Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1004592

57 (2016) 5391–5397
March

Taylor & Francis
Taylor & Francis Group

Comparing operational cost and performance evaluation of electrodialysis and reverse osmosis systems in nitrate removal from drinking water in Golshahr, Mashhad

M. Pirsaheb[a], T. Khosravi[b,*], K. Sharafi[c,d], M. Mouradi[c,e]

[a]*Environmental Health Engineering Department, Research Center for Environmental Determinants of Health Kermanshah University of Medical Sciences, Public Health School, Kermanshah University of Medical Sciences, Kermanshah, Iran*
[b]*Environmental Health Engineering Department, Kermanshah University of Medical Sciences, Kermanshah, Iran, Tel. +989189318647; Fax: +98 8318263048; email: touba_khosravi@yahoo.com*
[c]*Environmental Health Engineering Department, Public Health School, Kermanshah University of Medical Sciences, Kermanshah, Iran, Tel. +98 9183786151; Fax: +98 8318263048; email: kio.sharafi@gmail.com (K. Sharafi), Tel. +98 9183859910; email: mahfooz60@gmail.com (M. Mouradi)*
[d]*Environmental Health Engineering Department, Tehran University of Medical Sciences, Tehran, Iran*
[e]*Environmental Health Engineering Department, Iran University of Medical Sciences, Tehran, Iran*

Received 1 February 2014; Accepted 31 December 2014

ABSTRACT

The aim of this study was to compare the operational cost and efficiency of electrodialysis and reverse osmosis systems in removing nitrate from drinking water. Eighteen samples were selected to measure nitrate and other chemical parameters. Also, the present cost value and useful life of 15 years were used for comparing both systems. Results indicated that nitrate removal in the reverse osmosis system was about twice (90%) more than that of the electrodialysis system. Additionally, removal of bicarbonate, sulfate, chloride, calcium, magnesium, sodium, and potassium in electrodialysis and reverse osmosis systems was 16, 5, 31, 29, 25, 7.9, and 10% and 93.7, 96.3, 96.8, 96.5, 96, 92.6, and 91%, respectively. Considering the economic issue of both systems, the initial capital cost, annual present cost value of operation and maintenance during the project period, and total present cost value in the electrodialysis system were 2.3, 1.9, and 3.0 times more than those of the reverse osmosis system, respectively. According to the obtained results, reverse osmosis was superior to electrodialysis in terms of cost per cubic meter of treated water and removal of nitrate and other chemical parameters.

Keywords: Reverse osmosis; Electrodialysis; Nitrate; Nitrite; Operational cost

1. Introduction

Dealing with groundwater which is polluted with nitrate is a priority in both developed and developing countries due to both its toxicity and prevalent existence. Nitrate pollution is the result of using nitrogen fertilizers for agricultural purposes [1,2] and irrigation with domestic wastewater, which causes environmental pollution [3]. High concentration level of nitrate-nitrogen in drinking water can cause a

*Corresponding author.

methemoglobinemia disease called “Blue-Baby syndrome” in infants under six months of age and also carcinogens in the digestive organs [4–6]. Thereby, nitrate can be removed from drinking water sources by suitable and approved technologies including reverse osmosis (RO), ion exchange, and electrodialysis (ED) [4,7]. However, each of these technologies has their own advantages and disadvantages for water denitrification. Among these techniques, selecting a method with high removal efficiency is not known as the best method, because in addition to being efficient, it should be reasonable in terms of operational cost [8].

Previous studies have indicated different results in terms of comparison of the ED and RO systems; in a study by John et al. [9], results showed that RO was appropriate for treatment of groundwater with high nitrate, TDS, and trichloromethane concentrations in Brighton, Colorado, Canada, since residents of these cities would no longer use ion-exchange softening units. In contrast, American Water Works Association (AWWA) has indicated that electrodialysis reversal (EDR) is a membrane technology with the best hydraulic recovery and cost effectiveness for water denitrification compared with other membrane technologies, especially RO [10]. Also, Strathmann proposed RO system for desalting processes as a universal solution for many desalination troubles [11]. Strathmann showed that ED was more appropriate than RO for various industrial functions with different sizes in terms of cost effectiveness, because widespread pretreatment, higher pumping power, and more chemicals are required by RO process [12]. It should be noted that operational cost of RO and ED process is particularly different as follows: energy consumption of ED is higher than RO system in terms of waste of energy in EDR system; but, the cost of chemicals used by RO is greatly higher than the EDR system [13]. Results of another study by Japan International Cooperation Agency [14] showed that the cost and energy consumption of ED and RO for the desalination of brackish water with TDS = 2 g/l was similar, while the operational costs and energy consumption of RO were less than those of ED at TDS > 5 g/l. RO was, therefore, used for the desalination of salty and seawater, and ED was mostly applied for the desalination of water at TDS < 2 g/l [15]. In contrast, some other studies have proved that the ED process has a higher ability in treating water with high suspended solids than RO. Also, it has some advantages including water recycling by more than 90%, proportion of energy consumption with salt excretion, low chemical consumption for pretreatment, etc. [14,16]. However, according to the increasing concentration of nitrate in drinking water sources, it is essential to study nitrate removal technologies considering all operational costs.

According to the previous investigation, in removing nitrate from drinking well water in Mashhad by Panglisch et al. [17], most water of the 300 existing wells (88.6%) is used for drinking water supply in Mashhad city [18]. The present project was on the application of RO and EDR systems for nitrate removal to reach 40 mg/l nitrate in drinking well water in Golshahr, Mashhad; this water was not suitable for human consumption because of having the nitrate concentration of > 100 mg/l that was higher than WHO guideline (50 mg/l)) [18]. This study aimed to compare the operational cost and efficiency of RO and EDR in the removal of nitrate and other parameters including bicarbonate, sulfate, chloride, phosphate, calcium, magnesium, sodium, and potassium from drinking water and propose the best available and economical technique considering national circumstances.

2. Materials and methods

In this study, pilot plants of RO (Fig. 1) [18] and EDR (Fig. 2) were employed for nitrate removal of drinking groundwater in Mashhad, Iran. For the case of this study, the EDR and RO settled on one of the drinking water wells in the city of Mashahd was used. Pretreatment was performed using sand filter and activated carbon for removing suspended solid and, probably, existence organic matter in raw water. Then, groundwater of a well with the depth of 140 m was pumped into the EDR system with the flow rate of 108 m^3/h and power of 58 kW. Also, chemicals were added to the water via a tube along with a mixer for mixing chemicals and water. After the pretreatment process and adding chemicals, water was conducted to a pump. Afterward, flow out water from the pump with the pressure of 3.5 Bar, which was required to transfer water from the well to the EDR system, and flow rate of 1 m^3/h was pressed into the EDR system; as a result, both flow rates of permeated and concentrated water were 0.5 m^3/h. According to the quality of raw feed water and the manufacturer of the membrane, the useful life of Three years was considered for the membrane. Meanwhile, raw water from the same well was fed to the RO system by another pump with the flow rate of 4 m^3/h. In this system, flow rate of permeated and concentrated water was 3.4 and 0.6 m^3/h, respectively. Operated times of both systems were 20 h during the day. In the present study, 18 samples were taken from feed raw water and permeated and concentrated water. The collected samples were transferred to the laboratory for analysis and the parameters including electrical conductivity, pH, nitrate, bicarbonate, sulfate, chloride, phosphate, calcium, magnesium, sodium, and potassium were determined according to standard methods [17].

All data including capital cost of both systems in different phases such as chemical consumption, mechanical facility, and cost of each cubic meter of water consumption were collected from the assistant company on this project and Mashhad Wastewater Company. It should be noted that each kWh of electricity was calculated according to the electricity bill of Iranian Energy Ministry Department in 2010 (30,000 RLs/kW). Initial capital costs including costs of construction and buying mechanical and electrical tools, annual operation and maintenance costs of systems, such as those of consumed chemicals, repair and replacement of equipment, consumed electricity, building repairs, and cartridge and membrane replacement, along with personnel costs were considered in this project. Useful lives of both systems were reckoned for the period of 15 years. To compare these two systems, the present value was considered.

Fig. 1 shows that, at first, HCl and antiscalant were mixed with raw water to adjust pH and avoid precipitation, respectively. The resulting solution was proceeded to prefiltration. Then, the outlet water, through prefiltration, entered the first stage of RO system (which included two systems). Afterward, the concentrated water of RO system in the first step entered the second stage of RO with more recycling of water and reducing the amount of disposing concentrated water. Consequently, permeated water of the first and second phases in the RO system was directed to gas exchange column to reduce the amount of carbon (carbon dioxide). However, due to the removal of the majority of cations and anions from permeated water in the RO system, a part of the raw water was mixed with permeated water without passing the RO system to provide the required minerals of drinking water. The concentrated water in the RO system was disposed.

In this system, there were two ways which transferred raw water to the EDR system (main path and reserve path). The amounts of electrical conductivity and nitrate were measured in the effluent water from the system. In Tank 4 (T_4), HCl (for pH adjustment) and antiscalant (for precipitation avoiding) were added to a certain amount of raw water to produce a dilute solution. In Tank 2 (T_2), feeding tank, raw water was mixed with the permeated water out of the system; so, when raw water needs to be diluted due to increased amount of its minerals, it can be used to feed the system. The produced permeated water was used to rinse the electrodes in Tank 1 (T_1).

The concentrated water in the system (containing cations and anions with the minimal amount of nitrate ion) was returned to the system. Since, the purpose of this project was to reduce nitrate ions from raw feed water, this issue was not considered as a factor.

3. Results

Results of feeding permeated and concentrated water quality and chemical consumption in the RO and ED systems are depicted in Tables 1 and 2, respectively. Results of total capital cost including electricity consumption, initial capital cost, annual operation, and maintenance of both systems are also shown in Tables 3–5, respectively. Further, Tables 6–8 depict the comparison of each cubic meter cost of treated water owing to the initial and operating capital costs, the capacity of water production and each cubic meter costs in RO and ERD systems.

4. Discussion and conclusion

Results of the EDR system showed that the average concentration of nitrate in permeated water was

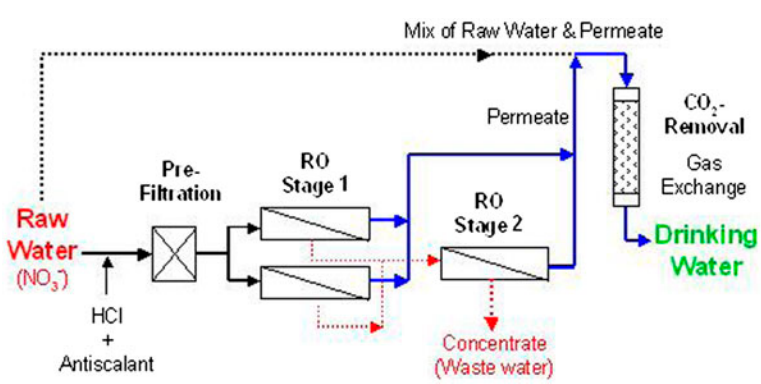

Fig. 1. The schematic diagram of the RO pilot plant for nitrate removal in Golshahr, Mashhad.

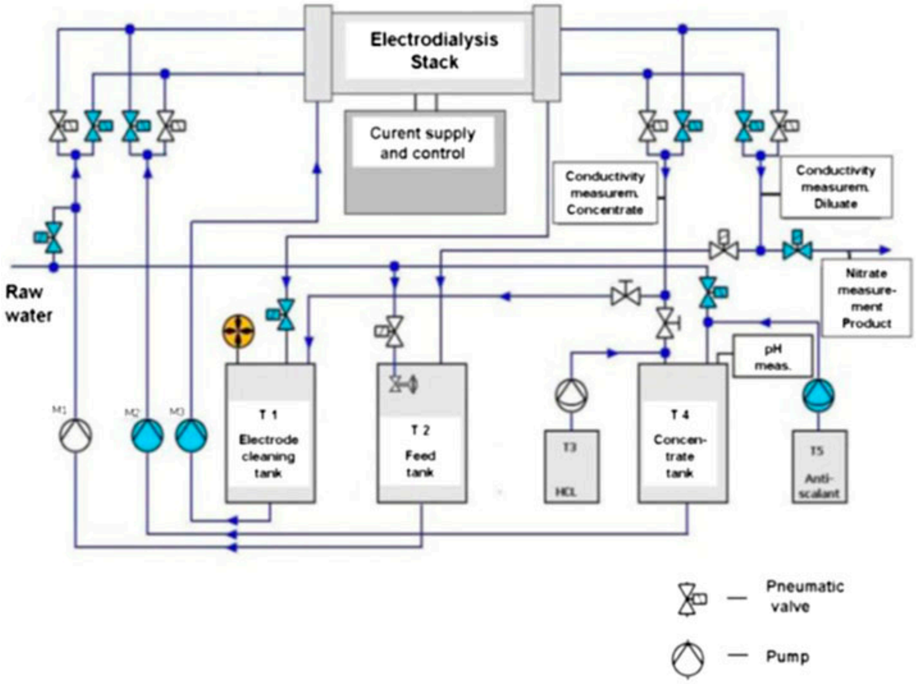

Fig. 2. The schematic diagram of the ED pilot plant for nitrate removal in Golshahr, Mashhad.

Table 1
The quality of feed, permeate, concentration rate water, and removal rate in RO and ED systems

Parameter	Systems	Raw feed water	Average of permeate water ± δ	Average of concentrate water ± δ	Removal %
Conductivity (µs/cm)	RO	1,650	1,115 ± 140	4,097 ± 41.6	–
	ED	1,546	1212.1 ± 82.3	4,255 ± 82.3	–
pH	RO	7.4	7.7 ± 0.1	7.5 ± 0.1	–
	ED	7.6	7.4 ± 0.2	6.5 ± 0.1	–
Nitrate (mg/l)	RO	138.8	12.7 ± 5.1	515 ± 123	90.85
	ED	127	67.6 ± 20.1	563.8 ± 32.3	46.77
Alkalinity as (CaCO3) (mg/l)	RO	345.3	21.6 ± 9.6	1,269 ± 246	93.74
	ED	324.5	303.7 ± 40.4	252.4 ± 26.7	6.40
Sulfate (mg/l)	RO	160	5.8 ± 1.7	579.3 ± 119	96.37
	ED	157	151 ± 5.3	197 ± 24.4	3.82
Chloride (mg/l)	RO	200	6.4 ± 3	815.7 ± 218.6	96.8
	ED	189	129.3 ± 32.5	806.3 ± 206.4	31.58
Calcium (mg/l)	RO	152	5.2 ± 3.7	584 ± 142.4	96.57
	ED	140	100.2 ± 22.6	435 ± 106.7	28.42
Magnesium (mg/l)	RO	49.8	2 ± 0.9	200 ± 36	95.98
	ED	48.8	36.7 ± 6.6	126.2 ± 31	6.76
Sodium (mg/l)	RO	120	8.8 ± 3.2	444.3 ± 99.9	99.33
	ED	113	116.7 ± 9.1	159.8 ± 17.2	−3.27
Potassium (mg/l)	RO	2.2	0.2 ± 0.1	9.4 ± 1.1	90.90
	ED	2.2	2 ± 0.1	6.1 ± 1.7	9.09
Temperature (°C)	RO	14.2	18.2 ± 6.2	20.8 ± 7.1	−28.16
	ED	14.2	16.9 ± 3.4	23.7 ± 0.5	−19.01

Table 2
Chemical consumption costs in RO and ED systems

System	Capacity (m^3/h)	Type of material	Consumption per day (l)	Consumption per year (l)	Cost per liter (RLs)	Cost per liter per year (million RLs)	Total chemical cost (million RLs)
RO	4	HCl	4.4	16.6	2,500	0.0415	194.0175
		Antiscalant	7.5	2,738	70,000	191.66	
		Citric acid	0.066	24	90,000	2.16	
		Alkaline	0.066	24	6,500	0.156	
ED	1	HCl	2	730	2,500	1.852	1.852

Table 3
Electricity consumption costs in RO and ED systems

System	Capacity (m^3/h)	Electricity consumption kW/d	Electricity consumption kW/year	Each kW cost (RLs)	Total cost per year (million RLs)
RO	4	114	41,610	773	32.16
ED	1	49	3,185	773	2.46

Table 4
Initial capital cost of RO and EDR systems (million RLs)

System	Capacity (m^3/h)	Constructed cost	Mechanical and electrical tools costs	Total cost
RO	4	1,473.5	2,736.5	4,210
ED	1	555	1,295	1,850

Table 5
Operational and maintenance annual capital costs of RO and ED systems (million RLs)

System	Capacity (m^3/h)	Chemical consumption	Electricity	Personnel	Repair and replacement	Building repairs	Exchange membrane cartridge	Total capital cost
RO	4	194.0175	32.16	421	210.5	84.2	18.7	964.516
ED	1	1.852	2.46	129.5	92.5	37	6.3	269.612

Table 6
Comparison of the capital costs of initial, annual and present value in RO and ED systems (million RLs)

System	Initial capital cost	Maintenance and operations	(P/A, 10%, 15)	Annual costs of operations and maintenance (within period of 15 year)	Total capital cost
RO	4,210	964.516	7.606	7,336.108	11,564.108
ED	1,850	269.612	7.606	2,050.668	3,900.668

greater than the standard rate (50 mg/l) and the nitrate removal efficiency of 46.6% was achieved in this system. However, nitrate removal efficiency in the RO system was about twice (90%) more than that of the EDR system. Results also indicated that average concentration of nitrate in permeated water in the RO

Table 7
The capacity of water production at various times

System	Total (m^3/h)	Treated water (m^3/h)	Constructed water (m^3/h)	Permeated water (m^3/20 h)	Permeated water m^3/years	Permeated water (m^3/15 years)
RO	4	3.4	0.6	68	24,820	372,300
ED	1	0.5	0.5	10	3,650	54,750

Table 8
Each cubic meter costs in RO and ERD systems (RLs)

System	Based on the initial capital costs	Based on annual operation and maintenance costs	Based on present cost value of operation and maintenance (within 15 years)	Total costs based on present value
RO	11,308	2,590.7	19,704.8	31,012.8
ED	33,790	4,924.4	37,455.1	71,245.1

system was 12.7 mg/l, which was less than the EDR system with the concentration of 67.6 mg/l. This amount was reduced to the lowest level in permeated water. Therefore, the permeated water was mixed with raw water to achieve the reasonable nitrate level.

On the other hand, recovery rates of permeated and feed water as 85 and 50% were estimated in the RO and EDR systems, respectively. In other words, performance efficiency of RO was better than that of EDR systems in terms of nitrate removal. This result was in contrast to the results of the study by Elyanow and Persechin who achieved 94 and 60% nitrate removal from drinking water by the EDR and RO systems, respectively [19]. In a study by Schoeman [20] on the comparison of small-scale technologies (RO, ion exchange, and EDR) for nitrate removal of water supplied to clinics for making potable water, the results demonstrated that the EDR process functioned well for nitrate-nitrogen and salinity removal. The RO and ion exchange processes were, therefore, suggested for nitrate-nitrogen removal at clinics due to the complicated operation of the EDR process [20]. Also, the obtained results were different from those of a previous study on removing nitrate.

However, nitrate concentration in the concentrated water was 515 and 563 mg/l in the RO and EDR systems, respectively, which were 3.7 times more than the nitrate of feed water. It had to be disposed into sewers or converted into nitrogen dioxide through biological denitrification. Thereby, there was no significant difference between the amounts of nitrate concentration in the concentrated water of both systems. Removal efficiency of bicarbonate, sulfate, chloride, calcium, magnesium, sodium, and potassium in the EDR and RO systems was 16, 5, 31, 29, 25, 7.9, and 10% and 93.7, 96.3, 96.8, 96.5, 96, 92.6, and 91%, respectively. According to the mentioned results, the removal efficiency of these parameters in the RO was better than the EDR system. Although the concentrated water in the RO system was disposed, the concentrated water in the EDR system (containing cations and anions with the minimal amount of nitrate ion) was returned to the system. It should be stated that the purpose was to reduce nitrate ions of raw feed water. In this system, nitrate anions moved toward the anode electrode and N_2 gas was formed and released from water.

In terms of economic comparison, cost small systems (<40 m^3/h) of the EDR were higher than those of the RO system. But, cost large systems of both EDR and RO systems were similar and depended on site details [21]. Thereby, cost small scale of both systems was similar in the present study.

Considering the useful life and economic issue of both systems in the present study, the cost per cubic meter of the treated water by RO based on the initial capital cost, annual present value of operation and maintenance during 15 years of the project period, and total present cost value was 11,308, 19,704.8, and 31,012.8 RLs, respectively, whereas these three costs in the EDR system were 2.3, 1.9, and 2.98 times more than the RO system, respectively (Table 8). Consequently, the RO system was superior to the EDR system in terms of cost per cubic meter of treated water and removal efficiency of nitrate and other chemical parameters. In a study which was carried out by Menkouchi et al. [22] on the nitrate removal of surface and groundwater by the EDR system in the center of

Marakesh, the result showed that nitrate removal cost was estimated as about 0.17 $ per cubic meter and cost of membrane exchange and power consumption of 0.05 $ and less than 0.04 $ per cubic meter of water was obtained according to the capital cost, respectively [20]. However, cost per cubic meter of nitrate removal in Golshahr, Mashhad, based on the preliminary capital cost was 3.3 $. In another study in a rural area in South Africa, an RO pilot plant was applied for nitrate removal; the results showed that the initial investment cost for removing nitrate with the flow rate of 50 m^3/d was estimated about 29,900 $ (0.5 $ per cubic meter) [22]. In the present study, however, cost per cubic meter of 1 $ was obtained; the difference in the initial capital cost of the system used in Mashhad from other studies can be attributed to the control and application of accurate instruments in this system. In contrast, annual operational costs were 1.74 and 1.1 times more than the initial capital cost in the RO and EDR systems, respectively (Table 6).

Acknowledgment

The authors wish to acknowledge the invaluable cooperating and supporting by the deputy and laboratory staff of Wastewater Company of Mashhad and Assistant Company of Nitrate Removal project for facilitating the issue of this project.

References

[1] L.W. Canter, Nitrates in Groundwater, CRC, Lewis Publishers, Boca Raton, FL, 1997.
[2] C. Su, R.W. Puls, Nitrate reduction by zerovalentiron: Effects of formate, oxalate, citrate, chloride, sulfate, borate, and phosphate, J. Environ. Sci. Technol. 38 (2004) 2715–2720.
[3] M.I.M. Soares, Biological denitrification of groundwater, Water Air Soil Pollut. 123 (2000) 183–193.
[4] M.A. Tisseau, Nitrates, in: IWSA (Ed.), The Blue Pages, The IWSA Information Source on Drinking Water Issues, IWSA, London, 1998.
[5] S.R. Tannenbaum, L.C. Green, Selected Abstract on the Role of Dietary Nitrate and Nitrite in Human Carcinogenesis, first ed., International Cancer Research Data Bank Program, National Cancer Institute, Washing-ton, DC, 1982.
[6] WHO, Guidelines for Drinking Water Quality, third ed., World Health Organization, Geneva, 2003.
[7] K.S. Haugen, M.J. Semmens, P.J. Novak, A novel in situ technology for the treatment of nitrate contaminated groundwater, J. Water Res. 36 (2002) 3497–3506.
[8] M. Escoo Nezhad, Engineering Economypers, thirty-two ed., Publication Amir Kabir University, Tehran, 2009, pp. 3–5. Available from: www.ie-iran.ir.pdf.
[9] J.N. Cevaal, W.B. Suratt, J.E. Burke, Nitrate removal and water quality improvements with reverse osmosis for Brighton, Colorado, Desalination 103 (1995) 101–111.
[10] AWWA, Committee report: Current perspectives on residual management for desalting membranes, J. AWWA 96 (2004) 73–87.
[11] H. Strathmann, Electrodialysis, a mature technology with a multitude of new applications, Desalination 264 (2010) 268–288.
[12] H. Strathmann, Ion-exchange Membrane Separation Process (Membrane Science and Technology), first ed., Elsevier, Amsterdam, 2004, pp. 1–19.
[13] Z. Wellpro, GE Power and Water, 2010. Available form: www.ge.com/water.
[14] Japan International Cooperation Agency (JICA), The study on brackish groundwater desalination in Jordan —Final report (summary and main reports), Ministry of Water and Irrigation, Amman, The Hashemite Kingdom of Jordan (1995).
[15] C.h. Amiri, Water Treatment Principles, Arkan, publication, Isfahan, 2005.
[16] L.H. Shafeer, M.S. Mintz, Electro dialysis, principles of desalination, New York, NY, 1966, pp. 200–287.
[17] S. Panglisch, O. Dördelmann, P. Patrick Buchta, F. Klegraf, A. Moshiri, A. Emami, M.R. Fakhraei, W. Höll, Nitrate elimination from raw waters an Iranian-German joint co-operation project, Austria, 2010. Available form: http://www.rcuwm.org.ir/En/Events/Documents/Workshops/Articles/7/6.pdf.
[18] H.O. Winston, W.S. Kamalesh, K. Sirkar, Membrane Handbook, first ed., publication. Van Nostrand Reinhold, 1992, pp. 217–355.
[19] APHA, AWWA and WPC, Standard Method for the Examination of Water and Wastewater, nineteenth ed., American Public Health Association, Washington, DC 1995.
[20] D. Elyanow, J. Persechino, Advances in Nitrate Removal, water and process technologies, 2005. Available form: http://www.gewater.com/Americas/English/TP1033EN.pdf.
[21] J.J. Schoeman, Nitrate-nitrogen removal with small-scale reverse osmosis, electrodialysis and ion-exchange units in rural areas, Water SA 35 (2009) 721–728.
[22] M.A. Menkouchi Sahli, M. Tahaikt, Technical optimization of nitrate removal for groundwater by ED using a pilot plant, Desalination 189 (2006) 200–208.