

Chapter 7

Coastal Evaluation and Planning for Development of Subsurface Intake Systems

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Abstract The feasibility of using a subsurface intake system for a seawater reverse osmosis (SWRO) water treatment plant is based on the site-specific hydrogeologic conditions which control the type of intake design that can be used and the capacity of the intake. Planning for future development of subsurface intake systems requires a careful analysis of the shoreline and shallow offshore area. Example regions, the Red Sea coast of Saudi Arabia and the shoreline of Florida (USA), were investigated to develop general feasibility criteria for possible development of SWRO intake systems. Within the Red Sea, it was found that various well intake systems could be feasible for low-capacity SWRO facilities and high capacity intake systems would be limited to seabed gallery intakes. Coastal Florida had more subsurface intake options available, including wells, beach galleries, and seabed galleries which could be used based on the required capacity and the specific site conditions. The presence of high transmissivity carbonate aquifers containing seawater in Florida would allow medium capacity SWRO systems to use conventional vertical wells. High capacity systems could be developed using beach gallery systems in many locations. The methods developed for shoreline and nearshore evaluation contained herein could be applied to any coastal region of the world for subsurface intake evaluation.

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7.1 Introduction

The intake system for a seawater reverse osmosis (SWRO) desalination facility is a critical part of the overall system design in that a specific volume of seawater must be delivered to the plant. Feed water flow to the plant must be reliable and have the best possible quality at all times of operation. Variation in water quality caused by extreme natural events, such as harmful algal blooms (HABs), or anthropogenic events, such as an oil spill, can lead to plant shutdowns or damage to the treatment process. SWRO facilities using surface or open-ocean intakes (Chap. 1) are subject to temporary shutdown during these events. An HAB occurred in the Arabian Sea and Arabian Gulf in 2009 and shut down many large SWRO plants by overwhelming the pretreatment processes (Berktaf 2011).

Natural seawater contains a wide range of constituents. Variable concentrations of algae, bacteria, and organic compounds occur in seawater, which tend to cause operating difficulties in SWRO plants, in particular biofouling. Feed water quality ranges from quite high with a minimal concentration of organic material to greatly impaired with high turbidity and concentrations of bacteria and biopolymers. Variations in organic compound concentrations are very common on a season or even daily basis. Therefore, feed water obtained via open-ocean intakes requires extensive pretreatment before it can be transmitted into the primary membrane process, otherwise the facility will suffer difficulties with membrane fouling, either physical or biofouling (Flemming 1997; Flemming et al. 1997). The intensity of pretreatment is a major cost factor in the operation of SWRO facilities, and despite extensive pretreatment, many SWRO plants still have problems with membrane biofouling (Matin et al. 2011).

Subsurface intake systems used for SWRO facilities have been proven to provide significant feed water quality improvement and reduced pretreatment requirements resulting in operational and economic benefits (Missimer 2009; Missimer et al. 2013; Rachman et al. 2014). However, use of subsurface intake systems is highly dependent on the geology and hydrogeology of the coastal area including the beach and nearshore belt paralleling the shoreline. Use of subsurface intake systems for SWRO feed water development should be considered in all facilities regardless of capacity, because of reduced cost of treatment, reduced environmental impacts, and lower chemical usage (Missimer et al. 2013).

The shoreline and nearshore environments are perhaps the most dynamic areas on Earth. Therefore, the location and construction of any intake system in this area (even open-ocean intakes) requires careful analysis and planning with particular attention given to the changes that can be anticipated during the operational life-expectancy of a SWRO facility which is a planning horizon normally ranging from 20 to 30 years. It is the purpose of this chapter to develop an approach for coastal mapping and system development planning to assess the general feasibility of using various types of subsurface intake systems, including vertical wells, angle wells, horizontal wells (or collectors), Ranney wells (or collector wells), water tunnels

with laterals, beach galleries, and seabed galleries. This technical approach must be considered as screening and once a general intake location is determined, a site-specific investigation would be required.

7.2 Methods

Coastal mapping for an initial assessment of the feasibility of specific types of subsurface intakes requires detailed analysis of the coastal geomorphology and the development of a coastal classification scheme relating specific environments to the use of various intake types. Coastal geomorphology reference texts provide classifications of coasts based on shoreline geology, offshore conditions, bottom profiles, intensity of normal wave activity, frequency and intensity of potential storm impacts and other factors (Sunamura 1992; Davis and Fitzgerald 2003; Davidson 2010). Classification schemes have been developed from the geology and process assessments at a number of global locations, such as coastal California and Florida (Inman and Nordstrom 1971; Tanner 1960). Each coastline contains a unique set of environments that characterize it and no single classification can be uniformly applied to all global shoreline systems. A second aspect is to superimpose and assess the desired intake system within a framework of engineering design within the coastal zone. This requires consultation with a standard coastal engineering reference (e.g., Sorensen 2005; Kamphuis 2010).

As an example, a combination of methods was used by Dehwah et al. (2014) to characterize the geomorphology of the Red Sea coastline of Saudi Arabia. The Red Sea contains a large number of seawater desalination facilities ranging in capacity from 5,000 to 200,000 m³/day and numerous additional facilities are being planned and constructed (Hoepfner and Lattemann 2002). Therefore, this is an important region for study of subsurface intake system feasibility.

The scope of the research included a literature search, field visits to 105 sites (Fig. 7.1), 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 of the shoreline and nearshore bottom, and data georeferencing. Aerial mapping was used to compile and classify the coastline. Field inspection, review of geologic maps, and analysis of satellite photographs were collectively used to define the large-scale features of the coastline, such as the occurrence of rocky headlands associated with active tectonism, marine carbonate terraces (limestone) with a cliffed geometry, presence or absence of fringing coral reefs, occurrence of ephemeral stream intersections with the coast, the occurrence of beachrock, the occurrence of marine hardgrounds in the shallow subtidal areas, and any evidence of erosion or accretion of the beach. Sensitive environmental features were mapped, such as the distribution and density of corals and seagrasses. Finer details were also assessed on a limited scale, such as the thickness and composition of unlithified sediment at various locations. Sediment samples were collected at representative sites for laboratory analysis of grain size distribution, hydraulic



Fig. 7.1 Map showing the Red Sea coast of Saudi Arabia with the sites visited and sampled (from Dehwah et al. 2014)

conductivity, and porosity. Overall, the Red Sea coastline of Saudi Arabia is very complex, containing a large number of geomorphological environments.

The characteristic geomorphological environments of the coastal area were assessed with respect to each type of 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 systems capacities that may be feasible. Site-specific, detailed feasibility assessments were conducted at five locations and were used to test the planning-level assessments (Sesler and Missimer 2012; Dehwah and Missimer 2013; Lujan and Missimer 2014; Mantilla and Missimer 2014; Al-Mashharawi et al. 2014). Progressively, the information base on this coastal area was improved to allow a general classification scheme to be developed with a relatively high degree of accuracy for initial feasibility screening.

A second classification scheme was developed for a much less complex shoreline, the full coastline of Florida. This is another region that has very large population growth in the coastal zone with limited future development of freshwater resources caused by saltwater intrusion and potential wetlands impacts. Evaluations were based on the past work of Tanner (1960) linked with various subsurface intake types.

7.3 Coastal Mapping and Subsurface Intake Evaluation of the Red Sea Coast of Saudi Arabia

7.3.1 Geologic and Geomorphological Setting

The Red Sea is a restricted-circulation water body that is characterized by low tidal fluctuation ranges, minimal wave activity at the shoreline, and a low frequency of comparatively low-intensity storms (Morcos 1970; Pedgley 1974; Sofianos et al. 2002; Sofianos and Johns 2003). Therefore, it is considered to be a low-energy system in terms of wave transport of sediment in the coastal zone. However, the Red Sea coastal area of the Saudi Arabia has a large number of geomorphological environments, because it is an area of active tectonism associated with the Red Sea spreading center (Bosworth et al. 2005). The tectonism is responsible for the occurrence of grabens and horst features in the offshore areas (Chap. 6, Fig. 6.3) and the occurrence of steep rocky headlands and uplifted marine terraces at the shoreline (Figs. 7.2 and 7.3). Steep-gradient and low-gradient ephemeral streams drain the Precambrian craton into the nearshore and deep water of the Red Sea (Chap. 6, Fig. 6.3).

The tropical nature of the Red Sea stimulates fringing coral reef growth along nearly the full-length of the coastline (Bemert and Ormond 1981; Colontani and Taviani 1982; Head 1987; DeVantier and Pilcher 2000). Active carbonate sediment production, transport, and marine lithification occur within and landward of the reef system and in some cases to the shoreline. The beach is commonly covered with beachrock and the nearshore area from the beach seaward to the inner margin of the reef tract is commonly a marine hardground.

7.3.2 Coastal Geomorphological Classification System

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, 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. If was necessary to group a number of similar sub-environments into a single category, because of their similarities and the objectives of the research.

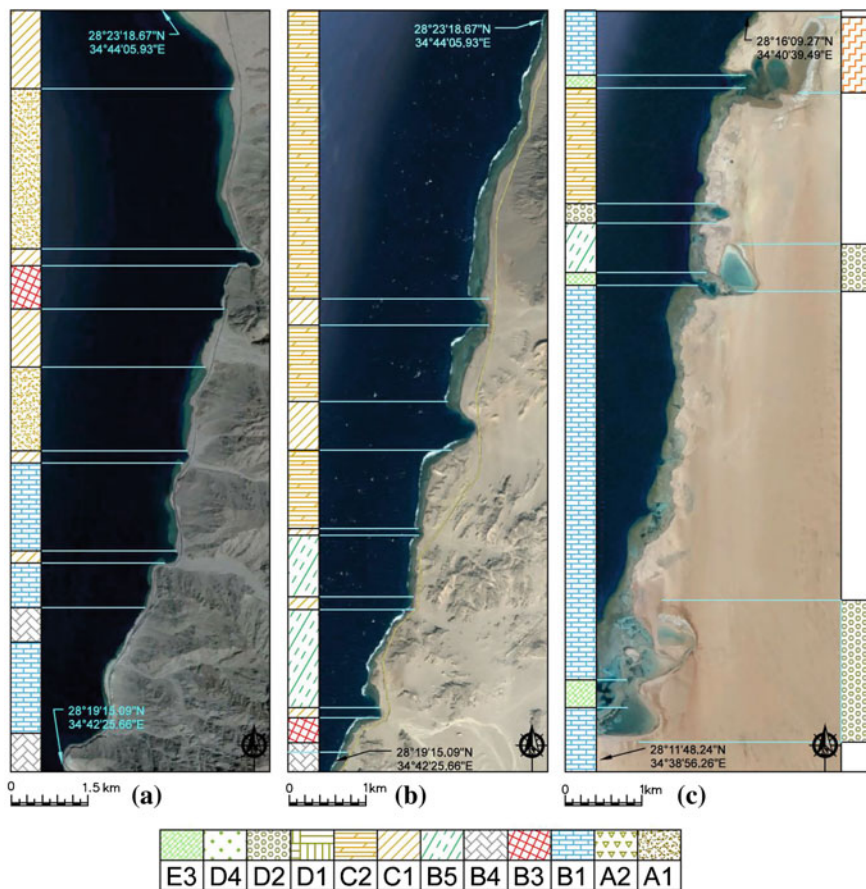


Fig. 7.2 Examples of the coastal mapping and resulting classifications along the Red Sea coastline of Saudi Arabia (from Dehwah et al. 2014)

The five general classifications include sandy beaches, rocky shorelines, wadi intersections, muddy shoreline (sabkhas, lagoons, and mangroves), and others. Each major classification is subdivided into two to five subcategories based on other criteria. A summary of the classifications is presented in Table 7.1 and a detailed description of each environment is contained in Dehwah et al. (2014). An example showing part of the Red Sea coastline of Saudi Arabia with the associated classification is given in Fig. 7.2. Note that the letter and number in the figure correspond to the key in Table 7.1.

7.3.3 *Linkage Between Subsurface Intake Type and the Geomorphological Coastal Classification*

The geomorphological classifications and assessments of the various subsurface intake types are given in Table 7.2. The data in the table has been modified to a degree from that originally presented by Dehwah et al. (2014). New data have been obtained at some sites and some re-evaluation was done. Also, the water tunnel subsurface intake type was omitted from the evaluation, because the equipment to construct this type of intake structure is not readily available in this region and this type of system is not appropriate for the general geology.

There are obvious and tenuous linkages between the coastal geomorphological environments and the development of subsurface intakes. For example, all of the environments within general classifications D and E in Table 7.1 contain muddy, low permeability sediments and some contain sources of hypersaline water, such as sabkhas (Gavish 1980; El Abd and Awad 1991; Missimer et al. 2014b). These

Table 7.1 Geomorphological classifications of the Red Sea coastline of Saudi Arabia (from Dehwah et al. (2014))

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

Table 7.2 Correlation between coastal environment and feasibility of using various subsurface intakes along the Red Sea coastline of Saudi Arabia (modified from Dehwah et al. 2013)

Intake type	Subsurface intake system					
Well/gallery	Well system				Gallery system	
Environments	Vertical	Horizontal	Radial (collector)	Angle	Beach gallery	Seabed gallery
A. Sandy beaches						
A1	1(b)	2	2(b)	2(b)	1(d)	1(d)
A2	1(a)	3	2(b)	2(a)	4	1(c)
A3	1(a)	2	2(b)	2(b)	1(d)	1(d)
B. Rocky shorelines						
B1	1(b)	2	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 (m³/day): (a) Capacity <20,000, (b) 20,000–50,000, (c) 50,000–100,000, (d) Unlimited

coastal environments are not conducive to the development of a subsurface intake system. Only an offshore, open-ocean intake could potentially be developed where these environments dominant the coastline. However, in some locations there are islands located offshore from lagoonal or sabkha environments. These islands, such as Um Al Misk Island, may contain very good sites for one or more subsurface intake types (Sesler and Missimer 2012).

To understand the limitations of some of the well intakes, it is necessary to provide additional information on the nature of some of the sandy beach and rocky shoreline environments. For example, the beachrock and marine terrace limestones located along the coast are limited in thickness within a range of 5 to 60 m in general. Therefore, vertical wells will tend to have limited yields based on aquifer thickness and likely transmissivity. At wadi intersections with the coast, the sediment consists

of particle sizes ranging from boulders to mud. Vertical and horizontal wells can be constructed using normal drilling methods through this material. However, the construction of horizontal wells through material containing boulders up to 25 cm in diameter creates potential deviation issues during drilling and potential for breakage of equipment and the primary screen. Even where the coastal aquifer contains limestone or a combination of limestone and un lithified carbonate sand, the feasible use of horizontal drilled wells is open to question because there are breaches through the limestone in the offshore area, which could cause short-circuiting of water into the wells, thereby providing no significant treatment. The breakthrough of algae into the horizontal intake system at Alicante, Spain is likely caused by vertical conduits into the limestone aquifer (Rachman et al. 2014).

Rocky headlands, classified as sub-environments B4 and B5, are outcrops of Precambrian shield rocks. This material has a very low hydraulic conductivity and the development of any type of subsurface intake in these environments is not feasible.

Another issue that affects well construction along the Red Sea coast is the occurrence of hypersaline water in the coastal plain near the shoreline and, in some cases, under the beach (Missimer et al. 2014a). The origin of this high salinity water is the common occurrence of the sabkha environment which is a supratidal system in which spring high tide water is trapped landward of a shallow berm. The water does not completely circulate back to the sea and intense evaporation takes place, causing the development of hypersalinity and precipitation of salt and gypsum. Some of this hypersaline water tends to flow in the subsurface toward the sea and beneath the beach area. Use of conventional vertical wells can pull this water into the wells, rendering it unusable as feed water to a SWRO system. Perhaps a solution to this issue would be the use of an angle well if the aquifer is sufficiently thick to produce enough distance from the beach to create primarily vertical recharge to the well through the seabed with little or no capture of water from the landward direction. Dehwah et al. (2014) and Al-Mashharawi et al. (2014) describe a hybrid well intake system constructed upon an artificial fill area jutting seawater onto the reef tract with subsequent construction of vertical wells on the fill. The production wells are actually located offshore and away from the source of hypersalinity (Fig. 7.3). Such a solution would not be viability in many parts of the world due to environmental permitting restrictions that prohibit filling of marine bottomlands, especially on a reef tract.

The coastal classification scheme developed for the Red Sea shoreline of Saudi Arabia provides general guidance to the location of subsurface intakes. However, it does not fully define any capacity limitations that may occur at a specific site. To supplement the database on subsurface intake feasibility, a series of field and laboratory investigations were conducted at 5 locations within the beach and nearshore areas (to water depths of 2 m) (Sesler and Missimer 2012; Dehwah and Missimer 2013; Lujan and Missimer 2014; Mantilla and Missimer 2014; Al-Mashharawi et al. 2014). These investigations were conducted near sites containing large-capacity SWRO facilities and were used to assess the feasibility of primarily seabed galleries. The strategy of mapping and limited-scope site-specific field investigations could be used to improve the database of any coastline that has potential use for SWRO intake development.

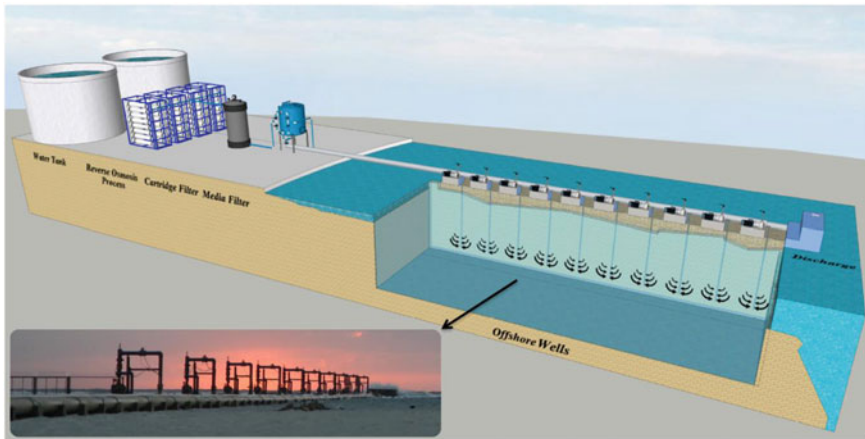


Fig. 7.3 Offshore wellfield intake (SAWACO facility) located south of Jeddah along the Red Sea coast of Saudi Arabia (from Al-Mashharawi et al. 2014)

7.4 Coastal Mapping and Subsurface Intake Evaluation of Coastal Florida, USA

7.4.1 Introduction

Florida lies within a subtropical area that receives an average annual rainfall of about 1,500 mm/year. Compared to the average rainfall of the Red Sea coastline at less than 60 mm/year, one could question why the State of Florida would require seawater desalination to meet water supply requirements. Currently, Florida faces water management challenges associated with rapid urban growth in its coastal zone, saline-water intrusion into coastal freshwater aquifers, and a rather sensitive internal environment with issues related to wetland impacts (Florida Council of 100, 2003). Florida is one of the leading regions globally in the use of brackish groundwater desalination and has one large capacity SWRO facility. The Tampa Bay Water facility is the only desalination system that uses a surface intake system in Florida and the plant has been plagued with membrane fouling problems.

It is anticipated that Florida will develop a number of SWRO systems in the future to diversify water supplies. Therefore, it is important to make a preliminary assessment of the coastlines to ascertain the potential development of subsurface intakes for SWRO facilities. Also, HAB's are common along the shoreline of the Gulf of Mexico and a subsurface intake system is a good method to avoid system shutdowns.

7.4.2 Coastal Geology and Geomorphological Classification Based on Energy and Depositional Environment

A summary of major and minor geomorphological classifications for the coastline of Florida is presented in Table 7.3. There are five major classifications and 1–3 subcategories under each major one. The classification system is primarily based on geomorphology and shallow geology. However, the underlying deep geology also must be considered when assessing potential subsurface intakes in Florida.

The vast majority of the shorelines of Florida are sandy beaches along the eastern coast facing the Atlantic Ocean and the western coast bounding the Gulf of Mexico. These beaches can be classified based on energy (A1 – A3) using the average wave heights and associated induced littoral processes. Tanner (1960) developed a useful coastal classification and demonstrated that most coastal areas contain sandy beaches with variable rates of sediment transport, but a low energy shoreline lies along the Gulf of Mexico shoreline north of Tampa within an area known as the “Big Bend” (Fig. 7.4). This area contains muddy sediments along the shoreline and contains the delta of the Suwannee River which along contributes some fine-grained sediment to the coast during floods. This area also contains some coastal marshes. An expansion of the Tanner (1960) classification system is given in Table 7.3.

A small segment of the Florida East Coast in Martin and Palm Beach counties contains a cliffed shoreline. The Anastasia Formation outcrops along the beach in some areas and the associated beach profile shows a beach sloping to a 1–2 m wave-cut bench and a rapid decline into deep water from the bench to the offshore area (Fig. 7.5). This is only a minor area within the entire coastline.

Table 7.3 Coastal classifications of Florida

A. Sandy beaches
A1. High energy beaches (Atlantic)
A2. Moderate energy beaches (Gulf of Mexico)
A3. Low Energy beaches (Gulf of Mexico and islands in Florida Bay and Ten Thousand Islands)
B. Rocky shorelines
B1. Limestone cliffed
C. Shallow shelf with fringing reef
C1. Restricted low energy beach
C2. Restricted muddy lagoon and mangrove swamps
D. Muddy or mixed mud and sand
D1. Lagoonal/deltaic shorelines
D2. Mangrove shorelines
D3. Coastal marshes
E. River or channel intersections
E1. River intersections
E2. Natural inlet intersections
E3. Man-made channel intersections

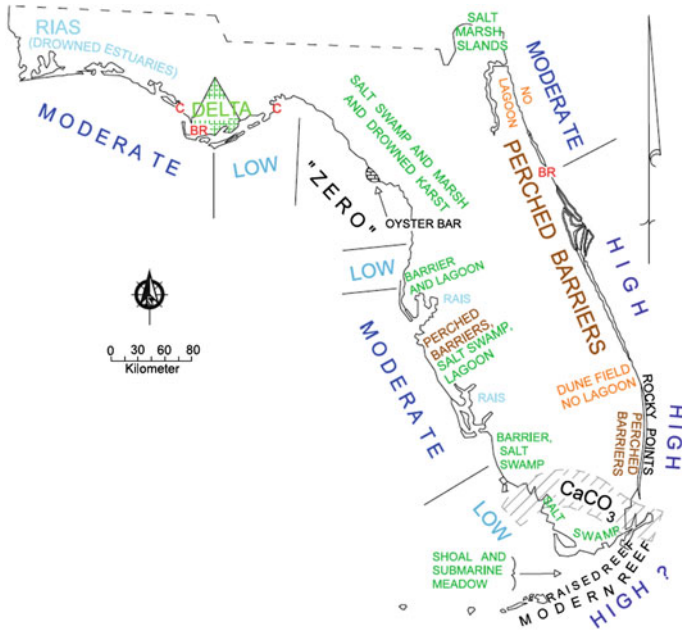


Fig. 7.4 Coastal classification of Florida based on wave energy (modified from Tanner 1960)



Fig. 7.5 Photograph of the outcrop of the Anastasia Formation in Martin County, Florida

The Atlantic margin of the Florida Keys contains some restricted-circulation low energy beaches with an offshore fringing reef. The shorelines along the land mass of the island chain has some sandy beaches and the offshore contains carbonate sands. However, some of the areas between islands and the shorelines of some islands contain mangroves and some muddy sediment. The western margin of the Florida Keys borders Florida Bay which contains predominantly muddy sediments.

There are a large number of lagoons and mangrove forests lying along the coastal areas of Florida. Most of these areas are bounded on the seaward margin by barrier islands that contain high to moderate energy beaches. However, along the southwest coast of Florida south of Marco Island to Florida Bay, the coastal lagoons and mangrove forest environments lie directly along the coast and contain a considerable amount of muddy sediment. Within the Big Bend area north of Tampa, some segments of the coast contain saltwater marshes (*Spartina*) north of the growth range for mangroves. This area also contains muddy sediments.

There are a number of channel or stream intersections with the shoreline along the Florida coast. These intersections with the coast are commonly unstable in terms of beach sediment movement, particularly in high energy areas (e.g., Florida East Coast). Some of the river intersections like the Suwannee and Caloosahatchee rivers contain mud deposition at their mouths. Overall the areas immediately near the associated high-energy unstable shoreline or within mud deposition areas are not viability for subsurface intake development.

A unique feature of the Florida peninsula is that many coastal areas are underlain either at shallow or deep depths by high permeability carbonate aquifers. Therefore, when assessing the viability of subsurface intakes, these aquifers, which commonly contain seawater, are highly productive in terms of yield and can support the use of a well intake system regardless of the nature of the surficial sediments. However, while conventional shallow, vertical “beach” wells can be used in places like the Florida Keys, deep vertical or angle wells might be used to develop feed water in areas like the “Big Bend” where the shallow sediments are muddy.

7.4.3 Linkage Between Coastal Classifications and Subsurface Intake Feasibility

A preliminary assessment of feasibility for development of subsurface intakes for SWRO facilities in Florida is given in Table 7.4. There are three key criteria that are considered within the assessment given; the intake type must produce the desired quantity of water reliably over the life-cycle of the facilities, the water quality must be stable and must show improved quality in comparison to surface seawater, and it must not impact coastal freshwater resources (particularly groundwater).

Development of SWRO intakes in the high to moderate energy shorelines of Florida has a high degree of feasibility over a wide range of capacities. Shallow wells could be used in certain areas where the underlying aquifer contains seawater and

Table 7.4 Correlation between coastal environment and feasibility of using various subsurface intakes along the coastline of Florida

Intake type	Subsurface intake system						
	Well systems					Gallery systems	
Environments	Vertical (deep)	Vertical (shallow)	Radial collector	Horizontal	Angle	Beach	Seabed
A. Sandy beaches							
A1. High energy	1(a–c)	1(a, b)	1(b, c)	2	1(b, c)	1(d)	1(b–d), 3
A2. Moderate energy	1(a, b)	1(a, b)	1(a–c)	1(a–c)	1(a, b)	1(a–c)	1(a–d)
A3. Low energy	1(a, b)	3	3	4	1(b, c)	1(b–d)	1(b–d)
B. Rocky shorelines							
B1. Limestone cliffed	1(b–d)	1(a, b)	1(b–d)	4	3	4	3
C. Shallow shelf with fringing reef							
C1. Restricted low energy beach	1(a)	1(a, b)	1(c)	2	3	4	1(a–c)
C2. Restricted lagoon and mangrove swamp	4	4	4	4	4	4	4
D. Muddy/mixed							
D1. Lagoonal/deltaic	4	4	4	4	4	4	4
D2. Mangrove	4	4	4	4	4	4	4
D3. Coastal marshes	1(a, b) ^a	4	4	4	1(a, b) ^a	4	4
E. Channel intersections							
E1. River	4	4	4	4	4	4	4
E2. Natural inlet	4	4	4	4	4	4	4
E3. Man-made channel	4	4	4	4	4	4	4

Feasibility factor: 1 Excellent, 2 Possible, 3 Questionable, 4 Not feasible

Estimated Capacity (m³/day): (a) Capacity <20,000, (b) 20,000–50,000, (c) 50,000–100,000, (d) Unlimited

^aIn locations where the underlying Floridan Aquifer Systems contain high permeability and seawater

has adequate hydraulic conductivity. Large capacity wells could be developed along the southeast Florida coast and areas further to the north. Care would have to be taken not to impact the freshwater resources. High-capacity seawater wells could be used in conjunction with saline-water intrusion control in some areas (Fig. 7.6).

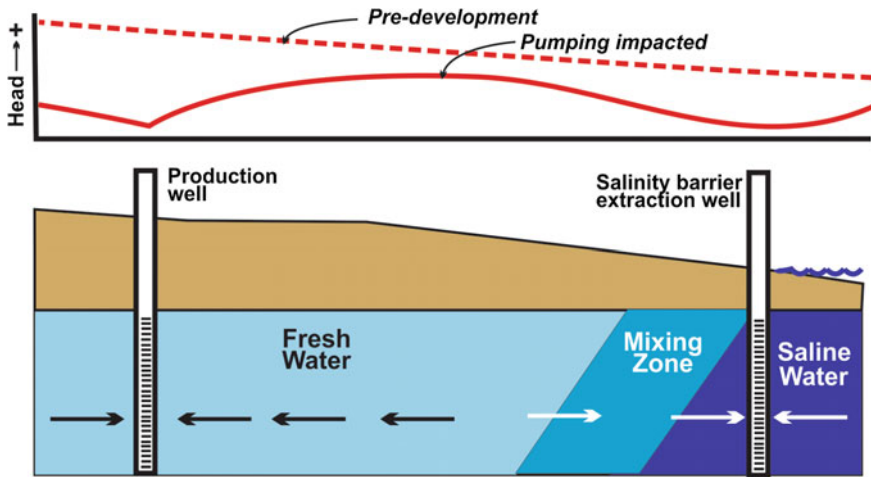


Fig. 7.6 Diagram showing the use of seawater extraction in the coastal zone to inhibit saltwater intrusion into shallow aquifers

Shallow well development would be more limited along the western Florida coastline and would tend to be feasible for only low capacity systems because of potentially low aquifer yields. The use of deep aquifer seawater wells would be feasibility along a large part of the Florida coastline, but the depths may have a wide range from perhaps 350 to 1,000 m. Also, the well capacities would vary greatly depending upon which aquifer with the Floridan Aquifer System that could be used. For example, the Boulder Zone in southern Florida could yield very large quantities of raw water, sufficient to supply SWRO plants with capacities over 100,000 m³/day. High yield aquifers from Tampa northward along the west coast could also produce very high capacities. The key issue is to carefully develop the Floridan Aquifer System without interfering with freshwater resources lying further inland. For example, the Tampa Bay SWRO facility uses a surface intake system, but a deep Floridan Aquifer System series of seawater wells could have been installed to meet the required capacity and would not have interfered with management of the freshwater resource. Angle wells could have been used to keep the intake of the wells further seaward from the freshwater/seawater interface if necessary.

Radial collector wells are another potential intake solution along a large part of the Florida coastline. Placement of the caisson at depths ranging from 20 to 60 m below surface could allow laterals to be extended into shallow, high-productivity aquifers, such as the Biscayne Aquifer, to create very large yield wells (e.g., 25,000–80,000 m³/day).

Galley intake systems could be very productive, especially beach galleries located along reasonably stable parts of the shoreline (see Chap. 10) (Missimer et al. 2014b). The use of offshore seabed galleries, which can be developed to meet virtually any capacity system, is perhaps most suited for moderate energy shorelines where there is no significant quantity of mud deposition. The location of seabed

galleries is limited in areas that have a steep offshore profile because of construction limitations based on economics. Some areas of the rocky shoreline along the Florida East Coast contain some steep offshore profiles that would not be conducive to seabed gallery development.

The only segment of the coastline containing a fringing reef system is located in the Florida Keys. Along the eastern margin of the islands that constitute the Florida Keys, there are a series of low energy sandy beaches and a low gradient seaward sloping, sandy bottom. The offshore area could be used to develop seabed gallery intakes where there is no significant occurrences of coral or seagrass. A seabed gallery intake could serve virtually any capacity SWRO plant if located in this area.

Development of subsurface intakes in areas that contain muddy sediments is unlikely with a few exceptions. The coastal marsh sediments located in the “Big Bend” area with a low energy shoreline are underlain by high permeability carbonate rocks occurring with the Floridan Aquifer System. Within upland environments, deep wells could be drilled into the aquifer system where it contains seawater. These wells would likely contain very high capacities that could support a wide range in SWRO plant capacities.

Development of large-scale SWRO facilities along the northeast Florida coastal area has been under consideration for many years. Because of the issue of impingement and entrainment and the overall cost of SWRO, these plans have been delayed. Since the cost of treatment would be lowered if a subsurface intake system would be used, it is timely to ascertain what types of intakes could be developed. In this area, deep angle wells tapping seawater in the upper Florida aquifer would be an option as well as high capacity beach galleries (Maliva and Missimer 2010). Seabed galleries may also be considered if the offshore bottom slope is sufficiently low to allow economic construction.

7.5 Discussion

7.5.1 Geological Control of Coastal Aquifer Yields and Potential Use of Well Intakes

Classification of coastal environments is a useful exercise to allow preliminary screening of the overall feasibility and potential viability of various types of subsurface intake systems. The occurrence and potential yield characteristics of coastal aquifers can be used to assess feasibility of conventional vertical wells, which are commonly termed “beach wells”. The study areas chosen for analysis, the Red Sea coast of Saudi Arabia and the Florida coastlines, have mixed results in terms of potential use of shallow well systems. Along the Red Sea coast of Saudi Arabia, well intake systems with low yields may be developed if the local aquifer does not contain hypersaline water. In Florida, high capacity wells could be locally used for feed water supply, if they have no impact on interior parts of the aquifer system that

contain fresh water. Both angle wells and radial collector wells have high potential in Florida for development of SWRO intakes. However, these subsurface intake types do not appear to be useful for development of high capacity systems along the Red Sea coastline of Saudi Arabia. The issues that primarily control the use of shallow wells for SWRO intake use are the potential well yields, aquifer water quality (e.g., presence of hypersaline water), and impacts to inland fresh water and wetlands.

Use of deep wells completed in parts of the Floridan Aquifer System that contain seawater has a high potential for use as a feed water source. However, these saline zones are also used for concentrate disposal using injection wells, so the systems would have to be located and designed to avoid recycling of the concentrate into the feed water. Along coastlines that do not contain high permeability carbonate aquifer systems (e.g., Red Sea), use of deep wells is not feasible, except for very low capacity systems. Other areas of the Middle East-North Africa MENA arid region, such as the Levant coast, contain carbonate aquifer systems that may be suitable for beach well development. Again, the role of local geological conditions is paramount in assessing the viability of any subsurface intake option using wells.

Horizontal well intakes have a great appeal based on the ability to use a single site to drill a “fan” of wells under the seabed. Both the Red Sea and parts of the Florida shoreline contain areas that have a reasonable potential for successful development of horizontal well intakes with high capacity. In Saudi Arabia, the nearshore, thin (< 20 m) carbonate system is the environment with the greatest potential and in Florida, the areas containing a sandy offshore bottom with a low slope have some potential for horizontal well implementation. The use of this technology is still open to question based on lack of operating experience at high capacities, the issue of oxidation/reduction reactions in the seawater as it passes from oxic to anoxic conditions in the aquifer, and the issue of long-term maintenance of the well screens. Therefore, it is considered to be a possible intake system option, but requires considerable further investigation.

7.5.2 Geologic and Process Controls on Siting and Operation of High Capacity Gallery Intakes

Beach and seabed gallery intake systems generally have the greatest potential to meet the feed water requirements for a wide range of SWRO plants capacities. A great advantage of these types of systems is that they use an engineered sand filter and thus have greater flexibility to be successfully implemented in settings where local geological conditions are less than ideal. Therefore, several chapters of this book are dedicated to describing the latest research in siting and designing gallery intake systems. While the fundamental design concept for these galleries is similar, the intensity of the process controls on sedimentation is different. In both cases, serious technical assessment is required to understand the shoreline and nearshore processes that control stability.

Beach galleries are constructed within the littoral zone of the beach, which is the most dynamic part of the shoreline. Sediment movement along the shoreline is controlled by the incident angle of the wave as it breaks across the shoreline and the energy is released based on wave height (Inman and Bagnold 1963; Komar and Inman 1970; Longuet-Higgins 1970; Inman and Dolan 1989). Even stable beaches undergo seasonal changes in profile, due changes in the direction and intensity of wave energy released at the shoreline (Inman 1953). These changes can completely rearrange the nearshore bottom bathymetry with temporary erosion of the beachface and storage of sand in offshore bars. The seasonal climate changes affecting beach sedimentation may occur both near the site and at great distance in the bounding sea, because waves can travel thousands of kilometers after being generated.

Siting of gallery intakes is the key to success for long-term operation. For beach galleries, the shoreline can be either stable or can be undergoing some minor degree of erosion (see Chap. 10). Therefore, the dynamics of the ocean offshore and along the beach must be clearly understood. Jenkins and Wasyl (2005) constructed a model that can be used to predict shoreline changes, which need to be understood before siting and design of either gallery type. Directed wave energy at the shoreline is derived from the behavior of approaching waves as they are refracted and redirected across the bottom and are affected by natural offshore obstructions and the bottom bathymetry (Jenkins and Wasyl 2005). An illustration showing the movement of waves approaching and impinging on the beach is shown in Fig. 7.7. It can be clearly observed that parts of the beach with focused erosion could be problematical for location of a beach gallery intake. Changing beach and nearshore

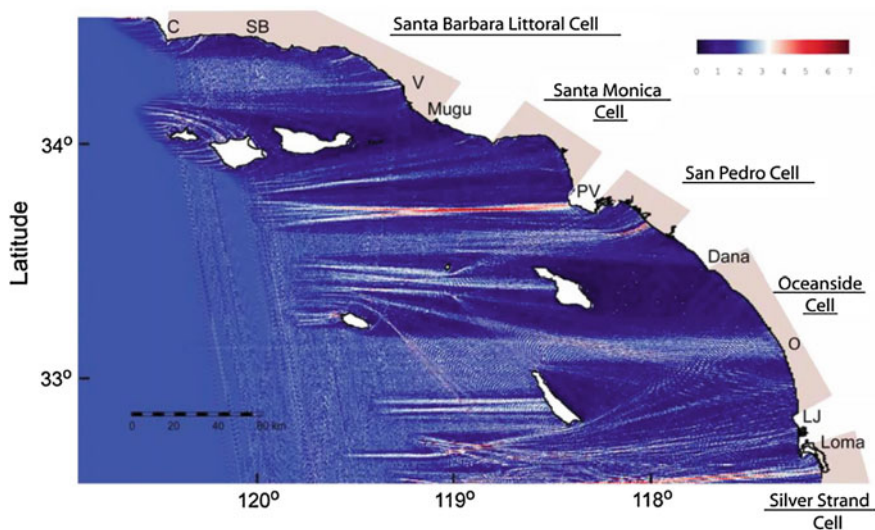


Fig. 7.7 Refraction/diffraction analysis for erosion hot-spot analysis on the 5 largest storms to strike Southern California in the El Niño winter of 1998 (from Jenkins and Wasyl 2005)

profiles can also affect the performance of seabed filters depending upon the distance a seabed gallery is constructed from the shore. A more detailed analysis of the methodology used in siting of gallery intakes is included in Chap. 12.

7.6 Conclusions

Coastal mapping of geomorphic and geological environments and relating them to the feasibility of developing various types of subsurface intakes is an important planning mechanism for the siting and development of SWRO systems. Since the feed water quality variation affects virtually all of the downstream process design and operation, an important design aspect is to deliver the highest and most consistent quality feed water possible to a SWRO plant, which can be accomplished by using subsurface intake systems.

A coastal mapping methodology was applied to two global regions with quite different geologic settings; the Red Sea coastline of Saudi Arabia and the coastline of the state of Florida, USA. It was concluded that the use of well intakes along the Red Sea coastline is limited to small to medium capacity SWRO systems. Further, the presence of sabkha features (coastal evaporation basins) causes the common occurrence of hypersaline groundwater along the beach, which does not allow use of shallow wells in some areas, despite favorable aquifer hydraulic properties. Seabed galleries are the intake system design most favorable for the Red Sea coast area.

The coastline of Florida contains primarily high to moderate energy sandy beaches, some limited coastal segments of rocky limestone out crops, restricted water with fringing coral reefs, and muddy environments associated with mangrove and coastal marshes. A large portion of the coastal part of the Florida peninsula is underlain by high permeability aquifers, some of which contain seawater. Therefore, Florida has a greater number of feasible subsurface intake options compared to Saudi Arabia. Many options are available to meet the demands for low to moderate capacity facilities. Subsurface intake options for large capacity facilities include high-capacity radial collector wells in some areas, high-capacity deep wells in southern Florida (boulder zone), high-capacity deep wells in areas such as the Big Bend, beach galleries in stable shorelines, and seabed galleries where the offshore bottom contain the appropriate characteristics.

Coastal mapping is useful in providing planning level assessments for feasibility determination of using various subsurface intake systems for SWRO facilities. However, detailed site-specific investigations are required for all final designs with the detail of the investigation necessary being related to the proposed system capacity. High-capacity SWRO facilities will require a greater scope of investigation to assure that the subsurface system of choice will meet the primary feasibility criteria consisting of the need to meet the required capacity and water quality requirements of the treatment facility under all conditions with no significant environmental impacts.

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