Large-scale brackish water desalination plants in Gaza Strip: assessments and improvements

Yunes Mogheir, Ahmad A. Foul, A. A. Abuhabib and A. W. Mohammad

ABSTRACT

Water scarcity is a serious challenge in the Gaza Strip, a region that is mostly considered to be semi-arid. In this region, the population's options for provision of potable water are limited to desalination of saline groundwater. Six large brackish water desalination plants (BWDPs) and one seawater desalination plant are operating and providing drinking water along with small private plants. The BWDPs were assessed in terms of operational conditions and quality of their feed and permeate with the aim of estimating essential improvements required as well as performance significance. All these plants are reverse osmosis plants and their operational conditions are similar in terms of production, recovery rate, and energy consumption. The quality of the plants' feed was found not to comply with WHO and Palestinian Standards in most cases, unlike the permeate from all plants. The assessment made through this study assists in better understanding of the current situation of the large-scale desalination plants in Gaza and recommending essential improvements needed to increase water production of these plants without increasing abstraction and feed quantities. In addition, multi-criteria analysis used to evaluate BWDPs performance may assist in prioritizing improvements application.

Key words | assessment, brackish, desalination, groundwater, wastewater

Yunes Mogheir
Ahmad A. Foul
A. A. Abuhabib (corresponding author)
Environmental Engineering Department,
Engineering Faculty,
Islamic University of Gaza, Gaza,
Palestine
E-mail: *azz200@hotmail.com*

A. A. Abuhabib
Department of Civil & Structural Engineering,
Faculty of Engineering & Built Environment,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor,
Malaysia

A. W. Mohammad
Department of Chemical and Process Engineering,
Faculty of Engineering & Built Environment,
Universiti Kebangsaan Malaysia,
43600 Bangi, Selangor,
Malaysia

INTRODUCTION

The desalination story in Gaza began with the first established reverse osmosis (RO) brackish desalination plant in 1991 in Deir El-Balah in the central Gaza Strip (El Sheikh *et al.* 2003). The plant was built with a capacity of 45 m^3/h by a subsidiary of the Israeli Mekorot water company. Since then, many small- and large-scale desalination plants have been built and operated to provide potable water for the population of Gaza Strip, which suffers shortages in water supplies and depends mostly on groundwater with very high salinity levels. Total dissolved solids (TDS) levels are considerably higher than 2,200 mg/l (Abuhabib *et al.* 2012). In the past 20 years, one seawater and six brackish water desalination plants (BWDPs) have been built. The desalinated water produced from these plants represents nearly 4% of the total water consumption by the population, with more than 90% of this population depending on desalinated water for drinking purposes (Al-Agha & Mortaja 2005). Additionally, ten small, private RO desalination plants were established and operated over the Gaza Strip.

The Gaza Strip is a semi-arid region, and as in other Gulf and Middle Eastern countries, there are acute water shortage, and options for providing potable water for the population are limited to brackish and/or sea water desalination. Freshwater availability in these countries is shown in Figure 1, which indicates that eight out of 14 countries have an annual per capita supply of less than 500 m^3 of renewable water resources. In addition, seven of these countries have less than 200 m^3 per capita per year, placing them among the world's 15 poorest countries in terms of water resources availability (ESCWA 2009). Consequently, desalination represents an important option to provide potable water for the population of most of these countries.

Worldwide capacity for production of desalinated water is estimated to be 61 million m^3/day. The share of the

doi: 10.2166/wrd.2013.089

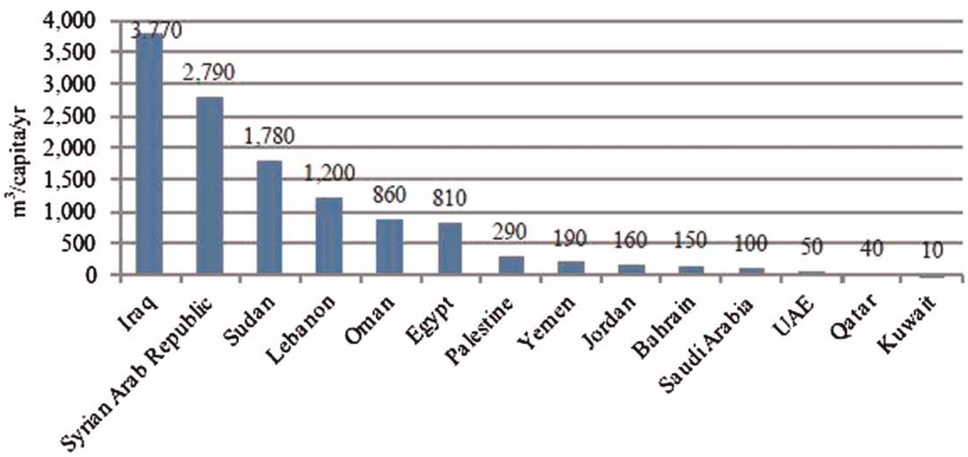

Figure 1 | Renewable freshwater (m^3/c/year) in western Asian countries.

countries of West Asia, including the Gulf and Middle East, is estimated to be 27 million m^3/day, or 44% of global capacity; this is due to increase in the near future (ESCWA 2009). Thermal and membrane desalination processes, as well as hybrid systems, are used in the desalination plants within these countries (Mezher *et al.* 2011). However, only membrane processes (mainly RO) have been considered for brackish or seawater desalination in the Gaza Strip due to the important advantages offered by the RO process (Petersen 1993; Afonso *et al.* 2004; Rahardianto *et al.* 2007; Kim *et al.* 2009; Lee *et al.* 2011; Misdan *et al.* 2012). In contrast, due to high capital costs and high energy consumption (Al-Subaie 2007; Reddy & Ghaffour 2007; Karagiannis & Soldatos 2008; Mezher *et al.* 2011) and limited fuel supplies in Gaza, thermal processes have not been considered as an option.

There are seven public desalination plants located all over the Gaza Strip (Figure 2); they are operated by Coastal Municipal Water Utilities (CMWU), the operating water body in the Gaza Strip (CMWU 2009). These plants provide drinking water for the population in central and southern parts of the Gaza Strip. These plants are BWDPs except for one seawater RO plant located in the central Gaza Strip. Three plants were built 2 or 3 years ago while the others have been operating for more than 12 years. These public plants produce more water at a higher recovery rate and less brine when compared to small private plants. In addition, these plants are directly linked to the municipal water networks whereas private plants have distribution

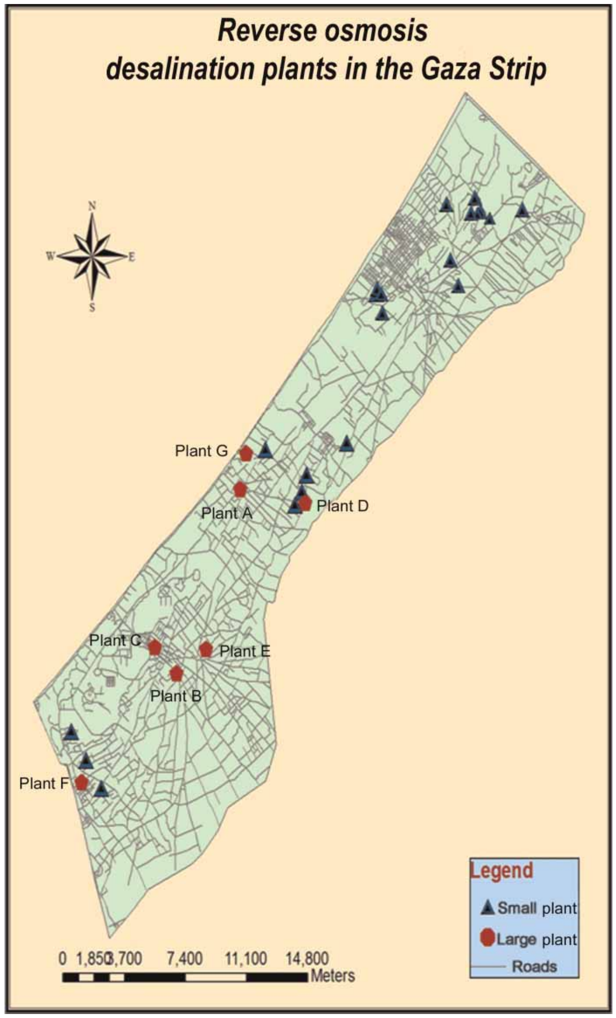

Figure 2 | Small and large (public) BWDPs locations in the Gaza Strip.

vehicles and collecting points where people have to collect the water on their own. According to the Palestinian Water Authority (PWA), the official water regulating body in Palestine (El Sheikh *et al.* 2003), more than 80 small RO private plants and distribution stations are operating and provide potable water for the population of the Gaza Strip at reasonable cost. However, only 37 of these plants are subjected to PWA licensing and regular monitoring.

Despite the fact that many researchers have recently shown interest in studying the desalination practices in the Gaza Strip, only a few studies could be found in the literature (El Sheikh *et al.* 2003; Al-Agha & Mortaja 2005; Baalousha 2006; Al-Khatib & Arafat 2009). El Sheikh *et al.* (2003) studied the desalination strategies in Gaza Strip to be considered from the decision making and strategic planning points of view. Baalousha (2006), assessed the environmental impacts of the desalination practice in the Gaza Strip. According to his study, improper disposal of the desalination plants brine effluent poses a serious threat to the environment in the Gaza Strip.

The present work focusses on assessing the large BWDPs in Gaza in terms of operational conditions and quality of desalinated water produced to identify and recommend possible improvements required in the near future. In addition, an evaluation has been made for all plants to classify the weakest and strongest performing plants to assist in prioritizing the introduction of improvements.

METHODS

The methodology of this study consisted of three parts. First, all large-scale BWDPs were assessed in terms of operational conditions including capacity, type of facility and membrane types, and other related operating parameters such as recovery rate and energy consumption.

The assessment was made by frequent field visits to all plants and observing the operational conditions on a daily basis for certain period of time. Second, samples were taken from all inlets and outlets of plants following the grab sampling method (Moore *et al.* 1981), a single sample or measurement taken at a specific time or over a short period as feasible. In this method a sample collected at a particular time and place can represent only the composition of the source at that time and place, although the source is known to be relatively constant in composition over an extended time. All samples were sent to a certified scientific laboratory (Birzeit University Testing Laboratories, ISO 17025 – Gaza branch) to obtain measures of: pH, TDS, electrical conductivity (EC), turbidity, hardness, chloride, fluoride, nitrates, sulphate, calcium, magnesium, sodium and potassium. These parameters were compared with both World Health Organization (WHO) and Palestinian Standards (PS) for drinking water (WHO 1996; Palestinian Standards Institution 2004). Third, evaluation criteria were established and used to determine the best and poorest performing plants to assist in prioritizing and recommending the introduction of improvements. A multicriteria analysis method was used to determine the strongest and weakest operating plant based on recovery rate, operational and maintenance cost, cost of product (desalinated water) per cubic metre, and TDS removal. Each parameter is rated on a scale of 1–5 points where 1 represents the lowest and 5 represents the highest score. The lowest score indicates the weakest performing plant and the highest score indicates the best performing plant.

RESULTS AND DISCUSSION

Operational conditions

Table 1 highlights all operational conditions of the BWDPs. Plants A, B, and C have been operating for 14–19 years. Plants D, E, and F, however, have been operating for 3 years or less. Plant C was found to have the highest production of about 640 m^3/day at the higher flow rate (80 m^3/h) while all other plants found to have nearly the same production (400–480 m^3/day) at the flow rate of 55–60 m^3/h. Plant A was found to have the highest energy consumption, which could be the reason why the cost per cubic metre permeate produced is approximately double that for all other plants. In terms of recovery rate, the best performing plant is plant D (83%) while the weakest performing plant is B (70%). Although the six plants have the same RO membrane type supplied by Koch, they have some slight differences in terms of performance.

Table 1 | Detailed information for large-scale BWDPs in the Gaza Strip

Plant name[a]	Location	Construction date	Cost (US$)	Capacity (m^3/h)	Production (m^3/day)	Recovery rate %	Energy consumption (kWh)	Cost of desalinated water per m^3 (US$)
Al-Balad (A)	Deir El-Balah	1991	650,000	60	420	75	120	0.72
Al-Sharqia (B)	Khanyounis	1997	500,000	55	440	70	60	0.31
Al-Saada (C)	Khanyounis	1998	250,000	80	640	70	60	0.34
Al-Bureij (D)	Al-Bureij	2009	NA[b]	60	480	83	60	0.28
Al-Nuwairi (E)	B. Suhaila – Khanyounis	2010	NA	50	400	75	60	0.34
Al-Salam (F)	Rafah	2010	NA	60	480	80	60	0.27

[a]Letter in parentheses identifies the plant on the map (Figure 2) and in Tables 2 and 3.
[b]NA: not available.

Water quality parameters

Some water quality parameters were investigated for all plants feed and permeate including: pH, turbidity, nitrates, and fluoride. Control of pH is important as lower and higher values of pH may lead to corrosion and incrustation of pipes. High levels of turbidity affect water taste negatively and indicate the presence of undesirable particles in the water. High levels of nitrates, which are common phenomena in Gaza, are considered as a health threat, as they cause so-called blue-baby phenomenon (Bohdziewicz *et al*. 1999). Fluoride at high concentrations potentially poses health concerns, as it is known to be the cause of dental fluorosis (Mohapatra *et al*. 2009; Richards *et al*. 2010).

Figure 3 shows the pH values measured for feed and permeate of all plants compared with maximum and minimum allowable standards for both WHO and PS (represented as WHO 1 and 2, and PS 1 and 2). All feed and permeate pH values were within the range of WHO and PS standards. Feed pH found to be higher than permeate for all plants. Generally, desalination media is acidic which considered as common trend for RO membranes used for desalination.

Turbidity is a determining parameter for drinking water quality. Generally, some suspended matter or impurities such as clay, silt, sand, and other particles may cause water turbidity. As shown in Figure 4, turbidity levels for both feed and permeate for all plants are below WHO and PS standards.

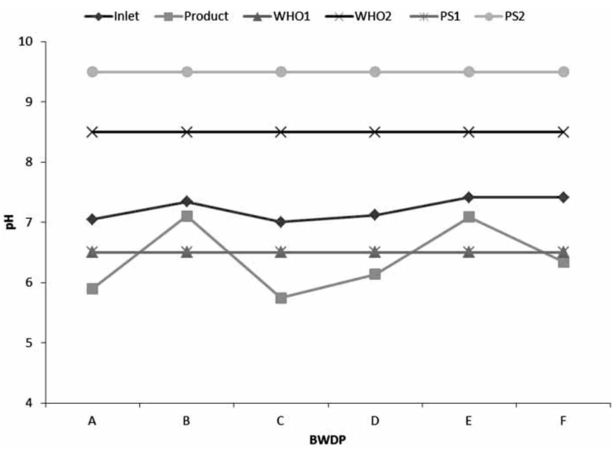

Figure 3 | pH values of inlet and product water against WHO and PS standards for all BWDPs.

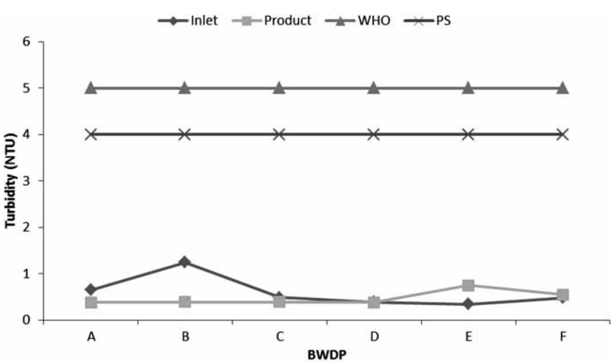

Figure 4 | Turbidity values (nephelometric turbidity units) of inlet and product water against WHO and PS standards for all BWDPs.

Figure 5 shows nitrate concentration levels in the feed and permeate of all plants. Nitrate concentrations of the feed for all plants are much higher than the maximum allowed by WHO and PS standards except for plants D and E, which showed lower concentrations than permitted levels. However, permeate from all plants have lower and allowable concentrations of nitrates by both WHO and PS standards except for plant B, which produced permeate with slightly higher nitrate concentration than permitted by the WHO. Significant nitrate removal could be found in plant C where the level was reduced from nearly 200 mg/l for feed to 50 mg/l for permeate.

Figure 6 illustrates fluoride concentration levels in the feed and permeate for all plants. All feed concentration levels were found to be lower than WHO and PS permitted standards except for plant B which showed very high fluoride concentration (3–3.5 mg/l). However, all concentration levels for permeate found to be lower than allowable according to WHO and PS standards.

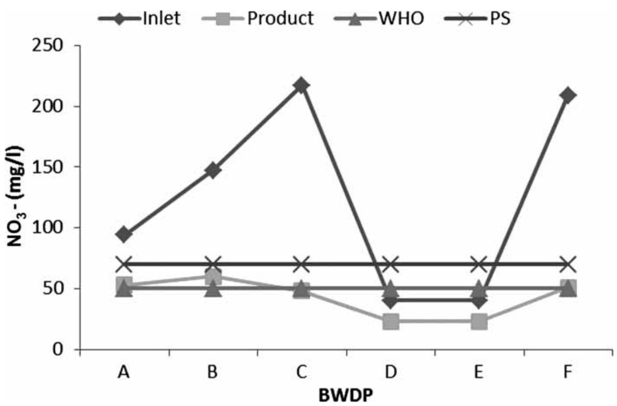

Figure 5 | Nitrates concentrations of inlet and product water against WHO and PS standards for all BWDPs.

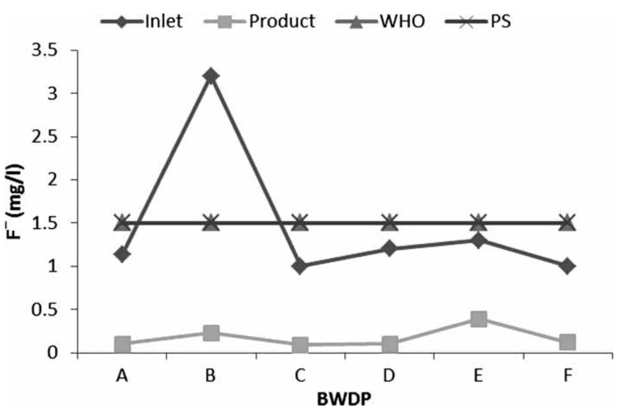

Figure 6 | Fluoride concentrations of inlet and product water against WHO and PS standards for all BWDPs.

Desalination capacity

Conductivity

Figure 7 shows the EC readings of feed and permeate for all plants compared with WHO and PS drinking water standards. All feed readings were found to be higher than WHO and PS standards except for plant E which had an EC reading of 2,000 μs/cm. Therefore, 83% of inlet samples did not comply with WHO and PS drinking water standards. These relatively high EC values of the inlet samples (4,000–6,000 μs/cm) were found to be significantly reduced in produced water of all plants (less than 1,000 μs/cm) and fit with WHO and PS standards. This may indicate the high desalination efficiency and salt rejection of the RO membranes of these plants, as most of the high conductivity measured in the feed water is caused by the presence of salts at high concentrations.

Total dissolved solids

TDS concentrations of feed and permeate of all plants are shown in Figure 8. All feed concentrations of all plants were found to be higher than WHO and PS standards. However, concentrations of permeates at all plants dropped to around 200 mg/l and below for plants C, D, and F, and

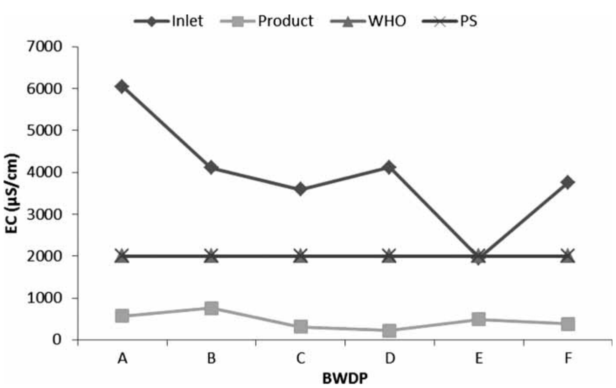

Figure 7 | Electrical conductivity of inlet and product water against WHO and PS standards for all BWDPs.

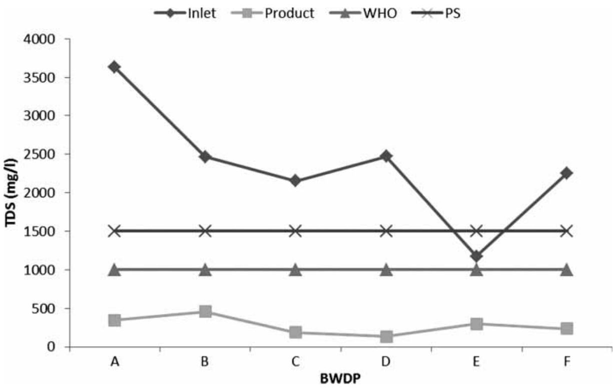

Figure 8 | TDS concentrations of inlet and product water against WHO and PS standards for all BWDPs.

400 mg/l and below for plants A, B, and E. Such concentrations comply with both WHO and PS standards.

Chloride removal

The presence of chloride is considered as one of the major causes of salinity in Gaza groundwater; chloride concentrations found in Gaza groundwater are much higher than the maximum allowed by WHO and PS standards. As shown in Figure 9, all investigated feed samples from BWDPs were found to have high chloride concentrations, ranging from 500 to more than 2,000 mg/l. The maximum chloride concentration was found in plant A feed (more than 2,000 mg/l) while the minimum concentration was found in plant E feed. Plants B, C, and D feeds had chloride concentration around 1,500 mg/l or below. The permeates from all plants were found to have lower chloride concentrations than the maximum allowed by WHO and PS standards. It is worth mentioning that chloride rejection percentage of 93–96% could be found.

Sulphate removal

Sulphate concentrations of plant feeds and permeate are shown in Figure 10. All plant feeds were found to have lower sulphate concentrations than the maximum allowable by WHO and PS standards, and all permeates were found to have acceptable sulphate concentrations, indicating sulphate removal percentage of around 75%.

Hardness removal

Water hardness is a major concern associated with groundwater, as high levels of hardness negatively affect water quality (Van der Bruggen *et al.* 2001). According to WHO and PS standards, maximum allowable values for hardness determined by $CaCO_3$ concentration should be 500 and 600 mg/l respectively. As shown in Figure 11, feeds of plants A and C were found to have higher levels of hardness than the maximum allowed by WHO and PS standards. In contrast, E, B, and D plants' feeds were found to have lower hardness levels. All permeates had lower levels of hardness, complying with both WHO and PS standards. In addition, hardness removal percentage found to be varying from 81 to 99%.

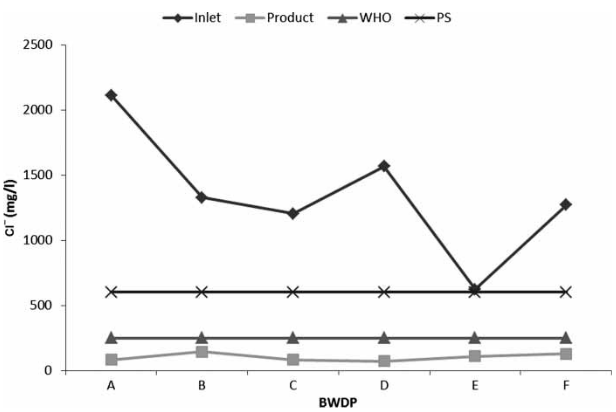

Figure 9 | Chloride concentrations of inlet and product water against WHO and PS standards for all BWDPs.

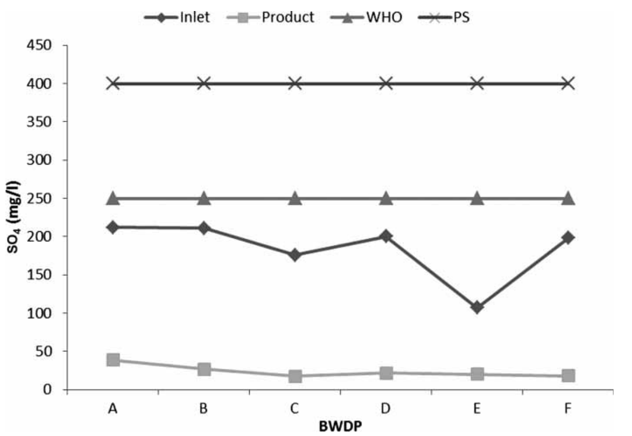

Figure 10 | Sulphate concentrations of inlet and product water against WHO and PS standards for all BWDPs.

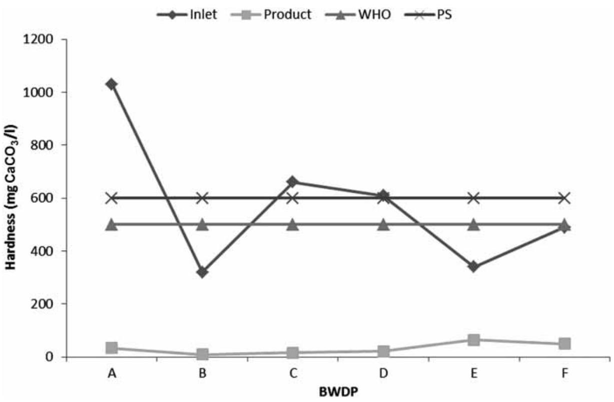

Figure 11 | Hardness concentrations of inlet and product water against WHO and PS standards for all BWDPs.

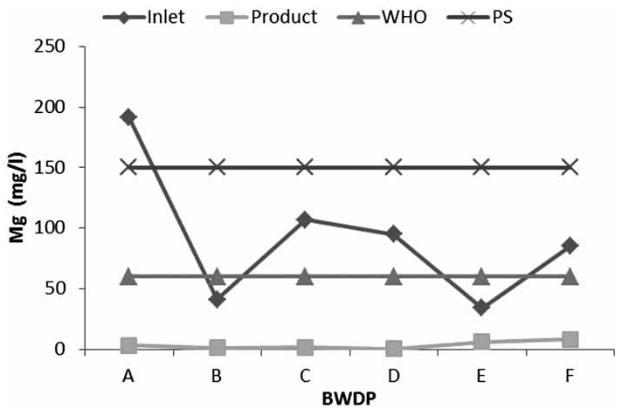

Figure 13 | Magnesium concentrations of inlet and product water against WHO and PS standards for all BWDPs.

Calcium removal

Calcium concentration levels were investigated for all feed and permeate plants and were compared to WHO and PS maximum allowable values. As illustrated in Figure 12, all feeds and permeate of all plants were found to have lower calcium concentration levels than WHO and PS standards.

Magnesium removal

Magnesium concentration levels for feeds and permeate of all plants are shown in Figure 13. Only feeds for plants B and E were found to have lower magnesium concentrations than the maximum allowed by WHO standards while feeds of plants C, D, and F were not. In addition, all feeds of plants were found to have lower magnesium concentrations than the maximum allowed by PS standards except for plant A, which had higher magnesium concentration than the maximum allowed by both WHO and PS standards. Permeate of all plants, however, were found to have lower concentrations than the maximum allowed by both WHO and PS standards. Magnesium removal percentage ranged from 75 to 95%.

Sodium removal

Sodium concentration is considered as a major parameter in groundwater desalination, especially when it is associated with chloride or sulphate. Figure 14 illustrates sodium concentration levels of feeds and permeates. Sodium concentrations of all feeds were found to be higher than

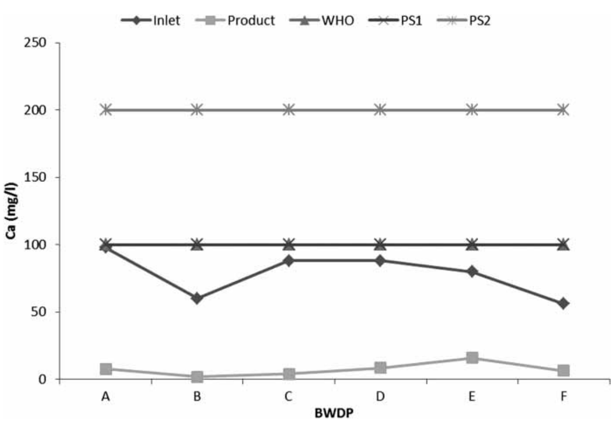

Figure 12 | Calcium concentrations of inlet and product water against WHO and PS standards for all BWDPs.

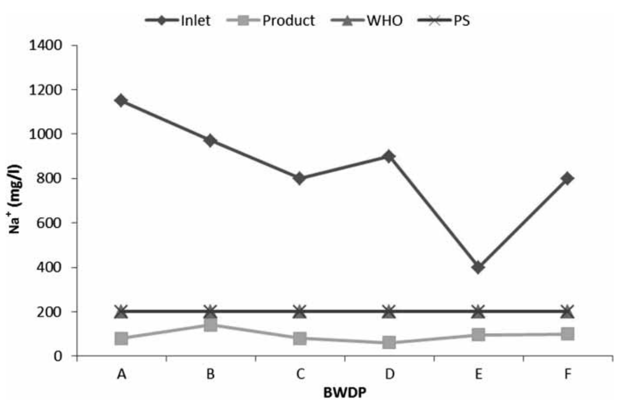

Figure 14 | Sodium concentrations of inlet and product water against WHO and PS standards for all BWDPs.

the maximum allowed by WHO and PS standards, ranging from 400 to 1,200 mg/l. However, all plant permeates were found to have lower concentrations than the maximum allowed by both WHO and PS standards, indicating of an average removal percentage of 87–95%.

Potassium removal

Potassium concentration levels were investigated for both feeds and permeate of all plants and compared with WHO and PS allowable concentration levels. As shown in Figure 15, all plant feeds were found to have higher concentration levels of potassium than allowed by WHO except for plant E, while all feeds were found to have lower concentration levels than the maximum allowed by PS standards except for plant A. However, all plant permeates were found to have lower concentration levels than the maximum allowed by both WHO and PS standards. Potassium removal percentage ranged from 20% for plant E which had the lowest feed concentration to 91% for plant A which had the highest feed concentration.

BWDPs evaluation

Consistent evaluation of all BWDPs is made based on: recovery rate, operational and maintenance cost, cost of desalinated water per cubic metre, and TDS removal. A multi-criteria analysis method was used to determine the strongest and weakest performing plant (Kondili *et al.* 2012).

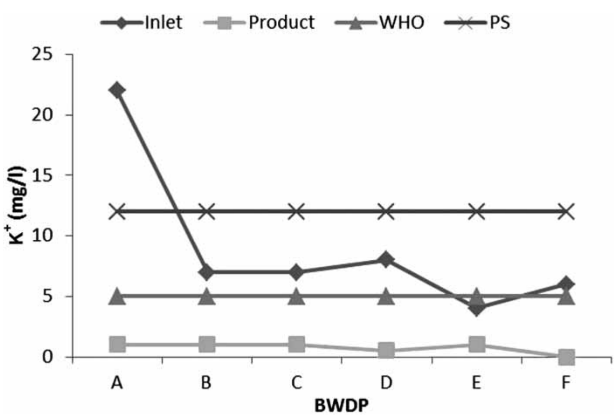

Figure 15 | Potassium concentrations of inlet and product water against WHO and PS standards for all BWDPs.

According to recovery rate, plant D had the highest recovery rate of 83% while plants B and C had the lowest recovery rate of 70% (Figure 16). Plants A and E had the highest and lowest operational and maintenance cost as well as cost of product desalinated water per cubic metre respectively (Table 2). Highest and lowest TDS removal was for plant D (94.66%) and E (74.8%) respectively (Figure 17).

A multi-criteria analysis was used to determine the best and poorest performing plant by rating on a points scale (Table 3). The highest and lowest scoring plants are D and E respectively, meaning that the best performing plant is D and the poorest performing plant is E.

Improvements to BWDPs

According to the evaluation of the BWDPs, the plants are operating well. However, essential improvements are very

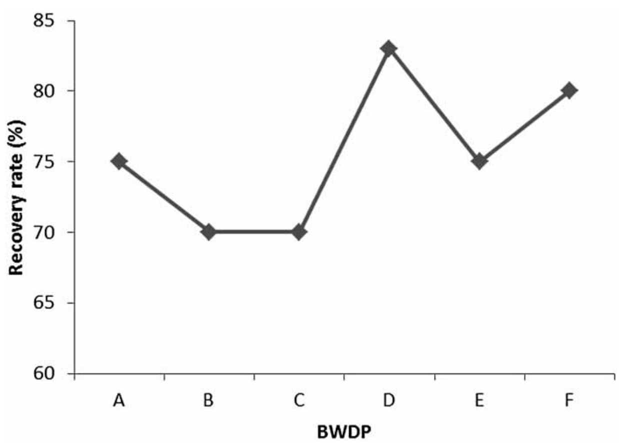

Figure 16 | Recovery rate of all BWDPs.

Table 2 | Operational, maintenance and cubic metre produced costs of desalinated water from BWDPs

	Operation and maintenance cost (US$/h)				
Plant	**Energy consumption**	**Spare parts**	**salaries**	**Total**	**Cost (US$/m³)**
A	16	3.73	12.80	32.53	0.72
B	8	2.40	6.67	17.07	0.31
C	8	2.40	6.67	17.07	0.34
D	8	2.13	4.00	14.13	0.28
E	8	2.40	6.67	17.07	0.34
F	8	2.13	3.47	13.60	0.27

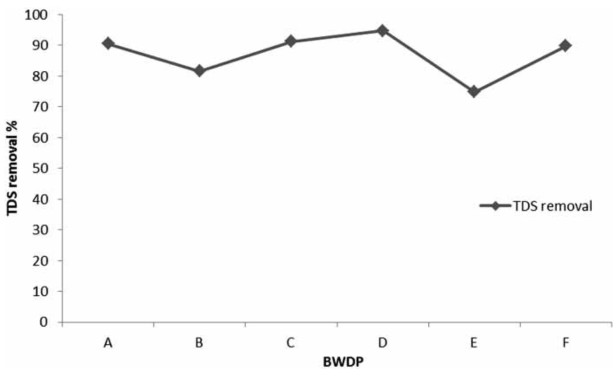

Figure 17 | TDS removal of all BWDPs.

Table 3 | Multi criteria analysis results

	Plants					
Parameter	**A**	**B**	**C**	**D**	**E**	**F**
Recovery rate	3	1	1	5	3	3
TDS removal	4	3	4	5	1	4
Total cost	1	3	3	3	3	3
Total	8	7	8	13	7	10

much needed. New technologies like pre-treatment using nanofiltration (NF) membranes, which was investigated by the authors in previous work (Abuhabib & Mohammad 2011; Abuhabib *et al.* 2012), is highly recommended. Using NF membranes, which have not been used in the Gaza Strip before, can significantly assist in reducing scaling and increase RO membrane lifetimes, as well as increasing recovery rates (Hilal *et al.* 2004). NF membranes are chosen, as the quality of the feed water is characterized by salinity levels that can be sufficiently removed by NF membranes.

Since plant E was found to be the weakest performing plant, it is highly recommended to use NF membranes to pre-treat the feed of this plant prior to using these membranes at the other plants.

CONCLUSION

An attempt to assess and investigate large-scale desalination plants in the Gaza Strip in terms of operational conditions and feed and permeate quality was made. Operationally, all plants found to have almost similar performance except for some slight differences in terms of capacity and cost per cubic metre of desalinated water. From the quality point of view, turbidity, pH, fluoride, hardness, and calcium concentration levels for feed and permeate of all plants were found to be within WHO and PS drinking water standards whereas nitrate concentration levels found to exceed maximum allowable concentrations of WHO and PS for the feed for all plants. Chloride, sulphate, and sodium in the feed for all plants were higher than WHO and PS standards but permeate complied with those standards significantly. However, magnesium, and potassium concentrations for feeds and permeates of all plants (except for plant A) were found to comply only with PS standards. Generally, all plants are performing normally but improvement and increase in their production without increasing their water resources abstraction and energy consumption is essential to meet the water demand of the Gaza Strip population. The multi-criteria method used to evaluate the BWDPs performance could be used as guiding tool to prioritize the application of improvements. In addition, pre-treatment of feeds with some new technologies such as NF membranes could significantly improve the plants' performance and potentially increase their water production.

FUTURE WORK

New technologies including NF membranes will be considered and experimentally investigated to measure the possibility of better performance of the desalination plants and increasing production in the near future. In addition, effluent brine treatment technology prior to disposal may be studied and recommended.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following students of environmental engineering at the Islamic University of Gaza for their work and valuable contribution in conducting this research: Adham Al-Yzaji, Tareq Al-Jourani, Salah Al-Ghazali, and Khaled Abu Ghali.

REFERENCES

Abuhabib, A. & Mohammad, A. W. 2011 Potential of nanofiltration for brackish water desalination in Gaza Strip. *Adv. Mater. Res.* **233**, 2356–2358.

Abuhabib, A., Mohammad, A., Hilal, N., Rahman, R. A. & Shafie, A. H. 2012 Nanofiltration membrane modification by UV grafting for salt rejection and fouling resistance improvement for brackish water desalination. *Desalination* **295**, 16–25.

Afonso, M. D., Jaber, J. O. & Mohsen, M. S. 2004 Brackish groundwater treatment by reverse osmosis in Jordan. *Desalination* **164**, 157–171.

Al-Agha, M. R. & Mortaja, R. S. 2005 Desalination in the Gaza Strip: drinking water supply and environmental impact. *Desalination* **173**, 157–171.

Al-Khatib, I. A. & Arafat, H. A. 2009 Chemical and microbiological quality of desalinated water, groundwater and rain-fed cisterns in the Gaza strip, Palestine. *Desalination* **249**, 1165–1170.

Al-Subaie, K. Z. 2007 Precise way to select a desalination technology. *Desalination* **206**, 29–35.

Baalousha, H. 2006 Desalination status in the Gaza Strip and its environmental impact. *Desalination* **196**, 1–12.

Bohdziewicz, J., Bodzek, M. & Wasik, E. 1999 The application of reverse osmosis and nanofiltration to the removal of nitrates from groundwater. *Desalination* **121**, 139–147.

CMWU 2009 Second Quarter Report for Disinfection & Bi annual Report of Water Quality in Gaza Strip Coastal Municipalities Water Utility.

El Sheikh, R., Ahmed, M. & Hamdan, S. 2003 Strategy of water desalination in the Gaza Strip. *Desalination* **156**, 39–42.

ESCWA (Economic and Social Commission for Western Asia) 2009 Role of desalination in addressing water scarcity. http://www.escwa.un.org/information/publications/edit/upload/sdpd-09-4.pdf (Accessed 2 April 2013).

Hilal, N., Al-Zoubi, H., Darwish, N. A., Mohmma, A. W. & Abu Arabi, M. 2004 A comprehensive review of nanofiltration membranes: treatment, pretreatment, modelling, and atomic force microscopy. *Desalination* **170**, 281–308.

Karagiannis, I. C. & Soldatos, P. G. 2008 Water desalination cost literature: review and assessment. *Desalination* **223**, 448–456.

Kim, Y. M., Kim, S. J., Kim, Y. S., Lee, S., Kim, I. S. & Kim, J. H. 2009 Overview of systems engineering approaches for a large-scale seawater desalination plant with a reverse osmosis network. *Desalination* **238**, 312–332.

Kondili, E., Kaldellis, J. K. & Paidousi, M. 2012 A multicriteria analysis for the optimal desalination–RES system. Special focus: the small Greek islands. *Desalination Water Treat.* **51**, 1205–1218.

Lee, K. P., Arnot, T. C. & Mattia, D. 2011 A review of reverse osmosis membrane materials for desalination – development to date and future potential. *J. Membr. Sci.* **370**, 1–22.

Mezher, T., Fath, H., Abbas, Z. & Khaled, A. 2011 Techno-economic assessment and environmental impacts of desalination technologies. *Desalination* **266**, 263–273.

Misdan, N., Lau, W. J. & Ismail, A. F. 2012 Seawater Reverse Osmosis (SWRO) desalination by thin-film composite membrane – current development, challenges and future prospects. *Desalination* **287**, 228–237.

Mohapatra, M., Anand, S., Mishra, B. K., Giles, D. E. & Singh, P. 2009 Review of fluoride removal from drinking water. *J. Environ. Manage.* **91**, 67–77.

Moore, B. E., Sagik, B. & Sorber, C. A. 1981 Viral transport to ground water at a wastewater land application site. *J. (Water Pollut. Control Fed.)* **53**, 1492–1502.

Palestinian Standards Institution 2004 *Water Quality Standards*. Ramallah, Palestine.

Petersen, R. J. 1993 Composite reverse osmosis and nanofiltration membranes. *J. Membr. Sci.* **83**, 81–150.

Rahardianto, A., Gao, J., Gabelich, C. J., Williams, M. D. & Cohen, Y. 2007 High recovery membrane desalting of low-salinity brackish water: integration of accelerated precipitation softening with membrane RO. *J. Membr. Sci.* **289**, 123–137.

Reddy, K. & Ghaffour, N. 2007 Overview of the cost of desalinated water and costing methodologies. *Desalination* **205**, 340–353.

Richards, L. A., Vuachère, M. & Schäfer, A. I. 2010 Impact of pH on the removal of fluoride, nitrate and boron by nanofiltration/reverse osmosis. *Desalination* **261**, 331–337.

Van der Bruggen, B., Everaert, K., Wilms, D. & Vandecasteele, C. 2001 Application of nanofiltration for removal of pesticides, nitrate and hardness from ground water: rejection properties and economic evaluation. *J. Membr. Sci.* **193**, 239–248.

WHO (World Health Organization) 1996 *Guidelines for Drinking Water*, 2nd ed. WHO, Geneva.

First received 9 November 2012; accepted in revised form 10 February 2013. Available online 17 April 2013