Chapter 9
Effects of Well Intake Systems on Removal of Algae, Bacteria, and Natural Organic Matter

Rinaldi Rachman, Abdullah H.A. Dehwah, Sheng Li, Harvey Winters, Samir Al-Mashharawi and Thomas M. Missimer

Abstract Analyses of the changes in concentration of algae, bacteria, transparent exopolymer particles (TEP), and the fractions of natural organic matter (NOM) impacts between surface seawater and the discharges of well intake systems were evaluated at seven different seawater reverse osmosis water (SWRO) treatment plants. In nearly all cases, travel of the raw seawater through the seabed into the aquifer and into the wells removed all of the algae. Bacteria removal was up to 98.5 %, but varied greatly between sites and in different wells at each site. The TEP concentration was significantly lowered compared to the natural seawater. The biopolymer fraction of NOM was significantly lowered at all sites, but the lighter fractions of the NOM were removed at lower percentages. The removal percentage of NOM fractions appears to be based on molecular weight (and size) with the lighter weight fractions removed at lower percentages. A key factor controlling the removal of organic material appears to by the hydraulic retention time which is controlled by the length of the flowpath and the type of aquifer porosity. Specific

R. Rachman · A.H.A. Dehwah · S. Li · S. Al-Mashharawi
Water Desalination and Reuse Center, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
e-mail: rinaldi.rachman@kaust.edu.sa

A.H.A. Dehwah
e-mail: abdullah.dehweh@kaust.edu.sa

S. Li
e-mail: sheng.li@kaust.edu.sa

S. Al-Mashharawi
e-mail: samir.mashharawi@kaust.edu.sa

H. Winters
Fairleigh Dickinson University, Teaneck, USA
e-mail: harvey@fdu.edu

T.M. Missimer (✉)
U.A. Whitaker College of Engineering, Florida Gulf Coast University, Fort Myers, FL, USA
e-mail: tmissimer@fgcu.edu

T.M. Missimer et al. (eds.), *Intakes and Outfalls for Seawater Reverse-Osmosis Desalination Facilities*, Environmental Science and Engineering,
DOI 10.1007/978-3-319-13203-7_9

site geology does not seem to be a significant factor. Vertical well systems showed greater organic materials removal compared to horizontal and tunnel intake systems. Again, this appears to be related to the length of the flowpath and the hydraulic retention time. The horizontal well system at Alicante, Spain showed poor removal of organic matter and breakthrough of algae occurred in the system.

9.1 Introduction

The marine environment is biologically active and productive, containing a variety of living organisms and natural organic compounds. Seawater reverse osmosis (SWRO) water treatment systems extract raw feed water from the sea, in most cases via open-ocean intakes that provide no real degree of pretreatment. Organic matter in seawater has a significant effect on the operation of seawater reverse osmosis membranes with the common result being biofouling (Flemming 1997; Flemming et al. 1997). There are relationships between concentration of organic matter in the feed water entering a SWRO facility, the type of pretreatment, the biological activity within the pretreatment and process trains, and the rate of membrane biofouling (Dehwah et al. 2014b).

In recent years, research on biofouling has focused on membrane conditioning and subsequent attachment of bacteria to the deposited substrate, leading to biofilm creation. The role of sticky polysaccharides and biopolymers on membrane conditioning as the precursors for membrane biofouling has been explored and many scientists conclude that transparent exopolymer particles (TEP) may be a key substance that has the most impact (Berman and Passow 2007; Bar-Zeev et al. 2009; Berman 2010; Berman et al. 2011). TEP is produced by algae and bacteria as an extracellular excretion of a “soup” of organic compounds which undergo self-assembly with the water column (Passow and Alldredge 1994; Passow 2000). Once TEP attaches to the membrane surface, it facilitates the attachment of bacteria which also use it as a food source (Villacorte et al. 2009b). An important issue is to remove as much of the dissolved natural organic material, TEP, and bacteria as possible in the pretreatment process to lessen the rate of biofouling.

Pretreatment in SWRO facilities can be quite intense (Kumar et al. 2006; Vedavyasan 2007). It commonly involves numerous processes ranging from conventional screening and mixed media filtration to use of conditioning filters followed by membrane filtration. Another strategy is to use a prefiltering stage followed by dissolved air flotation coupled with the use of a coagulant, such as ferric chloride, followed by additional filtering. The intensity of the pretreatment process train and cost of operation associated with it is based on the overall concentration of the organic matter in the feed water (Ghaffour et al. 2013). Therefore, any improvements that can be made to the quality of the feed water will lessen the complexity of the pretreatment process and reduce cost. Despite the use of quite extensive pretreatment processes, many SWRO facilities still suffer a high rate of biofouling with the necessity for frequent membrane cleaning.

Use of subsurface intake systems is known to improve the quality of feed water and lessen the environmental impacts in SWRO systems (Missimer 2009; Missimer et al. 2013; Table 9.1). The most common type of subsurface intake system uses various types of wells (Chap. 8). Pumping of wells located near the shoreline forces water in the sea to pass vertically through the seabed into the underlying aquifer, and then through the aquifer horizontally into the well (Fig. 9.1). The passage

Table 9.1 Comparison between bacteria, algae, organic carbon compound concentrations in natural seawater verses well intakes from select sites (modified from Missimer et al. 2013)

Location	Parameter	Seawater	Well 1	Well 2	Well 3	Well 4
Dahab, Egypt (Hassan et al. 1997)	DOC (mg/L)	1.6	1.2	2.3	0.6	0.8
	UV-254 (m^{-1})	1.4	0.8	0.9	0.8	0.6
Fuerteventura Island, Spain (Teuler et al. 1999)	TOC (mg/l)	0.5	0.7			
	UV-254 (m^{-1})	0.36	0.55			
	Phytoplancton, cell/L	57,720	0			
Al-Birk, Saudi Arabia (Jamaluddin et al. 2007)	Dissolved protein (mg/L	2.73 ± 0.78	0.75 ± 0.08	ND	ND	
	Dissolved carbohydrates (mg/L)	1.57 ± 0.23	0.52 ± 0.15	0.77 ± 0.10	0.50 ± 0.14	
SWCC Al-Jubail Test Site (Hassen et al. 1997)	TOC (mg/L)	2	1.2–2			
	Bacteria (CFU/mL), 0, 24, and 72 h	1.8×10^3	1.3×10^3			
		1.1×10^5	3.3×10^5			
		5.6×10^4	4.0×10^6			
Daheb beach well system, Egypt (Bartak et al. 2012)	DOC (mg/L)	1.6	1.2	2.3	0.6	0.8
	UV-254 (m^{-1})	1.4	0.8	0.9	0.8	0.6
Mediterranean location-Spring (Choules et al. 2007)	Total Picophyto-plankton (cells/mL)	1.6×10^3	1.3×10^2			
	Synechococcus (cells/mL)	1.3×10^3	1.0×10^2			
	Picoeukaryote (cells/mL)	1.1×10^3	1.9×10^1			
	Nanoeukarote (cells/mL)	1.2×10^2	1.7×10^0			
Site 1 (LaParc et al. 2007)	TOC (mg/L)	1.2	0.9			
	Polysaccharides (mg/L)	0.12	0.01			
	Humic substances + building blocks (mg/L)	0.5	0.4			
	Low-molar mass acids and neutrals (mg/L)	0.25	0.16			
	Low molar mass compounds (mg/L)	0.33	0.29			
Site 2 (LaParc et al. 2007)	TOC (mg/L)	0.9	0.6			
	Polysaccharides (mg/L)	0.4	ND			
	Humic substances + building blocks (mg/L)	0.26	0.16			
	Low-molar mass acids and neutrals (mg/L)	0.22	0.13			
	Low molar mass compounds (mg/L)	0.38	0.3			

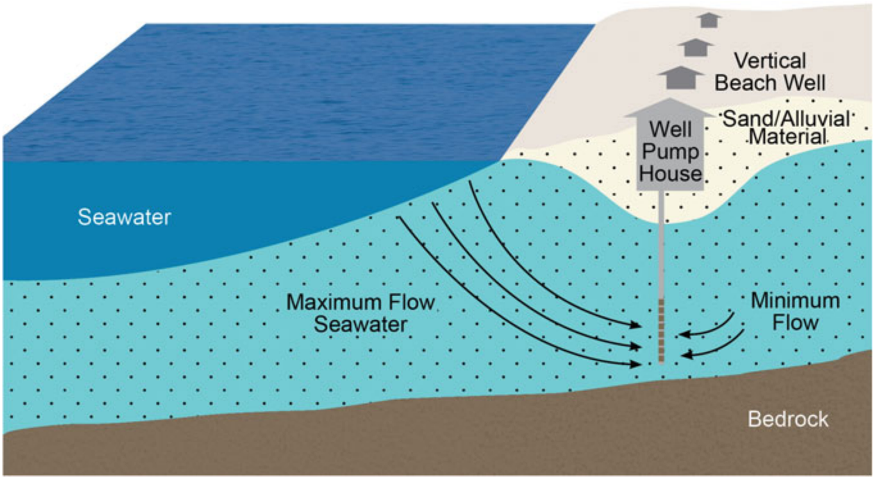

Fig. 9.1 Schematic diagram showing induced aquifer flow from the sea to a well (from Missimer et al. 2013)

through the aquifer system causes changes to occur in the feed water by removal of various substances, normally improving water quality by removal of particulates and some dissolved organic compounds (Missimer and Winters 2000, 2003; Schwartz 2003; Choules et al. 2007; Laparc et al. 2007; Missimer 2009; Missimer et al. 2013). Recently collected data show that well systems can be very effective in the removal of algae, bacteria, and natural organic matter (NOM), including TEP (Dehwah et al. 2014a, b, c; Rachman et al. 2014). It is the purpose of this chapter to summarize the most recent data on the effectiveness of well intake systems in the removal of algae, bacteria, TOC, NOM fractions, and TEP from the raw water.

9.2 Methods

9.2.1 Sampling Sites and Methods

Detailed research on organic substances removal by well intakes systems is reported for 9 systems located in Saudi Arabia (4), Spain (3), Turks and Caicos Islands (1), and Oman (1) (Dehwah et al. 2014a, b; Rachman et al. 2014). Most of these well intakes use conventional vertical wells with the exception of two sites in Spain which have a horizontal well system and a water tunnel containing radial collectors. The wells in Spain, the Turks and Caicos Islands, Oman and one system in Saudi Arabia are constructed into carbonate rocks or sediments. The other wells in Saudi Arabia were constructed into siliciclastic sediments consisting of alluvial outwash sands and gravels.

Water samples were collected from different locations within or near the facilities including surface seawater, at the well discharge, at the aggregated intake pipeline (blend of all wells), at the media filter outlet, and at the cartridge filter outlet and placed into the appropriate types of bottles, and transported to the lab facilities the same day inside coolers containing ice. Data reported in this chapter include only those collected from the raw seawater, at the wellhead discharges, and the aggregated well intake pipe.

After water sampling, a 0.02 % (w/v) sodium azide solution was added to the TEP sample bottles for fixation and to limit the bioactivity. For samples collected for bacterial and algae quantification, glutaraldehyde was added for fixation immediately after sampling. All the samples were stored at 4 °C and analyzed within 7 days of sample collection. Proper sampling, quality control and assurance measures were used based on the type of analyses to be performed.

9.2.2 TEP Measurement

In this research two types of TEP were investigated, particulate and colloidal. Particulate TEP has a size >0.4 μm, while colloidal TEP ranges in size from 0.05 to 0.40 μm (Villacorte et al. 2009a). Particulate TEP is formed predominantly by the self-assembly of precursor substances, such as dissolved polysaccharides and biopolymers, that are produced by algae and bacteria (Passow and Alldredge 1994; Passow 2000, 2002).

Analysis of TEP was accomplished based on the method developed by Passow and Alldredge (1995). A staining solution was prepared from 0.06 % (m/v) Alcian Blue 8GX (Standard Fluka) in an acetate buffer solution (pH 4) and freshly prefiltered through a 0.2 μm polycarbonate filter before usage. Between 150 and 300 mL of seawater from each water sample was filtered through a 0.4 μm pore size polycarbonate membrane using an adjustable vacuum pump at low constant vacuum. After filtration, the membrane was rinsed with 10 mL of Milli-Q water to avoid the coagulation of Alcian blue once it came into contact with the seawater in the staining process. The retained TEP particles on the membrane surface were then stained with Alcian Blue dye for 20 s. After staining, the membrane was flushed with 10 mL of Milli-Q water to remove excess dye. The flushed membrane was then placed into a small beaker, where it was soaked in 80 % sulfuric acid for 6 h to extract the Alcian Blue dye that was bound to the TEP. Finally, the absorbance of the acid solution was measured using a UV spectrometer at a 752 nm wavelength to determine the TEP concentration. The same methodology was applied to determine the colloidal TEP. The only difference is that, water sample permeate from the 0.4 μm polycarbonate membrane was filtered through a 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 a calibration curve (Fig. 9.2). The TOC

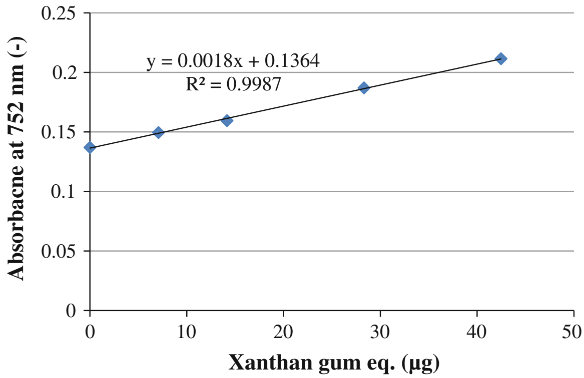

Fig. 9.2 Example of a xanthan gum calibration curve used to measure TEP concentration (from Dehwah et al. 2014c)

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. The TEP concentration then 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 μg/L by dividing the TEP mass on the corresponding volume of TEP samples. Because particulate and colloidal TEP is measured indirectly, these values must be considered to be semi-quantitative.

9.2.3 Algae and Bacteria Quantification

Counts of the number of algae and bacteria in the water samples were determined using a flow cytometer manufactured by BD Bioscience FACSVerse. Algal cell counting was performed by combining 1 mL of each sample with a 2 μL volume of a standard containing 1 μm beads into a 10 mL tube. The tube was then vortexed and measured using high flow with a 200 μL injection volume. The counting procedure was repeated three times to assess the precision of the measurements.

For bacterial counts, a comparative protocol employing SYBR® Green stain was used. A volume of 1 mL 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 (10 μL into 1 mL aliquot), vortexed, and incubated for another 10 min. The prepared samples were then analyzed in a low flow setting with a 9 μL injection volume. Triplet measurements were made on each sample to assess measurement precision.

9.2.4 Organics Analysis Using the LC-OCD Methodology

A Shimadzu TOC-VCSH instrument was used into determine the bulk organics concentration (TOC) in the samples. In order to determine the detailed fractions of dissolved organic carbon, a Liquid Chromatography Organic Carbon Detector (LC-OCD) from DOC-Labor was used employing the method developed of Huber et al. (2011) to measure the various fractions of NOM.

The samples for the LC-OCD were pre-filtered using a 0.45 syringe filter to exclude the non-dissolved organics. Before analyzing the samples, a system cleaning was performed by injection of 2000 μL of 0.1 mol/L NaOH though the column for 260 min. Following the cleaning step, 2000 μL samples were injected for analysis with 130 min of retention time. The analysis result is a chromatogram showing a plot of signal response of different organic fractions to retention time. Manual integration of the data was then performed to determine the concentration of the organic fractions including biopolymers, humic substances, building blocks, low molecular weight acids and low molecular weight neutrals.

9.3 Geological Background and Description of SWRO Intake Well Sites

9.3.1 Sur, Oman

The SWRO plant located at Sur, Oman uses a series of 28 production wells to yield the required 160,000 m^3/day of feed water (Fig. 9.3; Table 9.2). This facility is currently the largest capacity SWRO facility using wells as an intake (David et al. 2009). The plant permeate capacity is 80,200 m^3/day.

A coastal carbonate aquifer system occurs along the segment of the Oman coast at Sur. The heterogeneous limestone aquifer occurs within early Tertiary age sediments (likely Eocene in age) lying within the Seeb Formation of the Hadhramaut Group and some sediments within the overlying Dhofar and Fars Group (Beavington-Penny et al. 2006; Fournier et al. 2006). The aquifer located along the coast is unconfined at surface and becomes semi-confined with depth. It is a dual- or tri-porosity aquifer that

Fig. 9.3 Location of SWRO plant and wells at Sur, Oman (modified from Rachman et al. 2014)

contains solution cavities, fractures, and some remaining intergranular porosity. Based on the geology of the aquifer, the flowpath from the sea is likely directed downward through the seabed and then follows either a tortuous path or more direct path following preferential flow conduits.

The wellfield generally parallels the coastline, but there are wells lying near the beach and others further inland with distances ranging from 30 to 250 m from the high tide line (Fig. 9.3). Depths of the wells range from 40 to 100 m below sea level and are completed with PVC screens. Each well is equipped with a submersible pump.

Water samples were collected from September 22–23, 2012 and March 19–20, 2013. The detailed analyses of algae, bacterial, TOC, organic carbon fractions and TEP are reported by Rachman et al. (2014). The site was chosen for analysis due to its high frequency of harmful algal blooms (HAB’s).

9.3.2 Alicante, Spain

Wells systems are used to supply feedwater to two SWRO plants located at Alicante, Spain. The Alicante I and II facilities have permeate capacities of 50,000 and 65,000 m^3/day respectively. Three types of well intake systems are used to obtain feedwater, including conventional vertical wells, horizontal wells or drains, and a horizontal water tunnel containing lateral screens similar to those constructed on the horizontal plain in collector wells.

The conventional well system includes 30 individual production wells, each with a capacity of about 4,000 m^3/day that produce the 120,000 m^3/day required for Alicante I (Fig. 9.4). The combined yield of a horizontal well system and a water tunnel intake provide the feed water for Alicante II. The horizontal well system consists of 11 individual wells (differs between published papers and the numbers reported by the operators in the field) constructed using the Neodren configuration (Malfeito 2006; Farinas and Lopez 2007; Peters et al. 2007).

The vertical wells are constructed into Tertiary-age limestone (likely Miocene) containing some unlithified sediments (Gell et al. 1992). These wells are located between 60 and 110 m from the shoreline.

The horizontal drains or wells are constructed primarily into unlithified sediments that are carbonates with possibly some siliciclastic component (Gutierrez-Elorza et al. 2002). These wells may also penetrate soft limestone that occurs offshore. This carbonate unit does contain some solution cavities. The operators of the plant have suggested that the end of some horizontal wells may have been opened to the sea to allow greater capacity to occur. This has not been verified by observation. The horizontal wells are drilled at the ends of the water tunnel; three on the east side and 8 on the west side.

The water tunnel system is similar in concept to that developed by the City of Louisville in the United States as reported in Missimer (2009). It has a length of

Fig. 9.4 Location of SWRO plant and various well intake systems at Alicante, Spain (modified from Rachman et al. 2014)

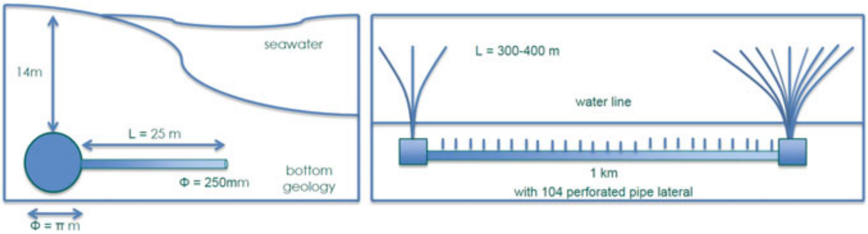

Fig. 9.5 Water tunnel intake system design at Alicante, Spain (from Rachman et al. 2014)

1 km and lies 14 m below the sea level. It is oriented parallel to the shoreline and has a diameter of 3.14 m (Fig. 9.5). Seawater enters the tunnel via 104 lateral wells drilled into the aquifer.

9.3.3 Turks & Caicos Water Company, Providenciales, Turks & Caicos Islands

The Turks & Caicos Water Company operates a SWRO facility that has a capacity of 10,000 m^3/day and uses conventional vertical wells that collectively produce about 24,000 m^3/day of feed water (Fig. 9.6). There are production wells that have maximum depths ranging between 30 and 50 m below surface. The wells contain PVC casings that are grouted between 15 and 20 m below surface. The wells are completed with open hole below the casing. The wells are located in the central part of the island, a distance of about 2000 m from the shoreline.

Little has been published concerning the subsurface geology of Providenciales. The surface geology was investigated by Kindler et al. (2008), and Wanless and Dravis (2008a, b, c). Based on a comparison to the geology of the Bahamas to the northwest beneath Andros Island, the age of the penetrated limestones is Pleistocene (McNeill et al. 2001). The aquifer is either semi-unconfined or semi-confined

Fig. 9.6 SWRO plant and wells at the Turks & Caicos Water Company, Provindenciales, Turks & Caicos Islands (modified from Rachman et al. 2014)

in nature based on the subsurface occurrence of low-permeability duricrusts. The production aquifer is karstic in nature, containing numerous large and small cavities and some preserved intergranular porosity.

9.3.4 Buhayrat City, Jeddah, Saudi Arabia

Four small to medium capacity SWRO facilities are being operated in the area within or near Jeddah, Saudi Arabia (Fig. 9.7). The Buhayrat city plant has a capacity of 6000 m^3/day and a feed water capacity of 12,400 m^3/day. Four production wells, located parallel to a tidal canal connected to the Red Sea, are used to produce the feed water. The wells are located between 70 and 80 m from the canal bank and have depths ranging from 30 to 40 m below surface and have a screened completion and three of the wellfields near Jeddah have a similar configuration, but with differing numbers of production wells (Fig. 9.8).

The shallow aquifer consists of siliciclastic sediments deposited as alluvial outwash. The aquifer is extremely heterogeneous with the aquifer containing sand and gravel with some large cobbles and a minor percentage of mud (silt and clay sized particles). Alluvial outwash aquifers in this region tend to have a high hydraulic conductivity and will effectively convey water from the canal into the wellbore (Missimer et al. 2012).

9.3.5 North Obhor, Jeddah, Saudi Arabia

The North Obhor SWRO facility has a permeate capacity of 13,350 m^3/day and the feed water capacity is about 33,375 m^3/day. The facility is using a well system that is constructed into a coral formation. A total of 13 vertical wells are used to supply the required capacity into the desalination facility. The wells range from 50 to 55 m in depth and are located 450 m from the seawater source. The wells were constructed in three different phases with the oldest being 13 years while the latest ones are 3 years old.

Fig. 9.7 Location of four SWRO plants that use vertical well intake systems in the Jeddah area, Saudi Arabia

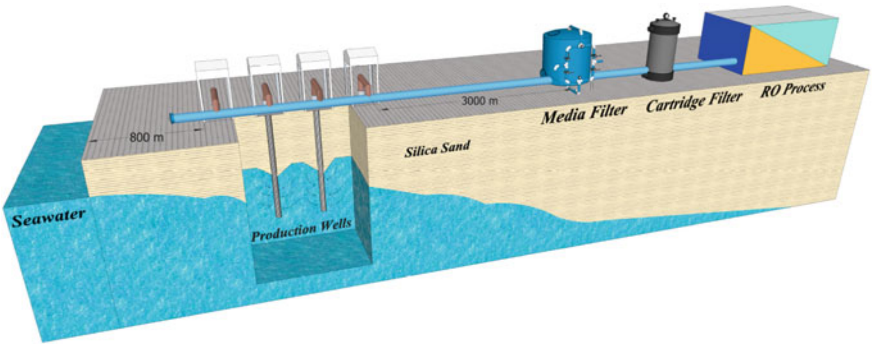

Fig. 9.8 Typical configuration of the SWRO facilities with well intake systems in the Jeddah area, Saudi Arabia

9.3.6 Corniche, Jeddah, Saudi Arabia

The SWRO plant located at the Corniche in Jeddah uses a series of 5 production wells to produce the required 11,250 m^3/day of feed water. This facility has a permeate capacity of 4,500 m^3/day. The vertical wells are constructed into siliciclastic sediments and the depth of these wells ranges from 46 to 50 m below sea level. These wells are located at a distance of 300 m away from the shoreline. The supplied water to this facility has a high iron concentration which causes a real problem for the pretreatment system. The cartridge filters used at this facility are replaced in a very short time due to an iron precipitation problem. The high iron concentration may be related to the water passage through the heterogeneous siliciclastic systems or some redox reaction.

9.3.7 South Jeddah Corniche, Jeddah, Saudi Arabia

The South Jeddah Corniche SWRO facility has a permeate capacity of 10,000 m^3/day and the feed water capacity is about 25,000 m^3/day. This facility utilizes a rather unique well intake system that consists of 10 production wells located on an artificial fill peninsula constructed into the Red Sea nearshore (Fig. 9.9).

During the initial construction of the plant, a series of wells were installed along the shoreline (beach wells), similar to many other low to medium capacity SWRO facilities in the region. After startup of the facility, it was discovered that the salinity of the feed water being produced from the wells was substantially greater that in the Red Sea. This is a rather common problem along the Red Sea coastline in areas where coastal sabkha environments are found. These environments contain trapped

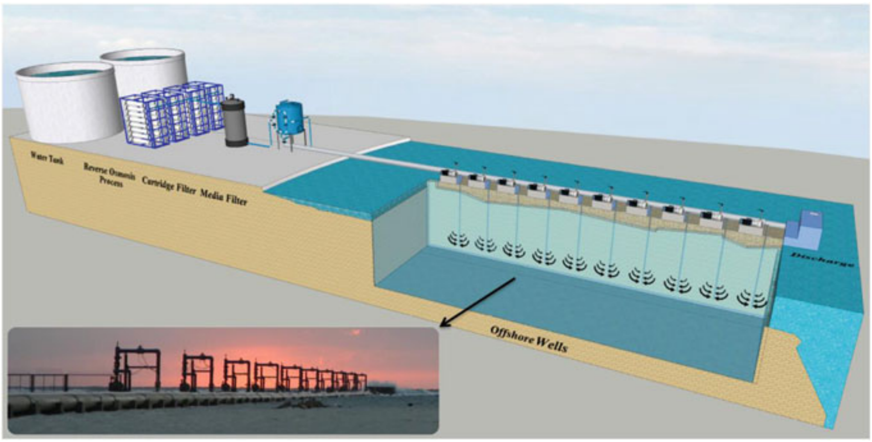

Fig. 9.9 Schematic diagram showing the offshore well system and SWRO plant constructed at South Jeddah, Saudi Arabia (from Al-Mashharawi et al. 2014)

seawater and are essentially evaporation basins that transmit hypersaline water toward the sea as density flows, thereby rendering the shoreline alluvial aquifer unusable for SWRO feed water development (Missimer et al. 2014). Therefore, an artificial peninsula was constructed from the beach seaward on the inner reef hardground. The wells are located 20 m apart and range from 40 to 50 m in depth. They have a screened completion. The aquifer beneath the Red Sea consists of interbedded limestone and carbonate sand.

9.4 Results

9.4.1 Introduction: Removal of Organic Particulates and Dissolved Compounds by Aquifer Transport to Wells

A relatively small quantity of data have been presented in the literature until recently on the effectiveness of aquifer removal of particulate and dissolved organic compounds within the marine environment. Most of the literature on aquifer treatment of organic compounds has occurred for freshwater systems associated with riverbank filtration and removal of organic compounds associated with aquifer treatment of domestic wastewater.

Missimer et al. (2013) summarized the historical data collected from SWRO well intake systems (Table 9.2). The early data suggest that significant reductions in

Table 9.2 Location and details of well intake systems investigated

System name	Location	Capacity (m^3/day)[a]	Well type	Aquifer type	No. wells
Sur	Oman	160,000	Shallow-beach	Carbonate	28
Alicante	Spain	130,000	Shallow-beach	Carbonate	30
Alicante[b]	Spain	130,000[b]	Tunnel with laterals	Carbonate	1
Alicante[b]	Spain	130,000[b]	Horizontal	Carbonate	11
Turk & Caicos I.	Providenciales	50,000	Shallow-inland	Carbonate	6
Buhayrat city, Jeddah	Saudi Arabia	12,500	Shallow-beach	Siliciclastic	4
North Obhor, Jeddah	Saudi Arabia	33,375	Shallow-beach	Siliciclastic	13
Corniche, Jeddah	Saudi Arabia	11,250	Shallow-beach	Siliciclastic	5
South Jeddah Corniche	Saudi Arabia	25,000	Shallow-offshore	Siliciclastic	10

[a]Capacity is defined as the capacity of the intake not the SWRO plant
[b]The required capacity for the combination of the horizontal wells and the tunnel is 130,000 m^3/day. Most of the time the tunnel is used and not the horizontal wells

organic compounds occurred, but these data were rather incomplete. The detailed analytical data included in this section were compiled from Dehwah et al. (2014a, b, c), Rachman et al. (2014a, b), and from unpublished data.

9.4.2 *Algae and Bacteria Removal During Aquifer Transport*

Data on algae within the surface seawater and in the discharge from wells was investigated at seven sites globally (Table 9.3). A large variation occurs in the natural concentrations of algae in seawater depending upon the climate, oceanic circulation, and nutrient balance of the site. The highest concentrations of algae in the investigated sites occurs al Sur, Oman, which shows a total algae concentration of nearly 200,000 cells/mL during one of the sampling periods. The lowest concentration occurred within the Red Sea at the South Corniche site with a total of 1,677 cells/mL.

Algae occurring in the water from the vertical intake wells sampled are labeled as numbers in Table 9.3. In all cases, the algae in the seawater were fully reformed during passage through the seabed and the aquifer feeding the wells. The detection limit varies based on overall algae concentration, but in all cases the measured concentration was less than the detection limit. The horizontal well intake at Alicante, Spain was the only subsurface intake system that showed any significant concentration of algae in the feed water. However, it was only 22.7 % of that in the surface seawater. The water tunnel intake system at the Alicante site was also 100 % effective in algae removal.

Bacteria occurrence within the marine environment varies greatly at the 7 sites sampled. The highest concentrations occur in the Arabian Sea at the Oman site at nearly a million cells/mL during the first sampling campaign and the lowest concentration was in the Red Sea near Jeddah at the North Obhor site at 112,790 cells/mL.

Vertical well intakes into coastal aquifers showed the highest percentage of bacteria removal in passage of seawater through the seabed and aquifer to the production wells (Table 9.4). The highest removal rates were found in the limestone aquifer system at Oman and the Turks & Caicos Islands site. The highest removal percentage achieved was 99.8 %. Within vertical well intakes at Alicante, Spain, removal percentages varied between 84.3 and 90 %. Vertical well intake systems in the Red Sea showed a reduced removal percentage with considerable variation between sites and within sites. In all cases, the reduction percentage was greater than 74.4 % and was as high as 96.5 %, The South Cornich Jeddah site, using the unique offshore well system, performed best.

Two different well intake systems at Alicante, Spain were also evaluated. The tunnel intake system produced a bacteria reduction of 69.9 %, close to the lowest reduction achieved using vertical wells within the 7 studied sites. The much-touted horizontal well or drain system produced only a 47.6 % reduction in bacteria

Table 9.3 Comparison of algae concentrations in surface seawater versus those in well intake discharges (values in cells/mL)

Samples	Prochlorococcus sp.	Synechococcus sp.	Cyanobacteria	Pico/Nanoplankton	Total algae
Sur, Oman					
SW	4,400	113,040	0	1,900	119,340
1	<100	<100	<100	<100	<100
2	<100	<100	<100	<100	<100
3	<100	<100	<100	<100	<100
4	<100	<100	<100	<100	<100
SW	2,810	194,310	0	435	197,555
1	<100	<100	<100	<100	<100
2	<100	<100	<100	<100	<100
3	<100	<100	<100	<100	<100
4	<100	<100	<100	<100	<100
Alicante, Spain					
SW	350	24,275	0	985	25,610
1	<100	<100	<100	<100	<100
2	<100	<100	<100	<100	<100
3	<100	<100	<100	<100	<100
4	<100	<100	<100	<100	<100
Hort.	135	5,460	0	225	5,820
Tunnel	<100	<100	<100	<100	<100
Turks & Caicos					
SW	770	37,225	0	250	38,245
1	<100	<100	<100	<100	<100
2	<100	<100	<100	<100	<100
3	<100	<100	<100	<100	<100
Buhayrat city					
SW	6,330	20,785	0	3,280	30,395
1	<100	<100	<100	<100	<100
2	<100	<100	<100	<100	<100
3	<100	<100	<100	<100	<100
4	<100	<100	<100	<100	<100
North Obhor					
SW	203	–	30,053	268	30,524
1	<50	–	<50	<50	<50
2	<50	–	<50	<50	<50
3	<50	–	<50	<50	<50
4	<50	–	<50	<50	<50
Corniche, Jeddah					
SW	243	0	3,300	60	3,603
1	<50	<50	<50	<50	<50
2	<50	<50	<50	<50	<50
3	<50	<50	<50	<50	<50

(continued)

Table 9.3 (continued)

Samples	Prochlorococcus sp.	Synechococcus sp.	Cyanobacteria	Pico/Nanoplankton	Total algae
South Jeddah Corniche					
SW	140	0	1,507	30	1,677
1	<5	<5	<5	<5	<5
2	<5	<5	<5	<5	<5
3	<5	<5	<5	<5	<5
4	<5	<5	<5	<5	<5

concentration. There is a question concerning this well system in terms of its possible opening to direct influx of seawater either at the well terminus (suggested by operators) or within a vertical solution cavity allowing direct enter of seawater without passage through the sediment.

9.4.3 TOC and DOC Removal During Aquifer Transport

There is a considerable difference in the concentration of TOC and DOC in the surface seawater at the 7 sampling locations (Fig. 9.4). TOC concentrations ranged from 0.88 to 1.677 mg/L with the highest concentration found at the Turks and Caicos Islands site and the lowest values occurring in the Red Sea sites (0.88–1.02 mg/L). Where DOC was measured, concentrations ranged between 0.890 and 0.997 mg/L.

TOC and DOC concentrations were reduced during aquifer transport in all wells sampled, but there were considerable variations in the percentage of removal (Table 9.5). The highest percentages of removal were achieved in the vertical wells at the Turks & Caicos Islands site with a reduction range of 76.9–82.8 % for TOC and 74.2–77.7 % for DOC. The lowest percentage of TOC concentration reduction occurred at the South Corniche Jeddah site (26.3–42.1 %). A very large difference between wells in terms of removal efficiency achieved occurred at the North Obhor site on the Red Sea (16.7–72.7 %). Seawater from the vertical wells at Alicante, Spain showed that reductions ranging between 53.0 and 60.2 % occurred for TOC and DOC. The water tunnel intake showed a reduction of only 23 % and the horizontal wells system only 6.5 %.

9.4.4 TEP Removal During Aquifer Transport

There are two types of TEP that occur in raw seawater; particulate and colloidal. The data from various sites show aquifer removal of particulate TEP during transport from the sea to the wells ranging from 36.9 to 92.1 %. Colloidal TEP

Table 9.4 Bacteria concentrations in surface seawater and the well intake discharges with the removal percentages achieved during transport

Site	Sample	Total bacteria concentration (cells/mg/L)	Percentage removal
Sur, Oman			
	SW	995,310	0
	1	3,270	99.7
	2	8,540	99.1
	3	13,630	98.6
	4	11,000	98.9
	SW	702,609	0
	1	5,109	99.3
	2	1,196	99.8
	3	3,043	99.6
	4	5,109	99.3
Alicante, Spain			
	SW	292,283	0
	1	29,348	90.0
	2	35,761	87.8
	3	45,870	84.3
	4	34,783	88.1
	Hor.	153,261	47.6
	Tunnel	89,891	69.2
Turks & Caicos			
	SW	698,152	0
	1	17,065	97.6
	2	20,978	97.0
	3	15,652	97.8
Buhayrat City			
	SW	320,870	0
	1	11,087	96.5
	2	10,978	96.6
	3	26,630	91.7
	4	13,804	95.7
North Obhor			
	SW	112,790	0
	1	10,054	91.1
	2	1,250	98.9
	3	8,370	92.6
	4	5,978	94.7

(continued)

Table 9.4 (continued)

Site	Sample	Total bacteria concentration (cells/mg/L)	Percentage removal
Corniche, Jeddah			
	SW	196,377	0
	1	30,652	84.4
	2	49,638	74.7
	3	38,804	80.2
South Corniche, Jeddah			
	SW	264,728	0
	1	9,185	96.5
	2	33,804	87.2
	3	12,283	95.4
	4	19,783	92.5

removal ranges from 40.5 to 78.5 % (Table 9.6). There is considerable variation in which form of TEP is removed at the greatest percentage with no consistent pattern. At Alicante, Spain, the average removal differences in the vertical wells between particulate and colloidal TEP is 68.15 to 51.45 % respectively. At the Corniche, Jeddah site the comparison is 60.1 to 55.1 % respectively. At the South Corniche, Jeddah site the removal percentage is nearly equal at 64.0 to 63.25 % respectively.

Aquifer removal during flow to vertical wells at the Turks & Caicos SWRO facility shows the highest removal of particulate TEP, averaging about 90 %. Removal of particulate TEP in water extracted from vertical wells at Sur, Oman and Alicante, Spain shows an average removal of 66.45 and 68.15 % respectively. Removal rates of particulate TEP using shallow wells along the Red Sea coast of Saudi Arabia show lower average rates ranging from 53.4 to 64 %. The South Corniche, Jeddah site has the average highest removal rate at 64 %. Also, there is considerable variation in the removal percentage between wells located on the same site. The worst performing intake system in terms of particulate TEP removal is the horizontal well system at Alicante, Spain.

9.4.5 NOM Fraction Removal During Aquifer Transport

Assessment of the aquifer removal of the NOM components including biopolymers, humic substances, building blocks, low molecular weight acids, and low molecular neutrals were determined for the seven sites. The general pattern of removal during aquifer transport from the sea to the wells was generally consistent (Table 9.7).

The highest removal rate of the NOM fractions occurred within the biopolymers. The range in average removal by site was 92.3 to 100 %. The highest removals occurred in the Alicante, Spain (vertical wells) and Turks & Caicos SWRO

Table 9.5 Organic carbon concentrations in surface seawater and from the well discharges with percentage of removal during transport

Samples	TOC (mg/L)	Percentage removal	DOC (mg/L)	Percentage removal
Sur, Oman				
SW	–	–	0.890	0
1	–	–	0.293	67.1
2	–	–	0.307	65.5
3	–	–	0.331	62.8
4	–	–	0.312	64.9
SW	1.053	0	0.957	0
1	0.266	74.4	0.210	78.1
2	0.478	54.61	0.442	52.8
3	0.533	49.38	0.481	49.7
4	0.514	51.19	0.425	55.6
Alicanti, Spain				
SW	1.12	0	0.856	0
1	0.568	49.3	0.396	53.7
2	0.560	50.0	0.392	54.2
3	0.602	46.3	0.402	53.0
4	0.567	49.4	0.374	56.3
Hor.	1.05	6.5	0.873	−2.0
Tunnel	0.714	23.0	0.548	36.0
Turks & Caicos				
SW	1.677	0	0.997	0
1	0.289	82.8	0.222	77.7
2	0.388	76.9	0.257	74.2
3	0.334	80.1	0.247	75.2
Buhayrat City				
SW	1.053	0	0.573	0
1	0.536	46.7	0.295	48.5
2	0.653	35.0	0.341	40.5
3	0.581	42.2	0.361	37.0
4	0.517	48.6	0.293	48.9
North Obhor				
SW	0.89	0	–	–
1	0.24	72.7	–	–
2	0.20	78	–	–
3	0.37	58.2	–	–
4	0.74	16.7	–	–

(continued)

Table 9.5 (continued)

Samples	TOC (mg/L)	Percentage removal	DOC (mg/L)	Percentage removal
Corniche, Jeddah				
SW	0.94	0	–	–
1	0.37	60.6	–	–
2	0.41	55.8	–	–
3	0.56	40.3	–	–
South Corniche, Jeddah				
SW	1.02	0	–	–
1	0.69	32.3	–	–
2	0.75	26.5	–	–
3	0.71	30.3	–	–
4	0.59	42.1	–	–

facilities with 100 % removal. Two sampling events at the Sur, Oman site produced about a 5 % difference in biopolymer removal, but the removal rate was still high. The average removals for all of the SWRO facilities located in the Jeddah, Saudi Arabia area showed high average rates of removal between 93.1 and 96.4 %. The horizontal well system at Alicante, Spain showed a reduction of 93 %, but the tunnel system produced only a 90.1 % removal.

Removal of humic substances was substantially lower compared to biopolymers. The range of sample group averages was 27.5 to 80.9 %. The highest removal occurred at Sur. Oman during the second sampling campaign. The first sampling at the site showed a much lower removal average of 58.4 %. Most of the sites showed removals between 43.9 and 45 % with the exception of the North Obhor site which averaged 70 %. The horizontal site system at Alicante, Spain was found to show a 24 % increase in humic substances compared to natural seawater and the tunnel intake system showed only a 24.3 % reduction in concentration.

The building blocks removal average percentage was lower at all sites compared to humic substances with the exception of the Turks & Caicos and Corniche, Jeddah sites. The range in average removal was 25.4 to 60.2 %. There was considerable variation within the groups of sampled wells at each site. Again, the horizontal well system at Alicante, Spain showed an increase in concentration of 11.8 %, similar to the increase found in the humic substances.

In most cases, the average removal percentages of the low molecular weight acids and neutrals were lower than the building blocks with the exception of the Turks & Caicos site (only acids), the Alicante site (vertical wells), and the Buhayrat site. The average removal percentage between the low molecular weight fractions varied with regard to which one was highest at a given site. The percentage of both low molecular weight fractions increased compared to the background seawater at the horizontal well site in Alicante.

Table 9.6 Particulate and colloidal TEP in surface seawater and from the well discharges with percentage of removal during transport

Samples	Particulate TEP (mg/L)	Percentage removal	Colloidal TEP (mg/L)	Percentage removal
Sur, Oman				
SW	0.036	–	–	–
1	0.007	80.4	–	–
2	0.008	77.4	–	–
3	0.011	70.2	–	–
4	0.015	58.9	–	–
SW	0.117	0	–	–
1	0.035	70.1	–	–
2	0.038	67.5	–	–
3	0.040	65.8	–	–
4	0.044	62.4	–	–
Alicante, Spain				
SW	0.521	–	0.171	0
1	0.147	71.8	0.080	53.2
2	0.156	70.1	0.090	47.4
3	0.177	66.0	0.074	56.7
4	0.184	64.7	0.088	48.5
Hor.	0.329	36.9	0.085	50.3
Tunnel	0.179	65.6	0.077	54.9
Turks & Caicos				
SW	0.642	–	–	–
1	0.051	92.1	–	–
2	0.066	89.7	–	–
3	0.053	91.7	–	–
Buhayrat City				
SW	0.058	–		
1	0.023	60.3		
2	0.038	34.5		
3	0.027	53.4		
4	0.020	65.5		
North Obhor				
SW	0.162	–	–	–
1	0.116	28.4	–	–
2	0.032	79.9	–	–
3	–	–	–	–
4	0.072	55.2	–	–

(continued)

Table 9.6 (continued)

Samples	Particulate TEP (mg/L)	Percentage removal	Colloidal TEP (mg/L)	Percentage removal
Corniche, Jeddah				
SW	0.121	–	0.073	
1	0.019	83.9	0.043	40.9
2	0.055	54.6	0.041	44.7
3	0.070	41.9	0.015	79.8
South Corniche, Jeddah				
SW	0.157	–	0.122	
1	0.038	75.7	0.071	42.2
2	0.069	56.1	0.032	73.8
3	0.057	63.8	0.026	78.5
4	0.062	60.4	0.051	58.5

9.5 Discussion

9.5.1 Processes Involved in Organic Removal Within Aquifer Systems

Removal of the particulates in the aquifer flowpath from the sea through the bottom and the connecting aquifer to the wells is likely caused by straining with some adsorption. The algae and bacteria loss is likely caused by straining, death and breakdown of the living organisms, and some adsorption, particularly onto subsurface biofilms within secondary porosity in the carbonate aquifers. Some of the bacteria may be removed by bacterial predation by groundwater species, but that is an unresolved issue.

Removal of TEP and the NOM fractions is likely a combination of physical, chemical, and biological processes. TEP and the biopolymer fraction of NOM contain large molecules, some of which are sticky polysaccharides that would tend to adsorb onto the aquifer matrix, particularly at the seawater/sediment interface. The largest molecules within the biopolymer fraction of NOM are also likely removed by straining and dispersion. Reduction in the overall TOC and the smaller NOM fractions is likely caused by chemical and bacterial activity with the aquifer. As the composition of the NOM becomes more refractory, the removal percentage of the NOM lessens. The NOM fractions data suggest that the large molecular weight fraction, biopolymers, have the highest removal with a reduction in removal percentage from the highest to lowest molecular weight.

It is likely that the uptake of organic matter within the aquifer system is somewhat dependent on operational time of the facility in that the bacterial activity in the aquifer will likely increase in time as more organic carbon flows through it.

Table 9.7 NOM fractions in surface seawater and from the well discharges with percentage of removal during transport

Samples	Biopolymers (ppb)	% removal	Humic substances (ppb)	% removal	Building blocks (ppb)	% removal	Low molecular Wt. acids (ppb)	% removal	Low molecular Wt. neutrals (ppb)	% removal
Sur, Oman										
SW	133		394		167		187		76	
1	8	93.98	74	81.22	38	77.25	68	63.64	22	71.05
2	13	90.23	180	54.31	85	49.10	120	35.83	44	42.11
3	11	91.73	215	45.43	97	41.92	110	41.18	48	36.84
4	9	93.23	186	52.79	88	47.31	96	48.66	46	39.47
SW	111		260		212.5		229		77.5	
1	1	99.25	85	78.43	80	52.10	95	49.20	32	57.89
2	8	93.98	41	89.59	59	64.67	150	19.79	49	35.53
3	0	100.00	91	76.90	77	53.89	125	33.16	38	50.00
4	2	98.50	84	78.68	83	50.30	117	37.43	26	65.79
Alicante, Spain										
SW	142		449		121		66		78	
1	0	100.00	238	46.99	70	42.15	41	37.88	47	39.74
2	0	100.00	243	45.88	70	42.15	33	50.00	46	41.03
3	0	100.00	259	42.32	72	40.50	29	56.06	42	46.15
4	0	100.00	247	44.99	59	51.24	26	60.61	42	46.15
Hor.	10	92.96	556	−23.83[a]	135	−11.57[a]	67	−1.52[a]	105	−34.62[a]
Tunnel	14	90.14	340	24.28	89	26.45	45	31.82	60	23.08

(continued)

Table 9.7 (continued)

Samples	Biopolymers (ppb)	% removal	Humic substances (ppb)	% removal	Building blocks (ppb)	% removal	Low molecular Wt. acids (ppb)	% removal	Low molecular Wt. neutrals (ppb)	% removal
Turks & Caicos										
SW	215		446		174		111		51	
1	0	100.00	142	68.16	52	70.11	3	97.30	25	50.98
2	0	100.00	163	63.45	60	65.52	4	96.40	30	41.18
3	0	100.00	158	64.57	58	66.67	3	97.30	28	45.10
Buhayrat City										
SW	47		343		82		16		85	
1	0	100.00	178	48.10	55	32.93	9	43.75	53	37.65
2	1	97.87	209	39.07	62	24.39	12	25.00	57	32.94
3	5	89.36	212	38.19	71	13.41	13	18.75	60	29.41
4	2	95.74	173	49.56	56	31.71	10	37.50	52	38.82
North Obhor										
SW	76		345		103		168		88	
1	2	97.4	110	68.1	55	46.6	103	38.7	52	40.9
2	2	97.4	89	74.2	33	68.0	107	36.3	41	53.4
3	4	94.7	145	58.0	53	48.5	105	37.5	71	19.3
4	3	96.1	70	79.7	23	77.7	120	28.6	44	50.0

(continued)

Table 9.7 (continued)

Samples	Biopolymers (ppb)	% removal	Humic substances (ppb)	% removal	Building blocks (ppb)	% removal	Low molecular Wt. acids (ppb)	% removal	Low molecular Wt. neutrals (ppb)	% removal
Corniche, Jeddah										
SW	90		360		91		192		94	
1	3	96.7	199	44.7	51	44.0	143	25.5	63	33.0
2	2	97.8	147	59.2	49	46.2	136	29.2	57	39.4
3	8	91.1	205	43.1	46	49.5	127	33.9	71	24.5
South Corniche, Jeddah										
SW	116		351		139		197		103	
1	7	94.0	247	29.6	99	28.8	146	25.9	84	18.4
2	6	94.8	282	19.7	114	18.0	158	19.8	87	15.5
3	3	97.4	244	30.5	120	13.7	191	3.0	117	−13.6
4	16	86.2	245	30.2	82	41.0	127	35.5	71	31.1

[a]Negative values of removal suggest that the measured concentration is higher than seawater at the site

Detailed sampling may indicate changes in aquifer assimilation based on seasonal changes in water temperature and dissolved oxygen concentrations in the aquifer. Further research would be required to assess this issue.

9.5.2 Effects of FlowPath Length on Organic Substances Removal

The length of the flowpath from the sea to the wells and the corresponding hydraulic retention time in the aquifer affects the removal percentage of bacteria and NOM. The longest flow pathway from the sea to the wells occurs at the Turks & Caicos SWRO facility. This site shows the highest percentage reduction in TOC, TEP, nearly all fractions of NOM, and the second highest reduction in bacteria. Wells at the Sur, Oman site contain a variation in flow pathway length and show a very high reduction in bacterial concentration, but a slightly lower TEP reduction. The depth of the screens at Alicante is deeper than most of the other sites investigated which increases the flowpath length and may be responsible for the relatively high removal percentage of bacteria, biopolymer fraction of NOM, and TEP.

The length of the flowpath of the sites sampled in the Jeddah area does not differ greatly, but there are observable differences in the removal percentages of organic matter between the sites. This may indicate difference in operational time or local changes in the biological activity within the aquifer.

The shortest flowpaths occur within the horizontal and tunnel intake systems at Alicante. Within the horizontal well system, breakthrough of algae is observed indicating a direct correction between the sea and the well system. These systems show the lowest percentages of bacteria removal. In addition, there is an increase in NOM within all fractions except the biopolymers.

9.5.3 Effects of Aquifer Type and Matrix on Organic Substances Removal

Three fundamental types of aquifers were investigated; carbonate systems with secondary porosity (Sur, Oman, Turks & Caicos, and North Obhor), combined lithified and unlithified carbonate (Alicante, Spain and South Corniche, Jeddah), and heterogeneous siliciclastic systems (Buhayrat City, Corniche, Jeddah). In general, there are no distinct differences in the removal of the organic matter between the different aquifer types. The highest bacteria removal percentages occur at the Turks & Caicos and Sur, Oman, but most of the other sites also exhibit high removal percentages. The carbonate aquifer types have a generally higher removal percentage for TEP compared to the siliciclastic aquifer sites. The results for removal of the NOM fractions are mixed and do not appear to be related to lithologic characteristics of the aquifer type.

9.5.4 Well Intake Design and Organic Substances Removal Efficiency

The design of the well system does have a significant impact on the removal of organic matter during the transport process. The sampling at Alicante, Spain allowed three types of well intake systems in close proximity to be evaluated; vertical wells, horizontal wells or collectors, and a water tunnel system with vertical collectors. Of the three intake types, the vertical wells significantly outperformed the other design types. Greater amounts of TOC, bacteria, TEP (with exception of the tunnel), and all NOM fractions were removed during transport from the sea to the wells. The horizontal well system performed quite poorly, showing a breakthrough of algae, less than 50 % removal of bacteria, only a 6.5 % removal of TOC, less than 40 % removal of TEP, and actual increases in most NOM fractions. The tunnel intake system produced significant removals of organic matter, but not as great as the vertical wells.

Based on the data collected and interviews with the operators, the horizontal wells system had operating problems and there may be some direct connection between the seawater and the installed wells at one or more locations. The transport distance of seawater to the horizontal well systems and the tunnel intake system were both much shorter compared to the transport distance from the sea to the vertical wells. The reduced distance and corresponding hydraulic retention time likely impact the removal percentage of the organic matter. The exact cause of the breakthrough of algae and poor performance of the horizontal well system is not known due to lack of detailed operational data.

9.6 Conclusions

Data collected from seven SWRO facilities in different geologic conditions and geographic locations clearly demonstrates that conventional vertical well intake systems provide a robust degree of pretreatment that significantly improves raw seawater quality. In all cases 100 % of the algae occurring in the raw seawater were removed and up to 99.8 % of the bacteria were removed during aquifer transport. Up to 92 % of the TEP was removed, but considerable variation occurred in TEP removal occurred between sites and internal within sites. Most of the biopolymer fraction of NOM was removed at all sites with reduction percentages ranging from 93.1 to 100 %. The removal of the NOM fractions appears related to molecular weight with the highest removal rates occurring in the biopolymer fraction and the lowest occurring in the low molecular weight acid and neutrals.

The combined removal of the bacteria, biopolymer fraction of NOM, and a significant amount of the TEP demonstrate that use of well intake systems tends to reduce the potential biofouling. The processes occurring within the aquifer during transport produce both physical entrapment and biodegradation of the organic matter, similar to that occurring in a sophisticated engineered pretreatment systems.

Perhaps the key factor affecting the degree of treatment achieved within the groundwater system is the length of the flow pathway from the sea to the wells. The longer flowpath length generally increases the hydraulic retention time, allowing biological processes within the aquifer to achieve greater assimilation of organic compounds. In the case of similar flowpath lengths, the geological materials forming the aquifer framework do not appear to be a significant factor impacting organic matter removal.

Performance of vertical wells was found to be significantly greater compared to a horizontal well system at Alicante, Spain. An innovative water tunnel intake system at the same location achieved significant reductions in organic matter, but not as great as the horizontal wells. This lower reduction is likely caused by a shorter flowpath from the seabed to the tunnel.

References

Bartak, R., Grischek, T., Ghodeif, K., & Ray, C. (2012). Beach sand filtration as pre-treatment for RO desalination. *International Journal of Water Science, 1*(2), 1–10.

Bar-Zeev, E., Berman-Frank, I., Liberman, B., Rahav, E., Passow, U., & Berman, T. (2009). Transparent exopolymer particles: Potential agents for organic fouling and biofilm formation in desalination and water treatment plants. *Desalination and Water Treatment, 3*, 136–142.

Beavington-Penny, S. J., Wright, V. P., & Racey, A. (2006). The middle Eocene Seeb Formation of Oman: An investigation of acyclicity, stratigraphic completeness, and accumulation rates in shallow marine settings. *Journal of Sedimentary Research, 76*(10), 1137–1161.

Berman, T. (2010). Biofouling: TEP-a major challenge for water separation. *Filtration & Separation, 47*(2), 20–22.

Berman, T., Mizrahi, R., & Dosoretz, C. G. (2011). Transparent exopolymer particles (TEP): A critical factor in aquatic biofilm initiation and fouling on filtration membranes. *Desalination, 276*, 184–190.

Berman, T., & Passow, U. (2007). Transparent exopolymer particles (TEP): An overlooked factor in the process of biofilm formation in aquatic environments. *Nature Precedings*. doi:10.1038/npre.2007.1182.1.

Choules, P., Schotter, J.-C., Leparc, J., Gai, K., & Lafon, D. (2007) Operation experience from seawater reverse osmosis plants. In Proceedings, American Membrane Technology Conference and Exposition, Las Vegas, Nevada.

David, B., Pinot, J.-P., & Morrillon, M. (2009). Beach wells for large scale reverse osmosis plants: The Sur case study. In Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse, Atlantis, The Palm, Dubai, UAE, November 7–12, 2009, Paper IDAW/DB09-106.

Dehwah, A. H. A., Al-Mashharawi, S., Kammourie, N., & Missimer, T. M. (2014a). Impact of well intake systems on bacterial, algae and organic carbon reduction in SWRO desalination systems, SAWAC), Jeddah, Saudi Arabia. *Desalination and Water Treatment*. doi:10.1080/19443994.2014.940639.

Dehwah, A. H. A., Al-Mashhawari, S., Missimer, T. M. (2014b). Impact of well intake systems on bacterial, algae, and organic carbon reduction in SWRO desalination systems, SAWACO, Jeddah, Saudi Arabia. In Proceedings, European Desalination Society Conference and

Exhibition, Desalination for the Environment: Clean Water and Energy, Grand Resort Hotel, Limassol, Cyprus, May 11–15, 2014.
Dehwah, A. H. E., Li, S., Al-Mashhawari, S., Rachman, R. M., Winters, H., & Missimer, T. M. (2014c). The influence of beach well and deep ocean intakes on TEP reduction in SWRO desalination systems, Jeddah, Saudi Arabia. In Proceedings, American Membrane Technology Association/American Water Works Association, 2014 Membrane Technology Conference & Exposition (18 p.), Las Vegas, Nevada.
Dravis, J. J., & Wanless, H. R. (2008a). Caicos platform models of Quaternary carbonate deposition controlled by stronger easterly Trade Winds—application to petroleum exploration. In W. Morgan & P. M. Harris (Eds.), *Developing models and analogs for isolated carbonate platform—Holocene and Pleistocene carbonates of Caicos Platform, British West Indies*. SEPM Core Workshop 22, Tulsa, OK, Society for Sedimentary Geology.
Dravis, J. J., & Wanless, H. R. (2008b). Pleistocene reefal and oolitic core sequences from West Caicos, Caicos Platform. In W. Morgan & P. M. Harris (Eds.), *Developing models and analogs for isolated carbonate platform—Holocene and Pleistocene carbonates of Caicos Platform, British West Indies* (pp. 171–177). SEPM Core Workshop 22, Tulsa, OK, Society for Sedimentary Geology.
Dravis, J. J., & Wanless, H. R. (2008c). Role of storms and prevailing energy in defining sediment body geometry, composition, and texture on Caicos Platform. In W. Morgan & P. M. Harris (Eds.), *Developing models and analogs for isolated carbonate platform—Holocene and Pleistocene carbonates of Caicos Platform, British West Indies* (pp. 13–20). SEPM Core Workshop 22, Tulsa, OK, Society for Sedimentary Geology.
Farinas, M., & Lopez, L. A. (2007). New and innovative sea water intake system for the desalination plant at San Pedro del Pintar. *Desalination, 203*, 199–217.
Flemming, H.-C. (1997). Reverse osmosis membrane fouling. *Experimental Thermal and Fluid Science, 14*, 382–391.
Flemming, H.-C., Schaule, G., Griebe, T., Schmitt, J., & Tamachkiarowa, A. (1997). Biofouling—the Achilles heel of membrane processes. *Desalination, 113*, 215–225.
Fournier, M., Lepvrier, C., Razin, P., & Jolivet, L. (2006). Late Cretaceous to Paleogene post-obduction extension and subsequent compression in the Oman Mountains. *GeoArabia, 11*, 17–40.
Geel, T., Roep, Th B, Kate, W., & Smit, J. (1992). Early-Middle Miocene stratigraphic turning points in the Alicante region (SE Spain): Reflections of western Mediterranean plat-tectonic reorganization. *Sedimentary Geology, 75*, 223–239.
Ghaffour, N., Missimer, T. M., & Amy, G. (2013). Technical review and evaluation of the economics of desalination: Current and future challenges for better supply sustainability. *Desalination, 309*, 197–207.
Gutierrez, M., Garcia-Ruiz, J. M., Javier Garcia, F., Goy, J. L., Gutierrez-Santolalla, F., Marti, C., et al. (2002). Quaternary, Chap. 14. In.: W. Gibbons & T. Moreno (Eds.). *Geology of Spain* (pp. 335–366). London: The Geological Society.
Hassan, A., Jamaluddin, A. T. M., Rpwaili, A., Abart, E., & Lovo, R. (1997). Investigating intake system effectiveness with emphasis on self-jetting well-point (SJWP) beachwell systems. In Proceedings of the 2nd Acquired Experience Symposium on Desalination plants O & M (p. 1350), Al-Jubail, Saudi Arabia, September 29–October 3, 1997.
Huber, S. A., Balz, A., Abert, M., Pronk, W. (2011). Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography—organic carbon detection—organic nitrogen detection (LC-OCD-OND). *Water Research 45*(2), 879–885.
Jamaluddin, A. T. M., Hassan, A. M., Al-Reweli, A., & Saeed, M. O. (2007). Operation of Al-Birk plant intertucing beachwell intake system. In Proceedings of the International Desalination Associate World Congress on Desalination and Water Reuse, Singapore.
Kindler, P., Godefroid, F., & Samankassou, E. (2008). Pre-Holocene island geology of the Caicos and Mayaguana (Bahamas) Platforms: Similarities and differences. In W. Morgan & P. M. Harris (Eds.), *Developing models and analogs for isolated carbonate platform—*

Holocene and Pleistocene carbonates of Caicos Platform, British West Indies (pp. 211–213). SEPM Core Workshop 22, Tulsa, OK, Society for Sedimentary Geology.

Laparc, J., Schotter, J.-C., Rapenne, S., Croue, J. P., Lebaron, P., Lafon, D., et al. (2007). Use of advanced analytical tools for monitoring performance of seawater pretreatment processes. In Proceedings, International Desalination Association World Congress on Desalination and Water Reuse, Maspalomas, Gran Canaria, Spain, October 21–26, 2007, IDAWC/MP07-124.

Kumar, M., Adham, S. S., & Pearce, W. R. (2006). Investigation of seawater reverse osmosis fouling and its relationship to pretreatment type. *Environmental Science and Technology, 40*, 2037–2044.

Malfeito, J. J. (2006). San Pedro Del Pintar desalination plant: First year of operation with a horizontal drilled intake. In Proceedings of the International Desalination and Water Reuse International Forum and Exposition, Tianjin, China, September 6–8, 2006.

McNeill, D. F., Eberli, G. P., Lidz, B. H., Swart, P. K., & Kenter, J. A. M. (2001). Chronostratigraphy of a prograded carbonate platform margin: A record of dynamic slope sedimentation, western Great Bahama Bank. In R. N. Ginsburg (Ed.) *Subsurface geology of a prograding carbonate platform margin, Great Bahama Bank: Results of the Bahamas drilling project* (pp. 101–136). SEPM Special Publication No. 70, Tulsa, OK, Society for Sedimentary Geology.

Missimer, T. M. (2009) *Water supply development, aquifer storage, and concentrate disposal for membrane water treatment facilities* (2^{nd} edn.). Sugarland, Texas: Schlumberger Water Services.

Missimer, T. M., Drewes, J., Amy, G., Maliva, R. G., & Keller, S. (2012). Restoration of wadi aquifers by artificial recharge with treated wastewater. *Ground Water, 50*(4), 514–527. doi:10.1111/j.1745-6584.2012.00941.x.

Missimer, T. M., Ghaffour, N., Dehwah, A. H. A., Rachman, R., Maliva, R. G., & Amy, G. (2013). Subsurface intakes for seawater reverse osmosis facilities: Capacity limitation, water quality improvement, and economics. *Desalination, 322*, 37–51. doi:10.1016/j.desal.2013.04.021.

Missimer, T. M., Jadoon, K. Z., Li, D., Hoppe-Jones, C., & Al-Mashharawi, S. (2014). Hydrogeology and water quality of a coastal alluvial aquifer and its potential use as an intake system for a seawater reverse osmosis water treatment system, Thuwal, Saudi Arabia. *Hydrogeology Journal* (in press).

Missimer, T. M., & Winters, H. (2000). Effects of well design and maintenance on biofouling at a seawater reverse osmosis plant, Grand Cayman Island, B.W.I. In Proceedings, American Desalting Association Meeting & Technical Program, Lake Tahoe, Nevada.

Missimer, T. M., & Winters, H. (2003). Reduction of biofouling at a seawater RO plant in the Cayman Islands. In Proceedings, International Desalination Association World Congress on Desalination and Water Reuse, BAH03-190.

Passow, U. (2000). Formation of transparent exopolymer particles, TEP, from dissolved precursor material. *Marine Ecology Progress Series, 192*, 1–11.

Passow, U (2002). Formation of transparent exopolmer particles (TEP) by phyto- and bacterioplankton. *Marine Ecology Progress Series*, *236*, 1–12.

Passow, U., & Alldredge, A. L. (1994). Distribution, size and bacterial-colonization of transparent exopolymer particles (TEP) in the ocean. *Marine Ecology Progress Series, 113*(1–2), 185–198.

Passow, U., & Alldredge, A. L. (1995). A dye-binding assay for the spectrophotometric measurement of transparent exopolymer particles (TEP). *Limnology and Oceanography, 40*, 1326–1335.

Peters, T., Pinto, D., & Pinto, E. (2007). Improved seawater intake and pre-treatment system based on Neodren technology. *Desalination, 203*, 134–140.

Rachman, R. M., Li, S., & Missimer, T. M. (2014a). SWRO feed water quality improvement using subsurface intakes in Oman, Spain, Turks and Caicos Islands, and Saudi Arabia. *Desalination, 351*, 88–100.

Rachman, R. M., Li, S., Al-Mashhawari, S., Dehwah, A. H. E., Winters, H., & Missimer, T. M. (2014b). Reduction in organic compound concentrations using well intakes for SWRO facilities in the Caribbean and the Red Sea of Saudi Arabia. In Proceedings, American Membrane Technology Association/American Water Works Association, 2014 Membrane Technology Conference & Exposition (9 p.), Las Vegas, Nevada.

Schwartz, J. (2003). Beach well intakes improve feed-water quality. *Water & Wastewater International*, November.

Teuler, A., Glucina, K., & Laine, J. M. (1999). Assessment of UF pretreatment prior to RO membranes for seawater desalination. *Desalination, 125*, 89–96.

Vedavyasan, C. V. (2007). Pretreatment trends—an overview. *Desalination, 203*, 296–299.

Villacorte, L. O., Kennedy, M. D., Amy, G. L., & Schippers, J. C. (2009a). Measuring transparent exopolymer particles (TEP) as indicator of the (bio) fouling potential of RO feed water. *Desalination and Water Treatment, 5*, 207–212.

Villacorte, L. O., Kennedy, M. D., Amy, G. L., & Schippers, J. C. (2009b). Fate of transparent exopolymer particles (TEP) in integrated membrane systems: Removal through pre-treatment processes and deposition on reverse osmosis membranes. *Water Research, 43*, 5039–5052.