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Technical feasibility of a seabed gallery system for SWRO facilities at Shoaiba, Saudi Arabia, and regions with similar geology

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ABSTRACT

Subsurface intakes can be used as part of the pretreatment system for seawater reverse osmosis facilities. Wells of various designs and galleries are being used for intakes at many sites globally to reduce pretreatment costs, chemical usage, biofouling potential, and environmental impacts (entrainment and impingement). The goal of using a subsurface intake is to reduce or replace conventional pretreatment processes. A field and laboratory investigation was undertaken to assess the feasibility of developing a seabed gallery intake offshore near the Shoaiba seawater RO (SWRO) plant site (150,000 m^3/d treatment capacity) that could be used to replace the current intake used for only the RO capacity. A survey of the beach and offshore area was made and 51 sediment samples were collected from the seabed for laboratory analysis of grain size distribution, porosity, and hydraulic conductivity. Field observations showed that the marine bottom has a low slope from the shoreline seaward a distance of about 100 m to a depth of about 1.0 m before it steepens to a depth of over 2 m at 150 m from shore. The site has a relativity thin cover of unlithified carbonate sands, 2–5 cm thick, sitting on a soft coralline limestone of Pleistocene age. The sediments investigated were found to be clean carbonate or slightly muddy carbonate sands with mean grain diameters ranging mostly between 0.25 and 0.5 mm. Most of the area investigated contained a mud percentage between 0 and 5%. The measured porosity values range between 0.33 and 0.45 and measured hydraulic conductivity values from about 1.6 to 79.5 m/d with 64.6 m/d being the maximum offshore value. A preliminary design was developed to meet the full operational capacity of the Shoaiba SWRO treatment plant which would require 375,000 m^3/d of raw water to produce 150,000 m^3/d of permeate (40% conversion assumed for Red Sea water with a TDS of 41,000 mg/L). The design of the RO plant uses 10 trains to produce the 150,000 m^3/d of product, but at full operational efficiency, only nine trains would produce the required capacity. The engineered gallery design included five layers with a total thickness of 3 m. The proposed infiltration rate is 7 m/d with the possibility of increasing it to 10 m/d. The gallery design consists of 10 cells (one for each train) producing 42,000 m^3/d each. The cells have dimensions of 30×200 m and an aggregate area of 60,000 m^2. It is believed that use of the seabed gallery at this site is feasible and would reduce environmental impacts by eliminating impingement and entrainment of marine organisms, the use of chlorine in the process, the use of coagulants in the pretreatment filtration process, the disposal of marine debris and coagulant sludge, and may eliminate the need for use of any additional pretreatment before the cartridge filters.

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Keywords: Seawater reverse osmosis; Intake; Seabed gallery; Red Sea; Sediment properties

1. Introduction

Growth in the global use of seawater desalination to provide water supplies necessitates innovation in the design and operation of facilities to reduce energy consumption and lower costs. Seawater desalination is an energy intensive process and any improvements in the process design and operation of full facilities will help achieve lower energy consumption with a corresponding reduction in cost. A key part of all seawater reverse osmosis systems is the intake.

The purpose of the intake is to provide adequate and consistent flow of feed water into the plant [1]. Obtaining feed water of reliable and consistent quality is a challenge in plant design. Water entering the primary desalination process should have low concentrations of suspended solids, particulate material, dissolved organic matter, and a consistent inorganic chemistry [2]. Feed water characteristics determine the design and performance of downstream desalination processes [3]. Intakes that provide high-quality water have many advantages, including protection of the downstream equipment, improving process performance, and reducing the operating cost of both the pretreatment and primary process equipments [4].

The importance of the intake system for desalination plants is commonly underestimated because of the typical simplicity in design and the practice of copying existing open-ocean intake types. Intake structures typically cost up to 20% of the entire facility cost and, in particular circumstances can cost up to 50% of the total facility cost (e.g. Australia seawater RO (SWRO) facilities) [5]. The type of intake used for a SWRO facility influences the potential environmental impacts, pretreatment processes, use of chemicals, and the overall operational costs for a facility.

Subsurface intakes tend to provide a higher quality feed water that requires less intense pretreatment and use of chemicals [1,4]. Subsurface intakes provide robust physical and biochemical treatment processes that can be considered to be part of the pretreatment process. Filtration reduces the concentration of suspended solids, and algae, bacteria, while the biochemical processes reduce the concentration of organic carbon and other organic compounds that promote membrane biofouling [6]. Successful design and construction of a subsurface intake is dependent on the local hydrogeology of the coastal and nearshore areas of the site under consideration.

The Red Sea coastline of Saudi Arabia is a region of heavy development of seawater desalination facilities with capacities ranging from 10,000 to over 1,000,000 m^3/d, with the facility at Shoaiba being the world's largest in terms of capacity having combined thermal and membrane systems. This facility currently utilizes a common intake for the power plant for both the thermal desalination and reverse osmosis desalination facilities. The freshwater production capacity of the thermal process is 880,000 m^3/d and the reverse osmosis production capacity is 150,000 m^3/d for a total of 1,030,000 m^3/d. It is the purpose of this research effort to develop a design concept for a subsurface intake and ascertain the feasibility of constructing this design for the Shoaiba site located along the Red Sea of Saudi Arabia (Fig. 1).

2. Methods

A field investigation was conducted to characterize the nearshore geology and sediment properties of the Saudi Arabian coast of the Red Sea from Thuwal south to Al-Qunfudah, a distance of about 370 km. Sediment samples were collected and inspected from the shoreline and the shallow offshore areas. Data collected from this preliminary coastal assessment were used to select a site for detailed analysis to investigate the feasibility of developing some type of subsurface intake system that could be used as an intake for a SWRO plant.

A detailed site investigation was conducted immediately north of the Shoaiba power and desalination site (not on the facility site). A sampling area of 400 × 150 m was mapped using five transects oriented perpendicular to the shoreline with each transect spaced at a distance of 100 m apart with a seaward extension of 100 m (Fig. 2). The grid pattern was set with a point of origin at latitude 20°41´39.07´´N and longitude 39°30´21.67´´E. The sampling was stopped on the outside of the coral reef tract where the density of coral was very low. At each of the 51 sampling sites, the water depth was measured and the thickness of unconsolidated sediment was measured by using a probe iron that penetrated the bottom until a shallow rock unit was encountered.

The sediment samples were analyzed in the laboratory to determine the grain-size distribution, porosity, and hydraulic conductivity. The grain-size distribution was measured using standard sieving techniques with

Fig. 1. Shoaiba power and water plant facility, and the nearshore sampling location, Red Sea, Saudi Arabia.

Fig. 2. Sediment sampling grid for the Shoaiba site field investigation.

34 sieve increments to provide the maximum amount in detail [7]. The porosity was measured by filling a graduated cylinder with a known quantity of water and then adding at least 300 cc of sediment into the cylinder. The cylinder was tapped lightly on the exterior with a rubber mallet to consolidate the column to a compaction similar to that occurring in nature. The volume of water and sediment were measured and the sediment volume was divided into the water volume to determine the porosity. The hydraulic conductivity of the sediments was measured using a standing head permeameter following standard laboratory techniques [8,9].

3. Investigation results

3.1. Site geology

The site geology shows a thin veneer of predominantly carbonate sediment lying upon a relatively soft limestone unit, similar to that previously described from other investigations of the Red Sea shoreline [10]

(Fig. 3). Sediment thickness ranges from 0 to 17 cm (Fig. 4). The sediment consists of a mix of skeletal grains, predominantly grains of coral, coralline algae, mollusks, and foraminifera, and non-skeletal carbonate grains (mostly peloids) with some siliciclastic grains, particularly in the nearshore area.

3.2. Sediment grain size properties

The sediments have a mean grain diameter, most commonly, ranging between 0.25 and 0.5 mm, which is classified as medium sand under the Wentworth-Udden scale (Fig. 5) [11]. There is a general trend of change in the mean grain diameter with the largest diameters occurring along the shoreline, a fine nearshore belt close to the beach, and a general seaward coarsening trend (Fig. 6). Also, the effective diameter of the fine-fraction of the sand (d_{10} = mean of the finest 10% of the sediment) increased in diameter moving seaward. The sediment uniformity coefficient, as defined by Punmia and Jain [12], tends to follow the observed changes in the mean grain diameter, but becomes quite uniform at about four moving seaward from 60 m offshore (Fig. 7).

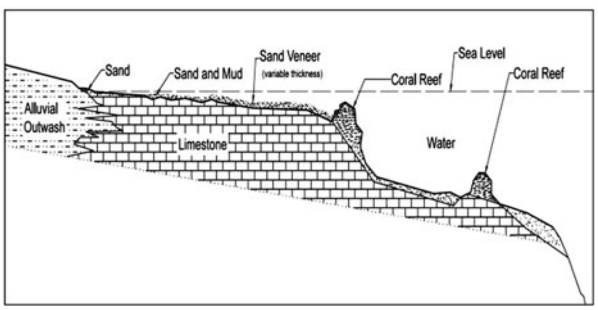

Fig. 3. Nearshore sediment facies along portions of the Red Sea shoreline [10].

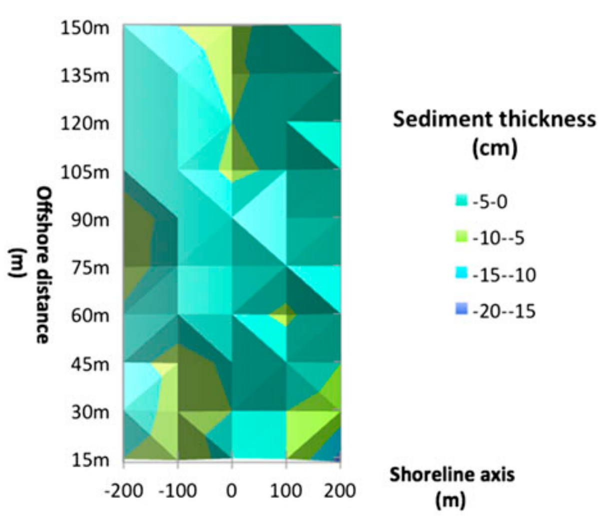

Fig. 4. Spatial variation in unconsolidated sediment thickness at Shoaiba site.

The fraction of mud in the sediment affects the hydraulic properties of unconsolidated sediments. Mud is defined as that part of the sediment that passes through the 0.0625 mm screen and includes silt- and clay-sized particles. Most of the samples contain less than 5% mud, but the southern part of the sampling grid does contain some values up to 15% (Fig. 8).

3.3. Sediment hydraulic conductivity and porosity

There is a wide range in the measured hydraulic conductivity from 2 to 80 m/d (Fig. 8). There is a relationship between the percentage of mud in the sediment and the low values of hydraulic conductivity with some skewing of the values as shown in Fig. 8, because the hydraulic conductivity of several samples with mud content above 10% could not be accurately measured. A general trend for increasing hydraulic conductivity from near the shoreline towards the offshore area was observed. There is also a relationship between the hydraulic conductivity and the mud percentage as can be clearly observed in Fig. 9.

Measured laboratory porosity values varied between 0.34 and 0.46. There was an observed trend of generally increasing porosity from nearshore to offshore in the sediments (Fig. 10).

3.4. Seafloor, tidal properties, and wave activity

The seafloor gently slopes seaward from a depth of 0 to a depth of about 1 m at about 100 m from the shoreline and the slope increases slightly with a water depth of 2 m occurring at about 150 m offshore. The diurnal tide range at Shoaiba ranges from 0.25 to 0.6 m (neap and spring tide average amplitude) [13]. A maximum seasonal tide is 0.9 m in this area of Saudi Arabia [14]. Wave action is relativity low ranging from 0.5 cm at the shoreline to about 15 cm at a distance of 150 m offshore (observed). Sand ripples were observed on the offshore bottom and relatively high-water turbidity occurs immediately adjacent to the shoreline.

3.5. Benthic fauna and flora: Environmental sensitivity

The offshore bottom consists of carbonate sand and some areas of bare carbonate rock to a depth of about 2

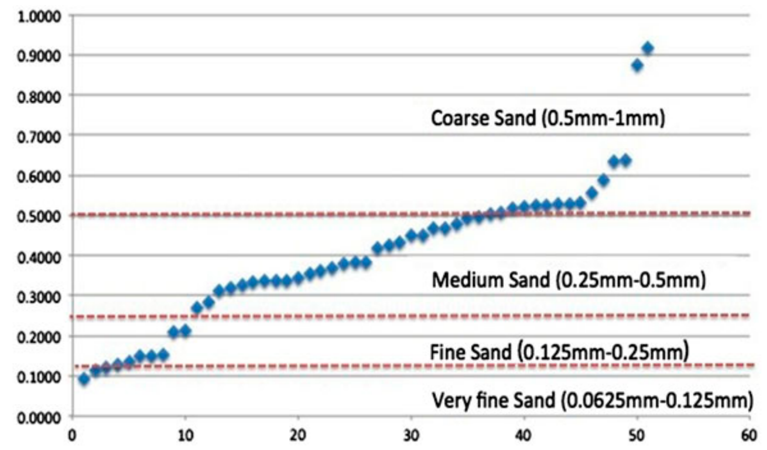

Fig. 5. Mean grain diameter of the sediment samples compared to the Wentworth-Udden scale.

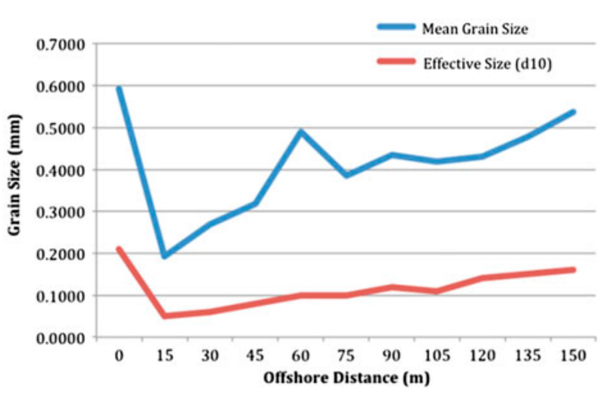

Fig. 6. Mean grain diameter (mm) and d_{10} diameter variations with distance offshore (m).

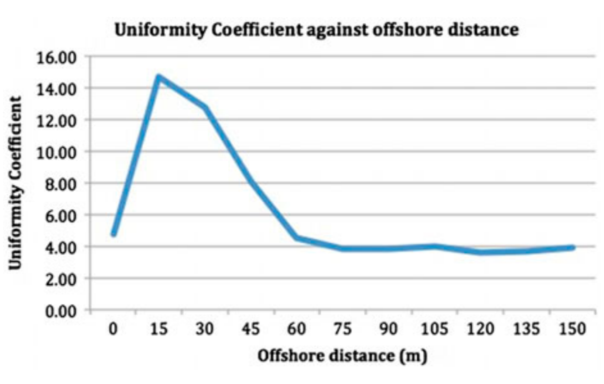

Fig. 7. Uniformity of unconsolidated sediment on seafloor at Shoaiba.

m within the sampling grid. A sparse cover of marine grass grows within in this area, but no living coral colonies were observed. The marine vegetation occurs mostly in the nearshore muddiest area and not within the area of the sandy bottom. Coral occurrence becomes denser in water depths greater than 2 m and is quite dense to the north of the sampling grid. The area is not considered to be environmentally sensitive based on the lack of coral and marine vegetation covers.

4. Feasibility and preliminary gallery design

4.1. General site feasibility

Based on the observed site conditions and the large feedwater requirement for the Shoaiba II SWRO facility, the feasibility of various subsurface intake options were assessed. The use of conventional beach wells is unlikely to be feasible because of the generally shallow thickness of the limestone in this area and the very large number of wells that would have to be used. Horizontal wells may be feasible, but there would be significant risk associated with a lack of detailed offshore geologic information and the sensitivity of offshore reefs. A beach gallery system would not be feasible because of the low-wave activity and the propensity of high turbidity to occur in the very shallow water. The use of a seabed galley intake system was determined to be feasible and the best option to use for the high volume of water production necessary to feed the Shoaiba II facility.

4.2. Gallery cell design

The best location for construction of a seabed gallery system is in the offshore area containing a barren sandy bottom, little seagrass and coral, low mud content, and the highest values of hydraulic conductivity of the sediments (Fig. 11). While the preliminary investigation shows that the design and construction

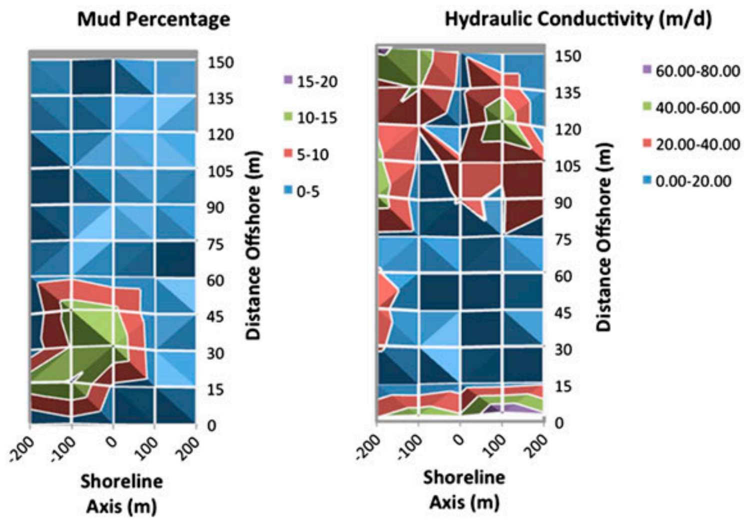

Fig. 8. Spatial variation in the percentage of mud and the hydraulic conductivity of the unconsolidated sediments.

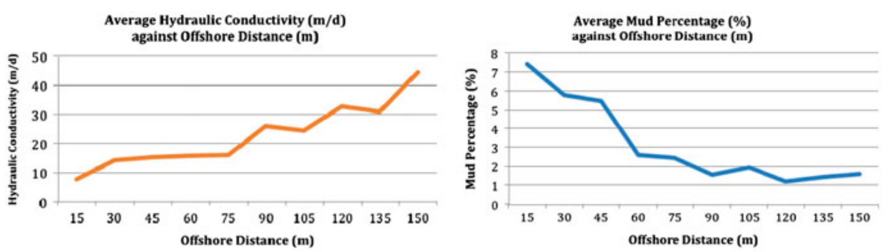

Fig. 9. Comparison of variation in average hydraulic conductivity and mud percent from the shoreline towards the offshore direction.

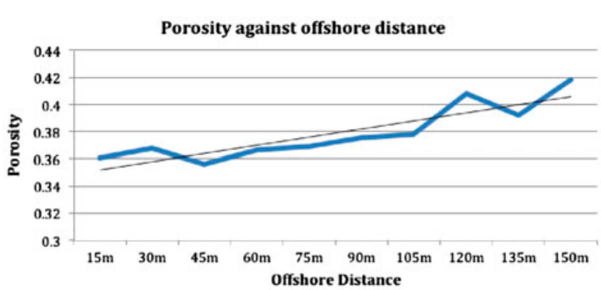

Fig. 10. Variation in porosity with distance from the shoreline seaward.

of a seabed gallery intake system is feasible, additional field investigation would be required including increasing the area of investigation to cover the full footprint of the facility, and test borings need to be made into the underlying limestone to test its properties for construction assessment.

Seabed gallery design incorporates an inclusive analysis of native sediment characteristics, conventional slow sand filter design guidelines, feed water quality requirements, seawater quality in the vicinity of the gallery, and flexibility of RO plant operations. The selected approach assumes that one gallery cell will feed one RO train. In the event that not all trains are operating simultaneously, the flow from the full gallery system could be reduced to produce the required feed water (reduced flow), but at a lower infiltration rate. The permeate production capacity of each RO train is 16,800 m^3/d and at a recovery rate of 40% (Red Sea TDS at this location is about 42,000 mg/L), requires a feed water source capacity of 42,000 m^3/d. The design infiltration rate would be 7 m/d over an area of 6,000 m^2.

The gallery cell dimensions would be 30 by 200 m with the landward boundary of the cells placed at 90 m offshore and not exceeding 120 m offshore within the general grid shown in Fig. 12. The native sediment in this area has a low percentage of mud and characteristics common to those typically used in slow sand filter media, including similar effective size, uniformity, and hydraulic conductivity.

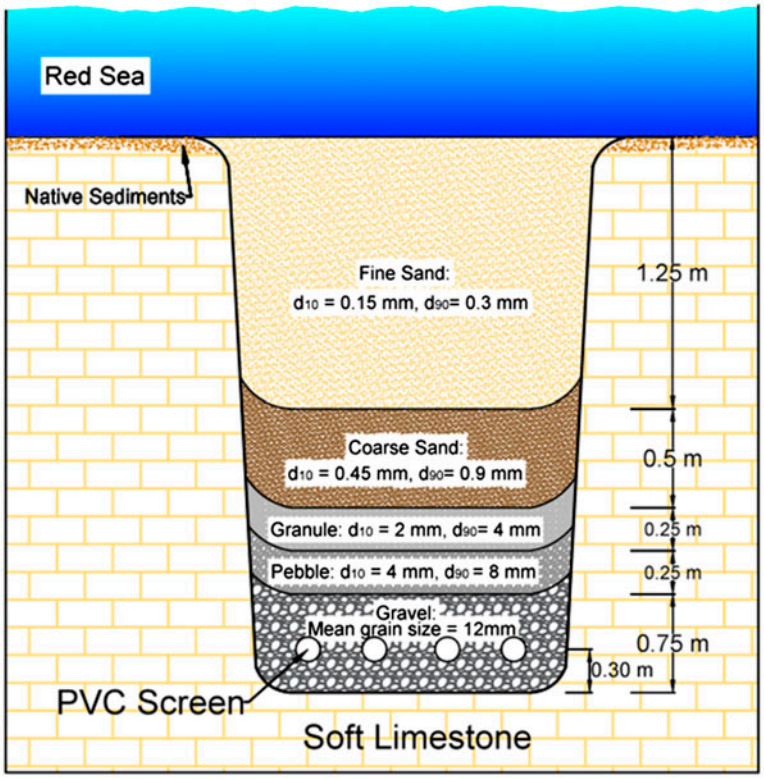

Fig. 11. Seabed gallery filter media layering design.

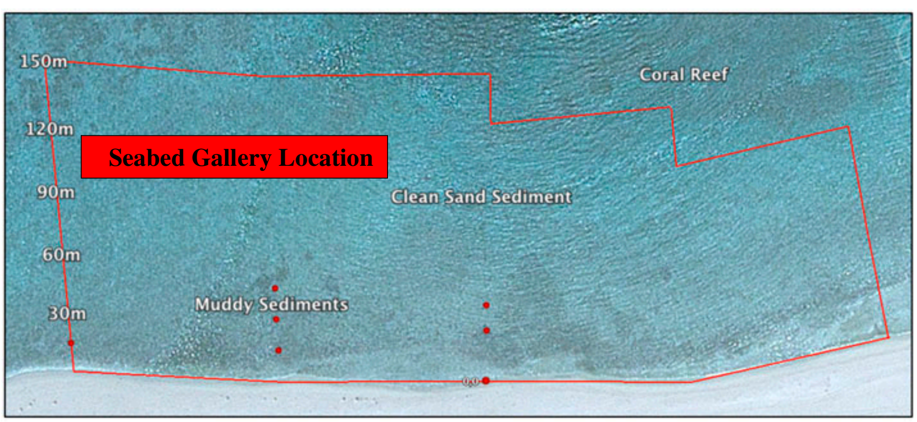

Fig. 12. Proposed boundaries for location of a seabed gallery intake system at Shoaiba.

Native marine sand at the site has insufficient thickness to provide enough material to create the top layer of the gallery filter. It is proposed to use rounded or sub-rounded quartz sand, having similar hydraulic properties to the native sand for filter construction. In the event that wave action or storm activity causes the deposition of some native sand atop the filter, it will have no effect on the media hydraulic conductivity and overall filter operation.

The selection of 7 m/d as the infiltration rate was determined by the media hydraulic properties, the number of media layers proposed, the overall filter thickness, and the calculated head loss across the filter. A computer program was used to assess a number of layer thickness and media configurations, all within the general design criteria set for slow sand filtration, to obtain the optimum design. While the proposed infiltration rate is higher than the normal recommended slow sand infiltration rate of 5.3 m/d [15], it is below many systems that operate continuously at up to 10.8 m/d [16].

4.3. Preliminary filter design

The proposed filter design is 3 m thick containing an upper fine layer, three intermediate layers, and a coarse lower layer (Fig. 11). Mean grain size of each layer increases progressively downward in the filter providing an overall retention time of over 10 h. This time is sufficient to allow the active biological processes in the filter to remove bacteria that are not removed in the upper few cm, to lower the concentration of organic carbon, and to remove most of the marine biopolymers and polysaccharides that lead to biofouling of membranes.

Gradation of the filter media is an important design principle because it prevents fine sediment infiltration from upper layers into lower layers and provides good hydraulic fluid flow through the filter. Abrupt changes in grain size between layers could create fluid velocity imbalances in the filter causing internal head differences leading to downward sediment movement. Each layer is composed of carefully graded sand with d_{10} and d_{90} values within the layer not varying more than a factor of two. In order to follow this grain size ratio, subsequent layers have effective sizes restricted to three times of that within the overlying layer [16]. The upper layer is designed to have a thickness of 1.25 m of fine sand with a d_{15} of 0.15 mm and a d_{90} of 0.3 mm. These values are in the range of recommended values for slow sand filter media [17]. Use of fine sand is most effective to enhance the layer of the filter that has the most effect on mechanical filtration processes that remove algae, bacteria, and viruses [16,18].

Removal of debris, inorganic sediments, and biologically active breakdown of organic matter would be expected to occur in the first 40 cm (most in the upper 10 cm). It is unknown if a schmutzdecke will form on top of the upper layer of seabed filters within the marine environment (all data on formation of this layer comes from freshwater systems). Below this depth, a zone of similar thickness is located where the organic residuals would be further oxidized and chemically degraded. Clogging of the uppermost layer may occur over a period of years and require disturbance or removal of 2–5 cm of sand. However, the operation of the Fukuoka, Japan, seabed gallery has required no cleaning after 8 years of operation which is the likely result of wave and current stirring of the sediment and bioturbation (benthic marine organisms eating the organic compounds in the sediment and creating hard, rounded fecal pellets) [19].

Coarse sand serves as an intermediate layer between the fine sand media and the supporting gravel base media. This layer would have a depth of 0.5 m with a $d_{10} = 0.45$ mm and a $d_{90} = 0.9$ mm (three times larger than the layer above). Both sand layers meet the design criteria of having a total sand depth more than 1,000 times its effective size (d_{10}) [20] (Table 1).

The uppermost layer of gravel following the coarse sand layer is recommended to have a d_{10} value in the range of four times greater than that of the d_{15} value in the sand layer and less than four times greater than the d_{85} of the same sand layer. Following this recommendation, the d_{10} for the uppermost gravel layer was set to be 2 mm. For the additional coarser gravel layers it is recommended to double the grain size from one layer to the next one in order to provide long-term stability to the filter [21].

The second gravel layer in turn would have a d_{10} of 4 mm and a d_{90} of 8 mm. The first two gravel layers would have a thickness of 0.25 m. The thickness value is designed to be larger than the recommended minimum range of 5–12 cm to minimize the probability of insufficient layer thickness in a relatively large filter cell area.

At the bottom of the filter, the gravel layer and piping system are found. Gravel in this layer is designed to have a mean grain size diameter of 12 mm which is large enough not to obstruct the slots in the infiltration screens and permit uniform drainage into the piping system. No grains in the bottom layer should be smaller than 8 mm to prevent the obstruction of the 4 mm screen slots. The screens are placed at a height of 30 cm up from the base of the filter.

The importance of proper base layer design is not only to support the seabed filter and drain system, but also to permit the free flow of filtered water towards

Table 1
Design specifications for the seabed gallery filter design

Filtration media	Thickness (m)	d_{10}	d_{90}
Fine Sand	1.25	0.15 mm	0.3 mm
Coarse Sand	0.5	0.45 mm	0.9 mm
Granular Gravel	0.25	2 mm	4 mm
Pebble Gravel	0.25	4 mm	8 mm
Gravel underdrain	0.5	Mean grain size = 12 mm	

piping without any kind of granular migration. A low-permeability geofabric layer could be installed at the base and the sides of the excavated area in order to prevent the intrusion of fine-grained sediments into the filter, but could create a condition leading to internal biofilm creation. Therefore, grading of the sediment is preferred over the use of a geofabric. Preventing the piping system from becoming clogged by granular material from upper layers is of extreme importance as any problem in the base layer cannot be inspected, cleaned, or repaired without a major disturbance to the bed as a whole.

4.4. Hydraulic head loss across filter during pumping

The pump suction head required to operate the seabed gallery is determined by the hydraulic conductivity of the media layers and the total depth of the filter. In contrast to a slow sand filter, where gravity drives the water filtration, a pump generates the required suction head through the filter. This suction can deliver a higher yield of filtered water and overcome head loss caused by flow through porous media, including any particles clogging the media pores creating additional head loss.

Total head loss through the filter was calculated taking into consideration the hydraulic conductivities and thickness of each layer. The projected head loss for the designed filter is 0.66 m, far from exceeding the 3.5 m suction head limit provided by a typical centrifugal pump. Changes in water levels overlying the gallery caused by tidal fluctuations may require the suction head for the pump to be adjusted. As the filter operates, it is probable that head loss will increase with time as the upper sand layer becomes progressively plugged. Pump suction head could be increased to maintain the required infiltration rate, and if the 3.5 m head loss limit is approached it might be a signal that the upper layer requires cleaning. The changes in suction head will affect the pumping rate, so the use of a variable frequency drives on the pumps should be considered to allow automatic adjustments to be made to keep flow at the desired rate.

4.5. Screen and piping system for a gallery cell

The under-drainage system lies on the bottom of the filter and plays an important part in the operation of the seabed gallery. This system consists of a screen and piped system covered with gravel. A collecting header pipe is placed along the center of the filter with lateral infiltration screens mounted perpendicular along both sides of the pipe (Fig. 13).

Filtered water would be pumped to the SWRO plant through the lateral infiltration screens. Screen laterals with a length of 12 m are oriented perpendicular to the collector pipe axis and are spaced 20 m apart. The larger spacing of the drains has a negligible effect on head loss since hydraulic resistance of the gravel is very small [21]. The pipes are spaced conservatively to maintain a uniform head loss in the lowest layer, thereby maintaining an even infiltration rate through the top of the filter. Slot width in the screens is a standard size at 3.2 mm, which is the indicated size to prevent migration of the gravel media into the screens (half the effective size of the bottom layer) [16]. The screen is designed with an open area of 10.5%, approximating the recommended design value of 10% [2].

Careful selection of materials should be made for the under-drainage system, as the pipe material should be resistant to the corrosion of seawater. High-density polyethylene should be used for piping system, while polyvinyl chloride should be the material used for the screens. Steel collection pipe of any type

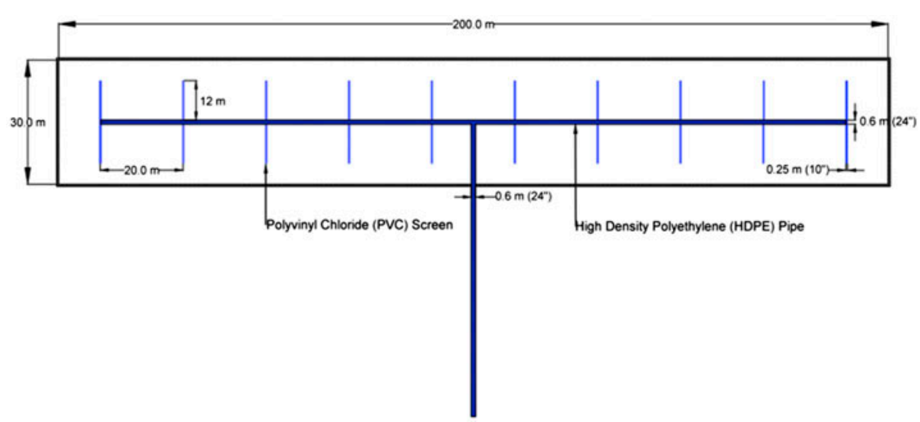

Fig. 13. Piping and screen configuration for a gallery cell at the Shaoiba site.

is not recommended due to potential corrosion of the piping caused by oxygenated seawater.

The design diameter of the main collector pipe is 60.96 cm. The flow area of the main conveyance pipe is sufficient to carry 42,000 m^3/d of flow at a velocity of 1.67 m/s, approximate to the recommended maximum value of 1.5 m/s [22]. Infiltration screen is designed to have a nominal pipe diameter of 25.4 cm with sufficient screen open area to allow an entrance velocity of 2.3 cm/s. Having an entrance velocity lesser than the recommended limit of 3 cm/s, leaves the possibility of increasing the filtration rate if needed. The piping system is based on the use of standard pipe and screen sizes, which reduces maintenance costs and delivery time during construction. Manufacturers are expected to supply further technical design and installation criteria for proprietary drainage equipment and material.

4.6. Production of total feed water required

The construction of additional seabed gallery cells could provide the totality of the feed water into the Shoaiba RO plant. A detailed study of the geological and hydrological conditions should be conducted in the area around Shoaiba to investigate the feasibility of constructing additional cells. An initial assessment of the zone showed similar sedimentological conditions with muddy nearshore zone and cleaner sediments offshore that could lead into the application of comparable design concepts. Corals are abundant in the area of the reef tract that would have to be identified and avoided to minimize impacts. An additional 3.5 km of coastline located north of the Shoaiba complex could be analyzed for the construction of additional seabed gallery cells (Fig. 14).

As the number of independent seabed gallery cells is increased, greater operational flexibility would be provided. If there were one seabed gallery cell serving each of the existing desalination trains, taking a single cell out of service would cause a manageable rate increase of the infiltration rate of the operating cells. There would be no need for backup of seabed gallery cells to compensate for decreased output from any single cell, as the combined operational flexibility of the rest of the cells would be sufficient to meet the normal operation of the plant.

4.7. Operational optimization

Opportunities are also possible to optimize the operation of the seabed gallery system by experimentation with the initial constructed cells before the entire system is completed or after the initial operational phases. The proposed infiltration rate of 7 m/d also allows for the possibility of increasing it up to the maximum recommended value of 10 m/d, which allows greater control in the rate of water being filtered. The proposed design permits a higher infiltration rate without surpassing the design head loss and flow velocity limits, or decreasing the filtered water quality significantly. Analyzing the effect that high infiltration rates have on operation parameters, filter clogging and water quality, could be validated in the first seabed filter built, leading into optimization of the remaining gallery cells to be constructed. Constructing additional seabed filters with a decreased area and higher infiltration rates could be proposed if

Fig. 14. Sandy shoreline and nearshore are where all of the seabed gallery cells could be located adjacent to the Shoaiba complex to meet the full plant feed water requirement.

the initial filter provides high-quality water without the need of constant cleaning of the upper layer. A phased construction approach could allow experimental data collection, leading to slight design improvements.

5. Conclusions

A survey of the Red Sea shoreline and nearshore geological conditions from Jeddah to Al-Qunfudah, and a site-specific investigation conducted at Shoaiba, have demonstrated that the subsurface intake type that is most feasible to use to supply feed water to SWRO facilities is the seabed galleries. A seabed gallery system can be used to supply 375,000 m^3/d of required feed water for the facility to produce 150,000 m^3/d of potable water. The nearshore marine bottom sediments have acceptable grain size and hydraulic properties to maintain the top layer of the gallery cells without causing clogging. The area generally contains low-mud content, critical to maintaining gallery infiltration. Also, a sandy offshore area occurs wherein the gallery cell construction would not impact marine grass growth or the coral reef system.

A series of nine gallery cells with a total area of 6,000 m^2 each and corresponding dimensions of 30 × 200 m would be required to produce the total feedwater requirement. The initial design infiltration rate is 7 m/d which could potentially be raised to 10 m/d based on initial testing and long-term operational data.

Long-term operational data from the Fukuoka, Japan seabed gallery system suggest that the design concept is sound and that substantial improvement in water quality can be expected. These water quality improvements and reduced use of chemicals during pretreatment (no chlorine and ferric chloride) would lead to lower operating costs. Also, in the event of a harmful algal bloom, the facility will continue to operate without service interruption caused by a possible pretreatment system failure. Therefore, a greater degree of operational reliability would also be achieved. Additional advantages of using a seabed gallery system will decrease environmental impacts due to impingement and entrainment and a general reduction in energy consumption.

Acknowledgments

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