An Assessment of Subsurface Intake Systems: Planning and Impact on Feed Water Quality for SWRO Facilities

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ABSTRACT

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Subsurface intake systems are known to improve the feed water quality for SWRO plants. However, a little is known about the feasibility of implementation in coastal settings, the degree of water quality improvements provided by these systems, and the internal mechanisms of potential fouling compounds removal within subsurface intake systems.

A new method was developed to assess the feasibility of using different subsurface intake systems in coastal areas and was applied to Red Sea coastline of Saudi Arabia. The methodology demonstrated that five specific coastal environments could support well intake systems use for small-capacity SWRO plants, whereas large-capacity SWRO facilities could use seabed gallery intake systems. It was also found that seabed intake system could run with no operational constraints based on the high evaporation rates and associated diurnal salinity changes along the coast line.

Performance of well intake systems in several SWRO facilities along the Red Sea coast showed that the concentrations of organic compounds were reduced in the feed water, similar or better than traditional pretreatment methodologies. Nearly all algae, up to 99% of bacteria, between 84 and 100% of the biopolymer fraction of NOM, and a high percentage of TEP were removed during transport through the aquifer. These organics cause membrane biofouling and using well intakes showed a 50-75% lower need to clean the SWRO membranes compared to conventional open-ocean intakes.
An assessment of the effectiveness of seabed gallery intake systems was conducted through a long-term bench-scale column experiment. The simulation of the active layer (upper 1 m) showed that it is highly effective at producing feed water quality improvements and acts totally different compared to slow sand filtration systems treating freshwater. No development of a “schmutzdecke” layer occurred and treatment was not limited to the top 10 cm, but throughout the full column thickness. Algae and bacteria were removed in a manner similar to slow sand filtration, but it took many months to produce consistent reductions in NOM fractions and TEP. The data suggested that a thicker active layer (2m) is needed to facilitate a more rapid reduction in the main potential fouling organics.
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CHAPTER 1 : Introduction

Although earth surface is mostly covered by water, shortage of fresh water resources is one of the main pressing challenges for humanity. Most of the existing water is saline and cannot be used for human needs directly without proper treatment (Figure 1.1).

![Distribution of water on the globe](image)

Figure 1.1. Distribution of water on the globe [1]

The quantity of freshwater within the earth is limited and unequally distributed around the globe. In addition, population growth will also play a role in increasing the demand for fresh-water resources which already started to deplete especially in the arid and semi-arid regions. A report published by the World Bank stated that by 2025, around 3.5 billion people will live in places where water is scarce or becoming scarce [2]. Therefore, it is important to invest in improving new and existing water treatment technologies to overcome the problem of fresh-water shortages and to satisfy the growing water demand. One of the most effective methods for water treatment is desalination. Desalination is used to separate salt from water in seawater and brackish water. The use of desalination has grown rapidly for the last 60 years. Globally, the total desalination capacity exceeded more than 80 million m³/day in 2013 [3]. This capacity is mainly provided by thermal and membrane based technologies (Figure 1.2). Currently, the most energy-efficient technology of desalination available in the market is the membrane-based technology, which contributes 60%
of the total production capacity, and it is expected to dominate the desalination market in the near future [4].

In the Red Sea region, 13% (3.6 million m³/day) of worldwide desalination capacity is produced from desalination plants distributed along the coastline [5]. Around 92% (2.6 million m³/day) of the desalinated water produced from the Red Sea region is coming from desalination facilities located at the Red Sea coast line of Saudi Arabia, such as Shoaiba desalination plant, which is considered to be the second largest water desalination plant in the world.

![Figure 1.2. Global desalination capacity by technology [4]](image)

1.1 Objectives:

Seawater desalination using the reverse osmosis process is very expensive in terms of energy consumption and general operations. It can have some significant environmental impacts as well [6]. It is the primary goal of this research to help reduce the cost of SWRO desalination by lowering the cost of pretreatment, which is 15 to 25% of the overall cost [7], by making improvements in the design and operation of intake systems which ultimately will reduce the environment impact.
The quality of raw feed water pumped to an SWRO plant affects the design and overall performance of the desalination plant. Therefore, it is highly important to have an intake system that can provide sufficient quantities of high quality raw seawater to the desalination plants while reducing the associated negative environmental impacts. The intake system is one of the main elements in any RO desalination plant. The performance of the intake system can significantly affect the performance of the downstream components of the treatment system, including pretreatment, membrane treatment and post-treatment. Currently there are two main methods to supply raw seawater to desalination plants; either through the use of a direct intake system (open-ocean intake) or an indirect intake system (subsurface intake). An open-ocean intake system is commonly used to supply unlimited quantities of raw seawater to desalination plants. This type of intake delivers the raw water from the sea without any prior treatment. Therefore, when using an open-ocean intake, extensive pretreatment is required to improve the quality of the raw water in order to reduce damage to downstream processes and membrane fouling potential. In addition, there are some environmental impacts associated with the use of this type of intake, such as impingement and entrainment of fish and marine organisms through or within the intake structure. Some desalination plants that use open-ocean intake have been forced to shut down temporary during the algal bloom events [8, 9].

The second type of intake system is the subsurface intake. Subsurface intakes are divided into two main categories; wells and galleries. Both categories utilize the sediments and geological formation to provide natural filtration for raw seawater before entering the desalination plant. This helps in providing high quality raw seawater that will require minor pretreatment. In addition, subsurface intakes are considered to be environmentally friendly with no known negative impacts in the surrounding environment. SWRO desalination plants using this type of intake have less
tendency for membrane biofouling since raw seawater obtained using this mean of intake has high quality with low organic carbon concentrations. The feasibility of using a subsurface intake system is highly dependent on the geological, hydrogeological and environmental conditions of the site [10].

In order to assess the feasibility of using subsurface intakes along the Red Sea coast line of Saudi Arabia, it is important to investigate the different environmental conditions along the shoreline. This investigation helps with deciding about the feasible environments for constructing various subsurface intake systems. Moreover, evaluation of existing desalination plants with subsurface intake systems (well system) is important to check the degree of water quality improvement provided by the intake system. Furthermore, simulation of other types of subsurface intakes which are not existing locally (galleries) is necessary to understand the internal processes that take place inside this system and to evaluate the degree of quality improvement provided by gallery intake systems. The main objectives of this thesis are:

1) Studying the applicability and feasibility of designing subsurface intake systems along the Red Sea coastline of Saudi Arabia.

2) Understanding the main factors that influence the performance of subsurface intake systems.

3) Studying the degree of water quality improvements provided by the subsurface intake systems.

In order to assess the feasibility of designing subsurface intake systems and evaluating their potential performance along the Red Sea coastline of Saudi Arabia, the following were done:
• Coastal mapping of the Red Sea shoreline area to assess feasibility of using subsurface intakes for SWRO facilities within different coastal environments.

• Studying the impact of intake type (well vs. deep water) on improving the raw seawater quality.

• Evaluating the existing subsurface intake plants along the Red Sea coastline of Saudi Arabia to assess the degree of water-quality improvements provided by well intake systems.

• Performing a long-term, bench-scale column filtration experiment in order to understand the internal processes that take place inside a seabed gallery system and that cause improvement in feed-water quality.

• Studying the impact of evaporation rate on the operation of a gallery intake type (seabed) along the shoreline of the Red Sea.

1.2 Thesis Structure:

This thesis is divided into 8 chapters:

Chapter 1 includes a brief introduction about the need for desalination and the importance of having an adequate intake system to provide raw seawater with high quality. In addition, it includes the objectives and structure of this thesis.

Chapter 2 includes the literature review about the different types of intake systems and the role of intake type in improving the quality of feed water. It also reviews the main challenges for different intake systems.
Chapter 3 includes mapping of the different environments along the Red Sea coastline of Saudi Arabia. This mapping was then used to identify the potential environments for constructing various types of subsurface intake systems.

Chapter 4 includes evaluation of raw seawater quality as it goes through the intake (open vs. subsurface) and the pretreatment processes within an SWRO desalination facility. This helps in identifying the role of different intake types and different pretreatment processes in removing or changing organic and biological content of the raw seawater.

Chapter 5 includes the evaluation of well intake system at three different desalination facilities with different geological formations and design parameters. This evaluates the role of design parameters (e.g. retention time, depth, well age) in improving the raw seawater quality.

Chapter 6 documents a bench scale filtration experiment to assess the treatment provides by the uppermost layer of a seabed gallery system. The results of this long-term study will help in understanding the internal mechanisms occurring within the seabed filter. It also helps in understanding the roles of different design parameters (e.g. media type, media thickness) in removing algae, bacteria, organic carbon, biopolymers, and other potential membrane fouling compounds.

Chapter 7 provides an assessment of the effects of nearshore evaporation rates on the design of seabed gallery intake systems. This research assesses the performance of seabed intake systems during high-temperature seasons in Saudi Arabia in which evaporation rate is very high.

Chapter 8 is a summary of the important results of this research as well as recommendations for future work in the area of subsurface intake development.
1.3 References


CHAPTER 2 : SWRO Desalination Intake Systems

An intake system is the first step in every SWRO desalination system. This first step is very important since its performance can highly impact the entire desalination process. It is of significant importance to have a reliable intake system that can provide constant quality of feed water to a desalination facility at all times. The main goal of an intake system is to provide sufficient quantities of good quality feed water to the desalination facility while minimizing the associated environmental impact. The intake system can serve as part of the pretreatment system that can help in the reduction of environmental impacts, chemical use and the operating costs of the desalination facility [1].

Intake systems can be classified into two main types (Figure 2.1):

1- Direct intake system  
2- Indirect intake system
2.1 Direct intake system

The direct intake system which is known as open-ocean or shoreline intake is the most commonly used intake type for SWRO desalination plants. Direct intakes can be used to supply unlimited quantities of raw seawater to the desalination plants. Some direct intake systems are constructed along the shoreline and are commonly used in association with power plant cooling water intakes [2]. Another type of direct intake is constructed offshore by connecting the intake structure to a pipeline lying upon the seabed. The structure type and the length and the depth of the pipeline will be vary from one site to another based on the site characteristics. Based on the intake pipe line depth, the direct intake system can be classified to either surface intakes or deep-water intakes.
In surface intake systems feed water is extracted from shallow water depths (1-6 meters) [3]. The raw water extracted at this depth is more vulnerable to poor quality water characteristics due to high organic content, suspended solids and the presence of photosynthetic microorganisms.

The other type of surface intake is the deep-water intake in which water is extracted at depths that are more than 35 m [3]. At this depth, the water quality is generally higher with the debris load up to 20 times less than the load at the surface [3]. However, there are some concerns that might limit the use of this type of intake such as downward movement of organic matter during algal blooms and the cool water temperature which could lead to some treatment inefficiencies in the SWRO process. In addition, the complexity of the intake structure construction and the maintenance/cleaning requirements at those depths make this option more challenging [4].

In general, the quality of raw water extracted through an open-ocean intake is variable based on the seawater quality changes around the intake point. The natural marine environment contains impurities, freely swimming organisms, organic content and biological activities that need to be controlled before seawater enters a desalination plant. Controlling the aforementioned particulates, organics and biological activities before entering the desalination plant helps decrease the rate and degree of membrane fouling. Unfortunately, an open-ocean intake does not provide protection to SWRO membranes from the mentioned organics and organisms. In addition, entrainment and impingement of fish and marine organisms through the open intake make it environmentally unfavorable to use this intake type without further protection at the pipe terminal [5]. In certain occasions, desalination plants with open-ocean intakes were forced to shut down during the red tide events. This occurred at the Galeelah Desalination Plant in UAE in 2009 [6,7]. Therefore, it is highly important to have a robust pretreatment system that can reduce the load of the organic and microorganisms in the raw seawater prior to entering a desalination plant.
Velocity caps and passive screens are used to prevent/decrease the passage of marine organisms and fish within the intake pipe at the point of seawater entry [8]. Velocity intake structures are also used to decrease the entrainment of swimming organisms (fish) that sense the changes in direction of water flow and swim away. They also inhibit the penetration of sunlight into the pipeline which reduces the rate of growth of the biofouling layer within the pipe structure and growth of large sessile organisms, such as corals or oysters. Moreover, periodic chlorination is also used to decrease the attachment and growth of marine organisms within the intake pipeline. Furthermore, extensive pretreatment system and a high load of chemicals are needed to provide protection for the SWRO membranes against the fouling when using open-ocean intake (Figure 2.2).

![Figure 2.2. Pretreatment requirements for different intake systems [9]](image-url)
2.2 Indirect intake systems:

The design of subsurface intake systems is based on the principles used in riverbank filtration systems which has been used for freshwater treatment of river and reservoirs in Europe and United States for more than a century [10, 11]. In subsurface intake systems, a geological unit always separates the point of intake from the water source to the water treatment facility. Subsurface intake systems utilize the natural sediments or constructed filters within the natural system to provide treatment for raw seawater before entering the desalination plant [2]. Size exclusion and biological degradation within the geological media help to reduce the organic content (TOC and NOM), suspended sediments and biological concentrations of the delivered raw seawater through this type of intake. The performance of a subsurface intake is highly dependent on the local hydrological and geological conditions at the intake site. The use of this type of intake has been proven to be cost-effective for small to medium capacity desalination plants. It was also implemented in several large-scale desalination plants where the production capacity exceeds 80,000 m³/day such as the Sur SWRO plant in Oman with a total capacity of 80,200 m³/day and the Fukuoka SWRO plant in Japan with a 103,000 m³/day capacity [12, 13].

Generally, the extracted seawater through a subsurface intake system has high quality which reduces significantly the complexity of pretreatment system. In addition, the environmental impact is minimal since no entrainment and impingement can occurs through this intake system. The main drawback of the subsurface intake systems is the capacity limitation which is based on the local geological conditions at the intake site.
Subsurface intakes are classified into two main groups; wells and galleries. Wells can be subdivided into vertical wells, slant wells, Ranney/collector wells and horizontal wells while galleries are subdivided into beach galleries and seabed filters/galleries [2].

2.3 Well systems

2.3.1 Vertical wells

Conventional vertical wells are the most commonly used type of the well system (Figure 2.3). Vertical wells are commonly used for small-capacity seawater desalination plants [14] (Table 2.1). However, there are some large-capacity desalination plants using vertical wells to supply raw seawater to the desalination plant such Sur plant in Oman with a total permeate capacity of 80,200 m$^3$/day [12]. Vertical well yields are limited based on the local geology at the drilling site. Therefore, it is important to complete a preliminary site investigation to evaluate the expected yield from each well and the aquifer as a whole [15].

![Figure 2.3. Vertical well configuration](image-url)
For large desalination plants, numerous wells will be needed to provide the required capacity. In this case, an evaluation of total cost of the well system construction against other intake options must be done. Vertical wells are better constructed near the shoreline in which wells are primarily recharged with seawater. Wells that are constructed further inland are more vulnerable to contamination from the nearby groundwater system. Therefore, location of wells is very important to guarantee an adequate yield as well as the quality of the produced water. Wells should be designed and constructed following the industry standards and the recommended materials to assure a long life and to protect it against corrosion [16]. Maintenance of vertical wells is also important to restore the well efficiency and to remove buildup of calcium carbonate scale or biofilm within the wellbore and the screens. Vertical wells have proved to be effective in improving the quality of raw seawater supplied to SWRO desalination plants [17-23]. Organic content, algal and bacterial concentrations were significantly reduced at the well discharges [23-31].
Table 2.1. Selected desalination plants using vertical wells as intake [9]

<table>
<thead>
<tr>
<th>Facility Name</th>
<th>Location</th>
<th>Capacity(^1) (m(^3)/d)</th>
<th>No. of Wells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sur</td>
<td>Oman</td>
<td>160,000</td>
<td>28</td>
</tr>
<tr>
<td>Alicate (two facilities)</td>
<td>Spain</td>
<td>130,000</td>
<td>30</td>
</tr>
<tr>
<td>Tordera</td>
<td>Blanes, Spain</td>
<td>128,000</td>
<td>10</td>
</tr>
<tr>
<td>Pembroke</td>
<td>Malta</td>
<td>120,000</td>
<td>-</td>
</tr>
<tr>
<td>Bajo Almanzora</td>
<td>Almeria, Spain</td>
<td>120,000</td>
<td>14</td>
</tr>
<tr>
<td>Bay of Palma</td>
<td>Mallorca, Spain</td>
<td>89,600</td>
<td>16</td>
</tr>
<tr>
<td>WEB</td>
<td>Aruba</td>
<td>80,000</td>
<td>10</td>
</tr>
<tr>
<td>Lanzarote IV</td>
<td>Canary Islands, Spain</td>
<td>60,000</td>
<td>11</td>
</tr>
<tr>
<td>Sureste</td>
<td>Canary Islands, Spain</td>
<td>60,000</td>
<td>-</td>
</tr>
<tr>
<td>Blue Hills</td>
<td>New Providence I., Bahamas</td>
<td>54,600</td>
<td>12 (?)</td>
</tr>
<tr>
<td>Santa Cruz de Tenerife</td>
<td>Canary Islands, Spain</td>
<td>50,000</td>
<td>8</td>
</tr>
<tr>
<td>Ghar Lapsi</td>
<td>Malta</td>
<td>45,000</td>
<td>18</td>
</tr>
<tr>
<td>Grikewwa</td>
<td>Malta</td>
<td>42,000</td>
<td>-</td>
</tr>
<tr>
<td>CR Aguilas, Murcia</td>
<td>Spain</td>
<td>41,600</td>
<td>-</td>
</tr>
<tr>
<td>SAWACO</td>
<td>Jeddah, Saudi Arabia</td>
<td>31,250</td>
<td>10</td>
</tr>
<tr>
<td>Dahab</td>
<td>Red Sea, Egypt</td>
<td>25,000</td>
<td>15</td>
</tr>
<tr>
<td>Turks &amp; Caicos Water Company</td>
<td>Providenciales, Turks &amp; Caicos Islands</td>
<td>23,260</td>
<td>6</td>
</tr>
<tr>
<td>Windsor Field</td>
<td>Bahamas</td>
<td>20,000</td>
<td>-</td>
</tr>
<tr>
<td>North Side Water Works</td>
<td>Grand Cayman</td>
<td>18,000</td>
<td>-</td>
</tr>
<tr>
<td>Ibiza</td>
<td>Spain</td>
<td>15,000</td>
<td>8</td>
</tr>
<tr>
<td>North Sound</td>
<td>Grand Cayman</td>
<td>12,000</td>
<td>-</td>
</tr>
<tr>
<td>Red Gate</td>
<td>Grand Cayman</td>
<td>10,000</td>
<td>-</td>
</tr>
<tr>
<td>Abel Castillo</td>
<td>Grand Cayman</td>
<td>9,000</td>
<td>-</td>
</tr>
<tr>
<td>Al-Birk</td>
<td>Saudi Arabia</td>
<td>5,100-8,700</td>
<td>3</td>
</tr>
<tr>
<td>Lower Valley</td>
<td>Grand Cayman</td>
<td>8,000</td>
<td>3</td>
</tr>
<tr>
<td>West Bay</td>
<td>Grand Cayman</td>
<td>7,000</td>
<td>-</td>
</tr>
<tr>
<td>Britannia</td>
<td>Grand Cayman</td>
<td>5,400</td>
<td>4</td>
</tr>
<tr>
<td>Bar Bay</td>
<td>Tortola, B.V.I.</td>
<td>5,400</td>
<td>-</td>
</tr>
<tr>
<td>Morro Bay</td>
<td>California, USA</td>
<td>4,500</td>
<td>5</td>
</tr>
<tr>
<td>AmberGIS Caye</td>
<td>Belize</td>
<td>3,600</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\)Capacity (approximated based on published reports or estimated based on the reported capacity of the plant divided by the reported conversion rate or a maximum of a 50% conversion rate where it is not reported)
2.3.2 Ranney or collector wells

Ranney wells which are also known as collector wells are similar to vertical wells but contain a central caisson and a series of lateral screens extending seaward at the bottom of the well [2] (Figure 2.4). The lateral screens help maximize the yield of the individual well. It is preferable to use this type of well in areas with variable hydraulic conductivity and horizontally bedded sediments where a gravel bed occurs that can be tapped to provide high yield. These types of wells have been used as intakes to provide large capacity of water along rivers in United States and Europe and it was proven to be effective at suspended particles and pathogenic organisms removal [32-34]. However, for SWRO applications there is only one known desalination facility that utilizes the collector well type which is the PEMEX Salina Cruz refinery in Mexico with a total capacity of 45,000 m³/day, obtained from three collector wells [35]. The maintenance of collector wells can be complicated and would likely require the shutdown of the well which might necessitate the addition of a backup well to maintain SWRO plant capacity during maintenance which increases the system cost. The location of the collector well must be very close to the intertidal zone of the beach to allow recharge through the lateral screens and to decrease inland aquifer impacts. This location makes Ranney wells subject to storm damage and erosional isolation [2]. In general, in the presence of the favorable geological conditions, radial collectors have the ability to supply feed water for large-scale desalination plants.
2.3.3 Angle-wells

Angle wells, which is also known as slant wells, are drilled from near the shoreline with an extension toward the seabed (Figure 2.5). The orientation of angle wells helps in maximizing the well recharge as well as reducing the interference with inland groundwater system [36].
Multiple angle wells can be constructed from a single site located in the back-beach or off the beach to form a cluster which minimizes the land area required for construction (Figure 2.6). Construction and maintenance of the angle wells are more complicated than vertical wells and it requires special techniques and equipment. Currently, there is no large desalination plant using angle wells as an intake but its feasibility has been evaluated for several desalination plants in California (USA) [37, 38]. It is more likely that it would be suitable for medium-capacity SWRO desalination plants. It is of importance to evaluate the yield of angle wells versus the construction and operation costs for the lifespan of the desalination plant.

Figure 2.6. Slant wells with clusters [37]
2.3.4 Horizontal wells

Horizontal wells are drilled from shoreline towards the seabed using a horizontal directional drilling (HDD) method (Figure 2.7). Horizontal wells can produce high yields since the recharge occurs through the vertical flow. In addition, the inland area required for horizontal wells construction is small since multiple horizontal wells can be originated from a single location (Figure 2.8) [39]. Before construction of a horizontal well system it is important to characterize the geology beneath the seabed to ensure that sediment are sufficiently permeable to meet the desired yield for the wells. Also, the water quality must be tested to be sure that metals yields will be low. In addition, oxidation-reduction conditions (mixing of oxygenated seawater with anoxic water beneath the bottom) must be evaluated to avoid the precipitation of undesired metals within the wells. Construction and maintenance of horizontal wells could be difficult and costly since special equipment and expertise are required. In general, if the hydrogeological conditions are supportive at the well site, then horizontal wells can produce an unlimited capacity of raw water. Currently, there are several desalination plants using the horizontal wells to supply raw water for SWRO desalination plants with the highest capacity being 172,800 m$^3$/day at San Pedor del piñata plant (Spain) [40-45]. However, difficulties have occurred with the system located at Alicante, Spain [46].
Figure 2.7. Horizontal wells configuration [9]

Figure 2.8. Horizontal wells cluster [39]
2.4 Gallery systems

Gallery intake systems are designed based on the concept of slow sand filtration and river bank filtration which has been used for fresh water treatment for more than a century [10, 47]. A gallery intake is designed by excavating part of the sea bottom and constructing an engineered filter within the seabed. The engineered filter could be located at the intertidal zone for a beach gallery or it might be extended and placed offshore for a sea bed gallery. The use of engineered sands in gallery systems helps control the hydraulic parameters of the filter and makes it more dependable compared to use of the natural geological sediments [48]. Among all the subsurface intake systems, gallery intake systems have the greatest potential to supply raw seawater for the large-capacity SWRO desalination plants.

2.4.1 Slow sand filtration

Slow sand filters are composed of engineered layers of media (sand) and underlined by a drain system consisting of a collection screen system with gravel support [49-52]. The typical thickness of a slow sand filter is between 1 to 1.5 m and the mean grain diameter of the media lies between 0.3 and 0.45mm. This system is always submerged with water passing through the system by the work of gravity alone at a typical infiltration rate between (1.2 to 4.8 m/day) [53]. As the water passes through the filter an active layer will be formed in the upper 10 cm of the filter (mostly at the surface). The upper 10 cm of the filter is where virtually all of the treatment occurs, especially the removal of biological particulates. This layer is called the Schmutzdecke and it consists of particulate material, natural bacteria, algae and protozoa [54]. This layer usually forms from a few days to several weeks of operation (based on the raw water quality) in the area of the sand-supernatant water interface. This layer is responsible of most of the purification processes that take
place in the slow sand filter [55-57]. Size exclusion, biological degradation, sedimentation and adsorption play important roles in removing pathogens, suspended materials and other organic matters from the raw water [58-65]. Over time, the Schmutzdecke layer grow in thickness and more sediments, organic material and microorganisms are deposited at the filter face which eventually causes plugging of the system. As a result, the flow rate decreases and the head loss increases which requires system cleaning to restore the filter performance. Cleaning is achieved by scraping the upper layer of the filter until the thickness of the filter is reduced below an operational threshold which requires rebuilding it with new sand. The main advantages of the slow sand filtration are the low cost, ease of operation and the efficiency in removing organic and microorganism content from the raw seawater. On the other hand, the main limitation of the slow sand filter is the very large footprint required for filter construction and operation. In addition, there is a limitation of raw water turbidity (10-50 NTU) that can be effectively treated by slow sand filtration [53]. Moreover, the removal efficiency of slow sand filter decreases under low temperature conditions [66]. Little is known about the long-term operation of slow sand filtration in a seawater environment.

Figure 2.9. Slow sand filtration design [65]
2.4.2 Beach gallery

Beach gallery intakes are constructed in the intertidal zone of the beach to take advantage of wave turbulence and generated currents for filter face cleaning [2, 68, 69]. Beach gallery intakes can operate in areas of sandy beaches with moderate wave that contain acceptable rates of hydraulic conductivity to allow effective infiltration rates to be maintained [70]. It is of importance to study the beach historical changes in shoreline position and tide fluctuation ranges to ensure that the gallery location is appropriate and is always covered with water. A beach gallery intake must be constructed with sufficient thickness to meet the water quality improvement needs and to maintain the gallery during storm events and large wave activities. Currently, there is no existing facility using a large-scale beach gallery intake system but several designs have been proposed for SWRO desalination plants [71]. This engineered filter can support the supply of unlimited quantities of raw water to SWRO desalination plants.

Figure 2.10. Beach gallery intake configuration [9]
2.4.3 Seabed filters

Seabed filters are constructed offshore beneath the seabed. The seabed filter intake option is preferable when the geological conditions and water quality characteristics at the coastline do not support the construction of other alternative intakes. Part of the offshore seabed is excavated to a defined depth. Then an engineered filter is constructed by adding several layers of sand with a gravel layer at the base which contains intake screens embedded in the basal layer [2]. The grain size of the sand layers is progressively decreased from bottom to top to avoid infiltration of finer material into the next underlying layer. The uppermost layer of the seabed filter is covered with sand that is compatible with native sediments that can move over top of the filter during storm events. Therefore, areas with low mud content are preferable for seabed filter construction to avoid filter clogging with time. The presence of natural biological process, such as bioturbation by marine infauna within the sediments, also helps maintain the filter from clogging [72]. Moreover, the availability of currents that keep fine sediments in suspension and move sediments across the bottom will help keeping the filter face clean with time. Currently, there is only one large desalination plant uses a seabed intake system which is the Fukuoka seawater RO plant in Japan with an intake capacity of 103,000 m³/day [13]. This seabed gallery operates at infiltration rate of 5 m/day with 7 hours of retention time. The facility has been in operation for 12 years with no need for gallery cleaning and the membrane cleaning requirements have been minimal [73]. The recorded silt density index (SDI) for the raw water pumped through the gallery system stared slightly below 3.0 and has been below 2.0 during most of the operational history. The seabed intake system was also tested in another facility at the city of Long Beach in California [74, 75]. Results proved that seabed intake system is effective at reducing turbidity, SDI and dissolved organic carbons. However, the system did accumulate silt, and particulate iron in the filter media which
was caused by movement of interstitial water from the sediments because the sides of the filter were open. The applicability of designing a seabed gallery system along the Red Sea coastline of Saudi Arabia was investigated and positive results were obtained [72, 76-79]. In general, a seabed intake system can be used to supply feed water for large-scale SWRO plants but the capital cost is higher since construction is performed offshore. The environmental impact of seabed intake system is minimal and it is mainly during the initial construction. In addition, the issue of entrainment and impingement of marine organisms is eliminated with the use of a seabed gallery intake.

Figure 2.11. Seabed gallery intake configuration [80]
Figure 2.12. Seabed intake design in Fukuoka SWRO plant [73]

Figure 2.13. Seabed intake configuration in Fukuoka desalination plant [73]
2.5 Discussion

The use of subsurface intake systems is proven to be effective at improving feed water quality for SWRO desalination plants. However, there is little documentation about the degree of water quality improvement provided in the literature. In addition, the internal mechanisms of removing organic matters, suspended sediments, biodegradable organics and other potential fouling debris and compounds within subsurface intake systems are not fully understood based on the literature. Moreover, there are almost no data available in the past studies about the performance of the seabed intake system in terms of raw water quality improvements and the design parameters that influence its effectiveness in the improvement of feedwater quality. The Fukuoka facility reports only improvement in SDI. No general guidelines were provided in the literature about the feasible environments for constructing subsurface intakes, especially along the Red Sea coastline of Saudi Arabia.

Without this information, the long-term operation and capacity of subsurface intakes within different environments is questionable especially for large-capacity SWRO desalination plants. It is the objective of this research to help decision makers, planners, and the water industry to understand the nature of the coastal areas in order to determine the potential for use of a subsurface intake for future development of SWRO facilities along the Red Sea coastline and around the globe. In addition, this research will help in understanding the internal mechanisms of removing potential fouling organics within a subsurface intake system. Moreover, the design parameters that influence the effectiveness of the subsurface intake system in terms of feed water quality improvement will be investigated in this research to ascertain how engineering design improvements can be made.
The general points that will be evaluated in this investigation are the following:

- Development of a methodology to evaluate the feasibility of using subsurface intakes for SWRO facilities along the Red Sea coastline of Saudi Arabia with global applications.
- The removal degree of algae, bacteria, and organic carbon compounds through subsurface intake systems.
- The internal mechanism of removal of the potential fouling bacteria and dissolved organic matter in subsurface intake systems.
- Assessment and improvement of the engineering design and operational parameters that influence the effectiveness of subsurface intake systems and pretreatment systems.
2.6 References


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CHAPTER 3 : Mapping to assess feasibility of using subsurface intakes for SWRO, Red Sea coast of Saudi Arabia

3.1 Summary

Use of subsurface intakes for seawater reverse osmosis desalination (SWRO) systems is known to improve raw water quality, reduce use of chemicals, improve operational reliability, and reduce the life-cycle cost of desalination. A key issue in the planning for development of a SWRO facility that would potentially use a subsurface intake is the characterization of the coastal and nearshore geology of a region to ascertain the types of subsurface intakes that could be used and their respective costs. It is the purpose of this research to document a new methodology that can be used for planning and assessment of the feasibility of using subsurface intake systems for SWRO facilities at any location in the world.

The Red Sea shoreline and nearshore area of Saudi Arabia was mapped and sediments were sampled from the Yemen border north to the Jordan border, a distance of about 1,950 km. Seventeen different coastal environments were defined, mapped, and correlated to the feasibility of using various types of subsurface intake systems. Six environments were found to have favorable characteristics for development of large-scale subsurface intakes. The most favorable these coastal environments includes: 1) beaches and nearshore areas containing carbonate or siliciclastic sands with minimum mud concentrations and environmentally sensitive bottom community biota or fauna (A1, A2, A3), limestone rocky shorelines with an offshore carbonate...

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or siliciclastic sand bottom underlain by soft limestone and a barren area lying between the shoreline and the offshore reef (B1, B5), and wadi sediments on the beach (mixture of pebbles, gravel, and sand) with a corresponding nearshore area containing either siliciclastic sand and/or a marine hard ground (soft limestone or sandstone) (C2).

It was found that seabed galleries were the subsurface intake type with the highest feasibility for development of large-capacity intakes. The geological characteristics of the offshore sea bottom were found to be favorable for the development of seabed gallery systems, but the shoreline geology was not adequate for the development of beach gallery intakes (low wave activity). Detailed field investigations were conducted at four sites located along the Red Sea coast at the King Abdullah Economic City, Shoaiba, Om Al Misk Island, and Shuqaiq city. Some of the environments are adequate to allow use of conventional wells, angle wells, radial collector wells, or horizontal wells. However, these intake types have some capacity limitation along the Red Sea coastline. There are several medium to small capacity SWRO facilities that utilize conventional shallow well systems (beach wells) as intakes along the Red Sea coastline.

3.2 Introduction

The supply of freshwater is becoming a pressing global problem as the world population grows, water sources diminish in quantity and quality, and climate change affects various regions, altering the availability of supplies. As new sources of freshwater are sought, seawater desalination has become a greater part of the supply solution in many regions. Although it is energy intensive and expensive, seawater desalination offers the only water supply solution in many areas and if the cost would be reduced, it could be applied to areas having less financial resources. Therefore, it is a goal of desalination researchers and the industry to reduce desalination cost by making the
process more efficient and reducing energy consumption. Use of subsurface intake systems can simplify the pretreatment process train, and reduce the energy use, the need for chemicals, environmental impacts, and the overall operational cost [1-5].

There are a variety of subsurface intake systems that can be potentially used for intakes to a seawater RO facility. These intake types include conventional wells, slant wells, Ranney or radial collector wells, horizontal wells, beach galleries, and seabed galleries [2]. The feasibility of using one or any of these intake types is dependent on the geology of the specific site available to construct an intake. Therefore, it is necessary to understand and evaluate the coastal, shoreline, and nearshore areas to plan for the future development of seawater RO facilities, especially when a subsurface intake system is being considered.

It is the purpose of this paper to present a methodology that can be used to evaluate the coastline area to assess the potential use of subsurface intake systems. The coastal area of the Red Sea of Saudi Arabia is used as an example because Saudi Arabia is currently the largest user of SWRO desalination and many existing facilities occur along the Red Sea shoreline with more being planned. The methods applied herein can be used to characterize any coastal/shoreline area for short- or long-term SWRO facility planning, especially when a subsurface intake system is being considered for use.
3.3 Methods

A combination of methods was used to characterize the geomorphology of the Red Sea coastline of Saudi Arabia. This included a literature search, field visits to 105 sites, collection and analysis of 485 sediment samples, use of archived satellite images to classify various segments of the coast with groundtruthing provided by field site visits, photographs, and data georeferencing.

A literature search was conducted to assess past geologic investigations of the shoreline and nearshore sediments and the processes that affect these areas. Some of the investigations provided some localized details on the sediment types and general characteristics. The coastline has a wide variety of geomorphological types such sandy beaches, wadi sediment beaches, rocky carbonate shorelines, Pre-Cambrian Shield cliffs at the shoreline, lagoons and bays, mangrove/coastal marine wetland areas, offshore islands, and urban-modified shoreline areas.

Site visits and direct visual observations revealed the detailed coastal characteristics (Figure 3.1). A series of sediment samples were collected; some of which occurred on the beach and others were collected from the offshore area in transects perpendicular to the shoreline. The qualitative nature of the shoreline and offshore sediments was recorded. Also, the presence or absence of a reef and the general wave height at the shoreline were also observed and recorded. Sediment properties were measured in the laboratory to assess mean grain diameter, mud percentage, porosity and hydraulic conductivity at selected sites.

The geomorphological characteristics of the coastal area were assessed with respect to each type of potential subsurface intake system that could be potentially designed and constructed to provide feed water to a SWRO facility. A qualitative, planning-level assessment was also made concerning the possible range of system capacities that may be feasible. Site-specific, detailed feasibility
assessments were conducted at four locations and were used to test the planning-level assessments [6-9].

Figure 3.1. Red Sea shoreline of Saudi Arabia showing the location of sites visited and sampled. Locations of some selected areas of the shoreline with mapped geomorphological zones are shown.
3.4 Results

3.4.1 Geologic and geomorphological characteristics of the Red Sea coastline

The shoreline of the Red Sea contains a diverse set of physical conditions ranging from sandy beaches containing variable composition (carbonates and siliciclastics) [9-14] to wadi sediments (gravel, pebbles and boulders) [15] to rocky shorelines containing limestone [16-19] or Precambrian rocks to coastal lagoons, bays, sabkhas [20], and mangroves [21]. A large part of the nearshore area contains a fringing coral reef tract occurring with a transition from shallow nearshore barren carbonate sands with some patchy corals to a full coral reef tract in deeper water offshore [22, 23]. Commonly, the beach and nearshore area contains modern beachrock and associated carbonate hardgrounds [24]. A Pleistocene-age limestone commonly occurs along the shoreline and sometimes forms a shallow offshore low-dipping shelf (<2 m of water depth) [16, 17]. The carbonate environment is transected by siliciclastic sediments carried into the marine environment via wadi features. Where the wadi sediments form channel deposits or lobes, the reef tract does not exist and there is a transition between the terrigenous siliciclastic sediments and the carbonate sediments associated with the reef tract [12]. In some areas, the wadi sediments extending offshore have significant mud content. Lagoons and small bays are common along the shoreline and contain restricted muddy sediments with or without an associated offshore reef. Carbonate sand islands occur offshore with seaward reef growth unaffected by terrigenous sediment input. Mangrove shorelines occur in restricted water areas and along shorelines containing offshore mud shoals with both occurrences being common.

Some technical investigations have been performed on the coastal area and nearshore marine environment for the purpose of developing management plans and to assess anthropogenic impacts
[25-27]. These geologic, geomorphological, and planning investigations have been combined with the direct observations, collected sediment sample data, and satellite photograph observations to produce a geomorphological classification of the Red Sea coast of Saudi Arabia.

3.4.2 Classification and descriptions of Red Sea coastal/shoreline/nearshore geomorphic environments

The coastal environments of the Red Sea were grouped into 17 different classifications based on the topography at the shoreline, the type of sediment (rock, sand, mud), the vegetation type at the shoreline, the general composition of sediment (or rock) in the nearshore, and the presence or absence of coral reefs (Table 3.1). Some grouping of environments was necessary because many sub-systems could be defined within each general classification.

3.4.2.1 Sandy beaches and associated offshore environments

Three classifications of coastal systems were defined within this general category. There can be considerable variability in the detailed physical framework of these classifications and in offshore sediment or rock types.

A1 has a sandy beach, with or without a back-beach dune system. The beach sand can be composed of skeletal carbonates or siliciclastic sediments or a mix of these lithologies. No large pebbles or cobbles are present and the sand is devoid of any mud. In some locations, the beach sand is fully or partially cemented by modern marine carbonate cements (beach rock). The nearshore sea bottom contains predominantly sand, sometimes with a minor belt of slightly muddy sediments lying near the beach. The sand may set atop a marine hardground (modern cemented sediment) or an older (Pleistocene-aged), soft, coralline reef complex. An offshore coral reef complex is present beginning in water depths ranging from 1 to 2 m.
Table 3.1. Geomorphological classifications of the Red Sea coastline.

<table>
<thead>
<tr>
<th>Classifications</th>
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<tbody>
<tr>
<td><strong>A. Sandy Beaches</strong></td>
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<tr>
<td>A1-Sandy beach with corresponding nearshore sand or slightly muddy sand, coral reef complex offshore</td>
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<tr>
<td>A2- Sandy beaches, restricted, with no reef</td>
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<tr>
<td>A3-Offshore island with nearshore sandy sediments and reef</td>
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<tr>
<td><strong>B. Rocky shorelines</strong></td>
</tr>
<tr>
<td>B1- Limestone rocky shoreline with corresponding nearshore sand, and offshore coral reef complex</td>
</tr>
<tr>
<td>B2-Limestone rocky shoreline with nearshore muddy sediments</td>
</tr>
<tr>
<td>B3-Limestone rocky shoreline, nearshore deep water, no reef</td>
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<tr>
<td>B4-Rocky headland with offshore rocky bottom, no reef</td>
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<tr>
<td>B5-Rocky shoreline, wadi sediments nearshore, offshore reef</td>
</tr>
<tr>
<td><strong>C. Wadi intersections</strong></td>
</tr>
<tr>
<td>C1-Wadi sediments (boulders, pebble, and gravel) at shoreline, variable sand, gravel and mud offshore with no reef</td>
</tr>
<tr>
<td>C2-Wadi shoreline sediments, nearshore marine hard ground, minor nearshore sand, coral reef offshore</td>
</tr>
<tr>
<td><strong>D. Sabkha, lagoons, and mangrove</strong></td>
</tr>
<tr>
<td>D1-Coastal sabkha shoreline and nearshore muddy sediments</td>
</tr>
<tr>
<td>D2-Muddy shoreline with lagoonal muddy sediments, nearshore sand and offshore reef complex</td>
</tr>
<tr>
<td>D3-Muddy shoreline /lagoon/ supratidal sabkha with no reef complex</td>
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<tr>
<td>D4-Mangrove shoreline with nearshore muddy sediments</td>
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<tr>
<td><strong>E. Others</strong></td>
</tr>
<tr>
<td>E1-Shoreline reef complex dropping to deep water in the nearshore off-reef area</td>
</tr>
<tr>
<td>E2-Artificial channels or urban shoreline with artificially filled nearshore dropping to deep water nearshore</td>
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<tr>
<td>E3-Natural channel</td>
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</table>

A2 occurs at the shoreline of restricted water bodies, particularly shallow bays and coves. It has a sandy beach with no associated coral reef system. The beach sediment is mostly siliciclastic and the same is true for the nearshore bottom sands. In most cases, the sand contains little or no mud at the shoreline, but may become muddier offshore.

A3 occurs on the beaches of offshore islands. There are many low-relief, emergent sand bodies occurring along the Red Sea coastline. These bodies are not generally associated with steep-relief islands containing a core of Precambrian rock (cliffed shoreline). They consist predominantly of clean carbonate sand devoid of mud and siliciclastic sediments. Commonly, the nearshore areas
on the windward side of these islands are composed of carbonate sand containing a barren bottom, seagrass with variable density, or patchy coral colonies. The sand bottom transitions offshore into a coral reef complex. The bottom can also contain a thin veneer of sand setting upon a marine hardground or older, soft, reefal limestone.

3.4.2.2 Rocky shorelines and associated offshore environments

There are 5 classifications of the coastal zone that contain rocky shorelines. Three of these classifications have a limestone shoreline of likely Pleistocene age while the remaining two shorelines consist of Precambrian cratonic rocks (rocky headlands).

B1 has a limestone rocky shoreline that can be cliffed, angular, or consist of rock rubble. In some cases, there is a narrow belt of sand paralleling the shoreline that is either emergent or submergent. The nearshore is generally covered by carbonate sand of variable thickness, commonly setting atop a soft limestone unit. Where the bottom is fully covered by sand, some marine grass or solitary coral may occur. Where the bottom is rocky, coral growth is commonly denser. The density of corals generally increases seaward until the fringing reef occurs in 1 to 3m of water. The offshore sediment contains a low mud concentration, except in the presence of dense marine grass beds.

B2 is a limestone rock shoreline that tends to be cliffed and lies near a wadi feature. There is no reef tract and the nearshore sediments can consist of sand, muddy sand, or mud.

B3 is a limestone rocky shoreline that is typically cliffed and may contain little or no very shallow water in the nearshore. Water depth from the rocky shoreline drops to over 2 m within less than 50 m offshore. In most locations, no offshore fringing coral reef is present.

B4 is a rocky shoreline that could be termed a headland. It consists of outcropping Precambrian-age shield rocks that are cliffed or contain a very narrow beach. The nearshore and deeper-water
offshore areas are rocky or strewn with large boulders. No coral reef is usually present, but solitary corals may grow atop of the rocks if the water is not turbid.

B5 is a combined rocky shoreline containing Precambrian rock or boulders along with wadi sediments in the nearshore and offshore in deep water areas. The wadi sediments consist of boulders, cobbles, pebbles, sand, and mud. The sediment composition is dependent on slope of the alluvial fan channel or wadi that allows transport of the sediment to the shoreline and nearshore, and the drainage basin characteristics of the sediment source area.

3.4.2.3 Wadi intersections

Surface-runoff originating inland enters the Red Sea via channels that occur on intersecting alluvial fans or from wadi channels. Flow in these channels is ephemeral, but when it occurs it is commonly a flash flood containing very high, water velocities. The sediment load contains a variety of rocks and debris ranging from 50 cm in diameter to mud (0.0625 mm). The sediments are highly unsorted when entering the shoreline or nearshore marine environment and can become better sorted when exposed to nearshore marine processes over an extended time period (wave action and currents). Therefore, they can be very muddy or sand dominated depending upon the length of time that they reside in the marine environment.

C1 occurs where wadi sediments lie on the beach and in the nearshore area. Mud percentage is variable offshore, but commonly over 10%. No offshore coral reef is present because the mud carried to the marine environment by the wadis inhibits reef growth.

C2 occurs where wadi sediments on the beach contain a low mud percentage. The beach wadi sediments can be cemented into beachrock. The nearshore area contains wadi sediments that are commonly cemented into hardgrounds. Siliciclastic or carbonate sand blankets the offshore rock.
Solitary corals grow on rock exposed on the bottom. The density of corals increases offshore with the reef tract beginning in 2 to 3 m of water depth. This environment occurs some distance away from the mouth of a wadi intersection with the shoreline and contains low mud content.

3.4.2.4 Sabkhas, lagoons, and mangroves

A series of four environments occur along the Red Sea coast that have restricted water circulation and are the primary depositional areas for muddy and organic sediments. The classifications used are rather general and could be broken into many more based on slight differences. For example, most of the mangrove shorelines contain muddy inshore and nearshore sediments and no coral reefs. However, in some cases the mangrove shorelines contain an outer series of mud banks within a lagoonal setting with a fringing coral reef further offshore.

D1 is a coastal sabkha that is in hydraulic connection with the sea. A sabkha is a supra-tidal to intertidal area wherein seawater is trapped during storms or high tide events and the trapped water evaporates to produce hypersaline conditions, commonly with the precipitation of evaporite minerals occurring on the sabkha plain. In many cases the sabkha environment is not directly connected to the sea and lies landward of a restricted water body, either a bay or lagoon. Sabkha sediment is characteristically muddy and may contain rock composed of gypsum, dolomite or calcite.

D2 is a muddy shoreline commonly associated with a landward-lying sabkha that may contain a nearshore subtidal sand belt lying seaward of the mud shoals. It commonly has a fringing coral reef lying in slightly deeper water from 2 to 4 m. The sand belt may lie on a Pleistocene paleo-reef complex and may contain some mud from the shoals. There is a clear separation between the muddy bottom environment and the offshore fringing reef.
D3 is a muddy shoreline that does not contain a transition to sand and an offshore fringing reef. Commonly, the shallow nearshore bottom is covered fully or in part by marine grasses. The grasses contain epibiots that produce some quantity of mud. Also, the very shallow water and the grass combine to trap suspended muddy sediments during windy conditions.

D4 is a mangrove shoreline that contains organic sediment deposits (peat) and trapped mud. The mangrove peat contains siliciclastic sediment trapped among the roots. The shallow nearshore areas are generally muddy and commonly mud shoals occur offshore of these areas. Sometimes the mangrove shoreline is associated with restricted water bodies, either bays or lagoons and circulation is maintained by narrow channels to the sea. The shoreline and restricted bodies are covered by muddy sediments and some seagrass where circulation is sufficient to keep salinities within an acceptable range. Reefs do not occur in this environment, but can occur further offshore both north and south of the primary drainage channels.

3.4.2.5 Others

There are three additional environments which are natural (channel intersections) or man-altered systems. The man-altered systems are the result of development practices that have fully changed the natural geomorphologic character of the shoreline.

E1 occurs in areas where there is a fringing reef complex lying immediately offshore from the coastline. There is no well-established beach. Where this environment occurs in a natural setting, the shoreline is rocky and no siliciclastic sediments have reached the shoreline from the interior by either water transport or aeolian processes. Reef growth occurs directly offshore where water depth increases rapidly from 0 to 5 m.
E2 is an environment created artificially by the purposeful filling of the entire inshore and shallow nearshore sand belt for seaside development (direct boating access and docks). In certain cases, even the inner, shallow zone of the reef tract has been filled leaving only the deeper corals at depths greater than 5 m. This heavily altered environment is common in the Jeddah area.

E3 occurs within the channels that intersect with the sea. Most of these channels drain natural coastal lagoons and bays and provide circulation to these restricted environments. However, there are also a series of channels artificially dredged for connecting the sea to harbors or basins. Many of these channels transect the fringing reefs and other nearshore environments.

3.5 Discussion

3.5.1 Application of coastal geomorphological principals to siting of subsurface intake systems

Development of subsurface desalination systems requires that the area along the shoreline must have some coastal aquifer that has moderate to high hydraulic conductivity or a sandy beach with moderate wave activity or a shallow offshore area containing a sandy bottom with low mud content and slow rates of sediment deposition. The objective is to locate geologic conditions that are conductive to allow large volumes of seawater to pass through sediments or an aquifer to produce primary treatment of the raw seawater. Descriptions of the coastal geomorphological environments are described in (Table 3.1) and the text and are shown in (Figure 3.2) and (Figure 3.3). These figures show some of the classified environments.
Figure 3.2. Geomorphological map of selected segments of the Red Sea coast of Saudi Arabia (north)
Figure 3.3. Geomorphological map of selected segments of the Red Sea coast of Saudi Arabia.

Sandy beaches with sandy offshore environments are favorable for development of large-scale subsurface intakes such as gallery systems (A1, A2, and A3 in Table 3.1). Seabed gallery intakes are expected to produce high quantities of raw water in areas with low mud content in the nearshore sediments. The occurrence of sandy sediments in the shallow offshore areas allows the development of seabed gallery intakes because it is indicative of high hydraulic conductivity of the natural sediments and low mud content, which could clog a constructed filter. On the other hand, a beach gallery system is preferable in areas with moderate wave activity and an active
intertidal zone in order to perform the self-cleaning mechanism for the filter face [28]. Beaches with low or no wave action at the shoreline or restricted sandy beaches with poor circulation and low wave action are not favorable for constructing this type of intake. Some sandy bottom environments occur where the installation of gallery intake systems is not feasible due to the potential adverse environmental impacts (e.g. coral reef or marine grass beds occurrence) associated with the construction activities.

A sandy beach or combined sandy beach and limestone rocky shoreline or offshore environment may be also adequate for the construction of well intake systems. Vertical, angle, horizontal or radial wells can produce moderate to large yields of feed water, especially in the presence of permeable rock and sufficient thickness of gravel and porous sand deposits underneath the coastal region. The yield of horizontal wells in these environments depends on the thickness of beach deposits as well as the lateral length (seaward) of the permeable sediment deposits. Use of angle wells requires some minimum thickness of permeable sediment in the nearshore area. Horizontal wells may be used when the thickness of permeable sediments and/or rock is relatively thin in the nearshore area (e.g., 5 to 10 m). In environments, such as restricted sandy beaches bordering sabkhas, wells may have low yields and the water may be hypersaline because of a hydraulic connection between the sediments and the sabhka brines. Construction of a well intake type is not recommended at rocky or boulder-laden shorelines with high wave and storm activities, because subsurface galleries or wells would be potentially damaged by the wave action or erosion processes.

For large SWRO facilities the utilization of vertical well intakes may not be economically feasible along many shorelines because of limited capacity obtained from an individual well, leading to the need for a large number of wells. Radial collector wells can potentially produce high feed water
yields. The occurrence of thick permeable layers (e.g. gravel) at shallow depths will support the high yields from radial collector wells. The use of horizontal wells in sandy and limestone rocky environments can be questionable because very detailed and expensive investigations would be required to guarantee that the subsea geology would support the withdraw of high quantities of raw water.

Rocky shoreline environments containing limestone with corresponding nearshore sand or wadi sediments can also be feasible to construct gallery and well intake systems under the same conditions mentioned for the sandy environments, including moderate wave activity, low mud percentage and sufficient thickness of beach deposits. Environments B1 and B5 commonly contain these conditions. Rocky shorelines with offshore rocky bottoms or nearshore muddy sediments or steep slopes to deep water are not feasible areas for development of subsurface intakes (environments B3, B4). An exception may be a limestone shoreline with muddy nearshore sediments that has a shallow offshore area with a sandy bottom (B2).

Areas with wadi shoreline sediments, nearshore marine hardgrounds covered with a thin veneer of sand and low mud percentage are feasible for gallery intake development (C2). On the contrary, shorelines that occur directly in front or nearby the mouth of a wadi (C1) are not feasible for subsurface intake development due to the high mud concentration (clogging of the gallery intake) and the relatively high overall sedimentation rate that could bury galleries or destroy well heads in a storm event.

Construction of subsurface intakes in environments where there is a high mud concentration in the sediments and no water circulation (sabkha, lagoons and mangrove) is not desirable due to the potential for clogging of the filter. The high organic content and high evaporation rate produce
additional unfavorable conditions. All restricted and nearshore muddy shorelines or mangrove coasts are not feasible for development of subsurface intakes (D1, D2, D3, D4).

Urban shorelines that were artificially filled out to the reef tract are considered to be not feasible for subsurface intake development due to the limitation on the availability of space for well and gallery construction (shoreline is adjacent to the deep-water area) (E1). Other areas within or near artificial or natural channels also cannot be used because of a lack of adequate subsurface aquifer thickness (E2, E3) and turbidity in the water column caused by human activities. An assessment of the coastal environments of the Red Sea with a correlation to the possible use of various subsurface intake systems is given in (Table 3.2). Some assessment of the limitation on capacity is also suggested.
Table 3.2. Correlation between coastal environment and feasibility of using various subsurface intakes along the Red Sea coastline.

<table>
<thead>
<tr>
<th>Intake Type</th>
<th>Subsurface Intake System</th>
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<tbody>
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<td></td>
<td>Well/ Gallery</td>
<td>Well system</td>
<td>Gallery system</td>
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<tr>
<td></td>
<td>Environments</td>
<td>Vertical</td>
<td>Horizontal</td>
<td>Radial (collector)</td>
<td>Angle</td>
<td>Beach Gallery</td>
<td>Seabed Gallery</td>
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<tr>
<td>A. Sandy Beaches</td>
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<td>B. Rocky shorelines</td>
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<td>C. Wadi intersections</td>
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<td>D. Sabkha, lagoons, and mangrove</td>
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<td>E. Others</td>
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</table>

Feasibility factor: 1=Excellent, 2=Possible, 3=Questionable, 4=Not feasible
Estimated Capacity (m³/day): a. Capacity <20,000, b. 20,000-50,000, c. 50,000-100,000, d. Any capacity
3.6 Conclusions

The type of geomorphological environment, rock and sediment properties at the shoreline and subtidal nearshore areas control the feasibility of using a subsurface intake system. Therefore, mapping of coastlines can be used to plan the location or to assess general feasibility of using a subsurface intake system for a SWRO facility. The characterization of the coastal environments should be the first step in evaluating feasibility of subsurface intakes in any coastal region. This will help decision makers, planners, and the water industry to understand the nature of the coastal area in order to determine the potential for use of a subsurface intake for future development of SWRO facilities. During the mapping exercise, emphasis should be placed on investigating and mapping potential intake development sites located near populated areas that will require expanded use of desalination in the future. A site-specific detailed analysis and an extensive environmental evaluation would be required at later stages of the system development to assure that the potential sites would yield the required capacity.

The mapping of the Red Sea coastline of Saudi Arabia showed that the sandy beaches containing a low percentage of mud and limestone rocky shorelines with corresponding nearshore sand and wadi sediments with low mud content are the most favorable environments for use of subsurface intakes. Seabed galleries were found to be the preferred subsurface intake type for large-capacity desalination facilities based on the geology. Conventional wells or horizontal wells could be used at shorelines containing limestone cliffs and reefs, but the relatively small thickness of these deposits is a limitation on potential system capacity. Nearshore or coastal wadi sediments not associated with a channel can also be used to develop low-capacity well intake systems. The use of the other types of well intakes along the Red sea coastlines requires a thorough assessment of geology to avoid the risk of not obtaining the required capacity.
3.7 References


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CHAPTER 4 : Changes in feedwater organic matter concentrations based on intake type and pretreatment processes at SWRO facilities, Red Sea, Saudi Arabia

4.1 Summary

Transparent exopolymer particles (TEP), natural organic matter, and bacterial concentrations in feedwater are important factors that can lead to membrane biofouling in seawater reverse osmosis (SWRO) systems. Two methods for controlling these concentrations in the feedwater prior to pretreatment have been suggested; use of subsurface intake systems or placement of the intake at a greater depth in the sea. These proposed solutions were tested at two SWRO facilities located along the Red Sea of Saudi Arabia. A shallow well intake system was very effective in reducing the algae and bacterial concentrations and somewhat effective in reducing TEP concentrations. An intake placed at a depth of 9 m below surface was found to have limited impact on improving water quality compared to a surface intake. The algae and bacteria concentration in the feedwater (deep) was lower compared to the surface seawater, but the overall TEP concentration was higher. Bacteria and TEP measurements made into the pretreatment process train in the plant and after the cartridge filters suggests that regrowth of bacteria is occurring within the cartridge filters.

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4.2 Introduction

Reverse osmosis has become the dominant water desalination technology because of lower cost and energy consumption in comparison with conventional thermal distillation techniques [1]. However, seawater reverse osmosis (SWRO) membranes are very sensitive to fluctuations in the feedwater quality and the concentration of certain organic compounds which makes them vulnerable to biofouling. Membrane fouling reduces operational efficiency and life-expectancy of the membranes, which in turn, increases the total cost of treatment [2, 3]. Therefore, the investigation of membrane fouling and biofouling along with the foulant characteristics has become a focus of many water researchers in the desalination field.

One of the organic substances found in seawater, transparent exopolymer particles (TEP), has been identified as a key compound that can lead to membrane biofouling [4, 5, 6]. TEP is produced by algae and bacteria as an extracellular excretion in the marine environment. It is created by the “self-assembly” of various organic compounds and has two general classifications based on size which are particulate (>0.4 μm) and colloidal (0.1-0.4 μm). It is a very sticky substance, mainly composed of acidic polysaccharides, and can be stained with Alcian Blue [7]. These gel-like particles help in forming a conditioning layer on the membrane surface which serves as an attachment substrate that accumulates colloids and particles and provides favorable conditions for bacterial colonization, thereby promoting bacterial attachment, growth and biofilm formation [8]. The removal of a biofilm layer from the membrane surface is very energy intensive, time-consuming, and necessitates the use of chemicals. Full removal of the biofilm is rarely achieved during the cleaning process. Therefore, removal of TEP and other potential foulants before the membrane process is paramount in reducing or delaying biofouling and makes the SWRO process more reliable and less expensive to operate.
The intake system design can play a significant role in management of algae, bacteria, TEP and natural organic matter (NOM) influx into a SWRO facility, and ultimately can influence the design and performance of the pretreatment system and downstream membrane processes. Water quality investigations were conducted at two SWRO desalination facilities located along the Red Sea in Jeddah City, Saudi Arabia to evaluate TEP, algae, bacteria, TOC, and NOM concentrations based on different intake types (Figure 4.1). The first site (site A) uses a well intake system that is constructed into siliciclastic sediments, while the second site (site B) uses a deep-open ocean intake that extracts water from a depth of 9 m below the sea surface (Figure 4.2). Very few analyses have been conducted on the algae and bacteria concentrations, TEP, and the fractions of organic carbon from the feedwater through the pretreatment processes and the cartridge filters which makes this research rather novel.

It has been demonstrated that many subsurface intakes produce feedwater with low concentrations of organic substances and TEP [9, 10]. It has been reported that a well intake system at Sur plant in Oman plays a vital role in improving the water quality significantly by removing all of the algae, most of the bacteria, and a significant percentage of the TEP, and organic substances from the feedwater [10, 11]. Similarly, the use of a deep ocean intake has been reported to provide better feedwater quality compared to the shallow open-ocean intakes due to lower biological productivity in deep water compared to shallow water [12]. Therefore, the risk of biofouling caused by TEP can be reduced by construction and operation of the appropriate intake type and pretreatment process.

Few data are available on the concentrations of algae, bacteria, TEP, and the organic fractions of NOM throughout the pretreatment process. These treatment facilities occur on the Red Sea, where
numerous other SWRO facilities are located and many additional ones are planned for future construction. Understanding the role of intakes in removing or producing lower concentrations of TEP and other fouling organics will help in planning and design of improved intake and pretreatment systems for future SWRO plants. This is quite important in consideration that there is currently an installed global SWRO capacity of about 25.1 million m³/d [13].

Therefore, the objectives of this research are: 1) to evaluate the impact of two intake systems, wells and a deep intake (significantly below the sea surface), on the concentrations of TEP, algae, bacteria and other potential fouling organics (NOM), and 2) to evaluate the effectiveness of the pretreatment processes in the removal of these organic substances.

**4.3 Methods**

**4.3.1 Sampling sites, methods, and information on facility operation**

Water samples were obtained from the SWRO facility using a well intake system on January 7, 2014 and the facility using a 9 m depth open-ocean intake was sampled on May 25, 2013. Water samples were collected within or near the facilities including surface seawater, at the intake, at the media filter outlet, and at the cartridge filter outlet. Samples were collected and placed into the appropriate types of bottles, and transported to the lab facilities the same day inside coolers containing ice. After 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 to maintain the condition of the seawater until it was analyzed. Proper sampling, quality control and assurance measures were used based on the type of analyses to be performed.
Both facilities do not use continuous chlorination, but the facility using a deep surface-water intake uses periodic shock chlorination to clean the intake pipe with the water being discharged to waste. No chemical additives are used at either site (e.g., no inorganic coagulants or anti-scalants). At the surface-water intake facility, the media filters are backwashed every day and at the system using the well intake they are backwashed every 300 hours. The backwash water used in flushing is filtered clean seawater and not from a stagnant tank source. The backwash water is discharged to waste.

Figure 4.1. Map showing the location of the SWRO facilities investigated
Figure 4.2. Schematic diagrams showing the intakes and process trains of the two SWRO investigated. Site A is a well intake system and site B is an open-ocean intake set at a depth of 9 m below surface.
4.3.2 TEP measurement

In this research two types of TEP were investigated, particulate and colloidal TEP. Particulate TEP has a size >0.4 µm, while colloidal TEP ranges in size from 0.1-0.40 µm [14]. 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 [15, 16, 17].

Analysis of TEP was accomplished based on the method developed by Passow and Alldredge [15]. A staining solution was prepared from 0.06% (m/v) Alcian Blue 8GX (Standard Fluka) in an acetate buffer solution (pH 4) and freshly pre-filtered through a 0.2 µm polycarbonate filter before usage. A 300 mL volume 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 the Alcian Blue with possible salt remaining on the filter after the seawater filtration which could cause overestimation of the TEP concentration. The retained TEP particles on the membrane surface were then stained with the Alcian Blue dye for 20 seconds. 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 hours 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 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 the calibration curve (Figure 4.3). The TOC concentrations of xanthan gum before and after 0.4 µm filtration were analyzed, and the TOC concentration difference was used to calculate the gum mass on each filter and the TEP concentration was estimated using the calibration curve. The same procedures were used for the 0.1 µm membrane to establish the calibration curve for colloidal particles. Afterwards, the TEP concentration was expressed in terms of xanthan gum equivalent µg/L by dividing the TEP mass on the corresponding volume of TEP samples. Because particulate and colloidal TEP are measured indirectly, these values must be considered to be semi-quantitative. Analysis of the two TEP types is very labor intensive and therefore, a limited number of samples were analyzed.

Figure 4.3. Xanthan gum standard curve for estimation of TEP concentration.
4.3.3 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. Light scattering properties and/or fluorescent intensity is determined by the flow cytometer to distinguish between the different organisms [18]. Lasers are used to excite both unstained autofluorescent organisms (algae) and stained bacterial cells. The Red laser wavelength was set at a wavelength of 640 nm and the blue laser at 488 nm. Algal cell counting was performed by combining 1 mL of each sample with a 2 μL volume of a standard containing 1 μm beads and placed into a 10 mL tube. The tube was then vortexed and measured using high flow with a 200 μL injection volume for 2 minutes. The counting procedure was repeated three times to assess the precision of the measurements. The different types of algae, Cyanobacteria, Prochlorococcus, and Pico/Nano plankton, were distinguished based on their autofluorescence as well as by the cell side angle scatter which is used to identify the size [19].

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 minutes and stained with the SYBR® Green dye (10 μL into 1 mL aliquot), vortexed, and incubated for another 10 minutes. The prepared samples were then analyzed in a low flow setting with a 9 μL injection volume for 1 minute. Triplet measurements were made on each sample to assess measurement precision.
4.3.4 Organics analysis using the LCOCD methodology

A Shimadzu TOC-VCSH instrument was used in to 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 (LCOCD) from DOC-Labor was used employing the method developed by Huber [20] to measure the various fractions of NOM.

The size exclusion chromatography column that was used for this experiment is (Toyopearl HW-50S) which is produced by the TOSOH company. Prior to the sample measurements, a calibration curve was established for both molecular masses of humics and detector sensitivity. For the molecular mass calibration humic acid and fulvic acid standards (Suwannee river Standard II) were used while potassium hydrogen phthalate and potassium nitrate (KNO3) were used for sensitivity calibration [20].

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 through the column for 260 minutes. Following the cleaning step, 2000 µL samples were injected for analysis with 130 minutes of retention time and a flow rate of 1.1 mL/minute. A mobile phase phosphate buffer with STD 28 mmol and a pH of 6.58 were used to carry the sample through the system. 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. The manual integration was performed based on the method developed by Huber [20].
### 4.4 Results

#### 4.4.1 Particulate and colloidal TEP in the surface seawater compared to the intake feed

The collected samples from both sites were analyzed to determine the presence of particulate TEP in the feedwater and at various locations within the treatment processes. A comparison between surface seawater and the intakes in terms of TEP concentration was made.

Measured particulate and colloidal TEP concentrations in the raw seawater were very close to equal (Figure 4.4). Particulate TEP concentrations in the wells were between 26 and 65% lower than that in the raw seawater. Colloidal TEP concentrations were also lower in the wells compared to that in raw seawater, but were comparatively lower than the particulate TEP with the differential ranging from 48 to 92% lower than the raw water. Well 2 showed the lowest comparative concentrations in both colloidal and particulate TEP differences, but there was some difference in the relative pattern of concentrations in the wells between particulate and colloidal TEP.

A comparison of the TEP concentrations in the surface seawater to the seawater at a depth of 9 m at site B is shown in (Figure 4.5). The particulate TEP has about equal concentrations comparing the surface to the 9 m intake depth. However, the colloidal TEP increases with depth by a factor of almost 5. Therefore, the total TEP increases with depth at this site.
4.4.2 Particulate ad colloidal TEP in the aggregated intake water, pretreatment train, and after the cartridge filters

TEP concentrations at site A which uses a well intake system were measured in the aggregate intake water and after the media filter and cartridge filters to assess the effectiveness of the treatment process in the removal of TEP before reaching the membranes (Figure 4.6). First, the concentration of particulate TEP was higher than colloidal TEP at each location. The media filter was effective with removal of 52% of the particulate TEP, but only 10% of the colloidal TEP was removed. The concentration of TEP after the cartridge filters shows only a small change compared to that in the media filter outlet.

An assessment of TEP through the pretreatment train at site B, which uses an open-ocean intake at a depth of 9 m below surface, is shown in (Figure 4.7). The media filter removes 56 and 25% of the particulate and colloidal TEP respectively. The particulate TEP concentration increases by 667% across the cartridge filter and the colloidal TEP increases by 30%. No detectable particulate TEP was found in the permeate.
Figure 4.4. Particulate and colloidal TEP concentrations measured in the surface seawater and selected wells at site A.
Figure 4.5. Particulate and colloidal TEP concentrations measured in the surface seawater and at a depth of 9 m below surface at site B.
Figure 4.6. Particulate and colloidal TEP concentrations measured in the aggregate inflow from the wells, after the media filter, and after the cartridge filter.
Figure 4.7. Particulate and colloidal TEP concentrations measured in the inflow from the intake at 9 m below the sea surface, after the media filter, and after the cartridge filter.

4.4.3 Algae and bacteria in the surface seawater compared to the intake feed

The algae and bacterial concentrations were measured at sites A and B and the results are shown in Table 4.1. Total algal concentrations in the surface seawater at sites A and B are 14,956 and 23,773 cells/mL respectively. The algae assemblage consists of three groups, including *Cyanobacteria*, *Prochlorococcus*, and *Pico/Nano plankton*. *Cyanobacteria* are the predominant
group at both sites. At site A, algal concentrations were below detection limits in the well discharges. At site B, the total algal count was 55% lower at a depth of 9 m compared to the surface. The relative composition of the algae changes to a small degree from the surface to 9 m below surface.

Table 4.1. Algae concentrations measured in the surface seawater and selected wells at site A and in the surface seawater and at a depth of 9 m below surface at site B (units in cells/mL).

<table>
<thead>
<tr>
<th>Sampling point</th>
<th>Cyanobacteria</th>
<th>Prochlorococcus</th>
<th>Pico/nano plankton</th>
<th>Total algae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well system (site A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface seawater</td>
<td>14,043</td>
<td>463</td>
<td>450</td>
<td>14,956</td>
</tr>
<tr>
<td>Well 1</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Well 2</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Well 3</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Well 4</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;100</td>
</tr>
<tr>
<td>Deep intake (site B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface seawater</td>
<td>14,488</td>
<td>8,590</td>
<td>695</td>
<td>23,773</td>
</tr>
<tr>
<td>Deep intake (9m depth)</td>
<td>6,823</td>
<td>3,735</td>
<td>243</td>
<td>10,801</td>
</tr>
<tr>
<td>% Difference</td>
<td>53%</td>
<td>57%</td>
<td>65%</td>
<td>55%</td>
</tr>
</tbody>
</table>

Measured bacterial concentrations in the surface seawater and selected wells at site A and in the seawater at surface and a 9 m depth at site B are shown in (Figure 4.8). The bacterial concentrations at site A are substantially lower in the wells compared to the surface seawater with differences ranging from 74 to 84%. At site B, the bacterial concentrations are 34% lower at the 9 m depth compared to surface seawater. It should also be noted that the bacterial concentration in the surface seawater at site B is nearly double that at site A.
Figure 4.8. Bacterial concentrations measured in the surface seawater and in selected wells at site A and in the surface seawater and at a depth of 9 m below surface at site B.

4.4.4 Bacteria in the aggregated intake water and pretreatment train

An assessment of changes in the bacterial concentrations in the pretreatment train for sites A and B is given in (Figure 4.9). At site A, the bacterial concentration in the aggregate well intake seawater was compared to the concentrations in the media filter and the cartridge filter outlets. There was an increase in bacterial concentration at both the media filter outlet and the cartridge
filter outlet compared to the feedwater. The increase from the raw water to the outlet of the media filter was 13% and the increase from the media filter outlet to the cartridge filter outlet was 25%.

The bacterial concentration through the pretreatment system at site B showed a different pattern with a lower concentration after the media filter and a higher concentration comparing the media filter outlet to the cartridge filter outlet. The reduction in concentration from the feedwater through the media filter was about 8% and the increase through the cartridge filter was 12%.

Figure 4.9. Bacterial concentrations measured in the aggregate intake seawater, after the media filter, and after the cartridge filters at site A and in the intake water from a 9 m depth and after the media filter, and after the cartridge filters at site B.
4.4.5 Total NOM and dissolved factions in the surface seawater to the wells at site A and a comparison of the surface and a 9 m depth at site B

TOC concentration in the surface seawater was compared to the well discharge concentrations at site A and between the surface seawater and the intake depth of 9 m at site B (Table 4.2). The TOC concentrations in the surface seawater at the two sites were similar at 0.88 and 0.83 mg/L respectively. TOC concentrations measured in the well discharges at site A were 49 to 62% lower compared to the surface seawater. The concentration of TOC at 9 m compared to the surface seawater at site B was 13% higher.

The differences between NOM fractions in the surface seawater at site A compared to the well discharge concentrations and the comparative concentrations at surface and a depth of 9 m at site B are given in Table 4.3. The concentration of total NOM in the surface seawater at site A was about 6% higher than at site B. The sum of the NOM concentration in the surface seawater at A is over 50% higher than the well discharges and confirms the TOC data. There is nearly a 100% reduction in the biopolymer fraction concentrations between the feedwater and the wells with minor detection in the well 1 discharge. The reduction in concentration between the other NOM fractions between the surface seawater and the well discharges is progressively lower in the humic acids, building blocks, low molecular weight neutrals, and low molecular weight acids respectively.

A comparison of the total NOM and the components at site B shows that there is very little difference between the concentrations found at the surface and at a depth of 9 m. A small increase in overall concentration and that of humic acids is noted.
4.4.6 Total NOM and dissolved fractions in the aggregated intake water and pretreatment train

Analyses of the total NOM and the dissolved fractions show little variation between the raw feed water and downstream of the media outlet and cartridge filters at both sites A and B (Table 4.4). The well intake system at site A produces a significantly lower concentration of biopolymers compared to the 9 m intake at site B. The pretreatment system and cartridge filters at site B provide some reduction in the dissolved organic fractions, the most significant of which is a 39% reduction in the biopolymer concentration.

4.5 Discussion

Having low concentrations of TEP, algae, bacteria and NOM in the feedwater of a SWRO desalination facility is important for membrane operation. Both systems investigated show variation in these concentrations based on the raw seawater source and the intake type. The pretreatment effectiveness of each plant in terms of TEP, algae, bacteria, TOC, and NOM fractions was evaluated. There was one sampling run conducted on these facilities and there could be variations in the concentration based on some seasonal factors. However, the in-plant pattern of variation is unlikely to change. There are some seasonal changes in the overall concentrations of organics in the Red Sea feedwater, but perhaps not as great as found in other locations where water temperatures vary greatly.
4.5.1 Effects of the well intake system on TEP, algae, bacteria, TOC and NOM concentrations

The TEP concentrations in the wells at site A were much lower than those in the surface seawater. It is apparent that there are pretreatment mechanisms occurring within the aquifer which reduce the concentration of particulate and colloidal TEP, but it is unclear whether the process is specifically filtration, adsorption, or biological in nature, but is likely a combination of all of them.

Algae were fully removed within the aquifer at site A along the flowpath from the sea to the wells, and the bacterial concentration was reduced by 74 to 84% compared to the seawater concentration. The aquifer must be considered to be very effective at removal of the living sources of TEP.

TOC concentration was reduced during pumping-induced groundwater flow by between 49 and 62%. Perhaps the most significant improvement in water quality was revealed within the fractions of NOM. Biopolymers were nearly 100% removed. This group contains polysaccharides and other sticky substances that, along with TEP, can lead to membrane biofouling. The other fractions of NOM were not removed in the aquifer to the same degree. In fact, the removal percentage clearly decreased with decreasing molecular weight following the order biopolymers, humic acids, building blocks, low molecular weight neutral, and low molecular weight acids. The data suggest that the removal process is molecular weight selective.

Table 4.2. TOC measured in the surface seawater and selected wells at site A and in the surface seawater and at a depth of 9 m below surface at site B.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Seawater</th>
<th>Well #1</th>
<th>Well #2</th>
<th>Well #3</th>
<th>Well #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC [mg/l]</td>
<td>0.88</td>
<td>0.34</td>
<td>0.41</td>
<td>0.45</td>
<td>0.40</td>
</tr>
<tr>
<td>Deep intake (site B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOC [mg/l]</td>
<td>0.83</td>
<td>Intake (9m depth)</td>
<td>0.94</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4.3. NOM fraction concentrations in (ppb) measured in the surface seawater and in selected wells at site A and in the surface seawater and at a depth of 9 m below surface at site B.

<table>
<thead>
<tr>
<th>Well system (site A)</th>
<th>Seawater</th>
<th>Well 1</th>
<th>Well 2</th>
<th>Well 3</th>
<th>Well 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biopolymers</td>
<td>63</td>
<td>9</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Humic substances</td>
<td>367</td>
<td>174</td>
<td>186</td>
<td>201</td>
<td>175</td>
</tr>
<tr>
<td>Building blocks</td>
<td>131</td>
<td>57</td>
<td>58</td>
<td>67</td>
<td>63</td>
</tr>
<tr>
<td>Low molecular weight neutrals</td>
<td>230</td>
<td>142</td>
<td>108</td>
<td>135</td>
<td>100</td>
</tr>
<tr>
<td>Low molecular weight acids</td>
<td>130</td>
<td>61</td>
<td>66</td>
<td>82</td>
<td>60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deep intake (site B)</th>
<th>Seawater</th>
<th>Intake (9m depth)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biopolymers</td>
<td>84</td>
<td>87</td>
</tr>
<tr>
<td>Humic substances</td>
<td>289</td>
<td>315</td>
</tr>
<tr>
<td>Building blocks</td>
<td>101</td>
<td>134</td>
</tr>
<tr>
<td>Low molecular weight neutrals</td>
<td>45</td>
<td>101</td>
</tr>
<tr>
<td>Low molecular weight acids</td>
<td>101</td>
<td>84</td>
</tr>
</tbody>
</table>
While the reduction in concentration of both TEP types was significant, not all of it was removed. TEP removal at Sur, Oman, Alicante, Spain, and in the Turks and Caicos Islands ranged from 62-70%, 37-87%, and 90-92% [11]. Also, the reduction in bacterial concentrations was lower compared to the sites mentioned above. The difference between Jeddah (site A) and other well intake sites investigated by Rachman et al. [11] is the length of the flowpath from the source water to the wells which was only about 70-80 m plus some depth penetration. The other sites, particularly in Oman and the Turk & Caicos Islands, had much longer flowpaths, ranging from 100 to 2000 m based on a combination of horizontal distance and depth to the top of the well screens or open hole. The increase in the length of the flowpath also suggests that the hydraulic retention time was considerably longer, thereby allowing the assimilation processes in the aquifer to remove a higher percentage of TEP. The composition of the aquifer was siliciclastic sediment compared to mostly carbonate rock or sand at the other sites. Difference in composition may be another factor that causes the lesser degree of TEP assimilation. The period of operation, which is less in the case of the Jeddah site compared to the others, may be another factor because of possible aquifer conditioning and the time-dependent development of bacterial assemblages that aid in assimilation.
Table 4.4. NOM fraction concentrations in (ppb) measured in the aggregate intake seawater, after the media filter, and after the cartridge filters at site A and in the intake water from a 9 m depth and after the media filter, and after the cartridge filters at site B.

<table>
<thead>
<tr>
<th>Well system (site A)</th>
<th>Aggregation of wells</th>
<th>Media filter outlet</th>
<th>Cartridge filter outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biopolymers</td>
<td>6</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Humic substances</td>
<td>172</td>
<td>171</td>
<td>178</td>
</tr>
<tr>
<td>Building blocks</td>
<td>65</td>
<td>79</td>
<td>67</td>
</tr>
<tr>
<td>Low molecular weight neutrals</td>
<td>107</td>
<td>133</td>
<td>134</td>
</tr>
<tr>
<td>Low molecular weight acids</td>
<td>61</td>
<td>62</td>
<td>57</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deep intake (site B)</th>
<th>Intake (9m depth)</th>
<th>Media filter outlet</th>
<th>Cartridge filter outlet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biopolymers</td>
<td>87</td>
<td>55</td>
<td>53</td>
</tr>
<tr>
<td>Humic substances</td>
<td>315</td>
<td>313</td>
<td>300</td>
</tr>
<tr>
<td>Building blocks</td>
<td>134</td>
<td>119</td>
<td>113</td>
</tr>
<tr>
<td>Low molecular weight neutrals</td>
<td>101</td>
<td>185</td>
<td>102</td>
</tr>
<tr>
<td>Low molecular weight acids</td>
<td>84</td>
<td>86</td>
<td>83</td>
</tr>
</tbody>
</table>

4.5.2 Effects of water depth on TEP, algae, bacteria, TOC and NOM concentrations

Natural variation in total TEP concentration between surface seawater and that at a depth of 9 m showed an increase with depth at site B. The measured particulate TEP concentration was similar from surface to 9 m, but there was a quite significant increase in the colloidal TEP concentration.
with depth. At this site, the general assumption that seawater quality improves with depth is not true in terms of TEP concentration at the time sampled.

The concentration of algae significantly decreased from the surface to 9 m with an overall 55% change. Bacterial concentration also decreased with depth by 34%. Therefore, there is a disparity between the improvement in feedwater quality exhibited by TEP concentration versus the variation of algae and bacterial concentrations.

TOC and NOM factions show little variation between the surface and 9 m at site B. There is a slight increase in TOC and the humic acid fraction of NOM between surface and 9 m. The very important biopolymer fraction remains nearly constant in the water column which is somewhat consistent with the TEP results.

Based on the water quality data collected in the Jeddah site, there appears to be no significant improvement for reduction in membrane fouling potential based on a change in water depth from near surface to a depth of 9 m. This does not preclude the possibility that water quality may improve at greater water depths or that some seasonal variations may have specific periods of improved water quality.

**4.5.3 TEP and NOM concentration changes and bacterial regrowth within the pretreatment processes**

It has long been assumed that the use of media filtration has a positive effect on reducing the concentration of potential membrane fouling organics, such as TEP and bacteria. It was confirmed that the media filter did indeed reduce the concentration of both particulate and colloidal TEP at both plants. Generally, the media filter was more effective in reducing the particulate TEP compared to the colloidal TEP.
Bacterial concentration across media filter increased at plant A by 13% and decreased at plant B by 8%. So, the media filter was ineffective or about neutral in reduction of bacterial concentration.

The effectiveness of the cartridge filters for TEP reduction showed mixed results based on the analyses. At plant A, small reductions were found in the concentrations of particulate and colloidal TEP, but only in the 7 to 8% range. In contrast, particulate and colloidal TEP concentration increased across the cartridge filters at site B. In fact, the particulate TEP increased by a staggering 667%.

Increases in the population of bacteria occurred across the cartridge filter from 25% at plant A and 12% at plant B. These results are similar to studies conducted at other SWRO facilities [11]. Particulate and colloidal TEP concentrations across the media filters at the two plants showed minimal change with reductions of only 8 and 7% at plants A and B respectively.

The very large increase in TEP concentration across the cartridge filter at site B coupled with the increase in bacterial concentration strongly supports the conclusion that bacterial regrowth is occurring in the cartridge filters at this site. While the evidence for bacterial regrowth at site A is not as strong, it is also probable. The difference between the sites is the much higher bacterial concentration in the feedwater at site B.
4.6 Conclusions

The water quality impacts of using a well intake system and a deep-water intake (9 m below surface) were assessed at two SWRO facilities located on the Red Sea of Saudi Arabia. Analysis was limited to measurement of TEP, algae, and bacteria, TOC and dissolved NOM fraction concentrations. These organic substances and particulates are responsible for biofouling of SWRO membranes during facility operation.

Shallow wells tapping an unconfined siliciclastic aquifer were effective at reducing concentrations of all of the organic substances investigated. The algae were fully removed and up to 84% of the bacteria were removed by the groundwater system (similar to bank filtration). A substantial reduction in the concentration of particulate TEP was observed which occurred likely by adsorption and biological activity in the aquifer with some possible straining occurring. The organic biopolymers were completely removed with a lower removal of lower molecular weight NOM fractions. The removal percentage declined with decreasing molecular weight. It can be concluded that well intakes along the Red Sea are effective at reducing organic foulant concentrations and will result in lower operating costs.

Investigation of the differences in algae, bacteria, TEP, and organic compound concentrations between shallow water and a deep-water intake were mixed. Total TEP increased from the surface to 9 m with particulate TEP being lower at the surface and colloidal TEP being significantly higher at 9 m. The TOC and NOM fraction concentrations were similar in both the shallow water and deep intake systems. The algae concentration was significantly lower with depth, but the bacterial concentration decline was moderate. In conclusion, the difference between using a surface seawater intake system and a deeper one at 9 m at site B may not be significant.
Analysis of bacteria concentrations within the facilities was measured at the intake, after the media filters, and after the cartridge filters. At both plants there was an increase in bacteria concentration after passing through the cartridge filters. At site B, the particulate TEP increased by 667%. These data suggest that bacterial regrowth is occurring within the cartridge filter and this regrowth of bacteria produces TEP that is transmitted directly to the SWRO membranes. Additional research will be required to assess how to control regrowth in cartridge filters. Consideration also should be given to bypassing the cartridge filter system in SWRO plants that have minimal risk of particulate bypassing of the pretreatment processes.
4.7 References


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17. U. Passow, Production of transparent exopolymer particles (TEP) by phyto- and bacterioplankton, Marine Ecology Progress Series 236 (2002) 1-12.


CHAPTER 5 : Subsurface intake systems: green choice for improving feed water quality at SWRO desalination plants, Jeddah, Saudi Arabia

5.1 Summary

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

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5.2 Introduction

The use of membrane technology in the desalination industry has increased rapidly during the last 20 years due to its lower cost and energy consumption in comparison with conventional distillation processes [1]. Currently, membrane technology is used in 60% of seawater desalination processes around the world [2]. The major persistent problem that most of seawater reverse osmosis (SWRO) desalination facilities face is membrane biofouling. Membrane biofouling causes the reduction of membrane life-expectancy, reduction of operational efficiency, and increases operation and maintenance costs [3, 4]. In some cases, membrane biofouling can lead to temporary plant shutdowns. As a means of reducing the effect of this problem, pretreatment processes are installed to improve the quality of raw water before it enters the SWRO process. Although expensive and extensive treatment processes using chemicals are operated for this purpose, frequent membrane cleaning is still commonly necessary [5]. Therefore, it is important to supply high feed water quality to the desalination facility at the initial intake stage in order to reduce the complexity of the pretreatment components. One way to achieve that is by implementing the appropriate type of intake.

Conventional open-ocean intakes are used by most SWRO desalination facilities for supply of unlimited feed water capacity. Generally, this type of intake provides poor and inconsistent seawater quality based on the seasonal changes, especially during harmful algal bloom events which can cause temporary plant shutdowns [6, 7]. In addition, the operation of surface intake systems makes the desalination plant more vulnerable to environmental impacts, such as entrainment and impingement of fish and other marine organisms [8, 9]. In general, extensive pretreatment systems have to be installed to improve the poor quality of the raw water supplied by
the open-ocean intake system to avoid membrane biofouling, particularly removal of algae, bacteria, and natural organic compounds.

An alternative “green” intake that can be utilized to improve the quality of feed water delivered to a SWRO desalination facility is a subsurface intake system. This type of intake is similar in concept to river bank filtration wherein the native geological media is used to naturally filter the raw water before entering the treatment facility [10, 11]. Subsurface intakes provide physical and biological mechanisms for filtering the feed water by straining and biodegrading of organic matter and other particulates while passing through marine sediments and the seabed similar to a slow sand filter used in freshwater treatment plants [12, 15]. The operation of this intake type is more environmentally friendly since no impingement and entrainment of marine organisms occurs as well as less or no chemical additives are required to be used during the pretreatment stage [14].

Since biofouling of SWRO membranes has been documented along the Red Sea coast of Saudi Arabia [16], the key research objective of this investigation is to evaluate the performance of subsurface intake systems in terms of improving the raw seawater quality with the potential of reducing the rate of membrane biofouling. Three SWRO desalination plants located in Jeddah city along the Red Sea coastline of Saudi Arabia were investigated (Figure 5.1). These three plants use vertical well systems as a means of extracting the raw seawater. The aquifer systems at these sites are composed of either siliciclastic or carbonate sediments. Water samples were collected from surface seawater and the well discharges for comparison. Algae, bacteria, fractions of natural organic matter (NOM) and transparent exopolymer particle (TEP) concentrations were measured to determine the degree of concentration reduction by the aquifer system during flow from the sea into the wells. The results of this research will be very useful in planning and improving the design of intake and pretreatment systems for existing and future SWRO plants.
5.3 Material and methods

5.3.1 Description of the studied SWRO plants

5.3.1.1 North Obhor (Site A), Jeddah, Saudi Arabia

The North Obhor SWRO plant is located north of Jeddah city and it has been in operation since 2001. This plant has a permeate capacity of 13,350 m$^3$/day. A total of 14 vertical wells are used to produce a total of 33,375 m$^3$/day of feed water required for operation (Figure 5.2, site A). The wells are constructed into a coralline limestone aquifer with depths ranging between 50 to 55 m. These wells are located inland at a distance of about 450 m from the seawater source. The age of the wells ranges from 4 to 14 years with wells 1A and 2A being 14 years, well 3A at 11 years, and well 4 at 4 years. Since 2007 the membranes at this facility are cleaned less than once every 2 years.
Figure 5.1. Location of studied SWRO facilities along the Red Sea coastline of Saudi Arabia.
Figure 5.2. Schematic diagram for the well intake designs at site A and site B (a), for site C (b).

5.3.1.2 Corniche (Site B), Jeddah, Saudi Arabia

The Corniche SWRO desalination plant is located in the middle of Jeddah city and has a total permeate capacity of 4,500 m$^3$/day. This facility requires 11,250 m$^3$/day of feed water which is extracted by a series of 5 vertical wells that are constructed into an aquifer consisting of siliciclastic sediments (Figure 5.2, site B). The total depth of these wells ranges from 46 to 50 m below surface. At this site, the wells are located at a distance of about 300 m from the sea. The ages of the wells range from 6 to 8 years. The raw water extracted from this site has a secondary problem with high iron concentration, which causes challenges for the pretreatment system. The life span of the cartridge filters used at this facility is very short due to the high iron concentration problem which is attributed to the passage of raw water through the heterogeneous siliciclastic system containing various natural and perhaps man-made sources of iron (buried metallic debris). Cleaning frequency
of the SWRO membranes occurs every 6 month due to the occurrence of dissolved iron in the raw water.

5.3.1.3 South Jeddah Corniche (Site C), Jeddah, Saudi Arabia

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

These wells are drilled on an artificial fill peninsula constructed into the nearshore area of the Red Sea (Figure 5.2, site C). During the initial construction of the plant, several wells were installed along the shoreline for raw water extraction. During the testing phase, it was found that the salinity of the produced feed water from these wells was significantly higher than that in the Red Sea and the wells had low yields. The geological conditions at this site were the reason for this high salinity and limited capacity of produced water. This site was constructed into a coastal sabkha environment which is an area where trapped seawater evaporates causing the precipitation of evaporite minerals and ultimately the formation of hypersaline conditions [17]. This sabkha environment is in hydraulic connection with the sea which causes the flow of hypersaline water toward the shoreline making the coastal alluvial aquifer unfeasible for subsurface intake development. An innovative design was implemented at this site to overcome this hypersaline condition problem, in which an artificial peninsula was constructed from the beach seaward on the inner reef hardground (no corals present). The wells were drilled using the artificial fill as a base. The aquifer beneath this artificial peninsula consists of soft limestone and unlithified carbonate sediments. The offshore wells are spaced 20 m apart and range in depth from 40 to 50 m.
5.4 Sampling methods

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

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

5.5.1 Fundamental water quality parameters

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

5.5.2 Micro-organism quantification

Algae and bacteria counts in the collected water samples were determined using a flow cytometer. A BD FACSVers flow cytometer was used to analyze the algae cells, while an Accuri flow cytometer was used for bacterial counts. Light scattering properties and/or fluorescent intensity was determined by the flow cytometer to distinguish between the different algal organism classifications [18]. Lasers are used to excite both unstained autofluorescent organisms (algae) and stained bacterial cells. The red laser wavelength was set at 640 nm and the blue laser at 488 nm. Algal cell counting was performed by combining 500 μL of each sample with a 1 μL volume of a standard containing 1 μm beads in a 10 mL tube. The tube was then vortexed and measured using the high flow rate with a 200 μL injection volume for 2 min. The counting procedure was repeated three times to assess the precision of the measurements. The different types of algae, *Cyanobacteria*, *Prochlorococcus*, and Pico/Nanoplankton, were distinguished based on their autofluorescence as well as by the cell side angle scatter which is used to identify them by size [19].
For bacterial counts, a comparative protocol employing SYBR® Green stain was used. A volume of 500 μL from each sample was transferred to a 10 mL tube, incubated in a 35 °C water bath for 10 min and stained with the SYBR® Green dye (5 μL into 500 μL aliquot), vortexed, and incubated for another 10 min. The prepared samples were then analyzed at a medium flow setting with a 50 μL injection volume for 1 min. Triplicate measurements were made on each sample to assess measurement precision.

5.5.3 Total organic carbon and NOM fraction concentrations

The total organic carbon concentrations in the samples were measured using a Shimadzu TOC-VCSH instrument. The detailed fractions of dissolved organic carbon were determined by using a Liquid Chromatography Organic Carbon Detector (LCOCD) from DOC-Labor. The protocols and methods developed by Huber et al. [20] were followed in order to measure the different fractions of NOM using LCOCD and have been previously described in Dehwah et al. [21].

The size exclusion chromatography column that was used for these measurements is a Toyopearl HW-50S which is produced by TOSOH. Prior to the sample measurements, a calibration curve was established for both molecular masses of humic substances and detector sensitivity. For the molecular mass calibration, humic acid and fulvic acid standards (Suwannee River Standard II) were used while potassium hydrogen phthalate and potassium nitrate (KNO₃) were used for sensitivity calibration [20].

The samples for the LC-OCD were manually 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 0.1mol/L NaOH through the column for 260 min. Following the cleaning step, 2000 μL of the sample was injected for analysis with 180 min of retention time and a flow
rate of 1.5 mL/min. A mobile phase of phosphate buffer with STD 28 mmol and a pH of 6.58 was used to carry the sample through the system. 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 different organic fractions including biopolymers, humic substances, building blocks, low molecular weight acids and low molecular weight neutrals. The manual integration was performed based on the method developed by Huber et al. [20].

5.5.4 TEP concentration measurements

Two types of TEP were investigated, particulate and colloidal. Particulate TEP has a size greater than 0.4 μm, while colloidal TEP size ranges between 0.1 and 0.40 μm [22]. Particulate TEP is formed predominantly by the self-assembly of precursor substances, such as dissolved polysaccharides and biopolymers, that are produced by extra-cellular excretion of algae and bacteria [23-25].

Analysis of TEP was conducted based on the method developed by Passow and Alldredge [23] which includes sample filtration, membrane staining with alcian blue and UV spectrometer measurements. A staining solution was prepared from 0.06% (m/v) Alcian Blue 8GX (Standard Fluka) in an acetate buffer solution (pH 4) and freshly pre-filtered through a 0.2 μm polycarbonate filter before usage. A 300 mL volume 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 the Alcian Blue with possible salt remaining on the filter after the seawater filtration. This helps avoid overestimation of the TEP concentration. The retained TEP particles
on the membrane surface were then stained with the Alcian Blue dye for 10 seconds. 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 hours 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 752 nm wavelength to determine the TEP concentration. The same methodology was applied to determine the colloidal TEP. The only difference is that a 250 mL volume of the water sample from the 0.4 μm polycarbonate membrane permeate 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 the calibration curve (Supplemental Information). The TOC concentrations of xanthan gum before and after 0.4 μm filtration were analyzed, and the TOC concentration difference was used to calculate the gum mass on each filter and the TEP concentration was estimated using the calibration curve. The same procedures were used for the 0.1 μm membrane to establish the calibration curve for colloidal particles. Afterwards, the TEP concentration was expressed in terms of Xanthan Gum equivalent in μg Xeq./L by dividing the TEP mass on the corresponding volume of TEP samples. Because particulate and colloidal TEP is determined indirectly, these values must be considered to be semi-quantitative.
5.6 Results

5.6.1 Fundamental water quality parameters

The fundamental water quality parameters, which include the conductivity, salinity, pH, and turbidity, are presented in Table 5.1. The results show that the conductivity and associated salinity are slightly higher in all well discharges compared to that in the adjacent surface seawater. The pH values in the seawater are higher than in the corresponding well discharge water at all sites. The turbidity is much lower in the well discharges at sites A and B and slightly lower at site C.

Table 5.1. Fundamental water quality parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conductivity [ms/cm]</th>
<th>Salinity [ppt]</th>
<th>pH</th>
<th>Turbidity [NTU]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seawater</td>
<td>58.1</td>
<td>39.1</td>
<td>8.2</td>
<td>1.94</td>
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<td>Well A1</td>
<td>61.1</td>
<td>41.4</td>
<td>7.3</td>
<td>0.3</td>
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<td>40.0</td>
<td>7.3</td>
<td>0.33</td>
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<tr>
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<td>7.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Well A4</td>
<td>60.3</td>
<td>40.7</td>
<td>7.4</td>
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</tr>
<tr>
<td><strong>Site B</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>38.8</td>
<td>8.5</td>
<td>0.5</td>
</tr>
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<td>7.6</td>
<td>1.4</td>
</tr>
<tr>
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<td>59.9</td>
<td>39.2</td>
<td>7.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Well B3</td>
<td>59.4</td>
<td>38.8</td>
<td>7.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Well B4</td>
<td>53.4</td>
<td>34.3</td>
<td>7.6</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Site C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>59.9</td>
<td>40.3</td>
<td>8.3</td>
<td>0.51</td>
</tr>
<tr>
<td>Well C1</td>
<td>69.3</td>
<td>47.7</td>
<td>7.4</td>
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</tr>
<tr>
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<td>60.3</td>
<td>40.7</td>
<td>7.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Well C3</td>
<td>59.3</td>
<td>39.9</td>
<td>7.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Well C4</td>
<td>59.4</td>
<td>40.0</td>
<td>7.8</td>
<td>0.4</td>
</tr>
</tbody>
</table>
5.6.2 Microorganism quantification

Algae and bacterial concentrations were measured in both the surface seawater and the well discharges. The algal count included three different clusters Cyanobacteria, Prochlorococcus, and pico/nanoplankton. The predominant cluster at all the three sites is cyanobacteria. The total algae concentration in the raw seawater was about 130,000 cells/mL for site A, 90,000 cells/mL for site B and 43,000 cells/mL for site C. The algal concentration in the wells was below the detection limit of the method at sites A and B. Therefore, the algae were totally removed by the aquifer system at sites A and B, but some very low concentrations of algae were present at site C (Table 5.2).

The original bacterial concentration of seawater was 520,000 cells/mL for site A, 254,000 cells/mL at site B, and 216,000 cells/mL at site C. The bacterial population was significantly reduced after the seawater passed through the aquifer from the sea into the wells (Figure 5.3). The average bacterial concentration removal by the aquifer system was 98% for site A and 88% for both sites B and C.
Figure 5.3. Measured bacterial concentrations at the studied sites.
Table 5.2. Measured concentrations of algae in the surface seawater and well discharges.

<table>
<thead>
<tr>
<th>Sampling point</th>
<th>Cyanobacteria (cells/mL)</th>
<th>Prochlorococcus (cells/mL)</th>
<th>pico/nanoplankton (cells/mL)</th>
<th>Total Algae (cells/mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site A</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seawater</td>
<td>99,420</td>
<td>25,455</td>
<td>4,863</td>
<td>129,738</td>
</tr>
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<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Well A2</td>
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<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Well A3</td>
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<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 100</td>
</tr>
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<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 100</td>
</tr>
<tr>
<td><strong>Site B</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>10,023</td>
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<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 50</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Well B3</td>
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<td>&lt; 50</td>
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</tr>
<tr>
<td>Well B4</td>
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<tr>
<td><strong>Site C</strong></td>
<td></td>
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<tr>
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<td>3,807</td>
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<td>487</td>
<td>&lt; 50</td>
<td>730</td>
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<td>Well C4</td>
<td>&lt; 50</td>
<td>77</td>
<td>&lt; 50</td>
<td>107</td>
</tr>
</tbody>
</table>

5.6.3 Total organic carbon and natural organic matter (NOM) fraction concentrations

The well discharges showed significant reductions of total organic carbon concentration from the surface seawater to the well discharges (Table 5.3). The reduction ranged between 16 and 70%. The highest percentages of reduction were observed at site A. The reduction percentage at site C was significantly lower compared with the other two sites.

The different fractions of natural organic matter were measured for the raw seawater and the well discharges. The measurements showed that humic substances and low molecular weight neutrals are the most abundant fraction in the raw seawater, followed by building blocks, biopolymers and low molecular weight acids (Figure 5.4).
The analysis of the well discharge samples revealed that most of the different fractions experienced a reduction in the concentration as seawater passed through the aquifer system from the sea to the wells (Figure 5.4). The percentage reduction of each fraction varied between the sites and internally between different wells at the same site. However, the highest removal percentage of most of the fractions was observed at site A. The fraction that exhibited the highest reduction percentage was the biopolymers. The average biopolymer removal percentage was 96%, 95% and 90% for sites A, B and C respectively. Reductions in humic substances and building blocks were observed in all wells compared to the surface seawater with greater removal percentages occurring in the humic substance concentrations. Significant reductions in the lower molecular weight acids also occurred. However, the removal of the low molecular weight neutrals was much lower and in certain cases there was an increase in concentration compared to seawater.
Figure 5.4. Natural organic matter fraction concentrations at the studied sites.
Table 5.3. Concentrations of total organic carbon (TOC) in the surface seawater and in the well discharges with a calculation of reduction in concentration provided by aquifer transport.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TOC (mg/L)</th>
<th>% Difference (TOC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Site A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seawater</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Well A1</td>
<td>0.3</td>
<td>70%</td>
</tr>
<tr>
<td>Well A2</td>
<td>0.3</td>
<td>70%</td>
</tr>
<tr>
<td>Well A3</td>
<td>0.4</td>
<td>58%</td>
</tr>
<tr>
<td>Well A4</td>
<td>0.3</td>
<td>69%</td>
</tr>
<tr>
<td><strong>Site B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seawater</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Well B1</td>
<td>0.6</td>
<td>41%</td>
</tr>
<tr>
<td>Well B2</td>
<td>0.5</td>
<td>51%</td>
</tr>
<tr>
<td>Well B3</td>
<td>0.5</td>
<td>51%</td>
</tr>
<tr>
<td>Well B4</td>
<td>0.5</td>
<td>50%</td>
</tr>
<tr>
<td><strong>Site C</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seawater</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Well C1</td>
<td>0.7</td>
<td>16%</td>
</tr>
<tr>
<td>Well C2</td>
<td>0.5</td>
<td>40%</td>
</tr>
<tr>
<td>Well C3</td>
<td>0.6</td>
<td>31%</td>
</tr>
<tr>
<td>Well C4</td>
<td>0.6</td>
<td>36%</td>
</tr>
</tbody>
</table>

### 5.6.4 TEP concentration

Particulate and colloidal TEP concentrations were measured for the natural surface seawater and the well discharges at the three studied sites (Figure 5.5). Particulate TEP concentrations measured in the raw seawater were about 320 μg Xeq./L for site A and about 250 μg Xeq./L for sites B and C. The colloidal TEP concentrations in the raw seawater were significantly lower than particulate TEP concentration at all sites. At the well discharges, particulate and colloidal TEP concentrations were significantly lower compared to corresponding values in the raw seawater (Figure 5.5). The particulate TEP concentration reduction in the well discharges averaged 86%, 73% and 72% for
sites A, B and C respectively. Moreover, the colloidal TEP concentration reduction by the aquifer transport averaged 59%, 56%, and 68% for sites A, B and C respectively.

Figure 5.5. Particulate and colloidal TEP concentrations at the studied sites.
5.7 Discussion

5.7.1 Improvement of feed water quality by the well intake system

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

The analysis of physical water quality parameters showed that physical straining by the aquifer system removes most of the particulates from the raw seawater as indicated by the lower turbidity values in most of the well discharges. The remaining turbidity likely occurs due to scour of some particulates from the aquifer. In general, the salinity and conductivity of water from the production wells were similar or slightly higher than the raw seawater which supports the assumption that wells are mostly recharged from the seawater source. The lower pH values at the well discharges compared to the seawater are related to the higher saturation of seawater with calcium carbonate compared to the groundwater samples. The high rate of evaporation along the Red Sea nearshore area causes increased calcium carbonate saturation within the water column. As the seawater passes through the underlying sediments, it is expected that some calcium carbonate would precipitate at the seafloor and dissolved carbon dioxide is slightly higher in the groundwater due to degradation of organic matter. Therefore, the raw seawater with less calcium carbonate content will pass through the aquifer system. Evidence for precipitation of CaCO₃ occurs on the seabed
where a limestone hardground is found in most areas. The sediments are cemented with fine-grained aragonite and high magnesium calcite.

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

In general, influx of raw seawater into the SWRO treatment facility with a lower microorganism concentration should improve the membrane performance since the tendency for biofilm formation should be lower. The reduction in the rate of biofilm formation may also be related to a lower concentration of associated organic compounds, such as algal-derived organic matter (AOM) and TEP, which are produced by algae and bacteria in the raw water. AOM is known to increase bacterial activity in seawater [26]. The elimination of algae is of a great benefit to the desalination plants especially in areas where algal bloom events are common. Having such a system will help in protecting desalination plants from the unexpected algal bloom events that might cause temporary plant shutdown [6, 26].

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

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

There is a tendency for the removal percentage of NOM fractions to be related to the molecular weight with the highest weights being removed at the highest percentages. Moreover, biochemical processes are playing a role in the NOM removal such as biodegradation by bacteria. The removal of the NOM is of significant importance to the operation of the desalination plants. The organic
matter is food for bacteria and its presence within the raw water causes an operational problem for the downstream components of the desalination plant. In addition, the biopolymer fraction contains proteins and polysaccharides [27] which enhance membrane biofouling by producing membrane conditioning [28], which harms the facility by reducing the membrane flux and its expected life. Filloux et al. [29] found that reducing the concentration of the biopolymer fraction of NOM reduces the fouling rate in low-pressure membranes.

The measurement of TEP concentrations showed that the aquifer matrix is effective in reducing particulate and colloidal TEP concentrations. The total percentage reduction of particulate TEP was > 70% and colloidal TEP > 55 % at all three sites. Most probably, filtration, adsorption and biological activities occurring within the aquifer matrix and the underlying sediments are the reasons behind TEP concentration reduction. Having low concentrations of TEP will help increase the membrane life expectancy, as well as minimizing the chemical cleaning frequency. TEP particles tend to form a conditioning layer on the membrane surface which leads to formation of a biofilm layer that ultimately causes flux reduction and operational problems within a SWRO desalination plant [30].

The use of well intakes at the facilities investigated showed a clear improvement in operations based on a lower frequency of membrane cleaning. At site A the cleaning membrane cleaning frequency was less than every 2 years, at site B it is every 6 months even with the dissolved iron problem, and at site C the cleaning frequency is every 6 months to one year. In comparison, a survey of SWRO plants using open-ocean intakes in this region showed a membrane cleaning frequency of 2.5 to 3 months.
5.7.2 Effects of well intake design by variation of travel distance and aquifer hydraulic retention time on improving raw seawater quality

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

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

Additional considerations that influence the potential treatment effectiveness are the length of the pumping-induced flowpath from the sea bottom to the wells and the aquifer retention time. These issues are directly related. To study the effect of flow pathway length and associated retention time in improving the raw seawater quality, the distances between the wells and the seawater source were measured. Site A wells have a flowpath length of at least 450 m from the seawater source and site B wells are 300 m from the seawater source. Site C has the shortest and most direct pathway since the wells are drilled into the sea directly. This flowpath may be as short as 50 m. Dissolution conduits at site C may have shortened the flowpath and retention time in some wells. The algae removal amounts showed a possible relation between flowpath and associated retention time in that site A had the longest flowpath and showed the highest removal percentage. However, the bacterial removal percentages were similar at sites B and C. The TOC and the NOM fraction data support a relationship between flowpath length with a longer aquifer retention time and a reduction in concentration, particularly the TOC and the biopolymer fraction of NOM. The retention time is considered in this case to be directly proportional to the length of the flowpath, so they work together in reducing the concentration of NOM. The data collected on the particulate and colloidal TEP shows the same general trend, but there is more scatter in the removal percentages. Another investigation of several well intake systems that supports the general relationship between flowpath/retention time and reduction in organic matter concentrations was
conducted by Rachman et al. [15]. They found that there is a direct relationship between flowpath from the shoreline to the production well and silt density index reduction and some influence on the concentration reduction of NOM.

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

Another possible impact to the removal efficiency of organic matter may be the age of the wells. Greater internal bacterial activity could be promoted by the continuing influx of NOM into the aquifer system. However, no direct correlation could be made between well age and NOM or TEP removal. A recent investigation by Dehwah and Missimer found that well age seems to have a minimal effect on organic carbon removal in well intake systems [31].
5.8 Conclusions

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

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


CHAPTER 6 : Seabed gallery intakes: Investigation of the water pretreatment effectiveness of the active layer using a long-term column experiment

6.1 Summary

Seabed gallery intake systems used for seawater reverse osmosis facilities employ the same principle of water treatment as slow sand filtration in freshwater systems. An investigation concerning the effectiveness of the active layer (top layer) in improving raw water quality was conducted by using a long-term bench-scale columns experiment. Two different media types, silica and carbonate sand, were tested in 1 m columns to evaluate the effectiveness of media type in terms of algae, bacteria, Natural Organic Matter (NOM) and Transparent Exopolymer Particles (TEP) removal over a period of 620 days. Nearly all algae in the silica sand column, 87% (σ=0.04) of the bacteria, 59% (σ=0.11) of the biopolymer fraction of NOM, 59% (σ=0.16) of particulate and 32% (σ=0.25) of colloidal TEP were removed during the last 330 days of the experiment. Total removal was observed in the carbonate sand column for algal concentration, while the bacterial removal was lower at 74% (σ=0.08). Removal of biopolymers, particulate and colloidal TEP were higher in the carbonate column during the last 330 days with 72% (σ=0.15), 66% (σ=0.08) and 36% (σ=0.12) removed for these organics respectively. Removal of these key organics through the 1m thick column, representing the active layer, will likely reduce the rate of biofouling, reduce chemical usage and minimize operating cost in SWRO systems. The data show that the media will require several months at the beginning of operation to reach equilibrium so that high organic

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removal rates can be achieved. No development of a “schmutzdecke” layer occurred. The experimental results suggest that unlike freshwater slow sand filtration wherein most water treatment occurs in the upper 10 cm, in seawater systems treatment occurs throughout the full active layer depth of 1 m. The results of this study will help in designing and operating seabed gallery intake systems in varied geological conditions.

**Keywords:** Seawater reverse osmosis, Membrane fouling/biofouling, Gallery intakes, Slow sand filtration, Natural organic matter

### 6.2 Introduction

Membrane biofouling is a major problem in the operation of seawater reverse osmosis water treatment (SWRO) plants and has a significant impact on the energy consumption and economics of a given facility [1-4]. Most large-capacity SWRO facilities use an open-ocean intake system to obtain raw seawater. This requires that a high degree of pretreatment must be employed to remove turbidity, algae, bacteria, and natural organic matter to the highest degree possible to slow, but not stop the membrane biofouling process [5, 6]. As an alternative to using a conventional surface intake and complex pretreatment, a subsurface intake system can be used to provide initial higher quality seawater to a facility, thereby requiring a less complex pretreatment train [7].

Types of subsurface intake systems can be classified into two groups; wells and galleries [7]. Research conducted on well systems has demonstrated that significant reductions in concentrations of turbidity, algae, bacteria, TOC, NOM fractions, and TEP occurs as seawater is transported through an aquifer into production wells [7-12]. Recent research also found that the use of well systems to extract raw seawater for SWRO desalination plants will help reduce biopolymers and Assimilable Organic Carbon (AOC) concentrations during aquifer transport into the well system.
Reduction of the AOC concentration during aquifer transport shows that raw seawater produced from wells makes the membranes less vulnerable to biofouling [14]. However, well intake systems have practical capacity limitations with regard to SWRO plant operation and are economically used to supply small and medium capacity facilities. The largest capacity SWRO plant using a well system occurs in Sur, Oman at 80,000 m$^3$/day (wellfield capacity at 160,000 m$^3$/day) [15].

Gallery intake systems have the potential to supply raw seawater to large-capacity SWRO facilities [16]. There are two types of gallery intake systems, which are beach galleries that are constructed beneath the intertidal part of the beach [17] and seabed galleries which are constructed in offshore subtidal areas [18,19]. There are no large-capacity beach gallery intake systems being used to supply an SWRO facility and only one large-scale operational SWRO plant using a seabed gallery. The Fukuoka, Japan SWRO plant uses an offshore seabed gallery system with an installed capacity of 103,000 m$^3$/day (Figure 6.1) [7]. This facility has been operating successfully for 9 years and has produced very high quality feedwater with a silt density index under 2 [7]. While the facility operates well, little is known regarding the differences in the raw water quality between the infiltrated seawater and the discharge from the gallery.

Seabed galleries are designed and operated similar to slow sand filter systems used for nearly two centuries in water treatment. However, they are constructed in the seabed, rather than in the treatment plant facility which saves space and reduces capital and operating costs. A medium to fine size sand is placed at the top of a slow sand filter which is commonly operated at infiltration rates ranging from 1.2 to 4.8 m/day [20]. During slow sand filtration of freshwater, more than 90% of the water treatment occurs in the upper 10 cm of the media and a thin biologically-active layer known as a “schmutzdecke” forms at the filter surface [21]. A pilot-scale test of slow sand filtration
was conducted over a 13-month period at the City of Santa Cruz, California in 2008-2009 and the downstream SWRO membranes did not require cleaning, had the lowest flux decline, and showed the lowest amount of foulant on the membrane surface compared to other pretreatment processes tested [22].

A number of conceptual designs for seabed gallery intake systems have been developed based on site-specific investigations along the Red Sea, Saudi Arabia [23-27]. Each of the preliminary designs used a different thickness (1-3 m) of the uppermost “active” layer of the filter where most water treatment is expected to occur during the corresponding retention time within the filter. Typical slow sand filtration design calls for an active bed thickness of 0.9-1.5 m [20].

The composition of the active layer may also impact the efficiency or rate of organic matter removal during filtration. Typical slow sand filtration media consists of medium to fine grain size quartz sand. Since the gallery intake would be constructed within the seabed, the composition of the upper part of the media in the Red Sea and many other subtropical or tropical locations will vary between quartz sand and carbonate sand [19]. It has been suggested that carbonate sand may be more bioactive compared to quartz sand based on organic compound assimilation studied in reef sediments. Marine biological research has been conducted in the Red Sea and it suggests that carbonate sediments are more bioactive in the removal of organic carbon compared to siliciclastic sediments [28, 29].

The goal of this research is to evaluate the removal process efficiency of an active layer using media of differing composition at the bench scale using columns. Assessment of the removal of algae, bacteria, TEP, TOC and the various fractions of NOM that occur in seawater was conducted along with investigation of the ripening period to equilibrium, the impact of media composition
and thickness, and if a “schmutzdecke” layer forms in a similar manner to slow sand filtration in a freshwater system. If a “schmutzdecke” would form, it should be observable at the surface of the columns and would cause reductions in hydraulic conductivity that, in turn, would cause a reduction in the infiltration rate necessitating an increase in pumping pressure to maintain the desired flow rate. The observed data are needed to enable the design of gallery intake systems in varied geologic settings.

Figure 6.1. Conceptual diagram of the Fukuoka, Japan seabed gallery intake (from Pankratz).
6.3 MATERIAL AND METHODS

6.3.1 Design, construction and operation of the sand columns

Two columns were constructed using transparent acrylic plexiglass material. The columns were 100 cm in length and 10 cm in diameter. Two screens made from acrylic plexiglass were installed inside each column, one at the top with 0.2 mm pore size to ensure uniform water distribution into the columns while the other screen with 0.1 mm pore size was placed at the bottom of the column to prevent the loss of media with the discharged water. Sampling ports were installed at three intermediate depths of 10, 25 and 50 cm from the top of each column (Figure 6.2). The sampling ports are tubes that were perforated using a laser to avoid the infiltration of the media into the tubes during sampling. In addition to the sampling ports, two sampling points were added at the inflow portal and at the discharged flow to measure the quality of inlet water versus the outlet water. The columns were painted black in order to prevent light penetration into the column media to avoid algal growth or other biological activity.

Different media were used for each column with the first column containing siliciclastic sand (primarily quartz) collected from a local interior dune near the village of Thuwal, Saudi Arabia located near the Red Sea coast. The second column was filled with natural carbonate sand collected from the beach at King Abdullah Economic City (KAEC) located north of Thuwal, Saudi Arabia. Both sediment types were separated into 34 different size fractions using sieves. A mix of these fractions was used to create the properties of the desired media. Design of the media was accomplished using a computer program that makes an accurate prediction of hydraulic properties for a known mix of sand size fractions (created media) [30]. The mix of sediment for both columns was as follows: 16% of 0.07 mm fraction, 19% of 0.09 mm fraction, 26% of 0.11 mm fraction,
16% of 0.13 mm fraction, 8% of 0.15 mm fraction, 8% of 0.18 mm fraction, and 6% of 0.21 mm fraction. The media is classified as a fine to very fine sand. The mean grain diameter, porosity and hydraulic conductivity of the media of the two columns were kept as close as possible to allow a detailed comparison of column performances. The sediment properties for effective porosity were 0.40 and 0.41 and for hydraulic conductivity were 5.38 and 5.95 m/day respectively for the siliciclastic and carbonate sand media.

Based on the hydraulic conductivity values obtained from permeameter testing of the media, an infiltration rate of 6 m/day with 4 hours of hydraulic retention time was established as a goal for the experiment to make sure that each column was always filled with water (to avoid the column becoming dry). A Masterflex peristaltic pump with a capacity greater than required was used to operate the experiment. A pumping rate of to 13 mL/min was used to transfer seawater from the source into both columns.

Before starting the experiment, the different grain size fractions for each column were mixed together (homogenized) and then heated in an oven to remove any naturally-occurring organic material. The sterile media were loaded into each column separately. The media were packed carefully while adding water to remove gaps or macro pores in the column. After that, the columns were saturated from bottom to top with MilliQ (MQ) water to make sure that all the air gaps were removed from the column.
A standard tracer test was conducted on each column to determine a sustainable infiltration rate and to assess the initial retention time. The tracer was seawater followed by MQ water. The inflow rate of seawater was controlled to be as close to 5 m/day as possible. The results of the initial tracer test showed that the 5 m/day infiltration rate could be maintained and the retention times were both very close to 4.7 hours (Figure 6.3). A similar test was conducted after completion of the experiment to determine changes in the retention time based on the retained organic matter within the column. The freshwater was purged from the columns using filtered seawater before the experiment began.
The experiment started on January 5, 2014 and was run until the middle of September 2015. Samples were collected from the (inflow portal), from the three sampling ports and the discharge location (outflow portal) for each column. Algae, bacteria, TOC, NOM fractions, and particulate and colloidal (TEP) were measured in the samples to study the behavior of the organic matter as it moved through the media in each column. The frequency of sampling was on a weekly basis for the first month then it was on a monthly basis for the first year. The frequency of sampling was reduced later during the second year. The experiment was run for a total period of 21 months (620 days).

Both columns were supplied with feed seawater from a pipe coming directly from the Red Sea located at the SWRO plant intake about 3 km from the laboratory. Seawater was constantly circulated from the pipe (open system) and was directed into an opaque tank (painted black on the
outside) to avoid biological growth inside the tank. The tank was cleaned and filled every 6 days, but samples were collected within 24 hours of filling the tank to avoid any potential change in water parameters. Water samples were collected from the inlet water rather than the tank to avoid any variation in the measured parameters within the tank. The intermediate sampling ports and the outlet were all sampled close to the same time as the inlet tube. The water temperature in the column inlet varied between 21-23°C and was the same at the column outlet. The same method was followed during the entire duration of the experiment.

6.3.2 Measurement of organic matter concentrations

The methods used to analyze the concentrations of algae, bacteria, TOC, the fractions of NOM (biopolymers (BP), humic substances (HS), building blocks (BB), low molecular weight acids (LMWA) and neutrals (LMWN)), and particulate and colloidal TEP are presented in Dehwah and Missimer (2016) [11].
6.4 Results

6.4.1 Analysis of retention time from the tracer tests

Tracer tests were conducted before and after the column experiment period to assess the hydraulic retention time in both the silica and carbonate sand columns (Figure 6.3). The silica sand column showed a retention time of 4.7 hr before the experiment began and 5.8 hours at the end of the experiment. The carbonate sand column had a retention time of 4.7 hr at the beginning of the experiment and 6.9 hr at the end of the experiment.

6.4.2 Total algae and bacteria

During the 21-month column experiment the concentration of algae entering the inlet of the columns ranged from close to zero to over 50,000 cells/mL (Figure 6.4). The very low concentrations of algae in the early part of the experiment may have been caused by a laboratory preservation problem. Spikes of higher concentrations occurred on September 18, 2014 (after 251 days of operation) and an upward trend occurred during Spring of 2015 (after 400 days of operation) and peaked in September of 2015 (621 days). While the algal concentrations varied considerably in the inlet water, the outlet water contained no algae, except on a few occasions (carbonate sand column on one occasion). The data collected from both columns show a generally regular reduction in concentration, but most algae were removed in the upper 10 cm. No significant differences were found in the removal efficiency between the two columns. The percentage of algae removed with time was mostly 100% with a single minor exception.
Bacteria concentration varied widely during the experiment period from about 20,000 to over 800,000 cells/mL (Figure 6.5). Note that some differences in the inlet concentrations between the columns occurred in the early part of the experiment which could have been influenced by a laboratory sample preservation problem (first few samples). There was a difference in the removal pattern between the two columns with the silica sand column reaching a more stable removal rate and an equilibrium beginning about 5 months into the experiment. The outlet bacteria concentration was below 80,000 cells/mL for the last 11 months of the experiment. The carbonate
sand column showed rather unstable behavior from the beginning of the experiment to 330 days with intermediate depths within the column showing higher concentrations of bacteria compared to the outlet. Stability was reached earlier in the silica sand column at 220 days into the run time. The bacteria concentration generally stabilized in the outlet at about the same time as the silica sand column, but at the end of the experiment the concentration was about double that found in the silica sand column. The bacteria concentrations at intermediate depths in the carbonate column showed more erratic behavior throughout the experiment compared to the silica sand column.

![Bacterial Concentration Diagrams](image)

**Figure 6.5.** Diagram showing the concentrations of bacteria at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.
6.4.3 TOC

The TOC concentration in the inlet seawater ranged from about 0.7 to 1.7 mg/L with an average close to 1 mg/L (Figure 6.6). The behavior of the TOC concentration was quite erratic with depth in both columns. The concentration at the 10 cm depth commonly was higher than the inlet concentration beginning a few months into the experiment (Figure 6.6). The overall pattern of TOC concentration behavior within the two columns was essentially the same. During the last 3 months of the experiment, there was consistent reduction in concentration occurring between the inlet and outlet concentration which appears to be about 20-30%. It appears that little difference occurs in the TOC reduction between the two columns.
Figure 6.6. Diagram showing the concentrations of TOC at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.
6.4.4 NOM fractions

6.4.4.1 Biopolymers

There was a general correspondence between increases in algae and bacterial concentrations entering the columns and the biopolymer concentrations (Figure 6.4, Figure 6.5, Figure 6.7). Biopolymer movement through the columns showed a somewhat erratic behavior in the silica sand column, but was more regular in the carbonate sand column. In both columns, the removal of biopolymers was not regular with depth. In the silica sand column at or after a spike in the inflow biopolymer concentration, the intermediate depths produced a higher degree of removal, sometimes greater than the outflow concentration. Similar behavior occurred within the carbonate column in a few cases, but the outflow concentration was generally lower than those within the intermediate concentrations. During the last 6 months of the experiment, the removal of the biopolymer fraction in the outflow of the silica and carbonate sand columns averaged 60 and 81% respectively. Based on the removal behavior within the columns, it appears that a quasi-equilibrium was reached between the inflow concentration of biopolymers and its removal during passage through the full thickness of the columns starting in December 2014 (after 330 days of operation).
Figure 6.7. Diagram showing the concentrations of the biopolymer fraction of NOM at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.

6.4.4.2 Humic substances

The behavior of humic substances was much different compared to biopolymers as it passed both columns (Figure 6.8). In most cases, only a minor amount of the inflow concentration was removed within the columns when comparing inflow to outflow concentrations. However, when spikes in the inflow concentration occurred, removal was significant, particularly in the carbonate sand column with the highest removal being up to 30%. Beginning in the fall of 2014 (after 257 days of operation), it appears that an equilibrium state began to occur within both columns showing
little variation between the inflow and outflow concentrations. During this time period, there was little variation in the concentrations throughout the depths within each column.

Figure 6.8. Diagram showing the concentrations of the humic substances fraction of NOM at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.

6.4.4.3 Building blocks

The building block fraction of NOM showed rather scattered results in the first several months of the column experiment (Figure 6.9). By summer of 2014 (after around 196 days of operation), the concentrations settled into a general equilibrium with the inflow concentrations being higher than the outflow with the intermediate column depths generally lying between them (with some
exceptions). The removal of building blocks was at a low percentage in both columns and showed little difference between them. At the end of the experiment the removal percentage was 15 and 20% for silica and carbonate columns respectively.

Figure 6.9. Diagram showing the concentrations of the building blocks fraction of NOM at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.

6.4.4.4 Low molecular weight neutrals

The concentration of the low molecular weight neutrals varied greatly with depth between the inlet and outlet within both columns (Figure 6.10). An interesting observation is that the concentration at the intermediate depths considerably exceeded the inlet and outlet concentrations. In particular,
the highest concentrations occurred at the 10 cm depth. Beginning in about February 2015 (after 400 days of operation), the concentrations began to equilibrate and become more regular with little difference between inlet and outlet concentrations.

![Diagram showing the concentrations of the low molecular weight neutrals fraction of NOM at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.](image)

Figure 6.10. Diagram showing the concentrations of the low molecular weight neutrals fraction of NOM at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.

6.4.4.5 Low molecular weight acids

The low molecular weight acids fraction of NOM had a significantly lower concentration in the inlet seawater compared to the low molecular weight neutrals (Figure 6.10 and Figure 6.11). The early data shows some scatter with intermediate column depth concentrations being higher than
both inlet and outlet concentrations. Roughly halfway through the 21-month experimental period, the pattern of concentrations within the two columns began to equilibrate and toward the end of the experiment showed a regular pattern with the inlet being the highest and the outlet being the lowest. The intermediate depth measurements still showed some variation outside the range of inlet and outlet values. The removal of the low molecular weight acids was quite low and there was no significant difference between the removal percentage between the silica and carbonate sand columns.

Figure 6.11. Diagram showing the concentrations of the low molecular weight acids fraction of NOM at the inlet, at 10 cm, 25 cm, 50 cm of depth in the columns, and at the outlet.
6.4.5 Particulate and colloidal TEP

Particulate TEP in the inlet seawater ranged from about 50 to nearly 600 μg Xeq./L (Figure 6.12). Some differences were found in the inlets between the two columns which may be indicative of variations within the seawater in the holding tank (samples were collected from the inflow tubes in each column and not the tank). Because of the long time required to measure TEP, it was collected only from the inlet and outlet and not at the intermediate depths in the columns. The general pattern of TEP removal is similar in both columns. During the last 6 months of the experiment, the removal percentage in the silica sand column was 41 to 67% and in the carbonate sand column was 63 to 76%. Removal of particulate TEP was significantly greater in the carbonate column compared to the silica column at specific sampling times with up to a 10% difference. The highest percentages of particulate TEP removal occurred during spikes in the inlet concentration.
In general, the colloidal TEP concentrations from in the inlet seawater were less than 50% of the concentrations of particulate TEP (Figure 6.12 and Figure 6.13). Some removal of colloidal TEP occurred in each of the columns and was highest during spikes in the inlet concentration. The average removal is about 32% for the silica column and 35% for the carbonate column for the entire period of the experiment. Large variations in the removal percentage did occur during the experiment.
Figure 6.13. Diagram showing the concentrations of colloidal TEP at the inlet and at the outlet.
6.5 Discussion

6.5.1 Assessment of algae and bacteria removal with time

With an exception of a few measurements, the 1 m columns of silica and carbonate sand removed 100% of the algae that entered through the inlet. This occurred even during high concentrations associated with minor algal blooms which produced concentrations at or above 50,000 cells/mL. No significant differences between the removal efficiency based on media composition were observed.

A quite high degree of removal of bacteria, reaching up to 85% by the end of the experiment period, occurred in both columns. The same general pattern of removal was observed in both columns, but the average percentage of removal was higher during the last year of operation in the silica sand.

6.5.2 Assessment of TOC and NOM fractions removal with time

Removal of TOC was nearly equal in both columns which both required over one year of operation to achieve some type of quasi-equilibrium. Within the column, the intermediate concentrations of TOC were higher than both the inlet and outlet values likely indicating that the transport of organic carbon within the column reaches this level and pauses. Then, the “collected” organic carbon is subjected to additional microbial activity before leaving the column. During the last 4 months of the experiment, the TOC concentrations occurring between the inlet and outlet were comparatively lower, suggesting that biological activity removed the higher concentrations previously occurring within the mid-column.
The biopolymers fraction of NOM, which contains many polysaccharides and proteins that impact biofilm development, was significantly removed during passage through both columns. However, the carbonate sand media appears to create a higher degree of removal, particularly during the last half of the experiment. Within the carbonate sand column, a quasi-equilibrium state was reached after about one year of operation and the intermediate concentrations were enveloped between the inlet and outflow concentrations. This state was never reached in the silica sand column. Therefore, the supposition by Rasheed et al. [28] and Wild et al. [29] that the carbonate sands in the reef sediment of the Red Sea are more bio-reactive compared to silica sands is supported by these data for this NOM fraction. The cause of the higher bio-reactivity of the carbonate sands is likely a combination of the higher porosity of some carbonate skeletal grains (e.g. corals) and/or the occurrence of naturally-occurring organic compounds on the surface of the grains which could encourage adsorption of additional organics perhaps as a biofilm.

Removal of the lower molecular weight humic substances and building blocks was substantially lower in both columns. The humic substances concentrations were in general consistently higher than the building blocks. There was little difference in removal of these NOM fractions between the columns. Little variation in concentrations occurred during the last half of the experiment period. There were considerable variations within the intermediate depths in the columns during the first 7 months of experiment operation in the building block fraction of NOM.

The low molecular weight neutrals fraction of NOM showed an interesting pattern of concentration variation within the intermediate depth concentrations in both columns, being commonly higher than both the inlet and outlet concentrations. This was most pronounced in the first year of the experiment. It is likely that the higher molecular weight substances trapped within the columns were being biochemically degraded within the column, likely mediated by bacteria to produce
these substances. During the last several months of the experiment all of the measured concentrations showed a narrow range with the inlet and outlet being nearly equal. It appears that a quasi-equilibrium state was reached for these substances within the column. The average removal in the last 11 months for LMWN was 13% and 14% for silica and carbonate columns respectively.

The least abundant fraction of NOM measured during the experiment was the low molecular weight acids. In general, they showed a rather minor pattern of fluctuation during the experiment compared to the low molecular weight neutrals fraction. They do not appear to be significantly affected by the biochemical process occurring with the two columns and there is no apparent impact of the media composition. The average removal in the last 11 months for LMWA was 24% and 20% for silica and carbonate columns respectively.

6.5.3 Assessment of particulate and colloidal TEP removal with time

The particulate TEP (P-TEP) showed concentrations nearly double that of colloidal TEP in the inlet seawater. Removal of the P-TEP was greater compared to the C-TEP in both columns which may be caused by the higher molecular weight and perhaps a greater abundance of acidic polysaccharides in the P-TEP. The average removal of P-TEP was higher for silica columns at 57% while the average removal for the carbonate column was 47% for the entire period of the experiment. The average removal of C-TEP for the same period was almost the same with 35% for the carbonate column and 32% for the silica column. It is likely that a greater removal rate could be achieved by increasing the length of flow (greater bed thickness) and the corresponding hydraulic retention time.
6.5.4 Operational maturing of treatment in comparison to slow sand filtration

Experimental work on the “ripening” of slow sand filters shows that the “schmutzdecke” forms in time periods of a few days to two weeks in freshwater systems. Without the formation of this surface layer, slow sand filtration is ineffective at removal of organic materials and the filtered water quality is poor [21]. Slow sand filtration in freshwater systems removes 1-3 log units of coliform bacteria, 2-4 log units of *Giardia* cysts, and >4 log units of *Cryptosporidium* which are similar in size to some seawater algae [31]. Dissolved organic carbon (DOC) is removed at 15-25% and trihalomethane precursors at 20-30% [31]. Higher and lower removal rates for DOC have been documented at some locations, but are dependent on the infiltration rate and water temperature [32]. Biochemical activity within freshwater slow sand filter systems is concentrated in the upper 10 cm of the media and declines with depth.

The column experiment that was conducted for 620 days showed no development of a “schmutzdecke” layer as found by physical observation. In addition, evaluation of breakthrough curves at the beginning and at the end of the experiment showed that the flow rate within both columns was relatively consistent through the entire experiment duration which also indicates that no “schmutzdecke” layer was formed. Also, by monitoring the performance of pump flow and the outlet flow of both columns during the whole period of the experiment, it was observed that there was no change in the outlet flow which would not be the case if a “schmutzdecke” was present (the flow rate will be reduced greatly). No cleaning of the top of either column was required during operation of the experiment.

The data clearly show that various organic materials were removed throughout the columns rather than only in the first 10 cm (Table 6.1). While the highest percentage of the particulate organic carbon forms, algae and bacteria, were removed in the uppermost 10 cm in both columns, the
dissolved organic compounds were removed throughout the column depth. Considerable variability in the percentages did occur which is to be expected in a biological active media. Biochemical processes acting within the columns likely had rate changes based on compositional changes occurring within the feed water and uneven breakdown rates of the large organic compounds.

Removal of algae was nearly 100% except for some of the sampling events at the beginning of the experiment. The bacteria removal also occurred without a “schmutzdecke” formation. The removal of the NOM fractions was more effective after the columns stabilized which occurred several months into operation. It appears that seawater slow sand filtration operates in a different biochemical regime compared to freshwater slow sand filtration systems.

Table 6.1. Comparison of organic carbon removal at the different depths through the 1m column (reference is the inlet seawater).

| Media type | Silica | | | | Carbonate | | | | |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Media Thickness | 10 cm depth | 25 cm depth | 50 cm depth | 1 m depth | 10 cm depth | 25 cm depth | 50 cm depth | 1 m depth |
| Algae | 91% | 95% | 97% | 100% | 93% | 97% | 99% | 100% |
| Bacteria | 72% | 72% | 72% | 87% | 64% | 68% | 68% | 74% |
| TOC | 4% | 2% | 1% | 16% | 2% | 3% | 9% | 15% |
| BP | 47% | 59% | 61% | 59% | 54% | 67% | 69% | 72% |
| HS | 7% | 9% | 8% | 4% | 7% | 12% | 10% | 10% |
| BB | 11% | 12% | 8% | 17% | 10% | 12% | 14% | 15% |
| LMWN | +11 | 0% | +6 | 13% | +18 | +15 | +17 | 14% |
| LMWA | 25% | 25% | 18% | 24% | 11% | 22% | 12% | 20% |
| P-TEP | | | | 59% | | | | 66% |
| C-TEP | | | | 32% | | | | 36% |

* (+) indicate that measured value at that sampling port was higher than the corresponding value at the inlet seawater
6.6 Conclusions

The effectiveness of a seabed gallery intake system in terms of improving raw seawater quality was assessed through the use of a long-term bench scale columns experiment. Two different media compositions (silica and carbonate) within a 1 m fixed column length were used in this study for a period of 620 days. The role of media type and penetration in the column (10, 25, 50 cm and 1 m depth) in improving the raw seawater quality was also evaluated at this study. Analyses included the measurement of algae, bacteria, TOC, NOM and TEP concentrations. The results showed that the 1m length column significantly improved raw seawater quality once it came into quasi-equilibrium. The columns required several months to reach the equilibrium state in which the removal pattern became more stable with higher percentage of removal efficiency.

Almost all algae 87 % (σ=0.04), and 74% (σ=0.08) of the bacterial population for silica and carbonate sand columns respectively were removed through the 1m length column for the last 11 months of the experiment. Biopolymers were removed at 59 % (σ=0.11) for silica column and at 72% (σ=0.15) for the carbonate column for the same period as well. The average removal of P-TEP was 59% (σ=0.16) and 66% (σ=0.08), while C-TEP removal rate was 32% (σ=0.25) and 36% (σ=0.12) for silica and carbonate columns respectively. TOC concentration showed the lowest percentage of removal with an average of 16% (σ=0.07) and 15% (σ=0.15) for silica and carbonate sand columns respectively for the same period.

The lower concentration of TOC is due to the short length of the column which indicates that 1m path length is not enough to significantly lower the TOC concentration. This finding is consistent with the results observed from the wells having longer flowpath lengths and associated residence times being more effective in removing TOC. The removal efficiency within the intermediate
depths was significant for the 10 cm depth in which the average removal was about 90% for algae, 72% and 64% for the bacterial population for silica and carbonate sand columns respectively for the last 11 months. The biopolymer removal percentage at the 10 cm length was 47% for silica column and 54% for the carbonate column for the same period. There was no clear difference observed between the average removal at 10 cm and the other two intermediate depths of 25 and 50 cm. It is clear that for NOM fractions a thicker active bed will be required to increase the removal efficiency while for algae and bacteria most of the removal occurs in the top layers by straining, but still the full column is contributing to the removal of both of them (Table 6.1). In general, the removal efficiency of the carbonate sand media is higher for biopolymers and TEP, but it is lower for the bacterial population.

The reduction of these organics, which are known to enhance biofilm formation, will help decrease the potential rate of biofouling on an SWRO membrane surface. Therefore, less complicated pretreatment system would be needed with less chemical usage within the SWRO plant which would ultimately reduce the operating cost. In addition, this natural seabed intake system is not harmful for the environment since impingement and entrainment cannot occur. Also, it was demonstrated that no schmutzdecke layer formed during the experiment period of 620 days suggesting that use of this intake type for seawater pretreatment may require less maintenance than its use in freshwater treatment systems.

The findings of this study will help the desalination plant designer in deciding about the appropriate thickness of the active layer for a seabed gallery as well as the type of media used. Moreover, for planning purposes it will be important to run the seabed intake system ahead of time before the commissioning of the desalination plant in order evaluate the full benefit of the seabed system with more biological stability and ultimately higher removal efficiency. Furthermore, the
findings will help operators to identify the cleaning requirements for the gallery system which was shown to be minimal at the only existing operating system in Japan.
6.7 References


CHAPTER 7 : Effects of Nearshore Evaporation Rates on the Design of Seabed Gallery Intake Systems for SWRO Facilities Located along the Red Sea Shoreline of Saudi Arabia

7.1 Summary

Feed water to seawater reverse osmosis (SWRO) desalination systems should have a constant salinity with minimal variation. Intake systems that extract water from shallow nearshore areas in arid regions can exhibit significant fluctuations in salinity caused by high rates of evaporation and lack of circulation. Such fluctuations in salinity could inhibit the design, construction and operation of seabed gallery intake systems located in shallow nearshore areas, such as the Red Sea inner shelf. Water depths range from 0 to 2 m between the beach and the edge of the fringing reef in the optimal locations for development of seabed gallery intakes along the coast of the Red Sea of Saudi Arabia. The evaporation rate in this area is between 2 and 3 m per year. The bottom consists of mostly a marine hardground containing a thin veneer of unlithified sediment and no significant cover of corals or seagrass. The rather barren nature of the bottom suggests that periodic hypersalinity may contribute to the formation of the hardgrounds on the bottom by causing supersaturation of the seawater with calcium carbonate and limit growth of corals and grasses.

To assess the changes in salinity, a conceptual model was developed which assumes that a shallow circulation cell develops between the shoreline and deeper water offshore. Lower salinity seawater should migrate landward to replace water loss caused by evaporation with seaward moving of high salinity water occurring along the bottom to balance flow with ultimate mixing before the reef

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tract. To test this circulation pattern, a series of sensors were deployed to continuously monitor the water temperature, conductivity, and salinity at the surface and at the bottom during several periods of high air temperature. Surprisingly, the results showed very little variation in salinity, despite the very high evaporation loss. The water salinity ranged between 39,000 and 40,000 mg/L with no diurnal variations of significance. Based on the monitoring and weather station data collected nearby, it appears that the predominant strong onshore wind, particularly during the afternoon and early evening, causes near-continuous mixing of the water between the reef tract and the shoreline. Therefore, the development of seabed gallery intake systems within the shallow water between 1 and 2 m of depth is feasible based on the measured salinity which is similar to that occurring further offshore in water depths between 2 and 20 m.

7.2 Introduction

It is an international goal to reduce the energy consumption and cost of seawater desalination to allow it to be used to provide water supplies to a greater number of people [1, 2]. A significant component of this goal is to improve the quality of the raw seawater that is treated by the seawater reverse osmosis process (SWRO) [3]. One method of improving the quality of raw seawater that enters a SWRO facility is to utilize some type of subsurface intake system which provides a significant degree of pretreatment using natural filtration, similar to the bank filtration process used in freshwater river intakes in Europe and other regions for over a century [4]. Recent investigations have demonstrated that subsurface intakes provide significant improvement in water quality by removing organic substances from the seawater, thereby decreasing the potential for biofouling of the SWRO membranes [5, 6].
A considerable amount of research has been conducted on the use of subsurface intake systems along the Red Sea coast of Saudi Arabia [7-11]. The primary conclusion of this research is that the best type of subsurface intake that could be used to supply SWRO facilities of virtually any capacity is the offshore seabed gallery system. A number of site-specific investigations showed that the galleries could be constructed in the nearshore subtidal zone between the reef and the beach (Figure 7.1).

Figure 7.1. Research sites on which investigations were conducted on seabed gallery feasibility
A key assumption with regard to the technical feasibility of successfully operating a seabed gallery along coastline of the Red Sea is that the raw water salinity would remain the same as the background salinity with time. Since this region is arid and has a high rate of free-surface evaporation. A question has been raised concerning whether the shallow water near the shoreline becomes more saline during daily cycles caused by evaporative concentration. It is the purpose of this research to evaluate the nearshore changes in salinity on a diurnal basis to determine if the evaporative loss of seawater would cause a limitation to the use of seabed gallery intake systems in the nearshore areas of the Red Sea of Saudi Arabia.

7.3 Methods

The potential evapotranspiration for the nearshore of the Red Sea was calculated using the Penman method as applied to the weather station data collected near the shoreline at the King Abdullah University of Science and Technology. This station is representative of the general Red Sea region of Saudi Arabia, but some variation in data can be anticipated.

Conductivity and temperature data from the shallow nearshore water was collected at a two sites; one located adjacent to the King Abdullah Economic City (KAEC) (Site A) and at another site adjacent to King Abdullah University of science and Technology (KAUST) (Site B) (Figure 7.2).
Transducers were deployed into the field to measure the top and bottom conductivity and temperature at the two locations (Site A, Site B). The details of installation are shown in (Figure 7.3). The 8 transducers were deployed at depths range from 0.6m up to 3.5m below surface. Site A data were recorded continuously for a period of 7 weeks. Site B-1, data were recorded for a period of 4 weeks, while data were recorded for a one-week period only for site B-2 due to installation error.
Since wind is a key component of shallow nearshore circulation, wind data were collected from an onshore weather station located at King Abdullah University of Science and Technology. These data were compiled into a wind rose and were used to assess potential for causing nearshore mixing of the water column.

7.4 Investigation Results

7.4.1 Potential evaporation analysis

Hourly meteorological variables were recorded at a weather station installed on the coast of Red Sea near KAUST. The Penman method was used extensively to estimate potential evaporation and it requires air temperature, wind speed, relative humidity, and solar radiation data to perform this estimate. In this study, we used the energized Penman equation proposed by Van Bavel [12], to calculate the evaporation rate.
Figure 7.4. (a) Hourly potential evaporation flux estimated over 365 days of a year and (b) monthly potential evaporation values estimated by Penman equation.

Figure 7.4 (a) and (b), respectively, depicts the hourly and monthly potential evaporation estimated over a period of one year. Zero day of the year corresponds to the first day of the year. The increasing trend of potential evaporation was observed in first 150 days of the year and a maximum potential evaporation rate of 0.17 cm/hr was estimated. Monthly potential evaporation shows similar trend and maximum monthly potential evaporation of 29.2 cm/month was observed in May. The ambient temperature decrease in the winter causes the potential evaporation to decrease and this can be observed especially after the month of September. In a year, 262.28 cm potential evaporation was observed near the coast of Red Sea.

7.4.2 Conductivity and temperature data

For both sites, there was a clear positive relation between temperature and conductivity measurements as shown in Figure 7.5 (a) and (b). At both sites, the conductivity values were in correspondance with temperature measurements. The measurements of top and bottom points were almost equal at both sites with no clear difference observed based on the depth change.
The conductivity measurements were in the range of 56 and 62 mS/cm during the deployment period while the temperature was in the range of 23 and 28°C. In order to clearly understand the temperature effect on electrical conductivity, a temperature standardized equation was used in which electrical conductivity values were standardized at a reference temperature of 25°C:

\[
C_s = \frac{Y_e}{1 - \left( (25 - T) \times \frac{a}{100} \right)}
\]  

(1)

Where \( Y_e \) = electrical conductivity, \( a = 2.1 \% / \) degrees Celsius (temperature coefficient) and \( T \) = the water temperature in degrees Celsius [13].
Figure 7.5. Electrical conductivity and temperature measurements for site A-1 top (a) and for site A-1 bottom (b). The standardized electrical conductivity is shown in black.
In order to identify the role of water depth on conductivity and temperature change, the standardized measurements of electrical conductivity from site A were plotted in Figure 7.7.

![Figure 7.6. Standardized conductivity measurements for site A.](image1)

The standardized conductivity measurements for site B are shown in Figure 7.8.

![Figure 7.7. Standardized conductivity measurements for site B](image2)
7.4.3 Wind data diagram

Figure 7.8. Wind data at KAUST weather station, values are in (m/s)

Figure 7.8 shows a wind rose diagram, based on one year of hourly wind data recorded by weather station installed at the coast near KAUST. This rose shows that the winds on the coast blow from the northwest most of the time which is an onshore direction. The wind speed was recorded in meters per second and the legend at the right bottom corner shows the wind speed categories and their associated colors. The 6 spokes around the northwest direction comprise 34% of all hourly wind directions. The wind rarely blows from the southwest or the northeast. The wind rose diagram also provides details on speeds from different directions. Examining winds from the northwest (the longest spoke) one can determine that approximately 3% of the time the wind blows from the northwest at speeds between 4 and 6 meters per second. Similarly, on this spoke it can be calculated that winds blow from the northwest at speeds between 6 and 8 m/sec about 2.8% of the time (5.8% - 3%), at speeds between 8 and 10 m/sec about 1.2% of the time, between 10 and 12 m/sec about 0.3% of the time.
7.5 Discussion

Thermohaline circulation is a common process of deep ocean circulation which controls the overall movement of large water masses [14, 15]. Perhaps similar thermohaline cells of a very small size can form in shallow, nearshore areas where there is a very high rate of free surface evaporation and wind-driven wave action is minimal. In these shallow areas, the seawater would be evaporatively concentrated at the surface, sink to the bottom and move seaward with the bottom slope. Fresher seawater would move landward to balance the mass of water lost through evaporation and the seaward moving density current (Figure 7.9). This nearshore circulation would have the tendency to cause the occurrence of hardgrounds and the absence of marine flora and fauna that are sensitive to high salinity water. This is the observed condition of a large portion of the Red Sea nearshore area of the Red Sea of Saudi Arabia.

![Figure 7.9](image)

Figure 7.9. Theoretical density circulation in the nearshore shallow area of the Red Sea based on evaporation.
It has been demonstrated that thermally-driven exchanges occur between a coral reef and the adjacent ocean at the northern end of the Gulf of Aqaba [16]. The heating of shallow water causes an offshore movement of water at the surface and a balancing onshore flow of water at depth. This is an opposing flow cell compared to potential seaward directed bottom flow caused by density. Wind-driven nearshore circulation in coral reef systems is known to facilitate circulation within reef and lagoon systems [17-19].

The occurrence of higher salinity bottom water during the summer months or during part of the diurnal cycle would be of great concern in the event that a seabed gallery intake was to be used to provide feedwater for a SWRO facility. The salinity of the nearshore water in the Red Sea is commonly between 40 and 42 ppt, and any increase would provide difficulties to the operation of the facility.

An analysis of the potential evaporation (PE) of the nearshore of the Red Sea shows that the total annual PE ranges from 2 to 3 m. The highest daily rates would occur during the day in the summer months. The calculated PE data appear to support the potential for allowing thermohaline circulation to occur during part of the year within the nearshore zone.

The monitoring of the shallow water during part of the year at sites A and Site B showed that no significant salinity and temperature gradient formed in the shallow nearshore area. The likely reasons for mixing in this area are: 1) the water depth may be too shallow to accommodate density current formation, 2) the bottom slope is insufficient to allow a density current to form, and 3) the strong onshore wind causes sufficient nearshore circulation to prevent formation of vertical density gradients and nearshore density circulation, and wave-driven shallow circulation. Based on the data observed from the site along the Red Sea shoreline, it is likely that a combination of wind-
and wave-driven circulation causes mixing and convection with nearshore outer and inner reef areas as described in locations of the Red Sea and other regions [20-22].

While this research is specific to the Red Sea coast of Saudi Arabia, the nearshore circulation could affect salinity changes at other geographic sites where seabed gallery intakes may be considered for installation. For example, the circulation of the Arabian Gulf is affected by an offshore wind direction along the Saudi Arabian coast and other locations where high salinity in shallow water is documented. Therefore, evaporative concentration of salinity could be a significant problem [23]. The coastlines of the Mediterranean tend to have a larger variation in wind direction and intensity, so site-specific investigations of nearshore circulation would be required during the intake design process in this locality.
7.6 Conclusions

An investigation of variations in nearshore salinity and temperature was conducted to ascertain the potential for formation of high salinity bottom water along the Red Sea nearshore area of Saudi Arabia. The formation of a high salinity water mass and seaward circulation could adversely affect in the operation of a seabed gallery intake by causing a fluctuation of the intake water salinity which would influence plant operations. The investigation showed that no such vertical density gradient formed and no significant shallow thermohaline circulation was occurring. It is likely that the absence of a vertical density gradient and formation of circulation are caused by wind mixing and the low degree of seaward-dipping bottom slope.

While the results of this investigation are positive with regard to the viability of using seabed gallery systems constructed in shallow, nearshore water of the Red Sea of Saudi Arabia, care still must be taken to map the bottom bathymetry to be sure that slope allows free movement of water. The presence of a shallow basin could allow high density water to accumulate within it and limit the impacts of mixing processes on the water column.
7.7 References


CHAPTER 8: Conclusions and Recommendations

8.1 Conclusions

The use of subsurface intake systems along the Red Sea coastline of Saudi Arabia was investigated. A new method for evaluation of different coastal environments was developed and applied to Saudi Arabia to determine the feasibility for constructing subsurface intake systems along the studied coastline. In addition, the use of well intake systems was evaluated in terms of raw water quality improvements and it was also compared with the performance of a deep surface-water intake. The performance of seawater reverse osmosis (SWRO) pretreatment systems were also evaluated for both well and deep surface-water intake facilities. Moreover, a detailed investigation was performed for three existing SWRO desalination plants with well intake systems along the Red Sea coastline of Saudi Arabia. The detailed investigation assessed the degree of raw water quality improvements through the use of different well systems that have different design parameters and geological formations. Furthermore, the effectiveness of seabed gallery type of subsurface intake system was investigated in terms of raw water quality improvement. For this investigation, a bench scale columns filtration experiment consisting of two different media types (silica and carbonate sand) was used to simulate the seabed conditions. During the various site investigations, algae, bacteria, total organic carbonate (TOC), natural organic matter (NOM) fractions and transparent exopolymer particles (TEP) concentrations were measured to assess the degree of water quality improvements provided by the different intake systems. Finally, the investigations were concluded by studying the impact of surrounding environment (evaporation rate in the nearshore zone) to assess if evaporative concentration would affect the performance of seabed intake systems.
8.1.1 Feasibility of Subsurface intake systems along the Red Sea coastline of Saudi Arabia

A new method was developed that can be used at any coastal location in the world to assess the feasibility of various subsurface intake systems for future SWRO facilities. This new method used the coastal geology and geomorphology along with the environmental characteristics of the shoreline and coastal area to provide guidance in the use of specific types of intake systems. The investigation of the coastal environments showed that subsurface intake systems are favorable for construction at coastal environments with sandy beaches and low mud content within the bottom sediments. Rocky shorelines composed of limestone with corresponding near shore sand and wadi sediments with low mud content are also favorable environments for subsurface intake construction. Other environments, such as sabkhas, lagoons, mangrove areas and natural channels are not feasible for the use of subsurface intake systems. It was also found that seabed intake system has the highest feasibility for the development of large-capacity (greater than 50,000 m³/day) desalination facilities based on the geology. Beach galleries were found to be not feasible for construction along the Red Sea shoreline due to the unfavorable geological conditions (low wave activity). Moderate wave activity produces a self-cleaning mechanism which does not exist along this coastline. Well intake types were found to be feasible for low-capacity SWRO facilities. This same methodology can be applied for any other coastlines around the world such as Arabian Gulf and Mediterranean Sea. The different coastal geology and geomorphology along with the environmental characteristics at the different coastlines could be identified, samples could be collected and analyzed then the feasibility and capacity estimation could be determined based on the findings. Seawater temperature and circulation should be monitored at the different studied coastlines because that might limit the feasibility of subsurface intake system construction. What is highly feasible along the Red Sea coastline might not be
feasible at the different coastlines around the world, it is highly dependent in the local geological conditions.

8.1.2. Impact of intake type (well vs. deep water) in improving the raw seawater quality

The evaluation two facilities using a well intake system and a deep water intake (9 m below water surface) in terms of water-quality improvements showed that well intake system was highly effective at removing all algae and biopolymers, up to 84% of the bacteria and substantial percentage of TEP while the concentration differences between the shallow-water and a deep-water intake were mixed and may not be significant. The well intake system provided a high degree of pretreatment, while the surface-water intake required more pretreatment within the facility. This research conclusively shows that aquifer treatment of seawater using well intakes acts as a pretreatment process.

At the facility using the surface-water intake, TOC and NOM concentrations at the surface were similar to their corresponding values at the 9m depth while algae concentrations were significantly lower with depth. Bacterial concentration at the 9m depth were moderately lower compared to the concentration at the surface. Total TEP was generally increased with depth. Particulate TEP was lower at the surface and colloidal TEP was significantly higher at the 9m depth.

The pretreatment systems at both sites were also evaluated. Generally, the media filter was effective in reducing TEP, algae and biopolymers for the open-ocean intake site but the impact was minimal for bacterial concentration. No significant impact of media filtration was observed for the facility with a well intake. On the other hand, the cartridge filter showed negative impacts (increased concentrations across the filters) for both TEP and bacterial concentration which
suggests that bacterial regrowth may be occurring through the cartridge filter process. The research shows that the current design of cartridge filters for SWRO pretreatment needs to be revised to avoid bacterial regrowth and TEP production.

8.1.3 Evaluation of existing subsurface intake plants with well intake systems along the Red Sea coastline of Saudi Arabia

The detailed investigation of three existing shallow well intake systems installed within different geological formations, quartz sands, and limestone/carbonate sands along the Red Sea coastline of Saudi Arabia were conducted. This research demonstrated that vertical wells are highly effective at improving raw water quality prior entering the SWRO desalination facilities. All algae, up to 99% of bacteria, up to 70% of TOC, > 90% of biopolymer fraction of NOM and a high percentage of the TEP were removed during the transport through the aquifer. Most probably the removal of these organics is caused by straining, biochemical degradation and adsorption of the organic matter within the aquifer matrix. It was also found that flow path length through the aquifer, as a proxy for retention time, plays an important role in improving the removal efficiency of organic matter (TOC and biopolymers). The wells drilled into carbonate sediments showed the highest reduction percentage within the different geological media which could be attributed to the high surface area of the carbonate sediments and high porosity that allows greater adsorption. The cleaning of the SWRO membranes at these facilities was 50 to 75% lower than facilities using conventional surface-water intake systems.

8.1.4 Evaluation of seabed intake active-layer performance through the bench scale column experiment

Seabed filtration or galley filtration systems have been found to be feasible for use as intake in large-capacity SWRO desalination facilities. However, little is known concerning the fate and
transport of organic matter through the upper (active) layer of the filter within a seawater environment.

The simulation of transport of organic matter within the active layer of seabed intake systems was investigated through the use of bench scale columns experiment conducted over a period of 22 months. A new method was applied to the design of column experiments by using a computer program to pre-determine the desired hydraulic conductivity and retention time for the experiment. Two columns, one with silica sand and the other with carbonate sand media, were conducted side-by-side and showed that the active layer (1 m thick in this case) is highly effective at improving raw water quality once it reaches a quasi-equilibrium state. Nearly all algae, 87% and 74% of bacterial population for the silica and carbonate columns respectively were removed through the 1 m length columns during the last year of the experiment operation. The biopolymer concentration removal during the same period was also high with percentages of 59% and 72% for silica and carbonate columns respectively. The average removal of colloidal TEP ranged between 32% and 36% for both columns while particulate TEP removal was higher at 59% and 66% for silica and carbonate columns respectively during the same period. TOC showed the lowest percentage of removal among the measured parameters.

The removal efficiency of the carbonate sand media is higher for biopolymers and TEP but it is lower for the bacterial population. The removal efficiency was increasing with depth but most of the removal of algae, bacteria and biopolymers concentrations occurs at the top 10 cm due to straining effect and adsorption. It was found that a thicker active bed will be required to improve the removal efficiency of TOC and the lower sizes of NOM fractions. The impacts of different design parameters in improving raw water quality in a subsurface intake system are summarized in Table 8.1. It was also discovered that no schmutzdecke layer formed during the experiment.
operation which suggest that seabed gallery intake operates in a much different manner compared to freshwater slow sand filtration systems.

8.1.5. Impact of evaporation rate on seabed intake operation

The successful use of an offshore seabed gallery intake system is based on the assumption that the salinity of the seawater will be constant over the operational life-cycle of the facility. Evaporative concentration of seawater in the nearshore zone above the gallery in Saudi Arabia is a potential concern.

An investigation of the high evaporation rate impact in the operation of a seabed gallery intake showed that no vertical density gradient and no significant thermohaline circulation was occurring along a part of the Red Sea nearshore area. Therefore, the use of a seabed gallery intake is viable at the shallow water depths along the Red Sea shoreline during the high temperature seasons with no concern regarding salinity variation. Most probably that the predominant strong onshore wind keeps near continues mixing of the seawater which prevents the formation of a vertical density gradient that would cause huge salinity water to pond above the seabed. The low degree of seaward dipping bottom slope is also responsible for the absence of vertical density gradient and formation of circulation to disrupt any the formation of a vertical density gradient at the studied site. The methodology developed to make this assessment could be used (and should be) during engineering designs of gallery intake systems.

Table 8.1. Comparison of slow sand filtration, the column experiment and selected well systems in terms of design parameters and water quality improvement.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Slow sand filter</th>
<th>Silica column</th>
<th>Carbonate column</th>
<th>Fukouka</th>
<th>North Obhor Wells (Site A)</th>
<th>Corniche Jeddah Wells (Site B)</th>
<th>South Jeddah Wells (Site C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed thickness (m)</td>
<td>0.9-1.5 [1]</td>
<td>1</td>
<td>1</td>
<td>3.85</td>
<td>400-450</td>
<td>300</td>
<td>40-50</td>
</tr>
<tr>
<td>Infiltration Rate (m/day)</td>
<td>1.2-4.8</td>
<td>5</td>
<td>5</td>
<td>5.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean grain diameter (mm)</td>
<td>0.3-0.45</td>
<td>0.07-0.21</td>
<td>0.07-0.21</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Residence time (hour)</td>
<td>3-12 [2]</td>
<td>4.7</td>
<td>4.7</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Run length</td>
<td>1-6 months</td>
<td>22 months</td>
<td>23 months</td>
<td>12 years</td>
<td>14 years</td>
<td>8 years</td>
<td>3 years</td>
</tr>
<tr>
<td>Regeneration method</td>
<td>Scrapping top</td>
<td>No need</td>
<td>No need</td>
<td>No need</td>
<td>Well rehabilitation</td>
<td>Well rehabilitation</td>
<td>Well rehabilitation</td>
</tr>
</tbody>
</table>

**Removal efficiency**
- **For seawater pilot:** ≥99% for particles larger in size than 2 microns were removed. The concentration of spiked kainic acid, used as a proxy for algal toxin, was reduced by 89–94%. [3]
- **For fresh water system:**
  1-3 log units of coliform bacteria.
  2-4 log units of Giardia cysts
  >4 log units of Cryptosporidium
  15-25% of dissolved organic carbon
  20-30% of trihalomethane precursors. [4]

<table>
<thead>
<tr>
<th></th>
<th>Slow sand filter</th>
<th>Silica column</th>
<th>Carbonate column</th>
<th>Fukouka</th>
<th>North Obhor Wells (Site A)</th>
<th>Corniche Jeddah Wells (Site B)</th>
<th>South Jeddah Wells (Site C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal efficiency</td>
<td>100% algae, 87% bacteria, 16% TOC, 59% Biopolymer, 59% P-TEP, 32% C-TEP. [5]</td>
<td>100% algae, 74% bacteria, 15% TOC, 72% Biopolymer, 66% P-TEP, 36% C-TEP. [5]</td>
<td>-</td>
<td>SDI &lt;2.5. [6]</td>
<td>100% algae, 98% bacteria, 67% TOC, 96% Biopolymer, 86% P-TEP, 59% C-TEP. [7]</td>
<td>100% algae, 88% bacteria, 48% TOC, 95% Biopolymer, 73% P-TEP, 56% C-TEP. [7]</td>
<td>99% algae, 88% bacteria, 31% TOC, 90% Biopolymer, 72% P-TEP, 68% C-TEP. [7]</td>
</tr>
</tbody>
</table>
8.2. Recommendations and future work

This research focused at studying the main issues related to the operation of subsurface intake systems. Based on the findings of this study, other research ideas are recommended which will help complement the findings of this study and to improve upon the design and operation of subsurface intake systems and SWRO desalination pre-treatment systems. The suggested research ideas are as follows:

- An assessment of scaling issues of the seabed intake system through a pilot scale test. This helps in evaluating how results differ in comparison with the bench scale in terms of water quality improvements and operational parameters. An experiment has already begun using a pilot-scale system consisting of a 1 m diameter tower containing carbonate sand media for the top layer and subsequent silica layers in the middle and supporting gravel layers at the bottom. An operational-scale system needs to be developed, operated, and monitored to help in the development of future engineering design criteria. It will also be of benefit to have plant-scale testing and documentation for a seabed gallery intake facility (e.g. Fukuoka) in which the seabed intake along with the pretreatment system can be evaluated side by side.

- Evaluation of changes in the bacteria community when the seawater bacteria passes through the aquifer system is needed. Are the bacteria found in the wells truly seawater bacteria or are they indigenous groundwater bacteria? It was found that bacteria concentration was significantly reduced after passing through the aquifer system but it’s unknown if the removal caused by bacterial predation by groundwater species or other mechanisms. In addition, it would be useful to understand the changes in bacteria types as
Seawater passes through the various in-plant pretreatment processes. Better media and cartridge filter systems could be developed using this information.

- Life cycle assessment (cost and the carbon footprint) of SWRO desalination plants using subsurface intake systems versus open-ocean intake systems need to be conducted. The gallery type intake system has not been evaluated from an economical and environmental prospective. This would help assess the capital and operational expenses as well as the associated carbon footprint through the life span of the desalination plant. The availability of such data will help decision makers to identify the potential of expenses saving and carbon footprint reduction through the use of the appropriate intake type. The operational savings found using a subsurface intake type may be demonstrated to overcome the larger capital cost in the construction. This is critical information for the future use of subsurface intake systems.
8.3. References


