

Chapter 12

Feasibility and Design of Seabed Gallery Intake Systems Along the Arabian Gulf Coast of Saudi Arabia with a Discussion on Gallery Intake Use for the Entire Arabian Gulf Region

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Abstract The Arabian Gulf coast of Saudi Arabia contains a large number of existing desalination facilities of which many use the seawater reverse (SWRO) osmosis process. Many SWRO facilities have had historical operational problems with membrane biofouling. Subsurface intake system feasibility was assessed generally for the coastline of Saudi Arabia and a site-specific investigation was conducted at Ras Abu Ali Island. It was found that the common occurrence of sabkhas along the shoreline of Saudi Arabia causes the use of conventional vertical wells to be risky due to migration of hypersaline water into them. All well types do not appear to be feasible based on the shoreline and nearshore geological conditions. Beach galleries were assessed and are also subject to failure caused by migration of hypersaline water and possible burial by dune sands moving eastward from the desert into the Arabian Gulf. Seabed gallery intake systems were found to be the most technically feasible subsurface intake type which could provide high capacity SWRO facilities with feed water. However, the low slope from the beach seaward and the tide range necessitate that seabed galleries would have to be constructed over 500 m seaward of the beach. This distance would make the construction complex and would require future design and construction innovations. Perhaps the seabed gallery cells could be constructed adjacent to an artificial fill peninsula that would allow easier access and less expensive construction.

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12.1 Introduction

The Arabian Gulf contains the largest concentration of seawater desalination capacity in the world with a total installed capacity of 11 million m³/d in 2008 (Lattamann and Hoepner 2008). Historically, thermal processes, in particular multi-stage flash (MSF) desalination, were the predominant methods used to desalt seawater. In recent years, seawater reverse osmosis (SWRO) has become an important component of desalination in the Arabian Gulf because of its lower energy usage and consummate lower cost (Ghaffour et al. 2013). Many MSF facilities are now being linked to SWRO plants in a hybrid configuration, because the high salinity of the Arabian Gulf water requires dilution if a single pass SWRO configuration is used (Awerbuch 2007). An MSF/SWRO blend produces an acceptable quality for potable use after post-treatment.

Operation of SWRO facilities using the Arabian Gulf for feed water has had a difficult history with all older facilities suffering from membrane biofouling to varying degrees (Hassan et al. 1989; Winters 1994, 1997; Winters and Isquith 1995; El Aleem et al. 1998). The very warm water temperature, limited circulation, and high degree of biological productivity collectively make the Arabian Gulf seawater difficult to treat; thereby, commonly resulting in membrane biofouling. Considerable research on pretreatment of Arabian Gulf seawater has been conducted to ascertain which methods provide the best results to control the rate of membrane biofouling (Winters and Isquith 1995; Matin et al. 2011; Nguyen et al. 2012). The open-ocean intake systems that are commonly used are also subject to fouling by marine growth at the intake and within the transmission pipeline. To control this growth, continuous chlorination has been used. Research on systems using continuous chlorination has shown that these systems have a greater rate of membrane biofouling (Applegate et al. 1989; Winters and Isquith 1995).

SWRO facilities in the Arabian Gulf almost exclusively use some type of surface-water intake system. Many of the hybrid plants use a common intake at the shoreline that is also used to supply cooling water to a co-located power plant and feed water for an MSF plant. Stand-alone SWRO facilities commonly use either a canal intake at the shoreline or a velocity-cap intake structure offshore. In all cases, the feed water is taken from the nearshore in relatively shallow water. The seabed slope is very low and it requires a pipeline of more than 10 km to get to deeper water of better quality. Harmful algal blooms are also a common occurrence in the Arabian Gulf and can cause temporary shut-down of SWRO facilities when they occur, such as the event that occurred in 2009 (Berktay 2011).

Another factor controlling membrane biofouling is the concentration of bacteria, natural organic matter (NOM), particularly the polysaccharides and transparent exopolymer particles (TEP). Biofouling of SWRO membranes has been linked to the concentration of TEP and other sticky polysaccharides in raw seawater (Berman and Passow 2007; Bar-Zeev et al. 2009; Berman 2010; Berman et al. 2011). TEP tends to coat or condition SWRO membranes and promote the formation of a biofilm by creating a sticky substrate that encourages attachment of bacterial cells

and by also providing a food source. It is a particularly significant issue in the Arabian Gulf.

Subsurface intake systems can provide a higher quality feed water by performing many of the pretreatment processes in the subsurface as water is forced through the seabed and travels in a coastal aquifer or artificial media to the pump intake (Missimer 2009; Missimer et al. 2013). Subsurface intake systems produce feed water with significantly lower concentrations of algae, bacteria, NOM, and TEP (Chap. 9). An investigation of the coastline of the Arabian Gulf of Saudi Arabia was conducted to assess the viability of using subsurface intake systems, either wells or galleries. A site-specific investigation was conducted to assess the technical feasibility of using a subsurface intake to supply a fish hatchery or a large SWRO facility.

12.2 Background on the Arabian Gulf

12.2.1 Geology of the Coast and Nearshore Zone of the Southern Margin of the Arabian Gulf

Because of the importance of the Arabian Gulf geology as a modern analog for ancient carbonate petroleum reservoirs, a considerable amount of data have been collected on the surficial carbonate and mixed carbonate and siliciclastic sediments. Purser (1973) provided a large number of technical papers that describe the shoreline geology and some of the nearshore bottom characteristics of the southern margin of the Gulf. Circulation and climate, including wind, temperature, and evaporation, play major roles in controlling sedimentation, diagenesis, and overall environmental conditions within the Arabian Gulf (Purser and Seibold 1973). The Arabian Gulf has a length of about 990 km, a maximum width of 370 km and an average depth of only 36 m (Kampf and Sadrinasab 2006). It is a very shallow water body with water over a depth of 70 m occurring only in a narrow zone through the Strait of Hormuz and running to the west off the coast of Iran and ending north of Qatar and many areas with a depth <20 m (Fig. 12.1). The surface area of the Arabian Gulf is about 239,000 km² (Emery 1956). It is generally classified as a semi-enclosed, marginal sea (Kampf and Sadrinasab 2006).

Overall, the Saudi Arabian coastline of the Arabian Gulf has not been studied in as much detail as coastal areas located further to the east, such as the Trucial Coast (United Arab Emirates). Emery (1956) produced a generalized map of the entire southern coast and nearshore of the Arabian Gulf. It shows areas of mud, sand, and rock along the Saudi Arabia shoreline and offshore. A later map shows the shoreline to be predominantly intertidal and supratidal flats with small bays containing muddy sediments and the shallow nearshore being covered with mixed carbonate and siliciclastic sands from an area parallel to the tip of Qatar and northward (Wagner and van der Togt 1973; Alsharhan and Kendall 2003). In the restricted water body between Saudi Arabia and Bahrain and southward into the area between Saudi Arabia and Qatar, the nearshore sediment types are more diversified and

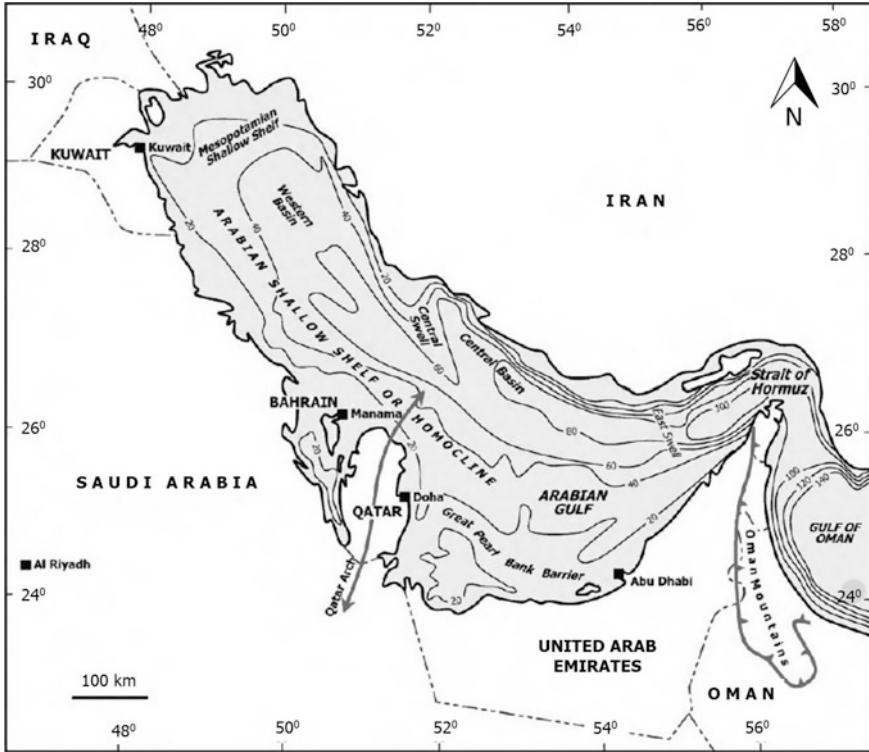


Fig. 12.1 General bathymetric map of the Arabian Gulf

muddier. Fryberger et al. (1983) describe the interplay at the shoreline of dune sand deposition, sabkha sediments, and offshore prograding mixed aeolian siliciclastic sand along the Saudi Arabia coast in the Dhahran area.

12.2.2 Circulation Within the Arabian Gulf and Impacts of Evaporation and the Freshwater Balance

Since the Arabian Gulf is a restricted water body, not open to typical oceanic circulation, it has some rather unique characteristics. Seawater travels from the Indian Ocean through the Arabian Sea Gulf and the Strait of Hormuz into the northern part of the Arabian Gulf off the coast of Iran (Kampf and Sadrinasab 2006; Fig. 12.1). The “fresher” seawater hugs the coast of Iran based on coriolis circulation. Since the Arabian Gulf has a very high evaporation loss rate and little freshwater enters it from ephemeral streams, much of the inflowing seawater evaporates and the more saline water leaves the Gulf as a density flow through the Strait of Hormuz (Swift and Bower 2003).

The nearshore area of Saudi Arabia has significant geographic and seasonal changes in salinity. The highest salinities found in the most restricted waters are over 46 ppt (Kampf and Sadrinasah 2006; Fig. 12.2). Yao (2008) found a similar pattern of the highest salinities in the western Gulf occurring in the winter months in a series of model simulations (Fig. 12.3). While the overall circulation patterns are greatly influenced by wind and salinity, the nearshore salinity pattern is influenced by the very high rates of

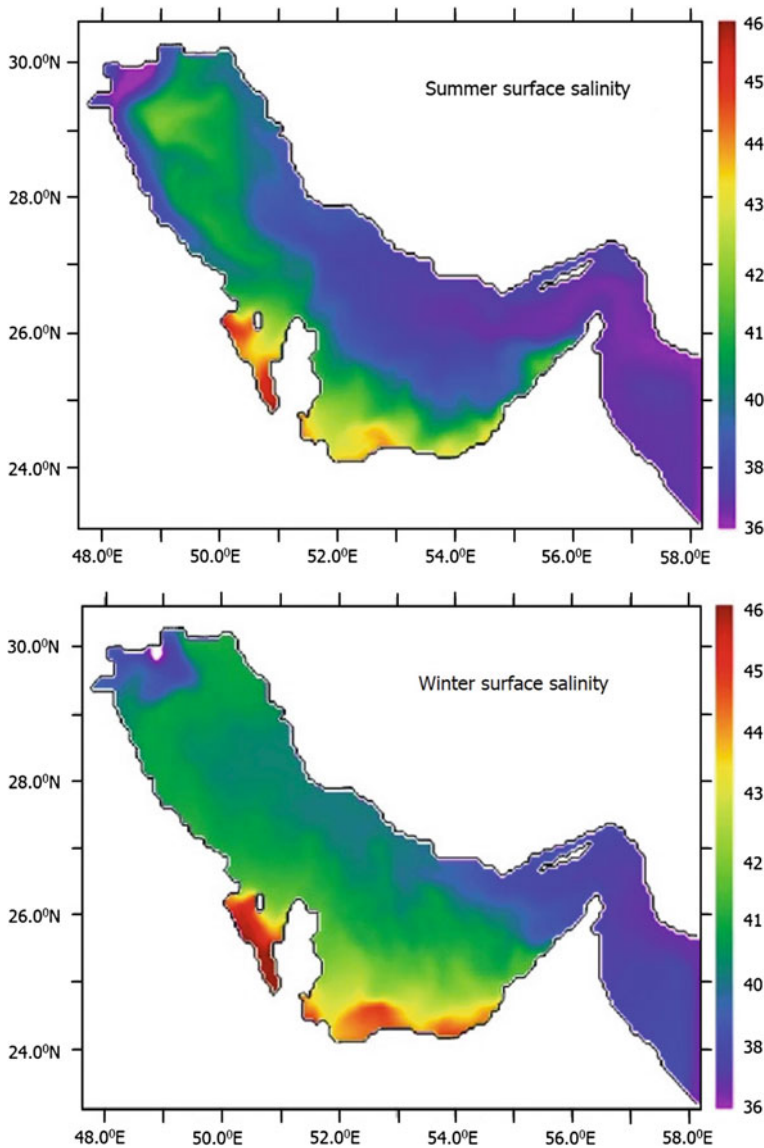


Fig. 12.2 Seasonal changes in distribution of salinity in the Arabian Gulf (Kampf and Sadrinasah 2006)

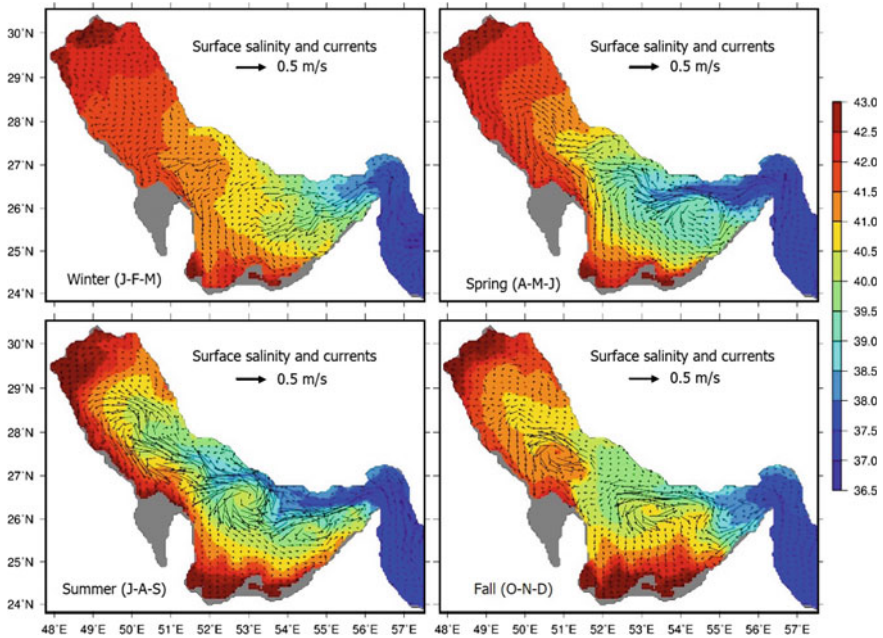


Fig. 12.3 Modelled salinity changes in the western Arabian Gulf showing the high nearshore salinities up to 46 ppt (from Yao 2008)

free-surface evaporation which can cause the formation of shallow water circulation cells. High evaporation rates can cause the formation of dense water flows along the bottom with seaward migration at calm periods or landward flows based on the predominant offshore wind direction during most of the year. The very high salinity and high saturation of calcium carbonate in the shallow seawater lead to the rapid marine cementation of bottom sediment with subsequent formation of extensive hardgrounds.

12.3 Methods

12.3.1 Literature Review on the Shallow Geology of the Shoreline and Nearshore Sediments of the Arabian Gulf with Emphasis on Factors that Affect Subsurface Intake Feasibility

A literature review was conducted on the surficial and shallow geology of the southern margin of the Arabian Gulf to assess shoreline and nearshore conditions. Particular emphasis was placed upon geological features that could potentially affect the development of a subsurface intake system that could be used to supply

feedwater for a SWRO facility. The key features for any coastal area were recently described by Dehwah et al. (2014). The type and mobility of the shoreline and nearshore sediments are very important as well as any coastal features that affect the quality of the groundwater near the beach and beneath the seabed (e.g., occurrence of sabkhas). The productivity in terms of coastal aquifer yield potential is another important issue. Also, oceanographic and climatic effects that may influence the quality of seawater in the nearshore also are of significance.

12.3.2 Investigation of a Specific Site Located at Ras Abu Ali Island, Saudi Arabia

A site-specific investigation was conducted by Rachman et al. (2014) at Ras Abu Ali Island, which is located north of Jubail between Ad-Dafi and Dawhats Al-Mussallamiyah, Eastern Province, Saudi Arabia (Fig. 12.4). The island has a



Fig. 12.4 Location of the site-specific field investigation at Ras Abu Ali Island, Saudi Arabia (from Rachman et al. 2014)

unique crescent shape with the outer section facing north where a proposed marine water intake system for a marine fish hatchery was proposed. The intake would have a required capacity of 6000 m³/d and is being developed as part of a marine conservation program initiated by Saudi Aramco, the world's largest oil company.

Initially, a simple open-ocean pipeline or dredged open-channel intake was proposed for a fish hatchery water supply. During design, some problems were discovered for both intake types. Water temperature fluctuated between 35 °C during late summer and 15 °C during early spring, and red tides and oil spill contamination were identified as potential threats that could 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. A 20 m deep monitoring well constructed on the beach revealed that the shallow groundwater, recharged by the sea, is hypersaline. The seaward-directed flow of brine from a sabkha causes the occurrence of hypersaline water that is inappropriate for fish larvae and hatchery conditions.

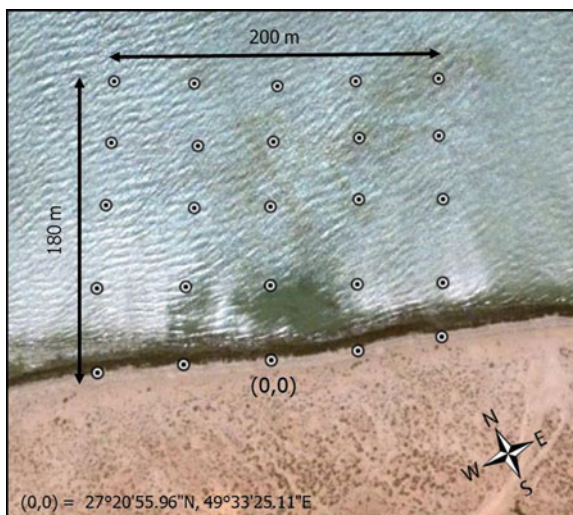
The offshore area near the hatchery and possible future SWRO plant facility was inspected to assess the bottom slope and condition (e.g., sediments, hardground, etc.). Also, the environmental sensitivity of the site was assessed by checking on the pattern of coral growth and occurrence of seagrass beds.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

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 a media 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 included the assessment of the shoreline and nearshore physical condition, including general characteristics of the marine bottom (sandy, muddy, rocky or combination), marine vegetation and coral distribution, wave action and tidal changes, and presence and thickness of unconsolidated sediment on the marine bottom. The latter evaluation is important because the upper layer of a gallery intake system would be affected by the native unlithified surface sediment as it moves across the gallery top. A preliminary engineering design of a system was made to assess the required surface area and for future cost estimates.

12.3.3 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 (Fig. 12.5). The sampling was organized within the grid system using a series of transects along which 35 samples were collected. At each point, unlithified surface sediment was collected and stored in a plastic container.

Fig. 12.5 Sampling grid used by Rachman et al. (2014) at Ras Abu Ali Island



Individual sediment samples were washed with fresh water having a neutral pH to remove the saline water and marine debris while conserving the mud content. After drying each sample, laboratory analyses of grain size distribution, sediment porosity, and hydraulic conductivity were made based on standard analytical methods as described in Tanner and Balsillie (1995), ASTM (2006), and Wenzel (1942).

12.4 Results of Initial Investigation

12.4.1 Site Description

The investigation conducted by Rachman et al. (2014) provided some very useful observations and results that have wide-spread use on ascertaining which subsurface intake types can be used along the coast and the nearshore of the Arabian Gulf. A preliminary field investigation revealed that the shoreline was covered with beachrock and an asphalt-like deposit (Fig. 12.6a). The beachrock was a tan color and was relatively hard. The black and goeey texture layer covered the beachrock and banded unlithified sediment in a layer 20–30 cm in thickness. The blacked area covered a belt within the intertidal zone about 10–20 m wide. It is believed that the oil spill during the Gulf War was the source of this material. Recent contracts have been awarded to remediate the beaches and intertidal area with removal of the oil contaminated sediments planned.

The nearshore marine bottom consists of predominantly a marine hardground with a veneer of unlithified muddy sand and carbonate sand (Fig. 12.6b). A subtidal (at high tide) marine-cemented limestone was observed all along the coast and seaward to the study area to water depths over 1 m. It extends at least 300–500 m

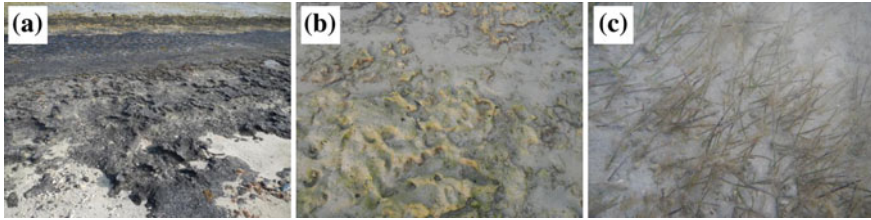


Fig. 12.6 Views of on-site conditions at Ras Abu Ali Island, Saudi Arabia. **a** Oil contamination deposited on the intertidal area of the beach. **b** Nearshore marine hardground with veneer of un lithified sediment. **c** Nearshore marine seagrass with generally sparse distribution (from Rachman et al. 2014)

from the shoreline (low tide point) seaward. Based on the field observations and literature review, the limestone is a marine-cemented, modern hardground. 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 mixed carbonate and siliciclastic sand sediment lying atop the hardground was found to vary, but follows a trend of increasing from the shoreline vicinity (less than 50 cm) towards offshore (up to 100 cm). Parts of the hardground are devoid of sediment.

No living corals were observed on the hardground from the beach seaward to a distance of over 500 m. Seagrass occurs in low density in a belt from near the normal low tide position to a distance 100 m seaward (Fig. 12.6c).

12.4.2 Unconsolidated Bottom Surface Sediment Characteristics

Un lithified sediment tends to migrate across the top of the seabed and it can affect the operation of a seabed gallery. Detailed assessment of the size and hydraulic characteristics of the un lithified sediment is therefore important in the selection of a gallery site and in the design of the gallery media.

The variation in the mean grain size is shown in Fig. 12.7a. The mean grain diameter, which is the first statistical moment of the sediment, ranges from 0.24 to 1.72 mm with an average of 0.48 mm. The sediment is classified as medium-grained sand according to the Wentworth-Udden classification (Pettijohn et al. 1987). From the grain size distribution, the mud content of the samples was found to be relatively low at <0.5 % and generally low for all samples which is less than previously suggested compositions of the sediment (Fig. 12.7b; Wagner and van der Togt 1973).

Porosity was also measured on sediment samples and the results are shown in Fig. 12.7c. The values range from 0.29 to 0.41 with an average of 0.35.

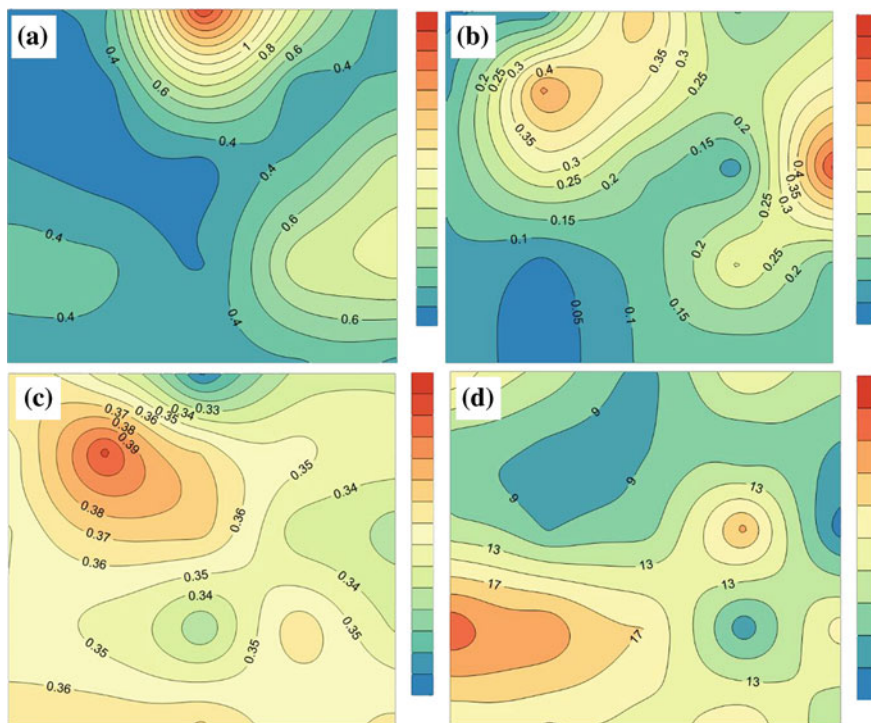


Fig. 12.7 Unconsolidated bottom surface sediment analyses results mapped in the study area **a** mean grain size, **b** mud percentage (decimal), **c** porosity (decimal), and **d** hydraulic conductivity (from Rachman et al. 2014)

The hydraulic conductivity measurements follow a similar pattern to the porosity values (Fig. 12.7d). Both properties are influenced by the percentage of mud in the samples. Hydraulic conductivity values range from 5.9 to 22.5 m/day and average 12.8 m/day.

12.5 Preliminary Seabed Gallery Design

12.5.1 General Site Feasibility for Seabed Gallery Intake Systems

Successful development of a seabed gallery intake system depends upon: (1) the type of the natural bottom sediments, (2) the sedimentation rate of fine sediments, (3) the tidal range (gallery must always be covered with water), (4) underlying site geology, (5) the impact on the marine ecosystem, and (6) stability of the nearshore marine bottom in terms of erosion and storm disturbance (Mantilla and Missimer 2014).

Table 12.1 Summary of study area characteristics in relation to key factors in 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 low 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

Groundwater quality issues can also have an impact on gallery design where hypersaline water can enter the gallery from the landward direction (Al-Mashharawi et al. 2014). Table 12.1 contains a summary of the site characteristics that are relevant to the design of a seabed gallery intake system at this location.

Two types of gallery intake systems are potentially feasible; beach and seabed (offshore) galleries. Beach galleries are constructed with the intertidal zone of a beach. The geology of the beach, in terms of the occurrence of certain sediment types, may not be significant because the gallery beds would have a fully engineered design developed to maximize efficient infiltration and treatment of seawater. However, rocky beaches or very high-energy beaches may not be appropriate locations for a beach gallery because the constructed filter bed could be eroded away. Also, some significant wave energy is required so that the mechanical energy of the breaking waves across the gallery surface causes cleaning of the gallery face. The risk of cementation calcium carbonate must be considered in areas where beachrock is actively forming.

The wide intertidal area and very low wave energy at the location investigated do not favor the construction of a beach gallery at this site. At low tide, the beach area would be located up to 500 m away from the gallery site, which would cause a short duration of the water covering the filter layer. This would give the facility a short daily duration of useful operation, would necessitate a greater gallery footprint to meet the required capacity, and may 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 gallery option that is most suitable with the conditions in the study area is a seabed gallery intake type that maintains continuous flooding.

Despite the low slope of the nearshore, a seabed gallery system could be successfully constructed and operated at a location seaward of the low tide elevation. An essential factor for gallery operation is that the filter must be submerged in water at all times with a desired depth of at least 1 m to provide continuous recharge and to maintain an acceptable salinity. Based on the low offshore slope and the position

of the normal low tide line, the seabed gallery would have to be located >500 m from the shoreline to provide adequate water depth under all conditions. Since the sediment studies conducted in the field at this site did not survey the area seaward of 500 m, the natural bottom sediment characteristics seaward area must be extrapolated. Therefore, it is assumed that similar sediment characteristics favorable for the development of a seabed gallery system occur in the area of deeper water. Past geological investigations in this region support this assumption (Emery 1956; Wagner and van der Togt 1973).

Location of the seabed gallery system at a considerable distance from the shoreline does complicate the construction and can increase capital cost. However, the very shallow water depth may allow a temporary artificial fill area to be constructed from the beach to the seaward site of construction, thereby lessening construction cost compared to using barges, driving sheet piling and dredging in deeper water.

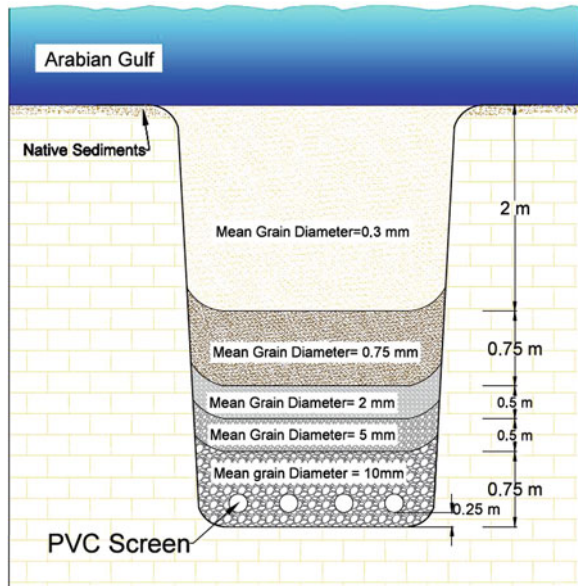
Maintenance of a slow sand filter is accomplished by manually by scrapping the filter top layer, which could also be accomplished in a seabed filter installed at a shallow water depth. Manual raking could be accomplished at low tide at this location. This effort becomes a challenging routine when the location is far offshore, especially if the water depth is great. In either case, special maintenance scheduling would have to be planned to allow safe access to the gallery (e.g., the low tide period providing that would provide temporary very shallow water between the filter location and the shoreline). Construction of a gallery intake at distance more than 500 m is technically feasible based on construction methodology, but may be very challenging based on capital cost.

12.5.2 Design of a Site-Specific Seabed Gallery Cell

A preliminary gallery design was proposed by Rachman et al. (2014) for Ras Abu Ali Island. The gallery filter system was designed similar to a slow sand filter, but with a thicker bed, greater hydraulic retention time and a generally more rapid infiltration rate. Typical slow sand filters operate at infiltration rates from 1.2 to 4.8 m/d and are constructed with media containing a mean grain diameter between 0.3 and 0.45 mm, and a head loss (gravitational) of 0.9–1.5 m (Huisman and Wood 1974). Slow sand filters in water treatment plants operate using gravity feed, but a seabed gallery filter is operated using pump suction. This allows more flexibility in terms of head loss and can allow greater variation in the design hydraulic retention time based on local water quality conditions.

Water treatment in a the gallery is determined to a large degree by the retention time inside the filter during which water undergoes physical and biological treatment by a series of processes, including size exclusion, adsorption, and bacterial breakdown (Huisman and Wood 1974; Ray et al. 2002; Missimer et al. 2013). The grain size and thickness of the uppermost layer and adequate retention time will collectively produce pretreatment. For example, the Fukuoka Desalination Plant

Fig. 12.8 Preliminary design of a seabed gallery for Ras Abu Ali Island, Arabian Gulf, Saudi Arabia (from Rachman et al. 2014)



utilizes seabed filtration with a 7 h retention duration, resulting in very high raw water quality with low silt density index, turbidity, and organic compound concentrations (Shimokawa 2012).

A preliminary design for the Ras Abu Ali Island seabed gallery system contains a 4.5 m gallery bed total thickness with the upper layer being 2 m thick (Fig. 12.8). The filter media design herein produces a retention time of 6 h, which was suggested by Rachman et al. (2014) because of the difficulty in treating Arabian Gulf seawater by SWRO. The retention time was estimated by considering the water passage through the upper 2 m active layer of the filter.

Design of the internal structure of the filter media was based on the average mean grain size of the natural bottom sediment. The composition of the unlithified sediment is a mix of skeletal carbonate sand and quartz sand with some coated grains. The mean grain diameter was about 0.3 mm, so the grain size of the media used for the top 2 m filter layer was also 0.3 mm to avoid any hydraulic intervention from clogging by smaller diameter grains. The lower layers of the filter are not very significant in treatment of the water, but have importance in supporting the filter and transitioning between the infiltration at the top and the extraction at the base. Design of the lower layers, including thickness and mean grain diameter, were based on the methodology described by Barrett et al. (1991). Care was taken to avoid top-down infiltration of finer sand into lower layers that would disturb uniform flow through the media (Barrett et al. 1991; Lujan and Missimer 2014). Therefore, the preliminary design contains 5 layers each with specific mean grain size and thickness. The head loss for passage of seawater through the media was estimated to be slightly less than 1 m based on the estimated hydraulic conductivity of the layers and the design

infiltration rate. The hydraulic conductivity of the layers was estimated based on the proposed grain size distribution using the spreadsheet program developed by Rosas et al. (2014). A second program was developed to include the water density and the infiltration rate to further refine the head loss through the filter.

Another important design aspect is the lowermost layer of the filter where recovery of the filtered water is captured by an underdrain system. Detailed design issues involved in achieving flow balance at the infiltration interface as controlled by the design of the underdrain system is covered in Chap. 11. The base layer in this case contains large mean grain diameter gravel with a corresponding high hydraulic conductivity (up to 100 m/day). The gravel has a mean grain diameter of 10 mm media, which will allow constant intake pumping via the PVC screen underdrains. A design summary of the gallery cells is contained in Table 12.2.

Operation of a seabed gallery is assumed to be long with possible periodic scrapping of the upper sediment surface to maintain the hydraulic conductivity of the media to mitigate clogging or cementation with calcium carbonate in the Arabian Sea environment. However, the seabed filter in Fukuoka Japan has been operated for 8 years without the need for upper layer refreshing (Shimokawa 2012). The self-cleaning process is likely associated with the sediment stirring effect from the wave activity and ocean currents, and bioturbation caused by sediment-ingesting benthic organisms that degrade and bind fine particles and organics as fecal pellets. These hard pellets have no detrimental effect on the hydraulic conductivity of the sediments because they act hydraulically like sand grains (Sesler and Missimer 2012).

The most reliable design configuration for a large capacity seabed gallery is to divide the capacity into a series of gallery cells, each equipped with one pump. Such a design approach was chosen by Rachman et al. (2014) for the Ras Abu Ali Island site. The preliminary design contains 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 proposed. The cell capacities are designed based on the larger requirements of a SWRO plant. One or two cells could be used to meet the lower fish hatchery requirements. The overall SWRO facility design capacity

Table 12.2 Gallery cell specifications

Parameter	Specification
Filtration rate	8 m/day
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	6 h

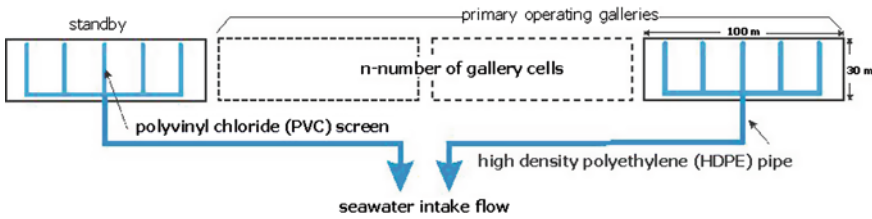


Fig. 12.9 Schematic showing a general configuration of multi-cell seabed gallery intake system (modified from Rachman et al. 2014)

considered is 54,000 m³/day of permeate. At a 45 % recovery rate, this would require 120,000 m³/day of raw seawater. Each cell was designed to provide 24,000 m³/day of filtered seawater with conservative 8 m/day infiltration rate provided by pump suction. Consequently, the required surface area is 3000 m², which designed to form 100 m × 30 m rectangular cell areas with the 100 m axis running parallel to the shoreline, thereby minimizing construction distance from the low tidal point. There are a large number of possible cell configurations and the choice in a final design would be based on the most cost-effective solution (Fig. 12.9).

12.6 Discussion

12.6.1 Unique Features of the Arabian Gulf and Subsurface Intake Feasibility

The Arabian Gulf has some rather unique features that provide challenges for intake design and limitations on what types of subsurface gallery intake systems that can be used. Salinity of the seawater is affected by circulation on a large-scale basis, involving the entire Arabian Gulf, and on a smaller scale basis driven by high rates of evaporation from the very shallow nearshore water. The slope of the offshore bottom is quite low. Therefore, access to deep water of a higher quality is quite difficult because it is located many kilometers from the beach. Another significant issue is the common occurrence of coastal environments that contain hypersaline water. Sabhkas and other supratidal or intertidal bodies are shallow evaporation basins which cause high salinity water to migrate seaward or occur at a location at which any type of induced hydraulic gradient would move the hypersaline water toward the pumping center. The high evaporation rates and natural high salinities of the nearshore waters also create high alkalinity within the seawater that promotes marine cementation of unlithified bottom sediment and reduces the hydraulic conductivity of the uppermost layer (Shinn 1969).

These features preclude the use of any vertical well type along a large part of Arabian Gulf coast of Saudi Arabia. Well intakes require a constant recharge rate which is limited by the normal tide range and the seaward position of the seasonal low tide which can be over 500 m seaward from the shoreline. A second issue is the common occurrence of hypersaline water directly beneath the beach area, inland from the beach, and possibly seaward of the beach to an unknown distance. All vertical wells produce a cone of depression that induces radial flow which would cause the high salinity water to enter the well along with normal salinity seawater. Also, the seawater salinity near the beach will likely contain higher salinity than the offshore seawater due to the very high evaporation rate and lack of adequate circulation within the shallow water.

Use of horizontal well technology is also questionable based on the very long distance required to construct the wells. The well screens would likely have to begin at a distance of over 500 m from the beach to assure that the marine bottom is always covered with seawater to maintain continuous recharge. Therefore, the length of the required horizontal systems would be very difficult and expensive to meet the required feed water capacity for large SWRO facilities. Another issue that must be considered is the potential for calcium carbonate precipitation within the horizontal well system. In conventional shallow wells, it is relatively easy to clean the scale using an acid treatment. However, the cleaning of a horizontal well system would be quite difficult, especially at the distal end of a screen located more than 500 m from the wellhead. Also, the hardground layers have a moderate to low permeability and contain higher permeability unlithified sand between cemented layers. It would be difficult to design and construct a horizontal well system that can produce predominantly from a high permeability zone within the shallow sequence.

The only possible well solution would be to construct an artificial peninsula into the Arabian Gulf and drill a series of vertical production wells to obtain the necessary raw water supply. This would be a similar system to that located at the South Corniche site in Jeddah (see Chap. 10). This type of system could potentially yield between 10,000 and 100,000 m³/d. The capacity would depend on a series of factors, including the seaward extent of the fill area, the number of wells constructed, and the yield of the individual wells. Additional capacity could be developed using a larger number of filled peninsulas.

A more flexible intake type for the conditions observed within the Arabian Gulf is some type of gallery intake system, either a beach or seabed design. Beach galleries would not likely be a widespread design solution because of limited area along the coast where suitable conditions are present based on normal design criteria as defined in Maliva and Missimer (2010). Some areas of the Arabian Gulf of Saudi Arabia do contain sandy beaches at which a beach gallery system could be feasible. Overall, the most likely subsurface intake system that is compatible with the geology of the Arabian Gulf is a seabed gallery system.

12.6.2 Compatibility of the Seabed Gallery with the Coastal Geology and Sediment Deposition in Relationship to Siting

It appears based on the geological literature that a significant part of the Arabian Gulf nearshore area of Saudi Arabia has high potential for development of seabed gallery intake systems. A large part of the area is covered by a marine hardground with a veneer of unlithified sediment lying on top of it. The seaward extent of the hardground has not been mapped, but at some sites the unlithified sediment component is more widespread and thicker. Production of carbonate sand offshore is not likely very fast, so there is a low potential for a seabed gallery to become buried with large quantities of carbonate sediment. Some areas of the coast do contain siliciclastic sand dunes that migrate to the shoreline and supply the offshore environment with sand due to the predominant offshore trending winds. Care would have to be taken in these dune areas to locate a seabed gallery a sufficient distance offshore to avoid being buried by aeolian sands.

Active areas of mud deposition occur within the restricted part of the Arabian Gulf located between Qatar and Saudi Arabia. Detailed oceanographic work in this area may be required before a seabed gallery system could be deemed to be feasible. Significant sedimentation episodes allowing carbonate mud to accumulate on the bottom atop a gallery could rapidly clog the filter top. The deployment of offshore sediment collection pans and general sediment studies would be needed in areas where the bottom contains muddy sediments.

12.6.3 Impacts of Marine Cementation on Gallery Placement and Design

Marine hardgrounds cover vast parts of the shallow nearshore of the Arabian Gulf (Shinn 1969). These areas are undergoing modern cementation with marine carbonate cements (aragonite and high-magnesium calcium carbonate). Some of the most active areas undergoing diagenesis are the beaches and intertidal zones where recent bottles and cans have been observed cemented into the limestone formed near the shoreline (Shinn 1969). A key design issue related to development of seabed gallery intake systems is to assess the position offshore where active cementation is either not occurring or is occurring at rates much lower than those in the intertidal areas. Typically, cementation occurs near the top of the sediment in offshore areas where active diagenesis is occurring with the most rapid rates occurring in the intertidal zones.

Since seabed gallery systems will move considerable volumes of seawater through the sediments, the calcium carbonate geochemistry of the water column

would need to be assessed at all times of the year. Slow cementation of the upper few centimeters of a gallery could be handled within the context of routine maintenance with the simple removal of the sediment or rock by mechanical or physical means. Robotic equipment has been designed to remove bottom hard precipitants from rapid infiltration ponds in the Orange County Replenishment District and such equipment could be used to control such a problem in the Arabian Gulf. The issue is the rate of rock formation, the degree to which formation lowers the vertical hydraulic conductivity (and thus infiltration rates) and the frequency of maintenance required.

12.6.4 Potential Salinity Issues in Design of Seabed Galleries

Very high evaporation rates in the shallow nearshore water of the Arabian Gulf could be a significant design factor in placement of a seabed gallery intake system. It is likely that a seabed gallery system would have to be sited at a location where some significant circulation of the water column occurs to disperse a higher salinity bottom layer. Along the southern shoreline of the Arabian Gulf, there is a seaward-directed density circulation with fresher seawater moving landward at the sea surface. Wind turbulence tends to mix the water as depth increases, so a balance must be achieved concerning the location of the gallery wherein “normal” seawater salinity occurs, which may be in the range of 38,000–45,000 mg/L. The area of the restricted circulation located between Qatar and the coastline of Saudi Arabia may tend to have high salinity compared to other areas of the Arabian Gulf and could affect the suitability for use as any intake for SWRO.

12.6.5 Capacity Limitations

A seabed gallery intake in the Arabian Gulf has no capacity limitation based on the existing geologic and water quality conditions. Using a modular design in coordination with the design of a SWRO facility, any number of cells could be developed to support a variety of intake capacities. Each cell could be equipped with a pump to give a system added operational reliability or more than one cell could be manifolded to one pump to reduce the number of pumps.

12.6.6 Pretreatment Economics

Successful operation of a seabed gallery intake in the Arabian Gulf will be based on the degree of organic matter removal and the savings in operating cost associated with the lesser degree of pretreatment required. Missimer et al. (2013) suggest that the complex pretreatment process train constitutes between 4 and 35 % of the

overall operating costs of a SWRO facility. The added capital cost associated with the design and construction of a seabed gallery system intake could be offset to a full degree if several pretreatment processes can be eliminated and the degree of membrane cleaning reduced. A thorough life-cycle analysis should be conducted to ascertain the overall cost reduction that would be experienced by using a seabed gallery intake. This would also assist in establishing the maximum capital cost that could be expended for the gallery intake versus a conventional open-ocean intake.

12.6.7 Research Needs for the Future

While considerable research has been conducted on the coastline of the Arabian Gulf in the United Arab Emirates, Qatar, Kuwait, and Bahrain, little research has been conducted on the Saudi Arabian coastline. Detailed mapping of the shoreline and nearshore areas needs to be conducted to ascertain the geological feasibility of using various subsurface intake systems. A recent investigation of the Red Sea coastline of Saudi Arabia has provided a planning level assessment of subsurface intake usage (Dehwah et al. 2014). This type of investigation along with some sediment data from the offshore environment would allow the use of subsurface intake options into new tender offers to construct and operate large SWRO facilities by reducing the tender risk.

Characterization of the organic chemistry of the Arabian Gulf needs to be accomplished to ascertain the not to optimum retention time for design of seabed gallery systems. This will require seasonal collection and analysis of water samples and analyses of algae, bacteria, TOC, NOM fractions, and TEP within the water column. Laboratory column experiments and local testing of one or more pilot systems should also be conducted to assess the effects of the media on rates of organic compound removal and degradation.

A life-cycle cost analysis should be conducted to provide guidance on the economic feasibility of seabed gallery intake systems for use in the Arabian Gulf. A series of scenarios could be developed to test the viability of replacing various pretreatment processes with consummate reduction in energy and chemical usage.

12.7 Conclusions

An analysis of the feasibility of using a subsurface intake system for SWRO facilities in the Arabian Gulf coastal region of Saudi Arabia shows that the most feasible method appears to be a seabed gallery system. Severe limitations occur, based on geologic and water quality conditions at the coastline, on use of all well intake systems. The only possible well intake type usable would be a multi-well system constructed on an artificial fill peninsula constructed into the sea. This design would also have some limitations.

The long-term difficulties in operating SWRO facilities using Arabian Gulf seawater suggests that using a type of subsurface intake system would provide a viable alternative to conventional open-ocean intake systems or a canal intake system. The reduction in algae, bacteria, TOC, NOM fraction, and TEP concentrations obtained using a gallery intake system suggest that such a system should be economically feasibility. An impediment to the implementation of seabed galleries is the limited documented operational history of such systems. Because of the very great costs of SWRO desalination of Arabian Gulf seawater, and operational advantages and cost savings of seabed galleries, a test system should be installed in the region as soon as practically possible. The system should be developed near one of the large capacity facilities with the intake water transported to a number of operating SWRO skids to conduct side-by-side testing.

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