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Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls

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ABSTRACT

Seawater reverse osmosis (SWRO) desalination has some environmental impacts associated with the construction and operation of intake systems and the disposal of concentrate. The primary impact of conventional open-ocean intake systems is the impingement and entrainment of marine organisms. These impacts can be minimized by locating the intake in a geographic position where oceanic productivity is low. Velocity-cap intakes tend to reduce impacts by minimizing the number of fish entrained and some new traveling screens can allow the survival of some marine organisms. Mitigation, such as environmental restoration of habitat or restocking, can provide an acceptable solution to impacts where they are significant. Subsurface intake systems avoid impingement and entrainment impacts, but can cause other, less important impacts (e.g., visual, beach access). Concentrate disposal can locally impact benthic communities, if poorly diluted discharge is allowed to flow across the marine bottom. Impacts to benthic communities from concentrate discharges can be minimized by using properly-designed diffuser systems, designed and located based current and flow modeling.

The experiences of SWRO desalination to date indicate that environmental impacts can be satisfactorily minimized with proper design based on a reasonably complete environmental impact analysis prior to facility siting and design.

1. Introduction

As the need for development of new fresh-water supplies increases, global seawater desalination capacity will continue to expand. Therefore, there is considerable worldwide interest in the assessment of the potential environmental impacts of all aspects of desalination processes including both thermal and reverse osmosis. The least energy-intensive, and as a result often the most economical, seawater desalination process is reverse osmosis (SWRO). This review paper carefully evaluates the environmental impacts associated with the SWRP process, which currently has the greatest rate of increase in installed capacity and will dominant future capacity increases [1]. In 2012, the global installed seawater desalination plant capacity was about 5000 million m^3/year with about 45% of this capacity located in the Middle East [1]. Future planned expansion of desalination use shows that at least 68% of the new facilities will use the SWRO process [1]. Few stand-alone thermal desalination plants will be used with the majority of the thermal facilities being constructed with SWRO systems as hybrids.

Environmental impacts of SWRO can be classified broadly into three categories, including energy consumption [2,3], intakes [4,5,6], and outfalls [4,7,8]. This review covers the environmental issues regarding solely intakes and outfalls. Since recent publications have covered many of the advances in intake and outfall design, including environmental impacts [4,6], this review will emphasize new data and publications on environmental investigations involving SWRO.

SWRO is being projected to become an integral part of future water supplies in many coastal regions that have not needed it in the past, such as California [9] and Texas [10] in the United States, parts of Europe [11], Southeast Asia [12] and China [13]. Higher quality and more up to date scientific information is required to assess the environmental impacts of SWRO desalination, as new projects are being evaluated sometimes based on old or misleading assumptions [14]. Perhaps two of the most important issues that have been raised are impacts of impingement and entrainment caused by open-ocean intakes [15] and concentrate impacts on marine benthic fauna and flora, and fisheries [16].

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2. Review: intakes

2.1. Environmental impacts of intake systems: introduction

Environmental impacts of intake systems for SWRO facilities are of three primary types, depending on the intake design, which are impingement and entrainment of marine organisms, construction (temporary and permanent), and facility operation [3,4]. The largest capacity SWRO facilities tend to use surface-water intake systems (which may be co-shared intakes with electric power generation plants), canal intakes, canal intakes with settling basins, off-shore intakes, deep-water intakes, or passive-screen intakes [15,17–20]. Each of these systems has a different set of potential environmental impacts, specific impacts of concern, or degrees of impacts.

Perhaps the environmental impact of greatest concern with regard to all surface intake systems is impingement and entrainment of marine organisms, which is a function of system design, operation, and local marine biology at the intake head. When designing any intake system, whether a surface-water or a subsurface system, a critical criterion is the proposed location of the SWRO plant and associated intake system, which can affect local seawater quality [15,21,22]. The quality of seawater impacts the design and operation of the downstream pretreatment processes of the SWRO plant and the ability to operate the primary membrane system in a viable and efficient manner [23]. Also, the quality of the raw seawater strongly influences the ultimate quality of the discharge water (concentrate) requiring disposal. In areas of greater biological activity, the pretreatment processes must be intensified, which causes greater chemical usage and associated potential impacts to the environment at the discharge end of the system. A global increase in the spatial and temporal frequency of harmful algal blooms also impacts facility location and pretreatment options [24,25]. A good example of the strategic location of new, large-capacity SWRO plants is in the United Arab Emirates, where the plants are constructed along the coast of the Arabian Sea instead of the Arabian Gulf because of lower average salinity and lower organic carbon concentrations. The water quality benefits offset the additional costs associated with building and operating a long pipeline to deliver the treated water to the larger population centers [26].

2.2. Impingement and entrainment

Impingement and entrainment are collectively defined as the removal (mostly permanently) of marine organisms during operation of an intake system, which could be used for power plant cooling or the operation of a desalination plant. The greatest amount of research on this issue has been performed by the electrical power generation industry for mostly freshwater intake systems and a few seawater systems [27–44]. As discussed in Hogan [15], there are specific definitions for impingable and entrainable organisms. The U.S.E.P.A defines impingable organisms to be "large enough to be retained by a mesh with a maximum opening of 14.2 mm, including 9.5-mm mesh and 6.35 by 12.7 mm mesh. The group includes larger, actively moving juvenile and adult organisms [45]". "Entrainable organisms are small enough to pass through the above specified mesh size. Entrainable organisms include small organisms with limited to no swimming ability. Some of these organisms (or life stages of organisms), such as fish eggs, may be fully passive, lacking the ability to avoid intake flow regardless of velocity [45]".

Impingement and entrainment of marine organisms in terms of probability and magnitude are impacted by intake location (issue of biological productivity), ambient hydraulics (low currents produce higher risk), water quality (water temperature and dissolved oxygen that impact organism mobility), species-specific morphology and physiology (dimensional attributes and geometry), and intake design and operation [15]. Within the United States, the European Union, and Australia, pre-design investigations of the marine environment are generally required before a system can be permitted for construction and operation. The details of the design must be evaluated within the context of the marine pre-permitting investigation. The scope of investigation and duration of these marine studies can be a significant cost in the overall facility budget and can delay project implementation for years. A detailed discussion of the typical scope and duration of these marine studies is given in Hogan [15].

There are considerable differences in the design approaches to reduce impingement and entrainment to acceptable levels. In open-ocean intake systems without passive screens, the intake velocity is minimized at the point of raw water entry into the system and traveling screens are used downstream of the intake to remove marine organisms before they enter the SWRO plant. Some SWRO systems use passive screen intakes in which impingement and entrainment are minimized based on the screen design and selected entrance velocity.

The actual impact of impingement and entrainment on the local and regional marine environment is very difficult to assess and has been controversial. For example, environmental regulatory agencies in the state of California in the United States basically assume that there is a 100% mortality of any marine organism entering the intake (entrainment) which is ultraconservative. Therefore, it is important to view this issue with great care and consider various technical approaches to impact analysis, because it can greatly impact the permitability and economics of an SWRO facility.

There are two different approaches to estimation of mortality caused by entrainment, which are the demographic and conditional mortality approaches [15]. The demographic methods convert the lost organisms to equivalent numbers of adults, which necessitates that the detailed life history of each organism must be known. The number of eggs and larvae that survive to adulthood must be estimated along with fecundity, age-of-maturity, and life span [33]. The estimates made using this approach can be the loss of biomass or the loss of mature females that produce the eggs. The conditional mortality approach, known as the empirical transport model, was developed to assess impacts of power plant cooling water intakes [46]. This model produces a ratio between the number of organisms entrained and the number of organisms at risk of entrainment to estimate the proportional ratio caused by entrainment [47]. This method does not necessitate detailed knowledge of the life-cycle history of a given organism. A comparison of the methods with the advantages and disadvantages is given in Table 1 taken from Hogan [15].

Specific investigations of the impacts of impingement and entrainment have been conducted for SWRO facilities [48,49,50]. Some regulatory jurisdictions (e.g., in the State of California) use the conservative assumptions that the loss of ichthyoplankton (eggs and larvae) caused by impingement and entrainment significantly impacts local and regional fisheries. However, few scientific investigations support this assumption, which has been questioned in a few recently conducted assessments [51].

An intake environmental assessment was conducted to quantify the impact of a 170,722 m^3/d SWRO facility for the West Basin Municipal Water District in southern California [48]. The number of entrained fish larvae, fish eggs, and target invertebrate larvae were 10,164,117, 834,490,494, and 3,936,378 respectively. Despite the seemingly large numbers, the natural high mortality of these ichthyoplankton and the reproductive capacity of the species are significant factors that reduce the real impact. The report concludes that.

> "*The estimates of impacts from the ETM* (*model*) *need to be considered with the levels of entrainment since the natural number of larvae entrained may be very small relative to the reproductive capacity of the particular species. Although this can be done using adult equivalent modeling approaches, this is not necessary when the absolute levels of entrainment are so very low as was the case in this study for all the taxa analyzed with the exception of silversides. For example, the total entrainment estimates for white croaker and California halibut larvae for*

Table 1
Comparison of the most common methods to assess the environmental impacts of impingement and entrainment.
(From Hogan [15]).

	Demographic approach		Conditional mortality approach
	AEL	FH	Empirical transport model
Description of model	Uses larval losses (entrained organisms) to estimate the equivalent number of adult fishes that would have been lost to the population	Uses larval losses (entrained organisms) to estimate the number of sexually-mature adult females whose reproductive output has been lost	Estimates the proportion of organisms in the source water body population that will be lost to entrainment while accounting for spatial and temporal variability in distribution and vulnerability of each life stage to water withdrawals
Requires biological sampling of entrained organisms?	Yes		Yes
Requires biological sampling of organisms in source water body?	No		Yes
Requires oceanographic data on currents near intake?	No		Yes
Requires life history data?	Yes		Limited
Advantages	Adult fish are easily understood in fisheries management context		Model output lends itself well to calculating mitigation in terms of area of production foregone (APF)
	Does not require biological sampling of organisms in source water body		Requires only limited life history information, specifically, an estimate of the duration over which an organism is vulnerable to entrainment
Disadvantages	Requires detailed life history data that are sometimes unavailable, incomplete, or uncertain		Requires collection of oceanographic data (currents) as model input (if not otherwise available)
	Accurate data on the status of the adult population are required to assess the impact of lost adults		Requires biological sampling of source water body in addition to intake sampling

the proposed full-scale project were 945,578 and 181,368 per year, respectively. These annual entrainment estimates represent the annual production of a few females for white croaker (*based on an average batch fecundity of 19,000 eggs and an average of 19 batch spawnings per year* [52]) *to perhaps only one for California halibut* (*based on an average batch fecundity of 522,000 eggs and an average of 12 batch spawnings per year* [53])."

A key issue that must be considered when evaluating true environmental impacts of entrainment, in particular, is the natural mortality rate of the fish and invertebrate eggs and larvae being impacted. Global studies of marine fish mortality during the egg and larval growth stages show losses of eggs between 10 and 20% per day in early life stages and slightly lower values for fish larvae [54]. Survival rates for various marine organisms vary widely based on fertility rates and oceanography.

Impacts along open-ocean coastlines may be lower compared to restricted circulation bays and estuarine locations. However, the issues of currents, general water circulation patterns, and nutrient recycling also have control real impacts linked to egg and larvae removal by desalination plant intakes. Little is known about impacts in restricted seas, such as the Arabian Gulf and the Red Sea.

2.2.1. Mitigation strategies for impingement and entrainment losses of marine organisms

Once real impacts to the marine organisms of concern are established, a strategy for mitigation of the impacts can be undertaken. Based on some know case studies, this is not a prohibitively expensive proposition. A common strategy is to first reduce impacts by using one of the more modern surface water intake designs or a subsurface intake. If additional mitigation is required via the regulatory process, three different strategies can be employed which include mitigation by the creation of marine wetland areas or other marina habitat allowing greater areas for fish and invertebrates spawning, paying a fee based on calculated economic loss caused by the facility operation, or restocking the marine system with either fish and invertebrate eggs, larvae, or juvenile or small adult forms, which can achieve a higher survival rate [55].

The wetlands re-creation strategy was used at the new Claude "Bud" Lewis Carlsbad SWRO facility in San Diego County, California. This 190,000 m^3/d facility was required to restore about 150,000 m^2 of wetlands area within a nearby lagoon. Based on the concept of using habitat restoration as a means of mitigation, lagoon or bay wetlands areas creation costs generally range from \$4–5/m^2 in coastal California. More complex habitat creation, such as an offshore rocky reef, can cost up to \$35/m^2. The issue becomes evaluation of how much area must be created to offset the calculated environmental impacts [56].

Use of a fee charged basis on the impingement and entrainment losses requires a considerable degree of sophistication and a governmental commitment to spend the collected funds for the improvement of the environment. Otherwise, this approach is ineffective. Therefore, a fee would be assessed based on the quantity of seawater pumped into the facility (e.g., \$0.50–2.70/3798 m^3/d estimated from the literature on California). For a 190,000 m^3/d facility, the cost could be \$25–135/d or annualized costs of \$9125–\$49,275. Some of these estimated costs were obtained from some California committee reports. However, the costs could range higher based on real estimates of impacts in other global locations.

The third mitigation method, not commonly employed, is restocking of the species of most concern. Many of the environmental impact assessments calculate the dry weight loss weight of marine ichthyoplankton and assess the mitigation costs from that calculation. The dry weight is assessed by assuming a volume of loss and applying a percentage of water to it. If the impact number is simplified to the loss of equivalent adult fish or other invertebrates, this mitigation strategy would be to restore the fishery with older, more mature fish of the species of concern. The fish or invertebrates would be raised in seawater basins and placed in the sea at designated locations to assure high survival rates. If the mortality rates are known from various life-cycle times, the restoration plan could use individuals with much lower mortality rates compared to the lost bulk mass of the ichthyoplankton. The cost of this method could be much lower than for the other methods and perhaps could provide a higher degree of certainty in the mitigation process.

2.3. Surface intake systems

Depending upon the type of surface intake system being used, the environmental impact from impingement and entrainment will vary greatly. In certain cases there will be no impingement impact and entrainment will be the primary cause of marine ichthyoplankton losses. Each intake type is discussed with regard to the potential for impingement and entrainment impact.

2.3.1. Co-located power plant and SWRO intakes

A significant number of SWRO surface intakes use the downstream seawater discharge from electric power generation facilities [21,22]. There benefits to operating SWRO plants in this manner include: 1) avoidance of the need to build an expensive offshore intake structure and connecting pipeline, 2) no need to maintain the offshore intake structure or use chlorine to keep it free of sessile marine organisms, 3) minimal environmental permitting necessary because the primary intake is already permitted, 4) the water temperature is warmer which may reduce SWRO operating costs, particularly in colder climate regions, 5) the primary impacts of impingement and entrainment are covered mostly under the operating permit of the power facility, and 6) the concentrate can be discharged downstream of the SWRO intake, which would provide significant dilution and reduce the permitting difficulty. However, a second permit is commonly required for the intake stream to the SWRO facility.

An example of a coupled SWRO intake with a power plant discharge is the Claude “Bud” Lewis Carlsbad SWRO facility in San Diego County, California. During the permitting of the SWRO plant intake, the entrainment mortality of the power station operation was estimated to be 97.6%, so the SWRO intake had to deal with the remaining 2.4% of the surviving ichthyoplankton [57]. Therefore, the loss caused by the SWRO intake is quite small compared to the losses created by the power station intake.

This intake system works quite well as long as the power station is operational or the single-pass cooling stream maintains a permit. In the case of California, the state enacted a ban on single pass-through cooling systems and this discharge stream will discontinue, causing the SWRO plant to face the full impact of their intake stream in the future.

2.3.2. Stand-alone inshore intake structures

Stand-alone surface intake structures require the use of various types of screens to avoid the entry of adult marine organisms and ichthyoplankton into the pretreatment process train. These mechanically-cleaned screens include traveling water screens, rotating drum screens, fine-mesh traveling screens, and Ristroph screens [23] (Fig. 1). These intake structures have a high mortality rate for impingement and entrainment of fish and ichthyoplankton. Some structures are equipped with fish diversion systems to avoid impingement and others are designed to gently wash off the screens, so that a significant percentage of fish and some of the ichthyoplankton can be returned to the sea via a secondary pipeline.

In many parts of the world, these structures are becoming difficult to permit. For example, in California (USA), they are essentially banned [51]. Perhaps the highest impingement and entrainment impacts occur at inshore, stand-alone intakes based on the inability of fish to swim away and the lack of currents across screens. Depending on the width of certain canals, the entrance velocity into the facility can be large enough to preclude marine organisms from being entrained.

2.3.3. Offshore velocity-cap intake systems

Velocity-cap intake systems tend to be the most commonly used system for stand-alone SWRO facilities with a > 50,000 m^3/d capacity. The velocity-cap intake system was designed to minimize the entrainment of fish of various sizes and ages. Design of the intake was based on the premise that the change in flow pattern at entrance velocities ranging from 0.3 to 0.9 m/s will trigger a response in fish that causes them to avoid entrainment [23] (Fig. 2). The response is based on the change from horizontal to vertical flow. While the velocity-cap intake allows fish to avoid capture, it still entrains virtually all of the marine ichthyoplankton.

Another environmental impact of all offshore intakes is that associated with the pipeline connecting the intake structure to the SWRO facility. Typically, the pipeline is designed and constructed as an emergent structure lying on the seabed and is buried beneath the nearshore area affected by wave action, the littoral zone, and the beach. The pipeline is commonly constructed with high density polyethylene (HDP) and the pipe joints are welded onshore into long sections which are floated and towed offshore where the pipeline is flooded to sink to the bottom. Concrete anchors are placed over the pipeline at various increments to prevent it from moving in storms or by normal orbital wave action. The environmental impacts of the pipeline are temporary increases in turbidity during construction, particularly where excavation to bury it occurs, and permanent loss of some benthic environment where the pipeline rests upon the seabed.

Several strategies are available to mitigate the impacts of offshore pipeline. Since sessile marine organisms tend to require hard material on which to attach, the concrete anchors commonly attract marine growth and any areas where the pipeline is armored with concrete creates increased habitat for growth of sessile marine organisms. This surface area of hard material can be used to mitigate loss of benthic habitat. Another strategy recently employed in Australia is to construct tunnels from the SWRO facility to both the intake, commonly a velocity cap, and outfall pipe [58,59]. Tunneling avoids both temporary construction and permanent benthic impacts to the marine environment. The footprint of the actual velocity-cap structure is generally insignificant in terms of benthic impacts because it is relatively small.

Many offshore intake structures require the use of chlorine to keep the intake pipeline from becoming fouled with sessile marine growth and biofilms. Generally, the chlorine is fully incorporated into the organic carbon it has oxidized and does not impact the marine environment. However, the debris created during the pipeline cleaning process, either by chlorination or by periodic pigging, is commonly returned to the sea.

2.3.4. Offshore passive screen intakes

Design, construction, operation, and environmental impacts of passive screen intakes have been discussed in detail by Missimer et al. [60]. The environmental impacts of passive screens intakes include: 1) turbidity during construction of the screen structures and the pipeline (see Section 3.3.3), 2) covering of the marine benthic environment by the screen base structure and the pipeline (see Section 3.3.3), 3) impingement and entrainment of marine organisms, and 4) debris generated during cleaning of the passive screens. Passive screen intakes have a significantly lower impingement and entrainment impact compared to conversional open-ocean intakes on shore-based canal intakes.

Because the entrance velocities in passive screen intakes are generally low, in the range of 15 to 30 cm/s, impingement is quite minor [36], but certain young fish larvae can be impinged based on their limited swimming ability and geometry. However, the primary issue is the entrainment of organisms that have a hydraulic radius smaller than the slot size of the screen [61,62]. Passive screens have three mechanisms that impact the passage of ichthyoplankton through the screen: physical exclusion based on the screen slot aperture, entrance velocity into the slots [31], and hydrodynamic exclusion caused by the rapid diffusion of the flow field close to the screen [60]. The current passing across the face of the screen (ambient velocity) can also create shear and turbulence that can aid in reducing entrainment [63,64].

It is difficult to assess the reduction in ichthyoplankton entrainment of passive screen intake systems using wedge-wire screens compared to conventional open-ocean intakes. However, a study conducted on the performance of cylindrical wedgewire screen in the Pacific Ocean near Santa Cruz, California concluded that a 2.0 mm aperture screen with an

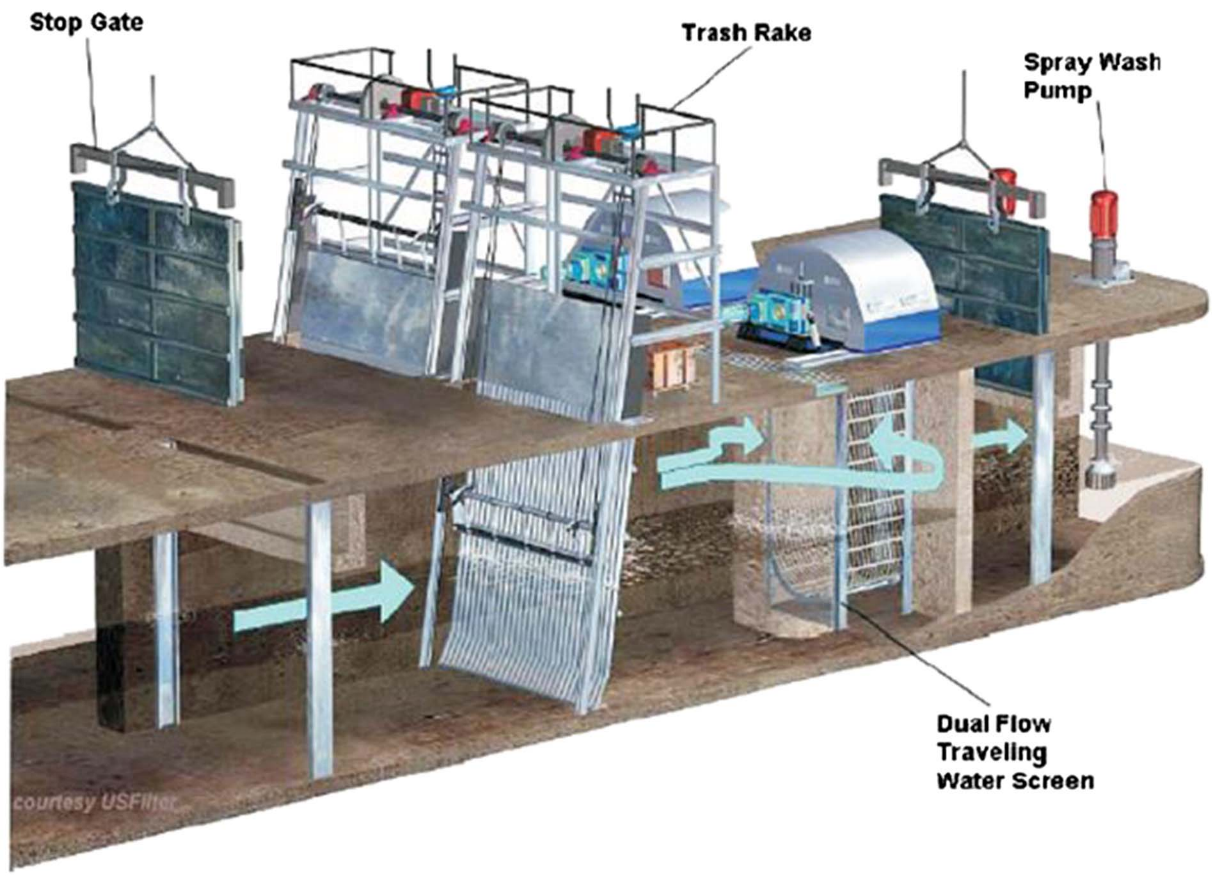

Fig. 1. Dual-floe traveling water screen.
(From Pankratz [18]).

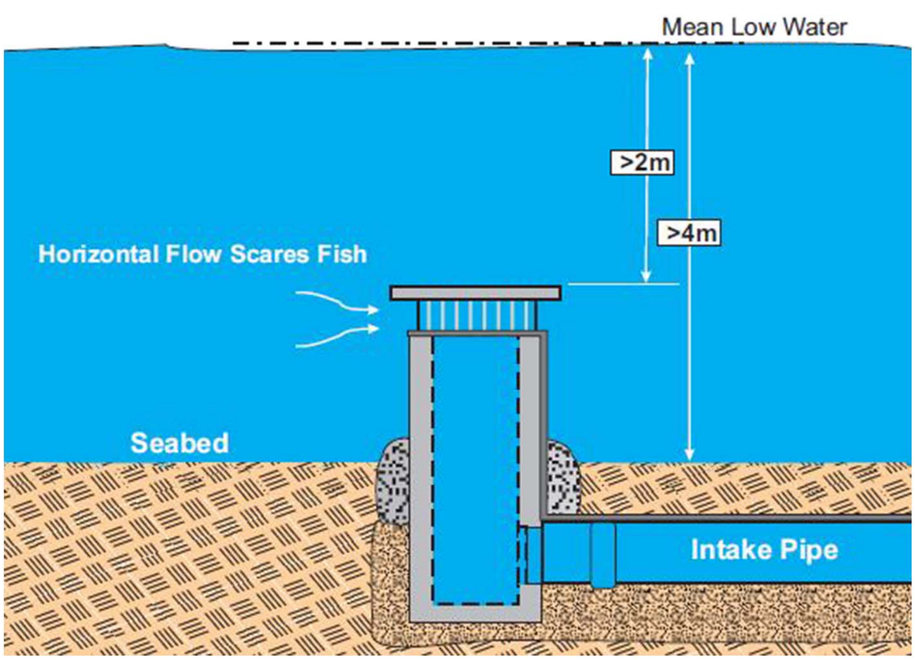

Fig. 2. Diagram showing a velocity-cap intake structure.
(From Pankratz [18]).

entrance velocity of 10 cm/s eliminated the impingement of large marine organisms and reduced entrainment by 20% [50]. The actual reduction in entrainment of ichthyoplankton is design and site-specific and cannot be generalized over wide regions.

2.3.5. *Hybrid systems*

A significant number of hybrid desalination systems, particular in the Middle East region, use a combination of a thermal distillation desalination plant (multi-stage flash or multiple effect distillation) with an associated SWRO plant [22]. These facilities tend to have combined intake systems and the discharge streams of concentrate are comingled. Therefore, if the impacts of impingement and entrainment are assessed of solely the SWRO component, they would be lower based on dilution in the combined discharge stream (see Section 3.3.1). Also, the temperature of the thermal plant discharge water could be slightly lower as caused by the combination with the SWRO discharge. The SWRO concentrate, typically close to double that of the ambient seawater, would also be dilute compared to the stand-alone system.

2.3.6. Deep water intake systems

Marine productivity tends to decline from shallow to deep water, especially below the photic zone. Based on this concept, some investigators believe that using deep water intakes would produce a higher quality of seawater and may have a reduced environmental impact because of the lower concentration of living marine organisms and ichthyoplankton.

Cartier and Corsin [65] proposed that "deep" means a range from 20 to 35 m below surface, whereas the Japanese-funded "Megaton" project suggested that deep intakes should be constructed at depths > 100 m [66]. Feasibility of using deep intakes is based on both the assumption that the seawater quality will be higher (lower organic component concentrations) and that the intake is constructible and can be operated without risk of failure. An assessment of using a deep intake system in the Red Sea coast of Saudi Arabia concluded that use of deep intake systems was not feasible based on the geology (sharp offshore cliff dropping from 20 m to over 500 m at nearly 90°) and the improvement in water quality would be slight [67].

Biological productivity does decrease with water deep in the sea and deep intakes may have a considerably lower impact based on lower rates of impingement and entrainment. However, practical issues, such as water temperature [68] and maintenance of the intake structure, may create unreasonable operating costs [67]. However, the issue of deep intake systems for SWRO should be researched in the future and some applications may be found that would have very low impingement and entrainment impacts.

2.4. Subsurface intake systems

Subsurface intake systems have been used successfully for decades to feed SWRO systems [21,22]. Subsurface systems can be classified as wells [69] and galleries [70]. The use of subsurface intake systems has been limited to small to medium capacity SWRO facilities. The largest capacity well system is about 160,000 m^3/d which is used to feed a 80,200 m^3/d permeate capacity facility at Sur, Oman [68]. The largest seabed gallery system in operation is the Fukuoka, Japan SWRO facility with a capacity of 103,000 m^3/d [69].

2.4.1. Introduction to subsurface intakes

Subsurface intakes are environmentally-friendly and do not have impingement and entrainment impacts. They provide a natural degree of filtration that can substantially reduce in-plant pretreatment process intensity. However, depending upon the intake type there may be other types of impacts on land or the beach area.

2.4.2. Well intake systems

2.4.2.1. Conventional wells (beach and interior seawater aquifer). Conventional vertical wells are used as feedwater sources in hundreds of SWRO facilities globally (Fig. 3). They generally produce operational benefits by providing very high quality water containing no algae, low bacteria concentrations, and significantly lower concentrations of transparent exopolymer particles (TEP) and the biopolymer fraction of natural organic matter (NOM) [71–75]. These organic components of seawater are important contributors to membrane biofouling and have to be removed in pretreatment when using conventional surface intake systems. Therefore, conventional well intakes have the environmental benefits of requiring lesser quantities chemicals to be added to the feedwater during the pretreatment process and improving the quality of the discharge water.

In some cases the seawater produced from wells contains naturally-occurring hydrogen sulfide. Since hydrogen sulfide passes freely through the SWRO membranes, it enters the concentrate stream. The hydrogen sulfide can adversely affect the marine environment and must be removed before discharge. Removal is commonly achieved using air-stripping, which can cause some minor, localized air quality problems. Other processes are available to remove hydrogen sulfide without affecting air quality.

If wells are used to feed high-capacity SWRO systems, a very large number can be required. In most sites, the production wells must be located very close to the shoreline to be sure that water is being produced from the sea and minimize the contribution from adjacent inland areas where the water quality could be different or could be contaminated [23,76]. The placement of numerous wells on beaches can lead to visual impacts (which can be an important concern in tourism areas) and obstructions that could be deemed to be hazardous, particularly on public beaches. Also, supporting infrastructure including pipelines and electrical power must be installed on or under the beach to use the wells. During construction and maintenance periods the beach would be unusable in the vicinity of the wells, pipelines and electrical conduits.

2.4.2.2. Angle wells. Angle or slant wells are drilled beneath the sea from the shore (Fig. 4). Angle well intakes potentially have less impact to the beach area, because their construction site and final well pad can be located in the back-beach zone or completely off the beach [77]. They generally have a small foot print and can be located in convenient positions, but have a limitation with regard to the distance to the sea. Multiple wells can be drilled radially outwards from a single drilling and well pad.

Only one angle well system has been tested in detail to date in California. While the well yields are sufficiently high to produce the required feedwater, the seabed aquifer penetrated by the well screens contains high concentrations of iron and is anoxic. The quality of water will require a greater degree of pretreatment and will produce a discharge that will contain larger concentrations of metals and the chemicals required to remove them. This cited issue may not occur at every site and therefore, the slant wells may have little impact to the environment.

2.4.2.3. Horizontal wells or drains. Horizontal wells or drains are installed under the seabed using micro-tunneling. A large number of these wells can be installed from a single pad site located off of the beach [78,79] (Fig. 5). Of all of the well systems, horizontal wells have potentially the fewest environmental impacts. However, there are few installations of high capacity and one studied system produced poor quality seawater that requires considerable pretreatment producing associated impacts to the concentrate discharge (more chemicals) [71].

2.4.2.4. Radial collector or Ranney wells. Radial collector or Ranney wells have been used in a few locations for development of feedwater [76,80,81]. A radial collector contains a vertical caisson with a series of horizontal collectors at the base (Fig. 6). The diameter can range from about 3 to 6 m. Since there is a limitation of the length of the laterals that are connected to the central caisson, the wells must be located on the beach as close to the shoreline as possible. Therefore, these wells have the same visual impact as conventional vertical wells. They have a much higher potential capacity per collector compared to conventional vertical wells and fewer of them would be required for a given SWRO facility. However, they also require connecting pipelines and electric connections that will have to cross the beach. This will disrupt use of the beach during construction and maintenance.

2.4.3. Gallery intake systems

Gallery intake systems have some significant advantages over well systems in that they have a potentially high capacity and can be used for nearly any capacity SWRO system [82]. However, there are some possible environmental impacts associated with their construction and

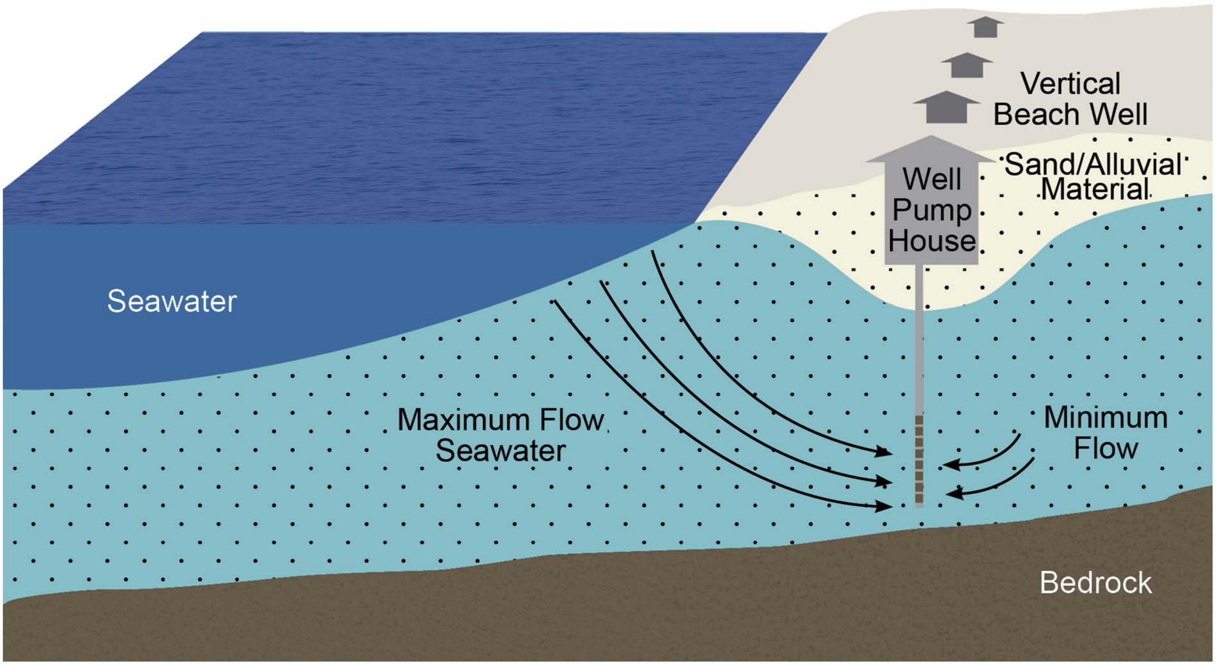

Fig. 3. Diagram showing well intake system located on the beach.
(From Missimer et al. [6]).

operation.

2.4.3.1. Beach galleries. The concept of a beach gallery is to construct a sand filter within the littoral zone of the beach [83,84]. Waves breaking across the top of the submerged filter will tend to continuously flush the system of the marine debris, and organic carbon is filtered out by the beach sand [83,84]. While this type of intake design is attractive based on its ability to continuously clean itself, there are several critical design and operational constraints. The beach must be stable and have minimum erosion or accretion, otherwise the system would fail. The beach cannot be high energy and subject to seasonal intense storm activity with associated rapid erosion and deposition.

A possible beach gallery intake design was evaluated for use at the City of Huntington Beach, California for a 190,000 m^3/d SWRO facility [85]. The capacity of the intake was to be 402,000 m^3/d. An independent science advisory panel concluded that the intake was not feasible because of the instability of the beach and the long period of construction [85]. Significant environmental and other infrastructure impacts would occur during a 3 to 7 year period of construction. Long-duration closure or great aesthetic impacts to beaches would be an unacceptable impact to the local tourism economy would not be acceptable. Also, the pipelines, pumps, and electric equipment would need to be placed on the beach and in close proximity to the beach (pumping station) which would have a variety of additional impacts. Smaller-capacity beach gallery systems, constructed at appropriate locations, would tend to have much smaller environmental impacts. No

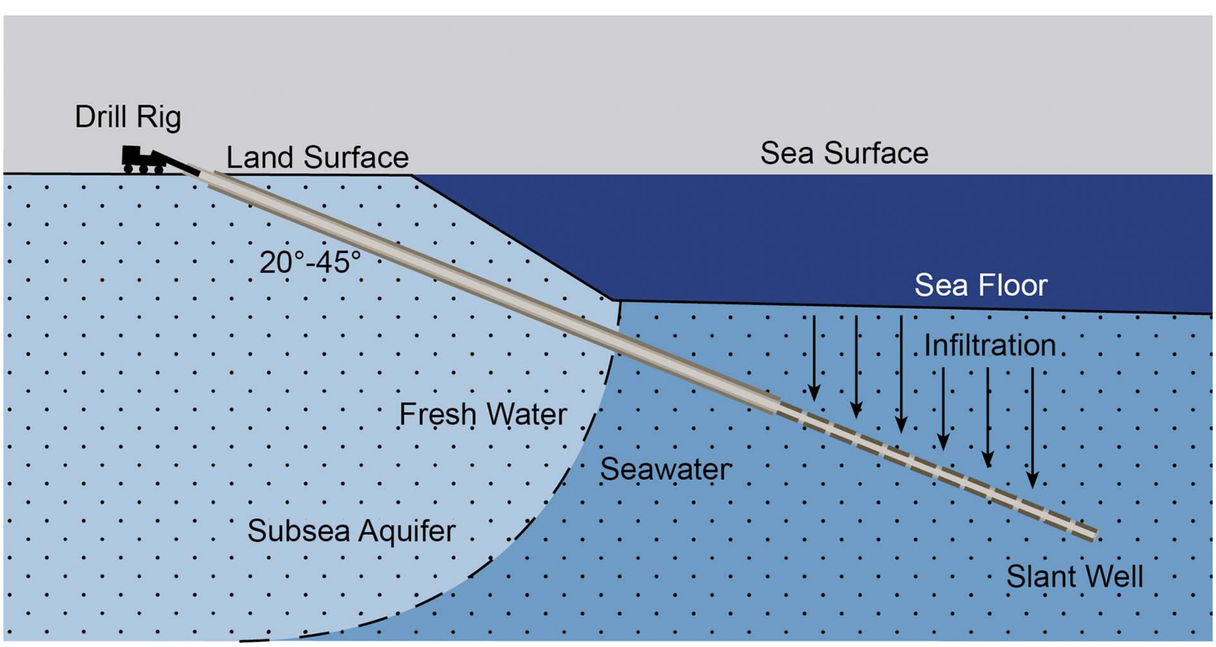

Fig. 4. Conceptual diagram of a slant well intake system.
(From Missimer et al. [6]).

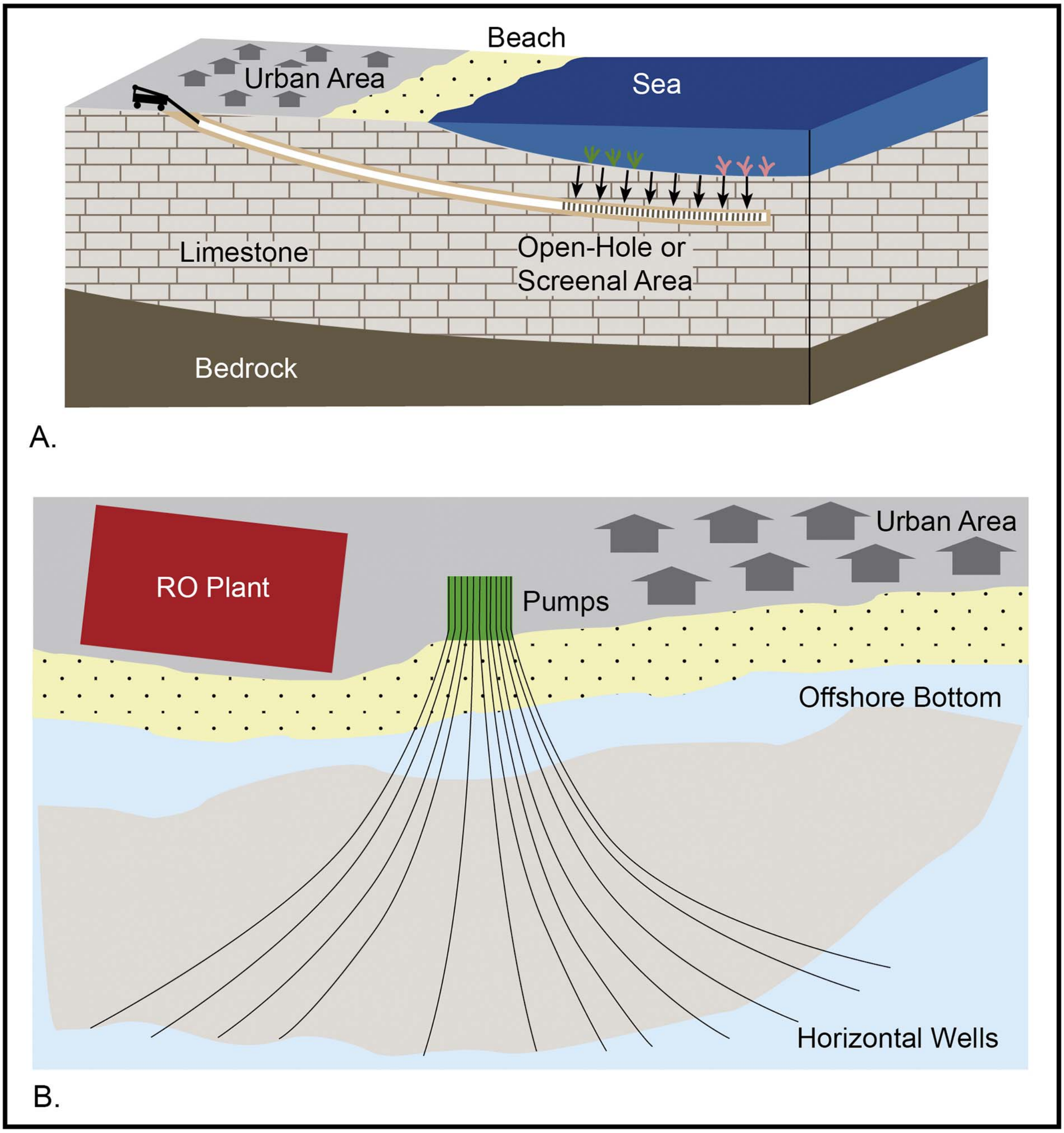

Fig. 5. Diagram showing the conceptual design of a horizontal well system.
(From Missimer et al. [6]).

large-scale beach gallery system is currently in operation.

2.4.3.2. Seabed galleries. Seabed gallery intake systems are essentially engineered slow-sand filter systems constructed in the seabed [86,21,22,87]. The textbook example of such a system has been operating at Fukuoka, Japan at a capacity of 103,000 m^3/d for nearly 10 years [88] (Fig. 7). Seabed galley intake systems can be successfully constructed at nearly any capacity and location in the world, but specific types of geologic or climatic circumstances can impact the design, construction (cost) and operation. It is particularly expensive to construct adjacent to high energy coastlines [85] and requires extensive pre-design investigations [89]. This type of system has generally low environmental impacts and no impingement and entrainment impacts.

The primary type of environmental impact associated with this intake type occurs during construction when the seabed must be excavated to install the engineered filter system [85] and possibly if maintenance is required during operation (removal of upper 10 cm of filter media). Such maintenance has not been required to date at the Fukuoka, Japan site. During operation of the intake system, the typical benthic marine organisms would be unaffected and could potentially benefit from the additional organic carbon being filtered by the media. It has been suggested that the feeding of polychaete worms may be responsible for maintaining the filter at the Fukuoka site [90].

2.5. Ongoing and future research on intake systems to make them more environmentally friendly

A considerable amount of research is ongoing to make seabed gallery systems less expensive to construct and to achieve economic benefits that can make them competitive with conventional open ocean intake systems [91]. Open ocean intakes are currently the method of choice to provide high-capacity SWRO systems with feed water because

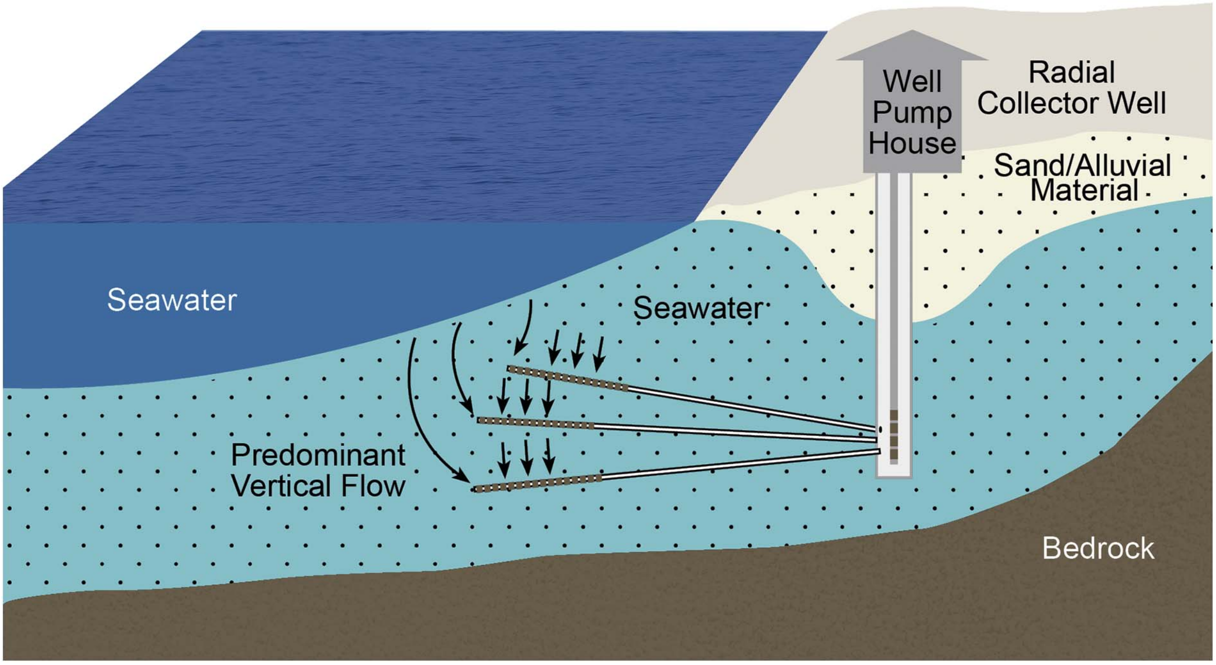

Fig. 6. Diagram showing the typical design of a Ranney well or collector.
(From Missimer et al. [6]).

of their generally reliability. However, the high levels of pretreatment required make the operation of SWRO facilities more costly and the heavy use of chemicals in these processes make the discharge impacts more environmentally unfriendly. Also, the increase in frequency of harmful algal blooms makes a subsurface intake system more attractive because the SWRO pretreatment processes can be overwhelmed by the high organic load during these events, causing plant shutdown and/or damage.

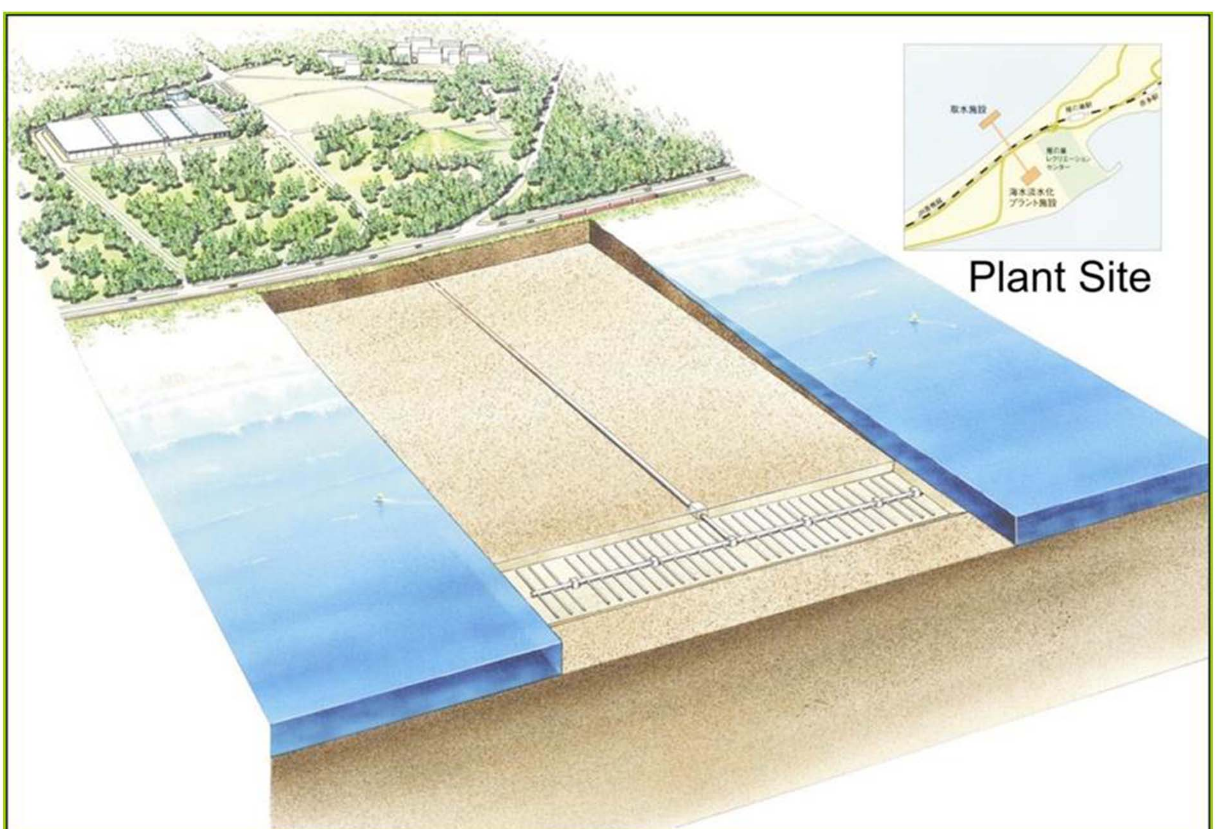

Fig. 7. Diagram showing the design of a sea galley intake system at Fukuoka, Japan with a design capacity of 103,000 m^3/d.
(From Missimer et al. [6]).

3. Review: outfalls

3.1. Environmental impacts of outfall systems

There has been much research on the environmental impacts associated with the disposal of concentrate, which range in geographic scale from local to regional to global. Potential impacts assessed are included in the life's work of Mickley [92–102] and others [8,103–121]. The primary environmental impacts associated with discharge of SWRO concentrate include:

- increases in the salinity of receiving water bodies, particularly restricted circulation bodies,
- local impacts of hypersaline brines on marine benthic communities at and near the point of discharge,
- discharge of chemicals used for pretreatment and membrane cleaning,
- discharge of metals from corrosion (Cu, Fe, Ni, Mo, Cr),
- aesthetic issues (visual impacts),
- impacts to aquifers from leaks from brine pipes,
- temporary damage during construction,
- temporary damage during maintenance,
- permanent damage from emplacement of infrastructure (pads, pipelines, etc.).

A list of the potential physical and chemical impacts of SWRO discharges on the marine environment is given in Table 2.

3.2. Conventional outfall systems

Conventional outfall systems discharge concentrate directly to marine surface-water bodies. The discharge may occur through an open pipe to deep water, a discharge pipe with diffusers, or by mixing with the much greater flows of discharged power plant cooling water. Environmental impacts may occur at the point of discharge where the salinity, temperature, and chemical composition of the concentrate flow differ significantly from that of the ambient seawater.

Seawater desalination involves the extraction of seawater from a surface-water body, removal of freshwater, and commonly, the return flow of concentrated salts to the surface-water body. The net large-scale impact on the surface water body is a gradual increase in salinity, provided that the produced freshwater does not eventually return to the surface-water body as a domestic wastewater flow. Higher salinity of the local seawater source will reduce the desalination plant recovery and hence, increase the cost of producing desalinated seawater.

A single desalination plant discharging concentrate to a bay or gulf would not have a material impact on the salinity of the receiving body. However, multiple desalination plants operating over a very long time could cause increases in salinity. Surface-water bodies that are most vulnerable are those with limited circulation (i.e., hydraulic connection to the oceans) and large present and anticipated future seawater desalination capacities. The Mediterranean Sea, Arabian Gulf, and Red Sea are particularly vulnerable to salinity increases, which have or will be exacerbated by decreasing freshwater inflows and warmer temperatures due to climate change. Bashitialshaaer et al. [122] estimated that brine discharge will increase the salinities of the Arabian Gulf, Mediterranean Sea, and Red Sea, by some extra 2.24, 0.81 and 1.16 g/L by the year 2050.

Increased salinities could also impact more sensitive elements of the biota, especially some of the single cell plankton. Marine organisms have varying sensitivity to changes in salinity. Osmotic conformers are organisms that have no mechanism to control osmosis and therefore their cells conform to the same salinity as their environment [123]. Large increases in salinity in the surrounding marine environment cause water to flow out of the cells of these organisms, which could lead to cell dehydration and ultimately to cell death. Organisms that can survive in only a narrow salinity range are referred to as “stenohaline”.

Osmotic regulators, on the contrary, can control the salt content and hence the osmotic potential within their cells despite variations in external salinity [123]. Most marine fish, reptiles, birds and mammals are osmotic regulators. Salinity tolerances of marine organisms vary, but some shellfish (scallops, clams, oysters, mussels or crabs) and reef-building corals, not already stressed from abnormally high salinities (e.g., Arabian Gulf), are able to tolerate very high salinities [123]. An additional factor when considering environmental impacts of concentrate discharges is the mobility of the organisms. Mobile organisms may simply move away from areas of higher salinity without adverse impacts. Sessile organisms (e.g., plants and corals) are more vulnerable to salinity changes.

Table 2
Physical and chemical properties of concentrate from seawater desalination facilities. (Modified from Maliva and Missimer [118]).

Physical properties	
Salinity	Up to 65,000–85,000 mg/L
Temperature	Ambient seawater temperature. Specific cases + 5 to + 10 °C
Plume density	Negatively buoyant
Dissolved oxygen	If wells used, typically below ambient seawater DO because of the low DO content of the source water. If open intake used, approximately the same as the ambient seawater DO concentration.
Biofouling control additives and by-products	
Chlorine	If chlorine or other oxidants are used to control biofouling, these are typically neutralized before the water enters the membranes to prevent membrane damage.
Halogenated organics	Typically low content before harmful levels
Removal of suspended solids	
Coagulants	May be present is conditioned and the filtered backwash is not treated (e.g., iron-III-chloride). May cause effluent coloration if not equalized prior to discharge.
Coagulant aids	May be present if source water is conditioned and the filter back-wash water is not treated (e.g., polyacrylamide).
Scale-control additives	
Antiscalants	Typically low concentrations below toxic levels
Acid (HCl or H_2SO_4)	Not present (reacts with seawater to form harmless compounds, i.e. water and chlorides or water and sulfates: the acidity is consumed by the naturally alkaline seawater, so the discharge pH is typically similar or slightly lower than that of ambient seawater)
Foam control additives	
Antifoaming agents	Not present (treatment not required)
Contaminants caused by corrosion	
Metals	May contain elevated concentration of iron, chromium, nickel, molybdenum if low quality stainless steel is used in the facility.
Cleaning chemicals	
Cleaning chemicals	Alkaline (pH 11–12) or acidic (pH 2–3) solutions with additives such as: detergents (e.g., EDTA), oxidants (e.g., sodium perborate), biocides (e.g., formaldehyde)

3.2.1. Discharge mixed with power plant cooling water

Collocating desalination plants at power plant sites using once through seawater cooling is common in that it avoids the need to permit and construct new desalination plant intakes and outfalls, while also improving on the desalination plant membrane performance in certain cases due to the readily available warmer water. Collocation of power and desalination plants may also be economically advantageous to the power plant host, by providing the power plant host with a customer with a very favorable power use profile—a steady and continuous power demand and a high power load factor. The continuous high-quality power demand allows the power plant to operate its electricity generation units at their optimal regime, which in turn reduces the overall costs of power generation [123].

The major environmental benefits of collocation are that the impacts of constructing a dedicated outfall are avoided and the power plant cooling water discharge flow dilutes the concentrate. For collocation to be viable, the power plant cooling water discharge flow must be greater than the proposed desalination plant intake flow, and the power plant outfall configuration must be adequate to prevent recirculation of concentrate into the desalination plant intake [117,124,125]. Also, the once-through cooling system for the power plant must be permanent, because in recent years the State of California has banned this practice which could complicate the permitting and operating processes for both existing and new SWRO facilities.

The thermal discharge of power plants is lighter than the ambient ocean water because of its elevated temperature. As a result, the discharge tends to float on the ocean surface. The heavier saline discharge from the desalination plant tends to draw the lighter cooling water downward and thereby, engages the entire depth of the ocean water column into the heat and salinity dissipation process and accelerates its mixing and blending into the ambient seawater [117].

3.2.2. Discharge pipe equipped with diffusers

The most commonly employed subsea modern outfall design is a discharge pipe with either multiport or rosette diffusers [126] (Fig. 8). Diffusers are essentially a series of nozzles that increase the mixing of concentrate within the seawater column and prevent accumulation on the seafloor. A diffusor system is separated from what is considered unimpaired seawater by a mixing zone, whose outer boundary is some specified dilution ratio (e.g. a 5% increase in salinity from that naturally in the waters around the point of discharge). The size and shape of the mixing zone depends upon the discharge rate, diffuser system design, concentrate salinity, and prevailing marine currents. Numerous studies have evaluated various aspects of the environmental impacts associated with marine outfalls using diffuser systems (Fig. 9).

Fernández-Torquemada et al. [128,129] investigated the impacts of concentrate discharge in the Alicante area (SE Spain), where a SWRO desalination plant was brought in operation in September 2003. Echinoderms are stenohaline osmoconformer organisms that are expected to be very sensitive to high salinity discharges. One year after the start of plant operation, echinoderms disappeared from the localities affected by the desalination concentrate. An increase of echinoderms in a northern locality may have been related to their movement away from the brine. When the desalination concentrate was diluted with seawater prior to discharge, a recovery of echinoderm densities in these localities occurred. Monitoring of a sea grass (*Posidonia oceanica*) meadow showed that, during the first year of monitoring, the desalination plant caused a regression of the meadow and decreased vitality of the plants. Fernández-Torquemada et al. [128,129] concluded that it was important to minimize the impact of desalination plants by locating the discharge away from the seagrass and to maximizing the dilution of the concentrate, which could be achieved by the dilution with local seawater prior to discharge.

Laboratory and field studies in the Spanish Mediterranean Sea showed that desalination effluent can adversely affect sea grass (*Posidonia oceanica*) [113]. It was recommended that brine discharges not exceed neither 38.5 ppt of salinity in any point in the sea grass meadow for > 25% of the observations (on an annual basis) nor 40 ppt of salinity in any point of the meadow for > 5% of those observations.

Raventós et al. [130] examined the possible effects of discharges from a desalination plant on the macrobenthic community inhabiting the sandy substratum off the coast of Blanes in Spain (NW Mediterranean) using multivariate and univariate analyses. No significant impacts to macrobenthic communities attributable to the brine discharges from the desalination plant were found. The failure to record any impact suggested that it was possible that the high natural variability is a characteristic feature of bottoms of this type. Further, the rapid dilution undergone by the hypersaline concentrate upon leaving the discharge pipe appeared to avoid significant harm to the microbenthic community.

Riera et al. [131,132] investigated the impacts of concentrate discharges from the Las Burras SWRO desalination plant, located south of Gran Canaria, on the abundance, assemblage structure and diversity of benthic meiofauna and macrofauna. Collection of samples took place twice at 0, 15 and 30 m away from the discharge point. Total meiofaunal and macrofaunal abundances and species diversity increased with increasing distance from the concentrate discharge point. The magnitude of differences was inconsistent between successive years which were suggested to be the result of a change in particle size distribution of the sediments between sampling events.

Del-Pilar-Ruso et al. [133] examined the use of polychaete assemblages as indicators for the impacts of concentrate discharges on

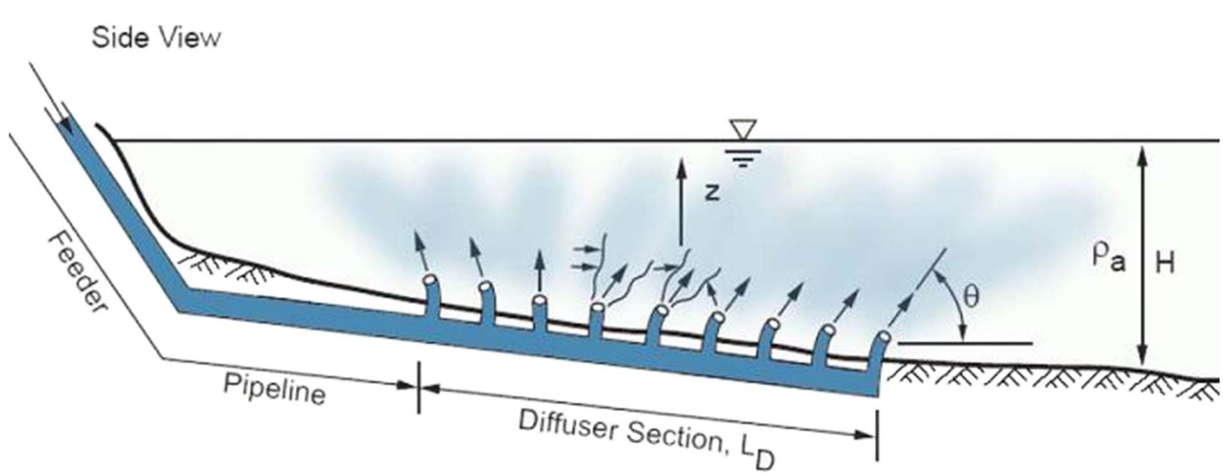

Fig. 8. Diagram showing a multiport diffuser system mounted at the end of a discharge pipe. (From Bleninger and Jirka [127]).

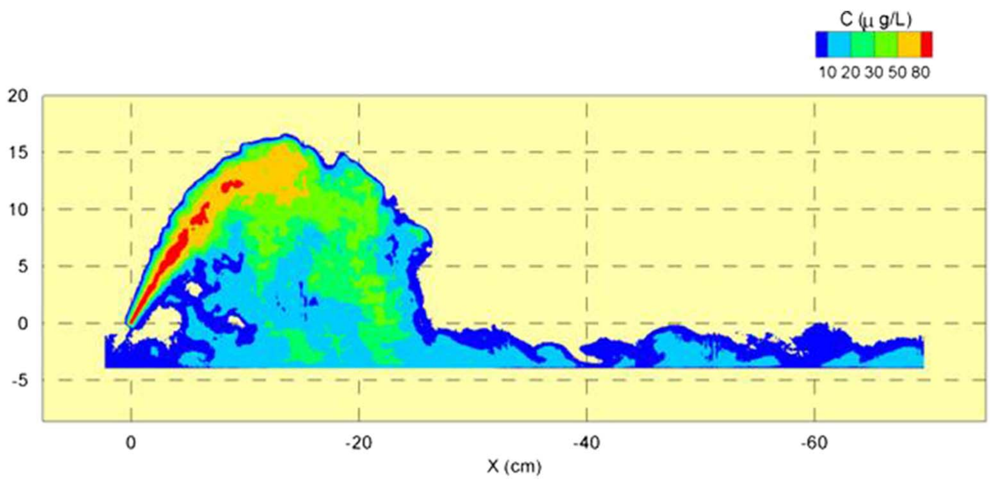

Fig. 9. Diagram showing a model of changes in concentration of an SWRO plant discharge using a diffuser discharge system.
(From Roberts [126]).

benthic communities at San Pedro del Pinatar (SE Spain). Discharge started in 2006 and produced a significant decrease in abundance, richness and diversity of polychaete families at the location closest to the discharge, where salinity reached 49 ppt. In 2010, a diffuser was deployed at the end of the pipeline in order to increase the mixing and thus reduce the impact on benthic communities. After implementation of this mitigation measure, the salinity measured close to discharge was < 38.5 ppt and a significant recovery in polychaete richness and diversity was detected, to levels similar to those before the discharge.

Viskovich et al. [134] investigated the impacts of three years of concentrate discharge from the Gold Coast Desalination Plant in Southeast Queensland (Australia). Since beginning operation in March 2009, the environmental impact of the discharge of concentrate on benthic infauna was reported to be minimal. Natural seasonal factors had a greater effect on the differences in the composition of benthic assemblages between impact and control sites. The authors concluded that in assessing impacts on benthic assemblages it is extremely relevant to understand natural fluctuations in the structure and composition of assemblages preferably at multiple control sites, rather than just relying on monitoring of impact sites alone.

Chemicals (coagulants and antiscalants) in discharged concentrate may also impact benthic communities in addition to salinity effects. Laboratory mesocosm experiments and in situ sampling by Belkin et al. [121] demonstrated that coagulants and polyphosphate-based antiscalants can reduce the diversity and compositions of bacterial and eukaryotic communities.

In general, the available data indicate that inadequately diluted concentrate discharges can locally impact benthic communities, but the effects are geographically restricted to the areas of higher salinity compared to the ambient salinity.

3.2.3. Single-pipe discharge to deep water

Concentrate from SWRO desalination plants approaches twice the salinity of ocean water. Due to its greater salinity, and thus density, discharged concentrate tends to sink and slowly spread out along the ocean floor. The simplest subsea outfall design is a single-pipe discharge with an inclined open end that is oriented upwards. The jet of concentrate ascends, as it leaves the pipe under pressure, and then descends under gravity to the seafloor [126]. This type of outfall design has been commonly used for municipal wastewater ocean outfalls.

Single-pipe discharges can be installed deep enough so that impacts to sensitive shallow-water ecosystems (e.g., reefs) and coastal environments (e.g., beaches) are avoided. An environmental disadvantage of single-pipe discharges is that there is relatively low degree of dilution due to the point discharge design and the usually low-energy conditions at depth. However, if the seabed is steeply inclined into a submarine canyon or over a cliff into very deep water, the concentrate discharge stream with cascade downward across the bottom and mix, caused dilution and lessening of downstream impacts.

3.3. Alternative discharge concepts

3.3.1. Discharge to injection wells

Injection well systems can be an environmentally benign method for the disposal of desalination concentrate provided that a suitable injection zone is locally present that is capable of efficiently accepting the plant concentrate flow. Injection wells can be divided into two types based on the fate of the injected waters; shallow wells in which injected waters will eventually seep out offshore and deep wells in which the injected water essentially remains permanently underground [135]. Shallow injection wells are used in some coastal settings, such as the Bahamas, Cayman Islands, and Barbados [136,137] where a transmissive limestone is present at depth than can efficiently accept plant concentrate flows. The injection zone can crop out below the sea at depth, typically on the order of a kilometer or more offshore. The concentrate undergoes dispersive mixing (dilution) during aquifer transport and, upon reaching the subcrop, is expected to slowly seep out over a broad area where it undergoes additional mixing in the marine environment. Depending on the effective porosity of the injection zone and surrounding aquifer, the concentrate may never leave the groundwater system.

Deep injection wells are commonly used for the disposal of desalination concentrate (brackish water RO), municipal wastewater, and other liquid wastes in South Florida. The liquid wastes are injected into an extremely high transmissivity fractured dolomite zone referred to as the “boulder zone” [138–140]. Deep well disposal is also used for disposal of desalination concentrate at the Kay Bailey Hutchison Desalination Plant in El Paso, Texas and will be used for San Antonio Water System (Texas) Brackish Water Desalination System. The injection zones are located 100s of m below land surface and the injected fluids are expected to remain permanently underground (at least on a human time scale) with no associated environmental impacts.

Properly located, designed, and constructed injection wells should allow for concentrate disposal to have no environmental impacts. However, adverse impacts to groundwater resources could occur if injection wells leak or inadequate confinement is present above the injection zone to prevent vertical migration of injected wastes into aquifers used for potable water supply. In the United States, the construction and operation of injection well systems is controlled by strict Underground Injection Control regulations, which include periodic mechanical integrity testing to detect casing leaks and other defects that could allow for vertical migration. Monitoring of water quality and pressure below aquifers considered underground sources of drinking water (USDWs) are also required in some states. Groundwater modeling of potential migration of injected liquid wastes in South Florida demonstrated the desalination concentrate will tend not to migrate upwards because of relatively high salinity and density [140]. There are no known instances of injection of desalination concentrate causing contamination of an aquifer used for potable water supply. The use of injection well disposal of SWRO is currently limited for use by small to moderate capacity SWRO systems.

Small or moderate capacity SWRO facilities installed in interior locations away for the coast could inject concentrate under high pressure into low permeability rocks or deep basement rocks, similar to the techniques used by the petroleum industry for disposal of produced water. This type of disposal can have some seriously environmental and human impact.

In recent years, induced seismicity from underground injection has become a serious concern, especially related to oil and gas production activities in the mid-continent of the United States. According to the U. S. Geological Survey [141], between the years 1973–2008, there was an average of 21 earthquakes of magnitude three and larger in the central and eastern United States. This rate has ballooned to over 600 M3 + earthquakes in 2014 and over 1000 in 2015. Through August 2016, over 500 M3 + earthquakes have occurred in 2016.

It is important to emphasize that most cases of induced seismicity are not a concern. Numerous earthquakes occur that are not felt at land surface and do not cause damage. Only a handful of the tens of thousands of waste disposal wells in the United States have been linked to induced or triggered earthquakes [142]. The National Research Council [143] reported that only a few of 150,000 of injection wells permitted in the US have associated “felt” events. The most severe were the earthquakes in 1966 associated with Rocky Mountain Arsenal injection well near Denver [144,145] and the 2011 earthquakes near Prague, Oklahoma, which magnitudes of 5.0 through 5.7 [146].

The basic causes of induced seismicity are well understood. Earthquakes are triggered by a weakening of pre-existing fault by increases in pressure. A fault remains locked as long as the applied shear stress is less than the strength of the contact. Increased pore pressure results in a decrease in the effective normal stress across the fault and thus, the strength of the contact is exceeded which allows movement [147,148,142].

Numerous studies have concluded that the triggering of earthquakes by increased pore pressure requires that the rocks in the fault zone are critically stressed to near their breaking point prior to injection and that the increased pressure must reach a suitably oriented fault [149,150,143,151]. There appears to be an increased potential for induced seismicity when increasing pressures caused by injection are transmitted to underlying crystalline basement [152,153].

Many areas in which earthquakes occurred have deep injection wells that are operated at high pressures (> 100 bars/1500 psi), which is typically not the case for injection well systems used for desalination concentrate disposal. Concentrate disposal wells usually use high-transmissivity injection zones, in which injection can occur without large increases in pressure [154]. The location and depth of injection wells appears to also impact their potential for inducing seismicity. Zhang et al. [151] concluded that the risks of induced seismicity can be reduced by avoiding injection zones in which there is not a bottom seal (isolation from bedrock). SWRO concentrate discharges will rarely encounter induced seismicity issues unless located within interior continental regions.

3.3.2. Discharge to beach and offshore galleries and trenches

Infiltration trenches, consisting of perforated pipes shallowly buried parallel to a beach, are used for concentrate disposal for some very small desalination systems in the Caribbean. The concentrate slowly seeps toward the offshore in a diffuse manner and is quickly dispersed without impacting the benthic environment. Infiltration trenches need to be constructed so as to not adversely impact animal life, especially nesting sea turtles. Once constructed, the infiltration trench system site could be restored and would have minimal aesthetic impacts or effects on land use.

Beach gallery disposal systems have been proposed for some seawater desalination facilities in coastal California. While this disposal option could be viable for large-capacity systems, the possibility exists that water could discharge through the top of the gallery rather than traveling only horizontally through the shallow sediments. If located offshore, the impacts of the dense water moving along or ponding by density on the bottom could adversely impact sessile organisms or infauna within the bottom sediments, such as mollusks. These impacts could be severe and would likely be unacceptable. An alternative would be to design the galleries within the intertidal zone (surf zone), where breaking waves would rapidly mix the concentrate with ambient quality seawater. This mixing would essentially eliminate impacts to marine life. The only other impacts would occur during construction when a dewatered excavation would be necessary to install the discharge pipes and gallery structure. The facility would be underground and would not be visible to people visiting the beach or swimming in the surf. Also, this disposal system would require the beach to be relatively stable otherwise the system could be exhumed or become submerged offshore. In the latter case, impacts to benthic marine organisms are possible. In the case of accretion, ponding of the concentrate at land surface is a possibility. For any gallery system, detailed aquifer characterization and modeling are needed to determine if the option is feasible and to optimize the design.

3.3.3. Dilution by forward osmosis using domestic wastewater

Osmosis is the natural process involving the potential fluid flow from high salinity to low salinity across a membrane. Desalination technology has focused largely on reverse osmosis technology, in which the osmotic pressure across a membrane is overcome by applying pressure to a high salinity solution (i.e., seawater or brackish water). The applied pressure forces freshwater to flow through the membrane leaving the salt behind as concentrate. Forward osmosis involves using a draw solution of higher salinity on one side of a membrane and a fresher fluid on the opposite side of the membrane. The osmotic gradient pulls the fresher fluid into the higher salinity fluid. Desalination concentrate can be used as a draw solution because of its high salinity.

Forward osmosis using municipal wastewater could be used to dilute desalination concentrate to salinities closer to or below ambient seawater concentrations, which could reduce the environmental impacts from concentrate discharge. The forward osmosis process would also reduce the volume of the wastewater stream. Forward osmosis is a very low energy process with the main technical challenges being the achievement an adequate flux and managing membrane clogging. The use of forward osmosis is currently limited to mostly experimental applications and it is not yet cost competitive with other treatment options [155].

3.3.4. Zero liquid discharge

Concentrate volume can be reduced through additional desalination and evaporation steps so that virtually all water is removed, leaving behind a dry crystalline residue. Zero liquid discharge (ZLD) technologies are the subject of considerable interest because they are potentially an environmentally acceptable means for concentrate disposal at sites (particularly in inland areas) where other more conventional concentrate disposal options are not viable [156–159,102,160,161]. Concentrate volume reduction techniques include thermal evaporators (brine concentrators) and secondary BWRO desalination. The former can produce high purity water. Techniques to reduce the concentrate to a solid include evaporation ponds, crystallizers, and spray dryers. A commonly proposed process sequence involves (after primary RO desalination) a concentrate treatment to prevent scaling during subsequent secondary RO desalination and then brine concentration and evaporation [156].

The final brine concentration and evaporation steps tend to be very expensive in that they are highly energy intensive, with associated large carbon footprints, or, in the case of evaporation ponds, require large land areas. An additional consideration is the disposal or, ideally, beneficial use of produced salt. Assuming a seawater salinity of 35 g per liter, a seawater volume of 3785 m^3 of seawater contains about 132,490 kg of salt. Hence, due to economic and salt disposal considerations, ZLD is likely viable for only small capacity brackish water desalination systems and perhaps very small capacity SWRO desalination facilities. Perhaps the best opportunities for development of cost-effective zero discharge facilities would be to either discharge to a natural environment that is unaffected by the saline water (e.g., sabkhas) or to find some offsetting economic value for the dry residue [118].

Recovery of commercial salts in ZLD systems has been thoroughly investigated and can only be viable if the desalination plant is located in an area in which there is an industrial demand for the salt or extracted chemicals. Jeppesen et al. [162] concluded that it may be financially feasible to recover, sodium, magnesium, potassium, rubidium, phosphorus, indium, cesium, and germanium from ZLD systems. As many of these metals become more valuable, the cost of extraction may become sufficiently profitable to offset the cost of desalination with ZLD.

The principle environmental impacts of ZLD are the high energy consumption and thus carbon footprint of engineered systems and potential impacts from the disposal of large volumes of salts (e.g., leakage of very high salinity waters from landfills). Evaporation ponds impact large land areas and depending, upon their location, could impact local groundwater. Blowing of salt dust and salinization of nearby soils is also a concern for evaporation ponds.

3.4. Research on seawater concentrate disposal

There is considerable ongoing research in the development of new diffusor systems and in modification of existing diffuser designs [126]. Also, linking near-field and far-field modeling of concentrate plumes is becoming more sophisticated to allow better projections to be made and to locate the discharge point where a maximum degree of mixing will occur [163].

Another issue is the acquisition of detailed monitoring data on active plumes to assess changes in concentration. Until recent years, this has been a difficult task because stations had to be chosen where vertical profiles could be collected using conventional oceanographic techniques. Jones et al. [164] have described the use of untethered gliders to collect continuous water quality information over large grid areas of the offshore to actually view the movement of plumes. This technique will greatly increase the understanding of dense plume migration and impacts to the environment.

4. Discussion and conclusions

Desalination of seawater has become a vital source of freshwater in many semiarid to hyperarid regions of the world, particularly in the Middle East-North Africa (MENA) region. The rise of the SWRO desalination process has made desalination more energy-efficient and economically viable. The key issue is now to make SWRO as environmentally-friendly as possible. There are solutions to make desalination more "green" now and in the future using various techniques available.

SWRO desalination can occur without impacting the environment to a significant degree based on proper pre-design environmental impact investigations and providing mitigation for impacts when necessary. Perhaps a more standard environmental impact statement scope could be adopted to bring a more uniform international approach to the issue. Of particular importance is the scientific approach to evaluating the impacts of impingement and entrainment, which is currently done is a large number of different ways that yield vastly differing conclusions. Also, the predesign environmental analysis of concentrate discharge should be made more uniform and should involve the most sophisticated near-filed and far-field models when evaluating large capacity SWRO plant discharges.

There is general agreement that the two most important environmental issues in SWRO desalination are impingement and entrainment of marine organisms, causing a reduction in fish, invertebrates and the ichthyoplankton in general and the impacts of the discharge of the concentrate on benthic organisms on and beneath the seabed. There is no agreement as to the threshold for impacts to be considered significant or unacceptable. A no impact threshold for any human activity, while superficially attractive, is typically not practical or economically viable. Clearly, sound science is needed to develop and implement measures that protect the environmental integrity of marine environments and avoid damage to local economies (e.g., fisheries and tourism), while still allowing needed freshwater to be economically obtained through SWRO.

Conventional shoreline and offshore open-ocean intakes have the highest impact on the marine ecosystem. A critical issue in the environmentally-friendly design of these facilities is to site them at locations where marine productivity is low to produce minimal impacts. Predesign measurements of the populations of impingable and entrainable organisms are needed to create a baseline for evaluation of potential impacts. Passive wedgewire screen or subsurface intakes should be used instead of surface-water intakes to reduce the impacts caused by impingement and entrainment wherever possible based on reasonable economic viability. However, when impingement or particularly entrainment impacts cannot be avoided, mitigation measures, such as habitat creation or restoration or restocking the sea with critical species of concern can be employed. Such measures have been found to be economically viable and allow desalination facilities to operation without significant impacts.

Discharge of concentrate in coastal SWRO systems can be conducted in an environmentally-friendly manner by conducting proper pre-design investigations, including evaluations of the living stock of marine organisms both in the water column and the benthic environment. Proper pre-design investigations need to take into consideration the natural seasonal variations in populations and possible changes caused by concentrate discharges. By developing baseline information, data collected during operation of a SWRO facility can be continuously evaluated to ascertain whether any true impacts are occurring. If impacts are found, modifications of the discharge system can be made. The key issue during SWRO operation is to perform monitoring to a degree that it is useful in evaluating impacts because many monitoring systems are properly designed and implemented so that they cannot be viably tied to true impact analysis. During this time of global climate change, environmental impact analysis is becoming more complex, so monitoring systems must use stations located beyond the impact zone to understand changes to the ecosystem not associated with the SWRO system operation.

The current base available technologies for minimizing concentrate discharge impacts are dilution near the point of discharge to reduce the density contrast between the receiving water and the discharge water, and the use of diffusor systems to induce rapid mixing. Both approaches require an area of mixing between the discharge point and a defined radius that allows mixing. Regulatory agencies must provide a reasonable "mixing zone" based on real science and not on an arbitrary basis. Diffusor systems can be carefully designed to meet virtually any reason mixing zone boundary regulation.

Where concentrate discharge impacts are deemed to be significant based on the best possible design and operation scenarios, either pre- or post-operation of the desalination facility, mitigation measures can be implemented to compensate for the impacts. The same general strategy used for mitigation of impingement and entrainment can be used. For benthic impacts, the creation of habitat to increase the population of impacted organisms outside of the discharge impact zone is a reasonable method. The introduction of benthic organism larvae or restocking may be as effective in environmental impacts deduction for affected swimming organisms, but not benthic organisms. The restocking strategy would be based on actual monitoring data.

It is concluded that SWRO desalination in all capacity ranges along shorelines of the world can be designed and operated without causing significant environmental impacts. However, proper environmental impacts analyses must be made before design and proper monitoring must be conducted during operation to continuously assess environmental conditions. This would allow adjustments to be made that can be used to alleviate actual impacts. For SWRO systems developed for use in interior locations, much research will be required to minimize impacts of concentrate discharge, especially on zero discharge systems options.

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