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Reverse osmosis desalination system and algal blooms part II: seawater intake technologies

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ABSTRACT

While thermal desalination processes require minimum pretreatment (mainly screening and chemical additions to prevent scaling), seawater reverse osmosis (SWRO) desalination plants require extensive pretreatment of the feedwater before entering the membranes. As the Arabian Gulf (AG) countries depend on seawater desalination, there is a strategic decision to move gradually to SWRO desalination technologies. The algal bloom (AB) events that have happened in the AG countries raise more concerns about seawater pretreatment. A seawater intake is a key limiting factor and is a real part of pretreatment for high performance desalination process. This paper (second part of a series of three parts) reviews several intake options and their effects on the quality of feed seawater and the major parameters causing membrane fouling, especially bio-fouling. These include the concentrations of algae, bacteria, total organic carbon, particulate and colloidal transparent exopolymer particles (TEP), and the biopolymer fraction of natural organic carbon. Several forms of algal organic matter (AOM) are produced by ABs with varying concentrations and include intracellular organic matter formed due to autolysis consisting of proteins, nucleic acids, lipids and small molecules; and extracellular organic matter formed via metabolic excretion and composed mainly of exopolysaccharides. Being comparatively large macromolecules, exopolysaccharides are most often insoluble in water. A significant fraction of these exopolysaccharides, known as TEP, are highly surface-active, sticky, and play a significant role in the aggregation dynamics of algae during AB events. This paper reviews the different seawater intake technologies and highlights advantages and disadvantages of each. It aims at recommending the best intake technology for the site-specific conditions of a given desalination project.

Keywords: Membrane desalination; Seawater intake systems; Biofouling; Arabian Gulf region

1. Introduction

Thermal desalination methods such as multi effect (ME) distillation, multi-stage flash (MSF), and ME-thermal vapor compression (ME-TVC) systems were the first desalination technologies applied in the Gulf Cooperation Countries (GCC) to produce desalted seawater (DW). DW satisfies good portions of freshwater demands in the GCC, (Fig. 1). DW satisfies

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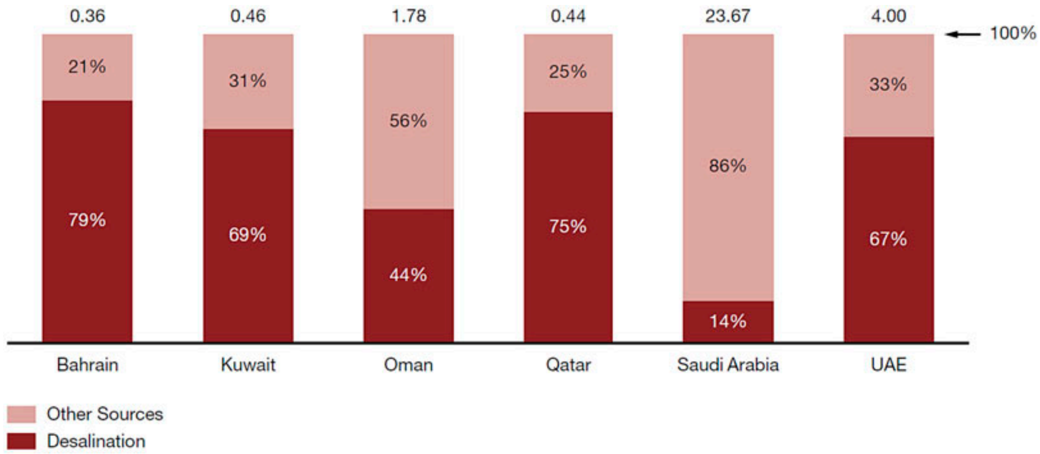

Fig. 1. Percentage of desalinated water in total water consumption (in billion cubic meters per year) [1].

the main municipal water needs in the GCC (about 99% in Qatar, 96% in Kuwait, 60% in Saudi Arabia).

The ME, MSF, and ME-TVC systems are known to be very reliable; need simple pre-treatment, have a large capacity per unit, but have a high energy use per m^3 of produced DW, and thus a high cost of product water. The GCC are now following the world trend by moving gradually to the use of seawater reverse osmosis (SWRO) desalination systems to produce DW because of their low specific energy consumption (SEC) and production cost.

Pretreatment of feed seawater (SW) to thermal desalination processes is simple and consists mainly of screening and chemical conditioning. Screening removes large particles by coarse and fine screens of vertical and rotating types. Chemical pretreatment includes chlorination, alkalinity reduction by pH control, and adding scale inhibitors. In general, chemical pretreatment is used to avoid scaling of $CaCO_3$, $MgCO_3$, and $CaSO_4$. The MSF is very robust with allowable particle size in feed SW in the range of 5–15 mm. The ME process needs finer water filtration, with the allowable particle size for SW going through the spray nozzles less than 0.5 mm. Thermal plants' intake screens do not remove fine particulates and algal cells. Chemical conditioning (like chlorination) is applied to cooling SW to the MSF heat rejection section, and anti-scalant is applied to makeup water (feed) to prevent scaling on the heat exchanger surfaces. Moreover, antifoaming agents are continuously added to thermal processes to prevent foaming in the de-aerator and flash chambers. Neither antifoaming chemicals (poly-propylene-polyethylene oxide, isopropanol) nor the anti-scalants (commonly poly-acrylactes, poly-carboxylic acids) are expected to assist in the removal of algal cells or detoxification of extracellular toxins. In thermal desalination systems, volatile organics with boiling points lower than that of SW may be carried over in the generated vapor and vented out in the process. It is often assumed that high molecular weight organics with high boiling points will remain in the brine rejected back to sea. Evaporation of organics from SW and their condensation into distillates are governed by several factors such as the temperature and pressure of the MSF stages or ME effects and their concentration, vapor pressure and the latent heat of condensation of the individual compounds.

For comparison, pretreatment of feed SW for SWRO desalination is much more complicated and generally classified to primary and secondary treatments to remove suspended solids (particulate, colloidal, microbial and some organic foulants, etc.), oil, and grease from feedwater. The primary pretreatment usually consists of coagulation and flocculation in combination with a clarification process such as sedimentation or dissolved air flotation (DAF). The secondary pretreatment consists of a filtration process, and can be classified as conventional when granular media filters (GMF) are used and advanced (or low pressure membranes) when microfiltration (MF) and ultrafiltration (UF) membranes are used. The SWRO pretreatment is necessity to avoid (or reduce) membrane fouling caused by deposits of particles on membrane surface or in membrane pores that degrade its performance. It was found that at least 63% of all RO membrane failures are related to the inadequate design and operation of pretreatment systems [2]. Membrane fouling can cause flux decline and affect the permeate water quality. There are various types of foulants, which can be summarized as:

(1) Particulate (suspended solids of clay, flocs, and silt).
(2) Colloidal (0.001–1 μm colloidal silica and iron).
(3) Mineral scaling (mainly salts of calcium, magnesium, and metal oxides of iron, manganese, copper, etc.).
(4) Organic (oils, polyelectrolytes, negatively charged humic and fulvic acids, and residual organics).
(5) Biological (bacteria, fungi), and microbial (poly-saccharides and proteins from algal and bacterial cells).

Fouling can be reversible or irreversible based on attachment strength of particles to the membrane surface. While reversible fouling can be removed by a firm shear force or back-washing in low-pressure membrane processes such as UF, back-washing cannot be applied for reverse osmosis (RO) membranes. Formation of a strong matrix of fouling layer with the solute during a continuous filtration process will result in reversible fouling being transformed into an irreversible fouling layer. Irreversible fouling is the sturdy attachment of particles, which cannot be removed by physical cleaning.

Villacorte [3] and Missimer et al. [4] showed several SWRO pretreatment options as illustrated in Figs. 2 and 3, respectively. The intakes, shown in Figs. 2 and 3 can be open intake (onshore or offshore) with coarse and fine screening; and subsurface intake (vertical, horizontal, slant wells; and onshore, beach, and offshore infiltration galleries) where SW is using natural geological properties of sediments and rocks to provide high-quality feed SW. After open intakes, small particulates in SW have to be agglomerated for easy sedimentation and filtration by (in-line or full) coagulation. This is to be followed by sedimentation (clarification) tanks or dissolved air floatation (DAF) to separate agglomerated particles. When coagulation is not enough, it is followed by flocculation. The clarified SW is then filtered by conventional granular media filers (operated by gravity or under pressure); or by low pressure membranes such as UF or microfiltration (MF). A final precautionary measure to save the SWRO membranes is passing the filtered water through cartridge filters. The trains a, b, and c in Fig. 3 are the desired simplified system with open intake, while train d in Fig. 3 is for subsurface intake. A subsurface intake is utilized to produce high-quality feed SW that can bypass the pretreatment system and flows directly to the cartridge filters [4].

The pretreatment system selection options are based on feed SW characterization by determining its turbidity, total suspended solids (TSS), silt density index (SDI), total organic carbon (TOC) determining the natural organic matters (NOM), algae, oil & gas, and chlorophyll-a. Details of the pretreatment processes are given in part three of this series.

Process options

Scheme A	Open intake → coag-flocculation → sedimentation → granular media filter (GMF) → ultrafiltration (UF) → cartridge filter → RO
Scheme B	Open intake → coag-flocculation → sedimentation → GMF → cartridge filter → RO
Scheme C	Open intake → coag-flocculation → sedimentation → UF → cartridge filter → RO
Scheme D	Open intake → coag-flocculation → dissolved air flotation (DAF) → GMF → UF → cartridge filter → RO
Scheme E	Open intake → coag-flocculation → DAF → GMF → cartridge filter → RO
Scheme F	Open intake → coag-flocculation → DAF → UF → cartridge filter → RO
Scheme G	Open intake → in-line coagulation → cartridge filter → RO
Scheme H	Open intake → in-line coagulation → UF → cartridge filter → RO
Scheme I	Subsurface intake → in-line coagulation → UF → cartridge filter → RO
Scheme J	Subsurface intake → UF → cartridge filter → RO
Scheme K	Subsurface intake → cartridge filter → RO

2. Water intake systems

The water intake system to the desalination plant (DP) is considered as part of the feed SW pretreatment process as shown in Figs. 2 and 3. The intake system should ensure reliable quality and quantity of the incoming SW to the DP. The choice of the SW intake design and its siting to the SWRO DPs is an important issue that highly affects the quality of the feed SW in terms of nature and quantity of foulants, and complexity of the pretreatment system. The pretreatment process removes debris, suspended solids, and organic compounds that adversely impact the primary membrane process. The intake system affects the SWRO plant capital cost; adopted pretreatment method to achieve the required feedwater quality for

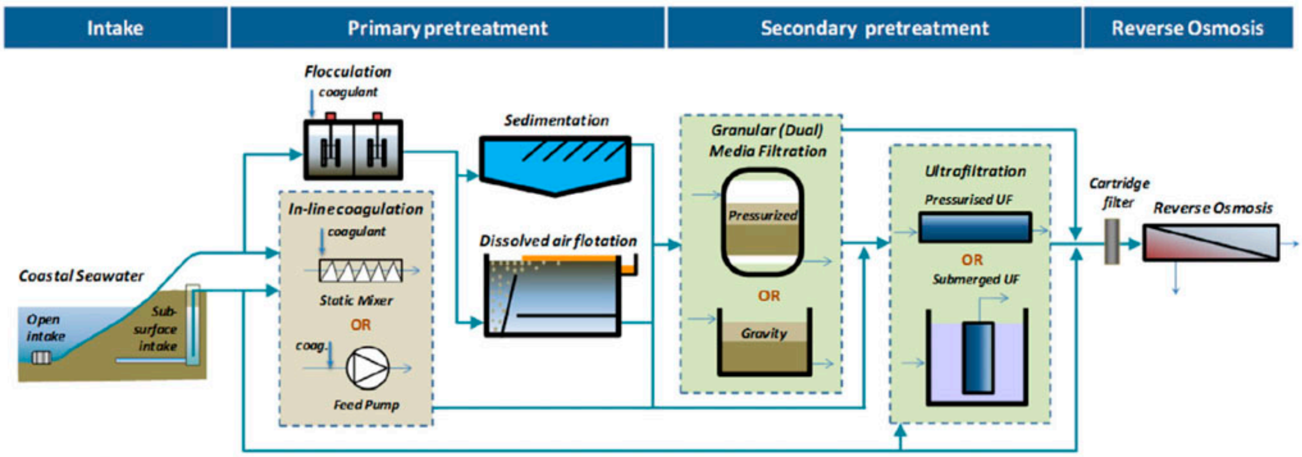

Fig. 2. Pretreatment options and process schemes applicable for SWRO plants [3].

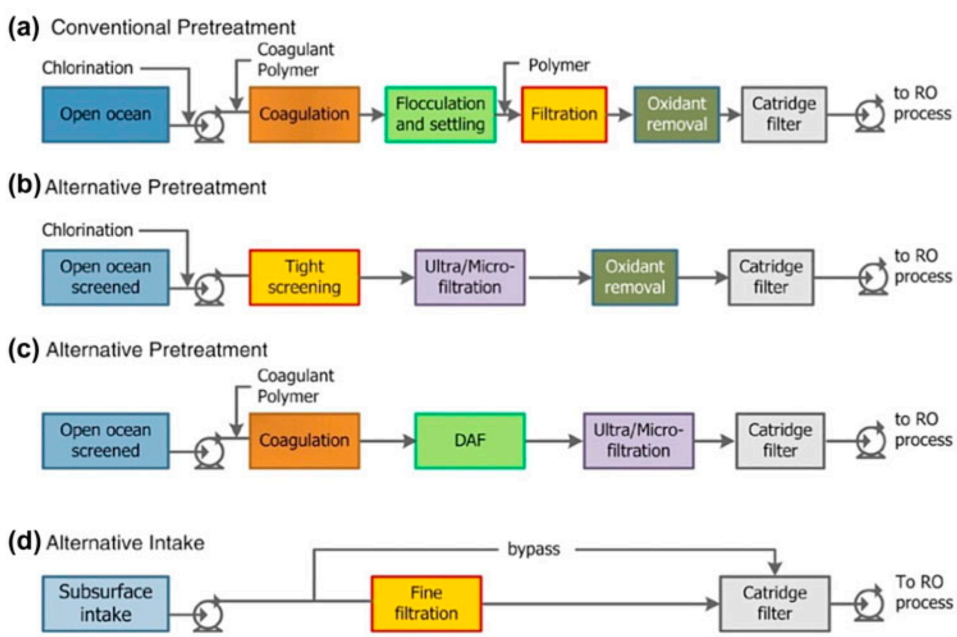

Fig. 3. Diagram showing typical pretreatment process trains for an SWRO plant [4].

the membranes; and reduce the negative impact of DP on the environment.

The negative impact on marine environment is caused by fish impingement and entrainment into the intake system. Fish impingement occurs when fish get stuck to the intake screen due to high intake velocity, while entrainment occurs when organisms smaller than the screen mesh are drawn into the intake. The intake to the DP can be classified as open intake (also called direct) and sub-surface intake (called indirect) type (Fig. 4a) [5].

Single-purpose direct intakes can be used for the DP only, or dual purpose intake for both DP and a power plant; and can extract SW from surface, shallow, or deep water on shore, near shore, or offshore. Shallow SW can be considered as that taken from 0 to 15 m depth while deep SW is considered as that from 20 to 35 m depth. The possibility of having deep-water intake is limited by the feasibility of finding deep water close to the DP. A floating intake is another direct system with an example proposed for Sicily DP using floating pump system; some 200 m from the shore to take SW from the open sea site one meter below the SW surface and connected to the DP by a flexible pipe [6].

Sub-surface intakes extract seawater from beneath the seafloor or beach; and can be located on or offshore. Onshore subsurface intakes include vertical wells (e.g. beach well), slant wells, horizontal radial wells, and beach-infiltration galleries. Furthermore, offshore indirect intakes include horizontal directionally drilled wells, and seabed infiltration galleries.

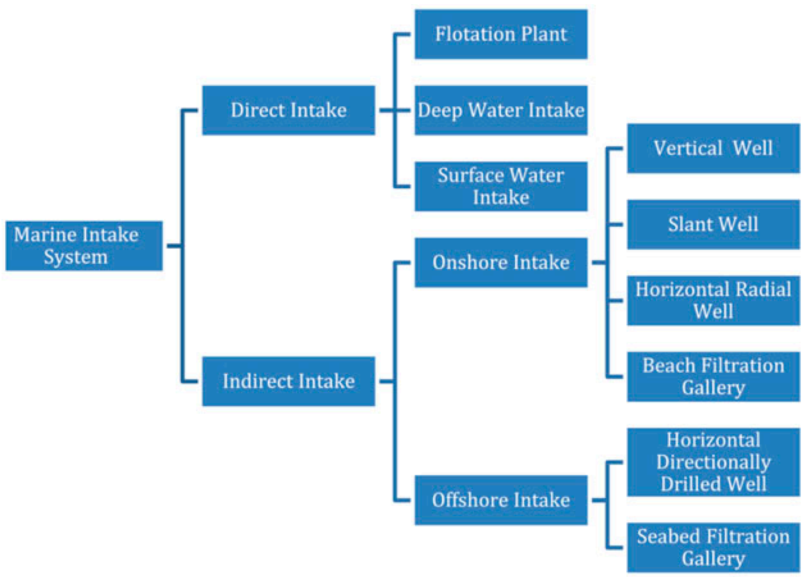

Fig. 4a. Marine intake systems for seawater DPs [5].

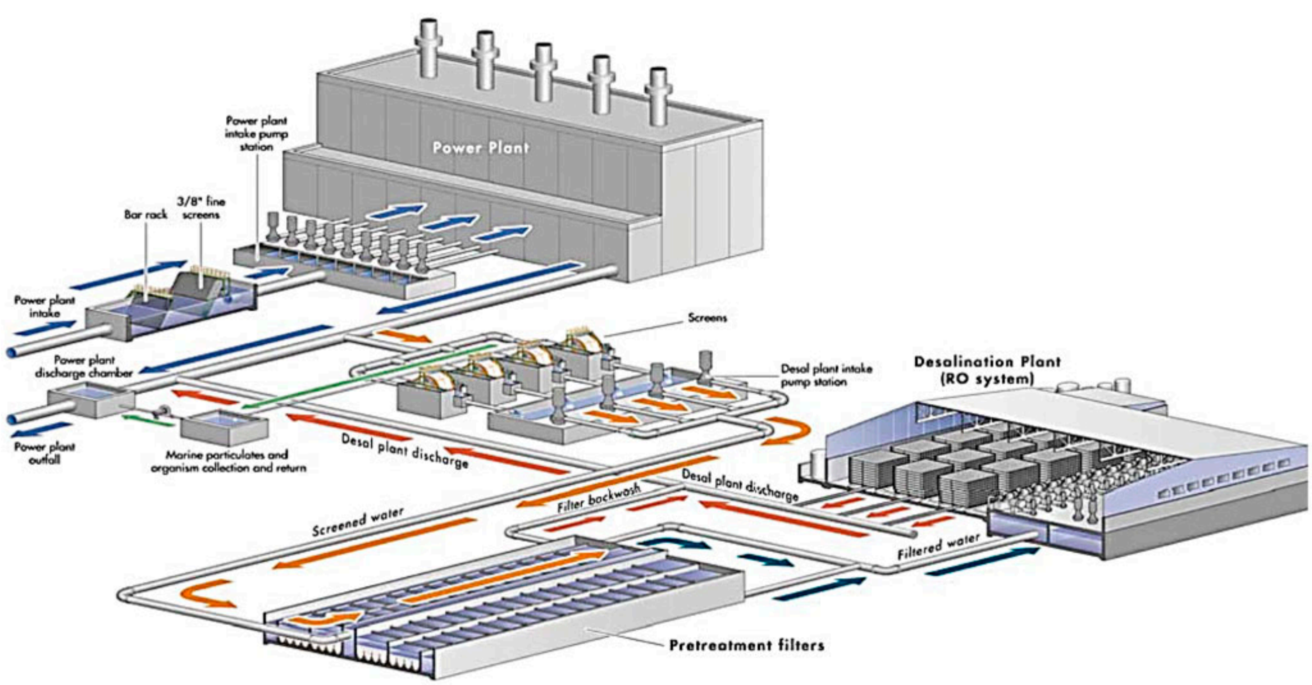

Fig. 4b. Co-location of a power plant with a DP [11].

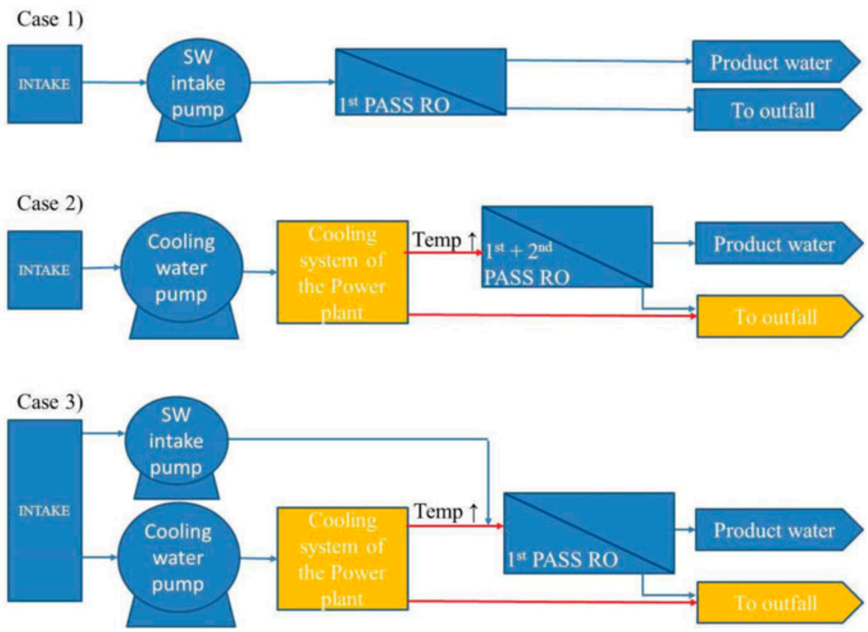

Fig. 4c. Three configuration of combining SWR DP with PP [12].

Examples of existing seawater intake systems for DPs of more than one million gallons per day (MGD) capacity are given in Table 1 [7].

Subsurface intakes contribute greatly to the pretreatment process, as the feed SW is filtered through natural soil or sand bed without adding chemicals; and bacteria, algae, and bio-polymers (e.g. proteins and polysaccharides) are removed before pumping. This reduces drastically the membrane bio-fouling. For example, the Fukuoka, Japan DP using a seabed infiltration gallery supplies seawater of SDI below 3 to the UF pretreatment step. This allows the UF to operate for long periods without back-washing. Moreover, subsurface intakes inherently eliminate impingement and entrainment, and eliminate marine life impact compared with open intakes [8].

The cost of the intake system can be a significant share of DP capital cost. Pankratz [9] gave two cost examples, one for the 35 MGD SWRO in Gold Coast, Australia where, the SWRO facility cost was US$ 557 million with Intake/outfall cost was US$ 280 million, or about 50% of the plant cost. The other example is the SWRO plant of 50 MGD in Carlsbad, California where the SWRO facility cost was US$ 300 million, while the additional intake/outfall cost was estimated for several types of intakes as: US$ 150 million for new open sea, US$ 415 million for slant well, US$438 million for horizontal Ranney', US$ 638 million for infiltration gallery, and US$650 million for beach wells. These estimated cost data given by Pankratz are not confirmed [9]. Voutchkov reported significantly smaller than those given by Pankratz [11]. The intake of the Gold Coast plant is only US$ 26 million and that of Carlsbad is only US$ 16 million because the Carlsbad DP is collocated with a power plant and it uses its existing intake.

A science technical advisory committee found recently that a 380,000 m^3/d offshore gallery for the Huntington Beach SWRO plant (50 MGD) would cost about US$ 900 million.

The choice of intake type depends on the site, plant capacity, needed feedwater quantity and quality, and environmental regulations. The type of the intake system can be decided by the DP capacity from the beginning. Low capacity DP (<5 MGD, or 19,000 m^3/d) may be able to use the beach well, large capacity (>20 MGD, or 76,000 m^3/d) normally uses the open intake system, and mid-range capacity (5–20 MGD) uses multiple alternatives [7].

The effect of algal blooms (AB) on membrane fouling depends on the type of the intake. In open intake system using deep SW, the amounts of algae species may be less than that at the surface, but still need algae pretreatment. Subsurface intakes provide SW with almost no algae, and thus the AB is not an issue in this case. Moreover, open intake is usually

Table 1
Water intake examples of some DP of more than one MGD Capacity [7]

Owner	Location	Intake type	Capacity
United Arab Emirates	UAE	Floating intake on barge	1 mgd (3,800 m^3/d)
Morro Bay	Morro Bay, California, USA	Beach wells	1.4 mgd (5,300 m^3/d)
Antigua	Antigua	Open sea intake	2.5 mgd (9,500 m^3/d)
N.V. Energie en Watervoorziening Rijnland	Leiden, Netherlands	Beach collector wells	2.6 mgd (9,800 m^3/d)
US Naval Base	Guantanamo Bay, Cuba	Open intake with fish trap	5 mgd (19,000 m^3/d)
Ghar Lapsi	Malta	Beach wells	6.3 mgd (24,000 m^3/d)
Veolia	Kindasa, Saudi Arabia	Open intake	7 mgd (26,500 m^3/d)
Bay of Palma	Mallorca, Spain	Beach wells	II mgd (42,000 m^3/d)
Pemex Refinery	Salina Cruz, Mexico	Beach collector wells	12 mgd (45,500 m^3/d)
Fukouka District Waterworks Agency	Fukuoka, Japan	Seabed infiltration gallery	13.2 mgd (50,000 m^3/d)
Pembroke	Malta	Beach wells	14.3 mgd (54,000 m^3/d)
Veolia	Sur, Oman	Open intake and beach wells	21 mgd (79,500 m^3/d)
Aqualectra Production	Santa Barbara, Curacao	Permeable pit intake	22 mgd (83.000 m^3/d)
Tampa Bay Water	Tampa, Florida, USA	Shared power plant intake	25 mgd (95,000 m^3/d)
Desalcott	Point Lisas, Trinidad and Tobago	Bar screen intake	28.8 mgd (109,000 m^3/d)
San Pedro del Pinatar	Cartagena, Spain	Horizontal bedrock wells	35 mgd (132,000 m^3/d)
Public Utilities Board	Tuas, Singapore	Open intake	36 mgd (136,000 m^3/d)
Sydney Water	Kumell, Australia	Passive intake screen risers	66 mgd (250,000 m^3/d)
Veolia	Ashkelon, Israel	Multiple-head open intakes	222 mgd (840,000 m^3/d)

disinfected by chlorine (either continuous or shock chlorination), and chlorine can damage the algae cells. Periodic shock chlorination of the open intake system is now the most common practice for biological control. This can prevent the cells from entering the DP, but the destroyed cell will produce high levels of sticky algal organic matter (AOM) containing polysaccharides and proteins, transparent exopolymer particles (TEP), and biopolymers. These materials are more difficult to remove than the cells and cause major SWRO fouling problems. These materials also create a favorable environment for bacteria to thrive, exacerbating biofouling issues in the SWRO [10].

3. Intake system for cogeneration power/DPs

In the Arabian Gulf (AG) area, most DPs are combined with power plants forming what is called co-generation power desalination plants (CPDP). The intake of DP is co-located with that for the power plant, Fig. 4b. Co-location of a power plant with a DP enables the use of one intake for both, and this reduces the intake's construction cost 10–30%, and allows use of the same screening facilities. Moreover, by using one outfall for the DP and power plant dilutes the DP rejects and reduces its negative impact on the marine environment.

It is a necessity to combine any thermal DP with a power plant to secure moderately low pressure bleeding steam rather than using expensive steam directly generated from a boiler. When a SWRO DP is used, its combination with a power plant is optional, although it has some benefits. The main benefit is to overcome the problem of low SW feed temperature in winter that results in decreased output and increased SEC. When a SWRO DP is combined with a power plant, the return cooling SW from the power plant at a temperature higher than that of ambient SW is used as a feed to the SWRO. Another benefit is to blend the discharged high salinity SWRO brine with the return power plant cooling SW (at ambient SW salinity). This reduces the salinity of the discharge from SWRO DP and the temperature of the power plant discharge, which negatively affect the marine environment. Benefits also include: reduction in capital cost for the SW intake and outfalls structures, as well as screening the incoming SW. Several arrangements of co-located the SWRO with power plant are given in Fig. 4c.

4. Open intakes

Open intakes extract SW from surface, and shallow or deep water for the DP (or CPDP) with onshore lagoon and channels and offshore pipe as shown in

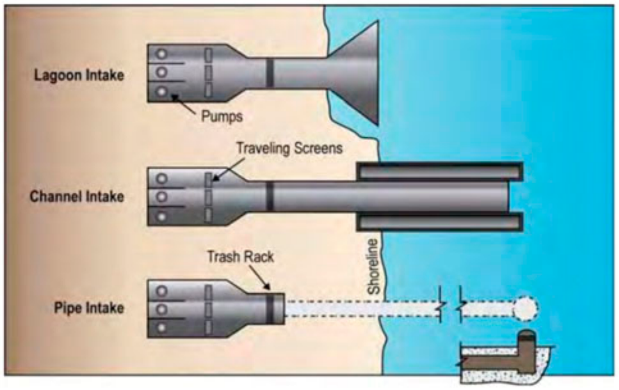

Fig. 5. Typical onshore (lagoon and channels) and offshore (pipe) open wet-well intake, line, and screen configurations [7].

Fig. 5 [7]. The open intakes are suitable for all plant capacities, but gives inferior feed SW quality.

In the case of onshore intake systems, SW is directed to a concrete conveyance channel with coarse screens, then to mechanical fine screens just before the pump station. The coarse screens prevent large debris and aquatic life from entering the intake structure. These are usually stationary and have low design velocity to minimize impingement of aquatic life. The low velocity design increases the intake area to account for partial area blockage by shellfish growth and debris accumulated on the surface of the coarse bars as in the offshore velocity cap intake shown in Fig. 6a.

Bar screens are used in onshore intakes and have an automated raking mechanism that periodically removes the accumulated debris and allows for maintenance. The fine screens' (3–10 mm) function is to protect the intake pumps from damage. They are placed following the course screens, and usually have rotating screens of band type, Fig. 6b or drum type, Fig. 6c, and both should have automated water-spraying cleaning system to remove the debris from the screen surface.

Fig. 6b. Example of band type traveling screen over an intake [5].

Fig. 6c. Sydney SWRO plant intake drum screens [14].

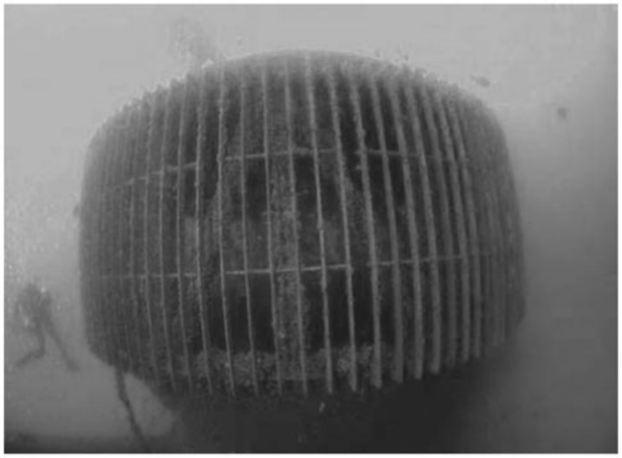

Fig. 6a. Coarse bar screen of open offshore cap intake [13].

4.1. Onshore open intake

A traditional conventional surface water intake for CPDP using an intake water channel is shown in Fig. 7a [9] and a water lagoon is shown in Fig. 7b [15]. Open intakes should have a suitable location such as adequate submergence at low tides, protected from storm wave motion, and away from near-shore sediment transport zone (silt and sediment deposits).

Fig. 7a. Conventional channel intake [9].

Fig. 7b. Conventional channel intake and outfall for Carlsbad seawater CPDP [15].

Fig. 8a. Al Fujairah CPDP plant [9].

Some intake locations should be avoided such as: in industrial ports, at wastewater treatment plants discharge, in ship channels, in area of frequent dredging, and in oil terminals.

Vertical traveling band screens are used over the intake, Fig. 6b [5], with incoming SW passing the moving mesh panels to the DP. High-pressure water sprays are used to eject the accumulated debris. These screens are specifically designed with low incoming SW velocity to reduce the entrainment and impingement. A through-screen velocity of 0.15 m/s has been determined to be protective of impingement sized fishes [16]. The open intakes are the most-used type of intake for large (>10 MIGD, or >45,000 m^3/d, production) plants. One example of onshore intakes for large DP of SWRO type is the 109,000 m^3/d Port Lisas in Trinidad equipped with coarse and fine screens and vertical turbine pumps [13].

An offshore-submerged intake is shown in Fig. 8a [9] with velocity cap-type inlet structure and one or more pipelines (or an intake tunnel) to on shore intake chamber, trash racks, fine screens, and SW intake pump station. The offshore intake should have a minimum distance of 30 m offshore.

4.2. *Offshore open intake using velocity cap*

The offshore open intake usually consists of a vertical riser open intake connected to a horizontal pipe to the intake pump station. The intake speed can cause a vertical downward velocity which fish cannot cope with. The results are a large number of entrained fish leading to marine environment impact. Many vertically opening offshore cap intakes are prone to draw fish down as shown in Fig. 8b.

A velocity cap is utilized to fit the vertical riser of the offshore intake pipe in order to guide aquatic organisms away from the intake structure in order to reduce entrainment, see Fig. 8c [17]. The velocity cap has a horizontal, flat cover located slightly above the vertical riser to convert a vertical flow into a horizontal flow at the intake's entrance, and works on the premise that fish will avoid rapid changes in horizontal flow, and typically operates at an entrance velocity of about 0.1–0.3 m/s. An intake terminal using velocity cap is shown in Fig. 8d [10,15]. In Fig. 8d the upper

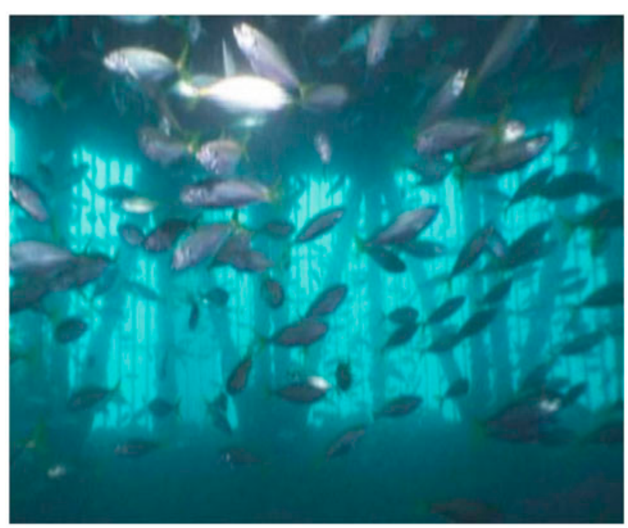

Fig. 8b. View of the Gold Coast SWRO plant velocity cap intake interior during operation [14].

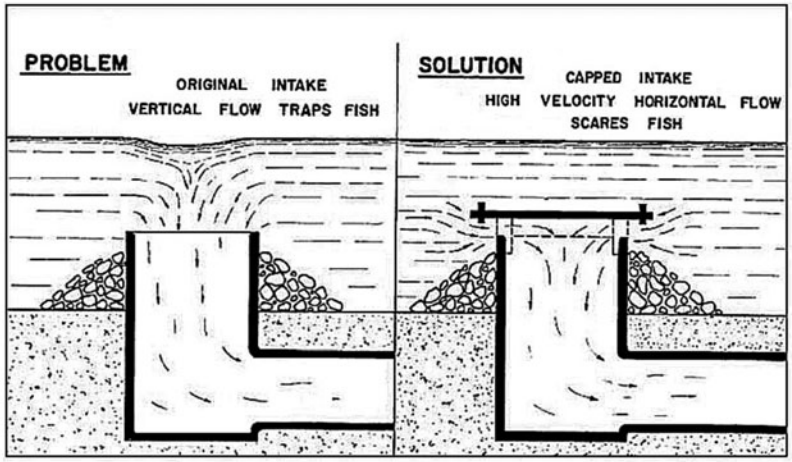

Fig. 8c. Velocity cap for entrainment reduction [17].

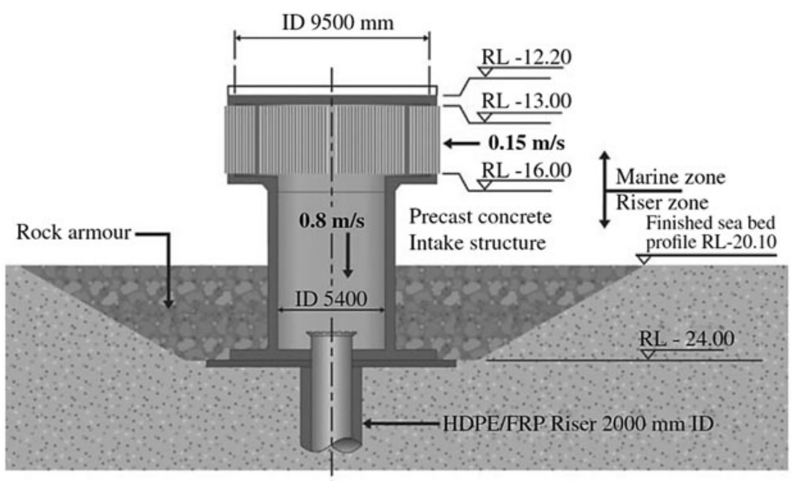

Fig. 8d. Velocity cap intake structure [4,13].

top and lower intake preferential area of the cap measured from SW level are as 13 and 16 m, the sea bed is at 20.1 m below sea level, and thus, the top of the cap is about 8 m above the bottom.

Fig. 8e shows the Sydney SWRO plant intake structure from the velocity cap on the seabed to the water tunnel. Very large velocity-cap intake structure is used at the Gold Coast SWRP plant, and pre-cast intake coarse screen structure/screen [16,17,18].

Examples of open offshore intakes for large SW DPs are [20]:

(1) The 300,000 m^3/d Adelaide, Australia with 0.15 m/s maximum entrance velocity of SW at 18 m depth below SW surface, and 0.5 m above bottom of sea, one inlet structure of 9.5 m length, and 100 mm screen size. A 2.8 m diameter concrete tunnel located 1,000 m from shore is used.

(2) The 170,000 m^3/d Al Fujairah 1, UAE with 0.10 m/s maximum entrance velocity of SW at 10 m depth below SW surface, and 6 m above the bottom of the sea, one 3 inlet structure of 3 m length, and 80 mm screen size. Three 2.0 m diameter GRP pipes located 380 m from shore are used.

(3) The 240,000 m^3/d Al Dur, Bahrain, with 0.10 m/s maximum entrance velocity of SW at 4 m depth below SW surface, and 2.3 m above bottom of sea, one 4 inlet structure of 7.2, and 80 mm screen size. Four 2.4 m diameter GRP pipes located 1,500 m from shore are used.

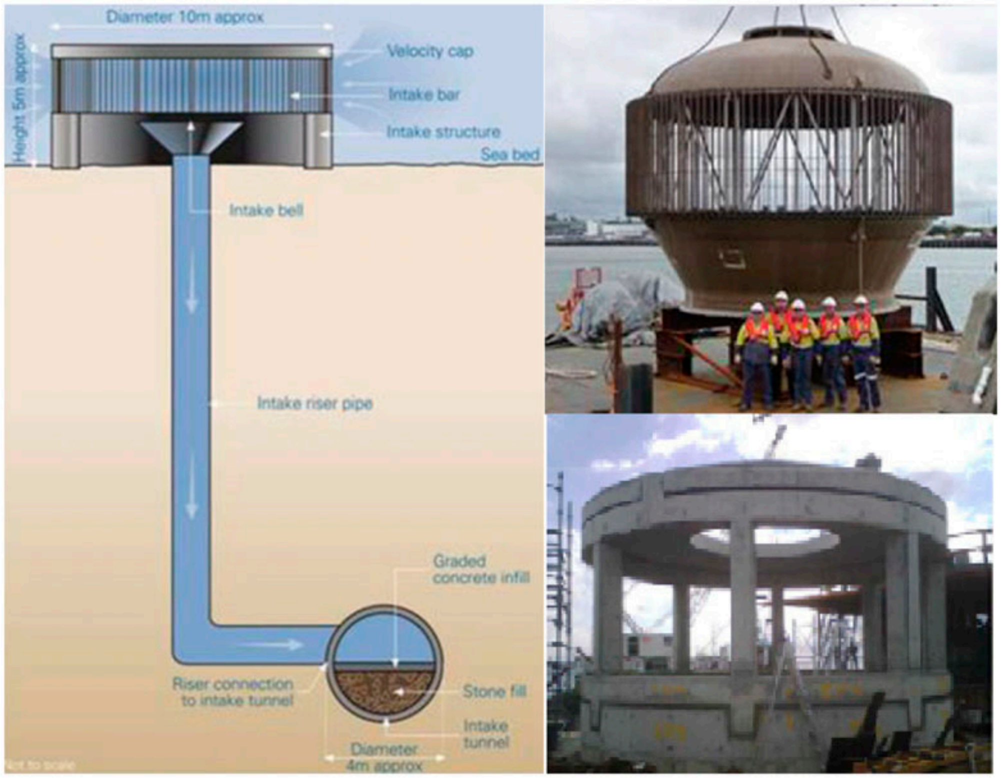

Fig. 8e. Sydney intake structure from the velocity cap on the seabed to the water tunnel, very large velocity-cap intake structure used at the Gold Coast SWRP plant, pre-cast intake coarse screen structure/screen [14,19].

The maximum entrance velocity in the cap shown in Fig. 8d can be calculated by dividing the intake volume by the intake area of the velocity cap, shown in Fig. 8d as $\pi(9.5\text{ m}) \times 3\text{ m} = 90\text{ m}^2$, and due to the screen bar existence, the effective area would be only 80% of total area, or equal to $0.8 \times 90 = 72\text{ m}^2$. If the DP capacity, say 240,000 m^3/d of recovery ratio 1/3, the intake volume would be 720,000 m^3/d (8.333 m^3/s), and the maximum intake horizontal velocity would be 0.115 m/s.

The feed SW is conveyed from the intake point to a wet well housing the intake pump through a tunnel or conveyance pipeline. Conveyance pipes are typically concrete, high-density polyethylene (HDPE), or fiber-reinforced polymer pipes with concrete collars-anchors, Fig. 9a. It can be laid directly on the seabed, Fig. 9b, but the portion of the pipeline that extended through the surf zone and onshore to the pump station is usually laid in a dredged trench and backfilled.

An emergent HDPE pipeline is usually installed by welding its segments on shore line, and plugging the ends. It is then withdrawn by a boat to the final location before being connected to the intake offshore, and the pumping well inlet at the shore, see Fig. 9c.

Due to shellfish growth on internal walls of intake pipes, the pipes are usually oversized (typically 130%) and need periodic cleaning. Chemicals are usually inadequate to suppress shellfish growth in the pipeline and this allows shellfish growth in the pretreatment system. Voutchkov [13] suggested addition of sodium hypochlorite, and sulfuric or hydrochloric acid for that purpose.

In Australia, tunnels were adopted for five SWRO plants connecting the intake pump stations of the DPs on shore with their open intakes' screens and brine concentrate outfall systems. Schematic diagrams of the tunnels used in both Gold Coast and Sydney SWRO plants seawater intakes are shown in Figs. 10a and 10b, respectively. Fine 3 mm screens, Fig. 10c, are usually placed upstream of the pumps to capture any material that may pass through the coarse ocean intake screens, including algae and non-motile marine life such as jellyfish, and to protect the pumps from damage. The intake pump moves SW from the intake location to the DP. Periodic screen maintenance requires raising and/or removal of screens for cleaning. The pumping station onshore must be equipped with traveling water fine screens or rotating drum

Fig. 9a. Conveyance pipelines with installing concrete ballasts [9].

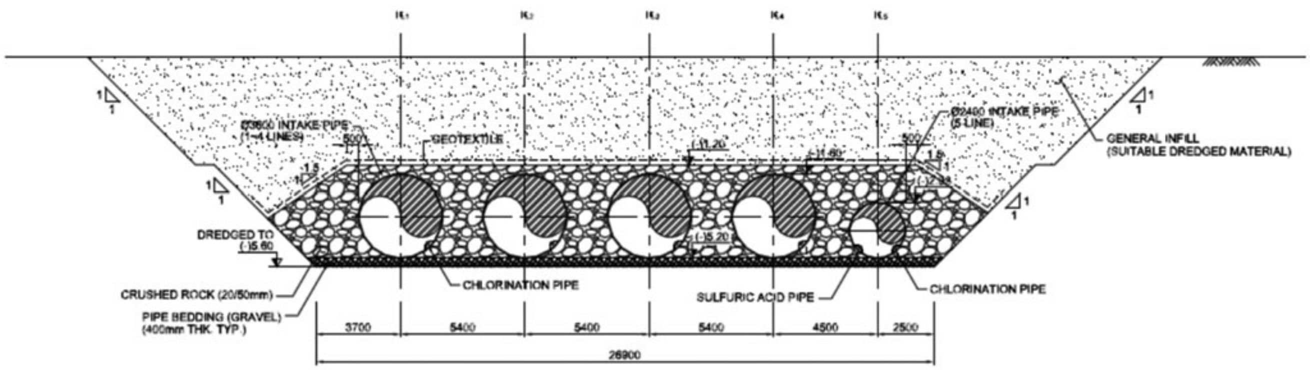

Fig. 9b. Conveyance pipes laid directly on seabed, suggested for a Qatar's DP.

Fig. 9c. Installation of conveyance pipeline for an intake system using the float, transport and sink method at Abu-taraba, Libya [21].

screens to protect downstream pumps and pretreatment equipment. Debris and particulate matter (both organic and inorganic) are removed from screens by the cleaning system.

SW from open intakes requires significant pretreatment to remove particles, dissolved NOMs, aquatic organisms, floating or suspended debris, oil and grease, and anything else that could foul or affect the membranes within the main treatment system. While screens for MSF or MED DPs require a traveling water screen or rotating drum screen with 6–9.5 mm wire mesh openings, screens for SWRO plants require finer level of screening wire mesh panels having openings ranging from 0.5 to 5 mm to reduce entrainment (up to 80%), see Figs. 10c and 10d. SW velocity through screens is usually less than 0.15 m/s. In offshore open-intake, small screen mesh size and slow inlet flow rate (<0.3 m/s, <1 ft/s) ensure low entrainment and impingement of waterborne organisms.

An offshore intake is usually located at least 10–15 m below SW surface for shallow intakes and 20–35 m for deep intakes to ensure good water quality (possibly free of algae and plankton), and are preferred for shallow coastlines. An open intake located

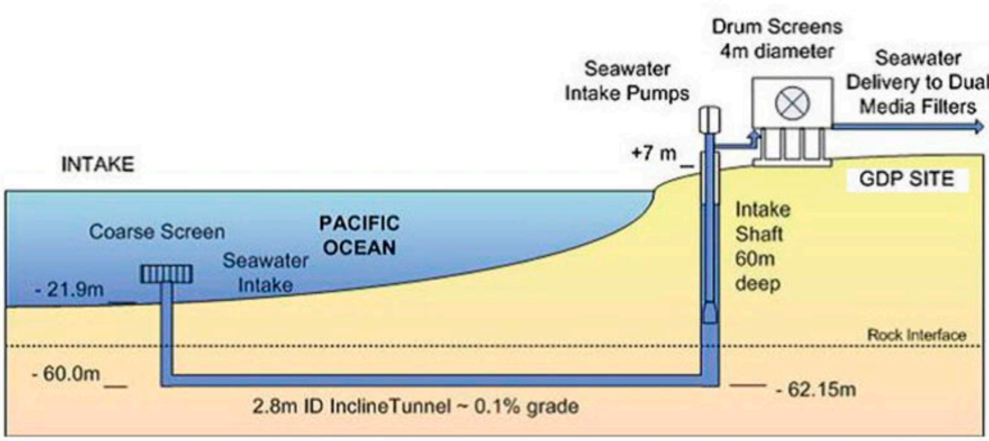

Fig. 10a. Schematic of the Gold Coast desalination seawater intake arrangement [19].

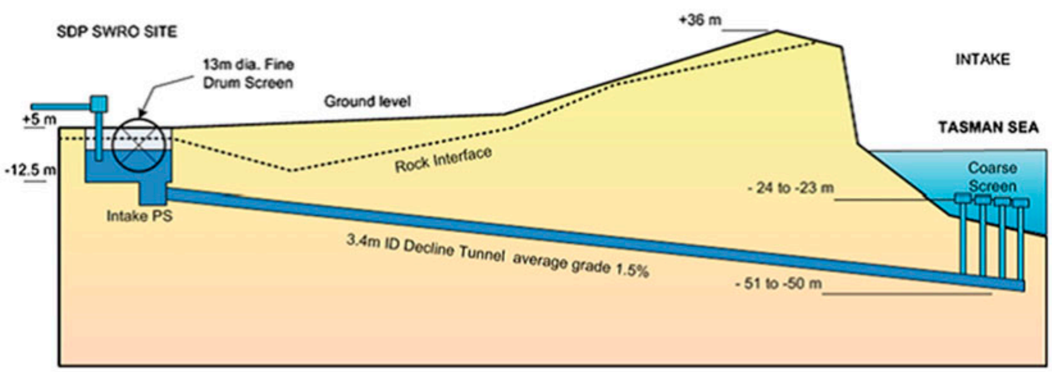

Fig. 10b. Schematic of the Sydney SWRO DP seawater intake arrangement [19].

above the seafloor is shown in Fig. 10e [22]. As given before, typical open intake design includes intake with coarse screens (50–225 mm), conveyance piping, and a wet well for housing the system pumps. The pump station is usually located on shore at a site easily accessible to the DP, and includes pumps, controls, chemical feed equipment, primary screening, e.g. bar rack screens, secondary traveling screen, and backwash system. The offshore intakes are usually located well beyond the surf zone to minimize the effects of waves. They can be located from 200 to 1,000 m offshore.

SW from deep intakes is supposed to have better quality than surface water, but has lower temperatures and this decreases water permeation velocity through the membranes. Examples of SW temperature variations in the Mediterranean Sea, and Red sea are shown in Figs. 11a and 11b, respectively. While SW temperature in the summer at the surface is about 25˚C in the Mediterranean Sea and 30˚C in Red Sea, it can reach up to 35˚C in the shallow water in the AG. The intake point should have sufficient water depth to maintain suitable head above the screens, and sufficient height above the seabed to prevent seabed vegetation and silt from entering in the intake.

In the AG area, seawater has high salinity (42–45 g/L), and the feed to product water flow rates ratio is about 3, and thus about two-third of the feed flow return back to sea as a concentrate of significantly high concentration. The concentrate discharge (outfall) structure should be positioned at sufficient distance from the intake to assure that the water concentration at the intake is be affected by concentrate salinity.

The velocity cap style intakes are prone to high seasonal jellyfish, migratory and near shore fish, and seaweed influx. Marine growth inside of the conveyance piping can limit the flow if proper disinfection is not applied.

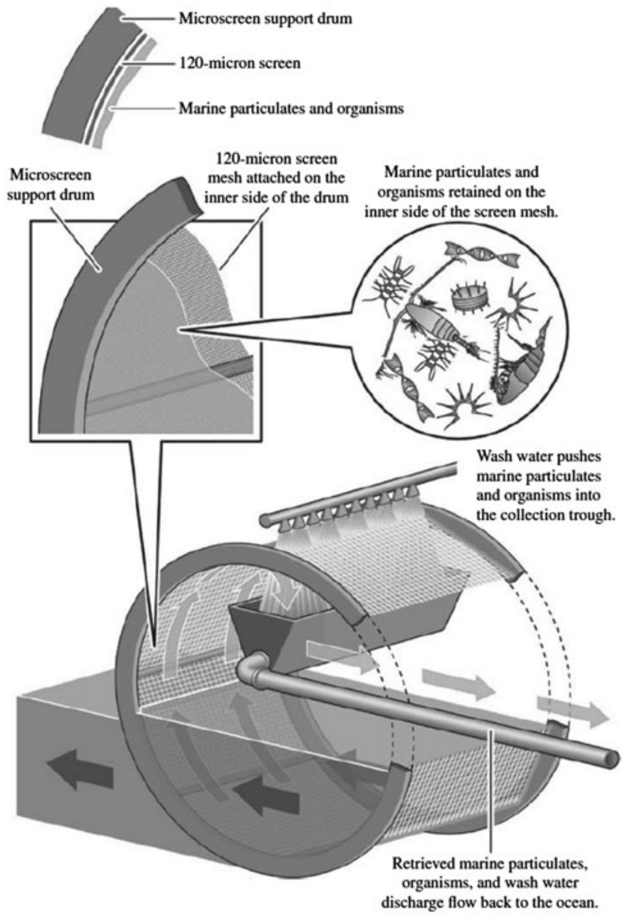

Fig. 10c. Debris collection system of drum screens [13].

Fig. 10d. Fine intake drum screens [13].

An example of an open intake system using vertical cap is in Ras Abu Fontas (RAF) B2 CPDP in Qatar [25]. This plant requires about 54,000 m^3/h of SW supplied through three intake pipes made of glass reinforced plastic (GRP) pipelines, 1,900 mm diameter each, and laid mainly above the sea bed extending two kilometers offshore. Intake pipelines are protected by armor stone from waves, small boats anchoring, etc., Fig. 12a. SW flows under gravity to the SW pumping station. The SW intake riser, shown in Fig. 12b, consists of a velocity cap and bar screen. This mitigates the entrance of large marine organisms. The incoming SW is chlorine treated to prevent microbial growth in the pipework, DP and ancillaries by continuous dosing of SW in the intake pipework with chlorine to each intake pipe by small nominal diameter (ND) 150 pipe runs up to the risers where a suitable solution of seawater combined with active chlorine is dosed inside the pipes.

The quality of SW taken from deep level is better than that taken from SW surface. An example was given by Dehwah et al. [23] for SW taken from 9 m below the surface at an SWRO plant near Jeddah, Saudi Arabia (SA). The quality of SW is linked by its low tendency to cause biological fouling, such as the concentration of TEP and polysaccharides in SW. The TEP tends to promote biofouling on the membrane surface. The results of their investigation are given in Figs. 13a and 13b.

They found that the size and number of the overall algae concentration is rather low, e.g. 23,773 cells/mL at surface and 10,801 cells/mL at 9 m depth or a 55% lower count with depth, and the dominant algae type is *Synechococcus*. Concentrations of bacteria show a similar pattern, and surface SW has a higher concentration than SW at the 9 m water depth. Deeper water has a 34% lower bacteria concentration.

A comparison of the particulate TEP, colloidal TEP, and total TEP shows the particulate TEP is substantially higher (72%) in surface seawater than at 9 m, but the colloidal TEP is 23% higher at 9 m compared to the surface. There is a 19% difference between total TEP between the surface (higher) and the 9 m depth. The concentration of TOC was nearly equal at the surface compared to the 9 m depth. The total NOM shows very little variation in composition between the surface and a depth of 9 m.

Dehwah et al. [23] concluded their work by stating that the general SW quality improvements in reduced organic matter concentrations were insufficient to reduce the intensity of pretreatment for an SWRO system. This means that assessment of using deep intake should be done to balance the benefit of using deep intake with the structural risk of installing and maintaining deep intake.

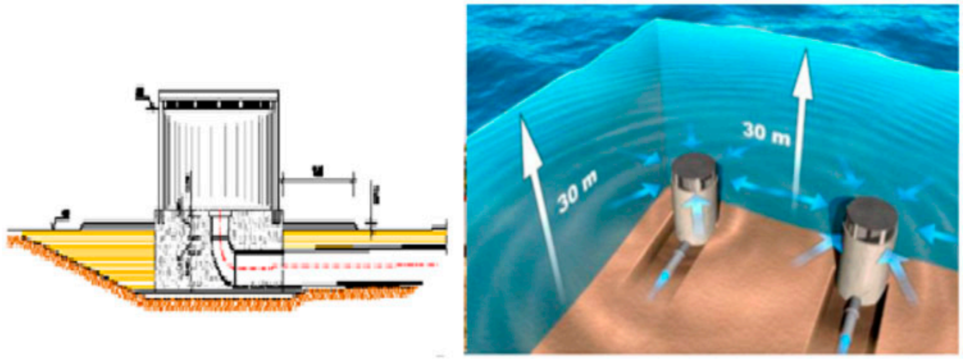

Fig. 10e. SWRO Barcelona Plant: 200,000 m/d open intake, seabed −30 m/W. Intake −22 m. 2 pipes PE, diameter 1,800 mm, intake: 2.2 km from the coast [22].

4.3. Offshore open intake using wedge-wire screens

Another type of intake is the passive screen intake known as the wedge-wire screen (with no mechanical moving parts). These are located offshore and connected through a pipe to the well pump located onshore. Fig. 14a shows a small module used for testing, and Fig. 14b shows a large 7 ft. unit used in SW cooling for a large power plant. A passive screen intake along a seawall or channel edge is shown in Fig. 14c. The most well-known type of the wedge-wire screen are the cylindrical metal screens with trapezoidal-shaped "wedge-wire" slots with openings of 0.5 to 10 mm (fine mesh screens). Combination of very low flow-through velocities (e.g. 0.15 m/s), small slot size (equal or less than 3 mm), and naturally occurring high screen surface sweeping velocities area minimize impingement and entrainment. When placed in water body having relatively high velocity (≥1 fps), marine organisms are allowed to be carried out with the flow. Wedge-wire screens eliminate the need for coarse filtration. The wedge-wire screens have been applied in the 150,000 m^3/d Beckton plant in the UK, and are located 3 m above seabed, made of copper–nickel alloy and have 3 mm (1/8-in.) openings with a through-screen flow velocity of 0.15 m/s [13].

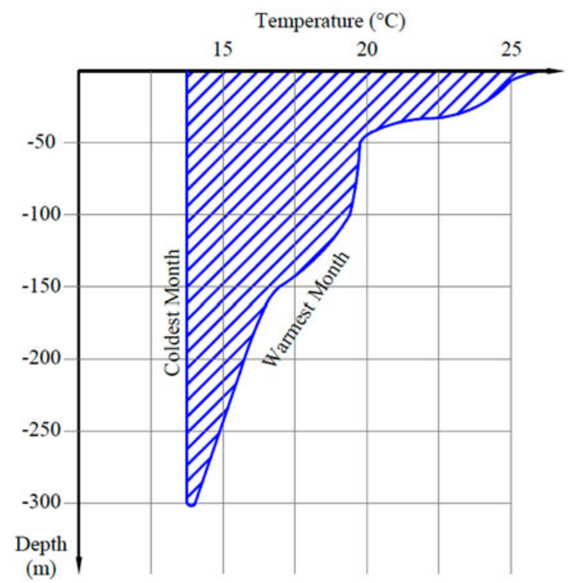

Fig. 11b. Vertical profile temperature of the occidental Mediterranean Sea [24].

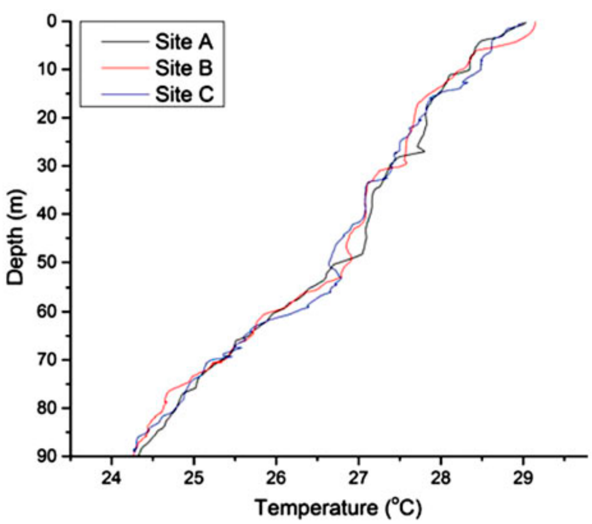

Fig. 11a. Profiles of the Red Seawater column showing variation in water temperature with depth [23].

Debris and marine life are excluded without moving or rotating the screen. An airburst back-flush system using compressed air to blow-off debris is usually integrated in each unit to blow debris back into sea, where it is carried away by the ambient cross-flow

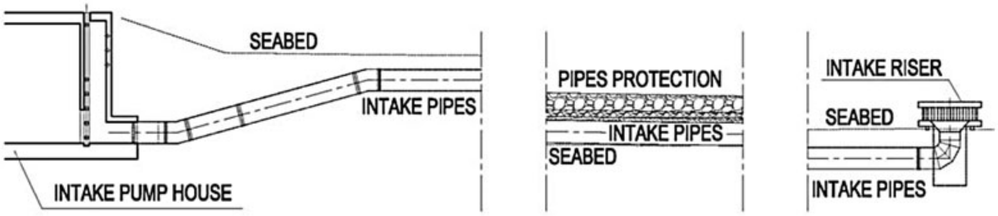

Fig. 12a. Intake system scheme for Ras Abu Fontas plant in Qatar, From left to right, pump-house, intake pipes and raiser [25].

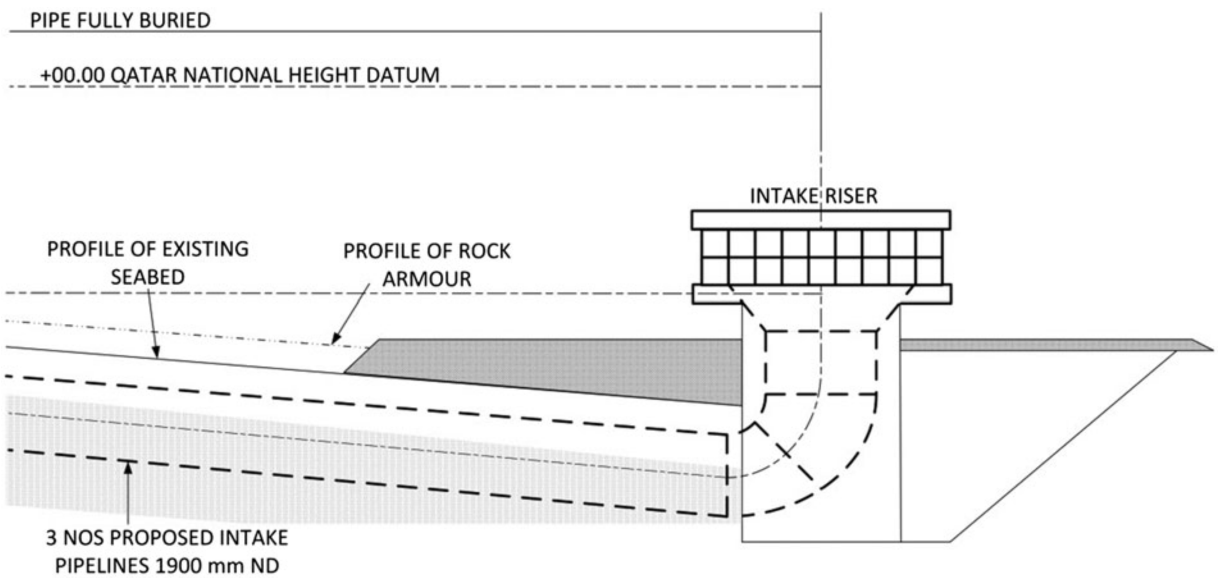

Fig. 12b. Intake riser (seawater inlet point) [25].

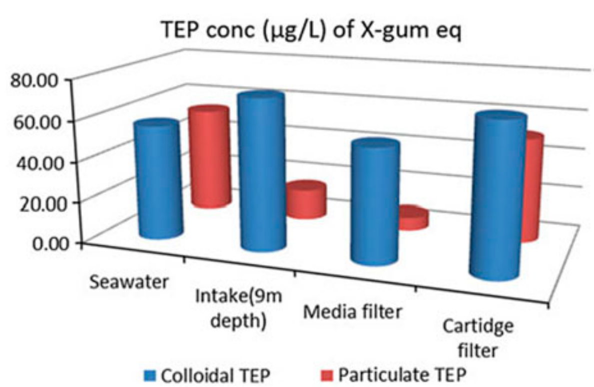

Fig. 13a. Comparison of bacteria concentration between the surface and a 9 m depth [23].

currents. Cleaning of the passive screens by high pressure is possible if the passive screen intake is greater than about 150 m from a shore-located compressor, then a boat mounted system would be required. Thus, the wedge-wire screens have low impingement and entrainment, but easily become clogged. They are susceptible to internal fouling when shellfish larvae pass through the screens and external blinding during jellyfish migrations. This type of wedge-wire screen is used extensively in once through cooling of thermal power plants, and started to be used in SWRO DPs. Examples of SWRO plants using wedge wire-screens are given in Table 2.

Data of the wedge-wire screen used in the 45,460 m^3/d SWRO facilities located in a test bed in Busan, South Korea, given in Table 2, are 5,540 mm screen length, 1,675 mm screen diameter, 3 mm screen slot aperture, and 13 cm/s SW velocity, through-slot intake velocity. It is noticed here that two velocity terms are used. The first is the approach velocity which is measured within 7.6 cm of the screen face. The National Marine Fisheries Service in the US suggested that the approach velocity must not exceed

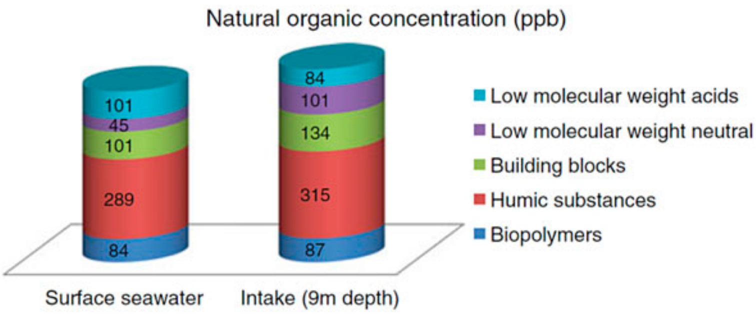

Fig. 13b. Comparison of NOM fraction concentrations between the surface and 9 m [23].

Fig. 14a. Wedge-wire screen module used in testing during studies for Santa Cruz and Soquel Creek Water Districts in 2009 and 2010, the screen had a slot width of 2 mm (0.8 in) and was sized to ensure a maximum through screen velocity of 0.1 mps (0.33 fps) [5].

12.2 cm/s for active screens, or 6.1 cm/s for passive screens.

The second is the through-slot intake velocity which is the velocity of the water as it passes through the slot of the screen, and is always higher than the approach velocity. Fig. 14d shows a close-up of the wedge-wire screen geometry. Fig. 14e shows the component of a classical "T"-shaped barrel screen at an offshore position. Fig. 14f shows the components of the air burst cleaning system.

5. Subsurface intakes

The use of a subsurface intake for SWRO plants is viable only if the site-specific geology and hydrogeology of the coastal area including the beach and near-shore are suitable to produce the required flow capacity, and reasonable installation cost. Numerous limitations for subsurface intake are low permeability soil conditions, negative beach erosion impact, shorter useful life compared to open intakes, and a large amount of coastal aquifer impact by their installation [27]. For example, in the Red Sea various well intake systems could be feasible for low-capacity SWRO facilities and high-capacity intake systems would be limited to seabed gallery intakes; in Coastal Florida more subsurface intake options are available, including wells, beach galleries, and seabed galleries which could be

Fig. 14b. 7-foot Diameter Wedge Wire Screen [26].

Fig. 14c. Passive screen intake along a seawall or channel edge (Courtesy of Gap Technology Limited) [21].

used, based on the required capacity and the specific site conditions. The presence of high transmissivity carbonate aquifers containing SW in Florida would allow medium capacity SWRO systems to use conventional vertical wells [28].

The vertical well, one type of subsurface intake, is the most known method for seawater abstraction everywhere. Subsurface intake systems use the natural geological properties of sediments and rocks to provide high-quality feed SW. The subsurface intakes are classified as wells and subsurface infiltration galleries, and both collect SW from near-shore (coastal) aquifer or offshore aquifer under sea floor. The subsurface intakes are recommended as the preferred technology for SW intakes in the state of California, US. The design of the subsurface intake is site-specific, and depends on hydrogeological and environmental conditions. Feed SW from subsurface intake has significantly lower concentrations of particulate matters in terms of SDI, algae, bacteria, organic compounds, oil, grease, and aquatic micro-organisms. These are the primary causes of membrane fouling. When SW from open and subsurface intakes are compared, SW from subsurface intake water has estimated 75–90% lower SDI, 90% lower content of bacteria, and almost no algae and biopolymers and polysaccharides [29].

Rachman et al. [30] compared the quality of SW from open intake and SW output from well intake systems at several SWRO DPs in SA, Spain, Turks and Caicos Islands, and Oman. They reported that flowing of SW through the seabed into aquifer and into the

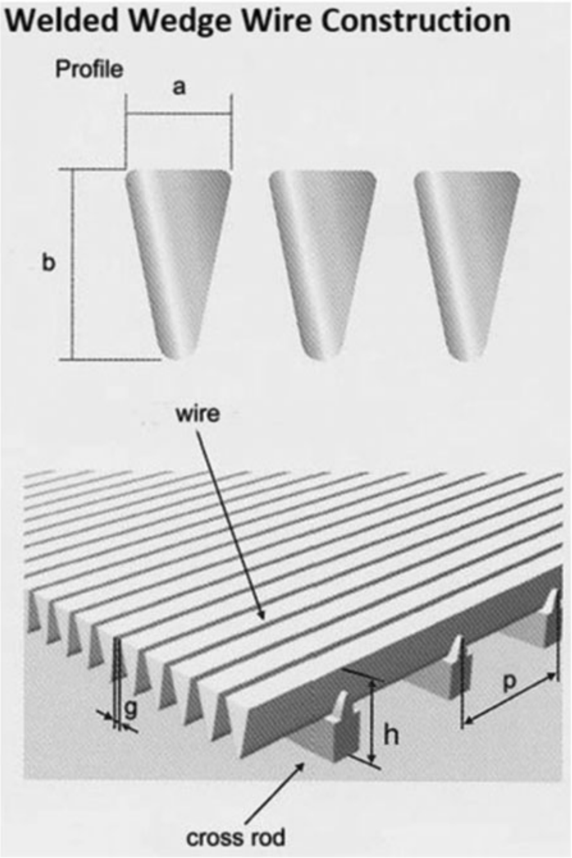

Fig. 14d. Close-up of the wedge-wire screen geometry. The width of the wire is denoted by a, and the thickness is denoted by b. The aperture width is g. The total thickness of the screen plus the cross rod is h [21].

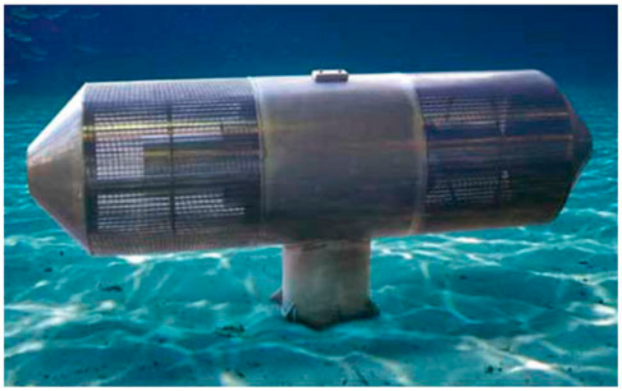

Fig. 14e. Classical "T"-shaped barrel screen at the offshore showing the components [21].

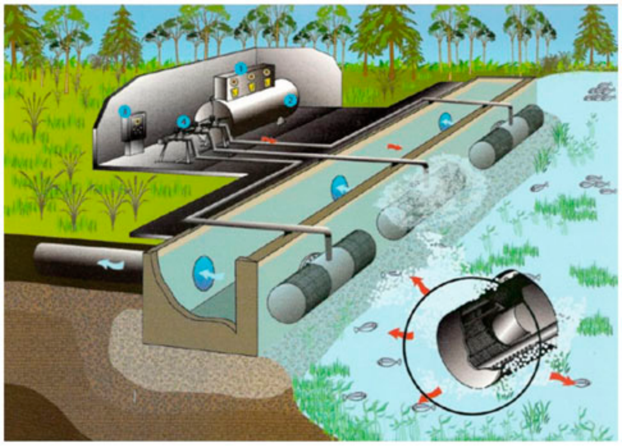

Fig. 14f. Diagram showing the components of the Johnson air burst cleaning system [21].

wells removes all of the algae, most organic material, and 98.5% of bacteria. Compared to ambient SW, the particles TEP concentration from subsurface intakes is much lower. The biopolymer fraction of natural organic matter NOM in SW from subsurface intake was significantly lower than that of ambient SW, but the lighter fractions of the NOM were removed at lower percentages. They suggested that the NOM removal fraction depends on the length of the seawater flow-path (and size) with lighter fraction removed at lower percentage. Vertical well systems have higher organic materials removal compared to horizontal wells and tunnel intake systems. Besides high-quality feed SW, subsurface intakes have other advantages of reducing the DP impacts on marine environment (e.g. impingement and entrainment of marine organisms), and much lower pretreatment complexity and cost.

5.1. Subsurface well intakes

Wells can have vertical, horizontal, or angle/slant orientations. Radial collector (Ranney) type using a vertical concrete caisson connected with horizontal pipe wells is also used. Vertical wells are usually drilled very deep (as compared to their diameter), while the galleries have shallow depths and are wide [31]. Horizontal wells are used for their high capacity. Angle or slant wells are extended from under the seabed to a position near the shoreline. The wells can be set back further from the shoreline compared to conventional vertical wells to induce primarily vertical recharge through the seabed.

5.1.1. Vertical well intake

Vertical beach wells, Fig. 15a, are the most used subsurface intake type, and were used mainly for small SWRO capacity DP, usually less than one MIGD, although large plants are now using vertical beach wells. Examples are shown in Table 3. Vertical wells produce predominantly horizontal flow in that the ratio between horizontal and vertical hydraulic conductivity ranges from 10 to 200 in most aquifers. The goal of a well intake system is to limit the horizontal flow component which is the reason the well must be located on the beach or very close to the sea, Fig. 15b.

Each well has the following components: casing well screen, filter pack, well seal, and surface seal, and has submersible or vertical pump installed inside the well casting, Fig. 15a. The diameter of the well casing is in the range of 200 to 1,200 mm, and its depth is usually less than 75 m. Most wells constructed in limestone use an open-hole construction, and screen and gravel pack are unnecessary.

The main vertical intake well characteristics are: the well yield, Q, (i.e. how much SW can be abstracted in m^3/s for a pre-set time period), static and pumping water levels (i.e. groundwater (GW) levels in the well when pumping from the well is on and off, and the cone of depression (i.e. GW surface takes the shape of inverted cone toward the well when the well is operational). The aquifer thickness, h_o, is based on hydrogeological investigation, k is determined from pumping tests in the target well field area [32].

Fig. 15c shows one of the 28 vertical wells used in the Sur, Oman plant, and which yields 160,000 m^3/d of feed SW. Typical capacity for vertical wells is 100 to 3,000 m^3/d.

Table 2
SWRO facilities using passive screen intake systems [21]

Facility Name	Location	Plant capacity (m^3/d)	Intake capacity (m^3/d)	Type of system	Distance offshore (m)
Test bed	Busan, S. Korea	45,460	108,000	Offshore	300
Beckton	London, England	150,000	350,000	Platform	0
Chennai	India	100,000	265,000	Offshore	600

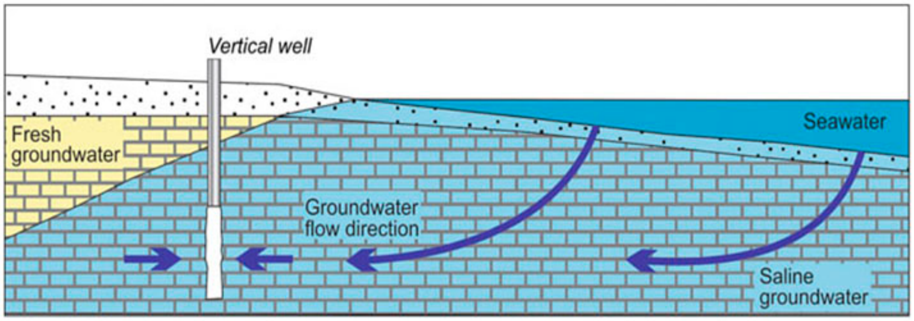

Fig. 15a. Well intake system located along a shoreline, with direct recharge comes from sea, and minimum flow from the shoreline direction to avoid aquifer impacts and entry of poor quality water [31].

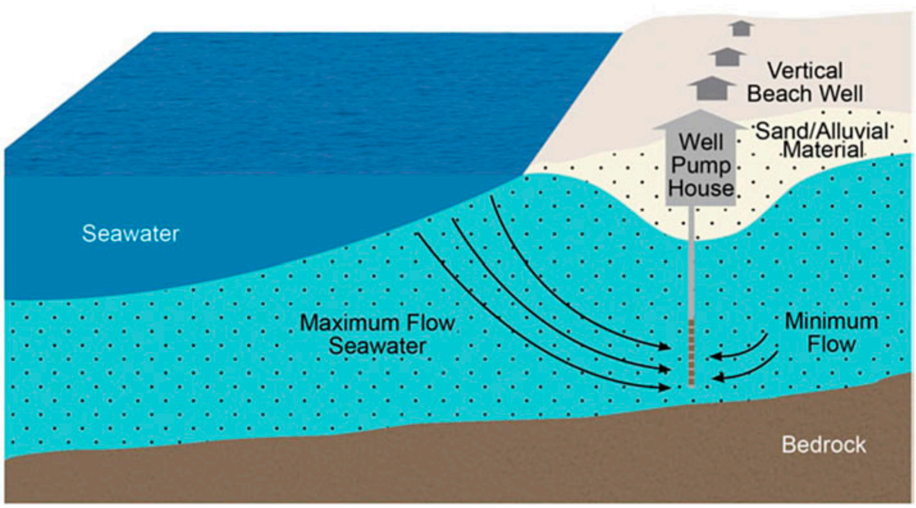

Fig. 15b. Schematic diagram showing induced aquifer flow from the sea to a well [4].

The well field in the Oman plant is almost parallel to the coast-line and at a distance of 30–250 m from the high tide line. The wells range in depth from 40 to 100 m below seawater level, and each well is equipped with a submersible pump. The well intake area consists of high-yield karstic formations that have an average transitivity of 7,000 (m^3/day)/m [33]. The well field includes 33 (25 duty and 8 standby) beach wells capable of producing 70–100 L/s (1.6–2.3 MGD) each. The well diameter is 14 in, and is equipped with 14 in. diameter PVC casing and a screen with a slot size of 3 mm. The wells are surrounded by gravel packs.

Onshore wells can be fitted with vertical drains, Fig. 15d [24], whose capacity varies with soil permeability. Soils can be made of sand, gravel, more or less cracked rocks (karstic soil). Sand and/or gravel soils are the most permeable. Vertical drains diameter never exceed 16´´. Most of the time, diameter is 10´´. In a sandy soil, maximum capacity is about 170 m^3/h (4,000 m^3/d approx.).

The wells are subjected to bacterial growth within the wellbore and cleaning and periodic disinfection of the wells may be necessary to lower bacterial concentrations. All conventional vertical wells used for SWRO intakes require periodic maintenance to remove any build-up of calcium carbonate scale or a biofilm on the "skin" of the well in open-hole designs or the well screens.

5.1.2. Directionally drilled wells

Directionally drilled wells include radial collector wells, which are often referred to as horizontal collector wells and "Ranney®" wells or beach well with radial laterals, and horizontally directional drilled collectors (HDD), and slant (or angle) collectors.

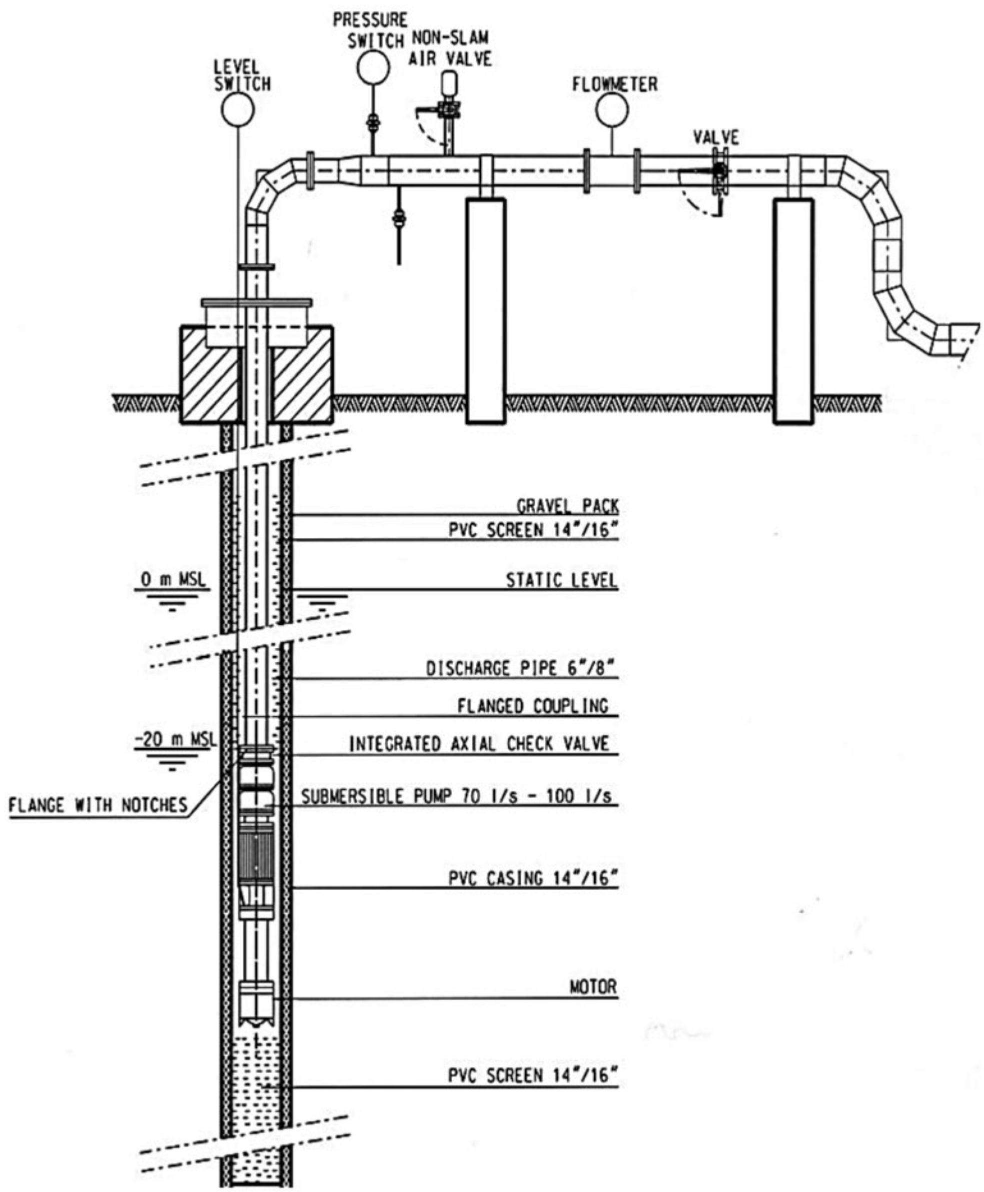

Fig. 15c. Typical beach well layout in Sur plant in Oman [33].

5.1.2.1. Radial or ranney collectors. Radial or Ranney, Figs. 16a and 16b, collectors have a concrete caisson extended below ground surface, and collecting SW from screened horizontal laterals that extend into water-bearing strata. The existing designs have proven to be of high reliability, with an example being the PEMEX Salina Cruz Refinery intake. This intake provided acceptable performance after significant damage caused by beach erosion caused by a hurricane. The Radial or Ranney collector has a high capacity since the screen wells are horizontal, and have typical capacity of 4,000–20,000 m^3/d, much higher than those of vertical wells. The inside diameter of the concrete caisson is in the range of 2.7–6.0 m, wall thickness is in the range of 0.5–1.0 m, and depth is in the range of 10 m to over 45 m. Typical dimensions of horizontal laterals, based on hydrogeology, are the diameter (0.2–0.3 m), and length extends up to 50 m, and usually one well has 2–14 laterals oriented toward the source water body. The intake pump station is typically installed above the well caisson, with possible use of submersible pumps to minimize noise levels. The largest Ranney well installation is located in 14,500 m^3/d Salina Cruz, Mexico DP and on the beach.

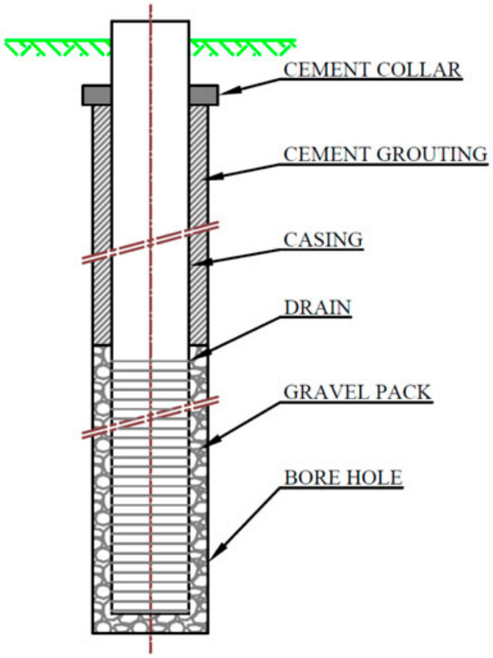

Fig. 15d. Typical beach well with drain [24].

5.1.2.2. Horizontal directionally drilled wells. The horizontal directional drilled (HDD), known as NEODREN, wells can be considered as non-linear slant wells. The HDD collector wells are casted with one or more horizontal perforated screens bored at an angle (typically inclined at 15˚–20˚) and extending from the surface entry point underground past the mean tide line, as shown in Fig. 17a. It has perforated pipes of 350 mm diameter with 120-μm openings through which the SW, naturally filtered through the sea bottom sediment, is collected. The pipe is laid at 5–10 m below the sea bottom and is in the range of 200–600 m in length. The drilling of the HDD well is conducted in three steps. First, a small diameter pilot hole is drilled from the entry to the exit point. Second, the hole's diameter is enlarged to the required size by reaming. Third, the conduit (pipe) is installed by being pulled from the exit point to the entrance point, Fig. 17b [31].

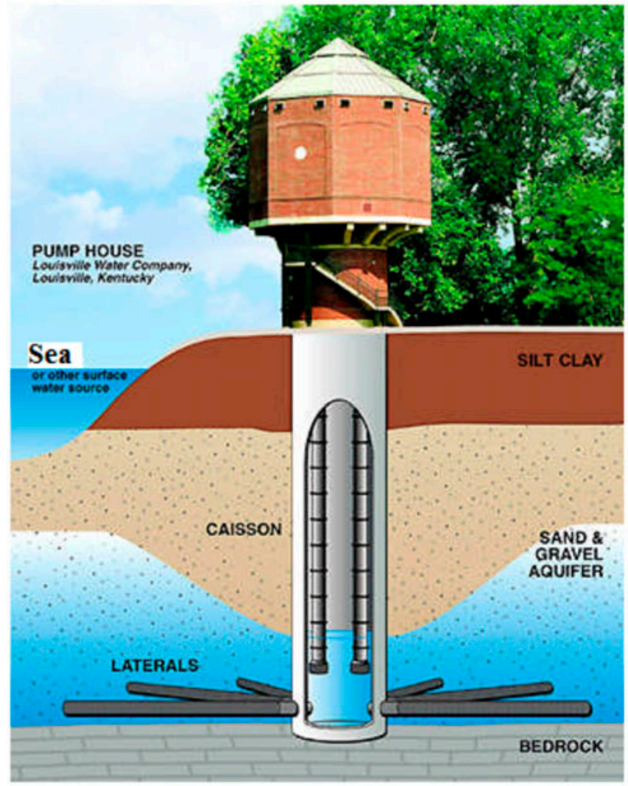

Fig. 16a. Typical Ranney installation [34].

The use of HHD is limited in DPs. Two examples of the HDD SW intake [13] are: San Pedro del Pinatar, Spain that has a 144,000 m^3/d using nine wells that deliver an average of 16,000 m^3/d each; and the 65,000 m^3/d Cartagena I, Spain SWRO Plant of 20 pipes of 350 mm diameter and 6,000 m^3/d per Pipe. The San Pedro plant has 20 HDD wells arranged in a fan shape, Fig. 17c. Each well produces between 100 and 140 L/s, and the source seawater is collected in a large wet well located underground and pumped to the plant using submersible pumps. Recent research at

Table 3
Examples of vertical well intake facilities [4]

Facility	Capacity (m^3/d)	No. of wells
Sur plant in Oman	160,000	28
Alicante plant in Spain	130,000	30
Tordera Blanes in Spain	128,000	10
Pembroke in Malta	120,000	10
Bajo Almanzora Almeria plant in Spain	120,000	14
SAWACO Jeddah plant in SA	31,250	10
Dahab Red Sea plant in Egypt	25,000	15

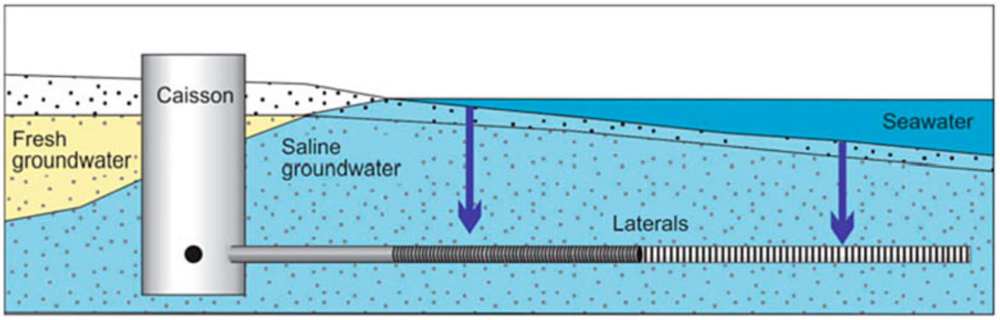

Fig. 16b. Typical design of radial collector or Ranney well. The laterals can be designed to extend beneath the seabed to all only vertical recharge through the seabed, precluding landward impacts. Note that the laterals occur on a single plane and many can be installed [31].

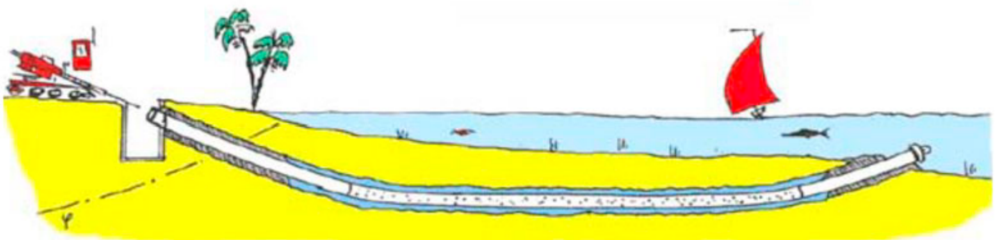

Fig. 17a. Horizontal wells can be drilled from the shoreline using older mature technology or the Neodren™ system. (a) General configuration of a horizontal system. (a) Horizontal well [4].

the site on water quality has found that the Neodren system is not operating well compared to the vertical wells and water tunnel located on the site [35].

5.1.3. Slant (or angled) well

A straight-drilled low-angled well (called slant well or angled well), Figs. 18a and 18b, is similar to vertical wells, but drilled on an angle (15°–25° from the horizontal) and produces SW from sub-sea aquifers recharged from both horizontal and vertical flow (i.e. leakage through the sea floor). Slant wells withdraw naturally filtered SW from subsea or near-shore aquifers, and have the same advantages of all subsurface intakes, i.e. no impacts on marine life and high-quality filtered feed SW. The product SW has almost no suspended organic matters and sediments or low turbidity and SDI. Williams [36] stated that field tests show the engineered artificial filter pack surrounding the screened portion of the intake wells results in low turbidity and SDI. Thus, the costly SWRO pretreatment processes are reduced or eliminated. Both slant and vertical wells have similar engineered filter packs and well casing and screen design.

Slant wells are drilled using the dual-rotary method of drilling, shown in Fig. 18c [37], which includes using a temporary casing to maintain borehole integrity during well completion. A telescoping well design, see Fig. 18d, allows slant wells to extend to lengths of 305 m or more into subsea aquifer systems and typically yielding 10,000–16,000 m^3/d [36]. Fig. 18e shows the well casing and screen installation and centralized within the temporary casing, with artificial filter pack to be pumped under pressure into the annulus between the temporary casing and well screen through a number of gravel feed pipes, (tremie pipes; Fig. 18e) [36]. The siting of a slant well will ensure that there is no well recharge derived from available inland fresh water supplies. This should be taken into consideration as illustrated in Fig. 18f. However, the slant well does have inshore impacts to aquifers which cannot be avoided. Recent modeling at Huntington Beach has demonstrated unacceptable impacts commonly occur.

The testing results of the Dana Point slant well (2010–2012) were applied to design nine slant wells of 113,600 m^3/d for the Dana Point Project, six slant wells of 83,000 m^3/d planned for the Monterey Penin-

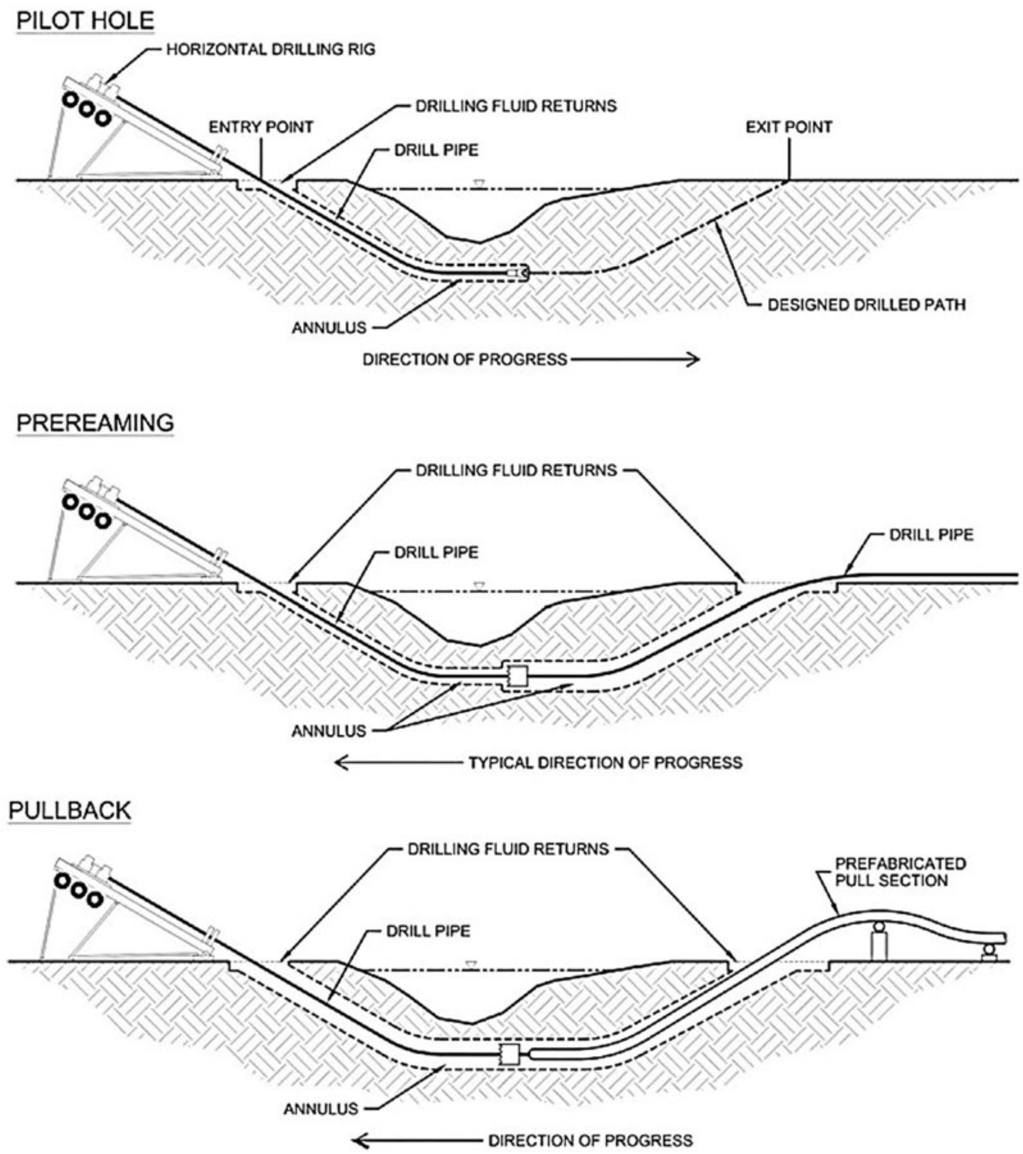

Fig. 17b. Utility-type HDD well construction sequence Source US Fish and Wildlife Service [31].

sula Water Supply Project, and 37,900–75,800 m^3/d project is in the planning stage for the City of Oceanside California. The slant well subsurface intake is an emerging technology with no wells in long-term operation and assessment of rehabilitation success is not yet known. The slant well connectivity to ocean and relevant amounts of water resources were tested in the Doheny test slant well during two years pumping. Tests showed that old marine groundwater is slightly acidic, anoxic, and enriched with dissolved iron and manganese. Concentration of dissolved iron and magnesium in pumped water peaked up to 11 mg/L and decreased to 5 mg/L by the end of the test. Test results support the increased capture of shallow, young marine groundwater. This test indicates that well project should be installed after the feedwater quality is known [28].

5.2. Subsurface infiltration galleries intakes

A subsurface infiltration gallery intake can be constructed under the seabed floor (near shore) or under the beach, called beach galleries. The gallery is a large size excavation trench which is filled up with filtration media. The gallery has vertical or horizontal collector (in the form perforated pipes that convey filtered

Fig. 17c. HDD intake of San Pedro del Pinatar SWRO plant [11].

source water collected from the bed to the wet well of an intake pump station located on shore. The wells are installed in equidistance (usually 30–60 m) inside the filter media, Fig. 19a.

Seabed galleries can be located where the marine bottom contains clean sand. Beach galleries are large slow sand filters constructed along a beach using a suction pump with bottom feeding to pass water through the sand.

Typical filtration media in a gallery with horizontal intake wells are 1.0–2.0 m sand at the bottom, topped by 1.2–2.0 m gravel pack layer surrounding the horizontal well screen and finally top layer 6.0–10.0 m layer of sand. The horizontal well collector screens are typically designed for inflow velocity of 0.12–0.25 m/h. The most common type of infiltration gallery is a horizontal well collection system with a single trench, Fig. 19b.

An example of a small gallery was reported by Foster et al. [34] to feed a SWRO DP with 9,225 m^3/d to produce 3,750 m^3/d permeate. This gallery uses $4 \times 1{,}825$ m^3/d operating wells plus $1 \times 1{,}824$ m^3/d standby well. The dimensions of the polyethylene pipe screens carrying the filtered water are: 60 m long and 600 mm diameter and are installed at a distance of 5 m from each other. The collector pipes have an inflow velocity of 3 cm/s. The screens collect the source water flow into a central pipe with a diameter of 1,580 mm and length of 1,178 m that conveys it into a two-tank water collection well for pumping to the DP. Another example of a seabed infiltration gallery was given, which uses slow sand media filtration, connected to various intake wells located on the shore as illustrated in Fig 19c.

The only large SWRO DP using seabed infiltration bed intake is the Fukuoka, Japan SWRO plant of

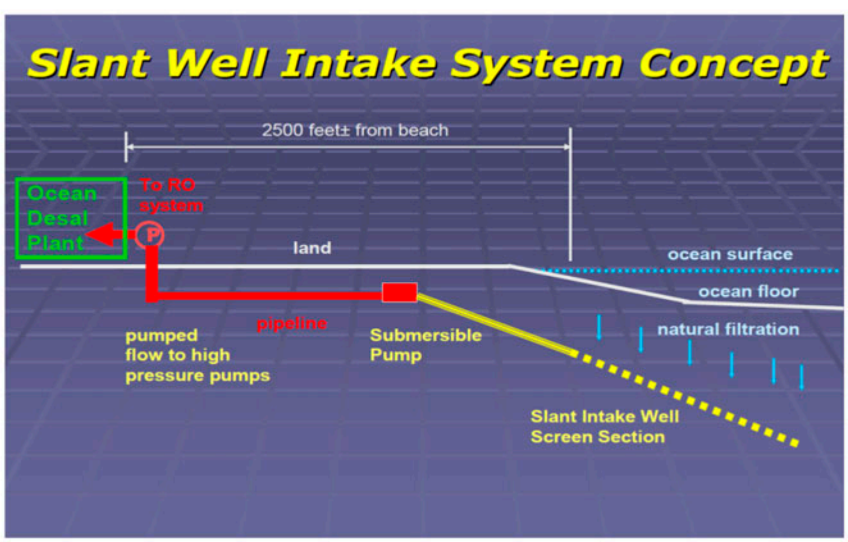

Fig. 18a. Diagram showing an angle well intake system. Note that the recharge direction is vertical compared to the typical vertical well intake system and the issue of impacts to coastal aquifers can be avoided [36].

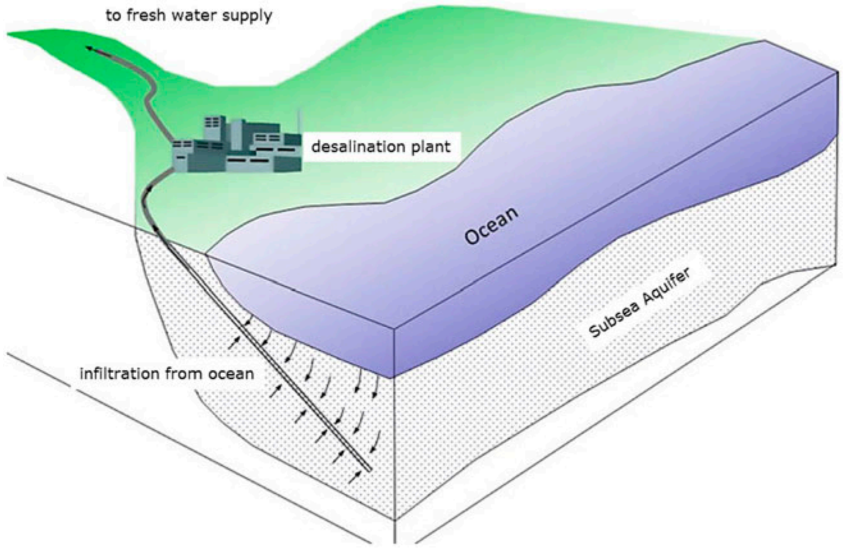

Fig. 18b. Slant well completed in subsea alluvial aquifer [36].

50,000 m^3/d capacity built in 2006, and is shown in Fig. 19d.

The gallery filtration media has: (i) graded gravel pack layer of 2.3 m thickness at the bottom with stone sizes between 20 and 40 mm that surrounds the horizontal well collectors in the bed, (ii) finer grade gravel of size 2.5–13 mm layer of 0.3 m thickness in the middle, and (iii) top layer of natural sand excavated from the ocean bottom, and has 1.5 m thickness. The filtration media is submerged at 11.5 m below the ocean surface. It has SW feed flow rate of 130,000 m^3/d. The gallery dimensions are 313.6 m long × 64.2 m or area of 20,133 m^2. This gives infiltration rate of (130,000/24)/20,133 = 0.269 m/h, and this is higher than the typical 0.12–0.25 m/h given before.

Fig. 18c. Dual-rotary drilling cradle which can be adjusted for any slant well angle [37].

Even with this high infiltration rate, it has been operating successfully with minimal cleaning of the membranes [4]. The reported SDI of the feed SW from the gallery over operating time was less than 2.0 (compared to SW level of 10 SDI), Fig. 19e. The seabed filtration media configuration of the Fukuoka SWRO plant is given by Fig. 19e; and a segment of a 600-mm intake collector screen used in the seabed infiltration gallery is given in Fig. 19f [13]. The collected water is pre-treated with UF membrane filtration prior to desalination in the SWRO membranes' system.

Missimer [4] reported designed, constructed, and tested another seabed gallery at the City of Long Beach, California. This gallery has infiltration rates ranging from 0.12 to 0.24 m/h and 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.

6. The effect of intake types on feed seawater quality

A subsurface intake system provides better quality feed SW to the SWRO DPs. But its capital cost can be much higher than that for open intake systems. This is the main reason that 90% of large capacity SWRO desalination systems are using open intake systems. The slow flow of SW through layers of sediments, sands, and rocks provides filtration and possibly

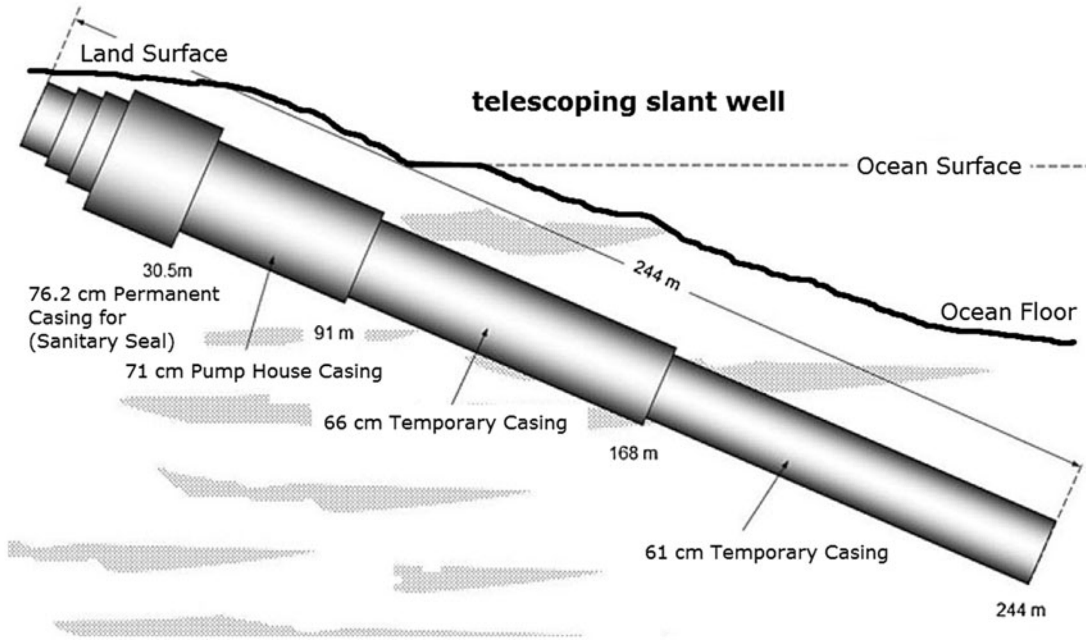

Fig. 18d. Telescoping design showing larger pump house casing used in the Monterey test slant well [28].

active biological treatment before entering the SWRO plant. The feasibility of using subsurface intakes depends on local hydrogeological conditions and capacity of the SWRO plants. When compared with open intakes, the subsurface intakes give reduced suspended solids, algae, bacteria, and dissolved organic carbon concentrations, and thus reduced bio-fouling.

The main function of the SWRO DP intakes is to supply the required quantity of feed SW with high quality and less negative impact on the marine environment. Large SWRO plants started with the use of

Fig. 18e. Installing the casing and screen of a slant well [35].

open SW intake types previously and commonly used for distillation desalination systems where SW feed quality is not an issue. Open intakes do not provide high-quality feed SW required for SWRO, as many constituents of SW cause membrane fouling and need extensive pretreatment. These include particulate matters (inorganic and organic) natural SW that can be classified as settable solids (>100 μm), supra colloidal solids (1–100 μm), colloidal solids (0.001–1 μm), and dissolved solids (<0.001 μm) [38].

Suspended solids or colloids escaped from the pretreatment reaching the SWRO membranes can be deposited within the membrane pores (known as pore blocking) or form a cake as suspended particles accumulate. The SW feed to the SWRO plants should have better quality than what manufacturers of membranes recommended to avoid colloidal fouling to promote good operation. These include feed turbidity < 0.1 NTU, and $SDI_{15} < 3$, TOC < 2 mg/l, and iron < 0.1 mg/l, to avoid colloidal fouling [2,38].

Suspended foulants include organic and inorganic particles in SW. The most common inorganic particles are aluminum silicate clay (size range of 0.3–1 μm), and colloids of iron, $CaCO_3$, aluminum, and silica. Organic particles include microorganisms, biological debris (plants and animals), poly-saccharides (gums, slime, plankton, fibrils), lipoproteins (secretions), oil, Kerogen (aged poly-saccharides), humic acids, lignins, carbohydrates, fats, oil, and grease. The Kerogen is a

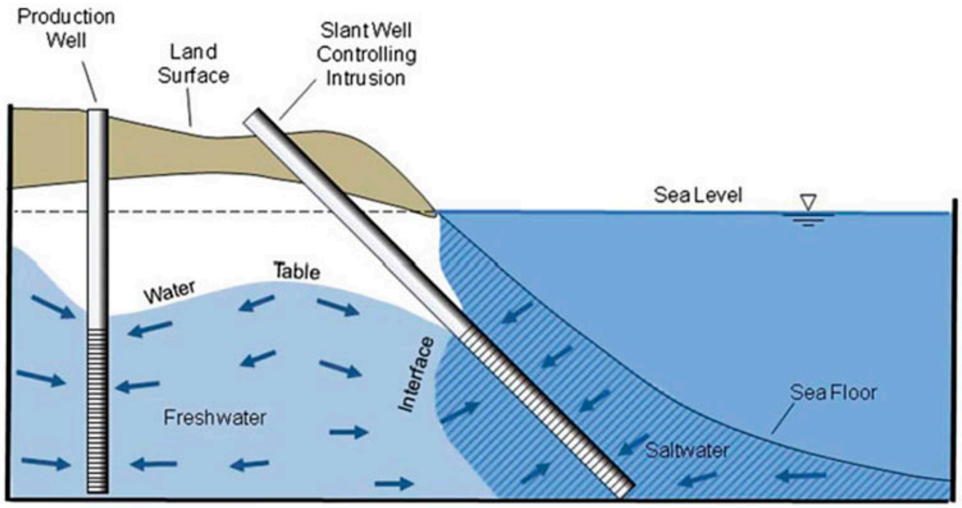

Fig. 18f. Telescopic construction used in slant wells [35].

mixture of organic chemical compounds that make up a portion of the organic matter in sedimentary rocks, and it is insoluble in normal organic solvents because of the high molecular weight (upwards of 1,000 Daltons or 1,000 Da; 1 Da = 1 atomic mass unit) of its component compounds. The organic matter in SW can badly affect the SWRO plants operation by causing membrane biofouling.

Filtration of SW before the RO membranes can efficiently remove suspended materials. Particulate are typically removed by granule media or membrane filtration. During ABs, the particulate loading increases significantly from multiplications of the algal cells, and associated AOM. NOM in SW include phytoplankton and bacteria or colloids. Colloidal NOM is usually described as a mixture of humic and fulvic acids. Humic acids are the product of organic matter biodegradation and are a mixture of long-chained organic acids containing several carboxyl and phenol groups. Fulvic acids are similarly characterized with the exception of having smaller molecular weights and higher oxygen content.

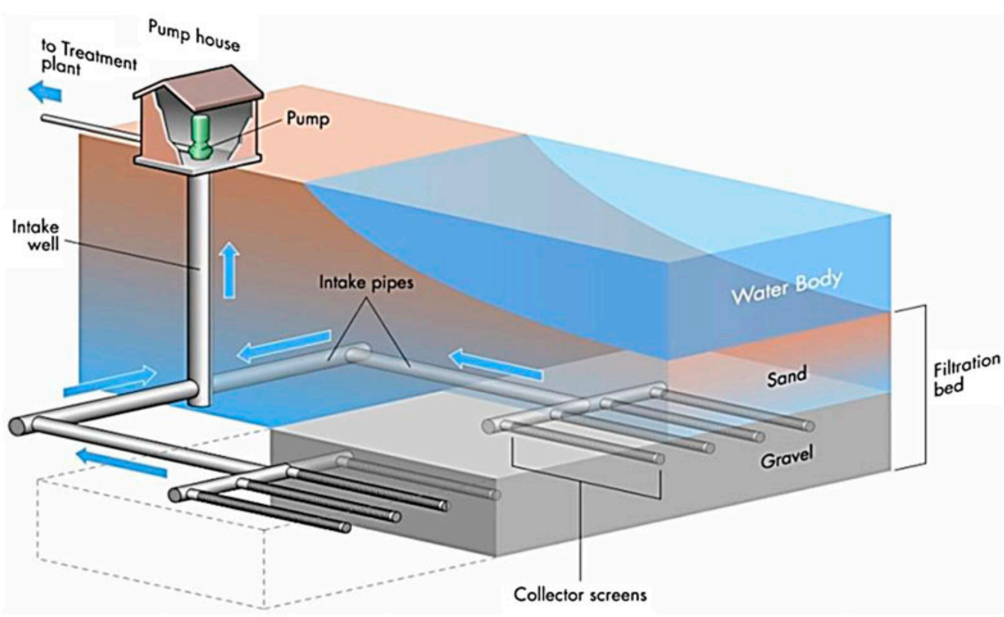

Fig. 19a. Infiltration seabed gallery [37].

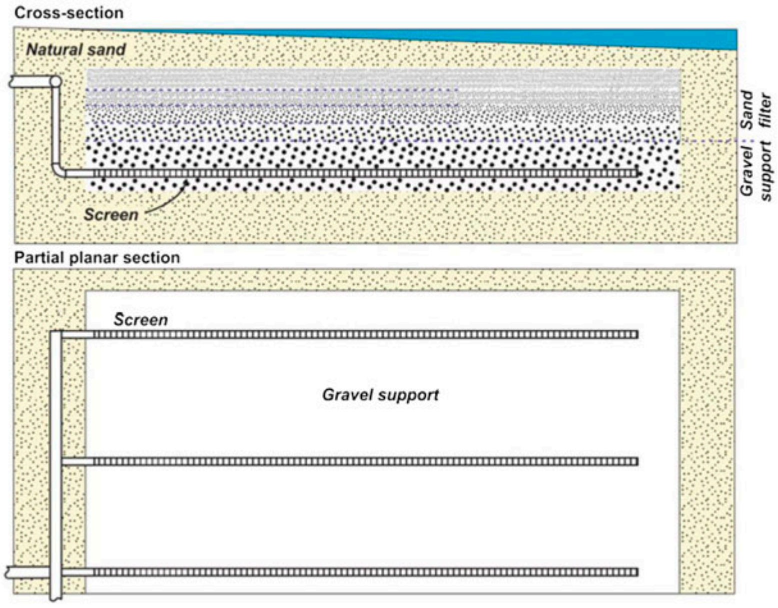

Fig. 19b. Conceptual diagram of a beach gallery. Thickness of gravel support and sand filter is approximately 1.5–2 m [39].

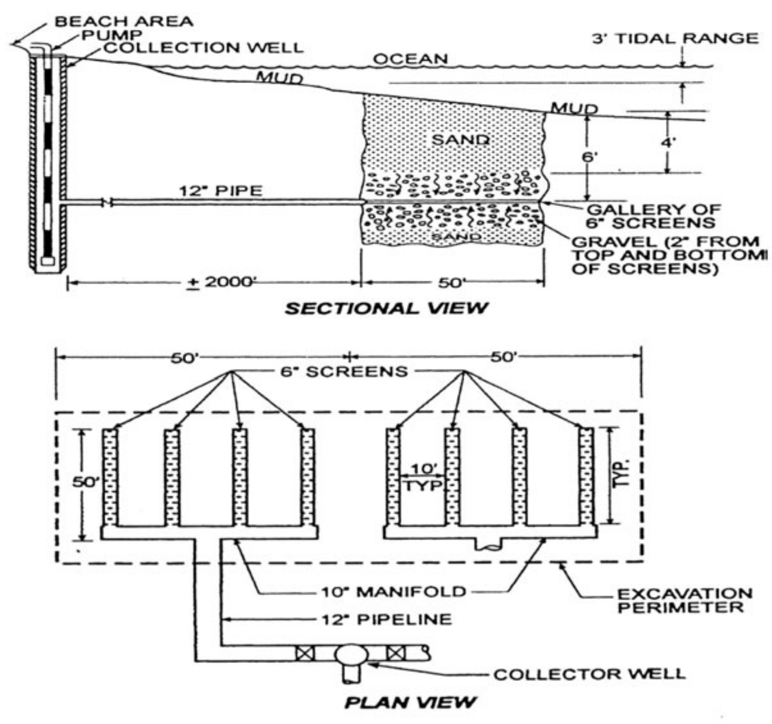

Fig. 19c. Seabed infiltration gallery [34].

While open ocean intakes are designed to minimize the entrainment and impingement, they are prone to marine growth inside of the conveyance piping if proper disinfection is not proper. Velocity cap style intakes can have high seasonal jellyfish, migratory and near shore fish, and seaweed influx. Also, passive-wedge-wire designs are prone to internal fouling by shellfish larvae passing through the screens

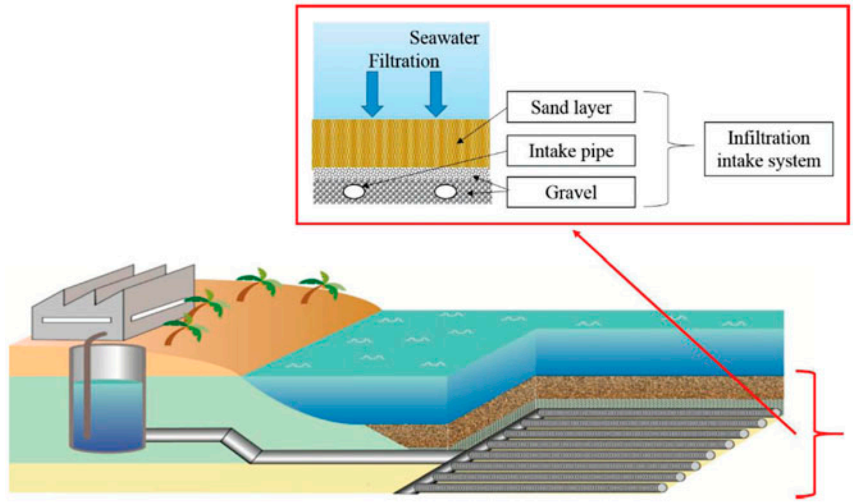

Fig. 19d. Seabed gallery at Fukuoka, Japan [40].

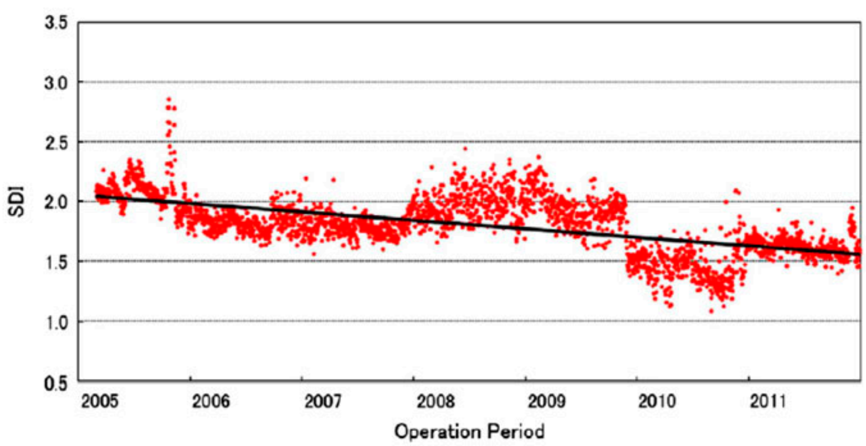

Fig. 19e. Long-term variation in the silt SDI of water coming from the seabed gallery at Fukuoka, Japan [4].

and external blinding during jellyfish migrations. Biogrowth at the intakes is solved by using biocidal materials of construction such as nickel, aluminum, and bronze to prevent growth-attachment of marine life within the intake structure. Feed SW supplied by open intakes is unlimited, but has poor-quality SW characteristics with high concentrations of different organic compounds, freely swimming organisms, algae, bacteria, and suspended sediment, especially during algal blooms (HAB's) and storm events. Thus, extensive pretreatment processes are required to overcome the problems of high-organic content and debris in the feedwater.

The use of subsurface intakes reduces significantly pretreatment requirements, by using geological media and marine sediments to filter out the particulates and reduces the seawater organic loads. Table 4 shows the effectiveness of subsurface intakes in reducing parameters that promote biofouling, e.g. algae (phytoplankton cells/L, polysaccharides (mg/L)), bacteria, and organic compounds measured by DOC, UV-254, TOC dissolved proteins and carbohydrates, phytoplankton cells/L, polysaccharides (mg/L), and others. Fig. 20 shows the seawater intake type on normal organic matters contents [41].

The use of subsurface intakes significantly reduces the complexity of pretreatment by using geological media and marine sediments to filter out the particulates and reduces the SW organic loads. The TOC in SW obtained from beach-wells, an example of subsurface intake, is lower than that taken from open intake as shown in Fig. 20. While open intake SW has

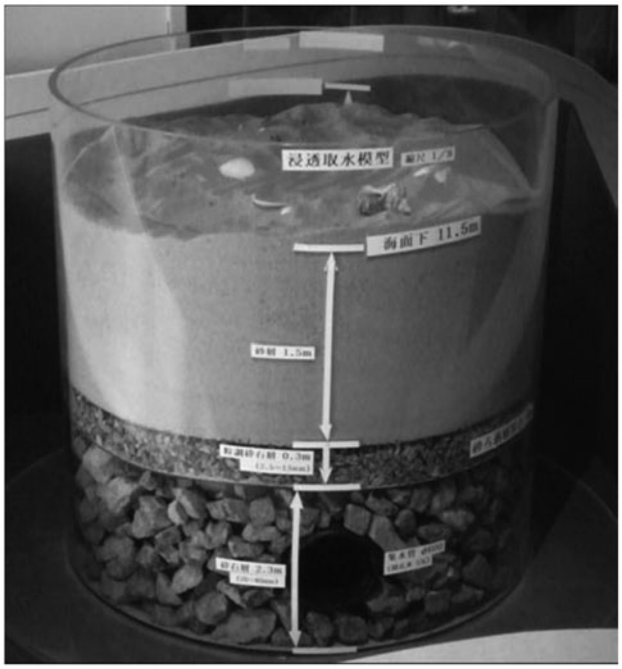

Fig. 19f. Seabed filtration media configuration of the Fukuoka SWRO plant [13].

Fig. 19g. Segment of a 600-mm intake collector screen used in the seabed infiltration gallery of Fukuoka SWRO plant [13].

TOC in the range of 0.8–4 mg/l, Fig. 20, it can peak to 9 mg/L at some sites. The TOC was less than 0.5 mg/L for SW taken from DP using beach-wells in Sur, Oman, and Aruba in Caribbean: and the TOC for SW taken from DP open intakes was 1–3 mg/L in Kindasa, Saudi Arabia, 1–5 in Fujairah 2, United Arab emirates, and <2 in Az-Zour Kuwait, and 1–3 in Ashkelon, Israel.

Gaid et al. [41] gave Table 5, which compares the required pretreatment for some open intake and wells subsurface intakes. It shows that the feed SW from wells used in Al Sur plant, Oman, and Aruba plants, Spain has low contaminant concentration, very low SDI, very good quality in terms of oil and grease, natural organic contaminations and aquatic microorganisms. This allows for a simple pre-treatment, including sand filtration without addition of chemicals and has very low SDI, very good quality in terms of oil and grease, natural organic contamination and aquatic microorganisms. No injection of chemicals, (e.g. H_2SO_4, $FeCl_3$) were needed. Meanwhile, all open intake examples given in Table 5 have high SDI, turbidity expressed by NTU, and TOC. Thus, they need extensive pretreatment including coagulation, flocculation, sedimentation, DAF, GMF, and UF.

Missimer and his co-workers [42–44] conducted comprehensive studies on the efficiency of subsurface intake systems (vertical well type) in terms of organic and micro-organism removal along the Red Sea coastline of Saudi Arabia (SA) to a SWRO DP located at the south part of Jeddah City, SA. They aim to evaluate the effectiveness of this offshore well intake system in the reduction of algal, bacteria, NOM, and TEP. They documented the effectiveness of a unique offshore well intake design with a depth of 40–50 m used to deliver raw SW to the desalination facility. Initially, several beach wells were constructed along the shoreline near the SWRO plant, but they gave limited SW supply of high-total dissolved solids (TDS) values (up to 90,000 mg/L) due to the geological conditions at the site located atop a filled coastal Sabkha environment that had hyper-saline conditions in the past. They found, by measuring the water physical parameters, organic carbon compounds, TEP concentration, algae, and bacterial concentrations that:

(1) The algae concentration was fully removed. The bacterial content was reduced up to 97% by the flow through the aquifer into the wells, see Fig. 21a.
(2) The TEP and biopolymer concentrations were also significantly reduced between the seawater and the well discharge, Fig. 21b.
(3) All of the NOM fractions showed some reduction in concentration, but the greatest reduction was observed in the biopolymers.
(4) Removal of the NOM fractions in the aquifer is selective based on the molecular weight of the fractions, Fig. 21c.

The reduction in concentrations of organics and micro-organisms demonstrates that the offshore well

Table 4
Comparison between bacteria, algae, organic carbon compound concentrations in natural seawater verses well intakes from selected sites [4]

Location	Parameter	Seawater	Well 1	Well 2	Well 3	Well 4
Dahab, Egypt	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	TOC (mg/l)	0.5	0.7			
	UV-254 (m^{-1})	0.36	0.55			
	Phytoplankton (cell/L)	57,720	0			
Al-Birk, Saudi Arabia	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	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	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	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	TOC (mg/L)	1.20	0.90			
	Polysaccharides (mg/L)	0.12	0.01			
	Humic substances + building blocks (mg/L)	0.50	0.40			
	Low-molar mass acids and neutrals (mg/L)	0.25	0.16			
	Low molar mass compounds (mg/L)	0.33	0.29			
Site 2	TOC (mg/L)	0.90	0.60			
	Polysaccharides (mg/L)	0.40	ND			
	Humic substances + building blocks (mg/L)	0.26	0.16			
	Low-molar mass acids and neutrals (mg/L)	0.22	0.13			
	Low molar mass compounds (mg/L)	0.38	0.30			

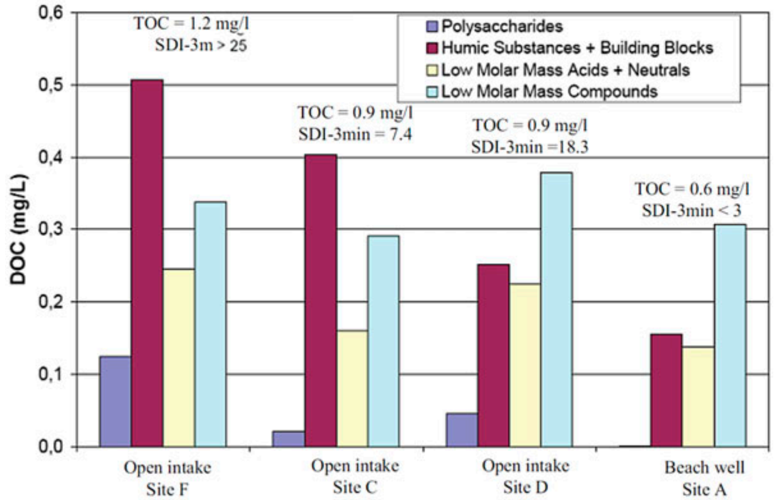

Fig. 20. Impact of the seawater intake type on normal organic matters contents [41].

Table 5
Pretreatment for different SWRO DPs [41]

Plant	Flow (MLD)	Origin SW	Turbidity (NTU)	TSS (mg/l)	SDI3	Algae (u/ml)	TOC (mg/l)	Pretreatment
Oman Sur (Oman)	80.2	Beach well	<0.5	<1	<1	No	<0.5	Direct filtration without chemical
Aruba (Caribbean)	24	Beach well	<0.5	<1	<1	No	<0.5	Direct feed with Screening
Ashkelon (Israel)	330	Mediterranean Sea	2–10	4–15	>33	Low level	1–3	Coag-floc-DMF
Gold Coast (Australia)	133	Coral sea	2–5	<15	25	Low level	<2	Coag-floc-DMF
Az zour (Kuwait)	136	Persian Gulf	2–14	5–20	>33	Low level	<2	Screening—coag-floc-DMF
Fujairah II (U.A.E)	128	Gulf of Oman	2–20	3–30	>33	Red tide	1–5	DAF(Spidflow)-DMF
Kindassa (SA)	25.5	Persian Gulf	2–15	5–30	>33	Low level	1–3	Gravity Filtration-Ultrafiltration

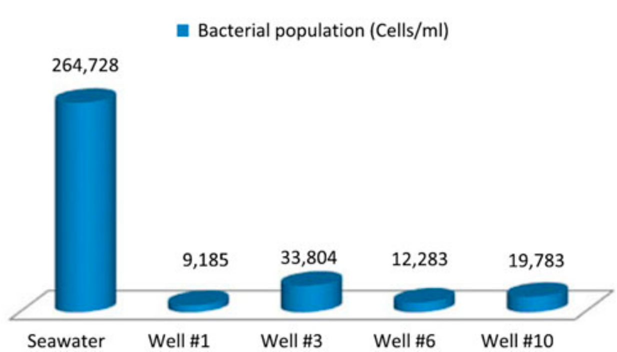

Fig. 21a. Bacterial counts in the seawater and the wells discharge [42].

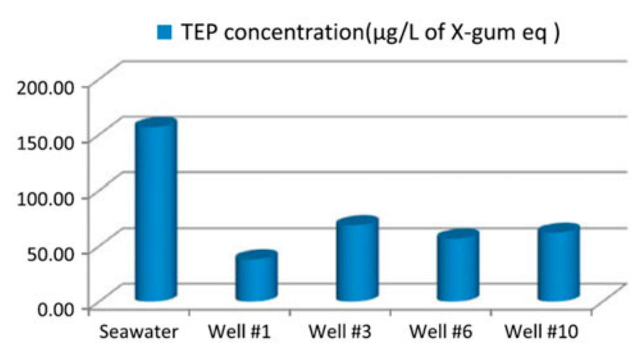

Fig. 21b. TEP concentrations in seawater and in the well system [42].

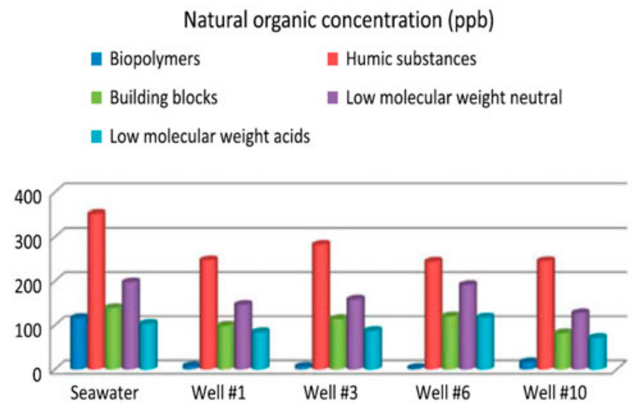

Fig. 21c. NOM fraction concentrations in seawater and well discharges [44].

system is quite effective at delivering a higher quality feedwater compared with an open-ocean intake. This allows the SWRO facility to operate using a lesser degree of pretreatment which lowers the frequency of membrane cleanings and reduces operating costs.

7. Conclusions

The GCC countries sooner or later will move from the predominantly used thermal desalination to SWRO desalination methods where biofouling is a major challenge. The increasing frequency of AB events and the failure of many SWRO plants pretreatment to deal with AB call for more research in the pretreatment in the case of ABs. The SW intake system is the first component of SWRO pretreatment that is the main factor in dealing with ABs. This paper provided an overview of alternative SW intakes including open (onshore and offshore) intakes, and subsurface well intakes (vertical, horizontal, and slant wells); and infiltration galleries (under beach and sea). Open intakes from deep water may reduce the amount of algae intake, but depending on the site specific conditions in the intake area they may or may not allow managing RO membrane biofouling during ABs. The subsurface intakes remove most (90–97%) of the algae and bacteria, and reduce the concentrations of both TEP and biopolymers. Although subsurface intakes are more expensive than open intakes, and have limited area of application in terms of volume of source water that can be collected, when suitable subsurface conditions exist, the savings associated with the simplification of the pretreatment process can make them a more favorable option than the subsurface intakes. Hundreds of small DPs use well type subsurface intakes. However, it should be noted that at present over 95% of the existing medium and all large SWRO DPs use open intakes because they are not suitable to remove large volumes of water and the larger the plant the less likely it is that suitable groundwater aquifer conditions will exist for their practical application. Wells have a number of other constraints associated with their changeable water quality, release of subsurface contaminants, and limited useful life, which have resulted in their limited application to date.

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