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Remediation of brackish groundwater in United Arab Emirates using electrodialysis technique

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ABSTRACT

Many Gulf countries including United Arab Emirates "UAE" suffer from major shortage of drinking water produced from natural resources. In these countries, it is essential to make use of water from underground reservoirs of different qualities. In Al Ain and, till recently, major percentage of drinking water resources had been produced from groundwater aquifers. Intensive discharge of groundwater resources in several aquifers given the limited replenishing inflows and the major percolations associated with farming activities overlying these aquifers have resulted in increasing their salt content and invalidate their usage for drinking purposes. Desalination of brackish water is a major potential way of producing low-cost drinking water. Electrodialysis, a technique based on the transport of ions through selective membranes under the influence of an electrical field, has proved its feasibility and high performance in the desalination of brackish water. In this research, the design and optimization of an electrodialysis cell for brackish water desalination of major aquifers of Al Ain City, UAE, is studied. Different laboratory experiments are conducted to analyze the sensitivities of different design parameters on the configured cell, evaluate different operational schemes of the configured cell, and select the one achieving the highest desired efficiency.

Keywords: Al Ain; Brackish water; Electrodialysis; Groundwater; Drinking water; Desalination

1. Introduction

The shortage of traditional drinking water resources is a major problem in the arid regions where precipitations are limited and it is, therefore, necessary to resort to underground resources. However, a large number of available aquifers become over exploited and suffer serious problems of saline contamination.

Groundwater aquifers are major sources of water in most of the Gulf countries such as lran, Saudi Arabia, Bahrain, Qatar, Kuwait, and UAE. However, water is the most important and binding constraint for any future development in this region. These countries have exploited their limited natural water resources and have no more sources to develop so they mostly turned to desalination.

A wide variety of desalination technologies effectively remove salts from salty water (or extract fresh-

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water from salty water), producing a water stream with a low concentration of salt (the product stream) and another with a high concentration of remaining salts (the brine or concentrate). Most of these technologies rely on distillation and/or membranes to separate salts from the product water. There is no best method of desalination. Ultimately, the selection of a desalination process depends on site conditions including the salt content of the water, economics, quality of water needed by the end user, and local engineering experience and skills [1,2].

The UAE attains most of its drinking water resources from both distillation and membranes desalination applied to sea water of high salinity (40 g/L and more). As both technologies require major costs and knowing that UAE has vast groundwater resources with brackish water of low salinity (2–5 g/L), it was necessary to seek other feasible yet cheaper techniques to produce part of UAE drinking water demands.

Electrodialysis (ED) is a technique based on the transport of ions through selective membranes under the influence of an electrical field. This technique has proved its feasibility and high performance in the desalination of brackish water [3,4], the desalting of amino acids and other organic solutions [5,6], effluent treatment or recycling of industrial process streams, and salt production [7]. The ED has a high recovery rate and can remove 75–98% of total dissolved solids (TDS) from feed water. The ED can produce more product water and less brine than distillation processes, can treat water with a higher level of suspended solids than reverse osmosis (RO), and needs fewer pretreatment chemicals [8].

The ED can remove or reduce a host of contaminants from feed water and the process is not as sensitive to pH or hardness levels in the feed water. The ED process is adaptable to various operation parameters, requires little labor, and the maintenance costs are generally low [9].

Electrodialysis reversal (EDR) is a modified ED process that regularly reverses the polarity of the electrodes, thereby freeing accumulated ions on the membrane surface. Such modification minimizes the effect of inorganic scaling and fouling by converting product streams into waste streams and thus increases the membrane life [10]. The EDR does not require added chemicals and eases cleaning as well. Yet, the process still requires additional plumbing and electrical controls. The EDR has several distinct and unique operating characteristics that make it a successful process. It has a capability to perform at very high water recovery as the polarity reversal allows the system to operate with concentrated salt scale factors well beyond saturation without any chemical feed. Combining EDR with anti-scalant addition increases the allowable concentration of these scale forming entities even further [11]. Improvements in EDR include improvements in the areas of design, operation, and brine reuse in bio-energy production [12]. Further and recent improvement in operating EDR with higher recovery rate is achieved without any anti-scalant and without requirements of acid addition [13]. That new EDR operated with Langelier saturation index at 2.29 and $CaSO_4$ saturation level 358.9% at lower dose and lower mean ion resident time.

The ED was found to be feasible when the salinity of the feed water is not more than about 6 g/L of dissolved solids [14]. For waters with relatively low concentrations (less than 5 g/L), ED is generally the most economic process in comparison to RO [15]. However, the desalination of waters with higher concentrations of dissolved solids (30 g/L) can successfully be performed through ED [16,17].

This paper investigates the usage of ED process in desalinating UAE-groundwater sample and optimizes its operation associated with maximum recovery rate and minimum energy cost. This is done via a number of laboratory experiments conducted on two sets of water samples as explained below.

2. Experiments

A PCCell ED 64 ED cell (Germany) was used in this research. The ED cell consisted of a stack of 10 pairs of PC–SK cation exchange and PC–SA anion exchange membranes with an active membrane area of 64 cm^2 per membrane. Both electrodes were platinum-plated titanium.

Two sets of experiments were conducted in this study. The first set was performed using solution of NaCl and the other used water collected from major Al Ain groundwater aquifers. All tests were performed at room temperature.

In all experiments, the effect of changing some of the parameters such as the applied voltage and the hydraulic flow velocity on the performance of the process was tested. The applied voltages used in the experiments were 8, 12, and 16 V while the tested hydraulic flow ranged from 47 to 72 L/h. The ED system was operated in continuous operation mode where the feed water was initially filled in both dilute and concentrate containers and was recirculated throughout the concentrate and dilute streams until the desired concentration was achieved. A solution of 0.5 M Na_2SO_4 with a flow rate of 2.5 L/min was used as the electrode rinse solution. Measurements of dilute and concentrate concentrations and current, dilute,

and concentrate electrical conductivities were taken over intervals of 15 min.

To increase the recovery rate and hence increase the efficiency of the ED process, different ratios of the volume of the solution in the concentrate compartment to the volume of the solution in dilute compartment were tested in each set of the experiments.

In all experiments, the objective was to reduce the salinity of the tested groundwater to 250 mg/L; a value near the lower limit of Abu Dhabi drinking water standards (100–1,000 mg/L) as defined by Abu Dhabi Bureau of Environment. Solution of 0.5 M HCl was used to rinse the membranes between consecutive runs.

3. Results and discussion

Eleven experiments with different conditions were conducted in this study. Summary of the different conditions of the conducted experiments is shown in Table 1. The last column in the table indicates the ratio of the initial volume of solution in the concentrate compartment to the initial volume of solution in the dilute compartment for each experiment.

Results of the first set of experiments, NaCl solution, are shown in Figs. 1–4. Fig. 1 shows the concentration of NaCl in the dilute stream and the energy consumed in the ED removal process as a function of time and voltage for initial salt concentration of 2.5 g/L. The applied hydraulic flow velocity was 60 L/h.

Fig. 1 results show that the dilute concentrations developed under 12 and 16 V applications were almost identical. The NaCl concentration in the dilute rapidly decreases within the 60 min. After this point, the decrease in salt concentration slowed down. Also,

Table 1
Experiments conditions

Run	Solution	Concentration (mg/L)	Voltage (volts)	Flow velocity (L/h)	Concentrate: dilute volumes
1	NaCl	2,500	8	60	1:1
2	NaCl	2,500	12	60	1:1
3	NaCl	2,500	16	60	1:1
4	NaCl	2,500	12	47	1:1
5	NaCl	2,500	12	72	1:1
6	NaCl	5,100	12	60	1:1
7	NaCl	2,500	12	60	1:3
8	GW1	2,500	12	60	1:1
9	GW1	2,500	12	60	1:3
10	GW1	2,500	8	60	1:1
11	GW1	2,500	8	60	1:3

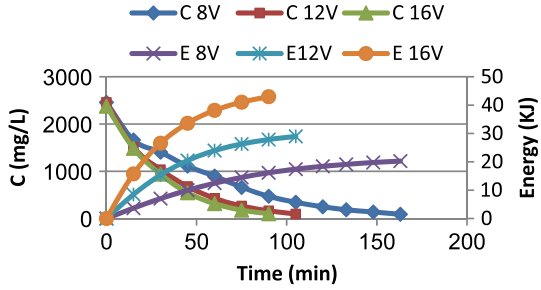

Fig. 1. NaCl dilute concentration (C) and energy (E) for 8, 12, and 16 V applications.

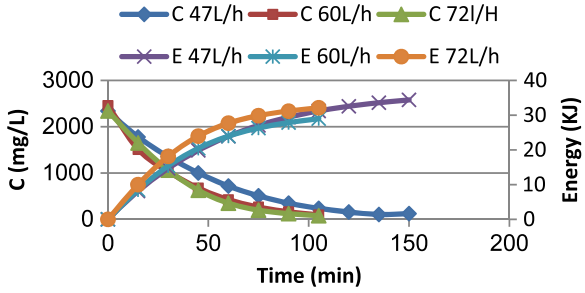

Fig. 2. NaCl dilute concentration (C) and energy (E) for 47, 60, and 72 L/h applications.

the consumed energy increased rapidly with time to the same point and then slowed down which accompanied smaller incremental decrease in the current between the two electrodes of the ED cell. This could be explained by depletion of electron carriers in the dilute stream. Fig. 1 shows that it took the dilute concentration exactly the same time (80 min) to reach 250 mg/L for both the 12 and 16 V applications. On the other hand, the developed dilute concentration as well as the time need to reduce the salinity to 250 mg/L for the 8 V application was almost double those of the 12 and 16 V. Fig. 1 also shows that the energy consumed in the 12 V application (26 kJ) was only 2/3 that of the 16 V (39 kJ). Results shown in the figure indicate that even though the desalination process of the 8 V application was considerably slow (took much longer time than the other two applications), this application consumed the least amount of energy (almost 18 kJ). The reason behind that is the energy remains almost constant for longer time due to the rapid decrease in the current between the two electrodes of the ED cell. Fig. 1 results revealed that the longer the time will be, the less its effect on the consumed energy and in this case, the consumed energy would depend mainly on the applied voltage and time would have a minor effect on it. Taking into account the energy consumed for 8, 12, and 16 V, it

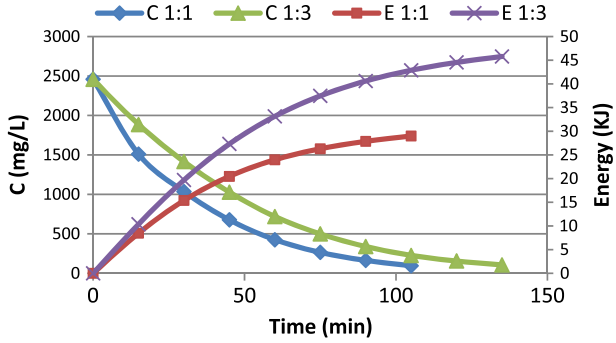

Fig. 3. NaCl dilute concentration and energy consumed for 1:1 and 1:3 volumes applications.

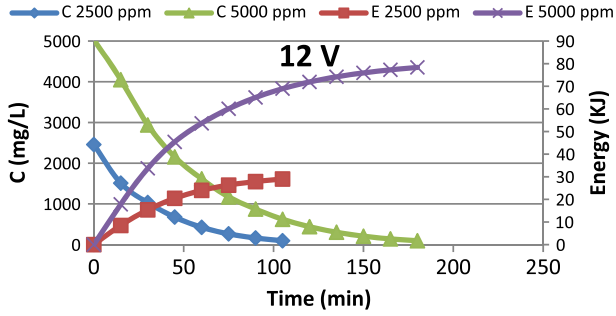

Fig. 4. NaCl dilute concentration and energy consumed for 2,500 and 5,000 mg/L solutions.

could be concluded from Fig. 1 results that the energy consumed by the ED was directly proportional to the applied voltage. This supports the usage of small voltage in the ED desalination process in order to reduce the energy consumed in the process and hence reduce the cost of the desalination process.

The effect of utilizing different hydraulic flow velocities on the performance of the desalination process of the ED cell for an applied electrical power of 12 V is shown in Fig. 2. It can be easily seen that the desalination processes were almost identical for both hydraulic flow velocities of 60 and 72 L/h. Slower desalination process was obtained in the case of 47 L/h. The velocity of 47 L/h seems to be too slow that for a given time; much less volume of water was desalinated compared to 60 and 72 L/h velocities. Fig. 2 also shows that the NaCl desalination process of hydraulic flow velocity of 60 L/h consumed the least amount of energy compared to both the 47 and 72 L/h velocities processes but the difference in the consumed energies was relatively small. The small deviation in the energy between the three tested hydraulic flow velocities indicated that energy does not depend on the velocity of the hydraulic flow. The results revealed from Fig. 2 indicate that the best ED cell configuration for desalinating 2,500 mg/L NaCl would be obtained by utilizing a hydraulic flow velocity of 60 L/h. So, the rest of the NaCl experiments was done using 60 L/h hydraulic flow velocity.

Fig. 3 illustrates the concentrations developed and the energy consumed for a 12 V and 60 L/h ED cell for two different ratios of the volume of the solution in the concentrate compartment to the volume of the solution in the dilute compartment (ratios of 1:1 and 1:3). Fig. 3 shows that the desalination process for the 1:3 application was relatively slower than that of the 1:1 desalination process. It took the ED cell 100 min to drop the concentration from 2,500 to 250 mg/L for the 1:3 application, while it took only 80 min to do the same in the case of the 1:1 application. The energy consumed by the 1:3 application (41 kJ) was almost in the ratio of 3/2 that of the 1:1 (26 kJ). Fig. 3 results indicate that it needs a 50% increase in the energy in order to have a 50% increase in the volume of the treated water.

The performance of the configured cell (12 V and 60 L/h) for two different initial salt concentrations 2,500 and 5,000 mg/L is shown in Fig. 4. The figure shows that the used configuration of the ED process was able to desalinate the 5,000 mg/L NaCl solution in 120 min with an energy consumed of almost 75 kJ. Although the time need to reduce the 5,000 mg/L salinity to 250 mg/L (120 min) was exactly twice as much that of 2,500 mg/L (60 min), the energy needed to desalinate the 5,000 mg/L solution (76.5 kJ) was more than double that of the 2,500 mg/L solution (26 kJ). Results shown in Fig. 4 indicate that the consumed energy by the ED cell was not directly proportional to initial consternation of the desalinating NaCl solution. The figure also indicates that the ED technique would be more economical in desalinating water with low TDS.

Chemical analysis of the tested Al Ain groundwater and the Abu Dhabi Bureau Maximums for drinking water is shown in Table 2. The table shows that almost all ions (except Na) presented in Al Ain groundwater were away above the maximum limits for Abu Dhabi drinking water. The measured TDS for this water was 2,480 mg/L which also away above Abu Dhabi Bureau maximum (100–1,000 mg/L).

Results of the second set of the experiments, Al Ain groundwater from site1 (GW1) are shown in Figs. 5–8. Fig. 5 shows the concentration in the dilute stream and the energy consumed as a function of time and voltage for a hydraulic flow velocity of 60 L/h. It can be easily seen from Fig. 5 that the ED desalination process was much slower in the case of 8 V application compared to that of the 12 V. The time required to drop the salinity to 250 mg/L for the 8 V process

Table 2
Al Ain GW analysis and Abu Dhabi Bureau drinking water limits

	Ions	Raw groundwater (mg/L)	Abu Dhabi regulation and supervision bureau maximum limit (mg/L)
Cations	Ca^{2+}	69.13	0.003
	Mg^{2+}	95.1	30
	Ba^{2+}	0.032	0.7
	K^{+}	31.7	12
	Na^{+}	112.9	150
	Sr^{2+}	5.24	
Anions	F^{-}	6.4	1.5
	Cl^{-}	776.8	250
	Br^{-}	47.8	
	NO_3^{-}	82.6	50
	CO_3^{2-}	3	
	HCO_3^{-}	216	
	SO_4^{2-}	495.5	250

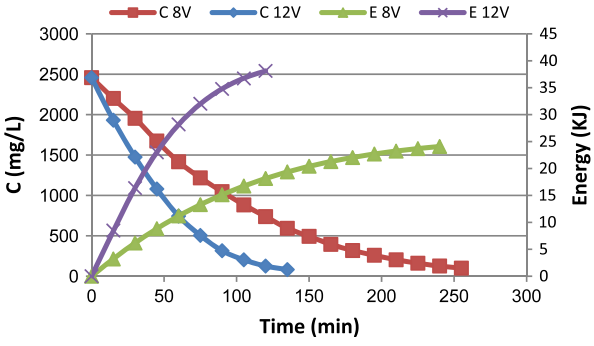

Fig. 5. GW1 dilute concentration and energy for 8 and 12 V applications.

(200 min) was exactly double that of the 12 V process (100 min). At any giving time, the concentration obtained by the 8 V process was almost more than double that of the 12 V. On the other hand, the energy consumed during the 8 V desalination process was almost 3/5 that of the 12 V process. The ratio of the consumed energy is almost the same as the ratio of the applied voltage which indicates that the consumed energy by the ED cell is directly proportional to the applied voltage. As a result, it is more economical to use low applied voltage in desalinating Al Ain groundwater with ED technique.

Fig. 6 illustrates the concentrations developed and the energy consumed for 8 V and 60 L/h ED cell for

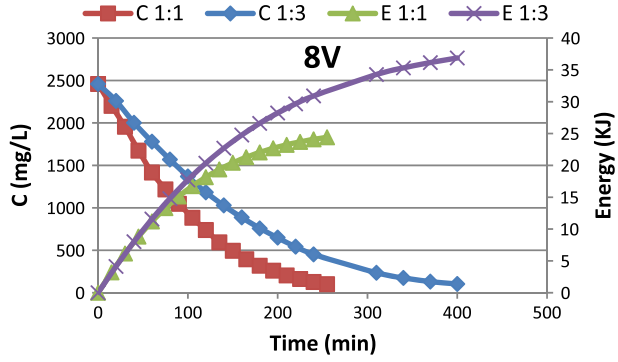

Fig. 6. GW1 dilute concentration and energy consumed for 1:1 and 1:3 volumes applications.

two different ratios of the volume of the solution in the concentrate compartment to the volume of the solution in the dilute compartment (ratios of 1:1 and 1:3). At any given time, the concentration developed under 1:3 application was higher than that of 1:1; however, the difference was small at the beginning of the process and increased as time increased. The energy and the time required to drop the salinity to the desired level in the 1:3 configuration was almost 3/2 that of the 1:1. The results show that 50% recovery rate will consume 23 kJ while 75% recovery rate will consume 34 kJ in the ED cell. These results indicate that it would require an increase in the energy by 50% in order to increase the volume of the treated Al Ain groundwater by 50%.

Fig. 7 shows comparison between the behavior of the 1:1 and 1:3 configurations for ED cell with 12 V applied voltage and 60 L/h hydraulic flow. The salinity profile for the 1:3 cell was slightly higher than the 1:1 profile. The time and the energy required to drop the TDS to 250 mg/L for the 1:3 process (150 min and 55 kJ) was almost 3/2 that of the 1:1 (100 min and 35 kJ). This ratio was also obtained in the case of the 8 V application which may reflect that the time and

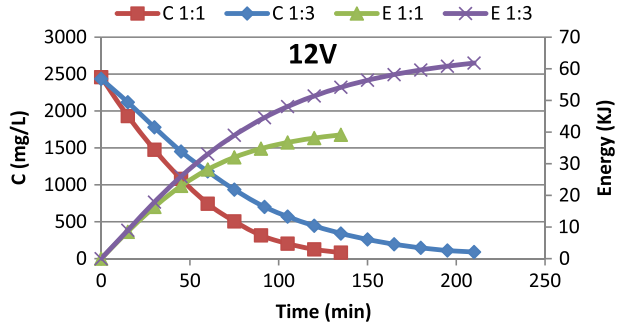

Fig. 7. GW1 dilute concentration and energy consumed for 1:1 and 1:3 volumes applications.

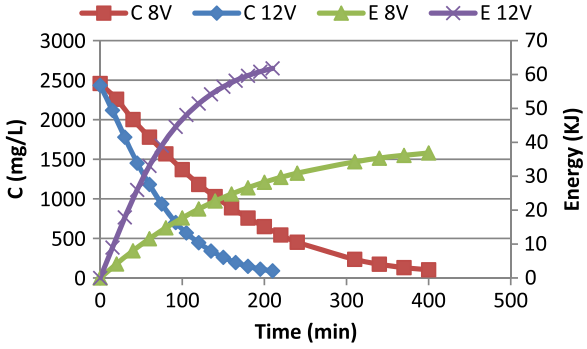

Fig. 8. GW1 dilute concentration and energy consumed for 8 and 12 V for 1:3 volumes applications.

the energy required to drop the salinity to a certain level are proportional to the ratio of the solution in the concentrate compartment to the volume of the solution in the dilute compartment.

The results shown in Fig. 8 indicate that even though the 8 V desalination process took twice as much time as the 12 V to desalinate Al Ain groundwater, the energy consumed by the 8 V process (34 kJ) was considerably less than the energy consumed during the 12 V process (52 kJ). The ratio of the consumed energy 34:52 was almost equal to the ratio of the applied voltage 8:12 for the 1:3 configuration. This observation was also obtained earlier from the 1:1 configuration.

Results of set 2 experiments highly recommend the use of 8 V and 1:3 configuration to desalinate 75% of the tested Al Ain contaminated groundwater with considerably reasonable amount of energy.

Table 3 shows the chemical analysis, the percentage removal of the presented ions from the dilute compartment, and the percentage loss of the mass of the ions of the desalinated Al Ain groundwater. Table 3 results illustrate that the used ED cell configuration was able to remove all the anions and cations presented in Al Ain groundwater. Very high removal percentages were obtained for almost all the ions found in the treated water. The used ED cell was able to reduce the concentrations of almost all ions (except calcium) to levels highly below the maximum levels defined by Abu Dhabi Bureau (Table 2). This indicates that the obtained treated groundwater is suitable for drinking purposes. Even though the removed HCO_3 represented only 58%, the hardness level of the treated water reduced to a level below the Abu Dhabi Bureau standards (200 mg/L). Mass balance calculations showed that there was mass loss of ions during the ED desalination process. This loss could be mainly due to precipitations of the ions on the ion exchange membranes of the used ED cell. Membrane scaling during ED is a major limiting factor in its use for water treatment, as the long-term chemical stability of membranes is influenced by the occurrence of scaling. However, part of these losses could be due to the introduced systematic and personal errors during the experiments.

Comparison between the performance of the used ED in desalinating NaCl solution and Al Ain Groundwater is shown in Figs. 9–11. This comparison was done to figure out the influence of having different ions in the treated solution on the performance of the

Table 3
Removal percentage and percentage mass loss for treated Al Ain groundwater with ED desalination process

	Ions	Raw groundwater (mg/L)	Desalinated groundwater with 8 V and 1:3 cell (mg/L)	Removal %	Loss %
Cations	Ca^{2+}	69.13	19.76	71.4	43
	Mg^{2+}	95.1	0.443	99.5	25
	Ba^{2+}	0.032	0.001	96.9	40
	K^{+}	31.7	0.512	98.4	38
	Na^{+}	112.9	29.09	74.2	39
	Sr^{2+}	5.24	0.083	98.4	39
Anions	F^{-}	6.4	0.4	93.8	68
	Cl^{-}	776.8	32.9	95.8	3
	Br^{-}	47.8	2	95.8	68
	NO_3^{-}	82.6	3.3	96	54
	CO_3^{2-}	3	0	100	17
	HCO_3^{-}	216	90	58.3	12
	SO_4^{2-}	495.5	4.26	99.1	3

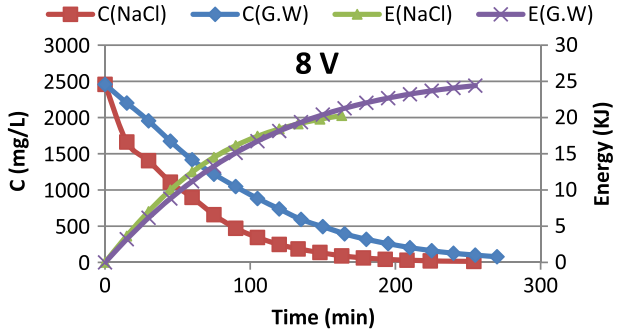

Fig. 9. GW1 vs. NaCl dilute concentrations and energy consumed for 8 V applications.

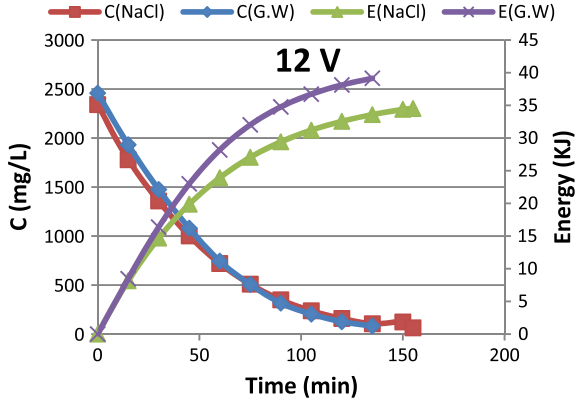

Fig. 10. GW1 vs. NaCl dilute concentrations and energy consumed for 12 V applications.

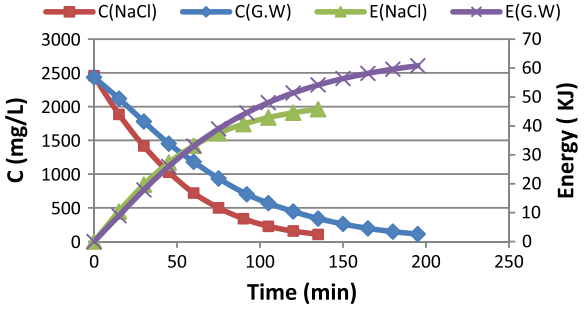

Fig. 11. GW1 vs. NaCl dilute concentrations and energy consumed for 12 V and 1:3 applications.

ED cell. Results shown in those figures indicate that the used ED took more time and consumed more energy to drop the salinity level to 250 mg/L in case of the Al Ain groundwater treatments compared to that of NaCl solution. Since the two solutions had the same initial TDS concentration (2,500 mg/L), this indicates that the energy consumed by the ED cell depends more on the number and type of ions existing in the treated water rather than on its TDS value.

4. Conclusion

This paper investigated the usage of ED process in desalinating brackish groundwater of low salinity extracted from Al Ain City of UAE. The effects of voltage, flow, and recovery rate on the removal time and energy consumed have been evaluated. The results indicate the feasibility of using ED in lowering the tested groundwater to acceptable limits enforced by local environmental authorities. This provides a valuable opportunity for producing cheap drinking water in UAE if compared to that produced from current processes, i.e. membrane or thermal desalination. Specific findings of this study can be summarized as follows:

(1) ED is effective method for desalinating Al Ain brackish groundwater to a level acceptable for drinking purposes.
(2) An ED cell that uses 8 V applied voltage and 1:3 configuration ratio can desalinate 75% of the tested Al Ain contaminated groundwater with a considerably reasonable amount of energy.
(3) The energy consumed by the ED cell during the desalination process is directly proportional to the applied electrical voltage and to the hydraulic flow velocity as well.
(4) The time and energy needed to drop the salinity to a certain level are proportional to the ratio of the concentrate volume to the dilute volume.
(5) A 50% increase in the energy is required to accommodate a 50% increase in the volume of the treated water.
(6) Energy consumed by the ED cell is not directly proportional to the initial concentration of the treated water.
(7) The energy consumed by the ED cell depends more on the number and type of ions existing in the treated water rather than on its initial TDS value.
(8) The energy consumed by the ED cell during the desalination process highly depends on the applied electrical voltage.
(9) Ion precipitation on the membrane is a major problem associated with the use of the ED desalination technique increasing with the feed concentration where EDR is recommended then.

Further work is required to test the performance of the ED with higher Al Ain groundwater salinity levels and to determine fouling mechanisms.

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