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Feasibility of using a subsurface intake for SWRO facility, south of Jeddah, Saudi Arabia

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ABSTRACT

The Kingdom of Saudi Arabia is the largest producer of desalinated water with about 13% of the global desalination capacity. Most of these desalination plants use the open-ocean intakes to deliver raw seawater to the desalination facility. Recently, some of the private desalination plants have shifted to subsurface intake systems, either wells or galleries, in order to obtain better water quality with a minimal environmental impact (e.g. minimal entrainment and impingement). The use of these intake types has improved the raw seawater quality extracted from the Red Sea and Arabian Gulf, providing better protection for the membrane component by eliminating/reducing algae, bacteria and organic matter concentrations from the seawater source. One of these desalination plants is located south of Jeddah city which is the second largest city in Saudi Arabia. The plant shifted from an open-ocean intake to beach wells to improve the water quality at the site. Currently, the plant employs 10 vertical wells to extract enough water to produce 10,000 m^3/d of product water via the reverse osmosis process. Studies show that quality of seawater significantly improved after shifting to the well system. The use of a larger capacity well system or a seabed gallery intake was investigated at this site for a proposed additional 20,000 m^3/d future expansion of the facility. More than 60 sediment samples were collected from the seabed along five different transects in an area of 25,000 m^2, starting from shoreline and moving seaward. Grain size analyses, hydraulic conductivity and mud percentage were analyzed in order to determine the characteristic of marine sediments at the studied site. The marine bottom at the selected site contains carbonate sediments which have a high potential of reducing the natural organic matter concentration in the raw seawater. In this study, the laboratory measurements showed that this site has low mud content and moderately high hydraulic conductivity, which make it feasible for seabed gallery construction as an intake. It is concluded that use of a seabed gallery intake for the future expansion will

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overcome the problem of limited water capacity produced by individual wells, but additional alignments of wells is also technically feasible.

Keywords: Seawater reverse osmosis desalination; Intakes; Seabed gallery; Wells; Red Sea

1. Introduction

The Kingdom of Saudi Arabia (KSA) lies in a desert region that has a low abundance of natural freshwater resources caused by low rainfall accumulation and very high evapotranspiration rates [1]. The water supply situation is further exacerbated by a rapidly growing population, an exceedingly high consumption rate, depleting fresh groundwater resources, and a low rate of water reuse [2]. Seawater desalination has become the primary source of supply to meet the ever increasing demand for water.

Seawater desalination in the KSA utilizes thermal processes, primarily multi-stage flash distillation with some multi-effect distillation. Thermal desalination processes use a considerably greater amount of energy to produce a cubic meter of freshwater compared to the seawater reverse osmosis process (SWRO) [3]. While SWRO is significantly more-energy efficient compared to thermal processes, it is still an energy-intensive process and is also subject to reliability issues during naturally occurring events, such as harmful algal blooms [4]. SWRO membranes are quite sensitive to the quality of the raw water. Biofouling of the membranes is a common problem that requires the necessity to operate a complex series of processes to pretreat raw seawater before it can enter the primary membrane process [5]. The capital and operating costs of pretreatment can add between 5 and 30% to the overall cost of water treatment [6]. Despite the considerable effort given to pretreatment, many SWRO facilities continue to have membrane biofouling problems which cause operating inefficiencies and loss of membrane life expectancy.

One method to control biofouling potential and to reduce SWRO operating cost is to improve the raw water quality before it enters the facility. This can be accomplished by using some type of subsurface intake system that could consist of wells or a gallery [5,6]. Subsurface intakes are known to remove a significant percentage of algae, bacteria, natural organic matter, and in particular, transparent exopolymer particles that is known to be a precursor to membrane biofouling [6–9].

The purpose of this research is to evaluate a site on the Red Sea south of Jeddah, Saudi Arabia to assess the feasibility of using a subsurface intake system to expand an existing SWRO facility from a permeate capacity of 10,000 m^3/d to a future capacity of 30,000 m^3/d and compare its efficiency in contrast with extending the current intake system (Fig. 1). The facility currently uses ten shallow wells located on an artificial-fill peninsula constructed from the shoreline into the nearshore area of the Red Sea (Fig. 2).

2. Research methods

2.1. Field investigation

A survey of the coastal area, approximately 5 km north and south of the plant, shown in Fig. 3, was conducted to assess the technical viability of using a seabed gallery intake system or an expansion of the existing well system which could be used to supply raw seawater for the SWRO plant expansion. The research area was limited to 5 km distance from the plant to keep transmission cost of the raw water to the plant as low as possible.

The survey shows that there are two types of coastal geologic settings in this area, including a rocky offshore (marine hard-ground), which occurs along the majority of the coastline line, and a sandy beach and offshore environment, which is limited. The rocky bottom environment, sample shown at site A in Fig. 3, begins at the shoreline and extends seaward to the fringing reef, where the slow steepens abruptly on the seaward side of the reef tract, dropping dramatically into the deep sea. This area, known as the inner reef

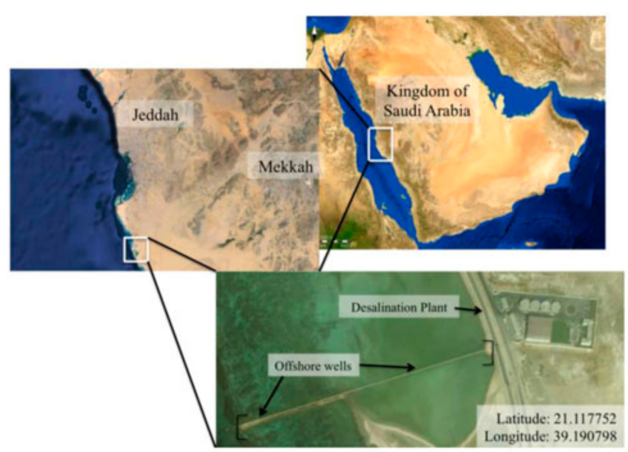


Fig. 1. Desalination facility and its intake system, south of Jeddah city, Saudi Arabia.

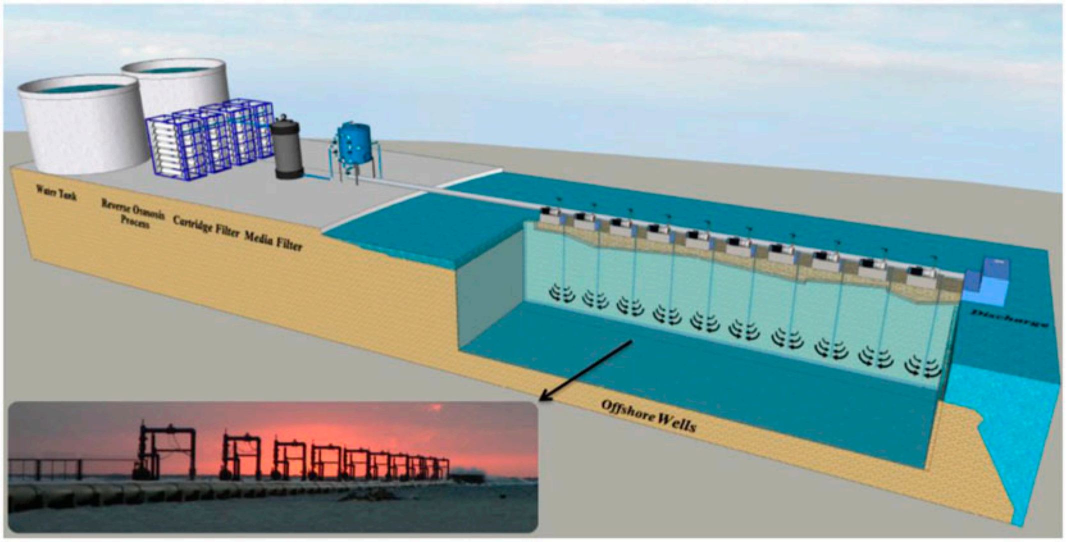


Fig. 2. Offshore shallow wells located on an artificial-fill peninsula used to supply feed water.

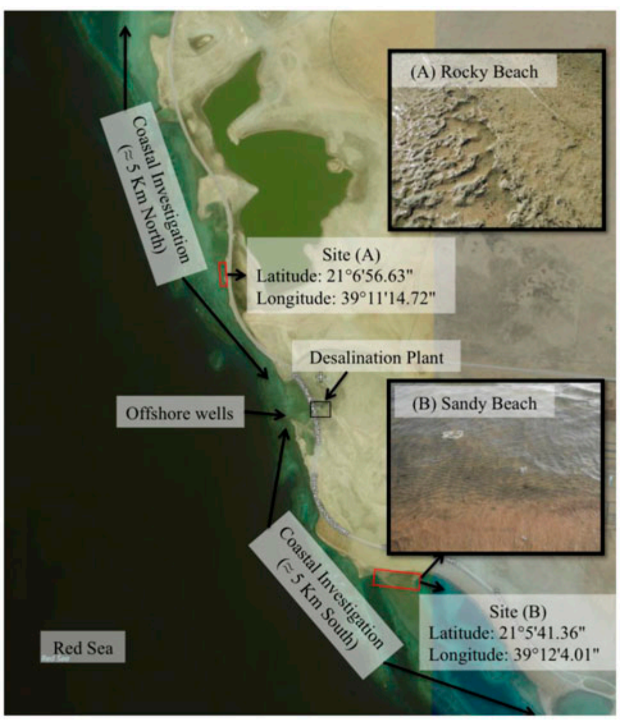


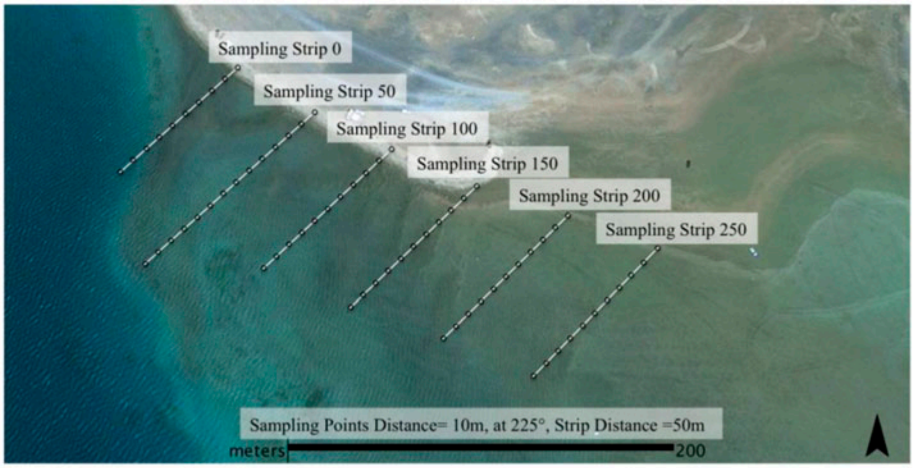
Fig. 3. Map showing the location of the study area.

tract, is flat and rocky and contains virtually no unlithified sandy sediment. This type of nearshore area is likely not feasible for construction of a seabed gallery intake because it is narrow, is wave swept and does not contain unlithified sand to maintain the top of the gallery during periods of extended wave action. Therefore, the investigation of seabed gallery development was limited to a sandy beach and offshore area located about 2.6 km south of the plant, site B in Fig. 3, where the general sediment characteristics were better suited for this intake type. Sediment samples were collected and analyzed to characterize them in detail. The site chosen is located at latitude 21˚5′ 41.36′′, longitude 39˚12′4.01′′ and is chiefly covered with sandy sediment. No muddy sediment was observed, thus lessening the questionability of feasibility (e.g. clogging of the gallery top). Also, accessibility for construction from the main road is not challenging. Proximity of the site to the SWRO plant is reasonable. Sampling of the site was conducted in a grid array to fully characterize the sediment properties (Fig. 4). The offshore bottom contained virtually no living corals and there was no significant growth of seagrass.

More than 60 sediment samples were collected from the sea bed along six different transects in an area of 25,000 m^2 for the purpose of determining grain size, hydraulic conductivity, and porosity. All samples were taken from the upper 5 cm because this depth contains mobile sediment that will be moving around on the bottom, where subsurface intake would be constructed.

2.2. Laboratory sediment measurements

Grain size distribution, hydraulic conductivity, and laboratory porosity analyses were carried out to study the hydrogeological properties of the sediments. Samples were washed carefully to remove salt and



Sample point	0,0	50,0	100,0	150,0	200,0	250,0
Longitude	21.095467	21.095239	21.095022	21.094822	21.094675	21.094492
Latitude	39.199767	39.200225	39.20065	39.20114	39.201611	39.202081

Fig. 4. Showing the shoreline and sampling grid.

plant residues without disturbing the naturally-occurring composition of the sediment samples. Drying overnight followed washing to eliminate any remaining water in the sample in order to allow effective grain size distribution analyses to be conducted via standard sieve analysis. The procedure followed the methodology of Tanner and Balsillie [10]. The standardized methods developed by the American Society for Testing and Materials [11] and Wenzel [12] were used to measure the hydraulic conductivity of the unlithified sediments using a constant-head permeameter. The porosity was estimated by placing a known volume of sediment in a 500 mL graduated cylinder and adding a measured volume of water. The cylinder was gently tapped with a rubber mallet to approximate the natural packing of sand on the marine bottom. The measured volume of the sediment column was divided into the measured amount of water required to saturate the sediment, yielding an estimate of porosity.

3. Results of investigation

3.1. Site description

Preliminary observations showed a generally shallow, flat area paralleling the shoreline with a water depth not exceeding 0.5 m. The sampling grid area is shown in Fig. 4 from strip 0 to 250. Each strip was located 50 m apart and the samples were collected along a straight line from the beach seaward at 10 m increments. At sampling strip 0 (Fig. 4), there was a gradual increase in water depth from the beach to a location about 50 m offshore, where the slope increased significantly with water depths reaching 7–10 m. In the southward direction, the shallow shelf area had an expanded horizontal extend seaward with a sharp increase in slope occurring 200–250 m offshore.

The tidal range along this increment of the Red Sea shoreline is very low at only 0.15–0.3 m daily except during specific seasons when it can be greater [13]. Wave run-up along the shoreline indicates that periodic wave heights can range from 0.5 to 1 m (swash line).

Investigation of the area took place on 10 January, 2014 at about 02:00 pm which coincides with the waxing gibbous moon phase indicating an average tidal fluctuation pattern for the month. However, the sampling time was conducted at the time of low tide to assure that samples were taken from an area that will always be covered with water. Waves around these shallow areas normally do not exceed a height of 0.75 m assuming a wave breaking point of 1.5 times the depth during a windy day. Wind speeds ranged from 28.0 to 39.0 km/h [14] at time of investigation and observed wave action was relatively high which indicates a relatively well-washed shallow seabed. The wave activity creates orbital motion of water above seabed and mixes the upper part of the sediment column.

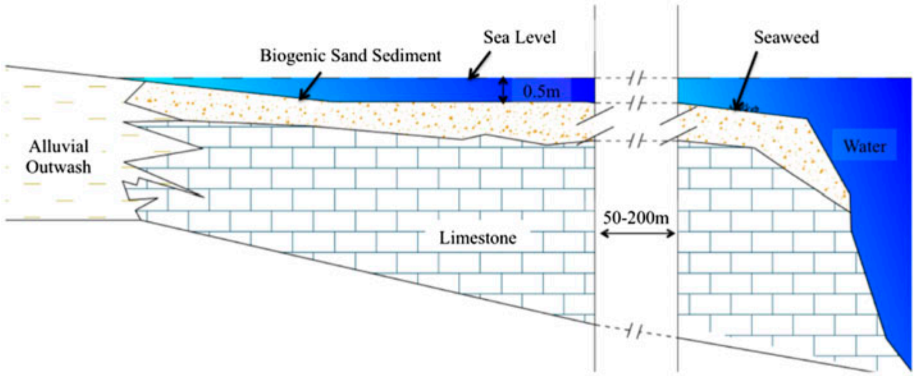


Fig. 5. Conceptual cross-section showing the geology of the shallow nearshore area at the site [15].

3.2. Geology

The geology of the site is illustrated in Fig. 5. There is a low slope of the bottom beginning at the shoreline and extending seaward for the first 100 m at most areas, such as at sampling strips 0 and 50 in Fig. 4 and up to 1,000 m southward as found in sampling strips 150–250 in Fig. 4. The water depth at the seaward extent of these transects is about 1 m, and water depth increases dramatically at the edge of the sand occurrence.

The marine sediments contain predominantly biogenic sand that is composed mostly of skeletal carbonates, such as corals, red algae, mollusks, benthic foraminifera, and others. The predominantly carbonate sand is common along the Red Sea shoreline, but is mostly a thin veneer atop the offshore hardground of the inner reef.

3.3. Sediment grain size properties

The sediment mean grain size generally ranges from 0.28 to 0.45 mm; one area had a maximum of 0.6 mm (Fig. 6). The predominant range in grain size, in the Wentworth-Udden classification, is considered as medium grain size [16,17]. This uniform distribution of mean grain size in study area and generally low mud content suggest the suitability of the site for the proposed galley intake system. This is also supported by the mean effective size distribution of 0.10–0.11 mm around the same area. Based on the data presented in the mean grain size distribution shown in (Fig. 6) the calculated mean grain size has an average of 0.37 mm.

Mud content less than 1% has also been observed from the samples (Fig. 6). Mud presence greatly affects hydraulic conductivity and porosity of the shallow marine sediments. Based on these data, the sediment can be described as predominantly well-washed medium-grain sand.

3.4. Sediment hydraulic conductivity and porosity

The measured hydraulic conductivity values range from about 2–14 m/d with a mean between 8 and 9 m/d. The lower values correspond to areas containing slightly higher mud concentrations, located mostly along the 0 transect. The porosity of the sediments is quite high with a full range from 20 to 47% with a mean near 40%. These high values are caused by the low degree of packing associated with the sediments in the marine bottom that are agitated by wave action and are bioturbated by benthic marine organisms.

4. Evaluation of subsurface intake types for a SWRO expansion

4.1. Plant expansion

There is an expansion plan to increase the permeate capacity of the plant from 10,000 to 30,000 m^3/d, which would require the development of additional raw water capacity of up to 57,000 m^3/d. There are several possible intake types that can be implemented in order to supply the raw water needed for the expansion plan. However, in this study the options are narrowed to three intake types, which are: (1) an open-ocean intake, (2) vertical wells and (3) a seabed gallery system. Even though open-ocean intakes are commonly used by most of the large-capacity desalination plants because it guarantees the ability to deliver any quantity of water required, it has some possible associated environmental impacts, such as impingement and entrainment of marine life, and requires extensive pretreatment processes to protect the membranes and reduce biofouling potential [16,17]. As a result, an overall increase in water treatment cost occurs when using an open-ocean intake. In contrast, the other two proposed intake systems can provide a better raw water quality and

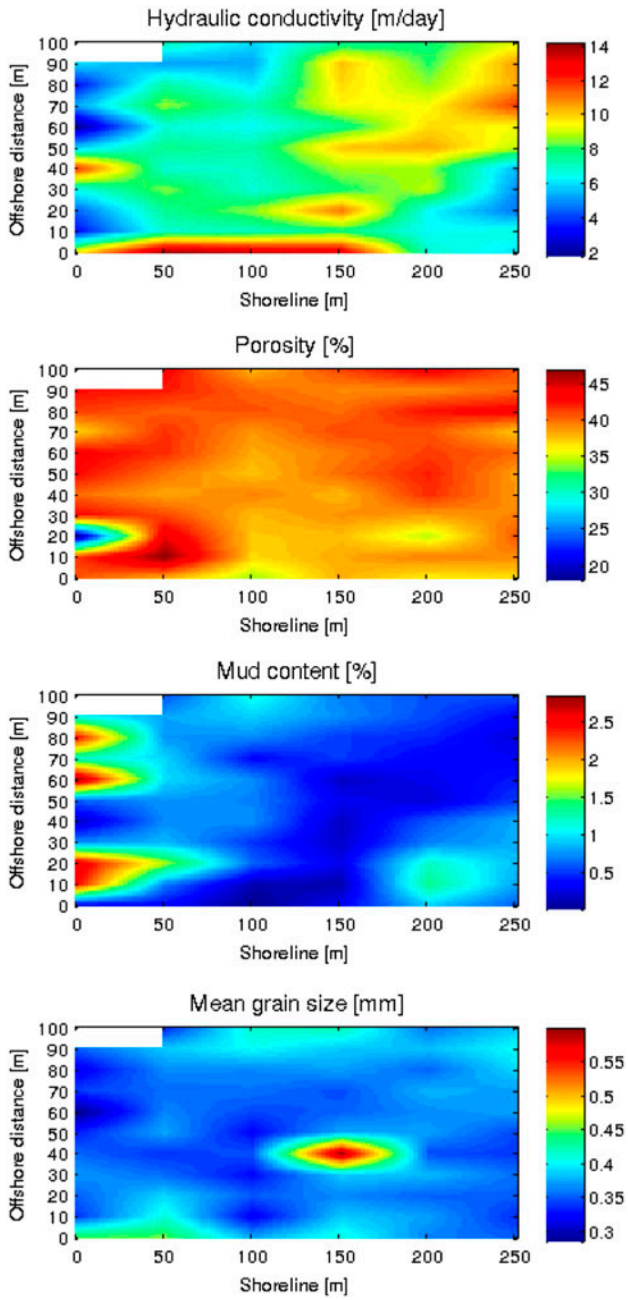


Fig. 6. Hydraulic conductivity, porosity, mud content and mean grain size distribution along the sampling area.

with significantly lower environmental impact and less use of chemicals during treatment.

4.2. Well feasibility

The plant currently produces 10,000 m^3/d of permeate with 10 wells providing a total amount of up to about 30,000 m^3/d of raw seawater with recovery rate about 35% based on the Red Sea salinity of about 42 parts per thousand [18]. The 20,000 m^3/d expansion of permeate capacity will require an additional 57,000 m^3/d of raw water, using the same recovery rate of 35%. The production rate per well is 125 m/h. Therefore, an additional 19 wells would be needed in order to supply the required amount of raw water.

The existing well system is rather unique in that an artificial peninsula was constructed atop the seabed and wells were constructed on this fill area. While it may be possible to add two new artificial-fill peninsulas and duplicate the existing system, this has both environmental impacts (e.g. filling the sea bottom near a reef complex), is expensive, and the additional of 19 wells does add some operational complexity and cost (e.g. pump replacement). The feasibility will depend on the ability to construct a new offshore system because wells located on the beach near the shoreline tend to pump higher salinity water than the Red Sea due to the presence of sabkha sediments. Further expansion of the SWRO facility in the future could be limited using the same conceptual design.

4.3. Seabed gallery evaluation

Seabed filters or galleries operate similar to a slow sand filter, but it is constructed offshore and not in an onshore plant facility. They are located in the subtidal zone so that they are continuously recharged by the vertical movement of seawater. They are self-cleaned to a degree by the wave motion and nearshore induced currents and also by bioturbation. Periodic scraping or "plowing" of the upper 5 cm of the filter top could be required to maintain the flow rate in the future. Compared to a well system, seabed gallery intake systems can be used for SWRO desalination plants of virtually any capacity [19]. Another evaluation factor is the location of the gallery and the distance from the plant. In terms of location, as shown in Fig. 3, accessibility for construction from the main road is not challenging and the location is suitable for any seabed gallery size. On the other hand, the study shows that the distance between the plant and the gallery site is about 2.6 km which will require extra construction of a large-diameter intake pipe and a pumping system that will have an operating cost of about 0.4 kWh/m^3 (Fig. 7). Nevertheless, since the expansion plan is considerably larger than the existing capacity, it may more feasible to utilize a seabed gallery than an offshore well system depending on the ability to obtain permits to construct the additional fill areas, and on the relative construction and operating costs.

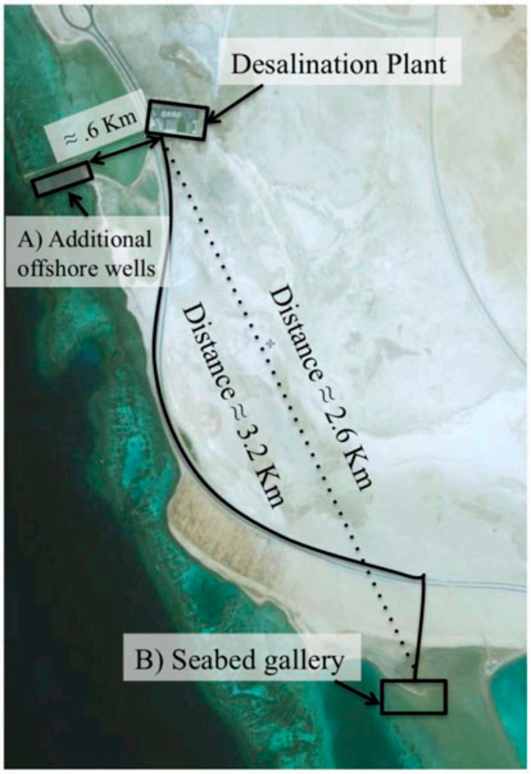


Fig. 7. Evaluation of potential intake types.

5. Seabed gallery preliminary design and assessment

5.1. Location of gallery cells

Positioning the seabed gallery can be determined based on the results of the physical studies made on the sediments, the data collected about the tidal range and the geology of the shallow nearshore of the site [20,21]. Based on the results shown in Fig. 6, it is noticeable that the mud percent is higher than average with a corresponding lower hydraulic conductivity in the area between transects 0 and 50 and decreases to <1.5% mud between transects 50 and 250. On the other hand, it is necessary for the top native sediment to be cleaned and washed out by the wave action that tends to cause oscillatory motion in the nearshore sediments. In this case the cell(s) should be placed at a location away from the steepening slope into deeper water because of possible instability and the higher cost of using a greater depth of sheet piling (Fig. 4). Therefore, the cell(s) could be located in the area between transects 50 and 250, preferably not exceeding the distance of 80 meters seaward in order to avoid construction in the deeper water (greater cost).

5.2. Design of gallery cell thickness, media, and retention time

Based on the planned future expansion permeate capacity of 20,000 m^3/d and assuming the same current conversion rate of 35%, a total gallery intake capacity of 57,000 m^3/d is required to feed the process of the plant. However, additional gallery area should be added to produce stand-by capacity to allow a greater reliability of operation. An additional 3,000 m^3/d of capacity has been added to the intake capacity to meet the emergency capacity. Therefore, the preliminary design of the gallery intake system has a normal operating capacity of 60,000 m^3/d.

One of the advantages of seabed gallery is that it is an adjustable version of the slow sand filter. While the infiltration rate for the latter ranges between 1.2 and 4.8 m/d [22] and is controlled by gravity feed, the infiltration rate for a seabed gallery is controlled by suction pressure using pumps to overcome the head loss and flow of water. A proposed cell filter design of 2.5 m thickness, starting from the native sediment at the top layer with an average mean grain diameter of 0.35 mm, followed by three intermediate layers with a gradual increase in the mean grain diameter downward ended by the gravel layer at the bottom to support and protect the slotted PVC pipes from being clogged, is suggested. The gallery follows the general methodology used in the design of slow sand filters to

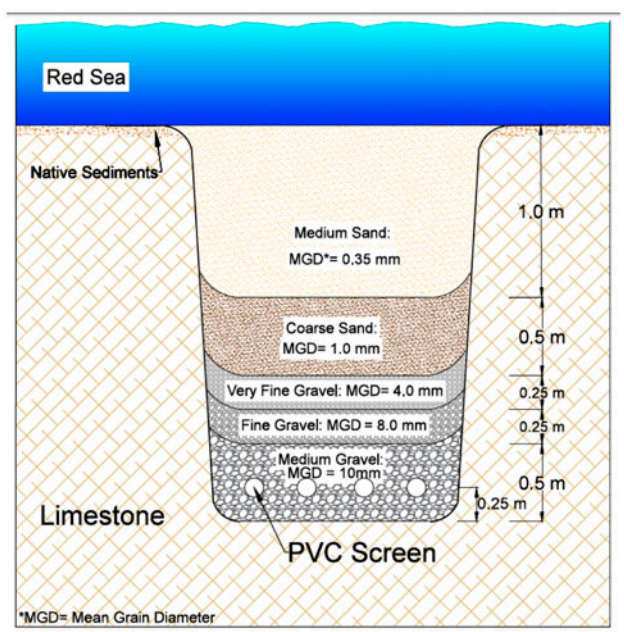


Fig. 8. Seabed gallery media layering design.

prevent infiltration of finer sand downward into the next lower layer [23] as applied to other seabed gallery designs [24] (Fig. 8).

An infiltration rate of 7 m/d was chosen in order to meet the water demand and to produce a hydraulic retention time of 8.8 h which should be sufficient to allow the system to clean the water by lowering the concentrations of organic carbon, the bacteria, and most of the marine biopolymers and polysaccharides that cause biofouling of the membranes. The 7 m/d infiltration rate, which is higher than a typical slow sand filter, will reduce the overall footprint of the gallery, in turn, reducing construction cost. A computer program was used to calculate the head loss through the filter design and showed that it is less than 1 m.

5.3. Optimization of gallery footprint

The large surface area required to develop the system is considered the biggest downside of the seabed galleries. In order to keep the footprint as small as possible, an improved design of the gallery can be achieved by increasing the infiltration rate. Consideration of the impacts of the higher infiltration must be considered because this design action may lead to a more rapid clogging rate which would require more frequent maintenance, thereby increasing the overall operating cost. However, in this study the smallest possible surface area was used with consideration of the redundancy requirements in order to secure high-quality feed seawater, while maintaining operational reliability of the whole facility.

The expansion plan will require a raw water capacity of 60,000 m^3/d and the proposed infiltration rate is 7 m/d. Therefore, the minimum required surface area is 8,571 m^2 (≈8,600 m^2). The surface area is divided into two primary galleries; each gallery would require an area of 4,300 m^2. One extra gallery cell should be added to the system in order to provide emergency capacity in the event of a pipeline or pump failure. In this case the total gallery area would be 12,900 m^2 ($3 \times 4{,}300$ m^2). Based on three cells of 215 m × 20 m each and 50 m separation distance between the galleries to avoid interference, the total required area for construction would be 15,000 m^2. Each gallery cell would be equipped with a separate pump. This configuration yields redundancy and an ability to operate all cells at a lower infiltration rate during periods of poor water quality to eliminate plant shutdowns and the need to use expensive pretreatment processes (Fig. 9). After acquiring operating experience, the third cell could be used to obtain a greater quantity of feed water for a future SWRO plant expansion.

5.4. Flow balance to create uniform filter infiltration

At the bottom of the cell the gravel and the piping system are found. The piping system consists of PVC pipes containing a high density of slots with apertures between 3 and 4 mm in width. The pumps pull water through this drain system to create infiltration through the gallery cells. The gravel layer is meant to provide support to the piping system by maintaining the pressure through the filter as well as to permit free flow of the water from the upper layers to the pipes without any kind of sediment passage. As shown in Fig. 8 above, the bottom gravel layer is proposed to have a mean grain diameter of 10 mm. This is large enough to avoid blocking the slots of the pipes and to allow uniform flow of the water to the piping system. Further, the design of the underdrain system will use the flow balancing scenario of gallery design as suggested by Mantilla and Missimer [20] to maintain an equal head loss in the screen, thereby producing a uniform infiltration rate at the surface of the gallery cells. This is an important issue, because if the flow is not uniform there could be high-velocity "patches" that could cause clogging problems.

5.5. Operational flexibility

It is important for the intake system to guarantee the stability of providing the required amount of water to the SWRO facility under any circumstances, such as during algal blooms or after tsunami or earthquake events. For that, the seabed gallery system was divided into three cells, where two of them would be used as the primary water supply and the third one will be as necessary. During an algal bloom the infiltration rate could be reduced and all three cells could be used to produce the desired feed water supply. This allows the system to operate on any two of the three cells or all three. In order to enhance the flexibility of the system, each gallery would have a separate pipeline and pump with a flow meter and variable frequency drive (VFD) control. All three pumps would be located at the pump station and the discharge pipes would be connected to each other by valves so that it is possible to shift from one pump to another in case of any pipe damage or pump failure. The VFD will allow the pumping rate to be maintained during tide changes or as minor clogging occurs over time. Monitoring of the pumping heads will allow gallery performance to be continuously assessed. If higher suction heads are required to maintain the desired flow rates, this data could be used to trigger maintenance activity (e.g. raking the gallery cell or removing 5–10 cm of the uppermost sand layer and replacing it).

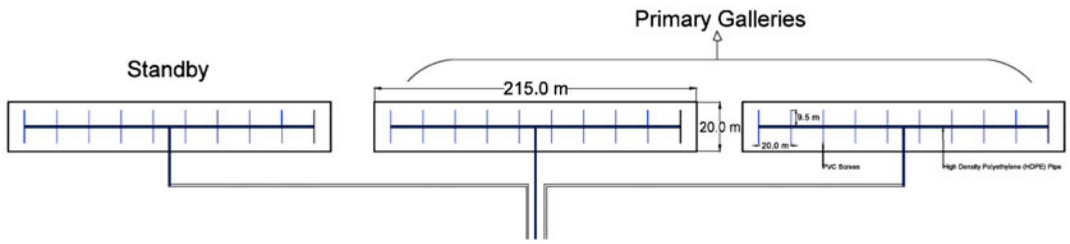


Fig. 9. Conceptual design of the cell group.

The standby gallery could be used simultaneously with the other two primary galleries to reduce infiltration rate or a rotational use of the gallery cells could be used to allow sufficient time for marine infauna to clean the uppermost layer of a gallery cell (bioturbation).

6. Discussion

The goal of this research was to assess the feasibility of using a subsurface intake to obtain the full raw water requirements of a 30,000 m^3/d SWRO facility (10,000 m^3/d current and 20,000 m^3/d expansion). An open-ocean intake is always an option, but it has issues associated with possible impacts to the marine environment caused by impingement and entrainment and has a high treatment costs caused by the extensive pretreatment process train [18,19]. Expansion of the existing well system was evaluated along with a new seabed gallery system. Subsurface intakes mitigate some of the environmental impacts of open-ocean intakes and would provide a better raw water quality.

Subsurface intake systems, vertical offshore wells or seabed galleries, can reduce or eliminate entrainment and impingement of marine organisms and reduce chemical use for pretreatment [6,25,26]. The study shows that an additional 19 wells would be needed in order to supply the 57,000 m^3/d of raw water needed for the 20,000 m^3/d SWRO plant expansion. In this case, the cost for construction and testing of the large number of wells with the additional pumps and its operation and maintenance cost makes the wells feasible, but may not be the most economical solution. The existing well system is rather unique in that an artificial peninsula was constructed into the Red Sea by filling an area of the inner reef hardground. Then, wells were constructed on this new land. Expansion of this system would require the construction of two additional alignments of wells into the Red Sea and would add 19 wells with pumps and perhaps one additional well and pump for backup capacity. The cost of the environmental impact assessment, construction of the fill areas, and the operation of an additional 20 pumps are high. The other subsurface option considered is the design and construction of a seabed gallery system which was evaluated at the site and was found to be technically feasible. Seabed gallery intakes have an advantage over well systems in that they can yield greater quantities of raw water. A seabed gallery intake system with a capacity of 103,000 m^3/d has been used successfully at the Fukuoka desalination facility in Japan for the past nine years [26]. Perhaps the final choice between expansion of the well system and the addition of a seabed gallery system at this site should be based not only on the capacity of the proposed expansion, but on possible future expansions that could not be met using the well system.

When proposing the use of a seabed gallery system, the key concern would be is the economics of construction of the proposed design. Environmental impacts of the seabed gallery would be very temporary, during construction, and if the upper layer of sand would have to be raked or replaced, some impacts could occur during maintenance. During operation there would be no impacts. Construction of the seabed filter at this site would require use of sheet-piling and dewatering to install the filter material and piping. A temporary access road could be constructed to the offshore construction site with removal after installation of the gallery cells. Because the well system would also require filling of the marine environment, the two projects may have capital costs that are quite similar. Another consideration is the distance from the SWRO plant site to the seabed gallery site which is about 2.6 km. This will require some additional pumping cost and the cost of the large-diameter pipeline. Based on the complexity of the two subsurface intake types, a full life-cycle cost analysis would be required to assess which option would be the most economical design solution and the issue of future expansion should be included in this analysis. It is highly likely that either subsurface intake option will be more economical compared to the use of an open-ocean intake based on a 20 or 30 year life-cycle cost analysis [6].

7. Conclusions

The purpose of this research was to evaluate a site on the Red Sea south of Jeddah, Saudi Arabia to assess the feasibility of using a subsurface intake system to expand an existing SWRO facility from a permeate capacity of of 10,000 m3/d to a future capacity of 30,000 m3/d. Two viable options were found; expansion of the existing offshore well system or development of a seabed gallery intake to provide the required 57,000 m^3/d of raw seawater. Both options were found to be technically feasible and superior to using a conventional open-ocean intake.

Expansion of the offshore well system would require the construction of two new offshore artificial-fill peninsulas and construction of 19 primary wells and one standby well. The geologic conditions assessed on and near the site show that a seabed gallery intake system could be constructed at a site located about 2.6 km away from the SWRO facility. It is concluded that use of either subsurface intake option is feasible, but if a substantial capacity expansion is planned for the future, then the seabed gallery option would be the most economical design solution. Also, the operating cost of SWRO treatment would be much lower comparing either subsurface option to a conventional open-ocean intake system.

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References

[1] A.S. Alsharhan, Z.A. Rizk, A.E.M. Nairn, D.W. Bakhit, S.A. Alhajari, Hydrogeology of an Arid Region: The Arabian Gulf and Adjoining Areas, Elsevier, Amsterdam, 2001, 331 p.
[2] World Bank, Making the Most of Scarcity: Accountability for Better Water Management in the Middle East, World Bank, Riyadh, 2010.
[3] N. Ghaffour, T.M. Missimer, G.L. Amy, Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability, Desalination 309 (2013) 197–207.
[4] A. Berktay, Environmental approach and influence of red tide to desalination process in the Middle East region, Int. J. Chem. Environ. Eng. 2(3) (2011) 183–188.
[5] T.M. Missimer, Water Supply Development for Membrane Water Treatment, Aquifer Storage, and Concentrate Disposal for Membrane Water Treatment Facilities, second ed., Schlumberger Water Services, Sugar Land, TX, 2009, 390 p.
[6] T.M. Missimer, N. Ghaffour, A.H.A. Dehwah, R. Rachman, R.G. Maliva, G. Amy, Subsurface intakes for seawater reverse osmosis facilities: Capacity limitation, water quality improvement, and economics, Desalination 322 (2013) 37–51.
[7] R. Rachman, T. Merle, S. Al-Mashharawi, T.M. Missimer, Removal of algae, bacteria, and organic carbon by the beach well intake system at Sur, Oman Seawater RO Facility, Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse, Tianjin, China, IDA TIAN13-227, 2013, 9 p.
[8] A.H.E. Dehwah, S. Li, S. Al-Mashhawari, R.M. Rachman, H. Winters, T.M. Missimer, The influence of beach well and deep ocean intakes on tep reduction in swro desalination systems, Jeddah, Saudi Arabia, Proceedings, American Membrane Technology Association/American Water Works Association, 2014 Membrane Technology Conference & Exposition, Las Vegas, NV, 2014.
[9] T. Berman, R. Mizrahi, C.G. Dosoretz, Transparent exopolymer particles (TEP): A critical factor in aquatic biofilm initiation and fouling on filtration membranes, Desalination 276 (2011) 184–190.
[10] W.F. Tanner, J.H. Balsillie, Environmental Clastic Granulometry, Florida Geological Survey Special Publication, vol. 40, 1995, 142 p.
[11] American Society for Testing and Materials (ASTM), Standard Test Method for Permeability of Granular Soils, Standard D2434-682006, American Society for Testing and Materials, ASTM, West Conshohocken, PA, 2006, 5 p.
[12] L.K. Wenzel, Methods for Determining the Permeability of Water-bearing Materials with Special Reference to Discharging well Methods, U.S. Geological Survey Water-Supply Paper 887, 1942, 192 p.
[13] Available from: http://easytide.ukho.gov.uk/EASYTIDE/EasyTide/SelectPort.aspx, accessed on January 30, 2014.
[14] Available from: http://www.windguru.cz/, accessed on January 30, 2014.
[15] A.H.A. Dehwah, T.M. Missimer, Technical feasibility of using gallery intakes for seawater RO facilities, northern Red Sea coast of Saudi Arabia: The King Abdullah Economic City site, Desalin. Water Treat. 51 (34–36) (2013) 6472–6481.
[16] T.M. Missimer, Water supply development, aquifer storage, and concentrate disposal for membrane water treatment facilities, Methods in Water Resources Evaluation Series No. 1, Houston, Schlumberger Water Services, Sugar Land, TX, 2009.
[17] T.M. Missimer, R.G. Maliva, M. Thompson, W.S. Manahan, K.P. Goodboy, Reduction of seawater reverse osmosis treatment costs by improvement of

raw water quality: Innovative intake designs, Int. Desalin. Water Reuse Q. 20(3) (2010) 12–22.
[18] Available from: http://www.sawaco.com/Sojeco.html, accessed on March 10, 2014.
[19] A.H.A. Dehwah, T.M. Missimer, Technical feasibility of using gallery intakes for seawater RO facilities, northern Red Sea coast of Saudi Arabia: The King Abdullah Economic City site, Desalin. Water Treat. 51 (34–36) (2013) 6472–6481.
[20] D. Mantilla, T.M. Missimer, Seabed gallery intake technical feasibility for SWRO facilities at Shuqaiq, Saudi Arabia, J. Appl. Water Eng. Res. (2014). doi:10.1080/23249676.2014.895686.
[21] K. Sesler, T.M. Missimer, Technical feasibility of using seabed galleries for seawater RO facility intakes and pretreatment: Om Al Misk Island site, Red Sea, Saudi Arabia, IDA J. Desalin. Reuse 4(4) (2012) 42–48.
[22] J.C. Crittenden, R.R. Trussel, D.W. Hand, K.J. Howe, G. Tchobanoglous, Water Treatment: Principle and Design, second ed., John Wiley & Sons, Inc., New York, NY, 2005, 1948 p.
[23] L. Huisman, W.E. Wood, Slow Sand Filtration, World Health Organization, 1974, 122 p.
[24] L.R. Lujan, T.M. Missimer, Technical feasibility of a seabed gallery for SWRO facilities at Shoabia, Saudi Arabia and regions with similar geology, Desalin. Water Treat. (in press). doi:10.1080/19443994.2014.909630.
[25] T. Hamano, H. Tsuge, T. Goto, Innovations perform well in first year of operation (Fukuoka SWRO), Desalin. Water Reuse Q. 16(1) (2006) 31–37.
[26] A. Shimokawa, Fukuoka District desalination system with some unique methods, International Desalination Intakes and Outfalls Workshop Proceedings, National Centre of Excellence in Desalination, Adelaide, South Australia, May 16–17, 2006.