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Overview of seawater concentrate disposal alternatives

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ABSTRACT

This article discusses the available alternatives for ocean concentrate disposal, site specific factors involved in the selection of the most viable alternative for a given project, and the environmental permitting requirements and studies associated with their implementation. The article focuses on the three most widely used alternatives for ocean discharge of concentrate: direct discharge through new outfall; discharge through existing wastewater treatment plant outfall; and co-disposal with the cooling water of existing coastal power plant. Key advantages, disadvantages, environmental impact issues and possible solutions are presented for each discharge alternative. Results from recent salinity tolerance and toxicity study completed at the Carlsbad, California seawater desalination demonstration plant for a variety of sensitive marine organisms are presented. The practical implementation of this study along with other methods for analysis of the environmental impact of ocean discharges from large seawater reverse osmosis plants is illustrated with case study examples.

1. Introduction

Seawater desalination is becoming increasingly popular for production of fresh potable water as many coastal municipalities and utilities worldwide are looking for new, reliable and drought-proof local sources of water supply. One of the key limiting factors for the construction of new seawater desalination plants is the availability of suitable conditions and location for disposal of the high-salinity side-stream generated during the desalination process commonly referred to as concentrate or brine. This article provides an overview of key environmental impacts of seawater desalination plant concentrate discharges and discusses alternatives and case-study examples for successful environmental impact minimization and mitigation.

The environmental impacts of seawater desalination plant operations have many common features with these of conventional water treatment plants for fresh water production from surface waters. Similar to conventional water treatment facilities, desalination plants have waste stream discharge which may impact the aquatic environment. Both desalination facilities and conventional water treatment plants use many of the same chemicals for source water conditioning, and therefore, have similar waste streams associated with the disposal of spent conditioning chemicals and source water solids.

Despite many of the similarities of their environmental impacts, desalination plants have several distinctive differences as compared to conventional water treatment plants: (1) they use approximately two times more source water to produce the same amount of fresh water; (2) they generate discharge of elevated salinity which typically has one-and-a-half to two times higher TDS concentration than that of the source seawater; and (3) they use eight to ten times more electricity for production of the same volume of fresh water.

The environmental impact of desalination plant operations should be assessed in the context of the environmental impacts of water supply alternatives that may be used instead of desalination [1]. Desalination projects are typically driven by the limited availability of alternative lower-cost water supply resources such as ground water or fresh surface water (rivers, lakes, etc.). However, damaging long-term environmental impacts may also result from continuation of those conventional water supply practices. For example over-pumping of fresh water aquifers over the years in a number of areas worldwide (i.e., the San Francisco Bay Delta in Northern California and fresh water aquifers, and rivers and lakes in northern Israel and Spain which supply water to sustain agricultural and urban centres in the southern regions of these countries), has resulted in a measurable environmental impacts of the traditional fresh water resources in such regions.

Such long-term water transfers have impacted the eco-balance in the fresh water resources to an extent that the long-term continuation of such water supply practices may result in significant and irreversible damage of the ecosystems of the traditional fresh water supply sources. In such cases, the environmental impacts of the construction and operation of new seawater desalination projects should be weighed

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against the environmentally damaging consequences from the continuation/expansion of the exiting fresh-water supply practices.

2. Concentrate characterization and quality

Concentrate is generated as a by-product of the separation of the minerals from the source water used for desalination. This liquid stream contains most of the minerals and contaminants of the source water and pretreatment additives in concentrated form. The concentration of minerals and contaminants in the concentrate from seawater desalination plants is usually approximately two times higher than that in the source water depending upon the recovery of the desalination plant. If chemicals such as coagulants, antiscalants, polymers or disinfectants, are used for seawater pretreatment, some or all of these chemicals may reach or may be disposed of along with the plant discharge concentrate.

The quantity of concentrate is largely a function of the plant recovery, which in turn is proportional to the total dissolved concentration (TDS)/salinity of the source water. Seawater desalination plant recovery is typically limited to 40 to 65% and the TDS level of concentrate from seawater desalination plants is usually in a range of 65,000 to 85,000 mg/l. The amount of particles, total suspended solids (TSS) and biochemical oxidation demand (BOD) in the concentrate are typically below 5 mg/l because these constituents are removed by the plant pretreatment system. However, if plant pretreatment waste streams are discharged along with the concentrate, the blend may contain elevated turbidity, TSS and occasionally BOD. Acids and scale inhibitors added to the desalination plant source water are rejected by the seawater reverse osmosis (SWRO) membranes in the concentrate and also have impact on its overall mineral content and quality. Often scale inhibitors contain phosphates or organic polymers.

The composition of the desalination plant concentrate is primarily determined by the composition of the source water (feed) and the efficiency (fractional recovery) of the membrane treatment system. The concentrate TDS can be calculated in terms of the feed and permeate TDS and the fractional plant recovery (Y):

$$TDS_{\text{concentrate}} = TDS_{\text{feed}}\left(\frac{1}{1-Y}\right) - \frac{Y \times TDS_{\text{permeate}}}{100(1-Y)}$$

where, $Y = \frac{\text{Permeateflowrate}}{\text{Feedflowrate}}$.

By neglecting the permeate salinity (which is usually about 1%) of feed salinity for seawater reverse osmosis (SWRO)), the concentrate TDS can be more simply defined as:

$$TDS_{\text{concentrate}} = TDS_{\text{feed}}\left(\frac{1}{1-Y}\right).$$

The brine concentration factor is then defined as $TDS_{\text{concentrate}}/TDS_{\text{feed}}$.

Since SWRO membranes reject some chemicals better than others, variable concentration factors may apply for specific chemicals. Exactly how the brine concentration factor impacts the disposal of concentrate depends mainly on the means of disposal. In some cases, volume minimization (high brine concentration factor) is preferred, whereas in cases where the concentrate is to be discharged to waterways, achieving lower TDS concentration is usually more important than low volume [2].

The brine concentration factor is primarily limited by the increasing osmotic pressure of the generated concentrate. For reverse osmosis seawater desalination systems this limit is approximately 65–80 parts per thousand (ppt). The combined effect of membrane rejection and source water concentration typically renders the optimum fractional recovery from a single pass SWRO system as low as 35–45% for seawater reverse osmosis plants. Therefore, concentration factors for single-pass seawater desalination processes are often in a range of 1.5 to 1.8. Some of the most efficient (high pressure) two-pass SWRO systems have overall recoveries as high as 55 to 60%.

For example, the Perth Seawater Desalination Plant in Australia is a two-pass RO plant operating with a first pass recovery of 45% and a second pass recovery of 90%. This corresponds to an overall recovery of 43% and brine concentration factor of approximately 1.7 times. Based on source water TDS of 33,000–37,000 mg/L the plant produces average RO concentrate TDS of approximately 65,000 mg/L.

For comparison, the considerably lower salt concentrations of brackish groundwater and municipal wastewater tend to allow for much greater fractional recoveries. Brackish groundwater RO plants typically operate at recoveries of 75 to 90%, corresponding to a concentration factor of 4.0 to 10. Wastewater treatment plants typically have recoveries of 80–85% for nanofiltration (concentration factor 5.0–6.7 assuming complete TDS rejection) and 70–85% for reverse osmosis (concentration factors 3.3–6.7).

As indicated previously, seawater desalination plants produce concentrate which is usually 1.5 to 2 times higher than the concentration of total dissolved solids (TDS or salinity) of the ambient seawater. When returned to the ocean without dilution, the concentrate may have a negative impact on the aquatic environment in the area of the discharge unless managed adequately. This impact is very site-specific and it depends to a great extent on the salinity tolerance of the marine organisms inhabiting the water column and benthic environment influenced by the discharge as well as the rate of its dissipation in the ambient seawater.

3. Mechanisms of concentrate impact on the environment

Typically, concentrate from seawater desalination plants using open ocean intakes has the same color, odor, oxygen content and transparency as the source seawater from which it was produced, and increase or decrease in salinity will not change its physical characteristics or aesthetic impact on the environment.

There is no relation between the level of salinity and biological or chemical oxygen demand of the desalination plant concentrate — over 80% of the minerals that encompass concentrate salinity are sodium and chloride and they are not a prime food source or a macro or micro nutrients for aquatic organisms.

Salinity contained in concentrate discharges from seawater desalination plants is not of anthropogenic origin as compared to the pollutants contained in discharges from industrial or municipal wastewater treatment plants or water reclamation plants. The minerals in the desalination plant concentrate discharge have originated from the same source to which they usually are returned along with the desalinated water in the form of wastewater treatment plant effluent discharge. Since in most coastal urban centers seawater desalination plant intakes and wastewater treatment plant discharges are well within a 10 to 30-killometer radius, the long-term regional environmental impact of seawater concentrate on the ocean is equivalent to the effect of naturally occurring evaporation.

Ocean water evaporation tends to concentrate salinity in shallow near-shore ocean bays and lagoons during the high-temperature dry periods of the year and to dilute them during the rainy periods of the year keeping a near net zero sum salinity increase year-round. Similarly, seawater desalination plants temporarily remove a small portion of ocean water, produce fresh drinking water, which in turns is returned to the ocean via the ocean discharges of the wastewater treatment plants located in the vicinity of the desalination plant, thereby re-uniting the separated fresh water and salts, both of which originated from the ocean, within a period much shorter than the seasonal interval which returns the water removed from the ocean by evaporation. This regional close-cycle balance between seawater intakes and discharges is often poorly understood and the environmental impact of concentrate discharges is commonly considered in isolation from the balancing dilution impact of the desalinated water returned in the vicinity of its origin and of the location where desalination plant concentrate is discharged.

Concentrate disposal may also have impacts other than direct changes in salinity. In some circumstances, concentrate plume density may lead to increased stratification reducing vertical mixing [3]. This stratification may in turn reduce dissolved oxygen level in the water column or at the bottom of the ocean in the area of the discharge, which may have ecological implications.

4. Key environmental issues and considerations for surface water discharges

The main challenges associated with selecting the most appropriate location for desalination plant's ocean outfall discharge are: finding an area devoid of endangered species and stressed marine habitats; identifying a location with strong ocean currents that allows quick and effective dissipation of the concentrate discharge; avoiding areas with frequent naval vessel traffic which could damage the outfall facility and change mixing patterns; and identifying a discharge location in relatively shallow waters, that at the same time is close to the shoreline, in order to minimize outfall construction expenditures. Key environmental issues and considerations associated with concentrate disposal to surface waters include:

- Salinity increase beyond the tolerance thresholds of the species in the area of the discharge;
- Concentration of metals and radioactive ions to harmful levels;
- Concentration and discharge of nutrients that trigger change in marine flora and fauna in the area of the discharge;
- Compatibility between the composition of the desalination plant concentrate and receiving waters (ion-imbalance driven toxicity);
- Elevated temperature from thermal desalination processes; and
- Disturbance of bottom marine flora and fauna during outfall installation.

The main issues which will need to be addressed during the feasibility evaluation of disposal of seawater desalination plant concentrate to the ocean include: (1) evaluation of discharge dispersion and recirculation of the discharge plume to the plant intake; (2) evaluation of the potential for whole effluent toxicity of the discharge; and (3) assessment whether the discharge water quality meets the numeric and qualitative effluent water quality standards applicable to the point of discharge; (4) establishment of the marine organism salinity tolerance threshold for the site-specific conditions of the discharge location and outfall configuration in order to design the outfall for dilution which meets this threshold within a short distance from the point of discharge.

4.1. Evaluation of concentrate dispersion rate and area

The main purpose of the evaluation of the concentrate dispersion rate from the point of discharge is to establish the size of the zone of initial dilution (ZID) required to dissipate the discharge salinity plume to down to within 10% of ambient seawater TDS levels; and to determine the TDS concentrations at the surface, mid-level of the water column, and at the ocean bottom in the ZID. The TDS concentration fields at these three levels are then compared to the salinity tolerance of the marine organisms inhabiting the surface (mostly plankton), the water column (predominantly invertebrates), and the ocean bottom sediments in order to determine the impact of the concentrate salinity discharge on these organisms.

The discharge salinity field in the ZID and the ZID boundaries is established using hydrodynamic modeling. This modeling allows determining the most suitable location, design configuration and size of the ocean outfall, and diffusers if a new outfall is needed, or to assess the feasibility of using existing wastewater or power plant outfall facilities. The model selected for determining the boundaries of the desalination plant discharge should be used to define the concentrate plume dissipation boundaries under a variety of outfall and diffuser configurations and operational conditions. Evaluation of concentrate dispersion and recirculation for large seawater desalination plants usually requires sophisticated discharge plume analysis and is completed using various computational fluid dynamics (CDF) software packages tailor-made for a given application [1,3,4].

4.2. Whole effluent toxicity evaluation

Whole effluent toxicity testing is an important component of the comprehensive evaluation of the effect of the concentrate discharge on the aquatic life. Completion of both acute and chronic toxicity testing is recommended for the salinity levels that may occur under worst-case combination of conditions in the discharge. Use of at least one species endogenous to the targeted discharge is desirable. In the case of concentrate discharge through an existing wastewater treatment plant outfall, at least one species of the echinoderms taxa (i.e., urchins, starfish, sand dollars, or serpent stars) is recommended to be tested for a worst case scenario blend of concentrate and wastewater effluent (typically, maximum wastewater effluent flow discharge combined with average concentrate flow).

4.3. Compliance with numeric effluent discharge water quality requirements

The key parameters that should be given attention regarding concentrate compliance with the numeric effluent discharge water quality standards are: TDS, metals, turbidity and radionuclides. At present, most countries do not have numeric standards for total TDS discharges and the maximum allowable salinity discharge regulatory requirements are established for the site-specific conditions of a given project [5–7].

Because metal content in ocean water is naturally low, compliance with numeric standards for toxic metals usually does not present a challenge. However, concentrate co-discharge with wastewater treatment plant effluent may occasionally present a concern, because wastewater plant effluent contains metal concentrations that may be higher than these in the ambient ocean water. Similar attention to the metal levels in the combined discharge should be given to co-disposal of power plant cooling water and concentrate, especially if the power plant equipment leaches metals such as copper and nickel, which may then be concentrated in the desalination plant discharge. If the desalination plant has a pretreatment system that uses coagulant (such as ferric sulfate or ferric chloride), the waste discharges from the source water pretreatment may contain elevated concentrations of iron and turbidity that must be accounted for when assessing their total discharge concentrations.

Radionuclide levels in the ocean water often exceed effluent water quality regulatory standards and the RO system concentrate is likely to contain elevated gross alpha radioactivity. This condition is not unusual for both Pacific and Atlantic Ocean water and must be well documented with adequate water quality sampling in order to avoid potential permitting challenges.

One important challenge with all concentrate water quality analyses is that most of the laboratory analysis guidelines worldwide are developed for testing freshwater rather than for seawater or high-salinity concentrate. The elevated salt content of the concentrate samples could interfere with the standard analytical procedures and can often produce erroneous results. Therefore, concentrate analysis must be completed by an analytical laboratory experienced with and properly equipped for seawater analysis. The same recommendation applies for the laboratory retained to complete the whole effluent toxicity testing and source water quality characterization using techniques designed for saline water.

4.4. Salinity tolerance of marine organisms

Environmentally safe disposal of concentrate produced by seawater desalination plants is one of the key factors determining the viability, size and costs of a given project. The maximum total dissolved solids concentration that can be tolerated by marine organisms living in the desalination plant outfall area is defined as the salinity tolerance threshold and depends on the type of aquatic organisms inhabiting the area of the discharge and the period of time these organisms are exposed to the elevated salinity [3]. These conditions are very site-specific for the area of each desalination outfall and therefore, a general rule of thumb for determining the salinity tolerance threshold is practically impossible to develop.

Marine organisms have varying sensitivity to elevated salinity. Some organisms are "osmotic conformers", i.e., they have no mechanism to control osmosis and therefore, their cells conform to the same salinity as their environment. Large increase in salinity in the surrounding marine environment due to concentrate discharge causes water to leave the cells of these organisms which could lead to cell dehydration and ultimately to cell death.

Marine organisms which can naturally control the salt content and hence the osmotic potential within their cells despite variations in external salinity are known as "osmotic regulators". Most marine fish, reptiles, birds and mammals are osmotic regulators and employ a variety of mechanisms to control cellular osmosis. Salinity tolerances of marine organisms vary, but few shellfish (scallops, clams, oysters, mussels or crabs) or reef-building corals are able to tolerate very high salinities.

Many marine organisms are naturally adapted to changes in seawater salinity. These changes occur seasonally and are mostly driven by the evaporation rate from the ocean surface, by rain/snow deposition and runoff events and by surface water discharges. The natural range of seawater salinity fluctuations could be determined based on information from sampling stations located in the vicinity of the discharge and operated by national, state or local agencies and research centers responsible for ocean water quality monitoring. Typically, the range of natural salinity fluctuation is at least $\pm 10\%$ of the average annual ambient seawater salinity concentration. The "10% increment above ambient ocean salinity" threshold is a conservative measure of aquatic life tolerance to elevated salinity. The actual salinity tolerance of most marine organisms is usually significantly higher than this level and often exceeds 40 ppt [1].

4.4.1. Method for salinity tolerance evaluation

A novel method to identify the salinity tolerance of the aquatic life inhabiting the area of a desalination plant discharge was developed at the Carlsbad seawater desalination demonstration plant in California. This method includes the following four key steps:

1. Determination of the Test Salinity Range;
2. Identification of Site-Specific Test Species Inhabiting the Discharge Area;
3. Biometrics Test at Average Discharge Salinity;
4. Salinity Tolerance Test At Varying Concentrate Dilution Levels.

4.4.1.1. Determining test salinity range. The first step of the salinity tolerance evaluation (STE) method is to define the minimum and maximum TDS concentrations that are projected to occur in the area of the discharge after the startup of desalination plant operations. This salinity range should be established taking under consideration the effect of mixing and associated dilution in the area of the discharge as a result of the site-specific natural hydrodynamic forces in the ocean (currents, winds, tidal movements, temperature differences, etc.) as well as the mixing energy introduced with the desalination plant discharge diffuser system. If the desalination plant concentrate is diluted with other discharge (i.e., cooling water from power plant or wastewater treatment plant effluent) prior to the exit from the outfall into the ocean, this additional dilution should also be accounted for when establishing the salinity range for which the salinity tolerance of the aquatic species is assessed.

Because of the complexity of the various factors that impact the mixing and dilution of desalination plant concentrate with the ambient ocean water, especially for medium and large projects (i.e. projects with discharge volume of 4000 m^3/day or higher), the actual salinity range that would occur in the area of the discharge should be determined based on hydrodynamic modeling [8,9].

As a minimum, the salinity test concentrations should range from that at the middle of the water column and the middle of the zone of initial dilution (ZID) to the maximum seabed salinity concentration at the edge of the ZID [8]. The ZID is defined as the area of the ocean within 300 m from the point of the desalination plant discharge.

4.4.1.2. Identifying test species. The purpose of the second step of the STE method is to identify the most sensitive, site-specific species that would be indicative of the salinity tolerance of the aquatic flora and fauna in the area of the desalination plant discharge. These species are used for the Biometrics and Salinity Tolerance Tests. At least three species should be selected for the tests: one representative for the fish population in the area, one for the invertebrate population and one for macro-algal population (i.e., kelp, red algae, etc.), if such species are present and occur in significant numbers [10–12].

The selection of the specific test species should be completed by an expert marine biologist who is very familiar with the site-specific aquatic flora and fauna in the area of the desalination plant discharge. The test species should be selected based on: (1) presence and abundance in the area; (2) environmental sensitivity (i.e., endangered/protected marine species are first priority); (3) sensitivity to salinity in the range projected to occur in the discharge; and (4) significance in terms of commercial and recreational harvesting/fishing.

4.4.1.3. Biometrics Test. The purpose of the Biometrics Test is to track how well the indicative test species will handle a long-term steady-state exposure to the elevated average discharge salinity that will occur in the middle of the zone of initial dilution after the desalination plant is in operation [13]. The Biometrics Test should be completed in a large marine aquarium (test tank) in which the desalination plant concentrate is blended with ambient seawater to obtain salinity not to be exceeded in the middle of the ZID in the ocean for at least 95% of the time. This salinity level should be maintained in the aquarium for the duration of the test. In addition, a second aquarium (control tank) of the same size and number and type of test marine organisms should be employed, with the main difference that this tank should be filled up with ambient seawater collected from the area of the discharge. The control tank should be operated in parallel with the test tank and observations from this tank are used as a base for comparison and statistical analysis.

Once the salinity in the aquariums is set to target levels, they should be populated with the selected test species and key biometric parameters (appearance; willingness to feed; activity; weight gain/loss, and gonad production) of these species should be monitored frequently (minimum every two days) by expert marine biologist over a prolonged period of time (minimum of three months, preferably five or more months). Percent weight gain/loss and fertilization for one or more of the test and control organisms should be measured as well. At the end of the test, the qualitative and quantitative biometric parameters of the marine species in the test and control tanks should be compared to identify if the species exhibit statistically significant differences — especially in terms of weight gain/loss and fertilization capabilities.

4.4.1.4. Salinity Tolerance Test. The main purpose of the Salinity Tolerance Test is to establish if the selected test species will survive the extreme salinity conditions that may occur within the ZID and on the edge of the ZID, and if the test organisms will be able to retain their capacity to reproduce after exposure to these conditions for a length of time that is expected to occur in full scale operations under worst-case scenario. The test species should be exposed to several blends of concentrate and ambient seawater that may occur within the range of the discharge salinities. The low end of the range should be the average salinity in the ZID (mid-depth) and the high end should be the maximum salinity above the seabed at the boundary of the ZID (i.e., 300 m from the point of the discharge). In general, discharge salinity is expected to decrease with increase of the distance from the point of concentrate discharge and to increase with depth. The rate of decrease of concentrate salinity from the point of discharge depends on the hydrodynamic conditions in the vicinity of the discharge.

Similar to the Biometrics Test, this experiment includes two sets of aquariums for each salinity concentration — a series of test tanks, one for each test salinity level, and a control tank. The duration of the Salinity Tolerance Test should be determined by the length of occurrence of the worst-case discharge salinity scenario. This duration should be established based on the results from the hydrodynamic modeling of the desalination plant discharge. Usually, extreme salinity discharge conditions are not expected to continue for more than two weeks. However, if this is likely in specific circumstances, than the length of the study should be extended accordingly. Starting from the low end of the salinity concentration, individual test tanks should be set for salinity increments of 1000 mg/L to 2000 mg/L to cover the range, until the maximum test salinity concentration is reached.

4.4.2. Case study — application of STE Procedure for the Carlsbad Desalination Project

The STE procedure described above was applied to assess the discharge impact of the 190,000 m^3/day Carlsbad seawater desalination project, located in Southern California, USA. This project includes direct connection of the desalination plant intake and discharge facilities to the discharge outfall of an adjacent coastal power generation plant using seawater for once-through cooling (see Fig. 1). The power plant has a total of five power generators and depending on the number of units in operation pumps between 760,000 m^3/day and 3,100,000 m^3/day of cooling water through the condensers. The warm cooling water from all condensers is directed to a common discharge tunnel and lagoon leading to the ocean. The full-scale desalination facility, is planned to tap into this discharge tunnel for both desalination plant feed water and for discharging high-salinity concentrate downstream of the intake area.

Water collected from one end of the power plant discharge canal will be conveyed to the desalination plant to produce fresh water, and the concentrate from the desalination plant will be returned into the same discharge canal, approximately 270 m downstream from the point of intake. The desalination plant concentrate, containing approximately two times the salinity of the source seawater (68 ppt vs. 33.5 ppt) will be blended with the remaining cooling water discharge of the power plant and conveyed to the ocean for disposal.

The salinity range of the mixed discharge from the Carlsbad seawater desalination plant and the power plant will be between 35 to 40 ppt. The average salinity in the middle of the ZID is projected to be 36 ppt. Therefore, the Biometrics Test was completed for this salinity, while the test range for the Salinity Tolerance Test covered 37 ppt to 40 ppt in 1 ppt increments. Both tests were executed by marine biologist very familiar with the local flora and fauna in the area of the future desalination plant discharge [13].

A list of the 18 marine species selected for the Biometrics Test for the Carlsbad Project is presented in Table 1. The Salinity Tolerance Test was completed using three local species which are known to have highest susceptibility to stress caused by elevated salinity [4,7]: (1) the Purple sea urchin *(Stronglyocentroutus purpuratus)*, Fig. 2; (2) the Sand dollar *(Dendraster excentricus)*, Fig. 3; and (3) the Red Abalone *(Haliotis rufescens)*, Fig. 4.

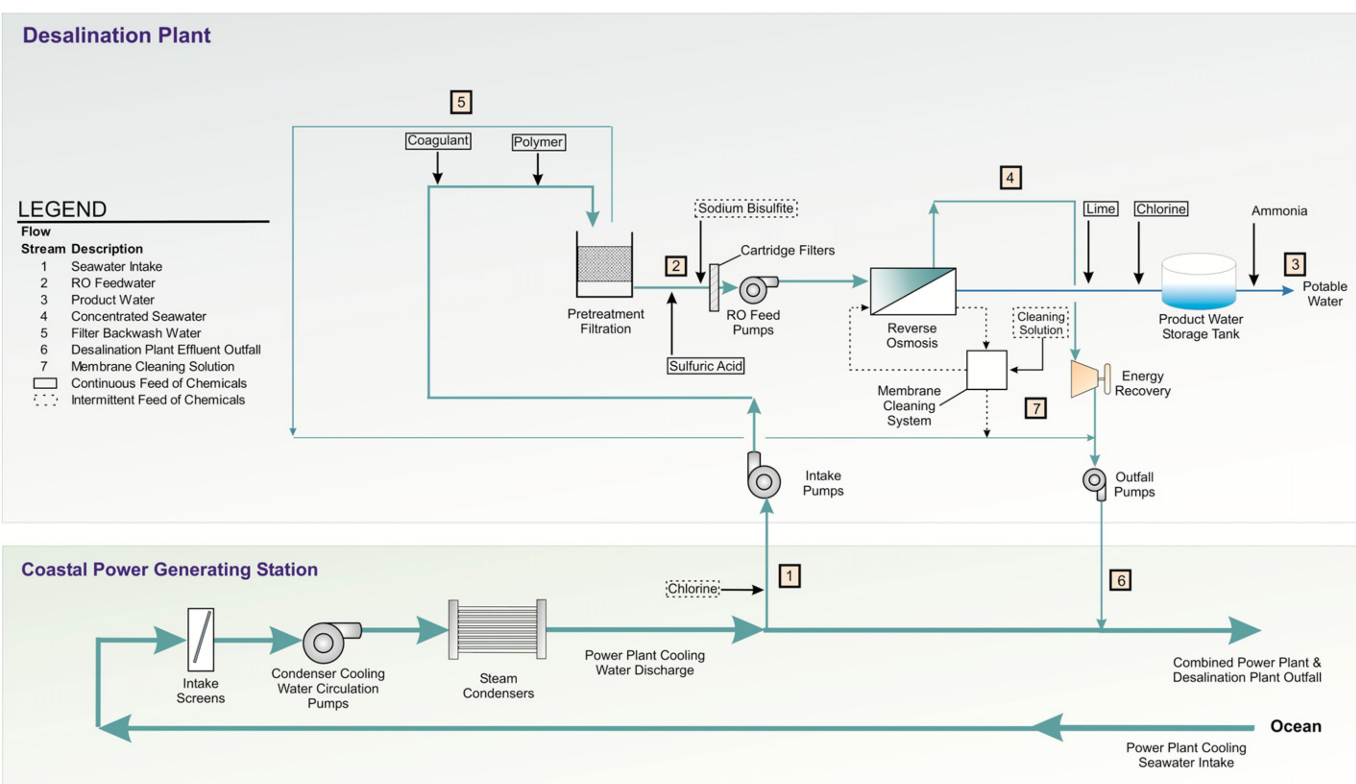

Fig. 1. Schematic of Carlsbad seawater desalination plant.

Table 1
Marine species used for the Carlsbad Biometrics Test.

	Scientific name	Common name	Number of individuals per species
1	*Paralichthys californicus*	California halibut	5 juveniles
2	*Paralabrax clathratus*	Kelp bass	3 juveniles
3	*Paralabrax nebulifer*	Barred sand bass	3 juveniles
4	*Hypsoblennius gentilis*	Bay blenny	5
5	*Strongylocentrotus franciscanus*	Red sea urchin	4
6	*Strongylocentrotus purpuratus*	Purple sea urchin	14
7	*Pisaster ochraceus*	Ochre sea star	3
8	*Asterina miniata*	Bat star	3
9	*Parastichopus californicus*	Sea cucumber	2
10	*Cancer productus*	Red rock crab	2
11	*Crassadoma gigantea*	Giant rock scallop	3
12	*Haliotis fulgens*	Green abalone	3
13	*Megathura crenulata*	Giant keyhole limpet	3
14	*Lithopoma undosum*	Wavy turban snail	3
15	*Cypraea spadicea*	Chestnut cowrie	3
16	*Phragmatopoma californica*	Sand castle worm	1 colony
17	*Anthropleura elegantissima*	Aggregating anemone	4
18	*Muricea fruticosa*	Brown gorgonian	1 colony
19	*Haliotis rufescens*	Red Abalone	5
20	*Dendraster excentricus*	Sand Dollar	5

Fig. 3. Sand dollar.

The Biometrics Test was continued for a period of 5.5 months. The results of this test are summarized in Table 2, and indicate that all organisms remain healthy throughout the test period. No mortality was encountered and all species showed normal activity and feeding behavior. The appearance of the individuals remained good with no changes in coloration or development of marks or lesions.

The duration of the Salinity Tolerance Test for the Carlsbad project was 19 days. The results of this test are given in Table 3 and show that both Sand dollars and Red abalones had 100% survival in all test tanks and in the control tank. One individual of in the Purple sea urchin group died in each of the test tanks and one died in the control tank. Therefore, the adjusted survival rate for the Purple sea urchins was also 100%. These test results confirm that the marine organisms in the discharge zone would have adequate salinity tolerance to the desalination plant discharge in the entire range of operations of the desalination plant (i.e., up to 40 ppt). All individuals of the three tested species behaved normally during the test, exhibiting active feeding and moving habits.

The Biometrics and Salinity Tolerance Tests were completed in 110-gallon marine aquariums (Fig. 5).

In summary, the Salinity Tolerance Evaluation Method applied to the Carlsbad seawater desalination project confirms that the elevated salinity in the vicinity of the plant discharge would not have a measurable impact on the marine organisms in this location and these organisms can tolerate the maximum salinity of 40 ppt that could occur in the discharge area under extreme conditions.

Additional acute and chronic toxicity studies completed subsequently for this project using the United States Environmental Protection Agency's standard whole effluent toxicity (WET) test [14] has confirmed the validity of the new STE method. WET testing using Abalone *(Haliotis ruefescens)* has showed that the chronic toxicity threshold for these species occurs for TDS concentration of over 40 ppt. An acute toxicity test completed using another standard WET species, the Topsmelt *(Atherinops affinis)*, indicates that the salinity in the discharge can reach over 50 ppt on a short-term basis (one day or more) without impacting this otherwise salinity-sensitive species.

The results of the salinity tolerance evaluation completed for the Carlsbad desalination project were well accepted by the state and local regulatory agencies (San Diego and Santa Ana Regional Water Quality Control Boards (RWQCBs) in California) responsible for environmental protection in California. These results were also used for the environmental review and permitting of the 190,000 m^3/day Huntington Beach desalination project, which is developed by Poseidon Resources in

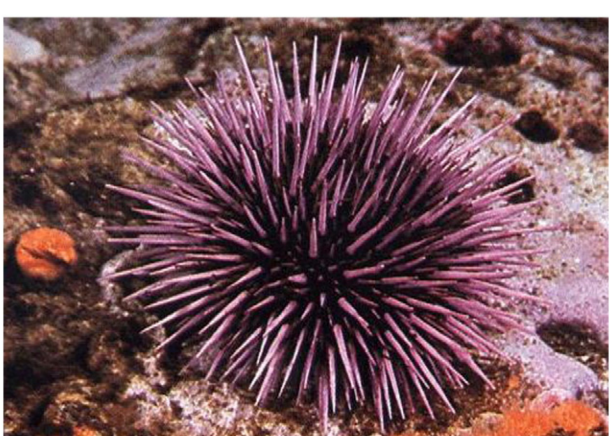

Fig. 2. Purple sea urchin.

Fig. 4. Red abalone.

Table 2
Overall condition and average weight gain of Biometrics Test species.

Scientific Name	Common Name	Avg.% wt. change (grams)	% wt. change (Control group)	Sig.	Appearance and Feeding
Paralichthys californicus	California halibut	91.3	96.9	n/s	Strong
Paralabrax clathratus	Kelp bass	114.3	104.8	n/s	Strong
Paralabrax nebulifer	Barred sand bass	106.8	113.5	n/s	Strong
Hypsoblennius gentilis	Bay blenny	120.0	107.1	n/s	Strong
Strongylocentrotus franciscanus	Red sea urchin	2.8	2.4	n/s	Strong
Strongylocentrotus purpuratus	Purple sea urchin	7.9	7.2	n/s	Strong
Pisaster ochraceus	Ochre sea star	3.8	4.6	n/s	Strong
Asterina miniata	Bat star	2.8	3.1	n/s	Strong
Parastichopus californicus	Sea cucumber	-2.2	2.3	n/s	Strong
Haliotis fulgens	Green abalone	9.6	7.7	n/s	Strong
Megathura crenulata	Giant keyhole limpet	5.1	4.7	n/s	Strong
Lithopoma undosum	Wavy turban snail	3.9	2.4	n/s	Strong
Cypraea spadicea	Chestnut cowrie	0.6	1.0	n/s	Strong
Anthropleura elegantissima	Aggregating anemone	115.9	48.9	n/s	Strong
Haliotis rufescens	Red abalone	9.2	7.8	n/s	Strong
Dendraster excentricus	Sand dollar	3.5	4.5	n/s	Strong

Note: n/s = not significant and Sig. = Statistical significance.

parallel with the Carlsbad project. In August 2006 both projects received permits to discharge their concentrate to ocean.

5. Seawater concentrate disposal alternatives

The three alternatives used most widely for disposal of concentrate from seawater desalination plants at present are: direct discharge through a new ocean outfall; discharge through existing wastewater treatment plant outfall; and co-disposal with cooling water of existing power plant (collocation). Each of these concentrate management alternatives has advantages, challenges and potential environmental impacts on the aquatic environment [15–17]. Overview of key challenges and solutions associated with the disposal of concentrate generated in seawater desalination plants is presented below.

5.1. Direct discharge through new ocean outfall

5.1.1. Description

Discharge of seawater desalination plant concentrate through a new ocean outfall is widely used for projects of all sizes. Over 90% of the large seawater desalination plants in operation today dispose their concentrate through a new ocean outfall specifically designed and build for that purpose. Examples of large membrane reverse osmosis (RO) seawater desalination plants with ocean outfalls for concentrate discharge are 330,000 m^3/day plant in Ashkelon, Israel (Fig. 6); the 136,000 m^3/day Tuas Seawater Desalination Plant in Singapore; the 64,000 m^3/day Larnaka Desalination Facility in Cyprus, and majority of the large plants in Spain, Australia and the Middle East.

The main purpose of ocean outfalls is to dispose of the plant concentrate in an environmentally safe manner, which in practical terms means to minimize the size of the zone of discharge in which the salinity is elevated outside of the typical range of tolerance of the marine organisms inhabiting the discharge area. The two key options available to accelerate concentrate mixing from an ocean outfall discharge is to either rely on the naturally occurring mixing capacity of the tidal (surf) zone or to discharge the concentrate beyond the tidal zone and to install diffusers at the end of the discharge outfall in order to improve mixing.

Although open-ocean near-shore tidal zones usually carry a significant amount of turbulent energy and usually provide much better mixing than the end-of-pipe type of diffuser outfall system, such zones have limited capacity to transport and dissipate the saline discharge load into the open ocean. If the mass of the saline discharge exceeds the threshold of the tidal zone's salinity load transport capacity, the excess salinity would begin to accumulate in the tidal zone and could ultimately result in a long-term salinity increment in this zone beyond the level of tolerance of the aquatic life in the area of the discharge. Therefore, the tidal zone is usually a suitable location for salinity discharge only when it has adequate capacity to receive, mix and transport this discharge into the open ocean.

The site-specific salinity threshold mixing/transport capacity of the tidal zone in the area of the desalination plant discharge can be determined using hydrodynamic modeling. If the desalination plant total dissolved solids discharge load is lower than the tidal zone threshold mixing/transport capacity, then concentrate disposal to this zone is preferable and much more cost effective than the use of a long

Table 3
Results of Carlsbad desalination project Salinity Tolerance Test.

Species observed	Salinity (ppt)	Mortality	Elapsed time to First mortality (Days)
Red abalones	33.5 (Control Tank)	0	N/A
Red abalones	37	0	N/A
Red abalones	38	0	N/A
Red abalones	39	0	N/A
Red abalones	40	0	N/A
Sand dollars	33.5 (Control Tank)	0	N/A
Sand dollars	37	0	N/A
Sand dollars	38	0	N/A
Sand dollars	39	0	N/A
Sand dollars	40	0	N/A
Purple sea urchins	33.5 (Control Tank)	1	1
Purple sea urchins	37	1	1
Purple sea urchins	38	1	4
Purple sea urchins	39	1	4
Purple sea urchins	40	1	6

Note: N/A — not applicable.

Fig. 5. Carlsbad Biometrics Test Tank.

Fig. 6. Tidal zone discharge of the Ashkelon SWRO Plant, Israel.

open outfall equipped with a diffuser system. Example of discharge in the tidal zone is that of the Ashkelon seawater desalination plant (Fig. 6).

For small plants (i.e., plants with production capacity of 1000 m^3/day or less), the ocean outfall is typically constructed as an open-ended (sometimes perforated) pipe that extends several hundred meters into the tidal zone of the ocean. This type of discharges usually relies on the mixing turbulence of the tidal zone to dissipate the concentrate and to quickly bring the discharge salinity to ambient conditions.

A comprehensive study on the effect of the disposal of tidal-zone seawater desalination plant discharges on near-shore communities in the Caribbean was completed in 1998 by the Southwest Florida Water Management District and the University of South Florida [18]. This study has undertaken a detailed analysis of the environmental impacts of the discharges from seven existing seawater desalination plants in the Caribbean with plant capacities between 170 m^3/day and 6000 m^3/day and discharge salinities between 45 ppt and 56 ppt. All of the plants use SWRO technology for salt separation and have been in operation for at least 4 years before the study was completed. The study has found no statistically significant impact of the desalination plant discharges on the benthic marine life, sea grass, microalgae and micro and macro-invertebrates inhabiting the area of the discharge.

Another example of facility which discharges its concentrate in the near-shore tidal zone is the 25,000 m^3/day Maspalomas II Desalination Plant in the Canary Islands, Spain [19]. This desalination plant has two concentrate outfalls, which extend 300 m away from the shore. The discharge depth is 7 to 8 m. The outlet of the discharge outfalls does not have diffusers and the mixing between the concentrate and ambient seawater is mainly driven by the velocity of the discharge and the fact that the discharge is located in an area with naturally occurring underwater currents of high intensity. The Maspalomas discharge has relatively high salinity of the concentrate (90,000 mg/L) and the discharge area is inhabited by sea grass, which is also habitat for fish and other marine species. The salinity of the discharge is dissipated down to 38 ppt within 60 ft from the discharge point. Based on environmental study of the discharge area, are not significantly affected by the desalination plant discharge.

Most of the ocean outfalls for large seawater desalination plants usually extend beyond the tidal zone. Large ocean outfalls are equipped with diffusers in order to provide the mixing necessary to prevent the heavy saline discharge plume to accumulate at the ocean bottom in the immediate vicinity of the discharge. The length, size and configuration of the outfall and diffuser structures for large desalination plants are typically determined based on hydrodynamic or physical modeling of the discharge diffuser structure for the site specific conditions of the outfall location [20,21].

Example of open ocean outfall discharging salinity outside of the tidal zone is the outfall of the 130,000 m^3/day Perth seawater desalination plant in Australia. The Perth desalination plant outfall is 1.2 m in diameter and has a 160-m long, 40-port diffuser where the ports are spaced at 5-m intervals with 0.22 m nominal port diameter, located 470 m offshore, at a depth of 10 m, adjacent to the plant in Cockburn Sound [22].

The diffuser is a bifurcated double-T-arrangement and incorporates a discharge angle of 60°. This design was adopted with the expectation that the plume would rise to a height of 8.5 m before beginning to sink due to its elevated density. It was designed to achieve a plume thickness at the edge of the mixing zone of 2.5 m and, in the absence of ambient cross-flow, 40 m laterally from the diffuser to the edge of the mixing zone.

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The discharge permit for the Perth desalination plant requires that certain dissolved oxygen levels are met in order for the plant to operate. Furthermore, a minimum of 45-time dilution must be achieved at the edge of the mixing zone, defined in terms of a 50 m distance from the diffuser [24]. The Perth plant discharge is located in Cockburn Sound, which is a shallow and enclosed water body with very limited water circulation, which frequently experiences naturally occurring low oxygen levels.

Extensive real-time monitoring was undertaken in Cockburn Sound for the first year of operations (2006) to ensure the model predictions are correct and that the marine habitat and fauna are protected. This monitoring included measurement of dissolved oxygen levels via sensors on the bed of the Sound [25]. In addition to the dye study, the project team has completed series of toxicity tests with a number of species in larval phase to determine the minimum dilution ratio needed to be achieved at the edge of the zone of initial dilution [23]:

- 72 hour macro-algal germination assay using the brown kelp *Ecklonia radiata*,
- 48 hour mussel larval development using *Mytilis edulis*,
- 72 hour algal growth test using the unicellular algae *Isochrysis galbana*,
- 28 Day copepod reproduction test using the copepod *Gladioferens imparipes*
- 7 day larval fish growth test using the marine fish pink snapper, *Pagrus auratus*.

The results of these toxicity tests indicate that the plant concentrate dilution needed to be achieved at the edge of the zone of initial dilution in order to protect the sensitive species listed above is 9.2:1 to 15.1:1, which readily achieved by the outfall structure designed to deliver a mixing ratio of 45:1.

All monitoring results since the Perth desalination plant began operation in 2006 indicate that the desalination plant operations have no measurable impact on the aquatic life in the area of the plant discharge and that the oxygen levels in Cockburn Sound were not altered by the plant discharge.

5.1.2. Key issues and considerations

The main challenges associated with selecting the most appropriate location for the desalination plant's ocean outfall discharge are: finding area void of endangered species and stressed marine habitats; identifying location with strong ocean currents that allows quick and effective dissipation of the concentrate discharge; avoiding areas with busy naval vessel traffic, which could damage the outfall facility and change mixing patterns; and selecting discharge location in relatively shallow waters that at the same time is close to the shoreline in order to minimize outfall construction expenditures.

Key advantages related to using a new ocean outfall are that this type of concentrate disposal option allows to accommodate practically any size of seawater desalination plant and that it provides for more freedom in selecting plant location, as compared to the other two disposal approaches where existing wastewater plant or power plant outfalls are used and therefore, the desalination plant location and capacity are most often driven by the location and size of the existing outfall facilities.

Principal challenges of this discharge alternative are that it usually is very costly and that its implementation requires extensive and lengthy environmental and engineering studies. Depending on the site-specific conditions, the costs for a new ocean outfall are significant, and they typically range from 10 to 30% of the total desalination plant construction expenditures. The higher end of this range applies for large desalination plants (i.e. facilities of fresh water production capacity 50,000 m^3/day, or more).

5.2. Direct discharge through existing wastewater treatment plant outfall

5.2.1. Description

The key feature of this combined discharge method is the benefit of accelerated mixing that stems from blending the heavier than ocean water concentrate with the lighter wastewater discharge. Depending on the volume of the concentrate and on how well the two waste streams are mixed prior to the point of discharge, the blending may allow to reduce the size of the wastewater discharge plume and dilute some of its constituents. Co-discharge with the lighter-than-seawater wastewater effluent would also accelerate the dissipation of the saline plume by floating this plume upwards and expanding the volume of the ocean water with which it mixes.

Direct discharge through an existing wastewater treatment plant outfall has found a limited application to date. The largest plant in operation at present which practices co-discharge of desalination plant concentrate and wastewater effluent is the 200,000 m^3/day Barcelona SWRO facility in Spain [26]. This disposal method had also been practiced during the short-lived operations of the Santa Barbara seawater desalination plant in California. There, the desalination plant concentrate discharge volume was comparable to that of the wastewater treatment plant effluent discharge (i.e., 20,000 m^3/day).

5.2.2. Key issues and considerations

Key considerations related to the use of existing wastewater treatment plant outfall for direct seawater desalination plant concentrate discharge are: the availability and cost of wastewater outfall capacity and the potential for whole effluent toxicity of the blended discharge that may result from ion imbalance of the blend of the two waste streams. Two other very important issues are: the potential need for modification of the outfall system of the existing seawater desalination plant due to altered buoyancy of the concentrate–wastewater mix; and the compatibility of the diurnal fluctuation of the secondary effluent flow with the diurnal fluctuation of the concentrate discharge flow.

First, for this concentrate disposal option to be feasible there has to be an existing wastewater treatment plant in the vicinity of the desalination plant, and second, this plant has to have available extra outfall discharge capacity. Third, the fees associated with the use of the wastewater treatment plant outfall have to be reasonable, and fourth, the wastewater treatment plant utility that would allow the use of their outfall for concentrate discharge has to accept the arrangement of handling and separation of liability for environmental impacts of the blended discharge between the owner of the desalination plant and the owner of the wastewater treatment plant. Usually, this beneficial combination of conditions is not easy to find, especially for discharging large seawater concentrate volumes.

Bioassay tests completed on blends of desalination plant concentrate and wastewater effluent from the El Estero wastewater treatment in Santa Barbara, California indicate that this blend can exhibit toxicity on fertilized sea urchin (*Strongylocentrotus purpuratus*) eggs. Parallel tests on desalination plant concentrate diluted to similar TDS concentration with seawater rather than wastewater effluent did not show such toxicity effects on sea urchins. Long-term exposure of red sea urchins on the blend of concentrate from the Carlsbad seawater desalination demonstration plant and ambient seawater discharged by the adjacent Encina power plant confirm the fact that sea urchins can survive elevated salinity conditions when the discharge is void of wastewater.

The most likely factor causing the toxicity effect on the sensitive marine species is the difference in ratios between major ions (calcium, magnesium, sodium, chloride and sulfate) and TDS that occur in the wastewater effluent–concentrate blend as compared to the concentrate–seawater blend and the ambient ocean water.

The seawater reverse osmosis (SWRO) membranes reject all key seawater ions at approximately the same level. As a result, the ratios between the concentrations of the individual key ions that contribute to the seawater salinity and the TDS of the concentrate are approximately the same as these ratios in the ambient seawater. As a result, marine organisms are not exposed to conditions of ion-ratio imbalance, if this concentrate is directly disposed to the ocean.

Since wastewater effluent has fresh water origin, and fresh water often has very different ratios of the same key ions to TDS, blending this effluent with seawater concentrate may yield a discharge which has ion ratios significantly different from these of the ambient seawater. This ion make-up shift (ion imbalance) caused by blending of the two waste streams may cause toxicity effect of the concentrate–wastewater blend on sensitive marine species. Therefore, the ion-imbalance effect has to be investigated in order to ascertain that marine organisms in the vicinity of the discharge are not negatively affected by the combined wastewater–concentrate discharge.

Use of existing wastewater treatment plant outfalls for concentrate discharge has the key advantages of avoiding costs and environmental impacts associated with the construction of new outfall for the seawater desalination plant. Mixing of the negatively buoyant wastewater discharge with the heavier than ocean water concentrate, promotes the accelerated dissipation of both the wastewater plume which tends to float to the ocean surface, and the concentrate which tends to sink towards the ocean bottom. In addition, often concentrate contains metals, organics and pathogens which are of an order of magnitude lower levels than these in the wastewater discharge, which helps reducing the overall waste discharge load of the mix.

Although the use of existing wastewater treatment plant outfalls or concentrate discharge to the sanitary sewer system may seem attractive for its simplicity and low construction costs, this disposal method has a number of limitations. Due to the potential toxicity effects of the concentrate–wastewater effluent blend the direct discharge of the seawater concentrate through existing wastewater discharge outfalls may be limited to relatively small concentrate discharge flows. Similarly, indirect discharge of the concentrate through the wastewater collection system may be severely constrained or practically impossible especially if the wastewater plant effluent is reused for irrigation of salinity-sensitive crops and ornamental plants.

Often, the seawater desalination plants are operated at a constant production rate and as a result they produce concentrate discharge with little or no diurnal flow variation. On the other hand, wastewater treatment plant availability for dilution of the desalination plant concentrate typically follows a distinctive diurnal variation pattern. Since adequate protection of marine life requires a certain minimum concentrate dilution ratio in the ZID to be maintained at all times, during periods of low wastewater effluent flows (i.e., at night) the amount of concentrate disposed by the desalination plant (and therefore, the plant production capacity) may be limited by the lack of secondary effluent for blending. In order to address this concern, the desalination plant operational regime and capacity may need to be altered in order to match the wastewater effluent availability patterns or diurnal concentrate storage facility may need to be constructed at the desalination plant.

As indicated previously, another issue to be considered when feasibility of using existing wastewater outfalls is evaluated relates to the change of the buoyancy of the mixed wastewater effluent–concentrate plume and the ability of the wastewater diffuser to provide proper mixing. Since the heavier concentrate discharge will reduce the buoyancy of the wastewater effluent, the initial momentum and mixing energy that are provided by the existing effluent diffuser structure will be altered. Depending on the volumes of the concentrate discharge and the wastewater discharge, the existing wastewater outfall may need to be modified (i.e., by closing diffuser nozzles or by changing diffuser configuration and direction of the nozzles) in order to accommodate the wastewater concentrate discharge. Therefore, the impact of the concentrate discharge on the ability of the existing wastewater outfall to provide adequate dispersal of the mixed concentrate–wastewater plume should be evaluated by hydrodynamic modeling for the size specific conditions of a given project.

An additional concern of combining wastewater and desalination plant discharges is that the high salinity may cause wastewater contaminants and other particles to aggregate in particles of different sizes than they would otherwise. This could result in an enhanced sedimentation or some of the metals and solids contained in the wastewater treatment plant effluent, and could potentially impact benthic organisms and phytoplankton in the vicinity of the discharge.

5.3. Concentrate discharge to sanitary sewer

5.3.1. Description

Discharge to the nearby wastewater collection system is one of the most widely used methods for disposal of concentrate from small brackish and seawater desalination plants worldwide [3]. This indirect wastewater plant outfall discharge method however, is only suitable for disposal of very small volumes of concentrate into large-capacity wastewater treatment facilities mainly because of the potential negative effects of the concentrate's high TDS content on the operations of the receiving wastewater treatment plant. Discharging concentrate to the sanitary sewer in most countries is regulated by the requirements applicable to industrial discharges and the applicable discharge regulations of the utility/municipality which is responsible for wastewater collection system management.

5.3.2. Key issues and considerations

Feasibility of this disposal method is limited by the hydraulic capacity of the wastewater collection system and by the treatment capacity of the wastewater treatment plant receiving the discharge. Typically, wastewater treatment plants' biological treatment process is inhibited by high salinity when the plant influent TDS concentration exceeds 3000 mg/L. Therefore, before directing desalination plant concentrate to the sanitary sewer the increase in the wastewater treatment plant influent salinity must be assessed and its effect on the plant's biological treatment system should be investigated. Taking under consideration that wastewater treatment plant influent TDS may be up to 1000 mg/L in many facilities located along the ocean coast, and that the seawater desalination plant concentrate TDS level would be above 65,000 mg/L, the capacity of the wastewater treatment plant has to be at least 30 to 35 times higher than the daily volume of concentrate discharge in order to maintain the wastewater plant influent TDS concentration below 3000 mg/L. This means, that for example a 40,000 m^3/day wastewater treatment plant would likely not be able to accept more than 1000 m^3/day of concentrate (i.e. serve a seawater desalination plant of capacity higher than 1000 m^3/day).

If the effluent from the wastewater treatment plant is used for water reuse, the amount of concentrate that can be accepted by the wastewater treatment plant is limited not only by the concentrate salinity, but also by the content of sodium, chlorides, boron and bromides in the blend. All of these compounds could have a profound negative effect on the reclaimed water quality, especially if the effluent is used for irrigation. Treatment processes of a typical municipal wastewater treatment plant, such as sedimentation, activated sludge treatment and sand filtration, do not remove a measurable amount of these concentrate constituents.

A number of crops and plants cannot tolerate irrigation water that contains over 1000 mg/L of TDS. However, TDS is not the only water quality parameter of concern when the desalinated water is used for irrigation. High levels of chloride and sodium may also have measurable negative impacts on the irrigated plants. Most plants cannot tolerate chloride levels above 250 mg/L. Typical wastewater plant effluent has chloride levels of 150 mg/L or less, while seawater treatment plant concentrate could have chloride concentration in excess of 50,000 mg/L. For example, using the chloride levels indicated above, a 40,000 m^3/day wastewater treatment plant cannot accept more than 80 m^3/day of seawater desalination concentrate, if the wastewater plant's effluent would be used for irrigation. This limitation would be even more stringent if the wastewater effluent is used for irrigation of salinity-sensitive ornamental plants which often have tolerance threshold levels for sodium of 80 mg/L or less and chloride of 120 mg/L or less.

5.4. Discharge through existing power plant outfall (Collocation)

5.4.1. Description

Under a collocation configuration, the intake of the seawater desalination plant is connected to the discharge canal of the power plant to collect a portion of the cooling water of this plant for desalination (see Fig. 7). After the seawater is pretreated, it is processed in a reverse osmosis membrane desalination system, which produces two key streams — low salinity permeate, which after conditioning is conveyed for potable water supply, and concentrate which is returned to the power plant discharge downstream of the point of cooling water intake. This configuration allows using the power plant cooling water both as source water for the seawater desalination plant and as a blending water to reduce the salinity of the desalination plant concentrate prior to its discharge to the ocean.

As shown on Fig. 7, under typical operational conditions the seawater enters the power plant intake facilities and after screening is pumped through the power plant condensers to cool them and thereby to remove the waste heat generated during the electricity generation process [27]. The cooling water discharged from the condensers typically is 5 to 15 °C warmer than the source ocean water which could be beneficial for the desalination process because warmer seawater has lower viscosity and therefore lower osmotic pressure.

Collocation of SWRO desalination plants with existing once-trough cooling coastal power plants yields four key benefits: (1) the construction of a separate desalination plant outfall structure is avoided thereby reducing the overall cost of desalinated water; (2) the salinity of the desalination plant discharge is reduced as a result of the mixing and dilution of the membrane concentrate with the power plant discharge, which has ambient seawater salinity; (3) because a portion of the discharge water is converted into potable water, the power plant thermal discharge load is decreased, which in turn lessens the negative effect of the power plant thermal plume on the aquatic environment; and (4) the blending of the desalination plant and the power plant discharges results in accelerated dissipation of both the salinity and the thermal discharges.

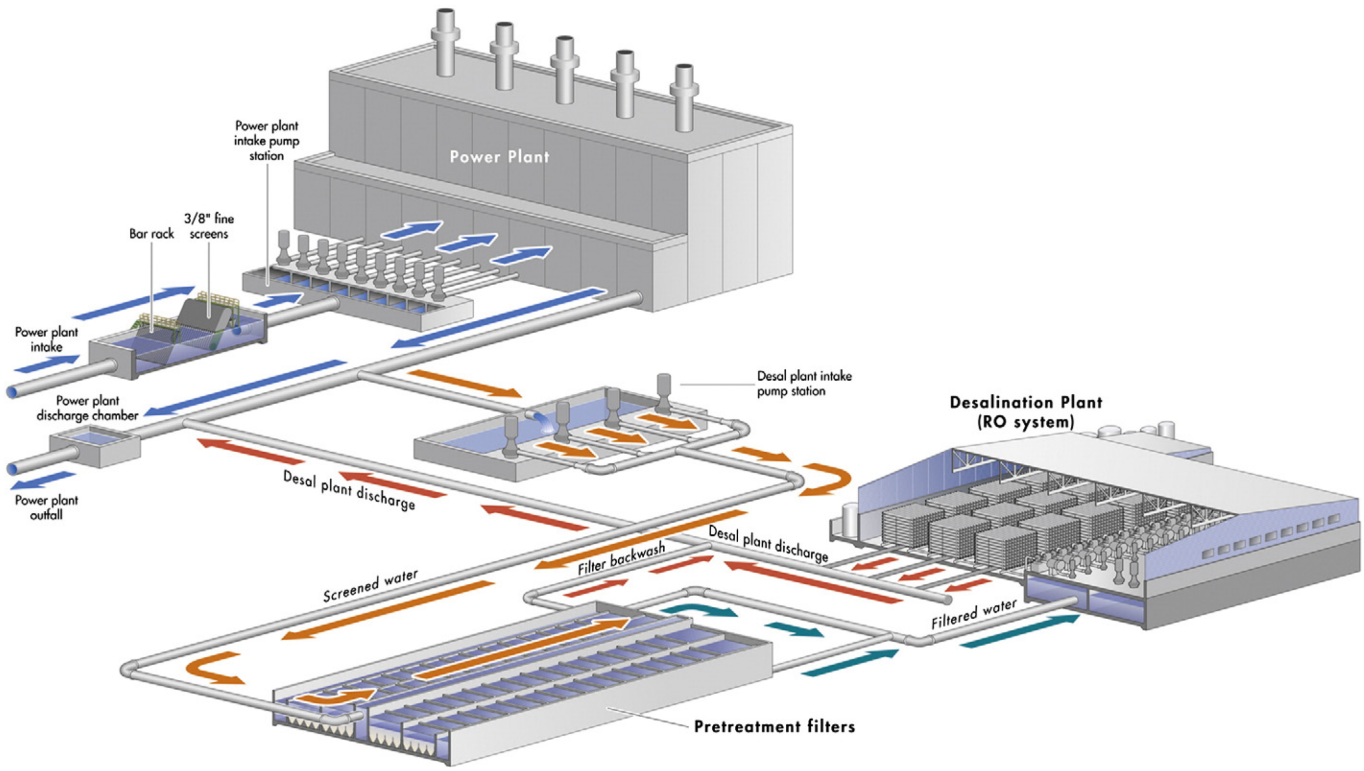

Fig. 7. Collocation of SWRO Plant and Coastal Power Generation Station.

Usually, coastal power plants with once-trough cooling systems use large volumes of seawater. Because the power plant intake seawater has to pass through the small diameter tubes (typically 10-mm or less) of the plant condensers to cool them, the plant discharge cooling water is already screened through bar racks and fine screens similar to these used at surface water intake desalination plants. Therefore, a desalination plant which intake is connected to the discharge outfall of a power plant usually does not require the construction of a separate intake structure, intake pipeline and screening facilities (bar-racks and fine screens). Since the construction cost of a new surface water intake structure for a desalination plant is typically 5 to 30% of the total plant construction expenditure, power plant collocation could yield significant construction cost savings.

The need for installation of additional fine screening facilities for the desalination plant intake is driven by the screenings disposal practice adopted by the power plant and the type of desalination plant pretreatment system. As indicated previously, power plants typically remove the screenings retained at their bar racks and fine screens, and dispose these waste debris to a landfill or return them back to the ocean. However, in some cases the screenings collected at the power plant's mechanical screens are discharged into the cooling water downstream from the plant's condensers. In this case, the power plant discharge would contain screenings that need to be removed at the desalination plant intake.

Sharing intake infrastructure also has environmental benefits because it avoids the need for new intake and outfall construction in the ocean and the seashore area near the desalination plant. The construction of a separate new open intake structure and pipeline for the desalination plant could cause a measurable disturbance of the benthic marine organisms on the ocean floor. Another clear environmental benefit of the collocation of power generation stations and desalination plants is the overall reduction of entrainment, impingement and entrapment of marine organisms as compared to the construction of two separate open intake structures — one for the power plant and one for the desalination plant. This benefit stems from the fact that total biomass of the impacted marine organisms is typically proportional to the volume of the intake seawater. By using the same intake seawater twice (once for cooling and the second time for desalination) the net intake inflow of seawater and marine organisms is minimized.

The length and configuration of the desalination plant concentrate discharge outfall are closely related to the discharge salinity. Usually, the lower the discharge salinity, the shorter the outfall and the less sophisticated the discharge diffuser configuration needed to achieve environmentally safe concentrate discharge. Blending the desalination plant concentrate with the lower salinity power plant cooling water often allows reducing the overall salinity of the ocean discharge within the range of natural variability of the seawater at the end of the discharge pipe, thereby completely alleviating the need for complex and costly discharge diffuser structures.

The power plant thermal discharge is lighter than the ambient ocean water because of its elevated temperature and therefore, it tends to float on the ocean surface. The heavier saline discharge from the desalination plant draws the lighter cooling water downwards and thereby engages the entire depth of the ocean water column into the heat and salinity dissipation process. As a result the time for dissipation of both discharges shortens significantly and the area of their impact is reduced.

It should be pointed out that seawater density is a function of both temperature and salinity. While seawater density increases with salinity, it decreases with the increase in temperature. A close to ideal condition for collocation of desalination and power plants is configuration where the increase in density of the blend of desalination plant concentrate and power plant cooling water as compared to the salinity of the ambient water is compensated by the decrease in density of this blend due to higher than ambient temperature.

For example, in the case of the Carlsbad desalination project illustrated on Fig. 1, the average annual ambient seawater temperature in the open ocean near the power plant is 18 °C and the seawater salinity is 33,500 mg/L. The seawater density at this temperature and salinity is 1024.12 kg/m^3. The desalination plant concentrate salinity is 67,000 mg/L. If this concentrate was not blended with the warmer and lighter cooling water from the power plant and instead it was discharged directly into the ocean at 18 °C, the density of the concentrate would be 1050.03 kg/m^3. Because the concentrate has significantly higher density than the ambient ocean water, immediately after discharge into the ocean, the concentrate will quickly sink to the ocean floor and expose the bottom marine habitat to significantly higher salinity which may have a detrimental effect to the aquatic life.

In the case of the collocated discharge, the concentration of the desalination plant concentrate will be reduced from 67,000 mg/L down to 36,200 mg/L as a result of the blending with the cooling water which has ambient salinity. In addition, the blend would typically have temperature which is 8 °C higher than the ambient seawater temperature (i.e. 26 °C vs. 18 °C). The diluted seawater concentrate with TDS of 36,200 mg/L and temperature of 26 °C, will have density of 1023.94 kg/m^3, which is slightly lower than the ambient seawater density of 1024.12 kg/m^3. As a result of the collocation and mixing of the two discharges, rather than sinking down towards the ocean floor the concentrate will actually float and quickly mix and dissipate within the water column as it moves upwards towards the ocean surface. For comparison, the discharge of concentrate through diffusers has to be released very high velocity (5 to 8 m/s) in order to achieve adequate mixing, which in turns requires significant energy expenditure associated with pumping concentrate discharge (see Fig. 8).

One of the key additional benefits of collocation is the overall reduction of the desalination plant power demand and associated costs of water production as a result of the use of warmer source water. The source water of the RO plant is typically 5 to 10 °C warmer than the temperature of the ambient ocean water. This is a significant benefit, especially for desalination plants with cold source seawater, because the feed pressure required for RO membrane separation decreases with 6 to 8% for every 10 °C of source water temperature increase. Since the power costs are approximately 30 to 40% of the total costs for production of desalinated water, the use of warmer source water could have a measurable beneficial effect on the overall water production expenditures.

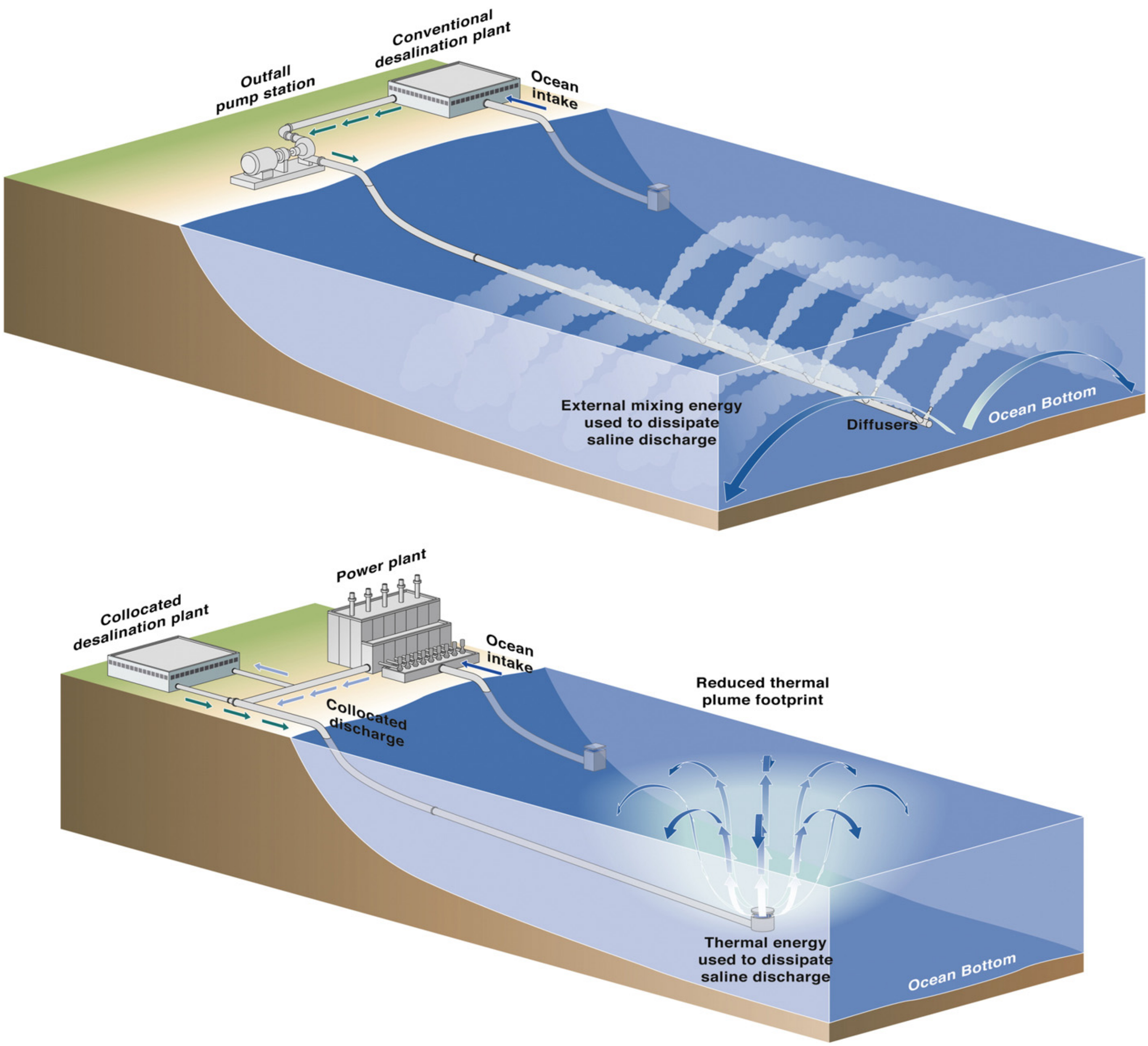

Fig. 8. Comparison of conventional and collocated concentrate discharges.

As a result of the collocation the desalination plant unit power costs could be further decreased by avoiding the need for using the power grid and the associated fees for power transmission to the desalination plant. Typically, the electricity tariff (unit power cost) structure includes two components: fees for power production and for power grid transmission. Often, the power transmission grid portion of the tariff is 30 to 50% of the total unit power cost. By connecting the desalination plant directly to the power plant electricity generation equipment, the grid transmission portion of the power fees could be substantially reduced or completely avoided, thereby further reducing the overall seawater desalination cost.

Collocation of power and desalination plants may also have advantages for the power plant host. In addition to the benefit of gaining a new customer and generating revenue by leasing power plant property to locate the desalination plant, the power plant host also gets a customer of very favorable power use profile — a steady and continuous power demand and a high power load factor. This continuous high-quality power demand allows the power plant host to operate its electricity generation units at optimal regime, which in turn reduces the overall costs of power generation.

Under a typical collocation configuration, the desalination plant uses the power plant discharge water both as a feed water for the desalination facilities and as a dilution water for the desalination concentrate. An example of collocation configuration where the power plant discharge is used only for dilution of the concentrate is the 120,000 m^3/day Carboneras desalination plant in Spain. Plant's concentrate is discharged to the cooling water canal of a nearby coastal power generation plant and thereby diluted to environmentally safe level before its return to the sea. The Carboneras seawater desalination plant has a separate open intake independent form the intake and discharge of the power plant.

5.4.2. Key issues and considerations

Collocation with power station at a large scale was implemented for the first time at the Tampa Bay Seawater Desalination Project in Florida, and since then has been considered for a number of SWRO desalination plants in the United States and worldwide. The intake and discharge of the Tampa Bay Seawater Desalination Plant are connected directly to the cooling water discharge outfalls of the Tampa Electric (TECO) Big Bend Power Station (Fig. 9).

The TECO power station discharges an average of 5.3 million m^3/day of cooling water. The Tampa Bay SWRO plant collects an average of 167,000 m^3/day of power plant cooling water to produce 95,000 m^3/day of fresh potable water [28]. The desalination plant concentrate is discharged to the same TECO cooling water outfalls downstream from the point of seawater desalination plant intake connection.

In order for the collocation concept to be cost-effective and possible to implement, the minimum power plant cooling water discharge flow has to be at least several times larger than the desalination plant production capacity. In addition, the power plant outfall configuration and hydraulics have to be such that entrainment and recirculation of concentrate into the desalination plant intake is avoided under all power plant operational conditions and ocean tide elevations, including high tide levels in combination with low power plant discharge flows.

It is preferable that the distance of the power plant outfall from the point of connection of the desalination plant discharge to the point of entrance of the discharge outfall into the ocean to be long-enough in order to achieve complete mixing of the concentrate and the cooling water. Complete mixing of the two streams upstream of the point of discharge minimizes the negative effect of the streams on the environment. The minimum distance required for complete mixing depends on numerous factors, including: location and angle of entrance of the concentrate pipe discharge into the power plant outfall; size of the concentrate discharge pipe and the power plant outfall; flow rates, temperatures and salinities of the cooling water and concentrate discharge streams. Because of the complexity of the outfall mixing phenomenon, use of computational fluid dynamics models is recommended to identify the optimum location and entrance of the concentrate discharge pipe into the power plant outfall/canal.

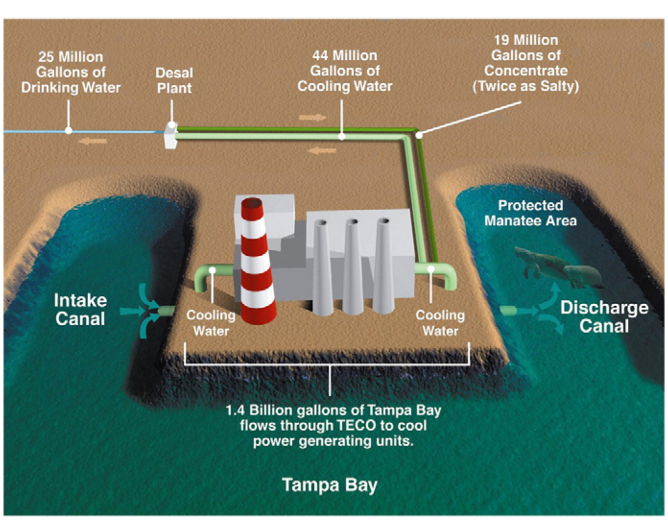

Fig. 9. Collocation configuration of Tampa Bay Seawater Desalination Plant.

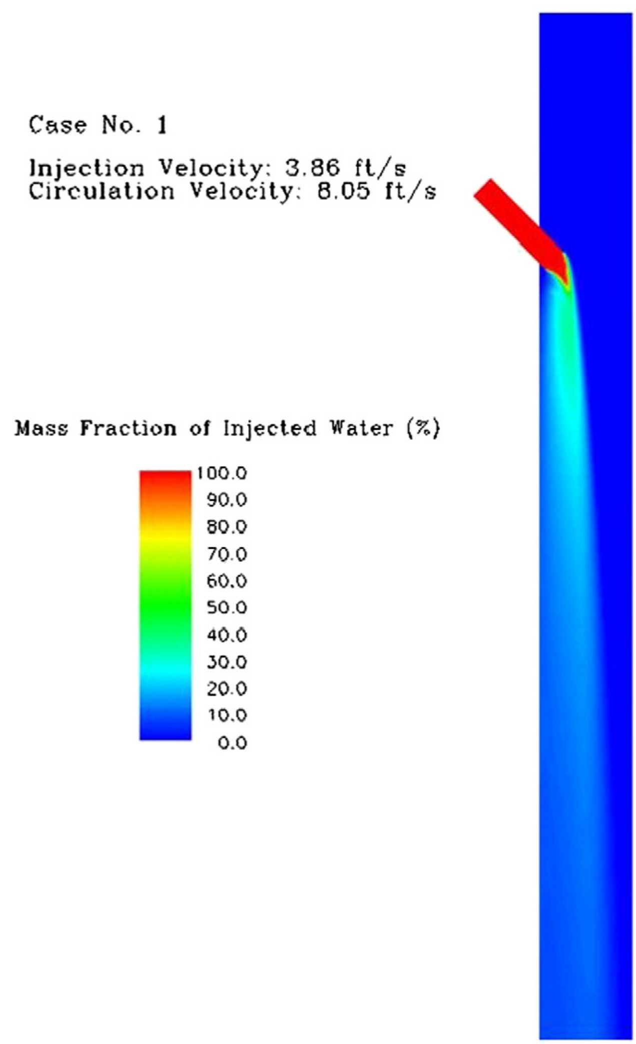

Fig. 10. Tampa Bay SWRO Project concentrate discharge entrance — Case 1.

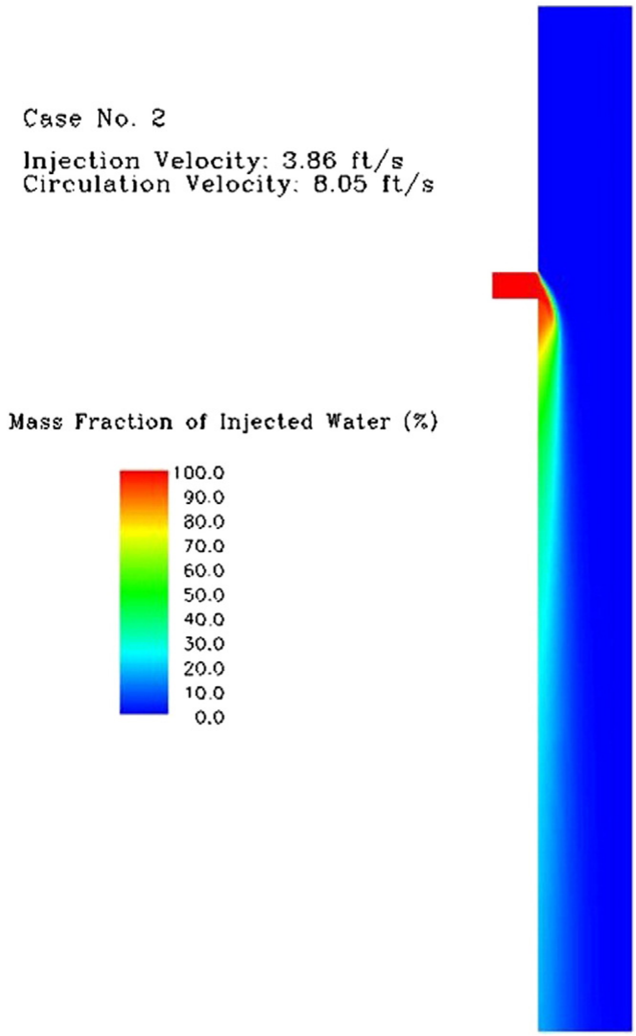

Fig. 11. Tampa Bay SWRO Project concentrate discharge entrance — Case 2.

Figs. 10 and 11 present the results of CFD model analysis of two alternative entrance configurations of the 760 mm (30-inch) concentrate discharge pipe of the Tampa Bay seawater desalination plant into the 2743 mm (108-inch) outfall of the Tampa Electric Power Plant. Fig. 10 depicts the level of concentrate discharge mixing with the power plant cooling water when the concentrate line enters the power plant outfall under a 45-degree angle protruding 0.75 m into the outfall (Case 1). This concentrate discharge entrance configuration was found to be optimal and was actually implemented for this project because it allows complete mixing to be achieved at minimum distance (less than 25 m) from the point of concentrate discharge into the power plant outfalls. In this case, this distance was a physical limitation that had to be accommodated in the design of the concentrate discharge pipe.

Fig. 11 illustrates the less efficient mixing achieved when the same size concentrate pipe enters into the power plant outfall without protrusion and at a 90-degree angle (Case 2), which is the lowest cost and the easiest to construct configuration. Comparison of the two figures clearly indicates the benefits of angled concentrate entrance and the projection of this entrance into the power plant outfall for this project.

A particular consideration has to be given to the effect of the power plant operations on the cooling water quality, since this discharge is used as source water for the desalination plant. For example, if the power plant discharge contains levels of copper, nickel or iron significantly higher than these of the ambient seawater, this power plant discharge may be not be suitable for collocation because these metals may cause irreversible fouling of the membrane elements.

Another potential challenge with collocation could be the location of the disposal of the power plant intake screenings. In most power plants the debris removed out by the intake screens are disposed offsite. However, this disposal practice may change during the course of the power plant and desalination plant operations. For example, in the case of the Tampa Bay seawater desalination plant, during the final phase of the desalination plant construction, the TECO power plant decided to change their intake screenings disposal practices and to discharge their screenings just upstream of the already connected desalination plant intake rather than to continue disposing them off site. This change in power plant operations had a dramatic effect on the Tampa Bay Water desalination plant startup and operations, and especially on the pretreatment system performance. Since the desalination plant was pilot tested and designed around the original method of power plant operations under which all screenings were removed from the cooling water, the desalination plant was not built with its own separate intake screening facilities. The presence of power plant waste screenings in the desalination plant intake water had a detrimental effect of the pretreatment filter operations because the screening debris frequently clogged the filter distribution piping, airlifts and sand media. This in turn was one of the key causes for the low quality of the filter effluent and the related short useful life of the plant's cartridge filters.

Although this problem had a significant effect on the desalination plant operations it also had relatively straightforward solutions — either installing separate fine screening facilities for the desalination

Table 4
Issues and considerations of desalination plant collocation.

Advantages	Disadvantages and feasibility considerations
Capital cost savings by avoiding construction of separate intake pipeline and structure, and new discharge outfall.	Use of warmer seawater may accelerate membrane bio-fouling, especially if the source water is rich in organics.
Decrease of the required RO system feed pressure and power cost savings as a result of using warmer water.	RO membranes may be exposed to iron, copper or nickel fouling if the power plant condensers and piping are built of low-quality materials.
Reduction of unit power cost by connecting directly to power plant generation facilities and avoiding power transmission charges.	Source seawater has to be cooled if its temperature increases above 40 °C in order to protect RO membrane integrity.
Accelerated environmental review process as a result of avoidance of construction of new intake and discharge outfalls in the ocean.	Permeate water quality diminishes slightly with the increase of source water temperature.
Reduction of marine organism impingement and entrainment because the desalination plant does not collect additional seawater from the ocean.	Use of warmer water may result in lower boron rejection and require feed water pH adjustment to meet stringent boron water quality targets.
Reduction of impact on marine environment as a result of faster dissipation of thermal plume and concentrate.	RO plant source water screening may be required if the power plant disposes off its screenings through their outfall and the point of disposal is upstream of the desalination plant intake.
Reduction of the power plant thermal discharge to the ocean because a portion of this discharge is converted to potable water.	Desalination plant operations may need to be discontinued during periods of heat treatment of the power plant facilities.
Use of already disturbed land at the power plant minimizes environmental impact.	

plant or moving the point of the power plant screening debris discharge downstream of the location of the desalination plant intake. It also indicates that the completing a successful collocation project requires close and continuous coordination with the power plant operations. The project owner of the Tampa Bay seawater desalination plant has decided to install separate screens for the water entering the desalination plant in order to address this challenge.

In order for the collocation concept to be cost-effective and possible to implement, the power plant cooling water discharge flow has to be larger than the desalination plant capacity and the power plant outfall configuration has to be adequate to avoid entrainment and recirculation of concentrate into the desalination plant intake. It is preferable that the length of the power plant outfall downstream of the point of connection of the desalination plant discharge is adequate to achieve complete mixing prior to the point of entrance into the ocean.

A special consideration has to be given to the effect of the power plant operations on the cooling water quality, since this discharge is used as source water for the desalination plant. For example, if the power plant discharge contains levels of copper, nickel or iron significantly higher than these of the ambient seawater, this power plant discharge may be not be suitable for collocation because these metals may cause irreversible fouling of the membrane elements. A summary of key issues and considerations for assessment of the feasibility of the collocation approach is presented in Table 4.

6. Summary and conclusions

At present, ocean outfall discharge is the most widely practiced method for disposal of concentrate from seawater desalination plants. New ocean outfalls are typically used for this purpose. However, co-discharge of concentrate with power plant cooling water has gained significant attention over the last five years due to the cost advantages and environmental benefits of this disposal method. Co-disposal with wastewater effluent is relatively less attractive than the other two concentrate management methods and it is usually viable for small-size seawater desalination plants.

Proving that concentrate discharge from a seawater desalination plant is environmentally safe requires thorough engineering analysis including: hydrodynamic modeling of the discharge; whole effluent toxicity testing; salinity tolerance analysis of the marine species endogenous to the area of discharge; and reliable intake water quality characterization that provides basis for assessment of concentrate's make up and compliance with the numeric effluent quality standards applicable to the point of discharge.

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