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Economic study of groundwater defluoridation of the North African Sahara

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ABSTRACT

The economic evaluation of defluoridation of Sahara groundwater is presented for three processes: electrodialysis, reverse osmosis and the electrochemical bipolar reactor (EBR). The economic study was accomplished for a drinking water unit production of 100 m^3/h. One of the findings was that the costs per cubic metre of treated water obtained with different processes were not too costly for the states of the North African region. The results also indicated that the most efficient process uses the EBR, followed by the electrodialysis and reverse osmosis process. However, the water produced by the first process does not have the required quality for drinking water; therefore, it has to be utilised for agricultural purposes. On the other hand, the electrodialysis unit do produce quality drinking water and appears to be an interesting solution to the fluorisis disease. Reverse osmosis method technique provides higher quality of drinking water with a salinity not exceeding 0.1 g_{salts}/l.

Keywords: Defluoridation; Groundwater; Reverse osmosis; Electrodialysis; Electrocoagulation

1. Introduction

Presence of fluorides in drinking water has become a public health problem [1–5]. High fluoride concentration in the groundwater and surface water from different geographical regions of the world is a cause of great concern [6,7]. The recommended concentration of fluoride in drinking water is between 0.5 and 1.5 mg/L [8,9]. More than 200 million people worldwide are affected by excess concentration of fluoride in their drinking water [10]. The adverse effects have increased the need to defluoridate water. Several methods like adsorption, coagulation, membrane processes and electrochemical techniques have been studied for defluoridation of water. However, the generations of large volumes of sludge, hazardous waste categorisation of metal hydroxides and high costs associated with chemical treatments have made them less acceptable [11].

Fluoride contamination was reported in different parts of Algeria including El Oued Souf, Touggourt, Ouargla and Biskra [12,13]. The amount of fluoride in groundwater in some parts of Algeria is above 3 mg/L [12]. High amounts of fluoride concentration in surface and groundwater have been reported in other regions of the world as well [13,14].

In the North African Sahara, drinking water extracted from groundwater aquifers contains an excess of fluoride which exposes people to fluorosis. An alarming percentage (about 20%) of the people of

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Table 1
Chemical characteristics of the Sahara groundwaters

Ion	Debila city concentration (mg/L)	Meghaiar city concentration (mg/L)	WHO standards (mg/L)
HCO_3^-	80	100	–
SO_4^{2-}	570	730	500
F^-	3	2.6	1.5
Cl^-	1,100	1,140	250
Mg^{2+}	120	135	50.0
Na^+	450	470	200
Ca^{2+}	245	320	200
K^+	4	45	–
Fe^{2+}	<0.1	<0.1	–
Cu^{2+}	<0.1	<0.1	2.0
Zn^{2+}	0.01	0.04	3
Cd^{2+}	<0.05	<0.05	0.003
Cr^{3+}	0.03	0.05	0.05

the Oued Souf region (South Algeria) have suffered this disease [15].

Earlier studies in this area performed by applying three different technologies investigated the defluoridation of the Sahara groundwater resulting in an efficient removal of excess fluoride from the drinking water. The technologies involved were: reverse osmosis and electrodialysis (based on Membranes), and, the electrochemical reactor equipped with bipolar aluminium electrodes both developed on a pilot scale [15].

In order to determine the most attractive process, an economic study had to be undertaken. This study was carried out in two pilot cities: Meghaier (100,000 people) and Debila (5,000 people). The chemical characterisation of these waters is presented in Table 1.

From this data, it is seen that the water in this area owns a high fluoride concentration of 2.6 and 3 mg/L, as well as, many other salts such as sodium, calcium, magnesium, chlorides and sulphates with a total salinity going up to 2.7 g/l.

The purpose of this paper is to select the most efficient process in terms of economic performance and to estimate the water treatment cost price for each technology.

2. Economic evaluation

The membrane techniques applied under the study made it possible to remove fluoride and other salts. However, a preliminary treatment of water was required to avoid $CaSO_4$ precipitation in the reverse osmosis method (RO) or electrodialysis method (ED) process [16,17].

The treatment for complete desalination of 100 m^3 per hour of drinking water required the elimination of 2.5–5 tons/day of salts contained in brine water.

Since the injection of salts in groundwater can hardly be considered, the study aimed for the recovery of solid salts after water elimination by natural evaporation.

In contrast, the electrochemical reactor only removed fluoride resulting in treated water with a high salt content (above O.M.S standard) but no longer with fluoride toxicity [15].

2.1. Electrodialysis method

The complete electrodialysis unit is presented in Fig. 1. The water is initially passed through two sand filters F_1 and F_2 which operate alternatively; one in filtration operation and the second in the cleaning operation. Then, water passes through the cartridge filter F_3 and it is submitted to a fine filtration before transferring it to the feed tank T_1 of the electrodialysis unit. This first step requires the utilisation of the compressor P_1 and the pump P_2. The water stored in the feed tank T_1 is pumped under the required pressure to the ED unit by means of the pump P_3. Polyphosphate and acid chloride solutions contained in tanks T_2 and T_3, respectively, are added to the natural water by using pumps P_4 and P_5 making the electrodialysis experiments, without salt precipitation onto ED membranes, possible. The water treated by the ED unit is stored in tank T_4 which serves the urban water network. The brine solution produced by the ED process is transferred temporarily to tank T_5 and is pumped by P_6 to the exposed area built for water elimination by natural evaporation.

In the cells, the water enters with a total salinity of about 2.7 g/l and a fluoride concentration of about 3 mg/L. The optimum parameters of importance are: tangential velocity of 10 cm/s, current density of about

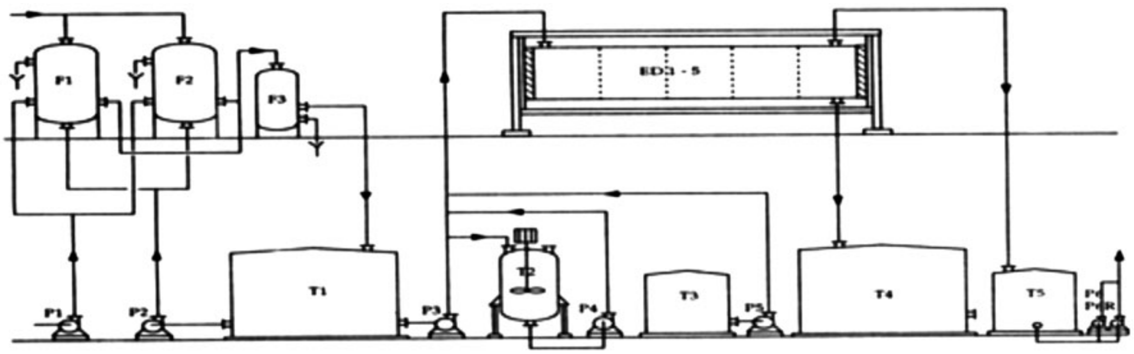

Fig. 1. Schematic representation of the complete electrodialysis unit for the production of 100 m^3/h of defluorinated water.

Note: F1–F2 sand filter, F3 cartridge filter, P1 air compressor, P2 cleaning pump, T1 tank for the storage of pretreated water, P3 feed pump of the ED unit, ED1–5 Electrodialysis unit, T2 polyphosphate solution vessel, T3 hydrochloric acid-vessel, P4 feed pump of polyphosphate solution, P5 feed pump of hydrochloric acid solution, T4 treated water tank, T5 brinesolution tank and P6-P6R pump for the transfer of brine solution.

Table 2
Diagram of the ED balance

	Natural water	Treated water	Brine water
Capacity (m^3/h)	117.6	100	17
Total salinity (S)	$S = 2.7$ g_{salts}/l	$S = 0.5$ g_{salts}/l	$S = 15.2$ g_{salts}/l

15 mA/cm^2 and a volumic concentration factor of 85%, i.e. 15% of the natural water solution will be transformed to brine solution, [17]. After this process, the fluoride concentration of the treated water will be of about 1 mg/L and the total salinity (S) reduced to 0.5 g/l.

The balance to produce 100 m^3/h is presented in the next section and Table 2.

2.1.1. Capital cost

The total number of membrane cells required for this purpose is estimated to be 3,856. It is calculated with ED membranes measuring 50 × 50 cm and with active surfaces of about 1,700 cm^2 each. Considering that each ED apparatus may be equipped with 800 cells, the number of ED apparatuses functioning in series is about five.

The cost of each cell is estimated at USD100 for maintenance and replacement of the ED membranes. The cost of the ED apparatus is established by taking into account the price of the ionic membrane exchangers, separators, neutral cells, electrodes, hydraulic circuits and the hydraulic press for sealing the ED unit (Table 3). The five ED units are estimated to USD 311,695 for the production of 100 m^3/h of drinking water.

An estimation of all the equipment comprising the ED unit is presented in Table 4. The total cost for the equipment is about USD 425,000. It is of importance to consider the cost of auxiliary equipment for regulation, control and measurement as well as for electric power installations and electric command installations (Table 4). The estimation of these items is expressed in a percentage of the cost of the main equipment.

The civil infrastructure for the treatment of the brine water consists in the construction of a contrived area with a surface of 25,000 m^2, calculated with an evaporation capacity in the range of 8–10 × 10^{-3} $m^3/h\,m^2$. The civil engineering works are evaluated to USD 117,500. The site for the ED unit and the control room etc. should have an area of about 700 m^2 and its cost is estimated at USD69,050. The total cost for civil engineering works and infrastructure is about USD186,550.

The subtotal cost for the construction of the ED unit for the defluoridation of Sahara water which is shown in Table 4 is obtained by the addition of the cost of the main items previously presented plus the cost of the transport and installation of all equipment and their spare parts. An estimation of these last items is also expressed as a percentage of the cost of the main equipment.

Table 3
Cost of the ED modules and membrane elements

Item	Unit cost (USD)	Number	Total cost (USD)
Membranes	32.5	4,000	130,000
Neutral cells	100	40	4,000
Separators	17.5	4,000	70,000
Electrodes	70.5	40	2,820
Hydraulic circuits	3,525	20	70,500
Hydraulic press	6,875	5	34,375
Total			311,695

Table 4
Estimation of the ED unit for the production of 100 m^3/h of defluorinated water

Category	Item reference and Description	Cost (USD)
Equipment	F1 & F2: Sand filter	34,900
	F3: Cartridge filter	3,000
	P1: Air compressor	5,875
	P2: Cleaning pump	3,625
	T1 Tank for the storage of pretreated water	9,100
	P3: Feed pump of the ED unit	5,500
	ED1–5: Electrodialysis apparatus	311,695
	T2: Polyphosphate solution vessel	4,625
	P4: Feed pump of polyphosphate solution	2,200
	T3: Hydrochloric acid vessel	1,800
	P5: Feed pump of hydrochloric acid solution	1,600
	T4: Treated water tank	17,600
	T5: Tank for brine water	10,700
	P6 & P6R: brine water Pump	9,600
Subtotal		425,000
Auxiliary equipment	Pipes and accessories	34,000
	Regulation apparatus	25,500
	Measurement and control apparatus	12,750
	Electric and power installation	85,000
	Electric command installation	21,250
Subtotal		180 000
Construction cost	Main materials	425 000
	Equipment installation (10%)	42,500
	Transport of the main material (3%)	12,750
	Auxiliary equipment	180,000
	Civil infrastructure and engineering	117,500
	Spare parts (5%)	21,250
	Construction site insurance (1%)	4,250
Subtotal		803,250
Engineering studies and all others costs (10%)		80 325
Total		883 575

The total cost is obtained by multiplying the subtotal obtained beforehand by 1.1 which represents 10% of the engineering studies and all other costs not planned. The total cost of the construction of the ED unit for the production of 100 m^3/h was found to be about USD885,000.

2.2. *Reverse osmosis method*

The reverse osmosis process also requires softening pretreatments. The first pretreatment consists of calcium carbonate precipitation, which prevents fouling of the RO membranes. The second concerns stabilisation of the pH solution to a value of about 6 by adding chloride acid (5). The complete RO unit is presented in Fig. 2.

The natural groundwater was, first, pretreated in the tank C_1 by adding sodium carbonate, contained in the hopper N_1, at the required flow rate. The sodium carbonate dissolves in tank C_1 and, by simple gravity, passes through the circular digester C_2 equipped with multiple scanning articulated arms. The calcium carbonate precipitates in this last apparatus. The water–calcium carbonate mixture is extracted from the digester by means of the pump P1 and transferred to the sand filters F_1 and F_2 which work alternatively, one in filtration operation and the second in a cleaning operation. Then, the water passes through the cartridge filter F_3 and is submitted to fine filtration before transfer to the feed tank T_1 of the RO unit. This first step requires utilisation of the compressor P_2 and the pump P_3.

The water stored in the feed tank T_1 is pumped under required pressure to the RO unit using the pump P_4. The hydrochloric acid solution and the anti-scale product contained in tanks C_3 and C_4, respectively, which were added continuously to the pretreated water, make it possible to conduct the RO experiments without damaging the RO membranes. The water treated by the RO unit was stored in tank T_2, which serves the urban water network. The brine solution produced by the RO process is transferred temporarily to the tank T_3 and is pumped with P_5 to the exposed area built for water elimination by natural evaporation.

2.2.1. Capital cost

Reverse osmosis is characterised by two main parameters: the permeate flux and the brine water flux. These parameters are linked to the water analysis, the transmembrane pressure, the yield and the salt concentration in the concentrate solution. The optimum experimental conditions in the RO can be given as follows:

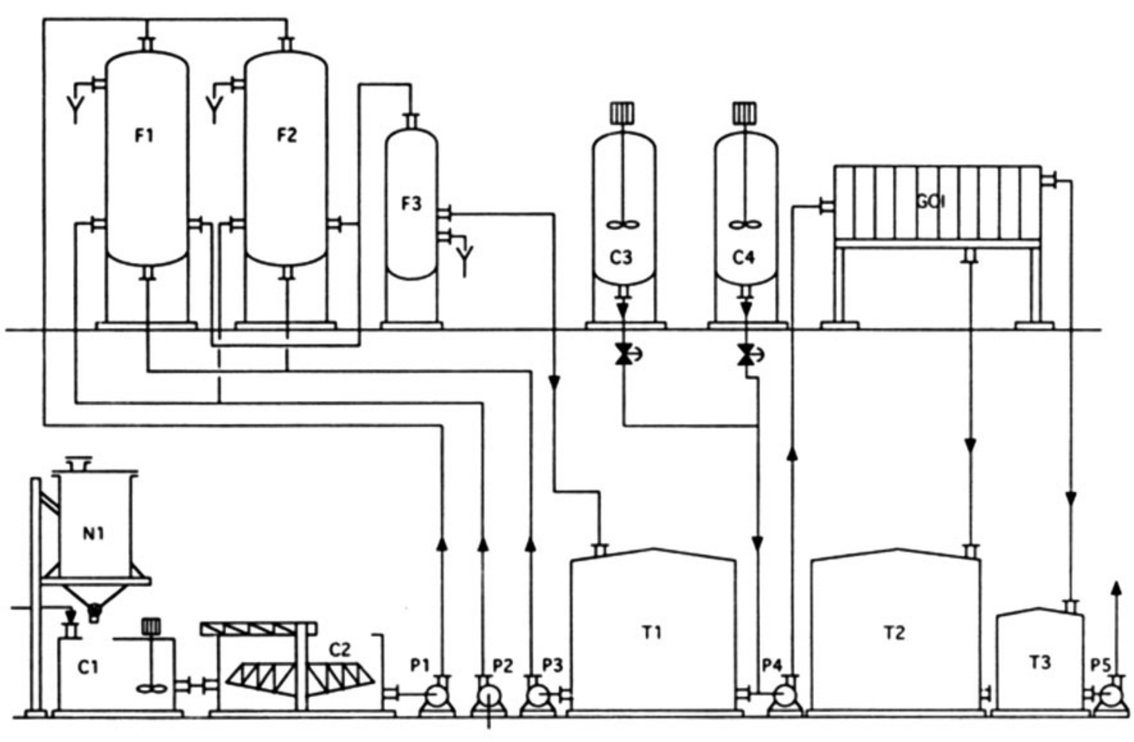

Fig. 2. Schematic representation of the complete reverse osmosis unit for the production of $100\,m^3/h$ of defluorinated water.
Note: N1 Hopper for the storage of sodium carbonate, C1 mixing and dissolution tank, C2 digester, F1–F2 sand filter, F3 cartridge filter, P1 pump for the transfer of pretreated water, P2 air compressor, P3 pump for cleaning operation, C3 hydrochloric acid solution vessel, C4 anti-scale solution vessel, T1 tank of pretreated water, T2 tank for the storage of treated water, T3 tank of the salt concentrate solution, P4 reverse osmosis feed pump, P5 pump for the transfer of salt concentrate solution and GOI reverse osmosis unit.

Table 5
Diagram of the RO balance

	Natural water	Treated water	Brine water
Capacity (m^3/h)	125 m^3/h	100 m^3/h	25 m^3/h
Total salinity (S)	2.7 g_{salts}/l	0.1 g_{salts}/l	12.2 g_{salts}/l

- Transmembrane pressure: 1.5 MPa
- Yield: 80%
- Brine solution: maximum solubility of about 85% of the less soluble salts.

The fluoride concentration of the treated water should be about 1 mg/L and the total salinity (S) is reduced to 0.1 g/l. To produce a 100 m^3/h, the balance presented in Table 5 has to be verified.

These optimum parameters were utilized to predict the dimensions and the design of the RO unit by software kindly offered and provided to the researchers by the Belgium company STEP. The results obtained are reported in Table 6. The cost of the RO is about USD57,092. It is important to add to this cost the cost of the membrane cleaning operation which requires a 2.5 m^3 mixed vessel and a pump for the injection of the cleaner solution into the RO unit and into all the pipes composing the unit. The cost of the equipment required for this last operation is at USD8,500.

Estimation for all the equipment composing the RO unit is presented in Table 7, which gives a total cost of about USD270,000. It is also important to consider the cost of auxiliary equipment such as regulation, control and measurement, as well as for electric power installation and electric command installation (Table 7). Estimates for these items are expressed in percentages of the cost of the main equipment. The civil infrastructure required for the treatment of the brine water consists in the construction of a contrived area with a surface of 30,000 m^2, calculated with an evaporation capacity in the range 8–10 × 10^{-3} $m^3/h\,m^2$. The civil engineering works are evaluated at USD141,000. The site for installation of the RO unit and the control room etc. has a surface of about 800 m^2 and their cost is estimated at USD218,000. The total cost for civil engineering works and infrastructure comes to about USD186,550.

The subtotal cost for the construction of RO unit for the defluoridation of Sahara water which is presented in Table 6 is obtained by the addition of the cost of the main items previously presented to the cost of transport and installation of the main equipment and spare parts. The estimation of these last items is also expressed as a percentage of the cost of the main equipment.

The total cost is obtained by multiplying the subtotal previously obtained by 1.1. The added 10% represents engineering studies and other non-programmed costs. The total cost of construction of the RO unit for the production of 100 m^3/h is about USD840,000.

2.3. The electrochemical bipolar reactor method

A new process was developed in 1998 based on electrocoagulation with bipolar aluminium electrodes [18]. In this process, the consummation of aluminium anode is controlled by the required aluminium–fluoride weight ratio of about 17/1 without the addition of soluble salts to the treated water [19,20]. The optimum experimental conditions were determined as follows: temperature close to 20˚C, inter-electrode distance of 2 cm, pH ranging from 5 to 7.6, current density of about 75 A/m^2 and an area/volume ratio on the order of 25 $m^2\,m^3$. The fluoride concentration was reduced from 3 to 0.8 mg/L.

This information indicates that the Sahara waters, which have temperatures exceeding 35˚C, have to be

Table 6
Cost of the RO modules and membrane elements

Item	Number	Unit price (USD)	Total
RO cell under pressure	12	1,010	12,120
Membranes	84	508	42,672
Tubular support	1	1,600	1,600
Diaphragm and parts	1	700	700
Total			57,092

Table 7
Estimation the RO unit for the production of 100 m^3/h of defluorinated water

Category	Item reference and description	Cost (USD)
Equipment	N1: Hopper for the storage of sodium carbonate	11,800
	C1: Mixing and dissolution tank	13,300
	C2: Digester	39,100
	F1 & F2: Sand filter	46,400
	F3: Cartridge filter	3,000
	P1: Pump for the transfer of pretreated water	5,500
	P2: Air compressor	5,875
	P3: Pump for cleaning operation	3,625
	C3: Hydrochloric acid solution vessel	8,550
	C4: Anti-scale solution vessel	10,925
	T1: Tank of pretreated water	9,100
	GOI: Reverse osmosis unit	57,092
	T2: Tank for the storage of treated water	17,600
	T3: Brine water Tank	10,700
	P4:Reverse osmosis feed pump	7,800
	P5: Pump for the transfer of brine water	9,600
Subtotal		270,000
	Cleaning material	8,500
Auxiliary equipment	Pipes and accessories	86,400
	Regulation apparatus	48,600
	Measurement and control apparatus	18,900
	Electric and power installation	54,000
	Electric command installation	13,500
Subtotal		225,000
Construction cost	Main materials	270 000
	Equipment installation (10%)	27,000
	Transport of the main material (3%)	8,100
	Auxiliary equipment	225,000
	Civil infrastructure and engineering	218,000
	Spare parts (5%)	13,500
	Construction site insurance (1%)	2,700
Subtotal		764,300
Engineering studies and all others costs (10%)		76,430
Total		840,730

cooled before the electrochemical treatment. On the other hand, the pH has to be maintained in the range of optimal conditions by adding hydrochloric acid.

The complete electrochemical unit is presented in Fig. 3. The natural water extracted from groundwater aquifer is directly cooled by an atmospheric cooling column L_1. The water with a temperature in the range 20–25°C is then transferred, by means of the pump P_1, from the column to the tank T_1 which may be utilised as a feed tank for the electrochemical reactor $R_{1–4}$. The water stored in tank T_1 is transferred to $R_{1–4}$ by means of the pump P_3. Before treatment, the hydrochloric acid contained in the vessel C_1 is added to the water. The fluoro-aluminium complex formed during electrochemical treatment is transferred to the centrifuge D_1. The solid fraction extracted from the centrifugation apparatus is then evacuated by screw conveyor V_1 to the exposed area built for the elimination of water by natural evaporation. The treated water obtained from centrifugation apparatus D_1 is then pumped (P_5) and submitted to fine filtration by means of the cartridge filter (F_1) and is stored in tank T_2 which is connected to the urban water network by using the pump P_6.

2.3.1. Capital cost

Use of an electrochemical reactor equipped with aluminium bipolar electrodes is a new process for

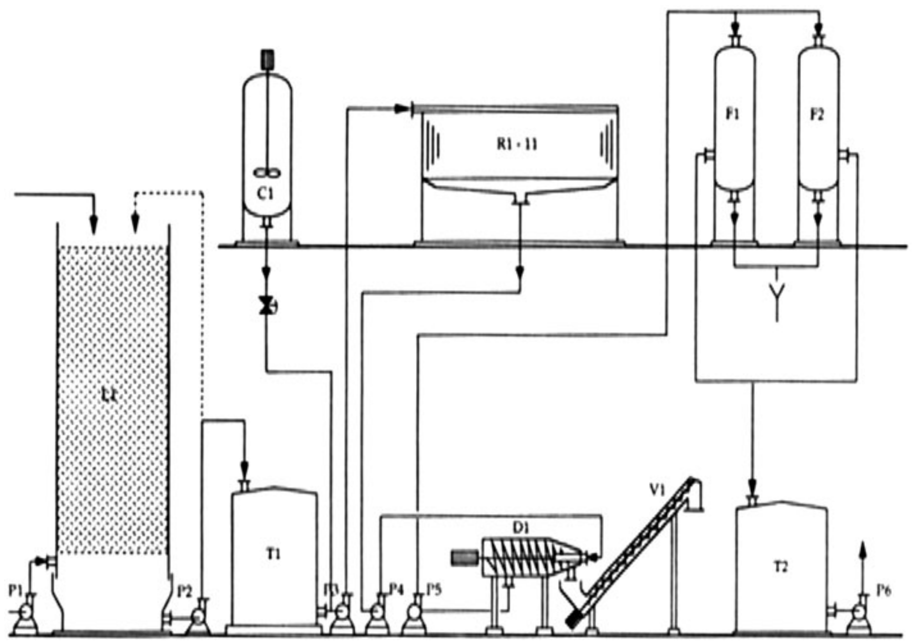

Fig. 3. Schematic representation of the complete EBR unit for the production of 100 m^3/h of defluorinated water.
Note: P1 helicoidal ventilator, L1 atmospheric cooling column, P2 pump for the transfer of the cooled water, T1 tank for the storage of the cooled water, C1 hydrochloric acid solution vessel, P3 feed pump of the EBR, R1–11 EBR, P4 pump for the transfer of the solid fluoro-aluminium complex, D1 centrifuge, V1 screw conveyor, P5 pump for the transfer of defluorinated water, F1–-F2 cartridge filter, T2 tank for the storage of the defluorinated water and P6 pump for the transfer of treated water to the water distribution network.

defluoridation. Economical evaluation of the cost of this process (Table 8) and in particular of the reactor cell is estimated to be accurate within 20%.

Previous work, with a pilot scale electrochemical reactor, has made it possible to determine the following relationship between the treated water flow (Q) and current density (I) [21].

$$Q = 20\ 10^{-3} I \quad (1)$$

To produce $Q = 100$ m^3/h, the current required calculated by the relation (1) is about 5,000 A. The electrochemical cell was designed with aluminium electrodes having square sections 1.4 × 1.4 m and an inter-electrode distance of about 1.5 cm. Each cell is equipped with 100 aluminium electrodes, giving an effective surface of about 200 m^2. Taking into account the optimum area/volume ratio which is on the order of 25 m^2/m^3 and the minimal space time of 0.25 h, the total electrode surface required to produce a water flow of 100 m^3/h is 625 m^2. It is clear that four electrochemical cells are required to obtain this treated water flow.

To estimate the functioning period before replacement of the electrode, it is assumed that the electrode will be replaced when its thickness attained 2 mm. A simple calculation integrating the amount of the fluoride to recover (0.22 kg/h or 5.3 kg/d) and assuming that the required aluminium–fluoride weight ratio is 17/1 makes it possible to determine the required aluminium mass per hour (3.8 kg/h or 91 kg/d) to produce a water flow of 100 m^3/h. Using the density of the aluminium metal (2,800 kg/m^3) and the total aluminium volume consumed until the electrode replacement (2.4 m^3) makes it possible to determine the aluminium mass (6,720 kg) which, divided by the consumed mass per day (91 kg/d), gives the functioning period of the unit estimated at 74 days. The price of the aluminium electrodes composing an electrochemical bipolar reactor (EBR) is estimated at USD6,850 on the basis of the price of machining (1USD/m^2) and the aluminium price (2.375 USD/kg). It is important to note that the aluminium remaining on the electrode may be sold at USD0.625/kg as second quality aluminium, which then reduces the cost of electrode replacement.

To avoid stopping the water production when the electrodes have to be replaced, it is also envisaged to add a fifth electrochemical cell to be used when the first reactor is stopped [22].

Table 8
Estimation of the EBR unit for the production of 100 m^3/h of defluorinated water

Category	Item reference and description	Cost (USD)
Equipment	P1& L1: Helicoidal ventilator and atmospheric cooling column	75,000
	P2: Pump for the transfer of cooled water	5,500
	T1: Tank for the storage of cooled water	9,100
	C1:Hydrochloric acid solution vessel	8,400
	P3: Feed pump of the EBR	5,500
	R1–5: Electrochemical bipolar reactor	72,250
	P4:Pump for the transfer of the solid fluoro-aluminium complex	6,000
	D1: Centrifuge	9,000
	V1: screw conveyor	8,250
	P5: Pump for the transfer of defluorinated water	5,500
	F1&F2: Cartridge filter	6,000
	T2: Tank for the storage of defluorinated water	17,600
	P6: Pump for the transfer of treated water	5,500
	Scoop engine	11,250
Subtotal		245,000
Auxiliary equipment	Pipes and accessories	12,000
	Regulation apparatus	14,400
	Measurement and control apparatus	7,200
	Electric and power installation	48,000
	Electric command installation	12,000
Subtotal		95,000
Construction cost	Main materials	245 000
	Equipment installation (10%)	24,500
	Transport of the main material (3%)	7,350
	Auxiliary equipment	95,000
	Civil infrastructure and engineering	85,000
	Spare parts (5%)	12,250
	Construction site insurance (1%)	2,450
Subtotal		471,550
Engineering studies and all others costs (10%)		47,155
Total		518,705

The cell in PVC material is reinforced by exterior steel supports which make it possible for the PVC vessel to carry the weight of the electrodes and the treated water. The estimated cost of an electrochemical reactor cell is USD14,450. The total cost of the five cells required to produce a water flow of about 100 m^3/h is USD72,250.

Estimations for all equipment composing the electrochemical reactor unit are presented in Table 8. The total cost is about USD245,000. It is important to consider the cost induced by auxiliary equipment such as regulation apparatus, control and measure apparatus, electric power installation and electric command installation (Table 8). The estimates for these items are expressed in percentages of the cost of the main equipment. The civil infrastructure for the storage of the fluoro-complex sludge (since there is no brine solution with this process) should consist of a contrived area with a surface of 200 m^2. The site for the electrochemical reactor and the control room etc. should have a surface of about 700 m^2. The total cost for civil engineering works and infrastructure is about USD85,000.

The subtotal cost for the construction of electrochemical reactor unit for the defluoridation of Sahara water, presented in Table 8, is obtained by the addition of the cost of the main items previously presented and the cost of transportation and installation of all the main equipment and spare parts. Estimates of these last items are also expressed in percentages of the cost of the main equipment.

The total cost is obtained by multiplying by 1.1 the subtotal obtained previously. The added 10%

Table 9
The cost price per cubic metre of the Sahara-treated water

Item	ED (USD/m^3)	RO (USD/m^3)	EBR (USD/m^3)
Power costs (0.05USD/kWh)	0.1	0.6	0.1
Membrane replacement (lifetime 4 years for ED and 3 years for RO)	0.125	0.018	/
Electrode replacement (lifetime 5,000 h for ED and 1,776 h for EBR)	0.01	/	0.139
Consumables (acid, polyphosphate solutions [ED], anti-scale and cleaning products [RO], cartridge for filtration [EBR])	0.01	0.025	0.01
Maintenance costs (3% per year of the investment)	0.033	0.032	0.02
Interest on the invested capital (3% per year of the investment)	0.033	0.032	0.02
Amortized capital cost (in 15-year period)	0.074	0.070	0.043
Labour costs (1% per year of the investment)	0.011	0.011	0.007
Total	0.396	0.788	0.339

represents engineering studies and other costs not scheduled. The total cost of the construction of the electrochemical reactor unit for the production of 100 m^3/h is about USD520,000.

2.4. Economical efficiencies and environmental issues of the processes

The performance of each process is evaluated on the basis of 8,000 h/year as a functioning period. The cost price of the m^3 of the treated water is determined by taking into account power costs, electrode replacement costs, consumables, maintenance costs, the interest on invested capital, amortized capital costs and labour costs.

Table 9 gives the cost of each item for the three processes. Consumable costs are estimated for each process at 0.01 USD/m^3. Maintenance costs and the interest on the invested capital are arbitrarily fixed at 3% per year of the invested capital. Fifteen years of amortized capital cost are considered for the three processes. The labour cost in North African may be arbitrarily considered of about 1% per year of the invested capital.

The results indicate that the EBR is the most efficient in economic terms. Indeed, the cost price per 1 m^3 of the treated water is estimated to at USD0.339, indicating that this process is very interesting for the defluoridation operation.

However, the quality of the treated water by EBR process is not in agreement with world health organisation norms. Indeed, the EBR technique has no effect on the total salinity since this process is specific to fluoride ions and then no change is encountered on others species such as chloride ions which are presented in a large amount in North African waters. This process does not have the required quality for drinking water, it may nevertheless be utilised for agricultural purposes. On the other hand, electrodialysis, which produces drinking water, appears to be more efficient than the reverse osmosis process. Indeed the RO cost price per 1 m^3 of the treated water (USD0.788) appears to be greater than that of the ED process. This result may be explained by the increase of the cost price induced by the two softening pretreatments required for this technique to prevent fouling of the RO membranes and the stabilisation of the pH solution acid pH. However, the RO technique provides highest quality drinking water with salinity not exceeding $S = 0.1\ g_{salts}/l$.

The electrodialysis technique appears to be the most attractive solution to the fluorosis disease for the production of drinking water at the cost price per cubic metre of treated water of USD0.396.

It is worth mentioning that the water cubic foot is billed based on governmental instructions and on a selective and progressive system that provides for an overall subsidy of 45–50%, without taking into account the real cost of water. Concerning the water produced by desalination, the tariff (real cost of production) is in the range of DZD (Algerian Dinar) 50–60 (1 USD is approx. 75 DZD) for SWRO and DZD 60–70 for MSF and the used power costs between DZD 2–3 per kWh. The difference is covered by the support of the Government as subsidy [23,24].

4. Conclusion

The cost price per cubic metre of the Sahara-treated water seems to be feasible and it could be considered by the states of the North African region.

The health problem of the Sahara people involving the exposition to fluorosis and many financial constraints induced by this disease, the treatment costs obtained are reasonable.

The EBR is an interesting alternative for the defluoridation of the groundwater for agricultural purposes. The electrodialysis process appears to be more efficient for producing drinking water, while the reverse osmosis process offers the highest quality water.

References

[1] N. Drouiche, H. Lounici, M. Drouiche, N. Mameri, N. Ghaffour, Removal of fluoride from photovoltaic wastewater by electrocoagulation and products characteristics, Desalin. Water Treat. 7 (2009) 236–241.

[2] N. Drouiche, N. Ghaffour, H. Lounici, N. Mameri, A. Maallemi, H. Mahmoudi, Electrochemical treatment of chemical mechanical polishing wastewater: Removal of fluoride—Sludge characteristics—Operating cost, Desalination 223 (2008) 134–142.

[3] N. Drouiche, N. Ghaffour, H. Lounici, M. Mameri, Electrocoagulation of chemical mechanical polishing wastewater, Desalination 214 (2007) 31–37.

[4] S. Aoudj, A. Khelifa, N. Drouiche, M. Hecini, HF wastewater remediation by electrocoagulation process, Desalin. Water Treat. 51 (2013) 1596–1602.

[5] N. Drouiche, S. Aoudj, H. Lounici, M. Drouiche, T. Ouslimane, N. Ghaffour, Fluoride removal from pretreated photovoltaic wastewater by electrocoagulation: An investigation of the effect of operational parameters, Procedia Eng. 33 (2012) 385–391.

[6] N. Drouiche, S. Aoudj, H. Lounici, H. Mahmoudi, N. Ghaffour, M.F.A. Goosen, Development of an empirical model for fluoride removal from photovoltaic wastewater by electrocoagulation process, Desalin. Water Treat. 29 (2011) 96–102.

[7] N. Drouiche, N. Ghaffour, S. Aoudj, M. Hecini, T. Ouslimane, Fluoride removal from photovoltaic wastewater by aluminium electrocoagulation and characteristics of products, Chem. Eng. Trans. 17 (2009) 1651–1656.

[8] WHO, Chemical Fact Sheets: Fluoride, Guidelines for Drinking Water Quality (Electronic Resource), vol. 1, 3rd ed., Incorporation First Addendum, Recommendations, Geneva, 2006, pp. 375–377.

[9] B. Palahouane, N. Drouiche, K. Bensadok, S. Aoudj, Remediation of post treated fluorinated photovoltaic wastewater by electrocoagulation, Chem. Eng. Trans. 32 (2013) 25–30.

[10] D. Mohan, R. Sharma, V.K. Singh, P. Steele, C.U. Pittman, Fluoride removal from water using bio-char, a green waste, low-cost adsorbent: Equilibrium uptake and sorption dynamics modeling, Ind. Eng. Chem. 51 (2) (2012) 900–914.

[11] N. Drouiche, S. Aoudj, M. Hecini, N. Ghaffour, H. Lounici, N. Mameri, Study on the treatment of photovoltaic wastewater using electrocoagulation: Fluoride removal with aluminium electrodes—Characteristics of products, J. Hazard. Mater. 169(1–3) (2009) 65–69.

[12] S. Nicolas, L. Guihard, A. Marchand, B. Bariou, A. Amrane, A. Mazighi, N. Mameri, A. El Midaoui, Defluoridation of brackish northern Sahara groundwater—Activity product calculations in order to optimize pretreatment before reverse osmosis, Desalination 256 (2010) 9–15.

[13] A. Ramdani, S. Taleb, A. Benghalem, N. Ghaffour, Removal of excess fluoride ions from Saharan brackish water by adsorption on natural materials, Desalination 250 (2010) 408–413.

[14] H. Mjengera, G. Mkongo, Appropriate deflouridation technology for use in flourotic areas in Tanzania, Phys. Chem. Earth Parts A/B/C 28 (2003) 1097–1104.

[15] N. Mameri, A.R. Yeddou, H. Lounici, D. Belhocine, H. Grib, B. Bariou, Defluorination of septentrional Sahara ground water of North Africa by electrocoagulation process using bipolar aluminium electrodes, Water Res. 32 (1998) 1604–1612.

[16] S. Nicolas, A. Marchand, L. Guihard, N. Mameri, D. Belhocine, A. Mazighi, B. Bariou, Proceedings International Congress on Fluorides, Nitrates and Pesticides in Mediterranean Waters, University Ibn Tofail, Kénitra, Morocco, 1997.

[17] H. Lounici, L. Addour, D. Belhocine, H. Grib, S. Nicolas, B. Bariou, Study of a new technique for fluoride removal from water, Desalination 114 (1997) 241–251.

[18] D.A. Abugri, K.P.B. Ba, Assessment of fluoride content in tropical surface soils used for crop cultivation, Afr. J. Environ. Sci. Technol. 5 (2011) 653–660.

[19] B. Zeboudji, N. Drouiche, H. Lounici, N. Mameri, N. Ghaffour, The influence of parameters affecting boron removal by electrocoagulation process, Sep. Sci. Technol. 48(8) (2013) 1280–1288.

[20] N. Boudjema, N. Drouiche, N. Abdi, H. Grib, H. Lounici, A. Pauss, N. Mameri, Treatment of Oued El Harrach river water by electrocoagulation noting the effect of the electric field on microorganisms, J. Taiwan Inst. Chem. Eng. (2013). Available from: http://dx.doi.org/10.1016/j.jtice.2013.10.006.

[21] H. Lounici, Doctoral thesis, Ecole Nationale polytechnique of Algiers, Env. Eng. Library, Algeria (2000).

[22] Z. Amor, S. Malki, M. Taky, B. Bariou, N. Mameri, A. Elmidaoui, Optimization of fluoride removal from brackish water by electrodialysis, Desalination 120 (1998) 263–271.

[23] N. Drouiche, N. Ghaffour, M.W. Naceur, H. Lounici, M. Drouiche, Towards sustainable water management in Algeria, Desalin. Water Treat. 50 (2012) 272–284.

[24] N. Drouiche, N. Ghaffour, M.W. Naceur, H. Mahmoudi, T. Ouslimane, Reasons for the fast growing seawater desalination capacity in Algeria, Water Res. Manage. 25 (2011) 2743–2754.