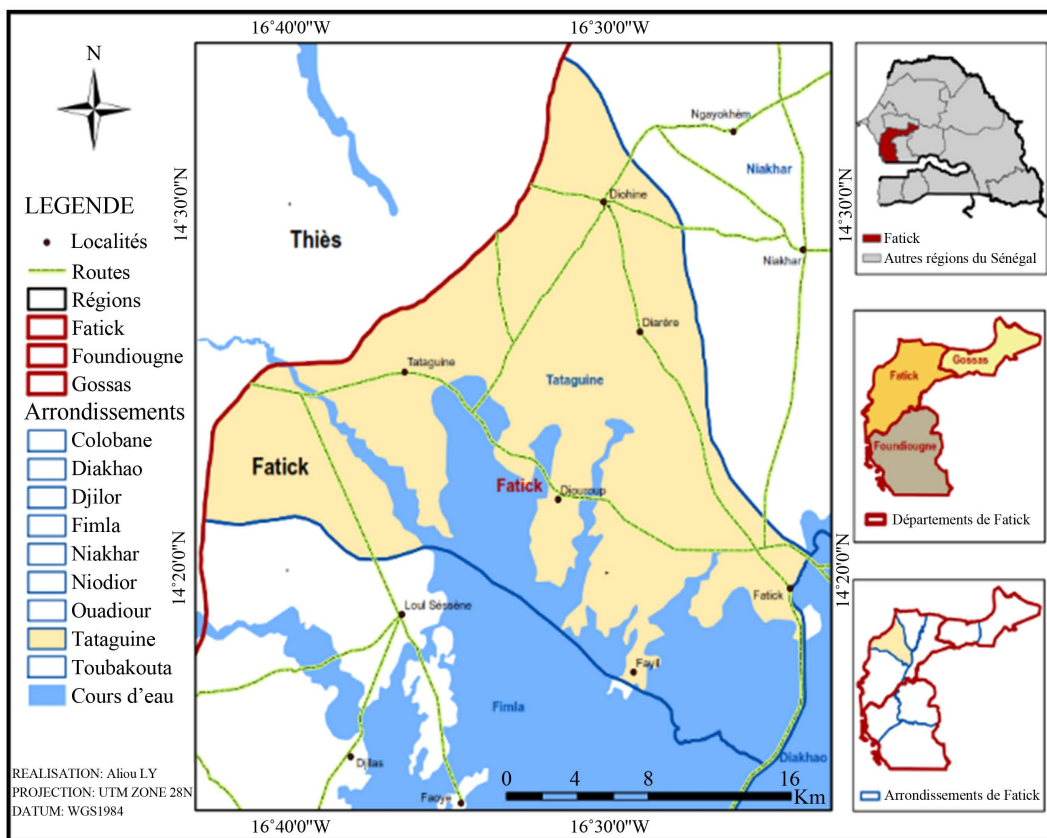

Figure 2. Location map of Diouroup.

Usually, in surface water, we find very low levels of fluoride ions because these minerals are not very soluble in water. On the other hand, the contact of these rocks with the physicochemical characteristics of certain salts and water tables at high temperatures, for example, leads to the dissolution of these fluoride minerals. The F⁻ ion, which is a very powerful oxidizer and the most electronegative halogen of the elements; this ionic form is the most stable state of fluorine. It is an atom of fluorine which has a layer saturated by the gain of an electron [14]. By gaining an extra electron, the chlorine atom becomes the chloride ion, which is a halide. The ion can also be obtained by the dissociation of hydrogen chloride in water. It can be inorganic (mineral, metallic) or organic (e.g. chloromethane, also called methyl chloride) [14]. Research has identified a wide variety of possible sources of fluoride and chloride, both natural and anthropogenic [14]-[19].

2.2. Choice of Treatment Process

There are several processes for the removal of fluorides and chlorides. Among them we can mention the membrane processes of electrodialysis, reverse osmosis and nano filtration and the physicochemical processes that precipitation, adsorption and ion exchange [20]-[26].

Among all the methods, we have chosen reverse osmosis. Reverse osmosis is a system of water purification by permeation through very thin semi-selective membranes that allow only water molecules to pass through. Two solutions of different concentrations are placed on either side of a membrane. The water leaves the less concentrated medium towards the more concentrated medium (this is the phenomenon of osmosis). On the side of the more concentrated compartment, a pressure is applied which is higher than the osmotic pressure of the water. By reversing the phenomenon of osmosis in this way, pure water is transferred from the concentrated medium to the diluted medium [27]. The influencing factors are operating pressure, temperature and permeate flow.

Like any membrane process, reverse osmosis has its advantages and disadvantages [28] [29] [30] [31].

The advantages are the removal of fluoride and chloride ions contained in water, bacteria, viruses of microorganisms and heavy organic compounds that can be carcinogenic. There is no selectivity between salts and very effective, the retention of Chemical Oxygen Demand lasts, as well as salts, metals and nitrates [32]. Based on the advantages, disadvantages and the nature of the pollutants to be removed, *i.e.* fluorides and chlorides, we have chosen the low pressure reverse osmosis process because of its performance, its hydraulic and qualitative security. Chlorides and fluorides have a comparable ionic radius of 100 and 50 pm respectively. The membranes that remove fluorides also remove chlorides. After proposing the reverse osmosis process, it is important to choose the types of membranes involved in order to optimize water productivity and energy costs [33].

In addition to these advantages, reverse osmosis makes it possible to meet the

requirements of the treatment of the main quality problems of raw water, obtaining a process that allows the distribution of water in accordance with the recommendations of the WHO and the distribution of a pleasant drink. Reverse osmosis membranes are also capable of removing chlorides and fluorides contained in water up to a respective percentage of 89.7% for chlorides and 94.4% for fluorides [34].

Reverse osmosis was one of the membrane technologies chosen for the treatment of groundwater containing fluoride concentrations up to more than 30 mg/L [35].

According to the studies of Walha *et al.* [36], the treatment of fluoride with reverse osmosis on water taken from the south of Tunisia containing a salinity of 3 to 6 g/L has allowed to obtain a retention rate of 95% with an elimination of inorganic elements which are present in the raw water. Other studies have also shown the effectiveness of reverse osmosis on the removal of fluoride and chloride with an elimination rate of about 60% for water containing a fluoride concentration of 1.7 mg/L [37] [38].

2.3. Sampling

Sampling was carried out at the test point at the water tower. The analysis of the physicochemical parameters temperature, pH, conductivity and total dissolved solids was carried out in situ with a portable multi-parameter Multi 340i field device. Afterwards we took the information in relation to the hourly and daily flow rates of the water drainage facility. The sample is stored in vials containing conservation reagents, kept cool in a cooler and sent to the laboratory for further physico-chemical analysis.

We used a Dionex DX-120 ion chromatograph to determine the chemical parameters of major ions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, F^-, SO_4^{2-}, NO_3^-).

The study was carried out on a sample of water from the Diouroup commune water drainage facilities.

2.4. Treatment Simulation

This simulation is carried out with the physico-chemical characteristics of the water from the Diouroup well on a reverse osmosis membrane filtration system, with: a 5 micron pre-filtration, an integrated membrane washing system, a programmable controller and a cycle indication by Light-Emitting Diodes (LED) lights. The dimensions are: 1.52 m W × 0.9 m D × 1.7 m H the control module and 0.53 m W × 0.33 m D × 1.7 m H per membrane.

Model: MiniMéga-4Number of membranes: 4; Type of membranes: Xtremely Low Energy (XLE)-440 from Filmtec. The software used is Reverse Osmosis System Analysis (ROSA) and Integral Configuration Method (ICM) configuration DB 35240041.

The reverse osmosis system analysis for FILMTEC ™ ROSA v6.1 membranes is done on the Diouroup project of 100 m³/d flow rate.

3. Results and Discussion

The water from the Diouroup commune water drainage facilities is underground water with an hourly flow rate of 20 m³/h, during the dry season, the daily flow rate is 40 m³/d and during the winter period, the daily flow rate is 50 m³/d.

3.1. Raw Water and Permeate Analysis

The analysis reveals that this water is brackish and hyperfluorinated. The data of physicochemical parameters on water are presented in Table 1.

A comparison of the results of the raw water and permeate analyses obtained during piloting allows us to observe that the desired water quality objectives were achieved. These objectives involved the following parameters: chlorides, fluorides, conductivity, total hardness, manganese and total dissolved solids. It is observed that each of the critical raw water parameters achieved values below the WHO standards for drinking water quality [39].

3.2. Treatment Simulation

In this simulation, we introduced into the simulator the raw water characteristics obtained from the sample analysis. The operating parameters used during this operation are presented in Table 2.

The operating parameters for each of the components of the low pressure reverse osmosis module during the simulation are presented in Table 3 below.

We present in Table 4 the scaling of the calculations of the different indices obtained with the simulation.

3.3. Equation

However, to balance, 3.50 mg/L Na is added to feed.

In this same Table 5, we also have the ion concentrations of the raw water. , permeate and percentages and comparison of results to standards and limits.

Table 1. Physicochemical characteristics of raw water.

Physico-chemical parameters		Contents	
pH		8.16	
Temperature ˚C		33.1	
Conductivity (μS/cm)		3500	
Total dissolved solids: TDS (mg/L)		2302.46	
Cations	Concentrations (mg/L)	Anions	Concentrations (mg/L)
Ca^{2+}	8.16	Cl^-	750.33
Mg^{2+}	3.75	SO_4^{2-}	123.80
Na^+	759.19	HCO_3^-	610.00
K^+	24.79	NO_3^-	5.16
		F^-	6.41

Table 2. Membrane treatment simulation parameters.

Parameters	Values	Parameters	Values
Feed flow in step 1	16.96 m³/h	Flow rate Permeate pass 1 (1st pass)	4.54 m³/h
Raw water flow in the network	6.06 m³/h	Recovery rate passes 1	75.01%
Supply pressure	11.58 bar	Supply temperature	25.0˚C
Fouling factor	0.85	TDS Power supply	2305.97 mg/L
Chemical doses (100% H_2SO_4)	0.00 mg/L	Number of elements	4
Total active area	163.50 m²	Average flow pass 1 (1st pass)	27.79 L/m²/h
Water Classification: Water drainage facilities Water SDI	<3		
Parameters	**Values**	**Parameters**	**Values**
Step	1	Element	XLE-440
Pass number	1	Element number	4
Feed flow (m³/h)	16.96	Supply pressure (bar)	11.24
Recirculation flow (m³/h)	10.90	Flow rate Concentrate (m³/h)	12.42
Concentrate pressure (bar)	9.10	Permeate flow (m³/h)	4.54
Average filtration flow (L/m²/h)	27.79	Permeate pressure (bar)	0.00
Boost pressure	0.00	TDS Permeate (mg/L)	184.90

Table 3. Operating parameters for each module element during the simulation.

	Elements	Recovery	Permeate flow rate (m³/h)	TDS Permeate (mg/L)	Feed flow (m³/h)	TDS feeder (mg/L)	Supply pressure (bar)
Step 1	1	0.09	1.45	133.72	16.96	6408.31	11.24
	2	0.08	1.23	167.54	15.51	6991.72	10.61
	3	0.07	1.03	210.72	14.29	7575.60	10.05
	4	0.06	0.85	266.08	13.26	8143.79	9.56

Table 4. Scaling of calculations of some indices obtained during the simulation.

Size	Raw water	Adjusted flow	Concentrate
pH	8.16	8.16	8.12
Langelier Saturation Index	0.22	0.22	1.30
Sniff & Davis Stability Index	0.37	0.37	0.95
Ionic strength (molar)	0.04	0.04	0.14

Continued

TDS (mg/L)	2302.46	2305.97	8680.12
HCO_3^-	610.00	610.00	2229.40
CO_2^-	4.64	4.64	14.33
CO_3^{2-}	10.85	10.85	74.72
(% saturation) $CaSO_4$	0.16	0.16	1.05
(% saturation) CaF_2	44.57	44.57	2448.69
(% saturation) $Mg(OH)_2$	0.00	0.00	0.01

Table 5. Flow of passage of ions, permeate, reduction percentages and standards and limits.

Symbole	Flow Initial (mg/L)	Flow Recycling (mg/L)	Flow Concentrate (mg/L)	Final Concentration (mg/L)	Recovery (%)	Permeate (mg/L)	Norms and Limits
K^+	24.79	66.29	89.26	3.54	85.72	3.54	12
Na^+	759.19	2128.01	2884.79	60.11	92.08	60.11	200
Mg^{2+}	3.75	10.79	14.70	0.11	97.07	0.11	30
Ca^{2+}	8.16	23.49	32.00	0.23	97.18	0.23	200
CO_3^{2-}	10.85	50.61	74.72	0.02	99.81	-	-
HCO_3^-	610.00	1654.55	2229.40	52.82	91.34	52.82	250
NO_3^-	5.16	10.27	13.07	2.64	48.84	2.64	50
Cl^-	750.33	2094.21	2839.00	59.09	92.12	59.09	250
F^-	6.41	17.72	23.99	0.59	90.08	0.59	1.5
SO_4^{2-}	123.80	352.34	479.18	5.74	95.36	52.82	250
CO_2	4.64	10.21	14.33	10.07	53.92	-	-
TDS	2302.46	6408.31	8680.12	184.90	91.97	184.90	1000
pH	8.16	8.17	8.12	6.88	15.69	6.88	6.5 à 8.5
Conductivity (µS/cm)						282	200 et 1100

The fluxes of each ion at the raw water, recycle and concentrate levels during the membrane filtration simulation are summarized in Table 5. The flow of the ions through the raw water supply, the recycling and the concentrate during the simulation are grouped together in Table 5. In this same Table 5, we also have the ion concentrations of the raw water, permeate and percentages and comparison of results to standards and limits.

The results of the physico-chemical characteristics of the water obtained after the simulation are presented in Table 5. Compared to the standards, these results allow us to deduce that this treatment is effective. The results of the chemical analyses in Table 5 of the permeate obtained under the conditions indicated

show that low pressure reverse osmosis is effective. Indeed, it allows to reduce the concentration of inorganic elements that are present in the raw water to meet the WHO standards and this without being obliged to resort to remineralization [40]. Below, we compare the individual concentrations of each ion (mg/L) in the raw and permeate water to the standards and limits.

The solubility warnings are as follows: Langelier saturation index > 0, Sniff & Davis stability index (SDI) > 0 and CaF_2 (% saturation) > 100%.

In the histogram (**Figure 3**), we represent the flux of each ion in the raw water, in the recirculated water and in the concentrate.

In this study, we adopted the experimental conditions so that the feed pressure was 11.58 bar for a raw water flow rate of 6.06 m³/h, corresponding to a permeate flow rate of about 27.79 L/m²/h. We thus have a permeate flow of 4.54 m³/h (108.96 m³/d), a recovery rate of 75.01% and a fluoride reduction rate of 90.08%.

Below, we compare the individual concentrations of each ion (mg/L) in the raw and permeate water to the standards and limits (**Figure 4**).

The concentrations of the various ions (mg/L) in the raw water and permeate, as well as the percentage removal of each ion individually, are shown in the histogram in **Figure 5**.
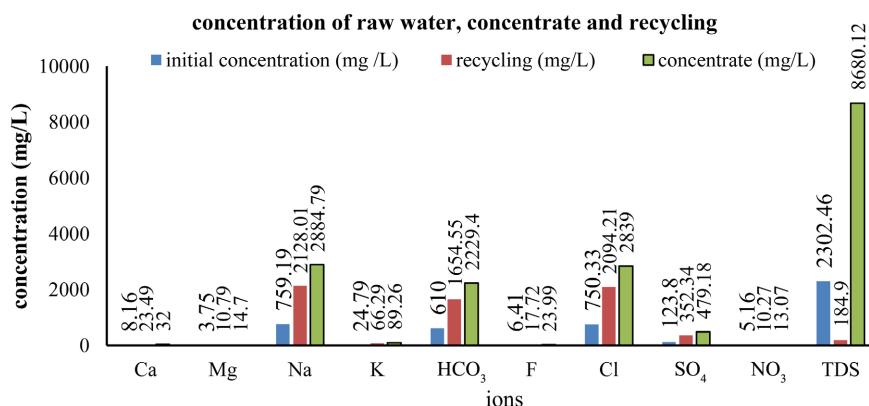

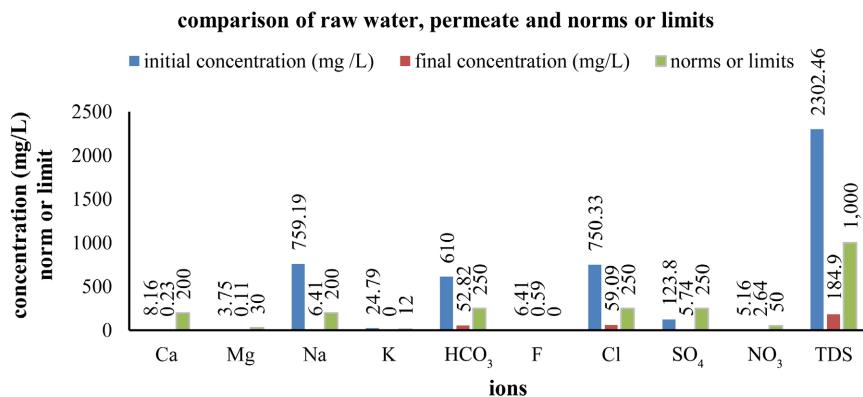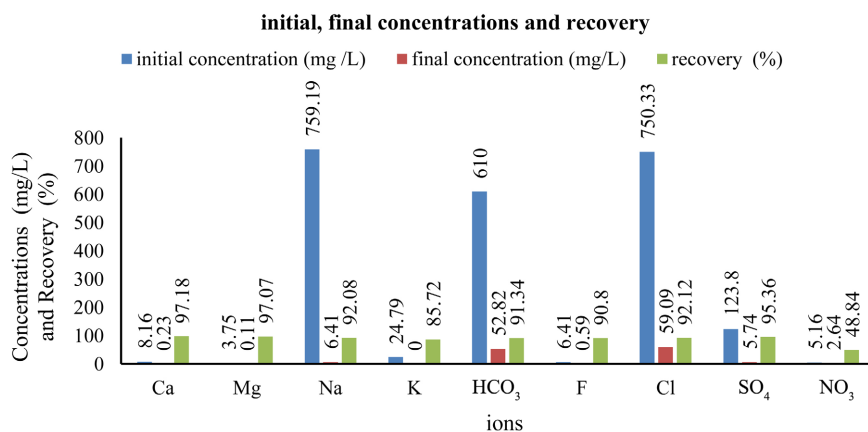**Figure 3.** Graph of concentrations, initials, recycling and concentrate.

Figure 4. Graph comparing raw water, permeate and standards or limits.

Figure 5. Overlay graph.

From the reading of this recovery histogram, we can conclude that this treatment technic is effective.

The results of the SDI (Silt density index) analysis performed on raw water samples revealed that the raw water contained an SDI smaller than 3, which means a very low clogging potential for the membrane. This result allows us to conclude that specific pre-treatments such as a sand filter or a multilayer filter are not necessary. Only an antiscalant dosage and the use of a 5 micron prefilter, upstream of the low pressure Reverse Osmosis (RO) system, are required.

With a recovery rate of 75%, the purified water flows are relatively stable, provided that the dosage of the antiscalant added to the raw water is well controlled. The quality of the treated water obtained by low pressure reverse osmosis largely meets the maximum standards allowed for drinking water. No pre-treatment other than an antiscalant injection and a 5 micron pre-filtration is required. The frequency of membrane washing can be once every 2 months of operation due to the stability of the flow rate at 12.41 bars.

This simulation allowed us to establish the necessary data for the configuration and proposal of a hyperfluorinated brackish water treatment system by reverse osmosis at low pressure configured with 4 membranes to treat the water of the Diouroup area's well.

3.4. Description of the Selected System

We will first describe the different parts that make up the processing system and briefly explain their functions and operation.

The technology is for low pressure reverse osmosis treatment of brackish groundwater for the removal of fluoride, chloride, sodium, hardness, calcium, and dissolved solids. It is a treatment chain involving only a dosage of antiscalants to reduce mineral deposition on the membrane followed by pressure membrane filtration through spiral modules.

In the Mini-Méga treatment system, an antiscalant solution is injected into the raw water. The pre-treated raw water passes through a 5-micron cartridge pre-filter with an integrated automatic washing system and then over tangential re-

verse osmosis membranes. A concentrate recirculation loop is provided to increase the flow velocity to the membranes and thus reduce their clogging. The entire flow of water to be treated will be filtered through the membranes (permeate) and the concentrate will be conveyed to the discharge. Chemical washing is required when the corrected transmembrane pressure has increased by 15%.

The flow diagram is shown in Figure 6.

The system is essentially composed of an anti-scaling pre-treatment, a filter and an automatic washing system incorporated, a low pressure reverse osmosis membrane system and a treatment station for possible pH corrections.

The selected system consists of pre-treatment, treatment and membrane characteristics.

Pre-treatment is primarily used against scaling to protect the membranes from rapid clogging in order to extend the life of the membranes. The antiscalant dosing is done by a dosing pump system with accessories from Prominent or equivalent for antiscalant injection including a 130 litre dilution tank (457 mm D × 813 mm H), operating in duplex mode for a concentration of 2.4 mg/L.

The different elements that make up the actual processing part and their characteristics are listed and described below.
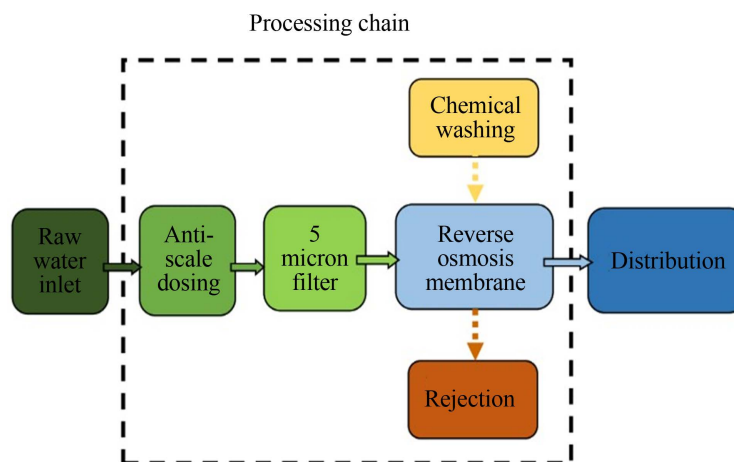
Mini-Mega membrane system:
- A reverse osmosis membrane filtration system,
- 5 micron pre-filtration,
- Integrated membrane washing system,
- Programmable logic controller,
- Cycle indication by LED lights.

Dimensions:
- The control module 1.52 m W × 0.9 m D × 1.7 m H,
- 4 membranes of 0.53 m W × 0.33 m D × 1.7 m H each,
- Model: MiniMéga-4,
- Number of membranes: 4.

Membrane type: XLE-440 from Film tec

Figure 6. Flow diagram.

Instrumentation:
- A conductivity meter from Endress and,
- Hauser or equivalent to check the water quality.

The characteristics of the membrane are as follows:
- Type of membrane used: XLE-440 from Dow-Filmtec,
- Filtration mode: pressure gradient with tangential flow,
- Membrane characteristics: spiral modules,
- Composition: Polyamide composite membranes,
- Diameter of a membrane module: 53 cm,
- Permeate tube diameter: 3.81 cm,
- Length of a module: 170 cm,
- Total filtration area: 37 m^2,
- Average cut-off: 200 Daltons.

We have presented the flow diagram of the selected proposed system, with the different elements that compose it in **Figure 7**.

The literature published by the various RO manufacturers indicates a wide range of fluoride removal from 40% to 90%. Although RO is not generally used on low TDS water and is not specifically used for fluoride removal, the process is an effective method. Membrane processes are a very efficient technique and no chemicals are required. It works in a wide pH range and interference by other ions is negligible [41].

In recent years, the reverse osmosis membrane process has emerged as a preferred alternative for providing potable water without the problems associated with other conventional methods. Progressive technical improvements in membrane design and materials have made the water treatment process economically competitive and highly reliable. In addition, the capital and operating costs of the reverse osmosis plant continue to decrease as the capacity of the plant increases. Thus, with better management, this new technology for drinking water
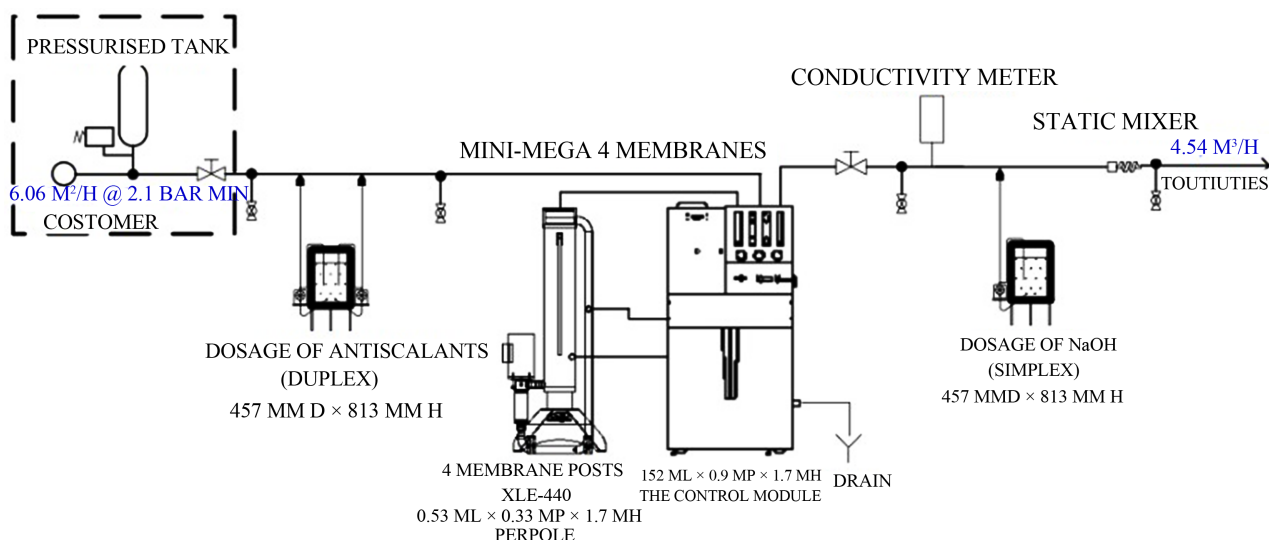
Figure 7. Flow diagram of the proposed system.

production could be the best option. In addition, membrane processes have real advantages over other treatment methods [42].

4. Conclusions

In Senegal, hyperfluorinated brackish groundwater is generally the cause of several diseases. Hydrochemical and geotechnical studies on the sedimentary basin of Senegal have shown that the waters of the Maastrichtian aquifer contain significant amounts of fluoride and chloride. However, these waters constitute an important source of supply for the populations of the groundnut basin. This therefore results in the need to treat this drinking water.

The simulation methodology with ROSA software and Film Tec XLE-440 membranes adopted in this study allowed us to obtain satisfactory results. These results can be summarized mainly into two categories. Regarding reasonable operating parameters, we observed a low supply pressure of 11.58 bars for an average raw water flow rate of 27.79 L/m²/h and the recovery rate of the first pass is by 75.01%. Fluorides with a content of 0.59 mg/L have a recovery rate of 90.8%. As for chlorides with a concentration of 59.09 mg/L, they have a recovery rate of 92.12%. There was a reduction of 92% for total dissolved solids of 184.90 mg/L.

The proposed system provides good quality water that meets WHO standards for drinking water. Unlike conventional chemical treatments which require expensive chemical additions, major civil engineering work and qualified maintenance, low pressure reverse osmosis makes it possible to obtain recognized quality water in a single step, at low energy cost and with a low level of maintenance. This technique also avoids the need for additional decontamination or remineralization treatments. The relatively low energy consumption makes it possible to envisage mobile units, coupled with photovoltaic or wind power supplies, but they would remain limited to daily productions of 10 to 20 m³.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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