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Technical feasibility of using gallery intakes for seawater RO facilities, northern Red Sea coast of Saudi Arabia: the King Abdullah Economic City site

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ABSTRACT

The Kingdom of Saudi Arabia is dependent on desalination of seawater to provide new water supplies for the future. Desalination is expensive and it is very important to reduce the cost and lower the energy consumption. Most seawater reverse osmosis facilities use open-ocean intakes, which require extensive pretreatment processes to remove particulate and biological materials that cause operating problems such as membrane fouling or shutdown during algal blooms. Subsurface systems, using the concept of riverbank filtration, can be used as intakes. These systems include wells of various designs and galleries that provide natural filtration and biological treatment to improve the quality of feed water before it enters the desalination plant. This reduces operating cost, lowers chemical and energy consumption, and reduces environmental impacts. Technical feasibility of gallery-type intakes, beach and seabed types, for use as intakes to seawater reverse osmosis (RO) facilities was evaluated along the northern Red Sea shoreline of Saudi Arabia. The geological characteristics of the offshore ocean 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. One of the potentially favorable sites for a seabed gallery system was located in the nearshore area at King Abdullah Economic City (KAEC). Detailed investigation of the site hydrology (tides and wave action), sediment grain size characteristics, and sediment hydraulic conductivity, and access for construction were assessed. It was determined that seabed gallery development is favorable at the site. Based on the seawater that has a salinity of about 41,000 mg/L and a conversion rate of 40%, a conservatively designed gallery cell with dimensions of 100 by 50 m would produce about 25,000 m^3/day of filtered seawater and seven cells (6 primary and 1 standby) could support a 60,000 m^3/day (permeate) seawater RO plant.

Keywords: Reverse osmosis; Intake; Desalination; Seabed; Offshore gallery

1. Introduction

An intake system is a key component of every seawater reverse osmosis (RO) desalination system. Great consideration should be given to the design and operation of the intake system since it can greatly influence and determine the performance of the other downstream components of a seawater RO desalination plant. The sensitivity of the membrane process to

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fluctuations in the quality of the feed water source makes it essential to have a reliable intake system which provides a constant supply of high-quality water [1]. The primary purpose of the intake system is to deliver feed water in sufficient quantities while minimizing the environmental impact. It is desirable for the intake system not just to supply a suitable quantity of feed water, but it should also serve as part of the pretreatment process for a desalination plant.

Most seawater reverse osmosis facilities use open-ocean intakes to supply raw water to the treatment plant. In general, the quality of feed water provided by this system is poor and inconsistent, which increases the complexity of the design and operation of the pretreatment processes. In addition, an open-ocean intake system makes the desalination plants more vulnerable to entrainment of large marine organisms and debris, such as jellyfish, and subject to system failure caused by red tide events or other algal blooms. A red tide bloom has caused the shutdown of desalination plants, such as the Galeelah Desalination Plant in the UAE in 2009 [2,3]. Furthermore, one of the common problems associated with an open-ocean intake system is the entrainment and impingement of fish and other marine organisms through or onto the intake. Generally, complicated and extensive pretreatment processes must be operated when using open-ocean intake systems to avoid membrane fouling.

Alternative intakes include various subsurface systems which utilize the concept of riverbank filtration, such as wells or galleries. These methods provide natural filtration and biological treatment of the feed water before it enters the desalination plant. Subsurface intakes, particularly beach and seabed galleries, have several advantages over open-ocean intakes, such as minimizing the impingement and entrainment of marine organisms, reducing or eliminating several pretreatment requirements, minimizing adverse environmental impacts (no chlorine required), and reducing the operating cost. Subsurface intake systems have been proven to be cost-effective for operation of small-scale plants with capacities not exceeding 4,000 m^3/day [4]. However, subsurface intake systems also have been implemented in several large-scale desalination plants where the production capacity exceeds 20,000 m^3/day [4]. The largest seawater RO desalination plant that is fully fed by water derived from wells alone is the Sur plant in Oman, which has a total capacity of 80,200 m^3/day and the wells yield about 160,000 m^3/day [5]. In addition, it has been reported that the largest seawater RO plant utilizing horizontal wells is the San Pedro del Pinatar plant in Spain with a 172,800 m^3/day capacity (intake) [6,7].

Gallery intakes are type of subsurface intake that utilizes the concept of sand filtration to naturally filter the seawater before entering an RO plant. Beach galleries operate in a similar manner to the rapid sand filtration mechanism and are constructed below the intertidal zone of sandy beaches. This system is virtually maintenance-free since the mechanical action of breaking waves helps keep the sediment-water interface (filter face) clean by naturally removing fine particles and marine organisms [8]. Seabed gallery-type intakes use a principle analogous to a slow sand filter and are constructed in the offshore subtidal area. This system requires a periodic cleaning of the uppermost layer of the seabed by raking or sand removal, similar to a slow sand filter in a water treatment plant. The purpose of the cleaning process is to remove clogging materials accumulated within the bed in order to maintain consistent flow of raw water over the life span of the filter. The Fukuoka seawater RO plant in Japan is the largest desalination plant that utilizes this concept and has an intake capacity of 103,000 m^3/day [9]. It has operated continuously over seven years without requiring cleaning of the seabed above the constructed filter. The City of Long Beach, California is also considering the seabed gallery concept and it is currently undergoing testing of a constructed cell [10].

The feasibility of using subsurface intake systems is site-dependent and it requires appropriate surface and hydrological conditions [11]. Consequently, the success of this system is highly dependent on the local hydrological and geological conditions at the intake site. A sub-regional and site investigation was conducted to determine whether the hydrological and geological conditions along the northern Red Sea coastline of Saudi Arabia are feasible for use of subsurface intake systems, particularly the seabed and beach gallery types [12].

2. Research methods

2.1. Field investigation

A series of field investigations were conducted to assess the feasibility of using gallery intakes in the northern Red Sea coastal area of Saudi Arabia. An initial survey covering the entire coastline area from Thuwal city to the northern part of the Red Sea coast of Saudi Arabia near the Jordan border (Gulf of Aqaba, Haqal city) was conducted (Fig. 1). The objectives of this investigation were to study the shoreline and offshore physical characteristics, including the observation of the general sediment characteristics (e.g., sandy, muddy, rocky), the wave action at

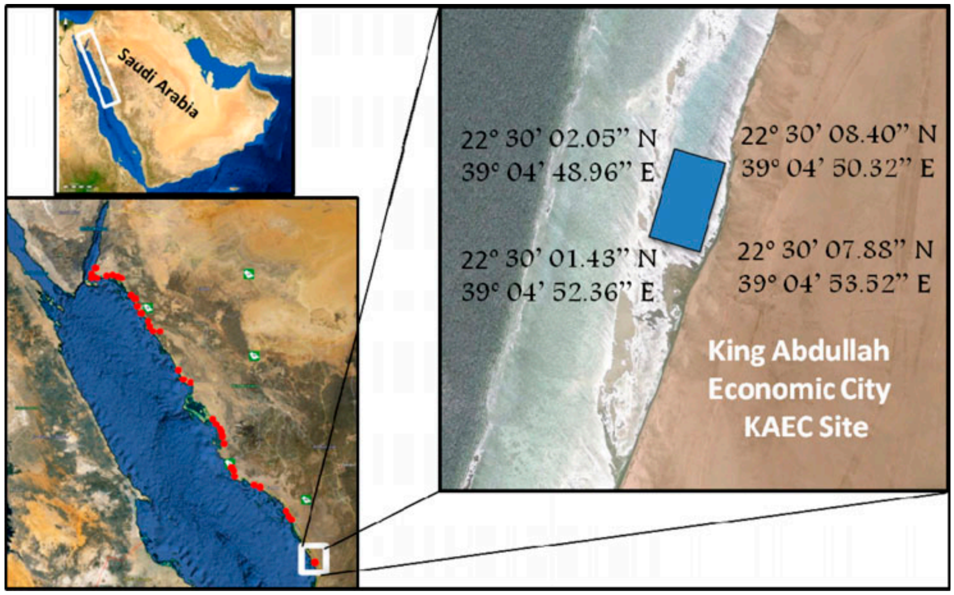

Fig. 1. Locations of sampling sites on the northern Red Sea coastline of Saudi Arabia.

the shoreline, and collection and analysis of sediment samples from the beach and offshore, and to determine the general tide range. The purpose of this initial investigation was to identify possible sites feasible for the development of gallery-type intakes. Several potential sites for the design and construction of seabed gallery systems were found in the nearshore area of this region. These sites have a predominantly sandy offshore bottom with shallow water depths, and a low tide range. The areas are always covered with water and are accessible for construction. However, many beaches that were observed have low wave energy (wave heights of less than 0.25 m) and muddy sediments present along the shoreline. The characteristics of such sites are not favorable for a beach gallery intake system since the sediment-water interface would not be cleaned by the wave action, which could cause the surface of a beach gallery to become clogged with mud [8]. Based on these preliminary observations, it was concluded that the offshore seabed gallery type instead of the onshore beach gallery had greater feasibility along this coastal area and research efforts were therefore focused on the offshore areas.

One of the potentially suitable offshore sites was located in the nearshore area at King Abdullah Economic City (KAEC), Saudi Arabia (latitude 22˚30.071′ N, longitude 39˚04.903′ E), which is located about 20 km north of King Abdullah University of Science and Technology campus (Fig. 1). The site was chosen for further investigation because the preliminary observations showed that the conditions at this site appear to be suitable for the development of an offshore gallery (seabed filter system). It contains a predominantly sandy offshore marine bottom with a shallow water depth and a low tide range. In addition, the nearshore bottom is always covered with water and contains a soft limestone unit below a sand mantle that would be easily excavated to facilitate the construction of a seabed filter. Some muddy sand occurs close to the shoreline, but not offshore wherein it would be problematic for the development of a seabed gallery system. Also, the site is located near a populated area that is supplied potable water from a seawater RO plant that will require expansion in the future.

Sampling of the shoreline and bottom sediments was conducted on the site based on a closely spaced grid to allow detailed assessment of the characteristics to be made (Fig. 2). About 50 samples were collected from this site within the grid in order to characterize the grain size and hydraulic properties of the sediments. The water depth within the sampling grid was measured and the thickness of sediment was determined from the sea bottom to the top of a soft limestone by using an auger.

Most of the samples were collected from the upper 5 cm of bottom sediment, because the native shallow sediments will tend to be mobile and move across the top of the gallery with time. However, the deeper sediments will not affect the gallery operation because the subsurface part of the gallery would be a constructed filter to optimize infiltration and treatment of the seawater.

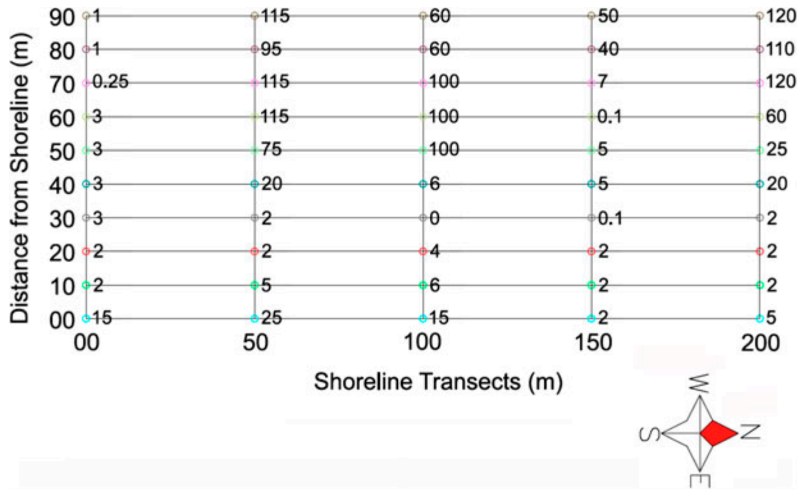

Fig. 2. Sampling grid at the KAEC showing the thickness of sand in centimeters.

2.2. Laboratory sediment measurements

Grain size analysis and hydraulic conductivity measurements were conducted on the samples collected from the KAEC site in order to study the hydrological and geological conditions. Each sample was washed to remove the salt and plant debris while care was taken not to remove any naturally occurring mud. After drying the sample, a standard sieve analysis was conducted on each collected sediment sample to determine the grain size distribution (33 sieve intervals and the pan). The procedure used followed the general method for sieving as described by Tanner and Balsillie [13]. In addition, a constant head permeameter was used to determine the hydraulic conductivity of each sediment sample. The methodology followed the standard method for determination of hydraulic conductivity for unlithified sediments described by Wenzel [14] and the American Society for Testing and Materials [15].

3. Results of investigation

3.1. Site geology

At the KAEC site, the shoreline is a low-energy beach that is very narrow at about 5 m. Wave heights occurring at the shoreline are very low, typically less than 0.25 m. The slope of the bottom from the shoreline seaward is almost flat for the first 100 m and slightly steepens seaward. The marine bottom contains a predominately carbonate sand veneer mixed with some slightly muddy sand lying upon a soft limestone unit (Fig. 3). Some patchy corals and coralline algae occur seaward of the sand veneer and a fringing coral reef separates the shallow slope area from deeper water (10 m+). The geological conditions of the site determine the feasibility of the site for development of a seabed gallery and the best location of the filter from a construction cost perspective and for future operation.

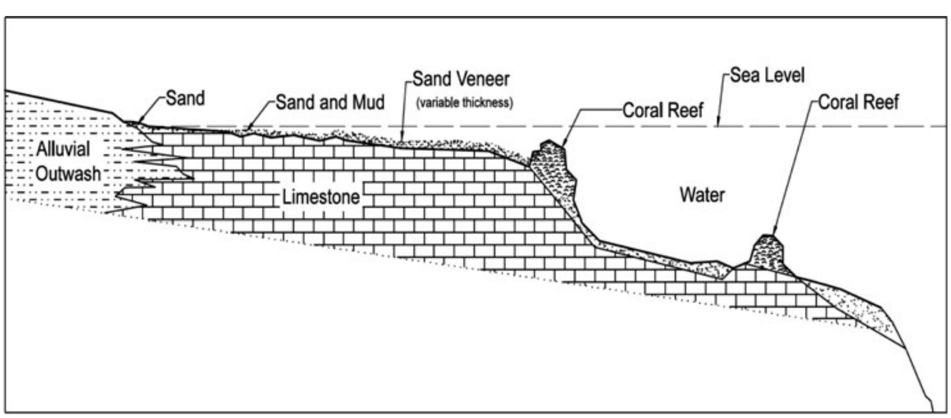

Fig. 3. The nearshore area can be classified as an arid carbonate rimmed shelf capped with a predominately carbonate sand veneer with some "patches" of muddy sand.

3.2. Sediment grain size properties

Bottom sediment grain size and hydraulic properties must be determined because they affect the design and operation of a seabed gallery. The mean grain diameter (first moment) of the sediment ranges from 0.15 to 0.5 mm (Fig. 4(a)). Since the majority of mean values fall within this range, the sediments at this site are classified as medium-grained sands according to Wentworth–Udden classification [16]. Based on the data collected, a mean grain size value of 0.3 mm was used in developing a design for the upper layer of the filter.

It was also found from the grain size analyses that the percentage of mud in the studied area is relatively low (Fig. 4(b)). The presence of highly muddy sediments in the offshore samples could present a problem for the gallery design and operation because it could reduce the vertical hydraulic conductivity of the filter, thereby clogging the upper layer of the filter. Also, if there would be a high rate of fine-grained sediment deposition on the site, it would cause clogging. No evidence for rapid mud deposition was found at the site and the percentage of mud in the samples was low-accept in a few samples collected in the northernmost inshore area.

3.3. Sediment hydraulic conductivity

The hydraulic conductivity of the uppermost sediment layer was measured using a permeameter (Fig. 4(c)). The infiltration rate of the constructed filter is controlled by the hydraulic conductivity of this upper layer which contains the native offshore sediments. Also, the grain size characteristics and hydraulic conductivity of the uppermost layer affect the lower constructed layers in the overall filter design. These data were critical in the determination of site suitability for use of this intake type.

4. Feasibility and design of a seabed gallery intake at the KAEC site

4.1. General feasibility of gallery intakes in the northern Red Sea

It is concluded based on the field investigations conducted along the shoreline and nearshore areas of the northern Red Sea in Saudi Arabia that the geological and physical conditions are very acceptable for the design and construction of seabed galleries. However, the small thickness of sandy sediments, the occurrence of mud, and low wave activity along the beaches of the northern Red Sea are not favorable for the development of beach gallery intakes. Wherever the nearshore area of the region contains geological conditions, such as shown in Fig. 3, the development of a seabed gallery can be achieved. Some sites are more favorable than others based on site-specific conditions that affect construction cost, such as water depth and the presence of mud. The KAEC site is representative of a large portion of the shoreline and a preliminary design for a seabed gallery was developed for this site-specific condition.

4.2. Location of a gallery cell

One of the factors affecting the positioning of a seabed gallery is the depositional area of offshore mud. Therefore, the development of a seabed filter should have a footprint utilizing the lowest mud percentage area possible (<5%) and in the case of the KAEC site, the cell(s) would be located offshore beyond a distance of 40 m from the shoreline (Fig. 5).

Another factor that affects the positioning of a seabed gallery is anthropogenic activities that could adversely affect the marine bottom conditions, such as induced turbidity and sedimentation. A large seaport will be constructed in the future at KAEC. This facility will be a busy shipping and boating area. A key consideration in selecting the location of the gallery was to be away from the ship channel. Ship movements might cause the mobilization of muddy sediments into the seabed filter area, which could plug the upper layer of the filter. The site selected is located away from the area where turbidity levels would be elevated in the future.

4.3. Design of a gallery cell

In a typical slow sand filter, the design infiltration rates range between 0.05 and 0.2 m/h with a medium mean grain diameter of 0.3–0.45 mm and a gravity head drop of 0.9–1.5 m [17]. The design criteria were modified for the seabed gallery since the potential head loss, and flow of water is controlled by the suction pressure and not by the gravity alone. The infiltration rate is controlled by the conductivity of the uppermost layer that contains the native offshore sand as well as the thickness of the filter and the suction head. The suction allows the seabed filter to be thicker than a standard slow sand filter and to have a generally higher yield.

A very conservative design for this site is to use solely the slow sand filtration criteria as the basis of design. The infiltration rate of the seabed filter is set to be 5 m/day, which is slightly higher than the maximum limit for slow sand filter design at 4.8 m/day

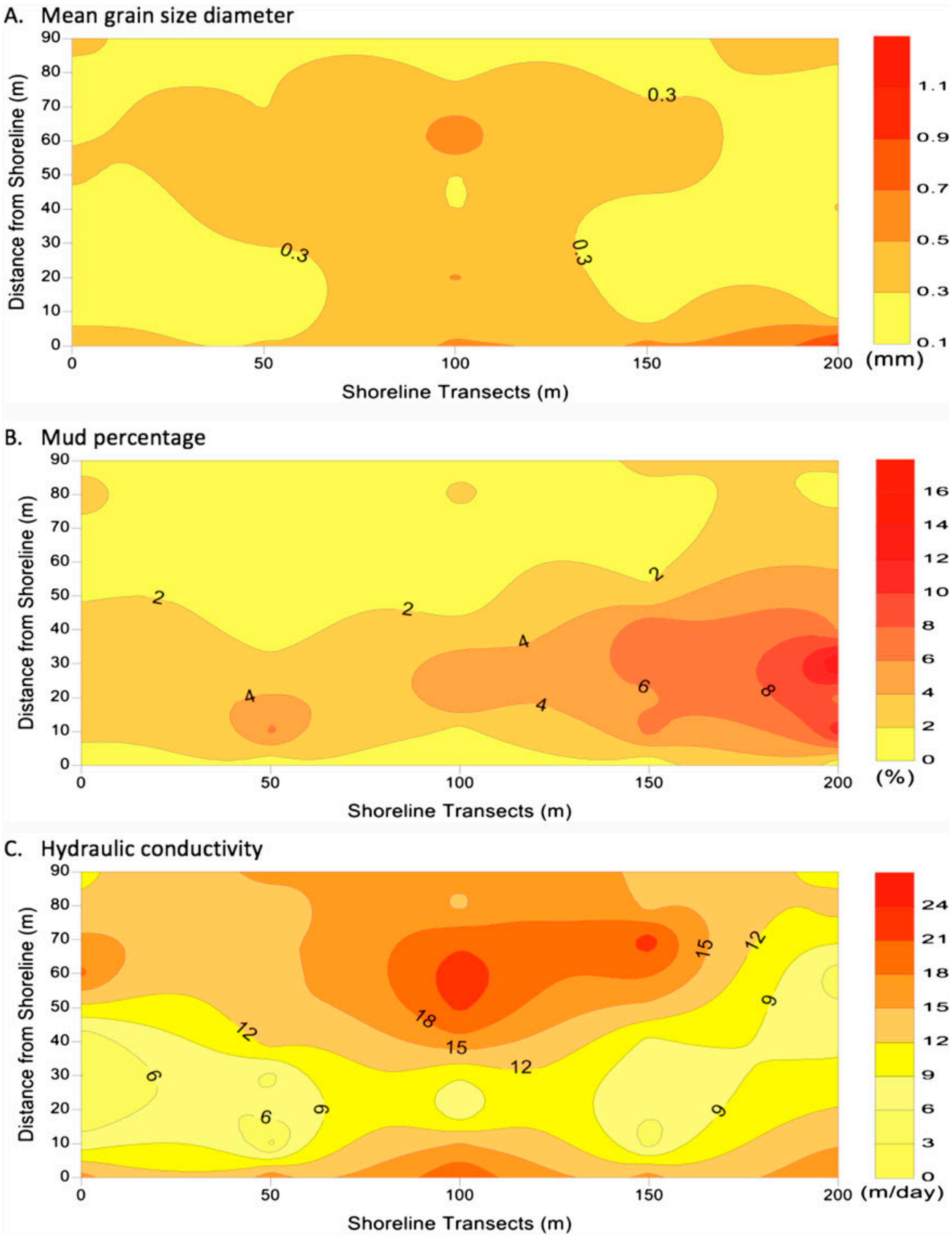

Fig. 4. Sediment grain size characteristics and hydraulic conductivity within the study area at the KAEC site.

[17]. The suction pressure should be less than 3.5 m of head based on the ability of a standard centrifugal pump to generate suction (note that another pump-type could be used). The suction pressure required for the designed filter was based on the selected criteria, utilizing a computer program calculation that allows analysis of head loses from various layer properties and infiltration rates. The head loss for the 5 m/day

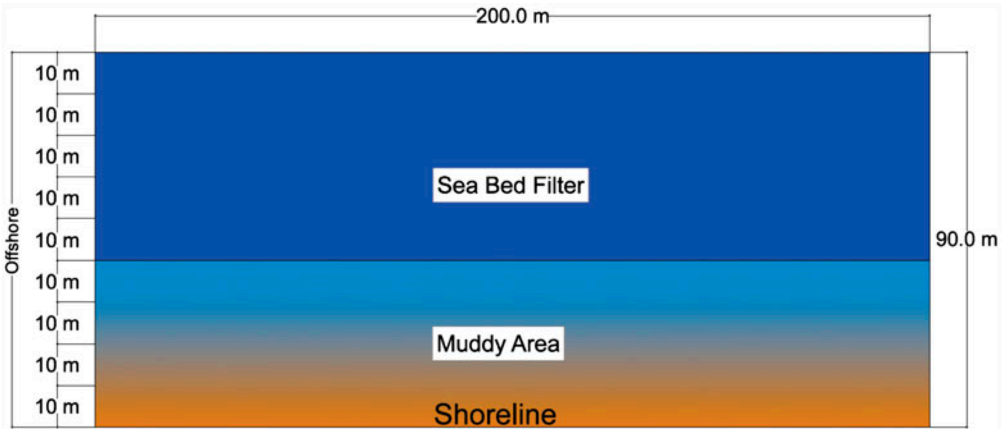

Fig. 5. The location of the seabed gallery cells should be located offshore of the muddy sediment area to avoid mud infiltration. This is about 40 m seaward of the shoreline.

infiltration rate was less than 1 m which is much lower than the maximum range of the standard centrifugal pump.

The total thickness of the filter is proposed to be 4.5 m and it consists of four intermediate layers of graded sand between the upper native sand media and the bottom gravel layer (Fig. 6). The uppermost layer thickness was conservatively based on giving the lower filter layers protection from storm excavation and from burrowing infauna that live in the natural marine bottom. Sequence layer thicknesses are also conservative in allowing continued removal of organic compounds via biological activity. The mean grain size diameter of each layer increases moving downward through the filter. The mean grain diameter of the uppermost layer is roughly equal to the low range of a slow sand filter which is 0.3 mm. The mean grain size diameter of each layer was selected carefully to prevent the infiltration of the fine sediments from the overlying layer into the subsequent underlying layers. A geofabric would be installed at the edges of the filter to prevent any invasion of fine-grained sediments from the sides. The base layer contains the screens used to withdraw water and these screens are surrounded by coarse gravel layer that helps maintain a constant pressure head drop within the lowermost layer which tends to cause a more uniform head distribution and induced infiltration rate.

Because of the small size of the study area, the preliminary design considers an intake system for only one train of an RO plant with a permeate capacity of 10,000 m^3/day. This train will require 25,000 m^3/day of raw water using a 40% conversion rate from seawater to product water based on current operating seawater reverse osmosis plants along the

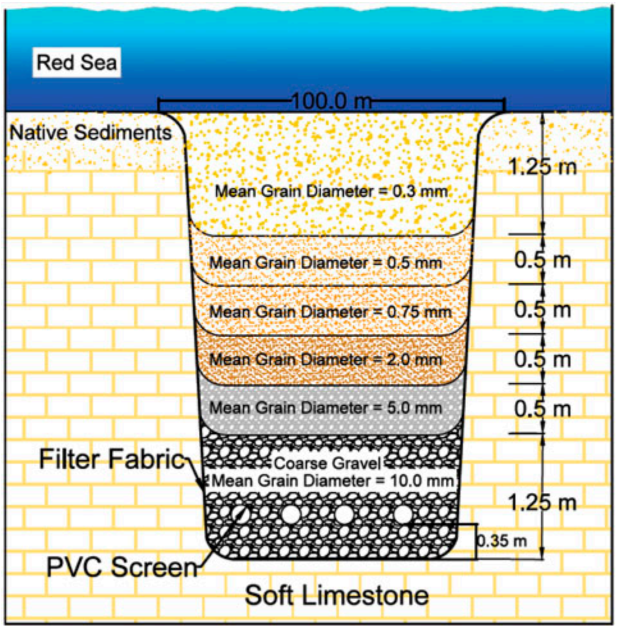

Fig. 6. Preliminary design of the KAEC seabed gallery.

Red Sea area (TDS = 41,000 mg/L). Based on an infiltration rate of 5 m/day, a surface area of 5,000 m^2 would be required to construct the filter with the desired capacity based on the very conservative design of the filter and the infiltration rate.

4.4. Optimization of seabed gallery cell footprint

There is a direct relationship between the footprint area of the cells and the overall cost of construction. Therefore, it is important to perform an optimization analysis of the design by balancing the maintenance cost for cleaning the uppermost filter layer with the increased or decreased capital cost based on the footprint area.

An optimization of the seabed gallery footprint can be achieved by increasing the infiltration rate of the filter. Since the corresponding head difference with the very conservative infiltration rate of 5 m/day is low, this infiltration rate could be increased to nearly double and still the head difference would fall within an acceptable range. In addition, since the KAEC offshore area has low wave energy (low potential for storm excavation) and it is always covered with water based on the tide water level data, the thickness of the first layer could be reduced to 0.4 m and the thickness of the underlying layers could be minimized as well. By doing so, the required footprint for constructing the gallery cell could be minimized to roughly half of the suggested footprint, but the maintenance cost might be increased. A tradeoff between the flexibility of operation, suction head, infiltration rate, thickness of layers, particularly the upper one, and maintenance requirements must be considered when optimizing the footprint of the gallery.

A conservative design approach is to suggest operation of the filter similar to typical slow sand filter. Based on the collection of experimental data, the infiltration rate could be adjusted later. In the event that positive operating data were collected, the infiltration rate could be increased upward to 10 m/day or greater and the footprint of the constructed seabed filter could be reduced. For any future expansion, data should be collected on the first filter cell which would be used to adjust the infiltration rate in subsequently constructed cells. Again, this is a very conservative design approach that could be improved and optimized.

4.5. Multiple seabed gallery configuration

A variety of capacities could be developed at the site to meet the future feedwater requirements of a seawater RO plant. Since the study area was small and the need for future water supply is large, an expansion plan for the intake system for the future needs was considered based on the assumption that the geological conditions of the surrounding area are similar to the studied site. The expansion plan covers the capacity required for an RO plant consisting of six trains with a total raw production capacity of 150,000 m^3/day with a recovery rate of 40% based on the Red Sea salinity of about 41,000 mg/L (product water production of 60,000 m^3/day). The preliminary design is to have six primary gallery cells and one standby cell for emergency and maintenance events. The total system surface area would be 35,000 m^2 based on an infiltration rate of 5 m/day. The optimal configuration of the gallery cells would be parallel to the shoreline to reduce the construction cost (decreased transmission pipe length and reduced water depth for construction equipment access) (Fig. 7). The standby gallery could be operated at the same time with the other primary galleries to reduce the infiltration rate of the system or a rotational use of the gallery cells could be implemented. To produce the maximum operational reliability, each gallery cell would contain an independent pipe to the onshore RO treatment facility. Each pump would be equipped with a variable frequency drive (VFD) control system. The VFDs would allow adjustments to be made to maintain a constant flow rate during tide changes and if partial clogging of the filter would occur. The individual gallery piping should be installed in a single trench at the landward center of the gallery cell

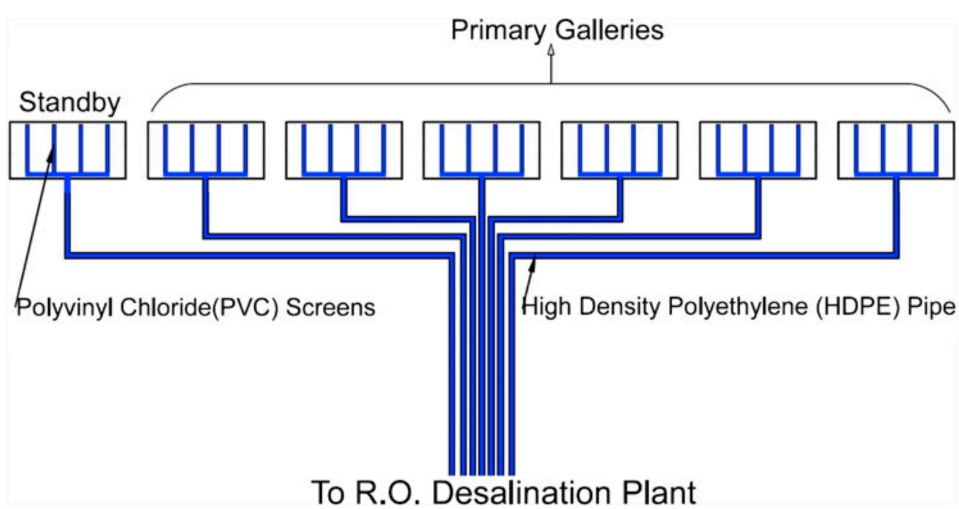

Fig. 7. Preliminary conceptual design of the expansion plan for KAEC seabed.

cluster to avoid separate trench construction. Standard pipe diameters and noncorrosive materials (high-density polyethylene and PVC) would be used to construct the conveyance pipes and gallery screens in order to reduce maintenance requirements (no corrosion). The redundancy of the pipes, pumps and number of gallery cells are very important for reliability considerations to protect the operation of the system from maintenance issues, pump failures, tsunami events, earthquakes, and storm events.

5. Discussion

A seabed gallery or filter system is analogous to a slow sand filter in that it operates with only downward flow and no back-flushing. Improvement to water quality occurs both by filtration and biological activity. Slow sand filtration of seawater is known to remove organic compounds and complex substances such as algal toxins [18]. In addition, a seabed gallery eliminates the entrainment and impingement impacts on marine organisms. It has been proven that the seabed filter system reduces the SDI and other fouling potential organics [8]. This system produces high-quality raw water that would necessitate less pretreatment requirements. With use of a seabed gallery intake, the raw water produced may be able to go directly to the cartridge filters without the need to pass through other conventional or membrane pretreatment processes.

Currently, there are two desalination plants utilizing the seabed system, one under operation in Japan since 2005, while the other is under testing in California. The Fukuoka seawater RO plant in Japan, which has an intake capacity of 103,000 m^3/day, has been proven to be successful through its full period of operation. Data collected from this facility show that during seven years of operation, the silt density index of the water passing through the seabed gallery has been consistently below 2.5 and commonly below 2.0 [9,19]. The Fukuoka gallery has demonstrated the ability to resist storm conditions and even earthquakes without affecting the operation of the filter (no cleaning) [19]. This facility has only one single pipe to convey the water from the seabed filter to the onshore RO treatment facility. The proposed design for KAEC is more conservative in terms of reliability of the piping system and gallery cell configuration which would be required to protect the operation of the system in case of maintenance and emergency events. The redundancy of the pipes, pumps and backup capacity are all considered to be additional improvements to the seabed gallery design.

A key consideration when designing a seabed gallery system is the economics of the proposed system. A comparison between the seabed and conventional open-ocean intake systems in terms of capital and long-term operation costs should be considered. The comparative analysis criteria between an open-ocean intake and seabed filtration should include all costs, including: the reduced need for pretreatment process equipment when using a seabed gallery intake; a lesser cost of pretreatment process operation when using the seabed system; the cleaning requirements for the seabed filter vs. the number of membrane cleanings required for operation of the plant when using an open-ocean intake; and the anticipated chemical usage in both systems (goal of zero chemical use with the seabed gallery system). Another criterion that should be considered is the potential for shutdowns of the RO plant in case of extreme events caused by man (e.g. oil spill) or naturally occurring events, such as red tides. These events cause shutdowns of seawater RO plants using conventional open-ocean intakes. However, the seabed filter system should be able to operate under these circumstances. Furthermore, the environmental impacts should be evaluated as well. The evaluation should include the impact of marine bottom excavation on the natural system around the seabed site vs. the impact of impingement and entrainment of marine organisms on the ocean natural system in case of using the open-ocean intake system as well as carbon footprints associated with both intakes (chemical use dependent). The only reasonable method to compare true costs of seawater RO facilities using open-ocean intakes vs. seabed gallery intakes would be to conduct a full life-cycle analysis for periods ranging from 20 to 30 years.

6. Conclusions

A field investigation of the northern Red Sea shoreline and adjacent offshore waters of Saudi Arabia revealed that the development of seabed gallery intake systems that can supply feed water for seawater RO facilities is technically feasible. However, beach gallery intake systems are not feasible based on the geologic conditions and the low wave energy.

A site located offshore from the KAEC was investigated in detail to characterize the tidal hydrology, geology, sediment grain size distribution, and hydraulic conductivity of the sediments. Based on the field data collected, the design and construction of a seabed gallery system is feasible at this site. A preliminary design of the filter was developed along with a determination of the footprint for individual gallery cells and the number of cells required to provide a reliable feed water source for an expanded seawater RO system that is anticipated to be constructed in the future. Using very conservative criteria for the design of slow sand filters, the area of a cell would be about 5,000 m^2 and would yield about 25,000 m^3/day of filtered seawater. To provide feed water for a 60,000 m^3/day, permeate seawater RO system at the site would require six primary gallery cells and one standby cell. The seawater at the site has a total dissolved solids concentration of about 41,000 mg/L and the conversion rate is estimated to be 40%.

Seabed gallery intakes have proven to be an effective means of providing feed water to seawater RO facilities. The Fukuoka, Japan seabed gallery system has operated quite well for a period of seven years, showing a historical declining trend in silt density index from near 2.5 to 2.0 or less. This type of intake could replace open-ocean intakes at large seawater RO plants and improve operational efficiency by reducing the need for expensive pretreatment processes, eliminating the need for chlorination, eliminating environmental impacts of impingement and entrainment, and improving facility reliability (will operate during red tide or oil spill events). Seabed gallery intakes should be evaluated and used at locations where the geologic conditions in the nearshore seabed are feasible.

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