Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2014.940639

55 (2015) 2594–2600
August

Taylor & Francis
Taylor & Francis Group

Impact of well intake systems on bacterial, algae, and organic carbon reduction in SWRO desalination systems, SAWACO, Jeddah, Saudi Arabia

Abdullah H.A. Dehwah[a], Samir Al-Mashharawi[a], Nizar Kammourie[b], Thomas M. Missimer[a,c,*]

[a]*Water Desalination and Reuse Center, King Abdullah University of Science and Technology, Thuwal 23955-6900, Kingdom of Saudi Arabia, Tel. +966 2 808-4964; emails: abdullah.dahwah@kaust.edu.sa (A.H.A. Dehwah), tmissimer@fgcu.edu (Thomas M. Missimer)*
[b]*SAWACO, Jeddah, Kingdom of Saudi Arabia*
[c]*U.A. Whitaker College of Engineering, Florida Gulf Coast University, 10501 FGCU Boulevard South, Fort Myers, FL 33965-6565, USA*

Received 31 March 2014; Accepted 16 June 2014

ABSTRACT

The intake system can play a significant role in improving the feed water quality and ultimately influence the performance of downstream components of the seawater reverse osmosis desalination processes. In most cases, open-ocean intakes produce poor feed water quality in terms of the abundance of naturally occurring organic matter, which increases the risk of membrane fouling. An alternative intake is the subsurface system, which is based on the riverbank filtration concept that provides natural filtration and biological treatment of the feed water prior to the entry of the water into the desalination plant. The use of subsurface intakes normally improves the raw water quality by reducing suspended solids, algae, bacterial, and dissolved organic carbon concentrations. Therefore, the risk of biofouling caused by these substances can be reduced by implementing the appropriate type of intake system. The use of well intake systems was investigated along the Red Sea shoreline of Saudi Arabia in the Jeddah region. Data were collected from a seawater reverse osmosis (SWRO) plant with a capacity of 10,000 m^3/d. The well system produces feed water from an artificial-fill peninsula that was constructed atop of the seabed. Ten wells have been constructed on the peninsula for extracting raw seawater. Water samples were collected from nearby surface seawater as a reference and from selected individual wells. The percentage of algae and bacterial removal by induced filtration process was evaluated by comparison of the seawater concentrations with the well discharges. Transparent exopolymer particles and organic carbon fractions reduction was also measured. The quality of raw water extracted from the well systems was highly improved compared with the raw seawater source. It was observed that algae were virtually 100% removed and the bacterial concentration was significantly removed by the aquifer matrix. The detailed analysis of organic carbon fraction using liquid chromatography-organic carbon detection instrument showed a high-percentage removal of the organic fractions consummate with the molecular weight.

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*Corresponding author.

Presented at the Conference on Desalination for the Environment: Clean Water and Energy 11–15 May 2014, Limassol, Cyprus

The results of this study can be used to improve the intake system design of existing SWRO facilities that might require expansion in future or new facilities that will be located along the Red Sea coastline.

Keywords: Seawater reverse osmosis desalination; Pretreatment; Well intake systems; Membrane biofouling; Transparent exopolymer particles

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1. Introduction

Supplying high-quality feed water to a seawater reverse osmosis (SWRO) desalination plant, while minimizing the environmental impact, is important to assure long-life expectancy for the process membranes [1]. Conventional open-ocean intake systems have been used globally by most SWRO plants to obtain an unlimited quantity of raw seawater. The feed water supplied from such systems usually has poor-quality water characteristics with high concentrations of different organic compounds, freely swimming organisms, algae, bacteria, and suspended sediment, especially during algal blooms (HAB's) and storm events [2]. Generally, extensive pretreatment processes are required to overcome the problems of high-organic content and debris in the feed water when using an open-ocean intake [3]. Moreover, entrainment and impingement of fish and other marine organisms are also associated with the operation of this intake type which can potentially have some impact to the marine environment.

The use of alternative intakes may be a possible solution for reducing the pretreatment requirements and the associated environmental impacts. The use of a subsurface intake system, similar in concept to riverbank filtration, which provides natural filtration and treatment of the seawater before it enters the desalination plant [4]. This system works by utilizing the geological media and marine sediments to filter out the particulates and also, the sediment is biologically active, causing natural organic matter (NOM) to break down. Forced filtration in subsurface intake systems helps in reducing the seawater organic loads, and ultimately in reducing the complexity of the pretreatment system, which lessens the potential for membrane biofouling and results in greater reliability and lower treatment cost [5].

The efficiency of subsurface intake systems (the well type) in terms of organic and micro-organism removal was investigated along the Red Sea coastline of Saudi Arabia. A SWRO desalination plant located at the south part of Jeddah city, Saudi Arabia was investigated to document the effectiveness of a rather unique well intake system (Fig. 1).

Initially, several wells were constructed along the shoreline near the SWRO plant to extract the raw seawater. The beach wells yield a limited supply of water with high-total dissolved solids (TDS) values (reach up to 90,000 mg/L) due to the geological condition of the site. This site is located atop a filled coastal sabkha environment that had hypersaline conditions in the past. Sabkhas are supratidal environments that tend to trap seawater during exceptionally high tides and concentrate it by evaporation because the tidal seawater does not flow freely back to the sea. Because of the hydraulic connection between the shoreline sediments and the sabkha brines, the natural groundwater has a much higher salinity compared with the Red Sea (42,000 mg/L) [6].

To overcome the hypersaline conditions at the intake site, a series of wells were drilled on an artificial-fill peninsula constructed from the shoreline into the nearshore area of the Red sea (inner reef hard ground area). Currently, 10 offshore wells with a depth of between 40 and 50 m are used to deliver the raw water to the desalination facility (Fig. 2). This rather unique wellfield design causes seawater to infiltrate into the seabed and flow into the wells without drawing water from the area landward of the shoreline. The purpose of this research is to evaluate the effectiveness of this offshore well system in the reduction of algal, bacteria, NOM, and transparent exopolymer particles (TEP).

2. Methods

2.1. Sampling methods

The site contains 10 offshore wells with a distance of 20 m between each well. The furthest well (#10) is located 800 m away from the desalination plant. Samples were collected from four different wells (wells 1, 3, 6, and 10) and from the surface seawater that feeds the wells to determine the water quality changes that occur during subsurface flow. Samples were collected and placed into the appropriate types of containers, and transported to the lab facilities the same day of collection. Preservation of the samples after collection was achieved by keeping them at 4˚C and using chemical preservatives as necessary.

2.2. Physical parameters

The general water quality parameters, turbidity, TDS, conductivity, and pH were measured on site for

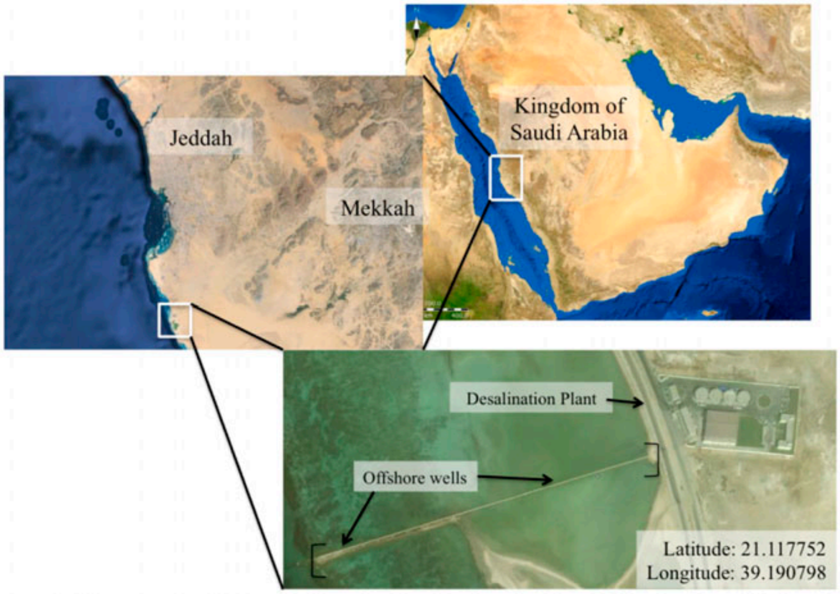

Fig. 1. Location of the studied SWRO facility.

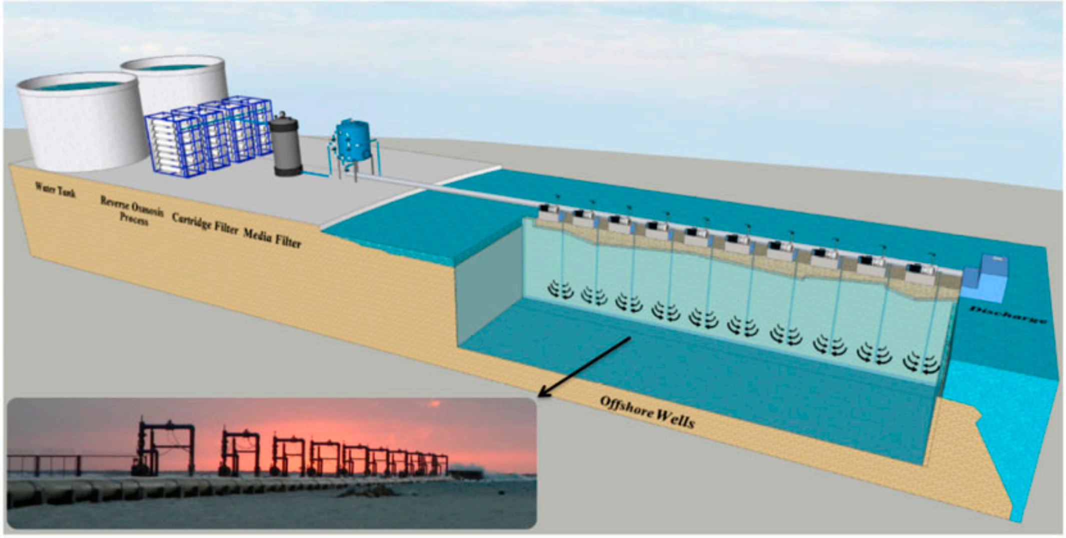

Fig. 2. Offshore wells intake used to supply feed water to the studied SWRO facility.

the collected samples. The turbidity measurements were performed using a portable turbidity meter (HACH 2100Q), while the conductivity measurements were performed using a portable conductivity meter (WTW Con 3210). The field TDS estimate was made using the meter conversion of specific conductance to TDS based on the temperature, and additional TDS measurements were made in the laboratory using a standard gravimetric method.

2.3. *Micro-organism quantification*

Bacterial and algae populations for the collected samples were quantified using a flow cytometer (BD FACSVerse). Collected samples were initially fixed with glutaraldehyde to preserve the original condition in the water. Micro-organism count was conducted based on particle relative size. SYBR Green was used to stain water samples before bacterial analysis and reference beads were added to algae sample for validation. Bacterial and algae content analysis of each sample was performed in triplicate to assure reproducibility.

2.4. Organic carbon

Total organic carbon (TOC) concentration was measured in the seawater and well water using a TOC analyzer from Shimadzu. In addition, the different fractions of dissolved NOM that can contribute to membrane fouling were measured. A liquid chromatography-organic carbon detection (LC-OCD) instrument from DOC-LABOR was used for this analysis [7]. The measured concentrations of NOM in order of increasing molecular weight are low molecular weight acids, low molecular weight neutrals, building blocks, humic substances, and biopolymers.

2.5. TEP measurements

TEP is one of the primary organic substances that can lead to membrane biofouling [8–10]. TEP measurements in this study were performed using the method developed by Passow and Alldredge [11]. Collected samples were initially fixed with 0.02% (w/v) sodium azide during the sampling to limit bioactivity. A quantity of 250 ml of the collected water sample was filtered through 0.4 μm polycarbonate membrane for TEP capturing. Later on, the retained TEP at the membrane surface was stained with alcian blue dye. After that a sulfuric acid with an 80% concentration was used to extract the alcian blue dye that was bound to the TEP at the membrane surface. Finally, the absorbance of the acid solution was measured using a UV spectrometer at (745–752) nm wavelength to quantify the TEP concentration. In order to relate the UV absorbance values to TEP concentrations, a calibration curve was established using xanthan gum solutions (Fig. 3). Then, TEP concentration was expressed in terms of xanthan gum equivalent (μg/L). The measurements conducted are for particulate TEP and colloidal TEP was not measured.

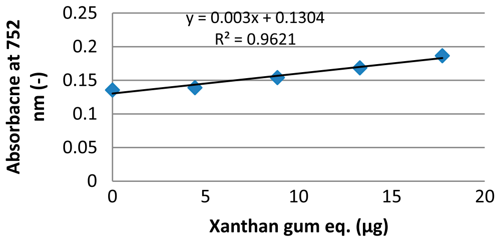

Fig. 3. Xanthan gum calibration curve.

3. Results

3.1. Physical parameters

General water parameters results include turbidity, TDS, conductivity, and pH are presented in Table 1. TDS and conductivity values for Red Sea water and the well discharges are similar, but do have some variation. The laboratory TDS measurements reported do show an inconsistency with the conductivity measurements. This is a common problem and the field conductivity measurements are considered to be more accurate for comparison. The wells do have a generally higher TDS compared with the seawater. Turbidity of the seawater is quite high compared with the well water which show measured values ranging from 57 to 85% lower. The pH of the seawater from the wells is consistently lower than that found in the surface seawater.

3.2. Micro-organism quantification

Bacterial and algae quantification of the wells discharges and seawater was investigated using flow cytometry. A comparison between seawater and well discharge in terms of bacterial and algae concentration was made to determine the removal efficiency by the aquifer.

It has been found that the bacterial concentration have been significantly reduced (up to 97%) by the well system (Fig. 4). The original bacterial population in the seawater was 265,000 cells/ml and in the wells it ranges from 9,000 to 34,000 (cells/mL).

Three types of algae clusters were found in the flow cytometer analysis, including cyanobacteria, prochlorococcus, and pico/nano plankton. The total algae concentration in the raw seawater is 1,677 cells/mL and the predominant group is the cyanobacteria with the prochlorococcus and pico/nonoplankton groups having a much lower count (Table 2). The algae counts in the wells were below the detection limit in all cases.

3.3. Organic carbon

Organic content in seawater is quite variable depending on productivity and physical conditions within the area. The TOC in the Red Sea at this location is 1.02 mg/L and the well discharges all showed concentrations between 26 and 41% lower (Table 3). The NOM fractions in seawater showed that the most abundant was humic substances followed by low molecular weight neutrals, building blocks, low molecular weight acids, and biopolymers (Fig. 5).

Table 1
General water quality parameters measurements at the site

Parameter	Seawater	Well #1	Well #3	Well #6	Well #10
TDS [g/l]	48.4	50.5	49.4	54.5	49.5
Turbidity [NTU]	3.67	0.55	1.58	1.07	1.09
Conductivity [ms/cm]	61.4	66.6	59.8	62.3	59.8
pH	8.24	7.49	7.7	7.63	7.71

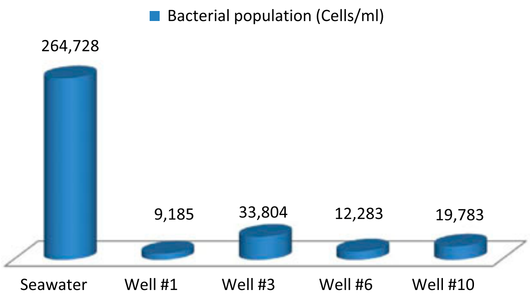

Fig. 4. Bacterial counts in the seawater and the wells discharge.

The concentrations found in the well discharges showed lower concentrations in every class of the NOM fractions. However, the lowest values were from the biopolymers which were very low. The percentages difference in concentration between the seawater and well water in other fractions was considerably less.

3.4. Transparent exopolymer particles

The concentration of particulate TEP was carefully measured for the seawater and the well discharges. Raw seawater has a concentration of about 150 μg/L with the well discharges showing between 55 and 75% lower concentrations (Fig. 6).

4. Discussion

4.1. Physical parameters

The generally higher TDS and conductivity between the seawater and the wells may be related to evaporative concentration of the seawater with the sinking of this water into the underlying sediments. Very warm temperatures, particularly during the summer months, causes a high rate of free surface evaporation in the inner reef area of the marine ecosystem. The higher salinity water will tend to sink to the bottom with most of the water circulating seaward as a density current, but some of it will percolate downward into the sediment underlying the seabed. There may also be some hydraulic connection of the high-salinity water in the sabkha lying to the landward side of the well alignment. However, the unique design of the wells in an offshore location tends to keep the pumping-induced flow path very localized with a minimal gradient from the land toward the sea.

Substantially lower turbidity in the well discharges shows the straining effect of the aquifer system underlying the seabed. The variation in the quantity of total suspended solids removed is a function of the localized geology which is a mix of lithified carbonates (limestone) and unlithified predominantly carbonate sediments.

Table 2
Algae concentration differences between seawater and well system (cells/mL)

Sampling Point	Cyanobacteria	Prochlorococcus	Pico/ nanoplankton
Seawater	1,507	140	30
Well #1	<5	<5	<5
Well #3	<5	<5	<5
Well #6	<5	<5	<5
Well #10	<5	<5	<5

Table 3
Measured TOC concentrations

Parameter	Seawater	Well #1	Well #3	Well #6	Well #10
TOC [mg/l]	1.02	0.69	0.75	0.71	0.59

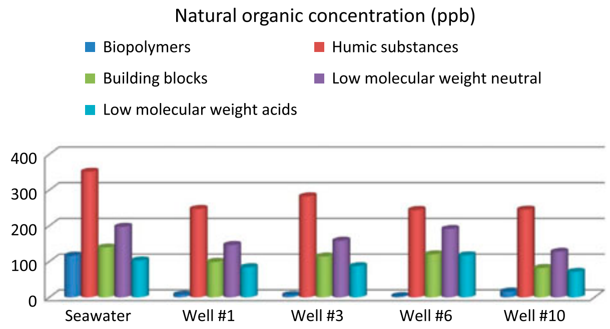

Fig. 5. NOM fraction concentrations in seawater and well discharges.

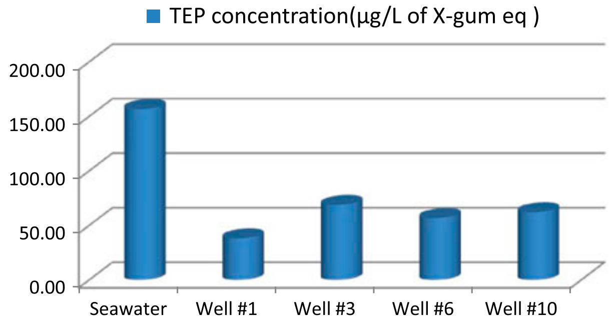

Fig. 6. TEP concentrations in seawater and in the well system.

The higher measured pH in the seawater compared with the well water is likely related to the near saturation of seawater with respect to calcium carbonate. Active cementation of the sea floor is ongoing at this location and therefore, a reduction of pH is expected when the water enters the underlying sediments. Similar pH reductions between the seawater nearshore and the underlying aquifer water were observed in another locations along the Red Sea coast, in Oman, in Spain, and in the Turks and Caicos Islands, where the coastal geology contains carbonate sediments [12].

4.2. Algae and bacteria concentrations

The algae count data shows the offshore well system is highly effective in producing a full removal of algae. While the general pumping-induced flow path is relatively short compared with other coastal well intake systems, full removal was still achieved by the forced filtration through the seabed aquifer. It must be noted that the algae concentrations at this location and time were quite small compared with many other locations, but it is still highly probable that the algae would be removed at a very high percentage even during HABs because the aquifer system below the seabed contain a mix of unlithified carbonate sediments and some shallow limestone which collectively cause intergranular flow which is very effective in particulate removal. This is a major issue because HABs have caused shutdowns of SWRO facilities by overwhelming the pretreatment systems [13,14].

4.3. TOC and NOM fraction concentrations

The induced flow within the offshore wellfield shows that between 26 and 41% of the TOC is removed during transport and all of the NOM fractions are also reduced. The very high removal of the biopolymer compounds which contains the biopolymers, polysaccharides, and TEP is of particular significance. These substances are known to create membrane conditioning that leads to membrane biofouling via a number of biological processes [9,15]. All of the NOM fractions show a reduction in concentration between the seawater and the well discharges. The average percentages of reduction are 93, 27, 25, 21, and 13 for the bioplomers, humic substances, building blocks, low molecular weight neutrals, and low molecular weight acids, respectively. There appears to be a preferential reduction in concentration based on molecular weight with the highest weight organics being removed at the highest percentage.

4.4. TEP concentrations

Between 55 and 75% of the particulate TEP is removed during seawater transport in the aquifer. Although this is significant, it is not as high a reduction as observed in well systems that have a longer induced flow path and a correspondingly longer retention time (e.g. Spain and Turks and Caicos) [12]. This system has been operating for about 2 years and as the underlying aquifer system becomes more biologically active, the removal percentage may increase.

4.5. Effects of well system design and flow path length

The offshore well system design at the site is unique and did solve the problem of production of very high salinity water in the beach well locations. The flow pathway through the seabed into the wells is similar to a gallery intake that has a more direct and shorter pathway. Despite the short flow path, 15–20 m in the vertical direction depending on the position of the uppermost well screen, the system is still quite effective at removal of algae and bacteria, but less effective in the removal of the organic fractions and TEP. As bacterial activity in the subsurface increases with time, the aquifer may become more effective at removal of TEP and the other organic fractions.

5. Conclusions

The water quality impact of a uniquely designed offshore well intake system for a SWRO facility located along the shore of the Red Sea of Saudi Arabia was investigated. Analyses included the measurement of water physical parameters, organic carbon compounds, TEP concentration, algae, and bacterial concentrations. The results showed that high-quality feed water can be obtained using a well system. The algae concentration was fully removed and up to 97% of bacterial content was reduced by the flow through the aquifer into the wells. The TEP and biopolymer concentrations were also significantly reduced between the seawater and the well discharge. All of the NOM fractions showed some reduction in concentration, but the greatest reduction was observed in the biopolymers. Removal of the NOM fractions in the aquifer is selective based on the molecular weight of the fractions.

The reduction in concentrations of organics and micro-organisms demonstrates that the offshore well system is quite effective at delivering a higher quality feed water compared with an open-ocean intake. This allows the SWRO facility to operate using a lesser degree of pretreatment which lowers the frequency of membrane cleanings and reduces operating costs. Also, the system does not impact the marine environment by causing impingement or entrainment of various biota.

Acknowledgments

Funding for this research was provided by King Abdullah University of Science and Technology, Thuwal, Saudi Arabia. The authors thank the Desalination and Water Reuse Center for the use of analytical equipment. The authors would like to thank Khaled Bin Bandar for field and lab support, SAWACO company team and Eng. Najm El-Jafery for access to the facilities and on-site support.

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