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Mapping to assess feasibility of using subsurface intakes for SWRO, Red Sea coast of Saudi Arabia

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ABSTRACT

Use of subsurface intakes for seawater reverse osmosis desalination (SWRO) systems is known to improve raw water quality, reduce use of chemicals, improve operational reliability, and reduce the life cycle cost of desalination. A key issue in planning for the development of a SWRO facility that would potentially use a subsurface intake is the characterization of the coastal and nearshore geology of a region to ascertain the types of subsurface intakes that could be used and their respective costs. It is the purpose of this research to document a new methodology that can be used for planning and assessment of the feasibility of using subsurface intake systems for SWRO facilities at any location in the world. The Red Sea shoreline and nearshore area of Saudi Arabia were mapped and sediments were sampled from the Yemen border north of the Jordan border, a distance of about 1,950 km. Seventeen different coastal environments were defined, mapped, and correlated to the feasibility of using various types of subsurface intake systems. Six environments were found to have favorable characteristics for development of large-scale subsurface intakes. The most favorable of these coastal environments includes: (1) beaches and nearshore areas containing carbonate or siliciclastic sands with minimum mud concentrations and environmentally sensitive bottom community biota or fauna (A1, A2, and A3), limestone rocky shorelines with an offshore carbonate or siliciclastic sand bottom underlain by soft limestone and a barren area lying between the shoreline and the offshore reef (B1, B5), and wadi sediments on the beach (mixture of pebbles, gravel, and sand) with a corresponding nearshore area containing either siliciclastic sand and/or a marine hard ground (soft limestone or sandstone) (C2). It was found that seabed galleries were the subsurface intake type with the highest feasibility for development of large-capacity intakes. The geological characteristics of the offshore sea 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 (low wave activity). Detailed field investigations were conducted at four sites located along the Red Sea coast at the King Abdullah Economic City, Shoaiba, Om Al Misk Island, and Shuqaiq City. Some of the environments are adequate to allow use of conventional wells, angle wells, radial collector wells, or horizontal wells. However, these intake types have some capacity limitation along the Red Sea coastline. There are several medium to small capacity SWRO facilities that utilize conventional shallow well systems (beach wells) as intakes along the Red Sea coastline.

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Keywords: Seawater reverse osmosis; Subsurface intakes; Water system planning; Coastal mapping

1. Introduction

The supply of freshwater is becoming a pressing global problem; as the world population grows, water sources diminish in quantity and quality, and climate change affects various regions, altering the availability of supplies. As new sources of freshwater are sought, seawater desalination has become a greater part of the supply solution in many regions. Although it is energy intensive and expensive, seawater desalination offers the only water supply solution in many areas, and if the cost is reduced it could be applied to areas having less financial resources. Therefore, it is a goal of desalination researchers and the industry to reduce desalination cost by making the process more efficient and reducing energy consumption. Use of subsurface intake systems can simplify the pretreatment process train, and reduce the energy use, the need for chemicals, environmental impacts, and the overall operational cost [1–5].

There are a variety of subsurface intake systems that can be potentially used for intakes to a seawater RO facility. These intake types include conventional wells, slant wells, Ranney or radial collector wells, horizontal wells, beach galleries, and seabed galleries [2]. The feasibility of using one or any of these intake types is dependent on the geology of the specific site available to construct an intake. Therefore, it is necessary to understand and evaluate the coastal, shoreline, and nearshore areas to plan for the future development of seawater RO facilities, especially when a subsurface intake system is being considered.

It is the purpose of this paper to present a methodology that can be used to evaluate the coastline area to assess the potential use of subsurface intake systems. The coastal area of the Red Sea of Saudi Arabia is used as an example because Saudi Arabia is currently the largest user of seawater reverse osmosis (SWRO) desalination and many existing facilities occur along the Red Sea shoreline with more being planned. The methods applied herein can be used to characterize any coastal/shoreline area for short- or long-term SWRO facility planning, especially when a subsurface intake system isbeing considered for use.

2. Methods

A combination of methods was used to characterize the geomorphology of the Red Sea coastline of Saudi Arabia. This included a literature search, field visits to 105 sites, collection and analysis of 485 sediment samples, use of archived satellite images to classify various segments of the coast with groundtruthing provided by field site visits, photographs, and data georeferencing.

A literature search was conducted to assess past geologic investigations of the shoreline and nearshore sediments and the processes that affect these areas. Some of the investigations provided some localized details on the sediment types and general characteristics. The coastline has a wide variety of geomorphological types, such as sandy beaches, wadi sediment beaches, rocky carbonate shorelines, Precambrian Shield cliffs at the shoreline, lagoons and bays, mangrove/coastal marine wetland areas, offshore islands, and urban-modified shoreline areas.

Site visits and direct visual observations revealed the detailed coastal characteristics (Fig. 1). A series of sediment samples were collected, some of which occurred on the beach and others were collected from the offshore area in transects perpendicular to the shoreline. The qualitative nature of the shoreline and offshore sediments was recorded. Also, the presence or absence of a reef and the general wave height at the shoreline were also observed and recorded. Sediment properties were measured in the laboratory to assess mean grain diameter, mud percentage, porosity, and hydraulic conductivity at selected sites.

The geomorphological characteristics of the coastal area were assessed with respect to each type of potential subsurface intake system that could be potentially designed and constructed to provide feed water to a SWRO facility. A qualitative, planning-level assessment was also made concerning the possible range of system capacities that may be feasible. Site-specific, detailed feasibility assessments were conducted at four locations and were used to test the planning-level assessments [6–9].

3. Results

3.1 Geologic and geomorphological characteristics of the Red Sea coastline

The shoreline of the Red Sea contains a diverse set of physical conditions ranging from sandy beaches containing variable composition (carbonates and siliciclastics) [9–14] to wadi sediments (gravel, pebbles,

Fig. 1. Red Sea shoreline of Saudi Arabia showing the location of sites visited and sampled. Locations of some selected areas of the shoreline with mapped geomorphological zones are shown.

and boulders) [15] to rocky shorelines containing limestone [16–19] or Precambrian rocks to coastal lagoons, bays, sabkhas [20], and mangroves [21]. A large part of the nearshore area contains a fringing coral reef tract occurring with a transition from shallow nearshore barren carbonate sands with some patchy corals to a full coral reef tract in deeper water offshore [22,23]. Commonly, the beach and nearshore area contains modern beachrock and associated carbonate hardgrounds [24]. A Pleistocene-age limestone commonly occurs along the shoreline and sometimes forms a shallow offshore low-dipping shelf (<2 m of water depth) [16,17]. The carbonate environment is transected by siliciclastic sediments carried into the marine environment via wadi features. Where the wadi sediments form channel deposits or lobes, the reef tract does not exist and there is a transition between the terrigenous siliciclastic sediments and the carbonate sediments associated with the reef tract [12]. In some areas, the wadi sediments extending offshore have significant mud content. Lagoons and small bays are common along the shoreline and contain restricted muddy sediments with or without an associated offshore reef. Carbonate sand islands occur offshore with seaward reef growth unaffected by terrigenous sediment input. Mangrove shorelines occur in restricted water areas and along shorelines containing offshore mud shoals with both occurrences being common.

Some technical investigations have been performed on the coastal area and nearshore marine environment for the purpose of developing management plans and to assess anthropogenic impacts [25–27]. These geologic, geomorphological, and planning investigations have been combined with direct observations, collected sediment sample data, and satellite photograph observations to produce a geomorphological classification of the Red Sea coast of Saudi Arabia.

3.2 Classification and descriptions of Red Sea coastal/shoreline/nearshore geomorphic environments

The coastal environments of the Red Sea were grouped into 17 different classifications based on the topography at the shoreline, the type of sediment (rock, sand, and mud), the vegetation type at the shoreline, the general composition of sediment (or rock) in the nearshore, and the presence or absence of coral reefs (Table 1). Some grouping of environments was necessary because many subsystems could be defined within each general classification.

3.2.1 Sandy beaches and associated offshore environments

Three classifications of coastal systems were defined within this general category. There can be considerable variability in the detailed physical framework of these classifications and in offshore sediment or rock types.

A1 has a sandy beach, with or without a back-beach dune system. The beach sand can be composed of skeletal carbonates or siliciclastic sediments or a mix of these lithologies. No large pebbles or cobbles are present and the sand is devoid of any mud. In some locations, the beach sand is fully or partially cemented by modern marine carbonate cements (beach rock). The nearshore sea bottom contains predominantly sand, sometimes with a minor belt of slightly muddy sediments lying near the beach. The sand may sit atop a marine hardground (modern cemented sediment) or an older (Pleistocene-aged), soft, coralline reef complex. An offshore coral reef complex is present beginning in water depths ranging from 1 to 2 m.

A2 occurs at the shoreline of restricted water bodies, particularly shallow bays and coves. It has a sandy beach with no associated coral reef system. The beach sediment is mostly siliciclastic and the same is true for the nearshore bottom sands. In most cases,

Table 1
Geomorphological classifications of the Red Sea coastline

A. Sandy beaches
A1-Sandy beach with corresponding nearshore sand or slightly muddy sand, coral reef complex offshore
A2-Sandy beaches, restricted, with no reef
A3-Offshore island with nearshore sandy sediments and reef
B. Rocky shorelines
B1-Limestone rocky shoreline with corresponding nearshore sand and offshore coral reef complex
B2-Limestone rocky shoreline with nearshore muddy sediments
B3-Limestone rocky shoreline, nearshore deep water, no reef
B4-Rocky headland with offshore rocky bottom, no reef
B5-Rocky shoreline, wadi sediments nearshore, offshore reef
C. Wadi intersections
C1-Wadi sediments (boulders, pebble, and gravel) at shoreline, variable sand, gravel, and mud offshore with no reef
C2-Wadi shoreline sediments, nearshore marine hard ground, minor nearshore sand, coral reef offshore
D. Sabkha, lagoons, and mangrove
D1-Coastal sabkha shoreline and nearshore muddy sediments
D2-Muddy shoreline with lagoonal muddy sediments, nearshore sand, and offshore reef complex
D3-Muddy shoreline /lagoon/ supratidal sabkha with no reef complex
D4-Mangrove shoreline with nearshore muddy sediments
E. Others
E1-Shoreline reef complex dropping to deep water in the nearshore off-reef area
E2-Artifical channels or urban shoreline with artificially filled nearshore dropping to deep water nearshore
E3-Natural channel

the sand contains little or no mud at the shoreline, but may become muddier offshore.

A3 occurs on the beaches of offshore islands. There are many low-relief, emergent sand bodies occurring along the Red Sea coastline. These bodies are not generally associated with steep-relief islands containing a core of Precambrian rock (cliffed shoreline). They consist predominantly of clean carbonate sand devoid of mud and siliciclastic sediments. Commonly, the nearshore areas on the windward side of these islands are composed of carbonate sand containing a barren bottom, seagrass with variable density, or patchy coral colonies. The sand bottom transitions offshore into a coral reef complex. The bottom can also contain a thin veneer of sand setting upon a marine hardground or older, soft, reefal limestone.

3.2.2. Rocky shorelines and associated offshore environments

There are five classifications of the coastal zone that contain rocky shorelines. Three of these classifications have a limestone shoreline of likely Pleistocene age while the remaining two shorelines consist of Precambrian cratonic rocks (rocky headlands).

B1 has a limestone rocky shoreline that can be cliffed, angular, or consist of rock rubble. In some cases, there is a narrow belt of sand paralleling the shoreline that is either emergent or submergent. The nearshore is generally covered by carbonate sand of variable thickness, commonly sitting atop a soft limestone unit. Where the bottom is fully covered by sand, some marine grass or solitary coral may occur. Where the bottom is rocky, coral growth is commonly denser. The density of corals generally increases seaward until the fringing reef occurs in 1–3 m of water. The offshore sediment contains a low mud concentration, except in the presence of dense marine grass beds.

B2 is a limestone rock shoreline that tends to be cliffed and lies near a wadi feature. There is no reef tract and the nearshore sediments consist of sand, muddy sand, or mud.

B3 is a limestone rocky shoreline that is typically cliffed and may contain little or no very shallow water in the nearshore. Water depth from the rocky shoreline drops to over 2 m within less than 50 m offshore. In most locations, no offshore fringing coral reef is present.

B4 is a rocky shoreline that could be termed a headland. It consists of outcropping Precambian-age shield rocks that are cliffed or contain a very narrow beach. The nearshore and deeper-water offshore areas are rocky or strewn with large boulders. No coral reef is usually present, but solitary corals may grow atop of the rocks if the water is not turbid.

B5 is a combined rocky shoreline containing Precambrian rock or boulders along with wadi sediments in the nearshore and offshore in deep water areas. The wadi sediments consist of boulders, cobbles, pebbles, sand, and mud. The sediment composition is dependent on the slope of the alluvial fan channel or wadi that allows transport of the sediment to the shoreline and nearshore, and the drainage basin characteristics of the sediment source area.

3.2.3. Wadi intersections

Surface runoff originating inland enters the Red Sea via channels that occur on intersecting alluvial fans or from wadi channels. Flow in these channels is ephemeral, but when it occurs it is commonly a flash flood containing very high water velocities. The sediment load contains a variety of rocks and debris ranging from 50 cm in diameter to mud (>0.0625 mm). The sediments are highly unsorted when entering the shoreline or nearshore marine environment and can become better sorted when exposed to nearshore marine processes over an extended time period (wave action and currents). Therefore, they can be very muddy or sand-dominated depending upon the length of time that they reside in the marine environment.

C1 occurs where wadi sediments lie on the beach and in the nearshore area. Mud percentage is variable offshore, but commonly over 10%. No offshore coral reef is present because the mud carried to the marine environment by the wadis inhibits reef growth.

C2 occurs where wadi sediments on the beach contain a low mud percentage. The beach wadi sediments can be cemented into beachrock. The nearshore area contains wadi sediments that are commonly cemented into hardgrounds. Siliciclastic or carbonate sand blankets the offshore rock. Solitary corals grow on rock exposed on the bottom. The density of corals increases offshore with the reef tract beginning at 2–3 m of water depth. This environment occurs at some distance away from the mouth of a wadi intersection with the shoreline and contains low mud content.

3.2.4. Sabkhas, lagoons, and mangroves

A series of four environments occur along the Red Sea coast that have restricted water circulation and are the primary depositional areas for muddy and organic sediments. The classifications used are rather general and could be broken into many more based on slight differences. For example, most of the mangrove shorelines contain muddy inshore and nearshore sediments and no coral reefs. However, in some cases, the mangrove shorelines contain an outer series of mud banks within a lagoonal setting with a fringing coral reef further offshore.

D1 is a coastal sabkha that is in hydraulic connection with the sea. A sabkha is a supra-tidal to intertidal area wherein seawater is trapped during storms or high-tide events and the trapped water evaporates to produce hypersaline conditions, commonly with the precipitation of evaporite minerals occurring on the sabhka plain. In many cases, the sabkha environment is not directly connected to the sea and lies landward of a restricted water body, either a bay or lagoon. Sabkha sediment is characteristically muddy and may contain rock composed of gypsum, dolomite, or calcite.

D2 is a muddy shoreline commonly associated with a landward-lying sabkha that may contain a nearshore subtidal sand belt lying seaward of the mud shoals. It commonly has a fringing coral reef lying in slightly deeper water from 2 to 4 m. The sand belt may lie on a Pleistocene paleo-reef complex and may contain some mud from the shoals. There is a clear separation between the muddy bottom environment and the offshore fringing reef.

D3 is a muddy shoreline that does not contain a transition to sand and an offshore fringing reef. Commonly, the shallow nearshore bottom is covered fully or in part by marine grasses. The grasses contain abiots that produce some quantity of mud. Also, the very shallow water and the grass combine to trap suspended muddy sediments during windy conditions.

D4 is a mangrove shoreline that contains organic sediment deposits (peat) and trapped mud. The mangrove peat contains siliciclastic sediment trapped among the roots. The shallow nearshore areas are generally muddy and commonly mud shoals occur offshore of these areas. Sometimes the mangrove shoreline is associated with restricted water bodies, either bays or lagoons, and circulation is maintained by narrow channels to the sea. The shoreline and restricted bodies are covered by muddy sediments and some seagrass where circulation is sufficient to keep salinities within an acceptable range. Reefs do not occur in this environment, but can occur further offshore both north and south of the primary drainage channels.

3.2.5. Others

There are three additional environments which are natural (channel intersections) or man-altered systems. The man-altered systems are the result of development or practices that have fully changed the natural geomorphologic character of the shoreline.

E1 occurs in areas where there is a fringing reef complex lying immediately offshore from the coastline. There is no well-established beach. Where this environment occurs in a natural setting, the shoreline is rocky and no siliciclastic sediments have reached the shoreline from the interior by either water transport or aeolian processes. Reef growth occurs directly offshore where water depth increases rapidly from 0 to 5 m.

E2 is an environment created artificially by the purposeful filling of the entire inshore and shallow nearshore sand belt for seaside development (direct boating access and docks). In certain cases even the inner, shallow zone of the reef tract has been filled leaving only the deeper corals at depths greater than 5 m. This heavily altered environment is common in the Jeddah area.

E3 occurs within the channels that intersect with the sea. Most of these channels drain natural coastal lagoons and bays and provide circulation to these restricted environments. However, there are also a series of channels artificially dredged for connecting the sea to harbors or basins. Many of these channels transect the fringing reefs and other nearshore environments.

4. Discussion

4.1 Application of coastal geomorphological principals to siting of subsurface intake systems

Development of subsurface desalination systems requires that the area along the shoreline must have some coastal aquifer that has moderate to high hydraulic conductivity or a sandy beach with moderate wave activity or a shallow offshore area containing a sandy bottom with low mud content and slow rates of sediment deposition. The objective is to locate geologic conditions that are conductive to allow large volumes of seawater to pass through sediments or an aquifer to produce primary treatment of the raw seawater. Descriptions of the coastal geomorphological environments are described in Table 1 and the text and are shown in Figs. 2 and 3. These figures show some of the classified environments.

Sandy beaches with sandy offshore environments are favorable for development of large-scale subsurface intakes, such as gallery systems (A1, A2, and A3 in Table 1). Seabed gallery intakes are expected to produce high quantities of raw water in areas with low mud content in the nearshore sediments. The occur-

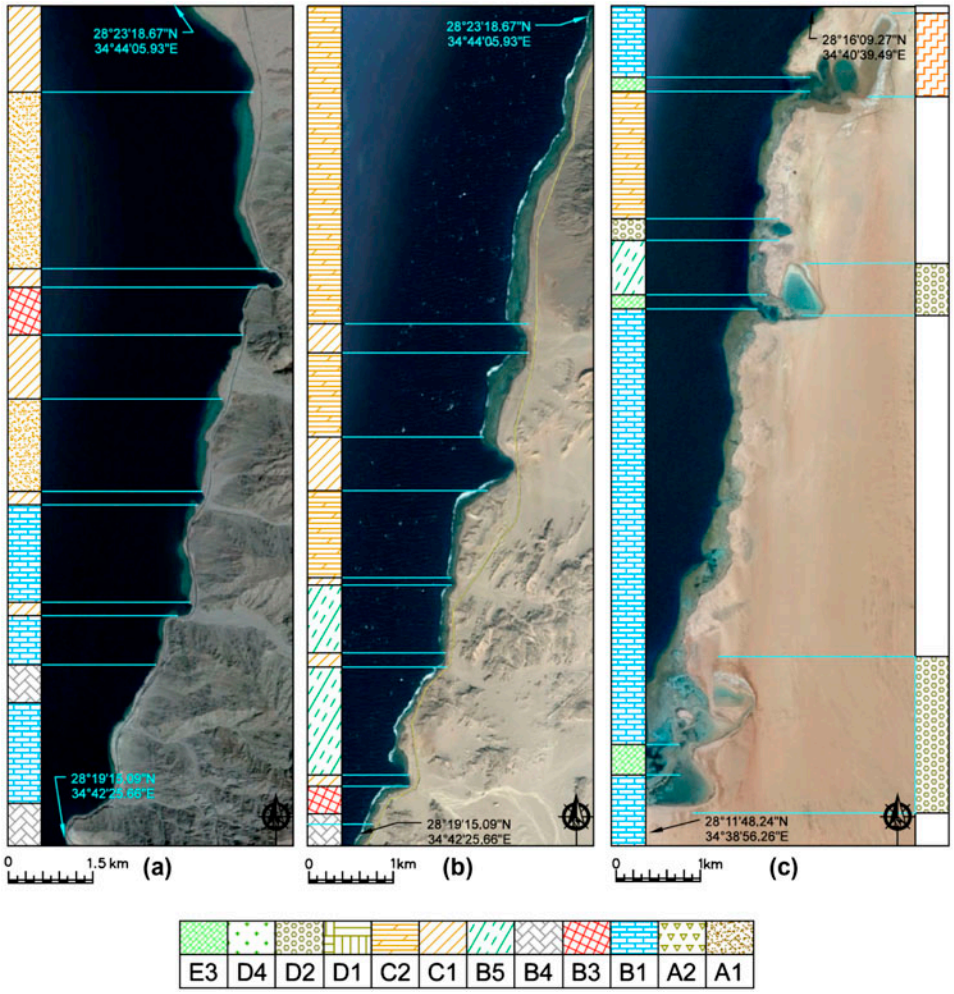

Fig. 2. Geomorphological map of selected segments of the Red Sea coast of Saudi Arabia (north).

rence of sandy sediments in the shallow offshore areas allows the development of seabed gallery intakes because it is indicative of high hydraulic conductivity of the natural sediments and low mud content, which could clog a constructed filter. On the other hand, a beach gallery system is preferable in areas with moderate wave activity and an active intertidal zone in order to perform the self-cleaning mechanism for the filter face [28]. Beaches with low or no wave action at the shoreline or restricted sandy beaches with poor circulation and low wave action are not favorable for constructing this type of intake. Some sandy bottom environments occur where the installation of gallery intake systems are not feasible due to the potential adverse environmental impacts (e.g. coral reef or marine grass beds occurrence) associated with the construction activities.

A sandy beach or combined sandy beach and limestone rocky shoreline or offshore environment may be also adequate for the construction of well intake systems. Vertical, angle, horizontal, or radial wells can produce moderate to large yields of feed water, especially in the presence of permeable rock and sufficient thickness of gravel and porous sand deposits underneath the coastal region. The yield of horizontal wells in these environments depends on the thickness of beach deposits as well as the lateral length (seaward) of the permeable sediment deposits. Use of angle wells requires some minimum thickness of permeable sediment in the nearshore area. Horizontal wells may be used when the thickness of permeable sediments and/or rock is relatively thin in the nearshore area (e.g. 5–10 m). In environments, such as restricted sandy beaches bordering sabkhas, wells may have low yields and the water may be hypersaline because of a hydraulic connection between the sediments and the sabhka brines. Construction of a well intake type is not

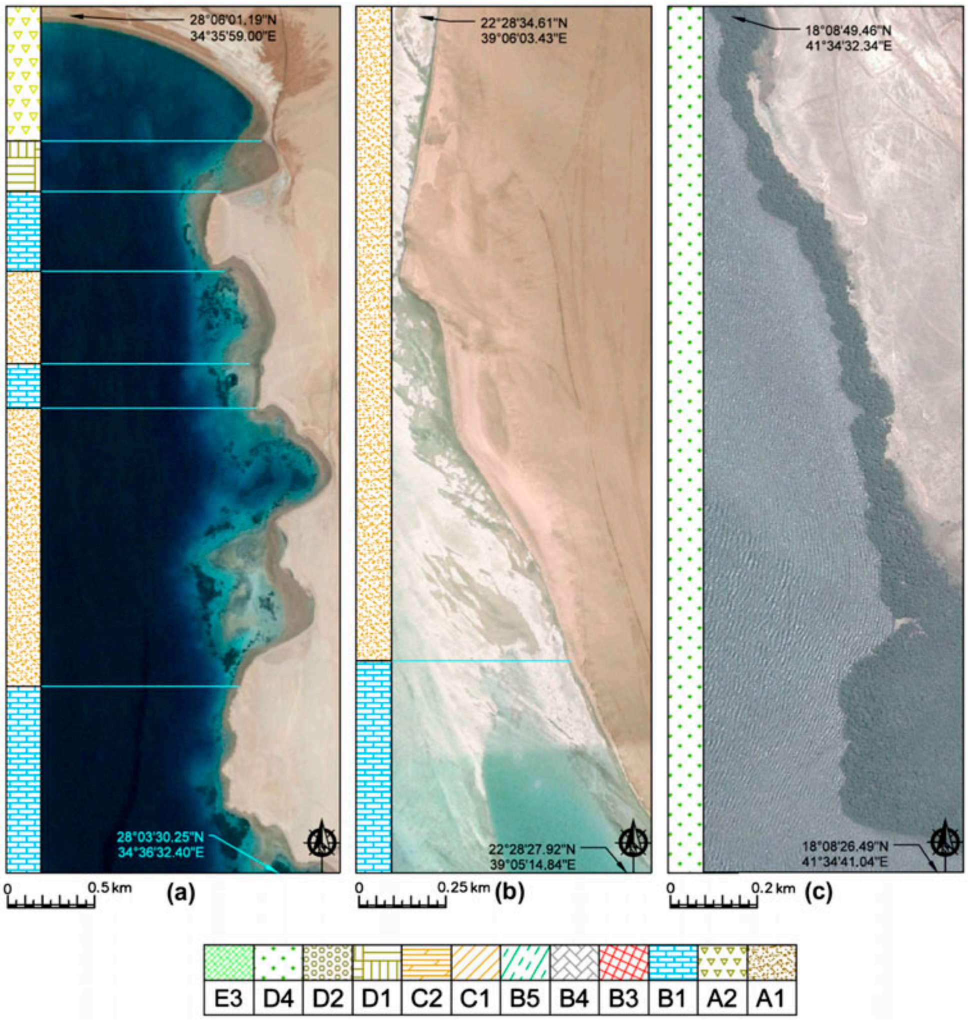

Fig. 3. Geomorphological map of selected segments of the Red Sea coastal of Saudi Arabia.

recommended at rocky or boulder-laden shorelines with high wave and storm activities, because subsurface galleries or wells would be potentially damaged by the wave action or erosion processes.

For large SWRO facilities, the utilization of vertical well intakes may not be economically feasible along many shorelines because of limited capacity obtained from an individual well, leading to the need for a large number of wells. Radial collector wells can potentially produce high feed water yields. The occurrence of thick permeable layers (e.g. gravel) at shallow depths will support the high yields from radial collector wells. The use of horizontal wells in sandy and limestone rocky environments can be questionable because very detailed and expensive investigations would be required to guarantee that the subsea geology would support the withdraw of high quantities of raw water.

Rocky shoreline environments containing limestone with corresponding nearshore sand or wadi sediments can also be feasible to construct gallery and well intake systems under the same conditions mentioned for the sandy environments, including moderate wave activity, low mud percentage, and sufficient thickness of beach deposits. Environments B1 and B5 commonly contain these conditions. Rocky shorelines with offshore rocky bottoms or nearshore muddy sediments or steep slopes to deep water are not feasible areas for development of subsurface intakes (environments B3 and B4). An exception may be a limestone shoreline with muddy nearshore sediments that has a shallow offshore area with a sandy bottom (B2).

Areas with wadi shoreline sediments, nearshore marine hardgrounds covered with a thin veneer of sand, and low mud percentage are feasible for gallery

Table 2
Correlation between coastal environment and feasibility of using various subsurface intakes along the Red Sea coastline

Intake type	Subsurface intake system					
	Well system				Gallery system	
Environments	Vertical	Horizontal	Radial (collector)	Angle	Beach gallery	Seabed gallery
A. Sandy beaches						
A1	1(b)	3	2(b)	2(b)	1(d)	1(d)
A2	1(a)	3	2(b)	2(a)	4	1(c)
A3	1(a)	3	2(b)	2(b)	1(d)	1(d)
B. Rocky shorelines						
B1	1(b)	3	1(b)	1(c)	1(c)	1(d)
B2	4	4	4	4	4	2(c)
B3	4	4	4	3	4	4
B4	4	4	4	4	4	4
B5	1(a)	3	2(b)	2(a)	2(c)	2(c)
C. Wadi intersections						
C1	4	4	4	4	4	4
C2	1(b)	3	2(c)	2(b)	2(c)	2(c)
D. Sabkha, lagoons, and mangrove						
D1	4	4	4	4	4	4
D2	4	4	4	4	4	4
D3	4	4	4	4	4	4
D4	4	4	4	4	4	4
E. Others						
E1	4	4	4	4	4	4
E2	4	4	4	4	4	4
E3	4	4	4	4	4	4

Feasibility factor: 1 = Excellent, 2 = possible, 3 = questionable, 4 = not feasible.
Estimated capacity (m^3/day): a. capacity < 20,000, b. 20,000–50,000, c. 50,000–100,000, d. Any capacity.

intake development (C2). On the contrary, shorelines that occur directly in front or nearby the mouth of the Wadi (C1) are not feasible for subsurface intake development due to the high mud concentration (clogging of the gallery intake) and the relatively high overall sedimentation rate that could bury galleries or destroy well heads in a storm event.

Construction of subsurface intakes in environments where there is a high mud concentration in the sediments and no water circulation (sabkha, lagoons, and mangrove) is not desirable due to the potential for clogging of the filter. The high organic content and high evaporation rate produce additional unfavorable conditions. All of the restricted and nearshore muddy shorelines or mangrove coasts are not feasible for development of subsurface intakes (D1, D2, D3, and D4).

Urban shorelines that were artificially filled out to the reef tract are considered to be not feasible for subsurface intake development due to the limitation on the availability of space for well and gallery construction (shoreline is adjacent to the deep water area) (E1). Other areas within or near artificial or natural channels also cannot be used because of a lack of adequate subsurface aquifer thickness (E2 and E3) and turbidity in the water column caused by human activities.

An assessment of the coastal environments of the Red Sea with a correlation to the possible use of various subsurface intake systems is given in Table 2. Some assessment of the limitation on capacity is also suggested.

5. Conclusions

The types of geomorphological environment, rock and sediment properties at the shoreline, and subtidal nearshore areas control the feasibility of using a subsurface intake system. Therefore, mapping of coastlines can be used to plan the location or to assess general feasibility of using a subsurface intake system for a SWRO facility. The characterization of the coastal environments should be the first step in evaluating feasibility of subsurface intakes in any coastal region. This will help decision-makers, planners, and the water industry to understand the nature of the coastal area in order to determine the potential for use of a subsurface intake for future development of SWRO facilities. During the mapping exercise, emphasis should be placed on investigating and mapping potential intake development sites located near populated areas that will require expanded use of desalination in the future. A site-specific detailed analysis and an extensive environmental evaluation would be required at later stages of the system development to assure that the potential sites would yield the required capacity.

The mapping of the Red Sea coastline of Saudi Arabia showed that the sandy beaches containing a low percentage of mud and limestone rocky shorelines with corresponding nearshore sand and wadi sediments with low mud content are the most favorable environments for use of subsurface intakes. Seabed galleries were found to be the preferred subsurface intake type for large-capacity desalination facilities based on the geology. Conventional wells or horizontal wells could be used at shorelines containing limestone cliffs and reefs, but the relatively small thickness of these deposits is a limitation on potential system capacity. Nearshore or coastal wadi sediments not associated with a channel can also be used to develop low-capacity well intake systems. The use of the other types of well intakes along the Red sea coastlines requires a thorough assessment of geology to avoid the risk of not obtaining the required capacity.

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References

[1] T.M. Missimer, Water Supply Development, Aquifer Storage, and Concentrate Disposal for Membrane Water Treatment Facilities, 2nd ed., Schlumberger Water Services, Sugarland, TX, 2009.
[2] T.M. Missimer, N. Ghaffour, A.H.A. Dehwah, R. Rachman, R.G. Maliva, G. Amy, Subsurface intakes for seawater reverse facilities: Capacity limitation, water quality improvements, and economics, Desalination 322 (2013) 37–51.
[3] B. David, J.-P. Pinot, M. Morrillon, Beach wells for large scale reverse osmosis plants: The Sur case study, in: Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse, November 7–12, 2009, Atlantis, The Palm, Dubai, UAE, IDAW/DB09-106, 2009.
[4] N. Voutchkov, Thorough study is key to large beach-well intakes, Desalin. Water Reuse Q. 14(1) (2005) 16–20.
[5] A.T.M. Jamaluddin, A.M. Hassan, A.A. Reweli, M.O. Saeed, Operation of Al-Birk plant introducing beachwell intake system, Technical Report. Saline Water Desalination Research Institute, Al-Birk Plant, Saudi Arabia, 2005.
[6] K. Sesler, T.M. Missimer, Technical feasibility of using seabed galleries for SWRO facility intakes and pretreatment, IDA J. 4(4) (2012) 42–48.
[7] A.H.A. Dehwah, T.M. Missimer, Technical feasibility of using gallery intakes for seawater RO facilities, northern Red Sea coast of Saudi Arabia: The king Abdullah Economic City site, Desalin. Water Reuse, doi:10.1080/19443994.2013.770949
[8] L.R. Lujan, T.M. Missimer, Technical feasibility of using seabed galleries for seawater RO intakes and pretreatment: Shoaiba, Red Sea, Saudi Arabia, in: Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse, Tianjin, China, 2013.
[9] D. Mantilla, T.M. Missimer, Feasibility of constructing a seabed galley system to supply the Shuqaiq-II SWRO facility in Saudi Arabia, in: Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse, Tianjin, China, 2013.
[10] N.V.N. Durgaprassada Rao, A.K.A. Behairy, Nature and composition of shore-zone sediments between Jeddah and Yanbu, eastern Red Sea, Mar. Geol. 70 (1986) 287–305.
[11] H.H. Roberts, S.P. Murray, Gulfs of northern Red Sea; depositional settings of distinct siliciclastic-carbonate interfaces, Am. Assoc. Pet. Geol. Bull. 67(3) (1983) 541.
[12] L.J. Doyle, H.H. Roberts, Histories of coexisting reefs and terrigeneous sediments; the Gulf of Elat (Red Sea), Java Sea, and Neogene basin of the Negev, Israel. in: G.M. Friedman (Ed.), Carbonate-Clastic Transitions, Developments in Sedimentology (42). Elsevier, Amsterdam, 1987, pp. 77–97.
[13] S. Al-Rousan, M. Rasheed, F. Al-Horani, R. Manasrah, Geochemical and textural properties of carbonate and terrigenous sediments along the Jordanian Coast of the Gulf of Aqaba, J. Oceanogr. 62 (2006) 839–849.
[14] M.A. El Sabrouti, Texture and mineralogy of the surface sediments of Sharm Obhur, West Red Sea coast of Saudi Arabia, Mar. Geol. 53(1–2) (1983) 103–112.
[15] A.B. Hayward, Coastal alluvial fans (fan deltas) of the Gulf of Aquaba (Gulf of Eilat), Red Sea. Sediment, Geol. 43(1–4) (1985) 241–260.
[16] A. Manaa, Late Pleistocene raised coral reefs in the eastern Red Sea—Rabigh, Saudi Arabia, research thesis, School of Earth and Environmental Sciences, University of Wollongong, 2011, http://ro.now.edu.au/theses/3501.
[17] A.K.A. Behairy, Marine transgressions in the west coast of Saudi Arabia (Red Sea) between mid-Pleistocene and present, Mar. Geol. 52 (1983) M25–M31.

[18] S.S. Al-Sayari, C. Dullo, H. Hotzl, A.R. Jado, J.G. Zotl, The quaternary along the coast of the Gulf of Aquaba, in: A.R. Jado, J.G. Zolt (Eds.), Quaternary Period in Saudi Arabia, 1984, vol. 2, Springer, New York, NY, 32–47.

[19] H. Hoetzl, Coastal region from Dhuba to Yanbu al Bahr; general topographical and geological considerations, in: A.R. Jado, J.G. Zolt (Eds.), Quaternary Period in Saudi Arabia, 1984, vol. 2, Springer, New York, NY, 60–66.

[20] A.M. Gheith, Mineralogy and diagenesis of coastal sabkhas sediments of the hypersaline lagoons on the eastern coast of the Red Sea. Saudi Arabia, Arab Gulf J. Sci. Res. 17(2) (1999) 199–219.

[21] M.A. Khan, A. Kumar, A. Muqtadir, Distribution of mangroves along the Red Sea coast of the Arabian Peninsula. Part 2. The southern coast of western Saudi Arabia, Earth Sci. India 3 (2010) 154–162.

[22] A.K.A. Behairy, C.R.C. Sheppard, M.K. El-Sayed, A review of the geology of coral reefs in the Red Sea, United Nations Regional Seas Reports and Studies No. 152 (1992).

[23] G.M. Friedman, Geology and geochemistry of reefs, carbonate sediments, and waters, Gulf of Aqaba (Elat), Red Sea, J. Sediment. Petrol. 38(3) (1968) 895–919.

[24] H.H. Roberts, S.P. Murray, Developing carbonate platforms; southern Gulf of Suez, northern Red Sea, Mar. Geol. 59(1–4) (1984) 165–185.

[25] P. Skipwith, The Red Sea and coastal plain of the Kingdom of Saudi Arabia, Technical Research T.R. 1973-1, Directorate General of Mineral Resources, Jeddah, Saudi Arabia, 1973, p. 149.

[26] O. Monnier, A. Guilcher, The Sharm Abhur, Hedjaz submarine valley, Red Sea: Geomorphology and impact of urbanization, Annales de Geographie, 569 (1993) 1–16 (French).

[27] A. Al-Gain, J.R. Clark, T. Chiffings, A coastal management program for the Saudi Arabian Red Sea coast, in: Proc. Symp. Coast. Ocean Manage, 5(3) (1987) 1673-1681, Fifth symposium on Coastal and Ocean Management, Seattle, Washington, USA.

[28] R.G. Maliva, T.M. Missimer, Self-cleaning beach gallery design for seawater desalination plants, Desalin. Water Treat. 13(1–3) (2007) 88–95.