Subsurface intake systems: Green choice for improving feed water quality at SWRO desalination plants, Jeddah, Saudi Arabia

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ABSTRACT

An investigation of three seawater reverse osmosis facilities located along the shoreline of the Red Sea of Saudi Arabia that use well intake systems showed that the pumping-induced flow of raw seawater through a coastal aquifer significantly improves feed water quality. A comparison between the surface seawater and the discharge from the wells shows that turbidity, algae, bacteria, total organic carbon, most fractions of natural organic matter (NOM), and particulate and colloidal transparent exopolymer particles (TEP) have significant reductions in concentration. Nearly all of the algae, up to 99% of the bacteria, between 84 and 100% of the biopolymer fraction of NOM, and a high percentage of the TEP were removed during transport. The data suggest that the flowpath length and hydraulic retention time in the aquifer play the most important roles in removal of the organic matter. Since the collective concentrations of bacteria, biopolymers, and TEP in the intake seawater play important roles in the biofouling of SWRO membranes, the observed reductions suggest that the desalination facilities that use well intakes systems will have a potentially lower fouling rate compared to open-ocean intake systems. Furthermore, well intake system intakes also reduce the need for chemical usage during complex pretreatment systems required for operation of SWRO facilities using open-ocean intakes and reduce environmental impacts.

1. Introduction

The use of membrane technology in the desalination industry has increased rapidly during the last 20 years due to its lower cost and energy consumption in comparison with conventional distillation processes (Ghaffour et al., 2013). Currently, membrane technology is used in 60% of seawater desalination processes around the world (GWI, 2012). The major persistent problem that most of seawater reverse osmosis (SWRO) desalination facilities face is membrane biofouling. Membrane biofouling causes the reduction of membrane life-expectancy, reduction of operational efficiency, and increases operation and maintenance costs (Flemming, 1997; Vrouwenvelde et al., 1998). In some cases, membrane biofouling can lead to temporary plant shutdowns. As a means of reducing the effect of this problem, pretreatment processes are installed to improve the quality of raw water before it enters the SWRO process. Although expensive and extensive treatment processes using chemicals are operated for this purpose, frequent membrane cleaning is still commonly necessary (Missimer et al., 2010). Therefore, it is important to supply high feed water quality to the desalination facility at the initial intake stage in order to reduce the complexity of the pretreatment components. One way to achieve that is by implementing the appropriate type of intake.

Conventional open-ocean intakes are used by most SWRO desalination facilities for supply of unlimited feed water capacity. Generally, this type of intake provides poor and inconsistent seawater quality based on the seasonal changes, especially during harmful algal bloom events which can cause temporary plant shutdowns (Berktay, 2011; Villacorte et al., 2015). In addition, the operation of surface intake systems makes the desalination plant more vulnerable to environmental impacts, such as entrainment and impingement of fish and other marine organisms (Lattmann and Hopner, 2008; WaterReuse Association, 2011). In general, extensive pretreatment systems have to be installed to improve the poor quality of the raw water supplied by the open-ocean intake system to avoid membrane biofouling, particularly removal of...
algae, bacteria, and natural organic compounds.

An alternative “green” intake that can be utilized to improve the quality of feed water delivered to a SWRO desalination facility is a subsurface intake system. This type of intake is similar in concept to river bank filtration wherein the native geological media is used to naturally filter the raw water before entering the treatment facility (Ray et al., 2002; Hubbs, 2005). Subsurface intakes provide physical and biological mechanisms for filtering the feed water by straining and biodegrading of organic matter and other particulates while passing through marine sediments and the seabed similar to a slow sand filter used in freshwater treatment plants (Schwartz, 2000; Laparc et al., 2007; Missimer et al., 2013; Rachman and Missimer, 2014). The operation of this intake type is more environmentally friendly since no impingement and entrainment of marine organisms occurs as well as less or no chemical additives are required to be used during the pretreatment stage (Missimer et al., 2013).

Since biofouling of SWRO membranes has been documented along the Red Sea coast of Saudi Arabia (Saeed et al., 2000), the key research objective of this investigation is to evaluate the performance of subsurface intake systems in terms of improving the raw seawater quality with the potential of reducing the rate of membrane biofouling. Three SWRO desalination plants located in Jeddah city along the Red Sea coastline of Saudi Arabia were investigated (Fig. 1). These three plants use vertical well systems as a means of extracting the raw seawater. The aquifer systems at these sites are composed of either siliciclastic or carbonate sediments. Water samples were collected from surface seawater and the well discharges for comparison. Algae, bacteria, fractions of natural organic matter (NOM) and transparent exopolymer particle (TEP) concentrations were measured to determine the degree of concentration reduction by the aquifer system during flow from the sea into the wells. The results of this research will be very useful in planning and improving the design of intake and pretreatment systems for existing and future SWRO plants.

2. Material and methods

2.1. Description of the studied SWRO plants

2.1.1. North Obhor (Site A), Jeddah, Saudi Arabia

The North Obhor SWRO plant is located north of Jeddah city and it has been in operation since 2001. This plant has a permeate capacity of 13,350 m$^3$/day. A total of 14 vertical wells are used to produce a total of 33,375 m$^3$/day of feed water required for operation (Fig. 2, site A). The wells are constructed into a coralline limestone aquifer with depths ranging between 50 and 55 m. These wells are located inland at a distance of about 450 m from the seawater source. The age of the wells ranges from 4 to 14 years with wells 1A and 2A being 14 years, well 3A at 11 years, and well 4 at 4 years. Since 2007 the membranes at this facility are cleaned less than once every 2 years.

Fig. 1. Location of studied SWRO facilities along the Red Sea coastline of Saudi Arabia.
2.1.2. Corniche (Site B), Jeddah, Saudi Arabia

The Corniche SWRO desalination plant is located in the middle of Jeddah city and has a total permeate capacity of 4500 m³/day. This facility requires 11,250 m³/day of feed water which is extracted by a series of 5 vertical wells that are constructed into an aquifer consisting of siliciclastic sediments (Fig. 2, site B). The total depth of these wells ranges from 46 to 50 m below surface. At this site, the wells are located at a distance of about 300 m from the sea. The ages of the wells range from 6 to 8 years. The raw water extracted from this site has a secondary problem with high iron concentration, which causes challenges for the pretreatment system. The life span of the cartridge filters used at this facility is very short due to the high iron concentration problem which is attributed to the passage of raw water through the heterogeneous siliciclastic system containing various natural and perhaps man-made sources of iron (buried metallic debris). Cleaning frequency of the SWRO membranes is every 6 month due to the occurrence of dissolved iron in the raw water.

2.1.3. South Jeddah Corniche (Site C), Jeddah, Saudi Arabia

The South Jeddah Corniche SWRO desalination plant is located south of Jeddah city and has a total permeate capacity of 10,000 m³/day. The intake system at this site has a feed water capacity of 25,000 m³/day, which is produced from 10 vertical wells that have been operating for 3 years. The SWRO membrane cleaning frequency at this facility typically ranges from 6 months to a year. A geochemical problem unrelated to biofouling affected operations for about a year in 2012.

These wells are drilled on an artificial fill peninsula constructed into the nearshore area of the Red Sea (Fig. 2, site C). During the initial construction of the plant, several wells were installed along the shoreline for raw water extraction. During the testing phase, it was found that the salinity of the produced feed water from these wells was significantly higher than that in the Red Sea and the wells had low yields. The geological conditions at this site were the reason for this high salinity and limited capacity of produced water. This site was constructed into a coastal sabkha environment which is an area where the trapped seawater evaporates causing the precipitation of evaporite minerals and ultimately the formation of hypersaline conditions (Dehwah et al., 2014). This sabkha environment is in hydraulic connection with the sea which causes the flow of hypersaline water toward the shoreline making the coastal alluvial aquifer unfeasible for subsurface intake development. An innovative design was implemented at this site to overcome this hypersaline condition problem, in which an artificial peninsula was constructed from the beach seaward on the inner reef hardground (no corals present). The wells were drilled using the artificial fill as a base. The aquifer beneath this artificial peninsula consists of soft limestone and un lithified carbonate sediments. The offshore wells are spaced 20 m apart and range in depth from 40 to 50 m.

2.2. Sampling methods

Seawater samples were collected from selected well discharges at the three different sites. A total of 12 wells were included in the study, four wells from each desalination plant. Samples for site A were collected at the end of October, 2014, site B at the beginning of November 2014 and site C at the end of December 2014. In addition, a sample from open seawater was collected at each of the three sites at the same time as the collection of the well samples. The seawater sample was used as a reference to evaluate the changes in the raw seawater quality as it passes through the aquifer system.

The water samples were collected using quality assurance protocols to preserve the constituents to be analyzed in the laboratory. Water was taken from the pump discharge of the operating wells, which is considered to be a representative sample. Upon collection, all samples were placed in bottles that were placed in a container filled with ice to minimize biological activity. The collected samples were initially fixed with 0.02% (w/v) sodium azide solution during the sampling to further control bioactivity. The collected samples were transported the same day to the laboratory for analysis of the concentrations of algae, bacteria, natural organic matter fractions (NOM), transparent exopolymer particles (TEP), and the physical parameters. Samples were stored at 4 °C in the laboratory before analysis to limit bioactivity. Sample retention time was minimized to be sure that the sample concentrations represented field conditions.
2.3. Water quality measurements

2.3.1. Fundamental water quality parameters

The collected samples were analyzed to measure the fundamental water quality parameters. The physical parameters included turbidity, salinity, conductivity, and pH. A portable turbidity meter (HACH 2100Q) was used to measure the sample turbidities while a portable pH meter (WTW pH 3310) was used to measure pH values. The conductivity and salinity measurements were performed using a portable conductivity meter (WTW Con 3210).

2.3.2. Micro-organism quantification

Algae and bacteria counts in the collected water samples were determined using a flow cytometer. A BD FACSVerse flow cytometer was used to analyze the algae cells, while an Accuri flow cytometer was used for bacterial counts. Light scattering properties and/or fluorescent intensity was determined by the flow cytometer to distinguish between the different organism classifications (Van der Merwe et al., 2014). Lasers are used to excite both unstained autofluorescent organisms (algae) and stained bacterial cells. The red laser wavelength was set at 640 nm and the blue laser at 488 nm. Algal cell counting was performed by combining 500 μL of each sample with 1 mL volume of beads in a 10 mL tube. The tube was then vortexed and measured using the high flow rate with a 200 μL injection volume for 2 min. The counting procedure was repeated three times to assess the precision of the measurements. The different types of algae, Cyanobacteria, Prochlorococcus, and Pico/Nanoplankton, were distinguished based on their autofluorescence as well as by the cell side angle scatter which is used to identify them by size (Radić et al., 2009).

For bacterial counts, a comparative protocol employing SYBR® Green stain was used. A volume of 500 μL from each sample was transferred to a 10 mL tube, incubated in a 35 °C water bath for 10 min and stained with the SYBR® Green dye (5 μL into 500 μL aliquot), vortexed, and incubated for another 10 min. The prepared samples were then analyzed at a medium flow setting with a 50 μL injection volume for 1 min. Triplicate measurements were made on each sample to assess measurement precision.

2.3.3. Total organic carbon and NOM fraction concentrations

The total organic carbon concentrations in the samples were measured using a Shimadzu TOC-VCSH instrument. The detailed fractions of dissolved organic carbon were determined by using a Liquid Chromatography Organic Carbon Detector (LC-OCD) from DOC-Labor. The protocols and methods developed by Huber et al. (2011) were followed in order to measure the different fractions of NOM using LC-OCD and have been previously described in Dehwah et al. (2015).

The size exclusion chromatography column that was used for this experiment is a Toyopearl HW-50S which is produced by Waters. For the molecular mass calibration, humic acid was used for the 0.1 μm pore size membrane to allow deposition of the colloidal TEP on the membrane surface.

In order to relate the UV absorbance values to estimated TEP concentrations, a calibration curve was established. Xanthan gum solutions with different volumes (0, 0.5, 1, 2, 3 mL) were used to obtain the calibration curve (Supplemental Information). The TOC concentrations of xanthan gum before and after 0.4 μm filtration were analyzed, and the TOC concentration difference was used to calculate the gum mass on each filter and the TEP concentration was estimated using the calibration curve. The same procedures were used for the 0.1 μm membrane to establish the calibration curve for colloidal particles. Afterwards, the TEP concentration was expressed in terms of Xanthan Gum equivalent in µg TEP/L by dividing the TEP mass on the corresponding volume of TEP samples. Because particulate and colloidal TEP is determined indirectly, these values must be considered to be semi-quantitative.

3. Results

3.1. Fundamental water quality parameters

The fundamental water quality parameters, which include the conductivity, salinity, pH, and turbidity, are presented in Table 1. The results show that the conductivity and associated salinity are slightly higher in all well discharges compared to that in the
adjacent surface seawater. The pH values in the seawater are higher than in the corresponding well discharge water at all sites. The turbidity is much lower in the well discharges at sites A and B and slightly lower at site C.

3.2. Microorganism quantification

Algae and bacterial concentrations were measured in both the surface seawater and the well discharges. The algal count included three different clusters Cyanobacteria, Prochlorococcus, and pico/nanoplankton. The predominant cluster at all the three sites is cyanobacteria. The total algae concentration in the raw seawater was about 130,000 cells/ml for site A, 90,000 cells/ml for site B and 43,000 cells/ml for site C. The algal concentration in the wells was below the detection limit of the method at sites A and B. Therefore, the algae were totally removed by the aquifer system at sites A and B, but some very low concentrations algae were present at site C (Table 2).

The original bacterial concentration of seawater was 520,000 cells/ml for site A, 254,000 cells/ml at site B, and 216,000 cells/ml at site C. The bacterial population was significantly reduced after the seawater passed through the aquifer from the sea into the wells (Fig. 3). The average bacterial concentration removal by the aquifer system was 98% for site A and 88% for both sites B and C.

### Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conductivity [ms/cm]</th>
<th>Salinity</th>
<th>pH</th>
<th>Turbidity [NTU]</th>
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<td>39.1</td>
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<td></td>
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<td>58.9</td>
<td>39.7</td>
<td>7.4</td>
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<tr>
<td></td>
<td>Well A4</td>
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</tr>
<tr>
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<td>39.5</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>Well B2</td>
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<td></td>
<td>Well B3</td>
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<td></td>
<td>Well B4</td>
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<td></td>
<td>Well C4</td>
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<td>7.8</td>
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### Table 2

<table>
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<tr>
<th>Sampling point</th>
<th>Cyanobacteria</th>
<th>Prochlorococcus</th>
<th>Pico/nanoplankton</th>
<th>Total algae (cells/ml)</th>
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<tr>
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<td>25,455</td>
<td>4863</td>
<td>129,738</td>
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<td>&lt;50</td>
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<td>&lt;50</td>
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<td>&lt;100</td>
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<td>&lt;50</td>
<td>&lt;50</td>
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<td>89,033</td>
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<td>&lt;50</td>
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<tr>
<td>Well B3</td>
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<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;100</td>
</tr>
<tr>
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<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Site C</td>
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<td>10,633</td>
<td>3807</td>
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<tr>
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<td>&lt;50</td>
<td>730</td>
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<td>230</td>
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<tr>
<td>Well C3</td>
<td>&lt;50</td>
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<td>80</td>
<td>677</td>
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<td>Well C4</td>
<td>&lt;50</td>
<td>77</td>
<td>&lt;50</td>
<td>107</td>
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</tbody>
</table>

Fig. 3. Measured bacterial concentrations at the studied sites.
sites B and C.

3.3. Total organic carbon and natural organic matter (NOM) fraction concentrations

The well discharges showed significant reductions of total organic carbon concentration from the surface seawater to the well discharges (Table 3). The reduction ranged between 16 and 70%. The highest percentages of reduction were observed at site A. The reduction percentage at site C was significantly lower compared with the other two sites.

The different fractions of natural organic matter were measured for the raw seawater and the well discharges. The measurements showed that humic substances and low molecular weight neutrals are the most abundant fraction in the raw seawater, followed by building blocks, biopolymers and low molecular weight acids (Fig. 4).

The analysis of the well discharge samples revealed that most of the different fractions experienced a reduction in the concentration as seawater passed through the aquifer system from the sea to the wells (Fig. 4). The percentage reduction of each fraction varied between the sites and internally between different wells at the same site. However, the highest removal percentage of most of the fractions was observed at site A. The fraction that exhibited the highest reduction percentage was the biopolymers. The average biopolymer removal percentage was 96%, 95% and 90% for sites A, B and C respectively. Reductions in humic substances and building blocks were observed in all wells compared to the surface seawater with greater removal percentages occurring in the humic substance concentrations. Significant reductions in the lower molecular weight acids also occurred. However, the removal of the low molecular weight neutrals was much lower and in certain cases there was an increase in concentration compared to seawater.

3.4. TEP concentration

Particulate and colloidal TEP concentrations were measured for the natural surface seawater and the well discharges at the three studied sites (Fig. 5). Particulate TEP concentrations measured in the raw seawater were about 320 μg Xeq./L for site A and about 250 μg Xeq./L for sites B and C. The colloidal TEP concentrations in the raw seawater were significantly lower than particulate TEP concentration at all sites. At the well discharges, particulate and colloidal TEP concentrations were significantly lower compared to corresponding values in the raw seawater (Fig. 5). The particulate TEP concentration reduction in the well discharges averaged 86%, 73% and 72% for sites A, B and C respectively. Moreover, the colloidal TEP concentration reduction by the aquifer transport averaged 50%, 56%, and 68% for sites A, B and C respectively.

4. Discussion

4.1. Improvement of feed water quality by the well intake system

It was observed that raw seawater quality was improved greatly after passing through the aquifer system at all the studied sites. The physical water characteristics did exhibit some minor increases in salinity and a decrease in pH, both of which have minimal impact on membrane treatment efficiency. The turbidity was reduced significantly between the raw water and the most of the well discharges. This improvement is significant and reduces the potential for general biofouling of the membranes. In addition, a significant reduction occurred in concentrations of algae, bacteria, TOC, NOM fractions (with exception of the low molecular weight neutrals), and TEP concentrations.

The analysis of physical water quality parameters showed that physical straining by the aquifer system removes most of the
algae with the exception of the wells at site C where some algae with the hardground is found in most areas. The sediments are cemented and would precipitate at the sea floor and dissolved carbon dioxide slightly is commonly higher in the groundwater due to degradation of organic matter. Therefore, the raw seawater with less calcium carbonate content will pass through the aquifer system. Evidence for precipitation of CaCO₃ occurs on the seabed where a limestone hardground is found in most areas. The sediments are cemented with fine-grained aragonite and high magnesium calcite.

The raw water extracted from the well system was almost free of algae with the exception of the wells at site C where some algae breakthrough occurs. Bacterial concentrations were significantly removed from the seawater during the transport through the aquifer. The reduction in microorganism count is associated with the organic carbon removal close to the marine sediment/water interface. Therefore, less organic matter will be available for bacterial uptake in the aquifer. There is also a possibility that these organisms have been strained and adsorbed by the aquifer matrix. Moreover, it is expected that the predation by groundwater bacterial species may also play a role in decreasing the seawater bacterial population. However, more research will be required to validate this assumption.

In general, influx of raw seawater into the SWRO treatment facility with a lower microorganism concentration should improve the membrane performance since the tendency for biofilm formation should be lower. The reduction in the rate of biofilm formation may also be related to a lower concentration of associated organic compounds, such as algal-derived organic matter (AOM) and TEP, which are produced by algae and bacteria in the raw water. AOM is known to increase bacterial activity in seawater (Villacorte et al., 2015). The elimination of algae is of a great benefit to the desalination plants especially in areas where algal bloom events are common. Having such a system will help in protecting desalination plants from unexpected algal bloom events that might cause temporary plant shutdowns (Berkay, 2011; Villacorte et al., 2015).

The total organic carbon concentration at the raw seawater was reduced by more than 50% as it passed through aquifer that feeds the vertical wells at both sites A and B. The removal percentage at site C was lower at 16–24% of the total organic carbon. Most probably, during the transport of seawater to the wellfield, this organic carbon was partially degraded by the bacterial population that lives within the aquifer matrix. Moreover, the additional biochemical processes within the aquifer matrix will play a role in organic carbon reduction. The adsorption of organic carbon into the sediment/water interface and within the aquifer matrix reduces the organic content as well.

A similar trend was observed in the NOM fractions compared to TOC, wherein most of the studied fractions showed a reduction in concentration as seawater is pumped through the aquifer and is yielded from the wells. The biopolymer fraction, which has the largest molecular weight among all other studied fractions, was significantly removed from the seawater as it percolates through the aquifer. Most probably the removal of the biopolymer fraction by the aquifer is attributed to the size exclusion mechanism (straining) and adsorption because it has the largest molecular size and may contain sticky polysaccharides. The other fractions which include humic substances and building blocks were also reduced greatly at site A (64%, 54%) and moderately at site B (45%, 31%) for humic substances and building blocks respectively. The total removal percentage at site C was low for both fractions (14%, 17%). The low molecular weight acids were also partially removed by the aquifer system, but the removal rate differs from one site to another. However, the low molecular weight neutrals were not effectively removed. The increase in concentration of this fraction in some wells may be the result of bacterial breakdown of large molecular weight substances in the groundwater system, causing some production of the low molecular weight organics as a result.

There is a tendency for the removal percentage of NOM fractions to be related to the molecular weight with the highest weights being removed at the highest percentages. Moreover, biochemical processes are playing a role in the NOM removal such as biodegradation by bacteria. The removal of the NOM is of significant importance to the operation of the desalination plants. The organic matter is food for bacteria and its presence within the raw water causes an operational problem for the downstream components of the desalination plant. In addition, the biopolymer fraction contains particulates from the raw seawater as indicated by the lower turbidity values in most of the well discharges. The remaining turbidity likely occurs due to scour of some particulates from the aquifer. In general, the salinity and conductivity of water from the production wells were similar or slightly higher than the raw seawater which supports the assumption that wells are mostly recharged from the seawater source. The lower pH values at the well discharges compared to the seawater are related to the higher saturation of seawater with calcium carbonate compared to the groundwater samples. The high rate of evaporation along the Red Sea nearshore area causes increased calcium carbonate saturation within the water column. As the seawater passes through the underlying sediments, it is expected that some calcium carbonate would precipitate at the seafloor and dissolved carbon dioxide slightly is commonly higher in the groundwater due to degradation of organic matter. Therefore, the raw seawater with less calcium carbonate content will pass through the aquifer system. Evidence for precipitation of CaCO₃ occurs on the seabed where a limestone hardground is found in most areas. The sediments are cemented with fine-grained aragonite and high magnesium calcite.
proteins and polysaccharides (Repeta et al., 2002) which enhance membrane biofouling by producing membrane conditioning (Baek et al., 2011), which harms the facility by reducing the membrane flux and its expected life. Filloux et al. (2012) found that reducing the concentration of the biopolymer fraction of NOM reduces the fouling rate in low-pressure membranes.

The measurement of TEP concentrations showed that the aquifer matrix is effective in reducing particulate and colloidal TEP concentrations. The total percentage reduction of particulate TEP was >70% and colloidal TEP >55% at all three sites. Most probably, filtration, adsorption and biological activities occurring within the aquifer matrix and the underlying sediments are the reasons behind TEP concentration reduction. Having low concentrations of TEP will help increase the membrane life expectancy, as well as minimizing the chemical cleanings. TEP particles tend to form a conditioning layer on the membrane surface which leads to formation of a biofilm layer that ultimately causes flux reduction and operational problems within the SWRO desalination plant (Bar-Zeev et al., 2015).

The use of well intakes at the facilities investigated showed a clear improvement in operations based on a lower frequency of membrane cleaning. At site A the membrane cleaning frequency was less than every 2 years, at site B it is every 6 months to one year, and at site C the cleaning frequency is every 6 months to one year. In comparison, a survey of SWRO plants using open-ocean intakes in this region showed a membrane cleaning frequency of 2.5–3 months.

4.2. Effects of well intake design by variation of travel distance and aquifer hydraulic retention time on improving raw seawater quality

The design of a subsurface intake system can control the performance and efficiency of downstream components within the desalination plant. The geological media, bottom conditions, flow line path length, and hydraulic retention play a role in improving the natural treatment effectiveness of a subsurface intake system (e.g., wells). In this study, three desalination plants with differing geological media and well intake designs were investigated.

The aquifer at site A consists of carbonate sediments and coralline limestone, site B wells were drilled into siliciclastic sediments, and the design of site C was unique, where the wells were drilled into an artificial fill peninsula that was constructed in the nearshore area of the Red Sea. Site C also has an underlying aquifer constituted of un lithified carbonate sediments and limestone. The limestone may contain some vertical solution cavities that may short-circuit travel of the seawater through the porous media. The shoreline geology at site C was originally not supportive for construction of production wells since the area was a sabkha containing high salinity within the groundwater system. Site A which contains carbonate sediments showed superb performance compared to the other sites. The reduction in algae, bacteria, TOC, NOM and TEP concentrations was extremely high. Most probably the high surface area of the un lithified carbonate sediments allows greater adsorption rates and the biochemical breakdown of organic matter. The aquifer system at site B consists of heterogeneous siliciclastic sediments of an alluvial nature, and also showed a significant improvement in seawater quality, but not as high as the carbonate sediments found at site A, especially in terms of NOM and TEP concentration reduction. The site C wellfield has the unique design, lying on an artificial fill peninsula, but showed the lowest reduction percentage of the organics in terms of TOC and NOM concentrations. The algae, bacterial and TEP removal percentages were similar to those found at site B, but some algae breakthrough was observed at site C. While there were differences in the geology, no clear relationship between the aquifer matrix material and the degree of treatment of the inflowing seawater was observed. However, the possible dissolution of the limestone within the subsurface limestone at site C may be responsible for the algae breakthrough.

Additional considerations that influence the potential treatment effectiveness are the length of the pumping-induced flow path from the sea bottom to the wells and the aquifer retention time. These issues are directly related. To study the effect of flow pathway length and associated retention time in improving the raw seawater quality, the distances between the wells and the seawater source were measured. Site A wells have a flowpath length of at least 450 m from the seawater source and site B wells are 300 m from the seawater source. Site C has the shortest and most direct pathway since the wells are drilled into the sea directly. This flowpath may be as short as 50 m. Dissolution conduits at site C may have shortened the flowpath and retention time in some wells. The algae removal amounts showed a possible relation between flowpath and associated retention time in that site A had the longest flowpath and showed the highest removal percentage. However, the bacterial removal percentages were similar at sites B and C. The TOC and the NOM fraction data support a relationship between flowpath length with a longer aquifer retention time and a reduction in concentration, particularly the TOC and the biopolymer fraction of NOM. The retention time is considered in this case to be directly proportional to the length of the flowpath, so they work together in reducing the concentration of NOM. The data collected on the particulate and colloidal TEP shows the same general trend, but there is more scatter in the removal percentages. Another investigation of several well intake systems that supports the general relationship between flowpath/retention time and reduction in organic matter concentrations was conducted by Rachman and Missimer (2014). They found that there is a direct relationship between flowpath from the shoreline to the production well and silt density index reduction and some influence on the concentration reduction of NOM.

Other factors also impact the removal of organic compounds during transport in a coastal aquifer system. The hydraulic conductivity, the effective porosity of the aquifer, and the well pumping rate (hydraulic gradient) control the rate of seawater flow. This rate affects the attenuation processes within the aquifer including absorption, adsorption, and biological assimilation and breakdown of organic compounds. Also, the type of pore geometry can influence the rates of organic carbon uptake based on the formation of internal biofilms. Therefore, while the hydraulic retention time is perhaps the most important factor in the removal rate of organic matter, other factors also exert some influence on the rate and ultimate concentration that occurs at the wellhead.

Another possible impact to the removal efficiency of organic matter may be the age of the wells. Greater internal bacterial activity could be promoted by the continuing influx of NOM into the aquifer system. However, no direct correlation could be made between well age and NOM or TEP removal. A recent investigation by Dehwah and Missimer (2015) found that well age seems to have a minimal effect on organic carbon removal in well intake systems.

5. Conclusions

Three different SWRO treatment facilities that use well intake systems with different geological characteristics and wellfield designs located along the Red Sea coastline of Saudi Arabia were investigated. The purpose of the investigation was to evaluate the performance of subsurface intake systems (vertical wells) in improving the raw seawater quality with particular emphasis on removal of organic carbon. Physical water parameters, algae, bacteria, TOC, NOM fractions and TEP concentrations were measured.
in this study. In general, the results showed that vertical wells are highly effective at improving the raw water quality before entering the various SWRO desalination plants. Almost all algae, up to 99% of the bacteria, up to 70% of the TOC, >90% of biopolymer NOM fraction, >70% of particulate TEP, and >50% of colloidal TEP were removed while passing through the aquifer from the sea into the wells. The length of flow pathway, and associated retention time in the aquifer during induced flow, appear to affect the removal percentage for the TOC and the biopolymer fraction of NOM, but no clear difference was observed in terms of other organic parameter concentrations based on the flow pathway length. The wells drilled into carbonate sediment and the coral formation showed the highest reduction percentage within the different geological media, but the association appears to be predominantly related to flowpath length and retention time. Other factors within the structure of the aquifer system also exert some influence, such as the hydraulic conductivity, pores types and distribution, and the well pumping rates which control the gradient inducing flow.

The lower concentration of bacteria, TOC, and the biopolymer fraction of NOM collectively decreases the probability of rapid biofilm formation on the SWRO membrane surfaces. Subsequently, the need for a complicated pretreatment system will be lower since the natural treatment mechanisms occurring within the aquifer will replace the sophisticated, engineered pretreatment systems. The natural treatment mechanisms occurring within the aquifer system includes straining, biochemical degradation and adsorption which help reduce the organic and microorganism content of the raw seawater during transport. Therefore, the need for membrane cleaning as well as chemical usage within an SWRO plant using a subsurface intake will be minimized and ultimately that will reduce the operating cost. In addition, this type of intake is environmentally friendly with no impingement and entrainment of marine organisms that occurs when using operation of conventional open-ocean intake systems. Also, the required membrane cleaning frequency to remove organic fouling material has been reduced by 50–75% by using the well intake system.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.watres.2015.10.011.

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