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Subsurface intakes for seawater reverse osmosis facilities: Capacity limitation, water quality improvement, and economics

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HIGHLIGHTS

- The use of subsurface intake types for seawater RO facilities was documented.
- Feedwater quality improvements by using subsurface intakes were demonstrated.
- Reduced environmental impacts using subsurface intakes were discussed.
- Capacity limits on various subsurface intake types were assessed.
- Life-cycle cost savings using subsurface intakes were preliminarily analyzed.

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ABSTRACT

The use of subsurface intake systems for seawater reverse osmosis (SWRO) desalination plants significantly improves raw water quality, reduces chemical usage and environmental impacts, decreases the carbon footprint, and reduces cost of treated water to consumers. These intakes include wells (vertical, angle, and radial type) and galleries, which can be located either on the beach or in the seabed. Subsurface intakes act both as intakes and as part of the pretreatment system by providing filtration and active biological treatment of the raw seawater. Recent investigations of the improvement in water quality made by subsurface intakes show lowering of the silt density index by 75 to 90%, removal of nearly all algae, removal of over 90% of bacteria, reduction in the concentrations of TOC and DOC, and virtual elimination of biopolymers and polysaccharides that cause organic biofouling of membranes. Economic analyses show that overall SWRO operating costs can be reduced by 5 to 30% by using subsurface intake systems. Although capital costs can be slightly to significantly higher compared to open-ocean intake system costs, a preliminary life-cycle cost analysis shows significant cost saving over operating periods of 10 to 30 years.

1. Introduction

Seawater desalination is an energy-intensive and costly means of treating water to potable standards and has some environmental impacts. With the development of advanced membrane technology and energy recovery systems, the energy consumption and cost of seawater desalination have been significantly reduced over the past several decades [1]. However, membrane fouling is still a major problem at most seawater reverse osmosis (SWRO) facilities, which reduces operational efficiency and the life-expectancy of the membranes [2]. Complex and expensive pretreatment processes are commonly required to reduce the rate of biofouling and the frequency of membrane cleaning (Fig. 1). Possible environmental impacts associated with conventional open-ocean intakes, such as impingement and entrainment of marine biota, can also create large permitting costs and construction delays [3,4]. There are also environmental impacts associated with the use of chemicals to keep the intakes and associated piping clean of organic growth, disposal of coagulants required in the pretreatment processes (e.g., ferric chloride), and disposal of macro-organic debris that accumulates on the traveling screens (seaweed, fish, jellyfish, etc.) and other parts of the pretreatment train [5].

Natural seawater contains a variety of macro- and micro-organic components that affect the treatment process [6]. Open-ocean intakes are seasonally clogged in some regions by seaweed [7] and some pretreatment systems are periodically fouled by influx of jellyfish. Also, natural environmental events, such as harmful algal blooms and red tides, can overwhelm pretreatment systems and cause temporary shut-downs of SWRO plants [8,9]. Improvements in the raw water quality can lead to reduction in the complexity of pretreatment systems,

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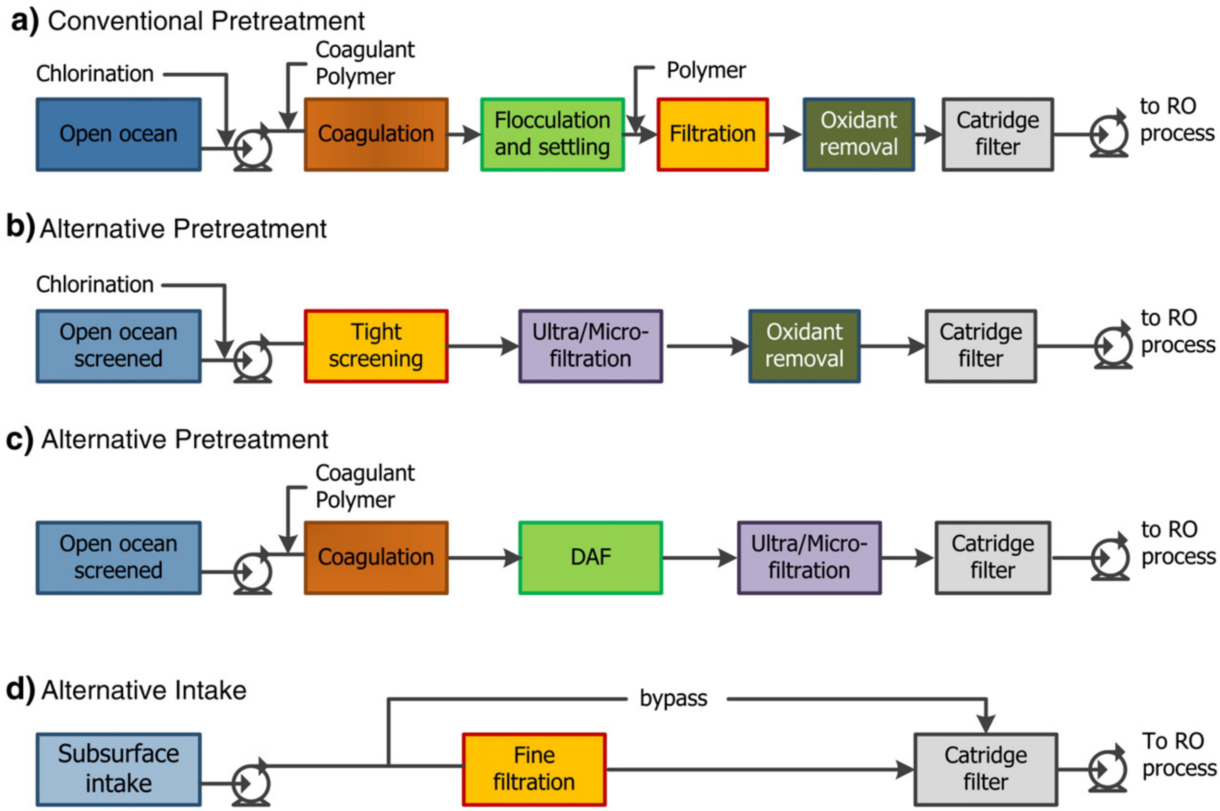

Fig. 1. Diagram showing typical pretreatment process trains for a SWRO plant (a, b, c) with the desired simplified system using a subsurface intake (d). A subsurface intake may be any to produce feedwater that can bypass the pretreatment system and flow directly to the cartridge filters.

thereby reducing the need for physical cleaning and amount of chemicals used, and increasing the operational reliability of facilities (e.g., avoid loss of production during algal blooms). Commonly, feeding higher quality raw water into the primary membrane process leads to a reduction in the rate of organic biofouling, reduced capital cost for construction of pretreatment processes, and reduced operating costs for maintenance, chemical use, and accessory operations. A key issue is how to improve the quality of the feedwater and, as a result, decrease the life-cycle cost of desalination or total cost per unit volume of product water.

The use of subsurface intake systems is one method to improve water quality, to increase operational reliability, to reduce the pretreatment train complexity, and to reduce operating costs [10,11]. Subsurface intake systems use the natural geological properties of sediments and rocks to strain and biologically remove organic matter, suspended sediment, and dissolved organic compounds before they enter the treatment processes [11]. Most of the subsurface processes function in a similar manner to river bank filtration (RBF) or bank filtration systems used to treat freshwaters in Europe and the United States for over a century [12,13]. Investigations of RBF systems have conclusively demonstrated that they are very effective in reduction or elimination of pathogens in the filtered water [14–18] and also reduce the concentration of suspended solids and organic matter entering the primary treatment processes [19]. RBF systems have also been effective at reducing algal toxin concentrations [20]. In Europe, RBF commonly is the primary treatment for many potable water systems with little or no subsequent additional treatment.

There are a number of different types of subsurface filtration systems that can be used depending upon the local geology and environmental conditions. Subsurface intake types can be grouped into two categories which include wells and galleries [11]. Wells can be subdivided into conventional vertical wells, horizontal wells or drains, angle/slant wells, and Ranney wells or collectors. Gallery-type intakes include seabed filters or galleries and beach galleries. It is the purpose of this paper to thoroughly review these subsurface intake types in terms of feasibility, design, function, and applicability to various capacity seawater desalination facilities and include an overview of facility economics.

2. Materials and methods

A general survey was conducted of SWRO plants located globally to ascertain the types and capacities of subsurface intake systems currently being used. Information was obtained from databases, books, and peer-reviewed publications on desalination. Design information was also collected on construction methods, materials, and pump types. At locations where the facility operators could be contacted, data were collected on the raw seawater, the inflow stream before pre-treatment, and after pretreatment. Information was obtained on the degree of membrane fouling experienced and on the frequency of cleaning required at the plant.

Water quality data were also collected from the literature and from some field surveys to assess the impact of subsurface intakes on removal of algae, bacteria, and organic compounds that tend to produce biofouling of membranes. These data were compiled to assess the effectiveness of subsurface intakes on improving overall feedwater quality.

3. Results

3.1. Feasibility of subsurface intakes under various natural geological conditions

Local hydrogeological conditions and the proposed capacity of SWRO plants control the feasibility of subsurface intakes and the specific choice concerning the type of system that best matches the facility requirements [10,11]. Many locations worldwide have local hydrogeological conditions sufficient to develop one or more different types of subsurface intakes while other locations do not have subsurface intake feasibility. A key issue is the pre-design technical assessment of the hydrogeological conditions before the facility design and bid process begin [10,11,21–26]. The pre-design geological and geotechnical investigations should be phased with a preliminary investigation scope developed to assess "fatal flaws" that would eliminate the use of any subsurface intake type and a primary investigation that would provide sufficient data upon which to base at least a preliminary design. In most cases the failure to conduct these investigations would effectively eliminate the use of a subsurface design in the bid process because of the perceived risk factor. The scope of the primary investigation should be developed within the preliminary study report and should contain a minimum amount of field data collection, some groundwater modeling assessment, and some preliminary economic assessments (Table 1). Should a subsurface intake be deemed to be infeasible, then the need for the primary investigation would be eliminated with associated savings in project cost.

There are some general coastal and nearshore characteristics that tend to favor the feasibility of subsurface intake development. The occurrence of permeable rock adjacent to the shoreline is a good indication that a subsurface intake may be feasible. Coastal carbonate aquifers (limestones and/or dolomites) have been commonly used for feedwater supply systems [27,28] (Fig. 2a). Coastal regions underlain by thick deposits of permeable sand, gravel, or a combination of these lithologies also have a high probability of successful development. Sandy beaches that are relatively stable and have adequate wave activity also have a good probability of being useful (Fig. 2b). Unvegetated offshore marine bottom areas that contain quartz or carbonate sands with a low percentage of mud are also acceptable for the development of subsurface intake systems provided that they are not environmentally sensitive (e.g., coral reefs or important marine grass beds are not present) (Fig. 2c). Areas having a high-energy, rocky shoreline containing low permeability rocks are likely not feasible. Low-energy shorelines with associated high-mud content in offshore sediments are also not likely to be feasible.

Table 1
Scope of preliminary and permitting investigations for subsurface intake feasibility to be provided to project bidders.

Regional investigation of coastal characteristics
1. Provide a detailed description of site for the desalination facility and coastal areas available for development of a subsurface intake system
2. Provide historical aerial photographs of the shoreline to assess shoreline stability
3. Provide geologic maps of the coastal area under consideration
4. Provide a copy of any oceanographic investigations conducted for permitting
5. Provide a bathymetric map of the offshore area adjacent to the coastal area of interest
6. Provide bidders with the overall coastal conditions package and give them a maximum distance from the plant in which they could develop a subsurface intake system

Site-specific investigation of surface and subsurface conditions
1. Drill test borings on the beach area at the proposed intake site
2. Construct detailed geologic logs
3. Collect sand samples from the beach and have the grain size distribution of the samples analyzed
4. Construct at least one observation well in any aquifer found to have high hydraulic conductivity, collect a water sample, and provide a chemical analysis of the inorganic chemistry, including analyses of all major cations and anions with alkalinity, hardness silica, strontium, barium, boron, arsenic, and any trace metals of concern (with some organic analyses such as TOC, DOC, TEP, biopolymers, and others)
5. Optional — if an aquifer is found in the test drilling that has a possibility of producing the desired quantity of water, an aquifer performance test should be conducted to measure aquifer hydraulic coefficients.
6. For gallery type intakes — obtain sediment samples from the beach offshore to a distance of up to 500 m and a water depth up to 10 m and have the samples analyzed for grain size properties and hydraulic properties. The sample grid should contain the entire area in which the galleries would be constructed and perhaps some additional areas from which sediment could be transported.
7. Produce a site-specific report containing the test data and any potential recommendations for subsurface intake feasibility.

Fig. 2. Typical coastal characteristics acceptable for the use of subsurface intake systems, a. Limestone shoreline at Sur, Oman, that has a high productivity limestone aquifer, b. Sandy beach in the northern Red Sea Coastline of Saudi Arabia which could support a number of subsurface intake types based on lithology, geology, and wave action, c. Shallow limestone and clean sand area of the Red Sea that could be used for seabed gallery development.

3.2. Well systems

3.2.1. Conventional vertical wells

There are many different types of wells that can be designed and constructed to provide feedwater [11]. The term "beach well" is commonly used to describe the most common type of subsurface intake, but this term is a misnomer that applies to only one class of wells that are directly recharged by seawater close to the beach area. Many well systems used to supply SWRO facilities are located inland away from beaches or even in interior areas of continents where high salinity waters occur at great distance from the sea or in deep regional aquifer systems that contain seawater (Fig. 3) (e.g., New Providence Island systems, Bahamas, the Bolson Aquifer of New Mexico).

The site geology must be adequate to allow individual well yields to be high enough so that the number of production wells needed to meet the required raw water supply is reasonable or cost-competitive with other supply options. In some cases the aquifer hydraulic conductivity found during a preliminary site investigation is insufficient to produce the necessary well yield requirements based on the site size or overall economic considerations. The type and design of a well system should be coordinated with the local hydrogeology and the required capacity needed to supply the facility. Key issues include maximization of the efficiency to withdraw water while meeting the plant capacity requirements as well as improving water quality. The well yields should be designed to match the plant design configuration (e.g., one well per train or two wells per train). Well intake system should have some reserve or emergency standby capacity to meet demands caused by pump failures or scheduled maintenance.

Well intake systems have been successfully used at hundreds of SWRO facilities worldwide with capacities up to 160,000 m^3/d (Table 2). Well intake systems have proven to be a reliable means of providing feedwater with positive impacts on water quality [27–35]. A key issue when a well system is contemplated is to obtain sufficient hydrogeologic information to predict well yields and to reduce operational risk to the facility operator [36]. Technical evaluation methods have been used that allow local groundwater system hydraulics to be evaluated prior to construction with positive operational experience as a result [37]. Well design and construction should follow industry standards with strong consideration of materials because of the highly corrosive nature of seawater (non-metallic casings and conveyance pipe should be used) [38].

Comparative analyses of seawater quality between open-ocean intakes and wells show that well intakes produce significantly lower concentrations of particulate matter, algae, bacteria, and organic compounds that promote membrane biofouling [39–46] (Table 3). While conventional vertical wells do significantly reduce organic carbon and bacterial concentrations, care must be taken to maintain the wells to avoid bacterial growth within the wellbore and periodic disinfection of the wells may be necessary to lower bacterial concentrations if regrowth occurs [47,48]. Based on operation of RBF systems, travel distance and residence time influence water quality changes. All conventional vertical wells used for SWRO intakes will require periodic maintenance to remove any buildup of calcium carbonate scale or a biofilm on the "skin" of the well in open-hole designs or the well screens.

The location of true beach wells is important because they must be recharged primarily by direct recharge with seawater or otherwise seaward movement of freshwater could occur. Induced seaward movement of water has been known to draw contaminated groundwater or water

Table 2
Selected seawater RO facilities using well intake systems.

Facility name	Location	Capacity[1] (m^3/d)	No. of wells
Sur	Oman	160,000	28
Alicante (combined for two facilities)	Spain	130,000	30
Tordera	Blanes, Spain	128,000	10
Pembroke	Malta	120,000	–
Bajo Almanzora	Almeria, Spain	120,000	14
Bay of Palma	Mallorca, Spain	89,600	16
WEB	Aruba	80,000	10
Lanzarote IV	Canary Islands, Spain	60,000	11
Sureste	Canary Islands, Spain	60,000	–
Blue Hills	New Providence I., Bahamas	54,600	12 (?)
Santa Cruz de Tenerife	Canary Islands, Spain	50,000	8
Ghar Lapsi	Malta	45,000	18
Cirkewwa	Malta	42,000	–
CR Aguilas, Murcia	Spain	41,600	–
SAWACO	Jeddah, Saudi Arabia	31,250	10
Dahab	Red Sea, Egypt	25,000	15
Turks & Caicos Water Company	Providenciales, Turks & Caicos Islands	23,260	6
Windsor Field	Bahamas	20,000	–
North Side Water Works	Grand Cayman	18,000	–
Ibiza	Spain	15,000	8
North Sound	Grand Cayman	12,000	–
Red Gate	Grand Cayman	10,000	–
Abel Castillo	Grand Cayman	9000	–
Al-Birk	Saudi Arabia	5100–8700	3
Lower Valley	Grand Cayman	8000	3
West Bay	Grand Cayman	7000	–
Britannia	Grand Cayman	5400	4
Bar Bay	Tortola, B.V.I.	5400	–
Morro Bay	California, USA	4500	5
Ambergris Caye	Belize	3600	–

[1] Capacity is for the well intake (approximated based on published reports or estimated based on the reported capacity of the plant divided by the reported recovery rate or a maximum of a 50% recovery rate where it is not reported).

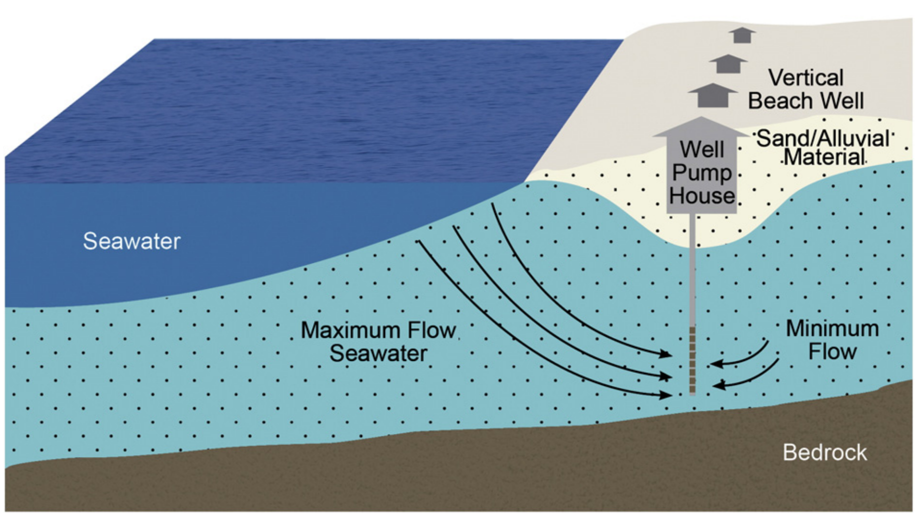

Fig. 3. Well intake system located along a shoreline. This is truly a "beach well" system that promotes direct recharge from the sea and minimizes capture of landward water resources. Minimal flow should come from the shoreline direction to avoid aquifer impacts and entry of poor quality water.

Table 3
Comparison between bacteria, algae, organic carbon compound concentrations in natural seawater verses well intakes from select sites.

Location	Parameter	Seawater	Well 1	Well 2	Well 3	Well 4
Dahab, Egypt [40]	DOC (mg/L)	1.6	1.2	2.3	0.6	0.8
	UV-254 (m^{-1})	1.4	0.8	0.9	0.8	0.6
Fuerteventura Island, Spain [41]	TOC (mg/l)	0.5	0.7			
	UV-254 (m^{-1})	0.36	0.55			
	Phytoplancton, cell/L	57,720	0			
Al-Birk, Saudi Arabia [42]	Dissolved protein (mg/L)	2.73 ± 0.78	0.75 ± 0.08	ND	ND	
	Dissolved carbohydrates (mg/L)	1.57 ± 0.23	0.52 ± 0.15	0.77 ± 0.10	0.50 ± 0.14	
SWCC Al-Jubail test sites [43]	TOC (mg/L)	2	1.2–2			
	Bacteria (CFU/mL), 0, 24, and 72 h	1.8×10^3	1.3×10^3			
		1.1×10^5	3.3×10^5			
		5.6×10^4	4.0×10^6			
Dahab beach well system, Egypt [44]	DOC (mg/L)	1.6	1.2	2.3	0.6	0.8
	UV-254 (m^{-1})	1.4	0.8	0.9	0.8	0.6
Mediterranean location-spring [45]	Total picophyto-plankton (cells/mL)	1.6×10^3	1.3×10^2			
	Synechococcus (cells/mL)	1.3×10^3	1.0×10^2			
	Picoeukaryote (cells/mL)	1.1×10^3	1.9×10^1			
	Nanoeukaryote (cells/mL)	1.2×10^2	1.7×10^0			
Site 1 [46]	TOC (mg/L)	1.2	0.9			
	Polysaccharides (mg/L)	0.12	0.01			
	Humic substances + building blocks (mg/L)	0.5	0.4			
	Low-molar mass acids & neutrals (mg/L)	0.25	0.16			
	Low molar mass compounds (mg/L)	0.33	0.29			
Site 2 [46]	TOC (mg/L)	0.9	0.6			
	Polysaccharides (mg/L)	0.4	ND			
	Humic substances + building blocks (mg/L)	0.26	0.16			
	Low-molar mass acids & neutrals (mg/L)	0.22	0.13			
	Low molar mass compounds (mg/L)	0.38	0.3			

with high concentrations of dissolved iron or manganese into beach wells (e.g., Morro Beach, California beach well system) [29]. High concentrations of dissolved iron or manganese, greater than those found in normal seawater, can create scaling problems in SWRO membranes. Wells located at significant distances from the shoreline can also cause adverse impacts to wetlands or produce water that has salinity higher than that in the adjacent sea (Flagler County, Florida) [49] or as in the case of Morro Beach, California can have high concentrations of dissolved iron or manganese that is common in the mixing zone between terrestrial freshwater aquifers and seawater.

While conventional wells can meet the feedwater requirements of small to intermediate capacity SWRO facilities, there is a limit on the use of wells for large-capacity facilities. When the number of wells and associated infrastructure is too large and costly, another intake system may be required. The issue of well pump replacement and maintenance, even with the use of special-order duplex stainless steel, is an important consideration because of the very corrosive nature of seawater. The ratio of well yield to overall feedwater requirement will dictate the feasibility of using wells as intakes. Also, the use of large numbers of beach wells can raise the issue of unacceptable aesthetic appearance which can adversely influence public opinion and make the permitting of well intakes difficult or impossible.

3.2.2. Angle wells

Angle wells can be drilled from a position near the shoreline with an extension under the seabed or close to it (Fig. 4). Angle-well intakes are currently being evaluated in field and general research investigations [50,51]. One advantage of using angle well technology is that the wells can be set back further from the shoreline compared to conventional vertical wells. This tends to induce primarily vertical recharge through the seabed, produces water that is stable and of similar quality to the seawater in the area, may have a lesser tendency

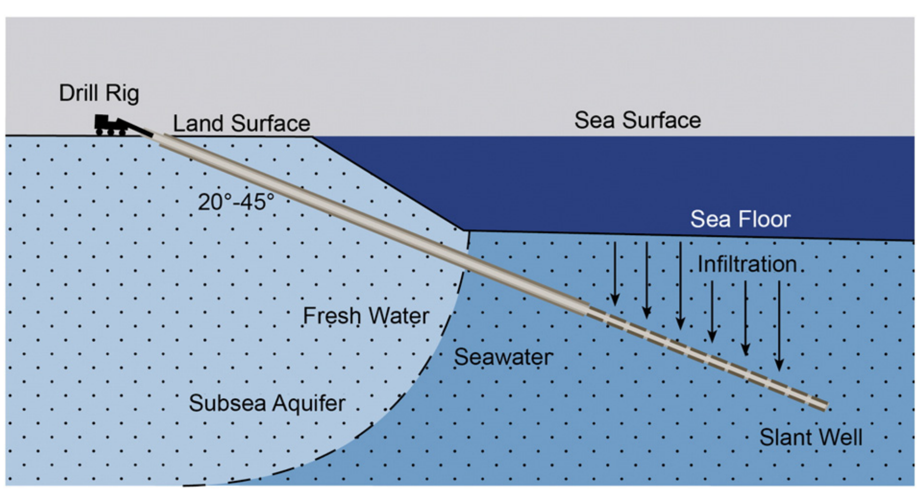

Fig. 4. Diagram showing an angle well intake system. Note that the recharge direction is vertical compared to the typical vertical well intake system and the issue of impacts to coastal aquifers can be avoided.

to induce landward to seaward flow that can cause water quality problems, and better protects pumps and associated infrastructure from storm damage. Also, several wells can be drilled from a single location to create clusters [50] (Fig. 4), thereby reducing the land area necessary for construction and infrastructure development.

Construction of angle wells is more complex compared to conventional vertical wells and requires the use of specialized equipment necessitating corresponding skilled operators. In coastal aquifers consisting of lithified rock, angle well construction is essentially no more complex than conventional well construction, but within unconsolidated sediments, dual-rotary drilling equipment may be required so that a filter pack can be installed with screens inside of a temporary steel casing that is subsequently withdrawn before well development [50]. The dual-rotary drilling method does have some limitations regarding the maximum length (or depth) of the well that can be constructed. This length is dependent on the geological materials penetrated and the diameter of the well. Within unlithified sediments it is likely a maximum of about 150 m for a casing diameter of 30.48 cm [50] or greater, but may be up to 400 m depending on the size of the rig and geologic conditions. Angle wells may also be more difficult to maintain, especially where specialized equipment is not locally available.

Although no large-scale seawater desalination facility currently utilizes an angle well intake system, several facilities are being evaluated in terms of feasibility [51]. It is likely that medium capacity SWRO facilities will be constructed using this type of well intake design. There will always be some limit on the overall yield of angle wells to meet very large-scale capacity SWRO facilities. Angle wells may have greater yields then vertical wells. However, a site-specific economic analysis is required to determine whether the potential greater yield per well (and thus less number of wells) offsets the greater construction and maintenance costs of angle wells.

3.2.3. Horizontal wells or drains

Horizontal well construction has rarely been used in the water industry, but has a variety of potential applications. A key issue is matching the technology to the specific geologic conditions at a given site to maximize the efficiency of withdrawal within the framework of the fundamental groundwater hydraulics. Most unlithified sediments are deposited in horizontal layers that make vertical wells very effective because the screens can be placed perpendicular to the bedding planes and tend to take advantage of the generally high horizontal to vertical ratio of hydraulic conductivity. If it is the purpose of a horizontal well to induce vertical flow, such as in the case of drilling beneath the seabed, then use of the technology does have the advantage of producing high yields per individual well. If the aquifer to be used is semi-confined or not well connected vertically to the overlying sea, then the wells may not be effective in producing high, sustainable yields. Also, great care must be taken in use of horizontal wells beneath the seafloor in terms of water quality because the well may pass through zones of sediments containing varying oxidation conditions along the axis of the well. Mixing of oxygenated seawater with anoxic seawater within the well, especially where hydrogen sulfide is present, can lead to the precipitation of elemental sulfur that would require removal before entry into the membrane treatment process. Also, the oxidation issue can also cause precipitation of ferric hydroxide or manganese dioxide. The configuration of using horizontal wells as intakes for SWRO plants appears to have considerable advantages [52].

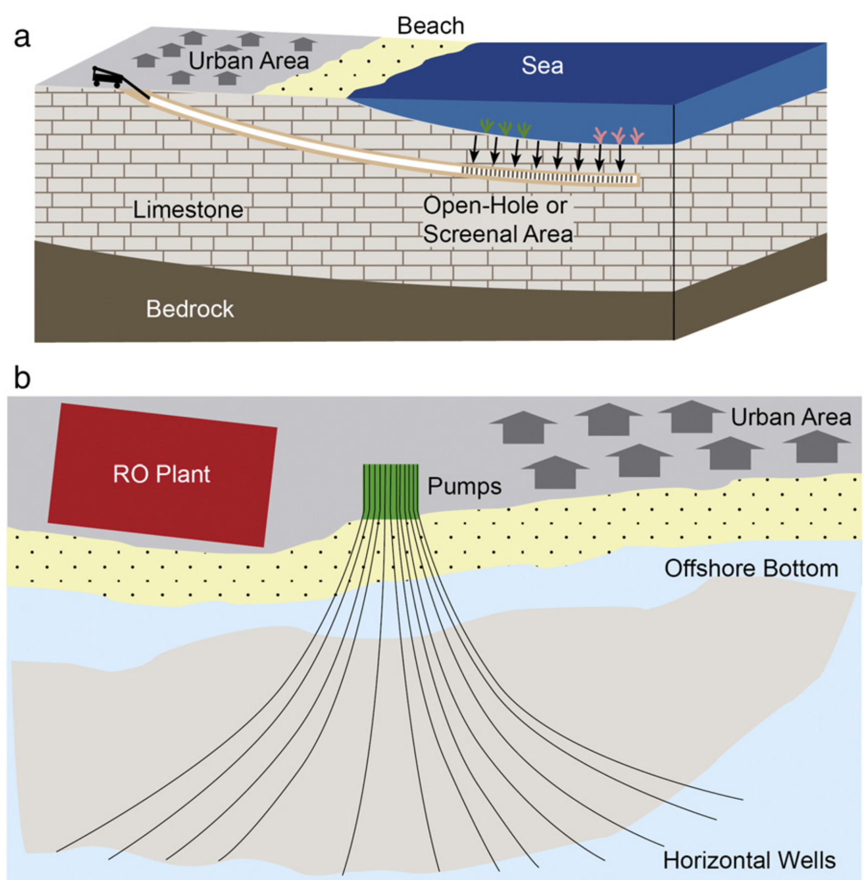

Fig. 5. Horizontal wells can be drilled from the shoreline using older mature technology or the Neodren™ system. a. General configuration of a horizontal system. b. Horizontal well systems can be configured to allow multiple wells to be drilled from a compact location, saving land cost and allowing pumps to be housed in a single building.

In recent years horizontal well intakes have been installed in several facilities in Spain with the highest capacity reported at 172,800 m^3/d [52–57] (Fig. 5a). The Neodren™ horizontal well system has been touted as being a state-of-the-art technology with potential widespread application [55]. Unfortunately, there have been few operating data reported from the larger capacity SWRO facilities currently using this intake type. Data on silt density index (SDI) for a Neodren™ system compared to multi-media filtration and ultrafiltration show a value of 5.1 compared to 3.4 and 3.2, respectively, on one system and 4.6 compared to 2.6 and 2.4, respectively, on another system with the locations of the systems not given [57]. Typical seawater SDI values commonly are greater than 10 (both SDI_{10} and SD_{I5}), which suggest that the horizontal well system does improve water quality. However, no data on organic carbon or bacteria removal are presented in the literature touting this technology.

An issue requiring consideration in the selection of a horizontal well intake is the elimination of feasibility and operational risk. While the assessment of groundwater sources adjacent to the shoreline is rather well established, the hydrogeologic characterization of the offshore sub-bottom requires specialized equipment and methods which are expensive and may still leave questions that cannot be easily answered, such as on sub-bottom oxidation state of the water and horizontal geological variations that could reduce or eliminate productivity of the well(s). The drilling of test borings and obtaining accurate water quality samples can be difficult if not impossible under some conditions, where the offshore bottom slope is very steep or where wave action is intense, not allowing use of barge-mounted drilling equipment.

Another important issue concerning the long-term operation of any horizontal well system is the ability to adequately clean the well when it becomes partially clogged [11]. All well types require periodic maintenance and cleaning which can be easily accomplished in conventional vertical wells using weak acid and various redevelopment processes, such as air or water surging, sonic disaggregation and redevelopment, or some combination of processes depending on the nature of the clogging, such as calcium carbonate scaling, iron nodule precipitation, or biofouling [11,38]. Maintenance work on a horizontal well can be quite complex because of its long distance from the shoreline and the presence of screen in the well that could be damaged during maintenance due to the cleaning pipe traveling on the lower screen surface of the well.

In the event that all obstacles are resolved with construction and maintenance, the use of horizontal well technology has some compelling advantages. An array of horizontal wells can be drilled from a small construction footprint, as shown in Fig. 5b, which allows considerable savings for land acquisition and a single building can house the pumps and associated electrical equipment. Therefore, horizontal well technology should be evaluated if the geology is adequate to support the required well yields, the seafloor does not have a high rate of muddy sedimentation, and the technical and feasibility risks can be minimized. The potential yield of horizontal beds beneath the seabed can be virtually unlimited if the geology is compatible and the risks can be managed. Also, the need for specialized cleaning equipment is likely to be necessary which may not be available in many locations.

3.2.4. Radial collector wells or Ranney collectors

Radial collector wells are characterized by a central caisson typically having a 3 to 5 m diameter with a series of laterals which are screened to allow water flow to move into the caisson during pumping (Fig. 6). Radial wells are commonly used to provide large-capacity intake capability along rivers in parts of the United States and in some European locations [11,58–60]. Operational radial collector well capacities range from 380 to 51,400 m^3/d [59,60]. The only known operating collector well system used for a SWRO intake is located at the PEMEX Salina Cruz refinery in Mexico [26], which has three wells each with a capacity of 15,000 m^3/d.

The geologic conditions that favor a radial collector well design over a conventional or horizontal well design are the occurrence of thick gravel beds at a relatively shallow depth that have a preferentially high hydraulic conductivity compared to the overlying sediments. High-yield radial collector wells could be successfully developed in the gravel unit by installing the collector laterals in the gravel that extend under the seabed. Collector laterals could be installed only on the seaward side of the well to eliminate impacts to fresh groundwater resources occurring in the landward direction and to also eliminate the potential for drawing contaminated water or water having high concentrations of undesirable metals, such as iron and manganese, into the wellfield (Fig. 6).

Proper aquifer characterization is required in the design of a radial collector well intake system. While the test program to determine potential yield of individual wells and the required space between them is relatively easy to perform (same as conventional wells), the assessment of water quality within the sediments can be more complex. It is quite important to assess the redox state of the water to be pumped because radial wells have a caisson that allows air to come in contact with the water originating in the laterals. If the water flowing into the well from the coastal aquifer contains hydrogen sulfide, iron (Fe^{2+}),

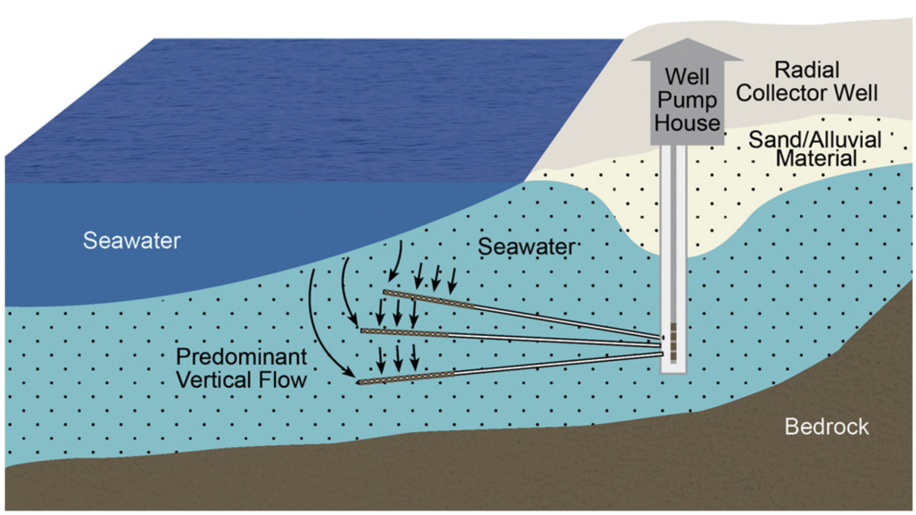

Fig. 6. Typical design from a radial collector or Ranney well. The laterals can be designed to extend beneath the seabed to all only vertical recharge through the seabed, precluding landward impacts. Note that the laterals occur on a single plane and many can be installed.

or manganese (Mn^{2+}), it could react with the dissolved oxygen in the water temporarily stored in the caisson and precipitate elemental sulfur, ferric hydroxide, or manganese dioxide respectively, any of which can foul the cartridge filters and membranes [11,59].

Radial collector wells have an advantage over conventional vertical wells in that the individual well yields can be very high. However, they do require location near the shoreline and are therefore subject to beach erosion and storm wave damage. They could be used to produce large quantities of feedwater in areas where the geology is supportive and the tidal water is relatively calm with low wave action. Since individual wells can yield up to about 50,000 m^3/d, they could be used to supply feedwater to very large capacity SWRO systems. However, no long-term operating data are available on the radial collector wells used for SWRO intakes. There is potentially greater risk associated with radial collector wells because a greater investment in their construction occurs before their performance can be known with certainty.

3.3. Gallery systems

3.3.1. Concept

A gallery intake system design for SWRO intakes is based on the concept of slow sand filtration used in the water industry for more than two centuries [61]. A classical gravity fed slow sand filter, depending on the turbidity of the water being treated, can operate at infiltration rates ranging from 0.1 to 0.4 m/h (2.4 to 9.6 m/d) [61] with minimal need to clean the upper layer of the filter. Modern design criteria for slow and rapid sand filtration tend to have a lower range for the recommended design filtration rate at 0.05 to 0.2 m/h (1.2 to 4.8 m/d which may reflect the treatment of higher turbidity waters [62]).

Gallery intake usage is very applicable to SWRO treatment because sand filters of various designs are commonly used in the pretreatment train in most plants. Slow sand filtration improves water quality by straining and biological activity that can bind or break down many different organic compounds commonly occurring in seawater. Particulate materials are commonly trapped and bound in the upper part of the filter in a layer termed the “schmutzdecke” which is a biologically active layer containing bacteria, bound particulates, and organic carbon compounds. While the entire filter is biologically active, the greatest activity of bacterial treatment occurs in the upper 10 cm of the sand column. Retention time of the water within the filter will tend to increase the assimilation of organic compounds to a greater degree. Therefore, a balance between hydraulic flow rate, which governs the area of the filter footprint, and the retention time that controls the quality of the filtered water, must be achieved. Cleaning a slow sand filter is commonly accomplished by scraping and removing the upper few centimeters of sand with the full sand column being replaced perhaps within a multi-year timeframe.

Testing of slow sand filtration of seawater on a pilot scale has demonstrated significant improvements to feedwater quality [63]. The piloting work was conducted during periods of normal marine bioactivity and during periods of harmful algal blooms. The experimental work on slow sand filtration by Desormeaux et al. [63] showed that the SDI_{15} was reduced to <4.0 99% of the time and <3.0 90% of the time, the removal of particles >2 microns in diameter was greater than or equal to 99%, and the total organic carbon (TOC) concentration was reduced to less than or equal to 2.0 mg/L. The concentration of spiked kainic acid, used as a proxy for algal toxin, was reduced by 89–94%. The operation of the pilot SWRO unit did not require cleaning during the 56-week pilot program and had the lowest amount of foulant observed on the membranes compared to the other pretreatment processes evaluated. The slow sand filter process required no coagulants or other chemicals to be added.

Gallery intakes use the concept of slow sand filtration by creation of an engineered filter that can be located on the beach near or above the high tide line, within the intertidal zone of the beach, or in the seabed. These intake types can be used as part of the pretreatment process, but eliminate the need for a large water treatment plant footprint required by in-plant slow sand filtration and/or dissolved air floatation (DAF).

3.3.2. Seabed galleries

The conceptual design of a seabed gallery or filter has existed since the early 1980's [10,11,64]. To assess the general feasibility and associated operational risks, a marine survey can be conducted to determine the presence of potentially sensitive environmental conditions on the bottom (e.g., marine grass beds or coral reefs), the type of bottom sediment, the general sedimentation rate, and the turbidity of the seawater. At locations where the marine bottom contains clean sand devoid of significant concentrations of mud, there is a high probability that the system is feasible. Since the filter media will be engineered, a key issue is the composition of the naturally-occurring sediment which is an indication of the natural processes acting at a given location. Muddy bottoms have questionable feasibility because mud deposition would clog the top of the gallery. Commonly, muddy bottom areas are associated with river or stream discharges into the sea. Favorable marine processes include currents that keep fine-grained sediment in suspension and move sediment across the bottom, thereby stirring the top of the filter which tends to clean it. Natural macro-scale biological processes, such as bioturbation within the sediment column, can also aid in making the gallery fully functional. Many marine infauna including polychaete worms and mollusks are deposit feeders that ingest sediments to extract nutrients and excrete fecal pellets that act hydraulically similar to sand grains. The deposit feeders act to prevent the building of a biological clogging layer at the sediment–water interface.

Only one large-scale operating SWRO system, the Fukuoka, Japan facility, has been constructed and operated utilizing this type of intake (Fig. 7). The capacity of the Fukuoka gallery is 103,000 m^3/d [65]. It has an infiltration rate of 5.1 m/d with a corresponding retention time of 7 h. Although the gallery infiltration rate is slightly above the normal recommended range for slow sand filtration, it has been operating successfully for 8 years without the need to clean the offshore gallery and with minimal cleaning of the membranes [66]. Monitoring of the feedwater pumped from the gallery shows a very significant improvement in water quality with the SDI being reduced from background levels exceeding 10 to consistently below 2.5 to the beginning of 2010 and mostly below 2.0 thereafter (Fig. 8).

Another seabed gallery has been designed and constructed at the City of Long Beach, California [67,68]. This system has been in the testing phase for a significant time period with infiltration rates ranging from 2.9 to 5.8 m/d [69]. This testing revealed substantial reduction in turbidity, SDI_{15}, total dissolved carbon (TDC), and heterotrophic total plate counts (mHPCs) with some reduction in concentrations of DOC and AOC (Table 4).

The filter media used in slow sand filters in the treatment of freshwater typically consists of graded quartz sand. It has been recently suggested that naturally-occurring carbonate sands may have a greater degree of bioreactivity, thereby potentially causing a greater removal rate of organic compounds [70,71]. Further research will be required to assess this possibility.

Large-scale seabed galleries can be technically complex to construct. In offshore locations where the bottom sediment is unconsolidated, construction requires the use of sheet piling, dredging and temporary dewatering to allow the placement of the bottom intake screens and the filter media (Fig. 9). In locations where the nearshore bottom contains soft rock, the gallery cells can be constructed in the wet using a backhoe resting atop a temporary access road [71]. The development of an artificial filter on the sea floor has been suggested to lessen the difficulty of marine construction [72]. As a greater number of large-capacity systems are constructed, more efficient construction methods will likely be developed to reduce overall construction costs.

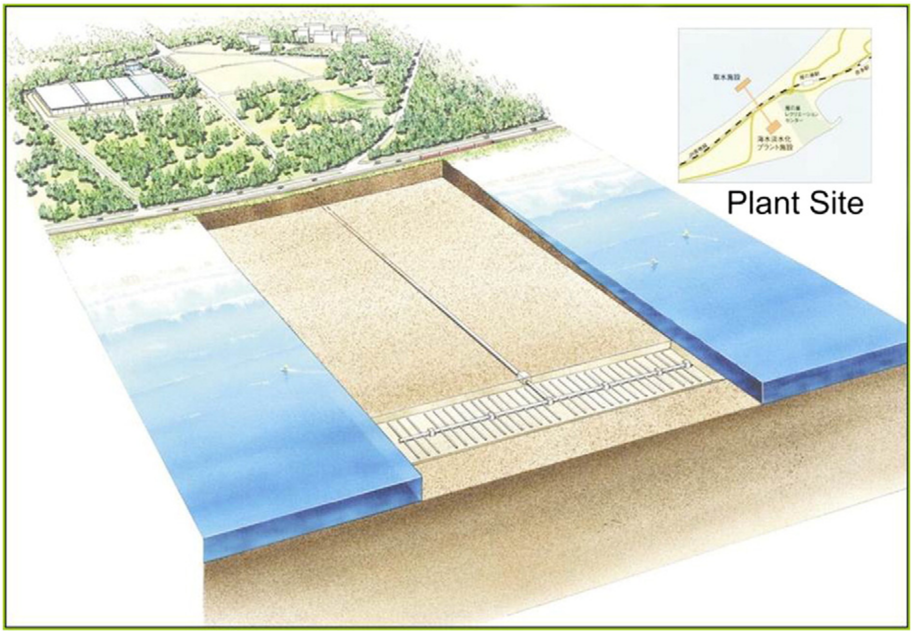

Fig. 7. Seabed gallery at Fukuoka, Japan. This gallery has a capacity of 103,000 m^3/day and has been operating successfully for 8 years [11,23].

Seabed galleries have a minimal environmental impact which occurs only during the initial construction. The major environmental impacts associated with impingement and entrainment of marine organisms in open-ocean intakes are eliminated. The post-construction marine bottom may actually be more productive in terms of infauna due to the increased flux of organic carbon compounds into the filter media over the top of the gallery.

3.3.3. Beach galleries

Another gallery intake type that has very great potential for use in large-capacity SWRO systems is the beach gallery [10,11]. Beach gallery intakes may be preferred over seabed galleries because they can be designed and constructed to be essentially self-cleaning [73]. The gallery is constructed within the intertidal zone of the beach with the mechanical energy of breaking waves being used to continuously clean the face of the filter (Fig. 10).

There are several key criteria that must be met to make beach gallery intakes feasible [74,75]. The shoreline should have significant wave height and a reasonable tidal range to allow the self-cleaning function to work properly. The beach should be relatively stable. While an eroding beach will still allow the gallery to function with the entire gallery continuously submerged, an accreting beach is problematical because the percolating seawater would require a longer flow path and the gallery could dewater if the hydraulic conductively is insufficient to maintain recharge into the gallery at the desired pumping rate. Beach galleries can be constructed successfully only on sandy or gravelly beaches with sufficient thickness of sediment to protect the underlying screens and to eliminate the potential for damage during storms. Care must be taken to design the galleries with sufficient sediment thickness to meet the water quality improvement needs and also to protect the media from storm damage. The thickness of the filter media would be likely greater than that for a seabed gallery.

While no large-scale beach gallery intakes have been constructed to date, several are in design or have been proposed [74]. The use of beach galleries for intakes is compelling because of the potential use for large-capacity systems, the self-cleaning aspect of the design, the lower construction cost compared to seabed galleries, and the minimal environmental impacts.

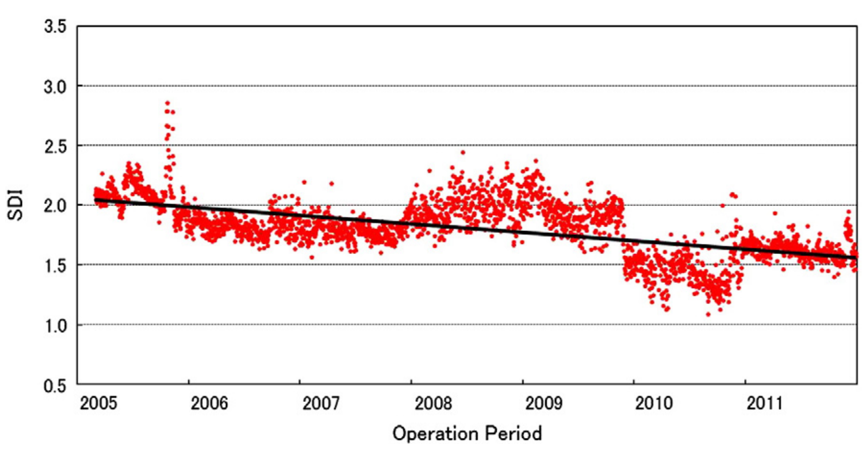

Fig. 8. Long-term variation in the silt SDI of water coming from the seabed gallery at Fukuoka, Japan. The water quality has been consistently good and has improved during the life of the facility [23].

Table 4
City of Long Beach, California seabed gallery water quality test data [68].

Parameter	Infiltration rate (m/d)	Raw seawater (range/mean)	Gallery effluent (range/mean)
Turbidity (NTU)	2.9	1.42–4.8/3.04	0.41–0.70/0.66
Turbidity (NTU)	5.8	1.86–4.56/3.10	0.38–1.23/0.48
SDI_{15}	2.9	Not reported	4.42–5.53/4.56
SDI_{15}	5.8	Not reported	2.74–5.45/4.06
ATP (mg/L)	2.9	1–1000/6.0	1.50–21.0/2.60
TDC (cells/mL)	2.9	3400–1,210,000/54,400	8500–241,000/13,300
mHPC (cfu/100 mL)	2.9	750–470,000/4500	156–5500/1000
DOC (mg/L)	2.9	0.39–0.70/0.41	0.30/0.35/0.35
AOC (mg/L)	2.9	11.0–17.6/12.0/12.0	8.9–11.0/9.8

4. Subsurface intake improvement to feedwater quality

A number of investigations have shown that significant water quality improvements can be achieved by using subsurface intakes instead of open-ocean intakes (Table 3). Recently collected data from the Sur, Oman site demonstrates that subsurface intake systems produce high quality seawater by removing nearly all of the algae, a high percentage of the bacteria, a significant amount of the organic carbon, and a high percentage of the marine biopolymers that are currently believed to facilitate membrane biofouling [76] (Table 5). The removal of virtually all of the turbidity, algae, and the large bacteria allows the use of a simpler, less expensive pretreatment system with a corresponding reduction in operating costs.

Fig. 9. Construction of the City of Long Beach, California seabed gallery system. This gallery required the use of sheet-piling and temporary dewatering to install the gravel and screen system.

In many cases, the water produced from a subsurface intake can be transmitted directly to the cartridge filters, thereby eliminating mixed media filtration, coagulation processes, and the need to use various chemicals (e.g., ferric chloride, chlorine). An example is the Fukuoka, Japan facility that uses a seabed gallery coupled to a membrane filtration pretreatment system, which is likely not needed based on the water quality obtained from the intake. The goal of all subsurface intake systems is to provide seawater that requires no additional pretreatment with the corresponding plant design being similar to brackish-water desalination systems that utilize well intakes and use only cartridge filters (with some chemical additives to prevent scaling) [10,11,77].

5. Economics of subsurface intake systems

Improvement of feedwater quality has a significant impact on the economics of desalination, particularly on operating cost. Therefore, the use of subsurface intakes should reduce the overall cost of desalination. However, the use of subsurface intakes will increase the capital cost for the construction of large-scale desalination facilities in many, but not all cases. While capital cost is important, it is not the major factor determining overall, long-term cost of desalination based on a simple life-cycle analysis. The cost analysis of a SWRO facility is commonly divided into capital or investment cost (CAPEX) and operating cost (OPEX) [78]. Therefore, each type of cost is discussed separately for general input into a preliminary life-cycle cost analysis.

The comparative CAPEX costs of a conventional intake system coupled with pretreatment versus a subsurface intake systems are instructive. For a typical, stand-alone SWRO facility having a capacity of 100,000 m^3/day, the combined cost for the intake, associated pumping station, and outfall is about roughly \$30 million USD or about 13.9% of the total facility cost (Table 6). If the intake is separated from this cost, it is about \$10 million USD or about 4.6% of total cost. The pretreatment system using conventional gravity filters with coagulation and periodic chlorination/dechlorination has a cost of \$25 million USD or constitutes about 11.6% of the total CAPEX. If a dissolved air flotation system and/or a membrane pretreatment system are used, the pretreatment process train cost would be considerably greater. While a subsurface intake system will have a greater CAPEX compared to a conventional open-ocean intake, there will be a corresponding reduction in the pretreatment train cost. If no pretreatment equipment is required, a total of \$35 million USD could be used to construct a subsurface intake system without altering the overall project CAPEX. If only polishing filtration is required, the reduction in CAPEX for the subsurface intake system associated pretreatment train would still significantly reduce pretreatment CAPEX cost. Therefore, in some cases the CAPEX cost differential between use of open-ocean and subsurface intakes may be similar and have a minimal impact on overall project cost.

OPEX costs have an overall much greater impact on the net water cost delivered to the consumer compared to CAPEX cost, especially as the useful life expectancy of the facility or the contract duration increases. It is clear that operational cost savings occur as a result of using subsurface intake systems [81–84]. Specific operational cost savings include: 1) reduced cost associated with maintaining an open-ocean intake, such as the use of divers to physically clean it and the periodic or continuous feed of chlorine to control accumulation of biological growth, 2) no need to operate traveling screens with associated removal of debris and disposal of biological waste, 3) no need to operate fish recovery and release programs, 4) no need to add coagulants in the pretreatment system, 5) reduced electrical costs associated with a complex pretreatment system, 6) no use of chlorination/dechlorination, 7) reduction in the frequency of required membrane cleanings, 8) increased life-expectancy of membranes, and 9) reduced labor costs. It is also probable that the higher quality water

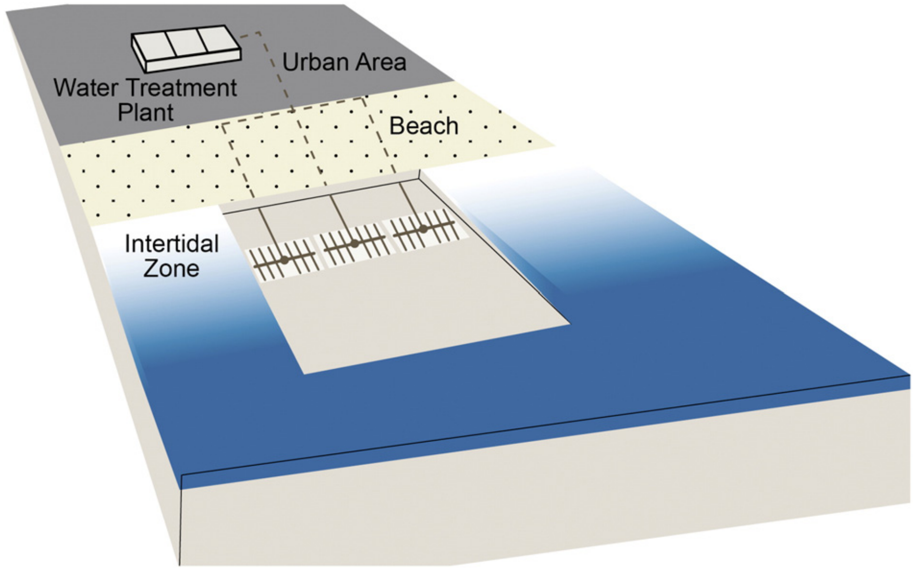

Fig. 10. Beach gallery intake system showing the concept of allowing the breaking waves at the shoreline to mechanically clean the face of the filter, reducing the potential for clogging.

would allow the membrane process to be operated at a higher efficiency by increasing the permeate flux without fear of increasing biofouling. Reverter et al. [85] found at the Palms III plant in the Canary Islands (Spain) that raw water treated from an open-ocean intake required the permeate flux rate to be between 11.8 and 13.4 L/m^2-h, while raw water obtained via beach wells allowed the permeate flux rate to be increased to 16.8 L/m^2-h or an increase of 20 to 30% efficiency. This saves up to 8% in operating cost. Another cost consideration is a reduction in the required environmental monitoring associated with permit special conditions for an open-ocean intake.

Table 5
Comparison of raw seawater and well intake water quality at the Sur, Oman SWRO facility [76].

Parameter	Seawater	Well 1W	Well 9W	Well 12C	Aggregated
Physical					
TDS (mg/L)	55.4	54.3	55.8	55.8	
Turbidity (NTU)	0.91	0.61	0.38	0.30	
SDI_{15}	16.52[a]	0.819	0.996	1.193	
Organics					
DOC (ppm)	0.544	0.101	0.170	0.133	0.128
Biopolymers (ppm)	222	1	8	ND	2
Humic substances (ppm)	520	85	41	91	93
Building blocks (ppm)	425	80	59	77	83
LMW neutrals (ppm)	458	95	150	125	117
LMW acids (ppm)	155	32	49	38	26
Algae					
Prochlorococcus sp. (cells/mL)	4400	<100	<100	<100	<100
Synechococcus sp. (cells/mL)	113,040	<100	<100	<100	<100
Piconanoplankton (cells/mL)	1900	<100	<100	<100	<100
Bacteria					
Total bacteria (cells/mL)	995,310	3270	8540	13,630	11,000
LNA bacteria (cells/mL)	582,750	2270	6110	9520	7540
HNA bacteria (cells/mL)	396,850	940	2230	3900	3266

[a] Seawater SDI was for 5 min instead of 15 min.

There is a large suggested range in potential OPEX savings by using subsurface intakes. If solely pretreatment cost is assessed, the annual savings could be as high as 35% based on a comparison of open-ocean intake versus a beach well system where challenging water quality occurs [81]. A review of relatively small-capacity seawater RO systems showed an OPEX savings range from 10 to 25% [83]. A preliminary analysis of the OPEX savings for all capacities of SWRO facilities using any type of subsurface intake showed a savings range from 10 to 30% based on the plant capacity and the duration of the operating life or contract [84]. A more detailed analysis between plants having open-ocean intakes and conventional pretreatment and those having a beach well system showed a cost reduction of 33.8% [81].

A preliminary life-cycle analysis was conducted to assess how much additional CAPEX cost could be absorbed using a subsurface intake system versus using a conventional intake with a corresponding pretreatment system (Table 7). The cost for a 100,000 m^3/day capacity stand-alone SWRO plant was used as a baseline (Table 6). The cost of a conventional open-ocean intake was assumed to be $10 million USD based on one-third of the line item shown in Table 6. Two scenarios were considered; a facility that would have a subsurface intake with a polishing filtration system with a corresponding reduction in pretreatment CAPEX cost from $25 million USD to $10 million USD and a facility that has a subsurface intake that allows direct discharge of water from the intake to the cartridge filters, which would reduce the pretreatment CAPEX to 0. If it is assumed that there would be zero savings in OPEX for using a subsurface intake, then the maximum CAPEX intake cost that could be induced without increasing the overall cost of water production would be $25 million USD for scenario 1 and $35 million USD for scenario 2. The range of potential OPEX savings using a subsurface intake system was 0 to 30%. The analysis considered OPEX or life-cycle durations of 10, 20, and 30 years. This exercise is significant because there is wide variation in the subsurface intake type that can be used for a specific site, thereby causing extreme variation in intake construction cost. An analysis of the numbers shows that a very large CAPEX investment in the construction of a subsurface intake system can be made without increasing the overall water cost. Considering case 2 with a 30-year operating period, the cost of using a subsurface intake could be as much as 86% of the overall facility CAPEX without increasing the cost of water. In most cases, there will be a clear reduction in cost. Also, this analysis does not consider any cost savings associated with reduction in environmental impacts.

Table 6
CAPEX cost of typical SWRO plant with a capacity of 100,000 m^3/day, including pretreatment [79,80].

Systems	System cost (USD)	Cost partitions (%)	Specific cost (USD/m^3/day)	Supplemental information
Intake, pump station, and outfall	30,000,000	13.9	300.0	
Pretreatment system	25,000,000	11.6	250.00	
–Membranes (MF/UF)		–	–	
–Without membranes	25,000,000	11.6	250.0	
Reverse osmosis part total	80,000,000	37.5	800.0	Isobaric ERD
–Membranes (without vessels)	8,000,000	3.7	80.0	
–Reverse osmosis without membranes	72,000,000	33.4	720.0	
Potabilization plant	10,000,000	4.6	100.0	
Drinking water storage and pumping	10,000,000	4.6	100.0	
Wastewater collection and treatment	5,000,000	2.3	50.0	
Mechanical equipment without membranes	152,000,000	70.6	1520.0	
Auxiliary systems	7,000,000	3.3	70.0	
Civil works	16,000,000	7.4	160.0	
Electrical works	15,000,000	7.0	150.0	
I. & C. Works	7,000,000	3.3	70.0	
Total	205,000,000		2050.0	
Contingencies (5%)	10,250,000	4.8	102.5	
Seawater RO plant total	215,250,000	100.0	2152.5	
	USD/year		USD/year	
Annual capital cost (annuity)	16,838,301		0.46	

Notes: SWRO plant net capacity = 100,000 m^3/day.
Type of pretreatment = gravity filters.
Type of potabilization = lime/CO_2.
Type of intake = open.
Plant lifetime = 25 years.
Interest rate = 6%/year.

Another economic consideration is the location of the RO plant in proximity to an acceptable site on which a subsurface intake could be developed versus using an open-ocean intake at a more proximal location to the distribution system. In locations where seawater quality is challenging, a considerably greater water transmission distance may be cost-effective to locate the plant at a site where treatment cost OPEX would be more favorable, especially where the cost reduction per cubic meter is greater than 20%.

6. Discussion

It is a common misbelief that subsurface intake systems are limited for use on only moderate and small capacity SWRO systems [86,87]. Greenlee et al. [88] stated "Today, as larger and larger RO plants are designed, beach wells cannot always provide enough water, and open seawater intakes are the only feed source option." While these authors may be correct concerning beach wells and their limitations on yield and numbers, beach wells are not the only subsurface intake option available. Horizontal and radial collector wells have the potential to yield very large quantities of water to meet the requirements of a large range of SWRO plant capacities. Beach and seabed gallery systems have the capability under favorable geologic circumstances to meet the requirements of virtually any capacity SWRO system.

Subsurface intake systems are largely a modular design, in which capacity can be increased by the construction of additional wells or galleries. Modular designs thus tend to be more flexible, but have a

Table 7
Economics of subsurface intakes showing the amount capital cost that can be spent on a subsurface intake verses an open ocean intake and not have an impact on the total life-cycle cost based on OPEX savings.

Type of intake	Open ocean intake	Detailed subsurface intake analysis						
Operational period (years)	10 years	10 years						
% of potential saving in operation cost for subsurface		0%	5%	10%	15%	20%	25%	30%
Operation cost ($/$m^3$)	1	1	0.95	0.9	0.85	0.8	0.75	0.7
CAPEX cost	215,250,000	215,250,000						
Annual OPEX cost*	36,500,000	36,500,000	34,675,000	32,850,000	31,025,000	29,200,000	27,375,000	25,550,000
Total OPEX cost along the operational period	365,000,000	365,000,000	346,750,000	328,500,000	310,250,000	292,000,000	273,750,000	255,500,000
Annual capital cost**	29,245,578	29,245,578						
OPEX cost saving	0	0	18,250,000	36,500,000	54,750,000	73,000,000	91,250,000	109,500,000
Annual OPEX cost saving	0	0	1,825,000	3,650,000	5,475,000	7,300,000	9,125,000	10,950,000
Annual capital cost amortization + annual OPEX cost saving**			31,070,578	32,895,578	34,720,578	36,545,578	38,370,578	40,195,578
Principal cost	215,250,000	215,250,000	228,682,159	242,114,318	255,546,477	268,978,635	282,410,794	295,842,953
Capital cost that can be added to the subsurface intake		0	13,432,159	26,864,318	40,296,477	53,728,635	67,160,794	80,592,953
Case 1 (25,000,000): 10 years of operation		25,000,000	38,432,159	51,864,318	65,296,477	78,728,635	92,160,794	105,592,953
Case 2 (35,000,000): 10 years of operation		35,000,000	48,432,159	61,864,318	75,296,477	88,728,635	102,160,794	115,592,953
Case 1 (25,000,000): 20 years of operation		25,000,000	45,932,606	66,865,212	87,797,819	108,730,425	129,663,031	150,595,637
Case 2 (35,000,000): 20 years of operation		35,000,000	55,932,606	76,865,212	97,797,819	118,730,425	139,663,031	160,595,637
Case 1 (25,000,000): 30 years of operation		25,000,000	50,120,817	75,241,634	100,362,451	125,483,267	150,604,084	175,724,901
Case 2 (35,000,000): 30 years of operation		35,000,000	60,120,817	85,241,634	110,362,451	135,483,267	160,604,084	185,724,901

Plant capacity = 100,000 (m^3/day), Interest rate = 6% per year, operation cost = 1($/$m^3$).
* Annual OPEX cost = plant capacity * operation cost * no. of operation days.

** Annual capital cost (annuity cost) = $P\left(i+\frac{i}{(1+i)^n-1}\right)$, where P = amount of principal (Capital), i = interest rate, and n = number of years.

Table 8
Comparative viability of subsurface intake types.

Type	Capacity limit (m^3/d)	Water quality improvement	Technical limitations	Maturity of technology
Conventional wells	<250,000	Major	Local geology, large capacity requirement	Mature
Angle wells	<250,000	Untested	Local geology, large capacity requirement	Immature
Radial collector wells	<500,000	Untested	Local geology, beach stability, large capacity requirement	Mature-non-seawater intake applications
Horizontal wells	Unknown	Minimal testing	Local geology, seabed sedimentation rate, water turbidity	Immature
Seabed galleries	Unlimited	Major	Offshore sedimentation rate, water turbidity	Moderate (one operational system)
Beach galleries	Unlimited	Untested	Shoreline stability	Immature

relatively small economy of scale. Conventional intakes, on the contrary, have a relatively large economy of scale with regard to construction costs. For example, increasing the size (diameter) of a screen and subsea intake pipe can accommodate twice the flow results in a much lower construction cost per unit volume of capacity. Operational costs (e.g., energy and chemical costs) are more proportional to system capacity. Hence for small and mid-sized systems, subsurface intakes can provide both CAPEX and OPEX savings. For large systems, the benefits are predominantly in OPEX costs.

A preliminary life-cycle economic analysis conducted shows that the increased capital cost of using a subsurface intake system is offset by a reduction in capital cost of the pretreatment train (reduced number of processes) and reduced operating costs make subsurface intakes quite attractive. There are a number of specific cost savings in operations which include elimination of traveling screens operation, elimination of solid waste disposal of marine debris, such as fish, jellyfish, and seaweed, reduction or elimination of chemical usage, reduction or elimination of electrical and maintenance costs for the pretreatment systems, and potential increases in the flux rate of seawater across the membranes resulting in increased productivity.

The economic analysis shows that the capital costs for the use of a subsurface intake can be increased by as much as factors of 54, 75, and 86% for corresponding operating periods of 10, 20, and 30 years using the summed life-cycle costs for these timeframes based on a cost reduction factor range of 30% for a SWRO plant with a capacity of 100,000 m^3/day. Therefore, from a purely economic viewpoint, the use of subsurface intake systems is preferred over an open-ocean intake system. It is anticipated that the operational cost reduction would be greater than 15% in nearly all cases. Also, this assessment does not include the elimination of environmental impacts associated with impingement and entrainment of marine organisms which could also be assigned a true cost. This cost includes a reduction in the permitting costs required to demonstrate that a facility does not have a significant impact or can include an elimination of mitigation measures required to offset environmental impacts.

Another factor in the use of subsurface intakes that has been raised is the issue of potential risk for bidders or facility owners in terms of the applicability of a given intake type to a specific site, operational risk for failure or unexpected upsets, and the proverbial question of maturity of technology. There are limits on the use of various subsurface intake types based on the local geology of a site and on the maximum capacity of a type based on the costs associated with operating a large number of wells (Table 8). In general, there are limits on the use of conventional vertical wells, angle wells, and radial collector wells for very large SWRO systems. These intakes likely are limited to feedwater capacity requirements ranging from no greater than a range of 250,000 to 500,000 m^3/day, which equates to permeate capacities ranging from 87,500 to 250,000 m^3/day, depending on the conversion rate (salinity based from 35 to 50%). The technical limitations on use of each intake type are shown, which are most commonly geologic factors or a high sedimentation rate that could produce filter clogging. Conventional well intake systems have been used for the longest time period and must be considered to be the most mature technology with demonstrated success. Radial well and horizontal well systems are operating and have shown to be successful for seawater intake use. The radial well technology is very mature based on applications associated with freshwater intakes adjacent to rivers and streams. Gallery intakes are relatively new and the application to SWRO intakes cannot be considered to be "mature technology", but the Fukuoka, Japan site has proven to be a quite successful demonstration of the technology. However, the design concept is analogous to the slow sand filtration process that has been used in water treatment for over a century. A fundamental advantage of gallery intake systems is that they can be used to supply virtually any capacity SWRO facility.

7. Conclusions

Fundamental goals for future desalination of seawater include reductions in the quantity of energy and chemicals, in the carbon footprint, and the overall cost of water to the consumer. The use of subsurface intake systems, wherever possible, helps achieve these goals. Subsurface intakes always produce a higher quality feedwater compared to conventional open-ocean intakes. This improvement in water quality leads to the simplification of required pretreatment processes with the elimination of many or all processes. The use of chlorine, coagulants, and other chemicals can be essentially eliminated by the use of subsurface intake systems. Reduction in chemical use and power consumption in operation of pretreatment systems causes a reduction in the carbon footprint of a SWRO system and in potential environmental impacts. Elimination of impingement and entrainment impacts on the environment is also an added advantage of using a subsurface intake system. Finally, the life-cycle cost analysis of virtually any capacity, stand-alone RO treatment system will show that the use of subsurface intake systems reduces the cost of desalination to the consumer, provided that the technology is locally available to construct the system. While not all facility locations can use subsurface intakes, it should always be a priority of a utility, project owner, or project developer to consider the use of a subsurface intake and provide tender bidders with sufficient technical information concerning subsurface or offshore conditions to allow a subsurface intake to be bid without great risk.

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