Chapter 6
Effects of Intake Depth on Raw Seawater Quality in the Red Sea

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Abstract It has been suggested that using a deep open-ocean intake would improve feed water quality and would reduce the cost of SWRO water treatment by lessening membrane biofouling potential. The feasibility of developing deep intake systems for large-capacity SWRO plants located on the Red Sea was assessed. A bathymetric survey showed that the continental shelf along the Red Sea nearshore has a nearly vertical drop into deep water beginning at depths between 20 and 40 m. The vertical nature of the bathymetric profile and the issue of active seismicity make the development of a SWRO intake at a depth of greater than 100 m below surface a very risky venture along the Red Sea coast of Saudi Arabia. Detailed assessment of temperature and salinity with depth show a decrease of 5 °C and an increase of 1100 mg/L respectively over 90 m. Concentrations of algae, bacteria, total organic carbon, particulate and colloidal TEP, and the biopolymer fraction of natural organic carbon all showed declines in concentration. However, the general water quality improvements in reduced concentrations of organic matter were insufficient to reduce the intensity of pretreatment for an SWRO system. Overall,

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the Red Sea does not appear to be a good location for the use of deep SWRO intakes because of the structural risk of installing and maintaining an intake at near or below 100 m of water depth.

6.1 Introduction

It has been suggested that seawater to be used as feed water for seawater reverse osmosis (SWRO) facilities improves with depth because of lower primary productivity caused by light absorbance and a lower concentration of suspended sediment in the water column (Gille 2003; Cartier and Corsin 2007). Therefore, some have concluded that "deep water" intakes can produce a higher quality feed water that has potential to reduce the pretreatment requirements and to lower the cost of SWRO desalination.

It is important to first define the difference between "deep water" and "shallow water" intakes. Cartier and Corsin (2007) suggest that shallow water intakes range between depths of 0–15 m while deep intakes range from 20 to 35 m. They further suggest that the feasibility of deep water intakes is limited to geographic locations where deep water is found adjacent to the physical SWRO plant location and that there is no limit to the intake depth caused by water temperature. Cooler feed water can cause a significant increase in SWRO treatment cost (Goosen et al. 2002; Wilf 2007). The Japanese government funded Megaton project research suggests that deep water intakes can be feasible to depths >100 m (Ito et al. 2013). Both of these investigations assume that seawater quality actually improves with depth; the intake design will be secure and not subject to failure during normal operation; and routine maintenance can be performed on an intake structure, regardless of depth.

Biofouling of SWRO membranes has been linked to the concentration of transparent exopolymer particles (TEP) and other sticky polysaccharides in raw seawater (Berman and Passow 2007; Bar-Zeev et al. 2009; Berman 2010; Berman et al. 2011). TEP tends to coat or condition SWRO membranes and promote the formation of a biofilm by creating a sticky substrate that encourages attachment of bacterial cells and also provides a food source. Therefore, if a deep water intake truly provides a better feed water quality, then the concentrations of TEP, mono- and polysaccharides, biopolymers, and other organic substances should be lower to lessen the potential for membrane biofouling.

TEP is formed predominantly by the self-assembly of precursor substances, such as dissolved acidic polysaccharides, that are produced by algae and bacteria (Passow and Alldredge 1994; Passow 2000; Passow et al. 2001; Passow et al. 2002b). TEP acts as part of the sedimentary flux that produces flocs and marine "snow" which move downward in the marine water column (Alldredge et al. 1993; Passow et al. 2001; Passow 2002a), but also can migrate upward by buoyancy to the sea surface (Azetsu-Scott and Passow 2004; Mari 2008). The primary source of TEP and

precursors has been considered to be phytoplankton with some bacterial production (Passow and Alldredge 1994; Passow 2002a). Abiotic polymerization of dissolved precursor compounds along with sedimentation remove TEP from the euphotic zone (Engle 2004). Bacteria play an important role in the release, creation, or coagulation of TEP at depth in the sea (Van Loosdrecht et al. 1989; Johnson and Kepkay 1992; Stoderegger and Hernl 1998, 1999; Radic et al. 2006; Sugimoto et al. 2007). Therefore, the concentration of TEP and other organic substances that contribute to membrane biofouling does not strictly decrease with water depth and has an irregular occurrence profile as found in the Southern Ocean (Ortega-Retuerta et al. 2009), Hudson Bay (Michel et al. 2006), northeast Atlantic Ocean (Engle 2004) and at other locations (Wurl et al. 2001).

It has been suggested that deep ocean intakes will produce a higher quality feedwater based on some oceanographic investigations at various locations (Hayashi et al. 2003; Takahashi and Ikeya 2003; Takahashi and Yamashita 2005; Takasashi and Huang 2012). The purpose of this research is assess the use of potential deep water SWRO intakes along the Red Sea coast of Saudi Arabia by providing data on the bathymetry from the shoreline to deep water (>100 m), and the concentrations of algae and bacteria, TEP, and other organic fractions of natural organic matter (NOM) from a series of profiles collected offshore to 90 m below sea level or greater, and to assess an operating SWRO facility that extracts feed water from a depth of 9 m with a comparison to the surface seawater at the same site (Fig. 6.1). These data will provide some insight into algae, bacteria, TEP and organic carbon dynamics in the Red Sea and the feasibility of using deep water intakes.

6.2 Methods

6.2.1 Measurement of Red Sea Depth Profiles

A detailed bathymetric survey of a section of the Red Sea near Thuwal, Saudi Arabia was conducted. A three-dimensional depth projection from the beach to water depths greater than 100 m was developed using data collected from a programmed marine data collection device. Three bathymetric profiles were constructed to show the width of the inner reef low slope area, depth changes seaward of the coral reef, and the bottom slopes.

The bathymetric survey data were collected using a EK60 3 KHz scientific echo sounder manufactured by Simrad-Kongsberg Maritime Subsea. Surveys were conducted during the period of April to May, 2014. Compilation of the data and graphics preparation was accomplished using the Fledermaus and ArcGis 10 computer programs.

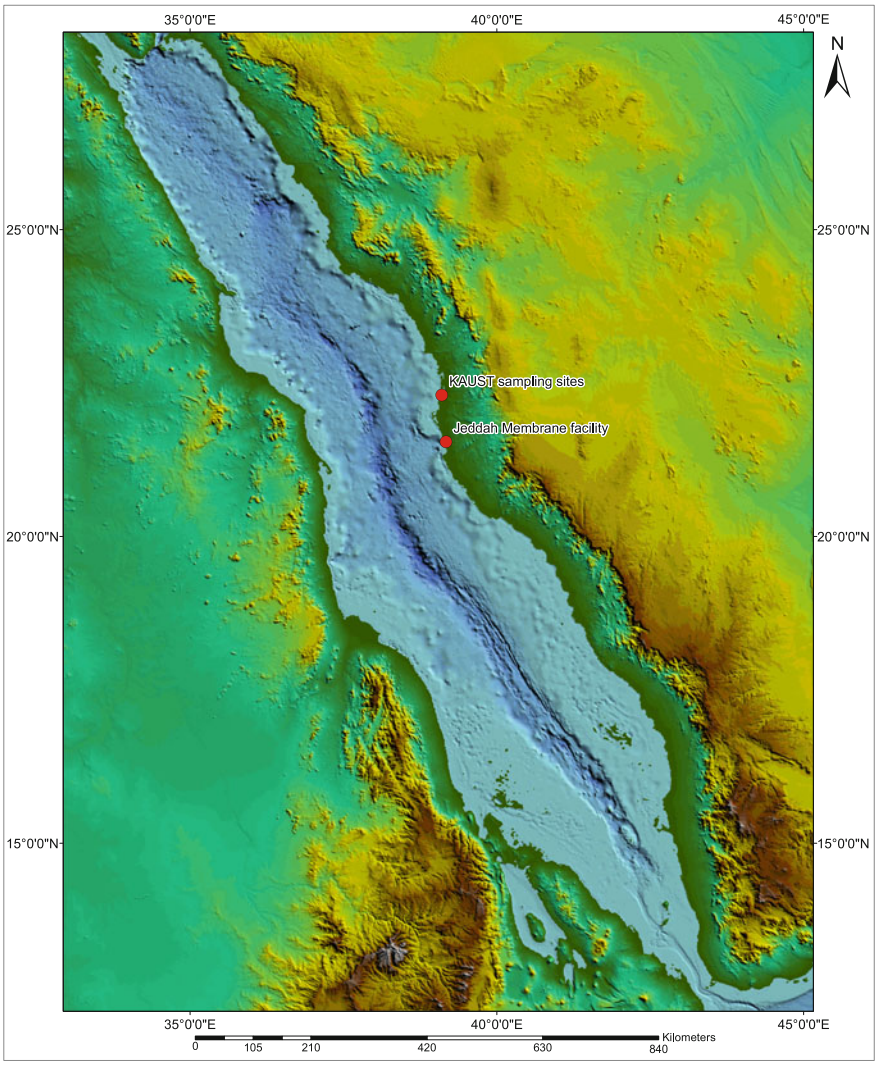

Fig. 6.1 Map showing the location in the Red Sea of the bathymetric profiles and profile sampling sites, and the membrane treatment facility where sampling was conducted

6.2.2 Water Sampling Methods

Water samples from the Red Sea were collected at 10 m depth increments from the sea surface to 90 m at three different sites in the vicinity of the King Abdullah University of Science and Technology which is located about 85 km north of Jeddah. Approximate 3 L of water was collected at each depth increment using a Seabird Carousel collection system. Physical parameters, including temperature,

conductivity, TDS, turbidity, and pH, were measured on the water samples. The water samples were immediately chilled to 4 °C to preserve the organic compounds and to lessen the potential for biological activity that could adversely affect measurement of the organic components.

Water samples collected for the purpose of TEP analysis were fixed using a 0.02 % (w/v) solution of sodium azide. For samples collected for algae and bacterial quantification, glutaraldehyde was added for preservation. Care was taken to carefully label and store all samples in opaque containers. The samples were quickly transported to the laboratory where the analyses were performed.

6.2.3 TEP Measurement

Analysis of TEP was performed using the Alcian Blue staining techniques developed by Passow and Alldredge (1995). Two types of TEP exist in the marine environment; particulate TEP with a size >0.4 μm and colloidal TEP with a size range from 0.05 to 0.4 μm (Villacorte et al. 2009).

A staining solution was prepared using a 0.06 % (m/v) Alcian Blue 8GX (Standard Fluka) solution that contains an acetate buffer (pH = 4) and the solution was pre-filtered through a 0.2 μm polycarbonate filter prior to staining. About 500 mL of seawater from each sample was filtered through a polycarbonate membrane with a pore size of 0.4 μm using an adjustable vacuum pump at a low constant vacuum. The membrane was then rinsed with 10 mL of Milli-Q water to avoid the coagulation of Alcian Blue once it comes in contact with the seawater during the staining process. Subsequently, the retained TEP on the membrane surface was stained with the Alcian Blue dye for 10 s. After staining, the membrane was flushed with 10 mL of Milli-Q water to remove the excess dye. The prepared membrane was then transferred into a small beaker, where it was soaked in 80 % sulfuric acid for 6 h to extract the Alcian Blue dye that is bound to the TEP. Finally, the absorbance of the resultant solution was measured using a UV spectrometer at 752 nm wavelength to measure the TEP concentration. For determination of the colloidal TEP concentration, the same general procedure was used, but 250 mL of the permeate water from filtering the seawater through the 0.4 μm polycarbonate filter was passed through a 0.1 μm polycarbonate membrane. Extraction of the colloidal TEP followed the same procedure as that for the particulate TEP.

To relate the UV absorbance values to TEP concentrations, a calibration curve was established. Xanthan gum solutions with different volumes, such as 0, 0.5, 1, 2, and 3 mL, were used to obtain a calibration curve. The total organic carbon (TOC) concentrations of xanthan gum before and after 0.4 μm filtration were analyzed (or 0.1 μm filtration for the colloidal TEP), and the TOC concentration difference was used to calculate the gum mass on each filter. The TEP mass was calculated based on the calibration curve as shown in Fig. 6.2. Note that curves for both particulate

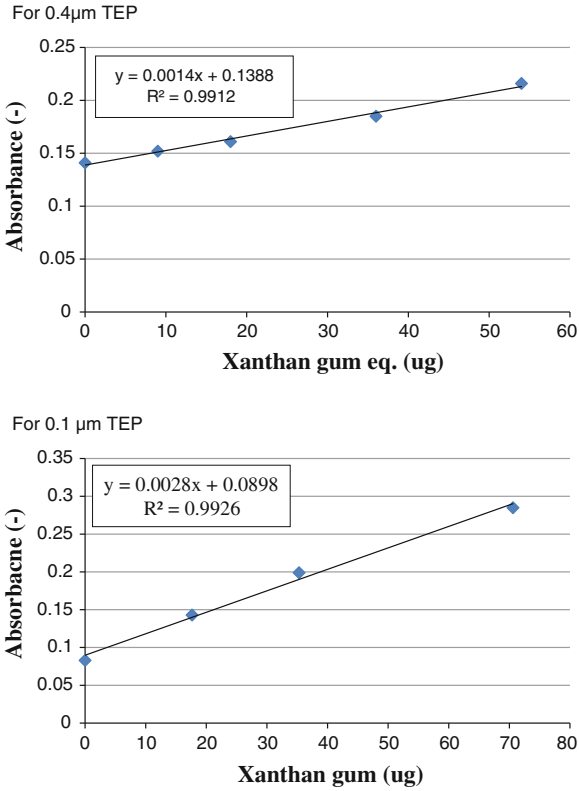

Fig. 6.2 Xanthan gum standard calibration curves for particulate and colloidal TEP

TEP and colloidal TEP are shown in the figure. Because of the methodology including the use of xanthum gum as a proxy, the estimated concentration of TEP is considered to be semi-quantitative.

6.2.4 Algae and Bacteria Quantification

Counts of the number of algae in the water samples were determined using a flow cytometer manufactured by BD Bioscience FACSVerse and bacteria concentrations were measured using a device manufactured by BD Accuri (C6). Algal cell counting was performed by combining 500 μL of each sample with a 1 μL standard containing 1 μm beads into a standard 10 mL tube. The tube was then vortexed and measured using a medium 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 staining protocol using SYBR® Green was used. A volume of 500 μL from each sample was transferred to a standard 10 mL tube, incubated in a 35 °C water bath for 10 min stained with the SYBR® Green dye

(5 µL into 500 µL aliquot), vortexed, and incubated for another 10 min. After that, 200 µL of the incubated sample was transferred into the measurement plate. The prepared samples were then analyzed in a medium flow setting with a 50 µL injection volume. Triplet measurements were made on each sample to assess precision.

6.2.5 Organics Analyses: Total and Fractions

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 organic carbon, a Liquid Chromatography Organic Carbon Detector (LCOCD) from DOC-Labor was used. The method developed by Huber et al. (2011) was used to measure the various fractions of the NOM.

The samples for the LC-OCD were pre-filtered using a 0.45 µm syringe filter to exclude the non-dissolved organics. Before analyzing the samples, a system cleaning was performed by injection of 4000 µL of 0.1 mol/L NaOH through the column for 260 min. Following the cleaning step, 2000 µL samples were injected for analysis with 180 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.

6.3 Results

6.3.1 Depth Profiles from the Beach to Offshore Deep Water Along the Red Sea Coastline

The bathymetric survey data are shown in Fig. 6.3. Figure 6.3a shows the location of the survey and the three depth profiles. Figure 6.3b shows a three-dimensional aerial view of the bathymetric data. Extreme variations in relief occur with water depths of 1–3 m occurring in the nearshore area with a low slope moving seaward from the shoreline and then a very steep slope (virtually vertical) occurs from 10 to 12 m to a depth of 400–500 m within an inner trough. A peninsular shallow area occurs from the shoreline to the south-southwest into deep water. This flat-topped feature contains some mud banks, seagrass flats, and reef corals, particularly along the seaward margin. The depth profiles illustrate the extreme slopes from shallow to deep water and some addition bottom features (Fig. 6.3c). The center profile shows a step within the depth profile from very shallow water flat-inner reef area with

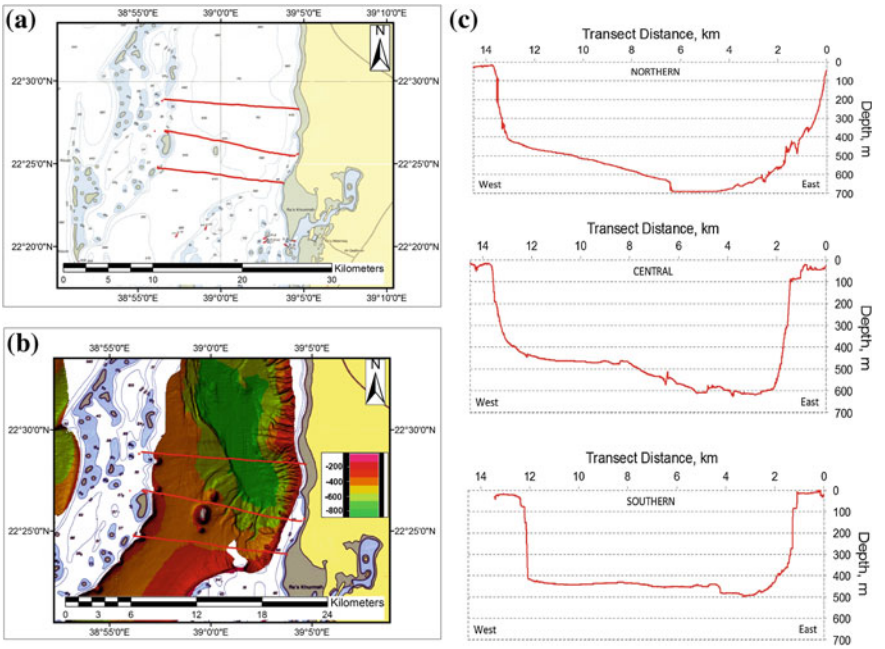

Fig. 6.3 Three-dimensional bathymetric projection of the bathymetry in the Red Sea near Thuwal, Saudi Arabia. **a** Map showing the location of the bathymetric survey and selected profiles. **b** Three-dimensional expression of the bottom bathymetry. **c** Selected profiles of the bottom topography from the shoreline to an offshore shelf area

depths range from 1 to 12 m to a depth of about 85 m, and then a near vertical cliff to a depth of almost 600 m. The 100 m depth at all locations occurs on a very steep slope or a vertical cliff.

6.3.2 Changes in Temperature, Salinity, Turbidity, Dissolved Oxygen, and PH with Depth in the Red Sea

Water temperature and salinity were continuously measured from sea surface to a depth of 90 m at three locations offshore from KAUST (Figs. 6.4). Temperature decreases in a regular manner about 5 °C with the lowest temperature being 24.3 °C at 90 m (Fig. 6.5). Salinity rises slightly with depth from about 38.9 ppt at surface to 40.0 ppt at the bottom (Fig. 6.6). Turbidity decreases very slightly by 0.02–0.05 NTU which is nearly insignificant. Differing trends of dissolved oxygen (DO) occur between sites. DO decreases at site A from 3.45 at surface to 2.25 ppm at 90 m, but at site B there is an increase from 2.20 to 4.20 ppm and at site C DO concentration increases from 2.10 to 4.07 ppm at 90 m (Fig. 6.7). Variation in pH is quite minimal at all sites with a very minor increase with depth.

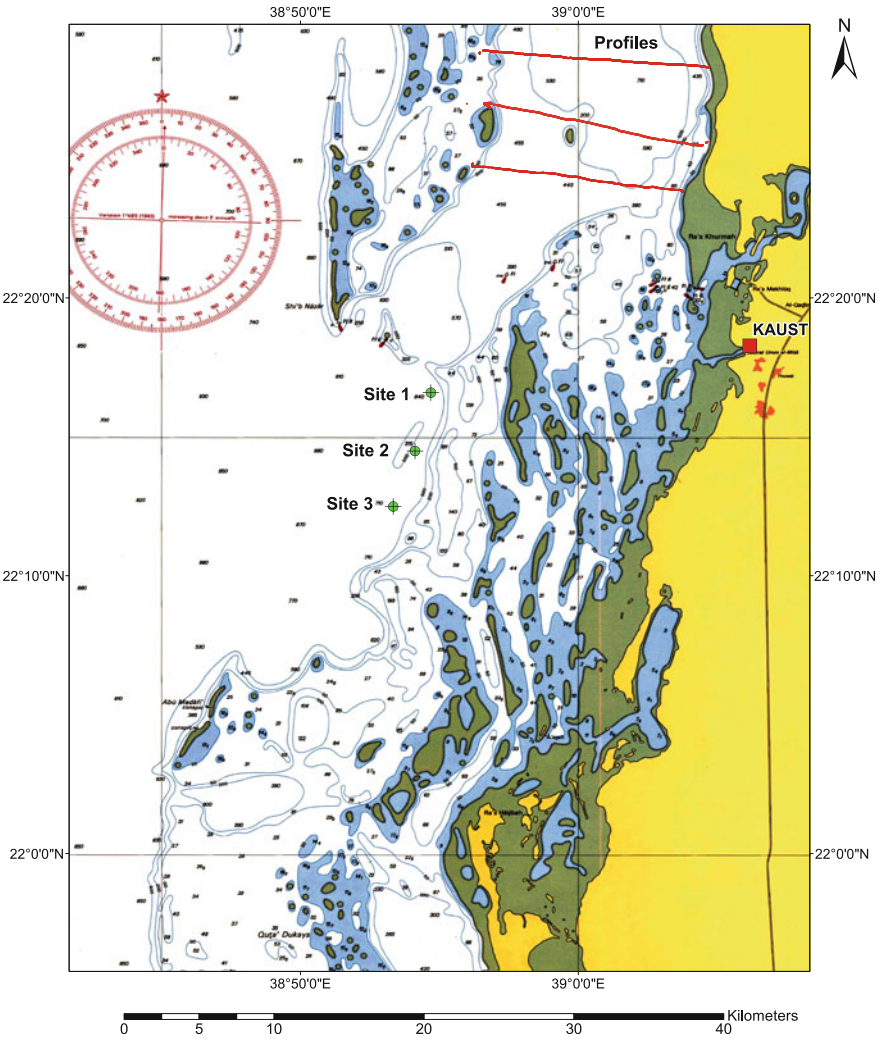

Fig. 6.4 Locations of depth profiles in Fig. 6.3 and sampling site locations A, B, and C

6.3.3 Distribution of Algae, Bacteria, TEP and the Biopolymer Fraction of NOM with Depth in the Red Sea

The concentration of total algae varied considerably with depth. The highest concentrations occurred at 50 m below surface instead of near surface (Fig. 6.8). The lowest algae concentrations were measured at the 90 m depth, which were about 2000 cells/mL. The surface algae concentrations ranged from about 30,000–60,000 cells/mL.

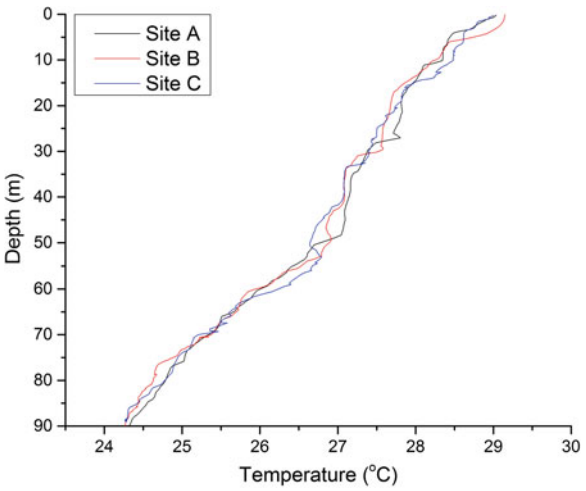

Fig. 6.5 Profiles of the Red Sea water column showing variation in water temperature with depth

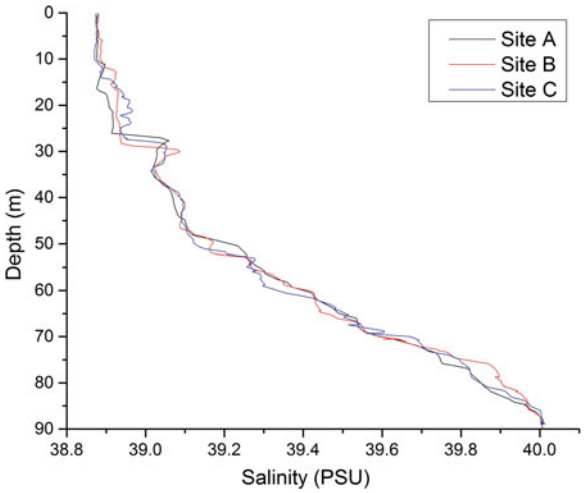

Fig. 6.6 Profiles of the Red Sea water column showing variation in salinity (conductivity) with depth

Total bacteria concentration trended downward from the sea surface to 90 m (Fig. 6.9). The data show an irregular decline in concentration with a decrease of about 79 %. The full range in concentrations for the three sites was found to be about 95,000–450,000 cells/mL.

Measured TOC profiles show a quite irregular variation with depth, but the trend is downward as would be expected. A spike in TOC occurs between 30 and 50 m below surface, but it is lower than surface except at site B where the surface concentration is quite low. The average of the three profiles is roughly 1.2 mg/L at surface and decreases to 0.95 at 90 m below surface (Fig. 6.10).

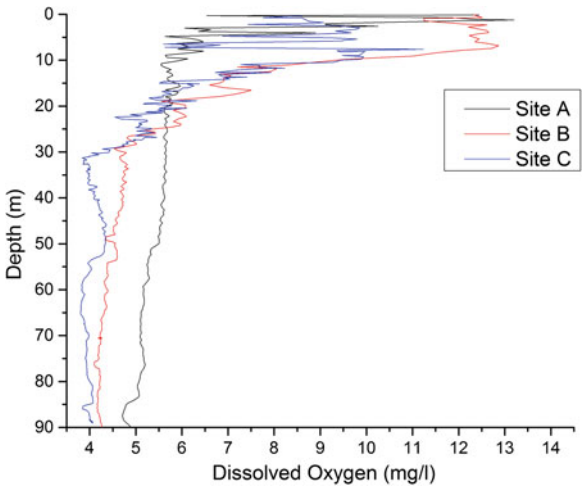

Fig. 6.7 Profiles of the Red Sea water column showing variation in dissolved oxygen with depth

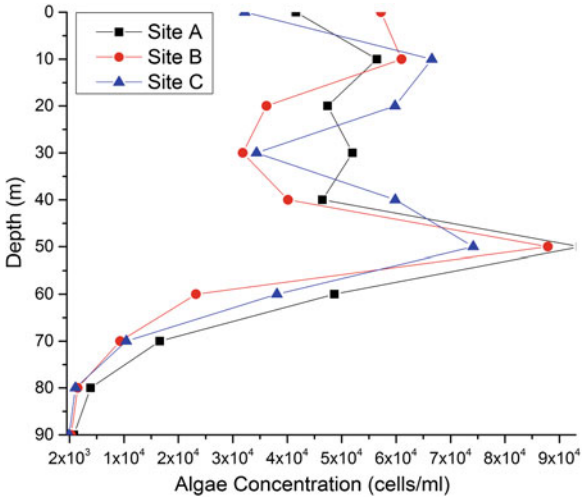

Fig. 6.8 Profile of the Red Sea water column showing total algal concentration with depth

Concentration of particulate and colloidal TEP are quite variable between the different sites with the highest concentrations occurring at surface, and generally decreasing with depth with the exception of colloidal TEP (Figs. 6.11 and 6.12). There is an upward spike in the concentration of both particulate and colloidal TEP at 40 m in all profiles except at site B.

The biopolymer fraction of NOM showed a steady decline from the sea surface to a depth of 90 m (Fig. 6.13). The highest concentrations were found at the B and C sites at a depth of 10 m below surface. Overall, the average concentration at surface was about 170 ppb and declined to about 100 ppb at 90 m below surface for an average decline of about 41 %.

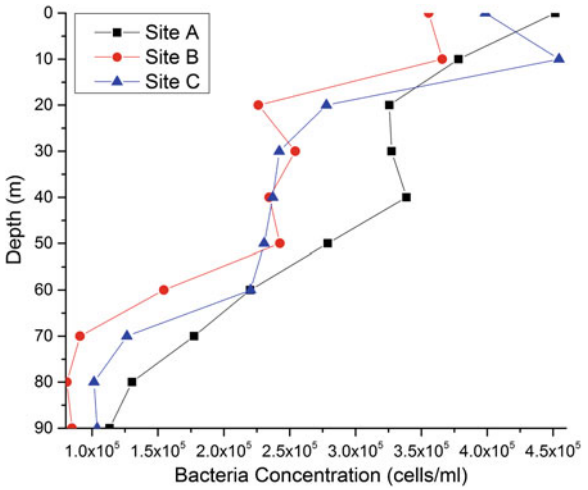

Fig. 6.9 Profile of the Red Sea water column showing total bacteria concentration with depth

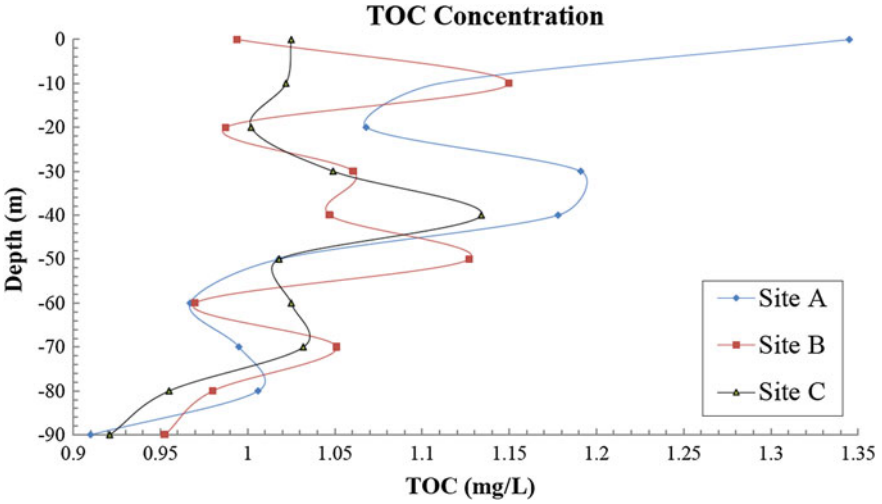

Fig. 6.10 Profiles of the Red Sea water column showing variation in concentration of TOC with depth

6.3.4 Comparison of Algae, Bacteria, Organic Carbon Fractions, and TEP at a 9 m Intake Depth with the Surface Seawater

A SWRO facility located near Jeddah uses an open-ocean intake that is located 9 m below the sea surface. While the depth of this intake is not really an example of a

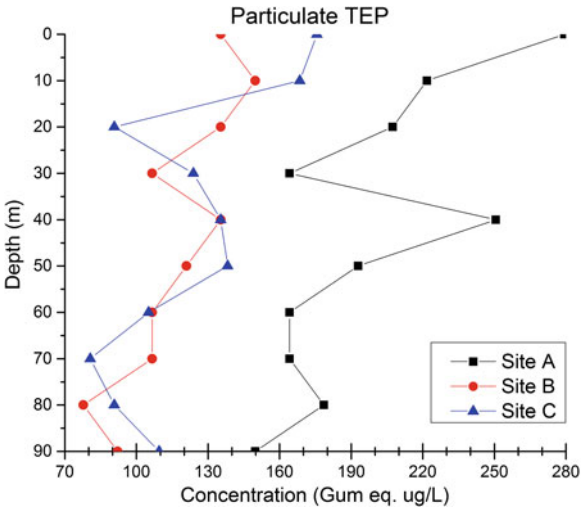

Fig. 6.11 Profiles of the Red Sea water column showing variation in concentration of particulate TEP with depth

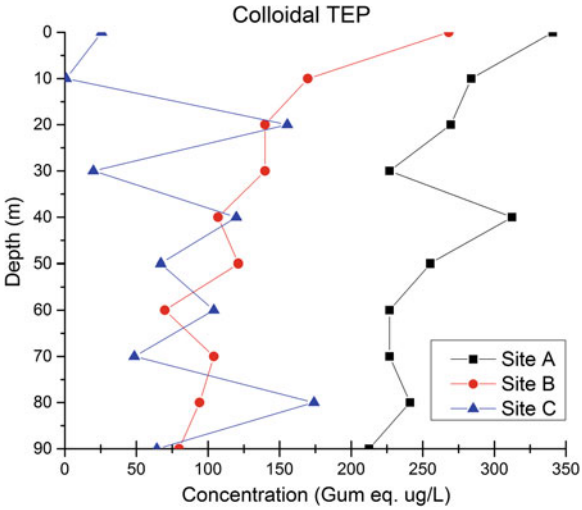

Fig. 6.12 Profiles of the Red Sea water column showing variation in concentration of colloidal TEP with depth

true "deep ocean" intake, it does allow some contrasts to be made on water quality changes with depth in the Red Sea. There are some interesting differences between the seawater at surface and at the 9 m depth. These data were extracted in part from Dehwah et al. (2014).

The flow cytometer analysis of the size and number of the algae shows that the overall concentration is rather low at 23,773 cells/mL at surface and 10,801 cell/mL at 9 m or a 55 % lower count with depth (Table 6.1). The dominant algae type is *Synechococcus*, which constitutes more than half of the population. The difference between concentration at the surface and the 9 m depth shows that all three algae

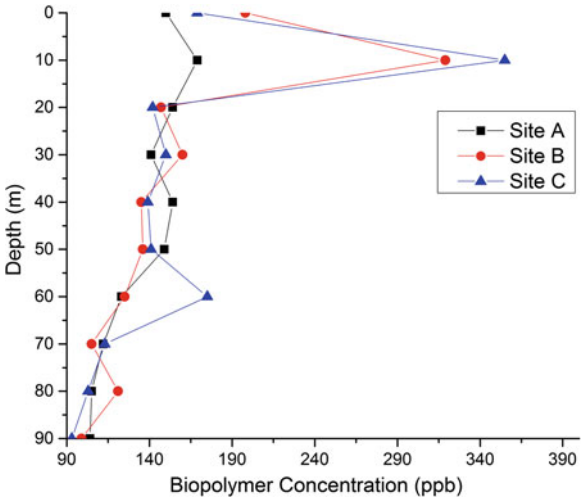

Fig. 6.13 Profiles of the Red Sea water column showing variation in concentration of the biopolymer fraction of total NOM with depth

Table 6.1 Measured algae concentrations at the sea surface and at a depth of 9 m (cells/mL)

Sampling Site	Synechococcus	Proclorococcus	Pico/nanoplankto	Total
Surface	14,488	8,590	695	23,773
9 m	6,823	3.735	243	10,801
Difference (5 less)	63	57	65	55

Table 6.2 Particulate, colloidal, and total TEP at surface and at a 9 m depth (μg/L of xanthan gum)

Sample location	Particulate TEP	Colloidal TEP	Total TEP
Surface	52.96	56.27	109.23
9 m	15.00	73.60	88.60
Percentage difference from surface	−72 %	+23 %	−19 %

types have a lower concentration with depth at this site which is located very close to the shoreline.

Concentrations of bacteria also show the same general pattern as the algae with surface seawater having a substantially higher concentration than seawater at the 9 m water depth (Fig. 6.13). Bacterial counts were relatively low at 317,174 and 210,761 cells/mL at the surface and bottom 9 m depth respectively, compared to concentrations that are commonly near 1 million cells/mL in seawater at other locations. The deeper water has a 34 % lower bacteria concentration.

A comparison of the particulate, colloidal, and total TEP shows that the variation with depth in the relatively shallow nearshore water is irregular (Table 6.2). Particulate TEP is substantially higher (72 %) in surface seawater than at 9 m, but the colloidal TEP is 23 % higher at 9 m compared to the surface. There is a 19 % difference between total TEP between the surface (higher) and the 9 m depth (Fig. 6.14).

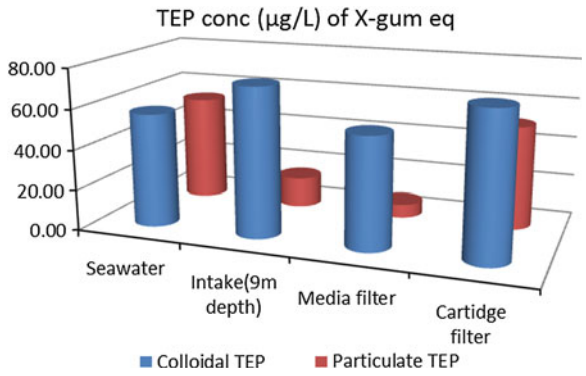

Fig. 6.14 Comparison of bacteria concentration between the surface and a 9 m depth (from Dehwah et al. 2014)

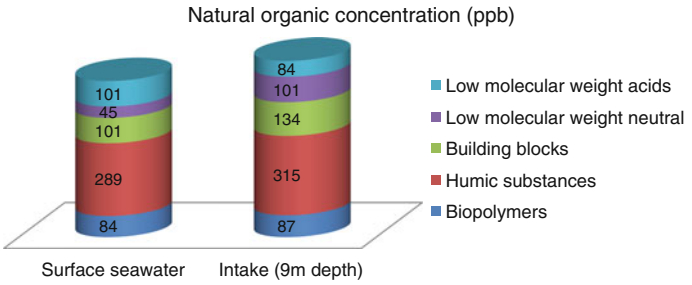

Fig. 6.15 Comparison of NOM fraction concentrations between the surface and 9 m (from Dehwah et al. 2014)

The concentration of TOC was nearly equal at the surface compared to the 9 m depth with the values of 0.88 and 0.83 mg/L respectively. Total NOM shows very little variation in composition between the surface and a depth of 9 m (Fig. 6.15). Each of the organic carbon fractions also shows a very similar concentration pattern with depth. Particularly noteworthy is that the biopolymer fraction, which contains the higher molecular weight polysaccharides and other organics that promote membrane biofouling, have nearly equal concentrations.

6.4 Discussion

6.4.1 Physical Bottom Bathymetry and the Feasibility of Using Deep-Ocean Intakes

The nearshore margin of the Red Sea along a section of the Saudi Arabia coastline has rather extreme relief with a narrow low-slope continental shelf. From the

shoreline water depth reaches a depth of 2 m between 150 and 250 m offshore. The bottom slope increases slightly to a depth of up to 12 m which occurs between 300 m and 2 km offshore. At this depth there is a steep drop to a narrow, flat shelf at about 85 m or a very steep slope (nearly vertical) to depths ranging between 420 and 600 m (middle transect in Fig. 6.3). The width of the continental slope is very narrow, perhaps 100 m to 2 km. The other transects show a nearly vertical wall occurring on the seaward margin of the reef tract with water depths reaching 500–600 m.

Based on the extremity of the nearshore topography, development of a deep ocean intake at a depth of about 100 m or a greater depth is not possible in this area of the Red Sea. The narrow step at a depth of 85 m at one location could be sufficiently wide and stable to support some type of bottom intake structure, but the connecting pipeline would have to be constructed with some very high strength material that is resistant to damage caused by downslope sediment transport during off-shelf transport events. This region is also subject to earthquakes which would cause sediment turbidity slides and would create shear forces on the pipeline (El-Isa and Shanti 1989).

The extreme steepness of the transition from shallow water to deep water along the coastline of the Red Sea of Saudi Arabia is common. Therefore, successful development of a deep water intake at a water depth greater than perhaps 20 m along the Saudi Arabia coastline is unlikely with the exception of perhaps a few limited areas. Construction and maintenance of a deep intake would be problematical based on the observed conditions.

6.4.2 Changes in Temperature, Salinity, and Turbidity with Depth and Effects on the SWRO Treatment Process

The general decrease in water temperature with depth in the Red Sea of <5 °C near the shoreline will not likely change the efficiency of the SWRO process. However, the observed increase of overall salinity of between 1100 and 1600 mg/L will have a slight impact on conversion efficiency because of a slight increase in the pressure required for the process. While there is a very minor decline in the turbidity, it appears to be insignificant in affecting the SWRO treatment process. Dissolved oxygen concentration shows an irregular change with depth. In two of the three profiles, the concentration decreases with depth by 50–70 % to an average of about 4.5 ppm at 90 m. These concentrations will not likely have a significant impact on SWRO treatment.

6.4.3 Potential Impacts of Organic Compounds in the Deep Sea Versus Shallow Water on Membrane Biofouling

The algae concentration generally declined with depth, but the highest values were found at a depth of 50 m below surface. Bacteria concentration declined relatively uniformly with depth and did not show any increase at 50 m.

The variation in TOC is between about 1.2 mg/L at surface and 1.0 at 90 m. There is generally a significant decrease in the concentration of both particulate and colloidal TEP with depth, but the trend is very irregular and profile B shows an increasing trend in colloidal TEP concentration. The biopolymer fraction of NOM shows a steady decline in concentration with depth. The spike in TOC and TEP concentrations at 40 m could be related to a high marine productivity zone.

It is interesting to note that there is some correlation of increased TOC concentration with the increase in algae concentration at between 40 and 50 m below surface. Particulate TEP seems to correlate to a degree with the spike in algae concentration between 40 and 50 m below surface. It appears that the particulate TEP may be moving upward in the water column. A spike in colloidal TEP occurs at 40 m below surface at 2 of the 3 sites tested.

Based on the data collected, the potential for SWRO membrane biofouling using the deeper water at 90 m would be somewhat decreased compared to the surface, but would still require the same general pretreatment train design compared to the surface seawater. Perhaps there would be less potential for membrane biofouling, but it is not possible to ascertain what impact it would have on the overall operation of a SWRO plant because the pretreatment processes would not be varied based on the data collected to date. This analysis of the organic compounds was conducted only to 90 m and seawater at greater depths may have a different trend. It is clear, however, that depth could be a significant issue in intake design, especially if the raw water was extracted from a high productivity zone, similar to that found between 40 and 50 m below surface.

6.5 Conclusions

Based on the observed bathymetric conditions, earthquake hazard, and the measured concentrations of bacteria, organic carbon, and TEP, it is concluded that design and construction of a deep water intake at over 90 m is not feasible in the segment of the Red Sea investigated. Furthermore, the very steep wall occurring seaward of fringing reef is a common feature along large segments of the Red Sea in coastal Saudi Arabia. This would make the construction of a deep intake very difficult and operational maintenance nearly impossible without using some type of submersible vehicle (below divers' depth range).

The water quality variation in temperature, salinity, turbidity, and dissolved oxygen between surface and a depth of 90 m in the Red Sea would not have a

significant impact on a SWRO plant operation. There is an overall decrease in algae, bacteria, TOC, TEP, and biopolymer concentration with depth, which could reduce the potential for membrane biofouling, but not to a large degree. A high productivity zone occurs between 40 and 50 m below surface, which would make this depth interval a poor option for locating a SWRO intake system.

Although a deep intake option may be a viable option at other locations, based on the data collected from the Red Sea, there is no clear advantage for using a deep sea intake system in the Red Sea. Also, there would be considerable construction and operational risk based on the extreme depth profile from the marine shelf to the deep water of the basin.

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References

Alldredge, A. L., Passow, U., & Logan, B. E. (1993). The adundance and significance of a class of large, transparent organic particules in the ocean. *Deep Sea Research, Part 1, 40*(6), 1131–1140.

Azetsu-Scott, K., & Passow, U. (2004). Ascending marine particles: significance of transparent exopolymer particles (TEP) in the upper ocean. *Limnology and Oceanography, 49*(3), 741–748.

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.

Berman, T. (2010). Biofouling: TEP-a major challenge for water separation. *Filtration and 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.

Cartier, G, & Corsin, P. (2007). Description of different water intakes for SWRO plants. In *Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse*, Gran Canaria, Spain, October 21–26, 2007, Paper IDAWC/MP07-185.

Dehwah, A. H. A., Li, S., Al-Mashharawi, S., Rachman, R. M., Winters, H., & Missimer, T. M. (2014). The influence of beach well and deep ocean intakes on TEP reduction in SWRO desalination systems, Jeddah, Saudi Arabia. *AWWA/AMTA Membrane Technology Conference Proceedings*, Las Vegas, Nevada, March 10–13, 2013, 18 pp.

El-Isa, Z. H., & Shanti, A. (1989). Seismicity and tectonics of the Red Sea and western Arabia. *Geophysical Journal, 97*, 449–457.

Engle, A. (2004). Distribution of transparent exopolymer particles (TEP) in the northwest Atlantic Ocean and their significance for aggregation processes. *Deep Ocean Research Part 1, 51*(1), 83–92.

Gille, D. (2003). Seawater intakes for desalination plants. *Desalination, 156*(1–3), 249–256.
Goosen, M. F. A., Sablani, S. S., Al-Maskari, S. S., Al-Belushi, R. H., & Wilf, M. (2002). Effect of feed temperature on permeate flux and mass transfer coefficient in spiral-wound reverse osmosis systems. *Desalination, 144*, 367–372.
Hayashi, M., Ikeda, T., Otsuka, K., & Takahashi, M. M. (2003). Assessment on environmental effects of deep ocean water discharged into coastal sea. In: Saxena, N. (ed.) *Marine Science and Technology, PACON International*, 535–546.
Huber, S. A., Balz, A., Abert, M., & Pronk, W. (2011). Characterisation of aquatic humic and non-humic matter with size-exclusion chromatography—organic carbona detection—organic nitrogen detection (LC-OCD-OND). *Water Research, 45*(2), 879–885.
Ito, Y., Hanada, S., Kitade, T., Tanaka, Y., & Kurihara, M. (2013). Clarification of impact of biofouling triggered by chemical addition for designing of Mega-Ton SWRO plant. In *Proceedings of the International Desalination Association World Congress 0n Desalination and Water Reuse*, Tianjin, China. Paper IDAWC/TIAN13-062.
Johnson, B. D., & Kepkay, P. E. (1992). Colloid transport and bacterial utilization of oceanic DOC. *Deep-Sea Research, Part A, 39*(5A), 855–869.
Mari, X. (2008). Does ocean acidification induce upward flux of marine aggregates? *Biogeosciences, 5*(4), 1023–1031.
Michel, C., Lapoussiere, A., LeBlanc, B., & Starr, M. (2006). Transparent exopolymeric substances (TEP) in Hudson Bay during fall. Significance and potential roles. *Reunion Scientifique Annuelle d'Arcticnet*, Victoria, Colombrie-Britanique (one sheet).
Passow, U. (2000). Formation of transparent exopolymer particles, TEP, from dissolved precursor material. *Marine Ecology Progress Series, 192*, 1–11.
Passow, U. (2002a). Production of transparent exopolymer particles (TEP) by phyto- and bacterioplankton. *Marine Ecology Progress Series, 236*, 1–12.
Passow, U. (2002b). Transparent exopolymer particles (TEP) in aquatic environments. *Progress in Oceanography, 55*(3–4), 287–333.
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 particules (TEP). *Limnology and Oceanography, 40*, 1326–1335.
Passow, U., Shipe, R. E., Murray, A., Pak, D. K., Brzezinski, M. A., & Alldredge, A. L. (2001). The origin of transparent exopolymer particles (TEP) and their role in the sedimentation of particulate matter. *Continental Shelf Research, 21*(4), 327–346.
Ortega-Retuerta, E., Reche, I., Pulido-Villena, E., Agusti, S., & Duarte, C. M. (2009). *Marine Chemistry, 115*, 59–65.
Radic, T., Ivancic, I., Kuks, D., & Radic, J. (2006). Marine bacterioplankton production of polysaccharidic and proteinaceous particles under different nutrient regimes. *FEMS Mircobiology Ecology, 58*(3), 333–342.
Stodergger, K., & Herndl, G. J. (1998). Production and release of bacterialcapsular material and its subsequent utilization by marine bacterioplankton. *Limnology and Oceanography, 43*(5), 877–884.
Stodergger, K., & Herndl, G. J. (1999). Production of exopolymer particles by marine bacterioplankton under contrasting turbulence conditions. *Marine Ecology Progress Series, 189*, 9–16.
Sugimoto, K., Fukuda, H., Baki, M. A., & Koike, I. (2007). Bacterial contributions to formation of transparent exopolymer particles (TEP) and seasonal trends in coastal waters of Sagami Bay. *Japan. Aquatic Microbial Ecology, 46*(1), 31–41.
Takahashi, M., & Ikeya, T. (2003). Ocean fertilization using deep ocean water (DOW). *Deep Ocean Water Research, 4*, 73–87.
Takahashi, M., & Huang, P.-Y. (2012). Novel renewable natural resource of deep ocean water (DOW) and their current and future practical applications. *Kuroshio Science, 6*, 101–113.

Takahashi, M., & Yamashita, K. (2005). Clean and safe supply of fish and shellfish to clear the HACCP regulation by use of clean and cold water in Rausu, Hokkaido, Japan. *Japan Journal of Oceanography, 4*, 219–223.

Van Loosdrecht, M. C. M., Lyklema, J., Norde, W., & Zehnder, A. J. B. (1989). Bacterial adhesion-a physicochemical approach. *Microbial Ecology, 17*(1), 1–15.

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

Wilf, M. (2007). *The guidebook to membrane desalination technology*. Balaban Desalination Publications, L'Aquila, Italy.

Wurl, O., Miller, L., & Vagle, S. (2001). Production and fate of transparent exopolymer particles (TEP) in the ocean. *Journal of Geophysical Research Oceans* 116(1) C00H13, doi:10.1029/2011JC0077342.