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Technical feasibility of a seabed gallery seawater intake at Ras Abu Ali Island, Arabian Gulf, Saudi Arabia

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ABSTRACT

Open-ocean intake systems require extensive and advanced pretreatment unit operation to produce feed water with low membrane fouling potential in seawater reverse osmosis (SWRO) facilities. Alternatively, subsurface intake systems tend to produce high quality raw seawater even before pretreatment. Subsurface intakes extract seawater indirectly through the geological structure of shoreline or nearshore sediments. Water percolation through geological units provides physical and biological treatment, so that the raw seawater is microbiologically stable with relatively low particulate and organics content. Overall, utilization of subsurface intakes will reduce the intensity of pretreatment, which reduces operating cost, lowers chemical and energy consumption, and reduces environmental impacts. An important aspect in the feasibility of a subsurface intake is the compatibility of the local geological environment. In this study, a field investigation was conducted at Ras Abu Ali Island in the Arabian Gulf. This location currently contains an of existing oil company facilities and a proposed governmental marine fish hatchery facility. Recreational, commercial, and domestic potable water uses require the need to use the SWRO process to meet demands. Characterization of the shoreline and marine offshore bottom were performed as well as observation of tidal fluctuations and wave heights. A specific grid area was chosen where 35 sediment samples were collected from the seabed floor for laboratory analysis of grain size distribution, sediment porosity, and hydraulic conductivity. Onsite observation showed that the marine bottom has a low slope creating a wide intertidal area. The lowest tidal zone is more than 150 m from the shoreline defining a far seaward boundary for the intake construction point. A relatively thin layer of mixed-type sediment (carbonate and siliciclastic) covers the marine hardground bottom. The unlithified bottom sediment contains a low mud percentage (less than 1%) with porosity ranging between 0.29 and 0.41 and hydraulic conductivities up to 22.5 m^3/d. It was determined that seabed gallery development is suitable at this location. Preliminary design for a seabed gallery filter was developed using a series of cells. Each gallery cell represents a unit that can be simply duplicated to meet the overall intake capacity requirement. Each gallery cell is designed to

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have minimum 8 m/d infiltration rate through five layers of engineered sand and gravel. The total thickness of the filter bed is 4.5 m (2 m top layer). The dimensions of the proposed cells are 100 × 30 m and each cell will conservatively provide 24,000 m^3/d of filtered water. The design is flexible to meet the required capacity. For example, a SWRO desalination plant which produces 54,000 m^3/d product water from 38,000 mg/L salinity seawater at a 45% conversion rate will require a minimum of 6 cells using the preliminary design.

Keywords: Seawater reverse osmosis desalination; Intakes; Seabed gallery; Arabian Gulf; Saudi Arabia

1. Introduction

The most common practice to obtain feed water for seawater reverse osmosis (SWRO) desalination facilities is to use some type of open-ocean intake system. This conventional method extracts seawater in its natural water quality which contains high concentrations of marine debris, organic matter, and micro-organisms. Natural seawater has a variable water quality depending on seasonal changes in temperature or physical oceanographic-induced changes, and periodic natural marine occurrences as storms (causes high turbidity), jellyfish infestations, and harmful algae blooms (HABs). SWRO plants require high volumes of feed water with low particulate, organics, and micro-organism content to prevent or lessen the occurrence of membrane fouling or biofouling [1,2].

The site investigated was chosen because it requires the development of an intake system for a marine fish hatchery and in the future may require the co-development of an intake for a SWRO plant. Fish hatcheries also typically require a seawater supply that has relatively constant temperature and low content of organics to maintain suitable living conditions for small fish larvae [3]. Thus, in order to put the seawater into use (e.g. desalination plant and hatchery plant), physical and chemical treatment of the impaired quality seawater would be required which is technically and economically challenging.

The improvement of raw seawater quality can be done in parallel with the intake process by utilizing a subsurface intake system. This intake method extracts the raw seawater that has percolated through the subsurface sediment of the shoreline and/or nearshore sediments. The natural geological properties of sediments or rocks perform physical and biochemical treatment by removing organic matter, suspended sediments, dissolved organic compounds, and micro-organisms by processes analogous to the concept of bank filtration [4]. Types of subsurface intakes vary from wells to galleries, all of which provide some degree of pretreatment [2]. Some publications have reported the improvement of water quality produced by wells and gallery-type intakes [5–8]. Consequently, subsurface intakes can potentially decrease the raw water treatment unit footprint, reduce environmental impacts (no impingement and entrainment issue), reduce chemical usage (e.g. chlorine and coagulants), and provide stable water quality for more reliable and economical downstream processes.

The feasibility of subsurface intake implementation is site-dependent and requires appropriate hydrogeological conditions [2,9–11]. Depending on the local geological condition of the shoreline and nearshore area at the intake location, the intake type and flow capacity needed must be carefully defined. This paper is a feasibility study on the implementation of a seabed gallery intake system based on the specific hydrogeological characteristics at an area along the Arabian Gulf shoreline of Saudi Arabia.

2. Methods

2.1. Field investigation and initial assessment of subsurface intake types

The study site is located at Ras Abu Ali Island, Eastern Province, Saudi Arabia (Fig. 1). It is situated to the north of Jubail between Ad-Dafi and Dawhats Al-Mussallamiyah. The island has a unique crescent shape with the outer section facing north where marine water intake systems were studied to provide seawater supply (6,000 m^3/d capacity) for a fish hatchery as part of a marine conservation program being developed by Saudi Aramco, the world's largest oil company.

A conventional pipeline (open-ocean) or an open-channel intake was initially chosen for use because of the common use of these intake types in the region. Later, some detractors were discovered for both intake types to be used for a fish hatchery water supply. Temperature fluctuations (35°C during late summer and 15°C during early spring), red tides, and oil spill contamination are problematic and would allow poor quality water to enter the sensitive seawater ponds. Marine biofouling control on inlet pipes, trash rack maintenance to remove marine debris, and extensive pretreatment to remove marine pathogens were also found to be necessary. A subsurface intake was then considered to resolve the issues related to impaired water quality using a surface water intake system. A 20 m monitoring well was constructed on the beach and demonstrated that the shallow groundwater has a hypersaline condition. It was found that there is seaward directed flow of brine from a sabkha which causes the occurrence of hypersaline water that is inappropriate for fish larvae and hatchery conditions.

The offshore area near the hatchery and possible SWRO plant facility was inspected to assess the bottom slope and condition (e.g. sediments, hardground, etc.). Also, the environmental sensitivity of the site was assessed by checking on the pattern of coral growth and occurrence of seagrass beds. The impact of tidal fluctuations on the site was also assessed.

Another subsurface intake option at the site is the use of a gallery-type intake which causes direct vertical flow of water from the sea through an engineered filter and does not allow horizontal water movement from the landward direction where the sabkha occurs. Therefore, a field investigation was performed to assess this possibility. The objectives of the investigation include the study of the shoreline and nearshore physical conditions, including general characteristics of the marine bottom (sandy, muddy, rocky, or combination), assessment of marine vegetation and coral distribution, the wave action and tide changes, and an assessment of the unconsolidated sediment over the marine bottom. The latter evaluation is important because the upper layer of the gallery bed will be affected by the native unlithified surface sediment as it moves across the bottom. A preliminary engineering design of a system was made.

2.2. Field sediment collection and laboratory analyses

A predetermined sampling grid was established using an area with dimensions of 200 × 180 m for inspection and collection of sediment samples (Figs. 1 and 2). The sampling was organized within the grid system using a series of transects along the shoreline from which 35 samples were collected (Fig. 2). At each point, unlithified surface sediment was collected and stored in a plastic container. Following collection, individual samples were washed with fresh pH neutral water (to remove the saline water and marine debris while conserving the carbonate mud content). After drying each sample, laboratory analyses of grain size distribution, sediment porosity, and hydraulic conductivity were made based on standard analytical methods [12–14].

Fig. 1. Abu Ali Island location.

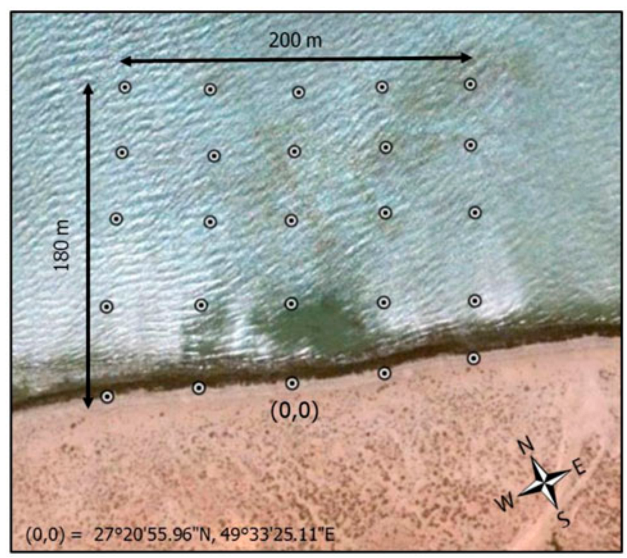

Fig. 2. Sampling points transect for surface bottom sediment analysis.

3. Results

3.1. Site description

Field observations showed that the shoreline was covered with beachrock and an ashpalt-like deposit (Fig. 3(A)). The black and gooey texture layer has a 20–30 cm thickness and occurs as a belt about 10–20 m wide between the normal high tide line seaward. It is believed that the oil spill during the Gulf War was the source of this contamination.

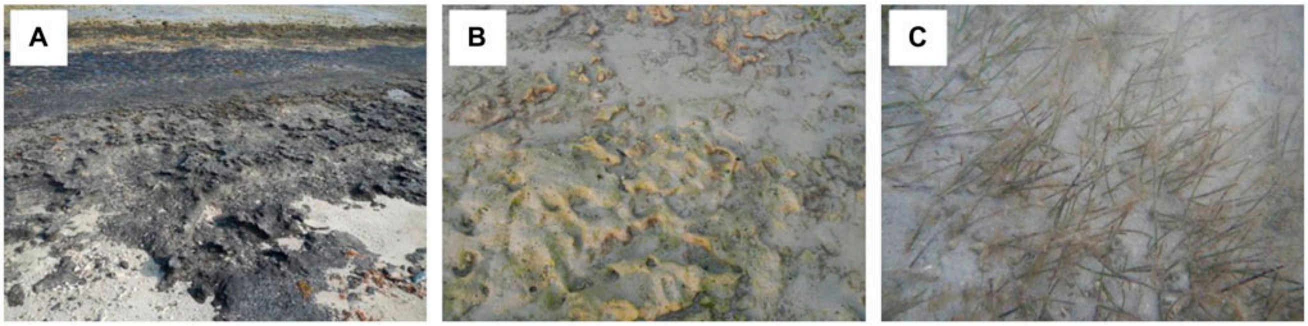

Fig. 3. (A) Asphalt-like deposition along the shoreline, (B) Bottom surface and unconsolidated sediment, and (C) Seagrass on the seabed.

The marine bottom consists of predominantly a marine hardground with some unlithified muddy sand and carbonate sand (Fig. 3(B)). The marine-cemented limestone was observed vastly and extends 300–500 m from the shoreline (high tide point) seaward. The thickness of the upper layer of limestone was observed to be about 30 cm in an excavation 1.5 m below the bottom at a location about 30 m seaward from the beach. The thickness of surface sediment was found to vary but follows a trend of increasing value from the shoreline vicinity (less than 50 cm) towards offshore (up to 100 cm). Seagrass appears as the only marine biota at the study site (no living corals) (Fig. 3(C)). It exists in low density and is randomly located near the shoreline, and it decreases toward offshore ceases to occur beyond a distance of 100 m.

3.2. Hydrogeologic bottom profile

The study location was characterized as a low energy beach with less than 0.25 m wave height. All day field observations on the shoreline and nearshore showed that the area has a very wide intertidal zone of up to 500 m from the beach to the low tidal point. This suggests that the distance from the shoreline to a location where there will always be some water submergence of the bottom is at least 0.5 km and may be greater during seasonal spring tides. This intertidal zone character is prone to high rates of water evapotranspiration over the zone, leading to a hypersaline condition and marine carbonate diagenesis which causes the formation of hard nearshore limestone (hardground).

3.3. Unconsolidated bottom surface sediment characteristics

The importance of the native surface sediment in the development of gallery-type intake is essential because it will affect the top layer of the gallery wherein the water treatment processes begins. The mapping of mean grain size is shown in Fig. 4(A). The mean grain diameter (first moment) of the sediment ranges from 0.24 to 1.72 mm with an average of 0.48 mm, which is classified as medium-grained sand according to the Wentworth-Udden classification [15]. From the grain size distribution, the mud content of the samples was found to be relatively low with less than 1% for all samples (Fig. 4(B)). It is evidence for no significant mud deposition that occurs at the study site. It is highly favorable to have low mud content sediment because its existence could cause clogging in the upper gallery layer, promoting reduced vertical conductivity, which leads to unstable filter performance.

Sediment porosity analysis results are shown in Fig. 4(C). The values range from 0.29 to 0.41 with an average of 0.35. The hydraulic conductivity results are affected by the mud percentage with the pattern of lower values of mud producing high hydraulic conductivity values. The results are shown in Fig. 4(D), with values ranging from 5.9 to 22.5 m/d and averaging 12.8 m/d.

4. Discussion

4.1. General site feasibility

The development of functional gallery intake relies on several factors as suggested by Mantilla and Missimer [16]: (1) the type of the natural bottom sediments, (2) the sedimentation rate of fine sediments, (3) the tidal range, (4) underlying site geology, and (5) the impact on marine ecosystem. The local groundwater water quality characteristics and climate information are also important issues to consider. Table 1 provides a summary of the study area related to the aforementioned factors. The tabulated information was used to develop a design concept for a seabed gallery intake at the area.

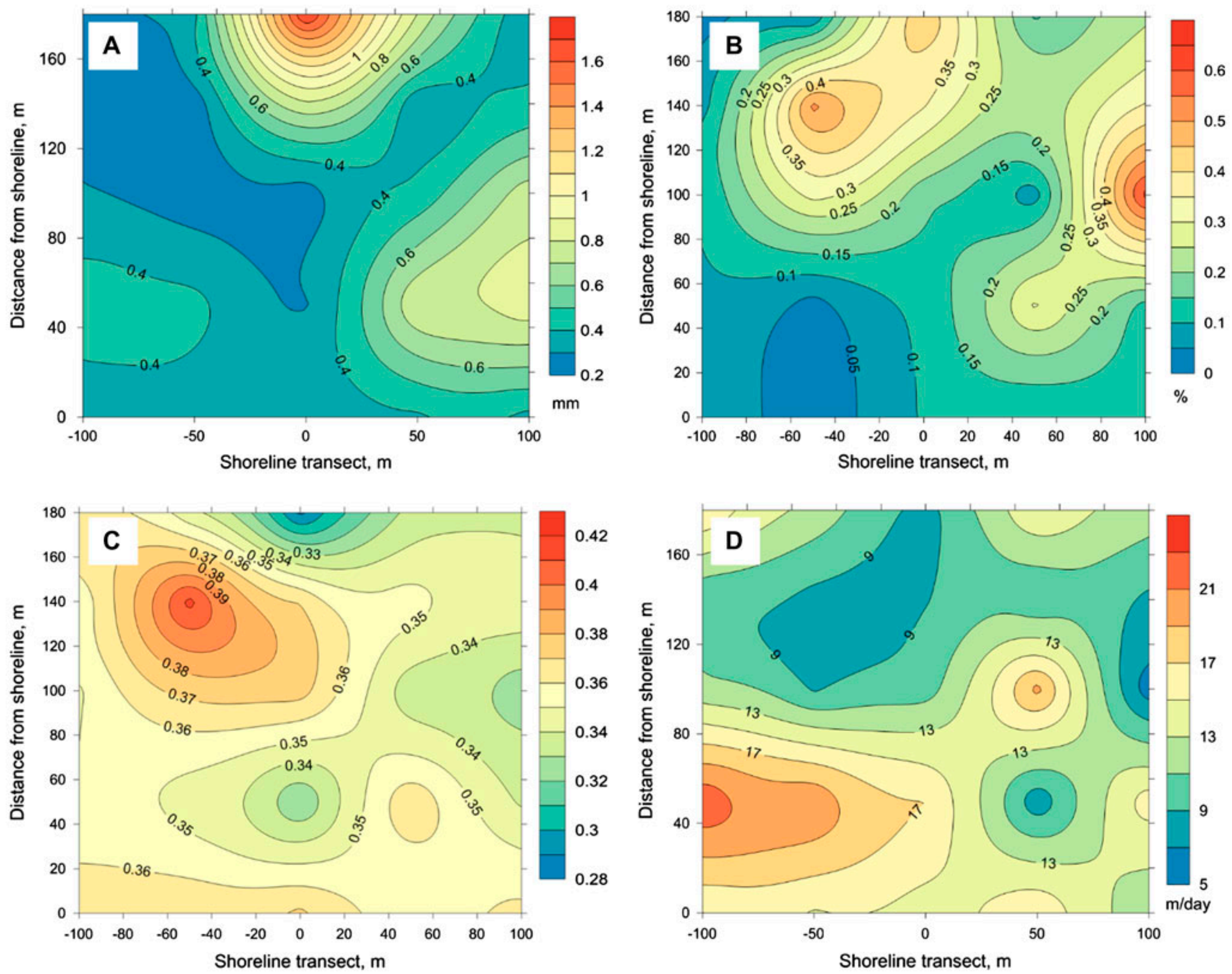

Fig. 4. Unconsolidated bottom surface sediment analyses results mapped in the study area (A) mean grain size, (B) mud percentage, (C) porosity, and (D) hydraulic conductivity.

Table 1
Summary of study area characteristics in relation to key factors in the development of gallery intake

Factors	Remarks
Natural bottom sediment	Medium-grained size sediment with relatively high hydraulic conductivity and low mud content
Tidal range	Low energy beach, wide intertidal zone, all-time covered water zone up to 500 m from high tide line
Sedimentation of fine sediment	Possibly high rate of hardground formation caused by rapid evapotranspiration
Marine ecosystem	Dead rocky coral (old) area with low density seagrass patches
Local groundwater system	Hypersaline groundwater found in the beach wells possibly caused by sabkha infiltrated water contamination

The first type of gallery intake that can be considered is a beach gallery, wherein a constructed filter is placed within the intertidal zone of the beach. The underlying geology can be modified by the construction of an engineered-graded sand to form the filter. The construction of such an intake is challenging since the intertidal zone lies at a great distance from the shoreline. A high-energy wave action is highly required in the operation of beach gallery as it is the key for filter cleaning [17,18]. The risk of hardground cementation is also a challenge to maintenance of favorable hydraulic characteristics of the top filter layer. The wide intertidal area would cause a short duration of the water covering the filter layer which could be an inadequate source of water to pass through the filter and would cause reduced hours of operation. This would necessitate a greater gallery footprint to meet the required capacity and would likely require onsite raw water storage. The absence of continuous flooding to promote continuous recharge of the gallery could promote preferential passage of hypersaline groundwater in the form of horizontal flow from the landward direction. Thus, the beach gallery option is not suitable with the condition of the study area.

The afore-mentioned geological and physical characteristics of the shoreline and nearshore study area are favorable for the development of a seabed gallery except for the intertidal zone width. An essential factor for successful operation of a seabed gallery intake is that it has to be submerged in water at all times with a preferred water depth of at least 1 m to provide continuous recharge. Based on the low offshore slope and the position of the normal low tide line, the seabed gallery would have to be located at least 500 m from the shoreline or even further to provide adequate water depth under all tidal conditions. Following the limitations on location, an assumption needs to be made that the natural bottom sediment characteristics of study area can be extrapolated to the desired location (further seaward) since the study area did not include the area of greater water depth. Past geological investigations in this region support this assumption [19,20].

Placement of the gallery at a considerable distance from the shoreline affects other key considerations of the intake system, which are construction cost and maintenance. These factors have influence on the system economics. Galley construction typically requires the use of sheet-piling and dewatering to assure proper construction of the filter media and underdrain collection system. The sheet piling erection is well known as a costly method of wet civil construction in the marine environment. The budget is dependent on the excavation area, especially the perpendicular distance from the shoreline. In other words, the further the location from the beach, the construction cost rises due to site access difficulties and required usage of transport barges or the construction of a temporary road from the beach to the construction site.

Maintenance of a typical gallery is accomplished by manually scrapping the filter top layer. This effort becomes a challenging routine when the location is far offshore although greater challenges would occur if the water depth were to be great. Furthermore, special maintenance scheduling would have to be planned to allow safe access to the gallery (e.g. the low tide period that would provide temporary dry land between the filter location and the shoreline). Thus, construction of a gallery intake at a distance more than 500 m is technically feasible from a construction point of view, but very challenging in the practical and economical point of view. However, the very successful Fukuoka seabed gallery intake is located over 1 km offshore in deeper water.

4.2. Design of a seabed gallery cell

The gallery filter system is designed similar to a slow sand filter, which includes filtration parameters (infiltration rate) and graded layers of filter media. Typical slow sand filters operate at infiltration rates from 0.05 to 0.2 m/h and are constructed with media containing a mean grain size from 0.3 to 0.45 mm in diameter with a head loss (gravitational) of 0.9–1.5 m [21]. Slow sand filters in water treatment plants operate using gravity feed. However, the seabed gallery filter is operated using pump suction pressure, which allows a span of head loss through the full thickness of the filter to be larger with retention time being an important design parameter.

The degree of water treatment in the gallery is determined to a large degree by the retention time inside filter during which water undergoes physical and biological treatment (i.e. size exclusion, adsorption, and bacterial breakdown) [3,8,20]. Adequate retention time will create a higher degree of pretreatment as experienced by the Fukuoka Desalination Plant, which utilizes a seabed filtration with a 7 h retention duration, resulting in a very high raw water quality (low silt density index, turbidity, and organic compound concentrations) feed water [22]. The filter media design herein utilizes a higher retention time of 8 h, which causes the active uppermost layer to be 2 m in thickness.

The gallery is subdivided into a series of cells with design capacities that are coordinated with a SWRO facility design or to meet the need of the marine fish hatchery that are proposed. The cell capacities are

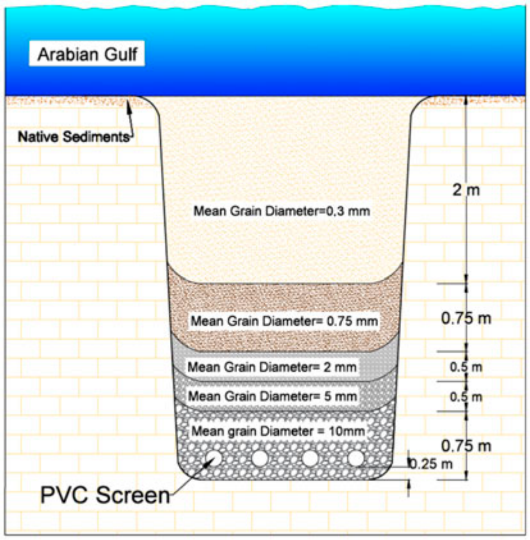

Fig. 5. Gallery filter cell design.

designed based on the larger requirements of a SWRO plant, while one or two cells could be used to meet the lower fish hatchery requirements. The overall SWRO facility design capacity considered is 54,000 m^3/d of permeate. At a 45% recovery rate, this would require 120,000 m^3/d of raw seawater. Each cell was designed to provide 24,000 m^3/d of filtered seawater with conservative 8 m/d infiltration rate provided by pump suction. Consequently, the required surface area is 3,000 m^2, which designed to form 100 × 30 m rectangular cell areas with the 100 m axis running parallel to the shoreline, thereby minimizing the construction distance from the low tide line.

Based on the average mean grain size of the natural bottom sediment, a 0.3 mm mean diameter media is used for the top 2 m filter layer to avoid any hydraulic intervention from clogging by smaller diameter grains. The succeeding layer thickness and medium grain diameter were determined by a method described by Barrett et al. [23], but the design allows grading of the mean grain size between layers to avoid infiltration of the media from top to down [24]. Thus, the gallery filter consists of five layers each with specific medium grain size and thickness (Fig. 5). The filter layer arrangement was chosen to perform a hydraulically feasible filter process with minimum head loss and was tested using a computer program designed to calculate the head loss for a given infiltration rate. For a centrifugal pump, the maximum head loss allowed is 2.5 m, whereas the designed cell head loss is approaches only 1 m based on a spreadsheet calculation involving relationships between mean grain diameter and hydraulic conductivity developed by Rosas et al. [25]. This relationship was further developed to include the water density and the infiltration rate to refine the head loss through the filter. The base layer has a large mean grain diameter and corresponding high hydraulic conductivity (up to 100 m/d) using 10 mm mean grain diameter media, which would allow a constant intake pumping rate via PVC screen underdrains.

A design summary of the gallery cells is provided in Table 2. The design should produce minimal maintenance with a long period between maintenance scrapping of the upper sediment surface to maintain the hydraulic conductivity of the media and to mitigate clogging. In fact, the seabed filter in Fukuoka Japan has been operated for eight years without the need for upper layer refreshing. The self-cleaning process is likely associated with the sediment stirring effect from the wave activity and ocean currents, also bioturbation caused by sediment-ingesting benthic organisms that degrade the organics and mud to be excreted as fecal pellets that have no detrimental effect on the hydraulic conductivity of the sediments [26].

4.3. Design of multi-cell seabed gallery system

In order to fulfill higher intake requirements, duplication of gallery cells can be made to form a

Table 2
Gallery cell specification

Parameter	Specification
Filtration rate	8 m/d
Media diameter	0.3 mm
Bed depth	2 m upper layer, total bed 4.5 m
Run length	Unlimited
Pretreatment	None required
Dominant filtration mechanism	Straining, biological activity
Regeneration method	Mechanical scrapping of upper layer or none
Maximum water turbidity	None
Hydraulic retention time	8 h

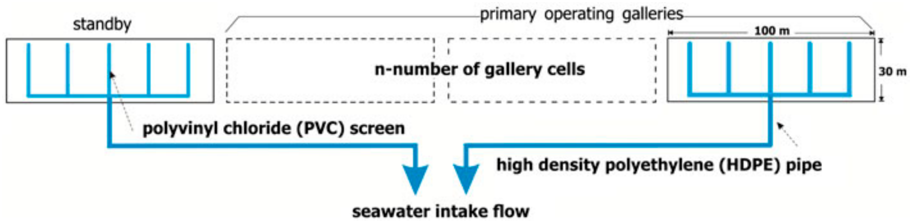

Fig. 6. Gallery filter multi-cell design.

geometric arrangement running parallel to the shoreline (Fig. 6). For example, a SWRO desalination plant with a 54,000 m^3/d capacity operating at 45% conversion (120,000 m^3/d), will require five primary cells and one backup to meet the feed water demand and system operational reliability requirements. The original fish hatchery project would have required one or two cells at a 24,000 m^3/d pumping rate. The SWRO final gallery cell configuration would be changed to more closely match the actual plant configuration. For process reliability and safety, the extra stand-by cell was added. Each cell is equipped with a pump to produce process compatibility and to avoid any special order high-capacity pump, which can be extremely expensive.

5. Conclusions

A better quality and more stable seawater quality can be provided using a subsurface intake vs. a conventional surface intake system. The natural processes provided by local geological conditions during induced filtration lead to some degree of water pretreatment resulting in low particulate content, low organic compound concentrations, and low microorganism concentrations, while reducing the required downstream pretreatment, lowering chemical consumption, and eliminating the marine environmental impact (impingement and entrainment). Application of a subsurface intake is highly dependent on the local geology of shoreline and nearshore area which determine selection criteria for which intake type can be used, such as wells, or a beach or seabed gallery system. Where the shoreline conditions contain hypersaline water and the tide range and low bottom slope causes the occurrence of a very wide intertidal zone, a seabed gallery is the best option. This likely applies to a large portion of the Arabian Gulf coastal region of Saudi Arabia.

The location of a seabed gallery system has to be carefully designed. It is important that the location is always covered by water with adequate depth to maintain recharge and to avoid the influx of high salinity water from the adjacent shoreline sabkha systems. In the case of a significantly wide intertidal zone such as the study site, the seabed gallery should be located seaward of the lowest tide elevation of the year which is over 500 m offshore at this location. The filter placement approach to such a distance is technically feasible from a construction point of view, but very challenging and expensive.

A gallery cell design was created based on slow sand filtration technology, used for over 150 years in the water treatment industry. The upper, active layer is a 2 m thick layer of 0.3 mm medium sand lying on 2.5 m of graded media designed to achieve the even flow of seawater into the underdrain system from which it is pumped to the SWRO plant or to the fish hatchery. The design produces an 8-h hydraulic retention time, which is conservative and would provide a very high degree of pretreatment. Cell design is scalable based on the required facility capacity and the degree of reliability desired by the facility owner.

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