A SunCam online continuing education course

Environmental Review and Permitting of Desalination Projects – Part 1

by

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1. Introduction

The environmental impacts of seawater and brackish water desalination plant operations have many similarities to these of conventional water treatment plants. Both conventional water treatment facilities and desalination plants have source water intake and waste stream discharge facilities which operation may alter the aquatic environment or groundwater aquifers in which they are located.

Desalination facilities and conventional water treatment plants use many of the same chemicals for source water conditioning, and therefore, generate similar waste streams. In addition, desalination facilities, like conventional water treatment plants, incorporate equipment (i.e., pumps, motors, air compressors, valves, energy recovery devices, etc.) and treatment processes which generate noise pollution, consume electricity, and are sources of direct or indirect greenhouse gas emissions.

Similar to conventional water supply projects, the construction of desalination plants generates traffic, noise and other auxiliary environmental impacts. Such impacts are only temporary in nature and typically are minimized by detailed project planning and coordination with local agencies and residents of areas impacted by project construction-related activities.

When desalination projects are evaluated as fresh water supply alternatives to conventional water sources, 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. Desalination projects are typically driven by the limited availability of alternative lower-cost water supply resources such as fresh ground water aquifers or surface water (rivers, lakes, etc.). However, damaging long-term environmental impacts may also result from continued over-depletion of those conventional water supplies, including inter-basin water transfers.

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; wetlands in the Tampa Bay region of Florida; 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 substantial environmental impacts of the traditional fresh water resources in these regions. Such long-term fresh water transfers have affected the eco-balance in the fresh water resources to an extent that the long-term continuation of current water supply practices may result in significant and irreversible damage of the ecosystems of traditional fresh water supply sources or the intrusion of saline water into the freshwater aquifers, such as the cases in Monterey County and the Salinas Valley, California. In such instances, the environmental impacts of construction and operation of new seawater desalination projects should be weighed against the environmentally damaging consequences from the continuation/expansion of the existing fresh-water supply practices.

A rational approach to water supply management must ensure that sustainable and drought-proof local supplies are available, and long-term reliance on conventional water supply sources (i.e., surface water, groundwater) is reconsidered in favour of a well-balanced and diversified water supply portfolio, which combines surface water, groundwater, recycled water, water conservation, and desalination. The overall goal of a well-balanced and sustainable water supply portfolio is to identify a combination of alternative water supply sources which as a whole has the lowest overall environmental impact.

Despite many of the similarities of their environmental impacts, desalination plants have several distinctive differences as compared to conventional water treatment plants:

- Use more source water to produce the same volume of fresh water;
- Generate discharge of elevated salinity which typically has 1.5 to 10 times higher TDS concentration than that of the source water;
- Consume 2 to 10 times more electricity for production of the same volume of fresh water.

Therefore, this course focuses on the three key environmental impact aspects, which differentiate desalination projects from other water supply alternatives:

- Intake impingement and entrainment (I&E);
- Concentrate (brine) impact on aquatic environment and
- Carbon footprint of desalination plant operations.

2. Intakes - Environmental Impacts and Mitigation Measures

Desalination plat intakes either collect saline water directly from the water column of surface water sources (open intakes) or from underground aquifer/s (subsurface intakes).

2.1. Open Intakes

Environmental Challenges

As with any other natural surface water source currently used for fresh water supply around the globe, surface brackish water and seawater contain aquatic organisms (algae, plankton, fish, bacteria, etc.). Impingement occurs when such organisms are trapped against the intake screens by the force of the flowing source water. Loss of marine life through the desalination plant treatment facilities (pumps, filters, etc.) is typically referred to as entrainment.

A third term, entrapment, describes impacts associated with offshore intake structures. These structures are typically comprised of an offshore pipe riser covered with a velocity cap, a long intake tunnel, and an onshore screening facility. Organisms that pass through the offshore velocity cap and are unable to escape the intake velocity in the intake tunnel are often referred to as entrapped. They have technically been entrained into the intake system, but their ultimate fate has not yet been determined.

Depending on the mesh size of the screens at the onshore screening facility, these organisms can impinge on or entrain through the final screen mesh. It should be pointed out that impingement typically involves adult aquatic organisms (fish, crabs, etc.) that are large enough to actually be retained by the intake screens, while entrainment mainly effects aquatic species small enough to fit through the particular size and shape of intake screen mesh.

Impingement and entrainment of aquatic organisms are not unique to open intakes of desalination plants only. Conventional open freshwater intakes from surface water sources (i.e., rivers, lakes, estuaries) may also cause measurable impingement and entrainment.

Attention to intake impingement and entrainment issues associated with desalination plant operation is partially prompted by the Section 316(b) of the 1972 Clean Water Act that regulates cooling water intake of the steam electric industry by the environmental scrutiny associated with the public review process of desalination projects in California. The magnitude of environmental impacts on aquatic organisms caused by impingement and entrainment of desalination plant intakes is site specific and varies significantly from one project to another.

Open ocean intakes are typically equipped with coarse bar screens followed by fine screens (Figures 1 and 2), which preclude the majority of the adult and juvenile aquatic organisms (fish, crabs, etc.) from entering the desalination plants.

Figure 1 – Intake Bar Screen

Figure 2 – Intake Coarse Screen followed by Fine Screen

Most aquatic organisms collected with the saline source water used for production of desalinated water are removed by screening and filtration before this water enters the reverse osmosis desalination membranes for salt separation.

A comprehensive multi-year impingement and entrainment assessment study of the open ocean intakes of 19 power generation plants completed by the California State Water Resources Control Board in 2010 provides an insight into the magnitude of these intake-related environmental impacts (SWRCB, 2010). Based on this study, the estimated total average annual impingement of fish caused by the seawater intakes varied between 0.12 grams/m^3.day (0.31 lbs/MGD) for Diablo Canyon Power Plant and 6.27 grams/m^3.day (52.29 lbs/MGD) - for Harbor Generating Station; and for all 19 plants it averaged 0.8 grams/m^3.day (6.63 lbs/MGD).

Taking into consideration that this amount is the total annual impact, the average daily impingement rate is estimated at 0.002 grams/m^3.day (0.018 lbs/MGD) of intake flow (0.8 grams/m^3/day /365 days = 0.002 grams/m^3. day = 0.018 lbs/MGD).

The above-mentioned I&E study also provides baseline for assessment of the entrainment impact of seawater intakes. The results of this study indicate that the magnitude of such annual impact on larval fish can vary in a wide range – from 20 larval fish/m^3.day (0.08 million larval fish/MGD for the Contra Costa Power Plant to 1,530 larval fish/m^3.day (8 million larval fish/MGD) for the Encina Power Plant and illustrate the fact that the entrainment impact is very site-specific.

The average annual entrainment for all of the 19 existing coastal power plants in California is estimated at 565 larval fish/m^3.day (2.14 million of larval fish per every million gallon a day) of intake flow. Prorated for a 100,000 m^3/day (26 MGD) intake of a 40,000 m^3/day (11 MGD) seawater desalination plant, this annual entrainment impact would be 56.5 million of larval fish/yr. While this number seems large, based on expert evaluation and research, such large larval fish entrainment numbers do not necessarily equate to a measurable impact on adult fish population.

Using the California impingement and entrainment study results as a baseline, for a medium size desalination plant of 40,000 m^3/day (11 MGD) production capacity collecting 100,000 m^3/day (26 MGD) of intake flow, the daily impingement impact is projected to be 0.2 kg per day (0.002 grams/ x 100,000 m^3/day = 200 grams/day = 0.2 kg/day = 0.44 lbs/day), which is minimal.

Due to the large natural attrition mortality rate of larval fish and food chain supply availability, very few larval fish actually develop to juvenile and adult stages in the natural environment. The majority of larvae are lost to predation and exposure to destructive forces of nature such as wind and wave action. Such forces have several orders of magnitude higher impact on fish populations than seawater intakes.

Potential I&E Reduction Solutions

While impingement and entrainment associated with open intake operations are not expected to create biologically significant impacts under most circumstances, best available site, design, technology, and when needed, mitigation measures, are prudent for minimizing loss of marine life and maintaining the productivity and vitality of the aquatic environment in the vicinity of the intake.

Deep Offshore Intakes. Intakes in enclosed bays and estuaries have the greatest potential to cause elevated impingement and entrainment impacts. Since the number of marine species in unit volume of water decreases with depth, intakes at least 300 m (1,000 ft) from the shore and depth of 6 m (20 ft) or more below the surface usually result in significantly lower environmental impacts. As indicated previously, open intakes may also exhibit an entrapment effect - fish and other aquatic organisms that are drawn into the offshore conduit cannot return back to the open ocean because they are stranded between the intake forebay and fine screens. The use of velocity caps and low forebay through-screen velocity can reduce this entrapment effect.

Low Through-Screen Velocity. Impingement occurs when the intake through-screen velocity is so high that the marine species cannot swim away and are retained at the screens. The US Environmental Protection Agency has identified a velocity threshold of 0.15 m/s \0.5 fps), below which impingement is practically nonexistent. Therefore, designing intake screening facilities to always operate at or below this velocity should address impingement impacts.

Small-Size Bar Screen Openings. Use of bar screens with distance between the exclusion bars of no greater than 23 cm (9 inches) is recommended for preventing large organisms from entering the seawater intake (WateReuse Association, 2011).

Suitable Fine Screen Mesh Size. After entering the bar a screen, the saline water has to pass through fine screens to prevent debris from interfering with the downstream desalination plant treatment processes. The fine screen mesh size is a very important design parameter and should be selected such that it is fitted to the size of a majority of the larval organisms it is targeting to protect.

Typically, the openings of most fine screens are 9.5 mm (3/8 inch) or smaller because most adult and juvenile fish are larger than 10 mm in size. Many fish larvae are larger than 2 mm and mesh of this size or smaller (i.e., 0.5 to 2 mm) could be an effective barrier and entrainment reduction measure.

Design Enhancements for Collection of Minimum Intake Flow. Membrane reverse osmosis desalination plants typically collect saline water for one or more of the following three purposes: (1) to use it as a source water for fresh water production; (2) to apply it as a backwash water for the source water pretreatment system; and (3) to pre-dilute concentrate generated during the salt separation process down to environmentally safe salinity levels before it is discharge.

Most desalination plants which incorporate filtration for pretreatment of source water collect 4 to 10% of additional water to wash their pretreatment filtration systems and discharge the spent filter backwash. A design approach, which may allow reducing this water use significantly, is treatment and reuse of the backwash water. Such backwash treatment and reuse approach has cost implications but is a prudent design practice aimed at reducing overall plant intake flow and associated impingement and entrainment.

Collecting additional source water for concentrate pre-dilution may be needed when existing wastewater intake or power plant outfalls are used for concentrate discharge and the existing outfall volume is not sufficient to produce adequate dilution of the saline discharge. This additional flow intake could be eliminated by designing facilities for storing concentrate during periods of low outfall flows when adequate dilution is not available or by installing a discharge diffuser system which allows enhancing concentrate dissipation into the ambient marine environment without additional dilution.

If the desalination plant production capacity has to vary diurnally, the design and installation of variable frequency drives on the intake pumps could also allow decreasing impingement and entrainment of the plant intake by closely matching collected source water volume to the plant production needs.

Use of Low-Impact Intake Technologies. Currently, there are no federal and state regulations, which specifically define requirements for reduction of impingement and entrainment caused by desalination plant intakes. However, the US EPA Section 316(b) of the Clean Water Act federal regulations have stipulated national performance standards for intake impacts from power generation plants which require 80 to 95% reduction of impingement and 60 to 90% reduction of entrainment as compared to these caused by uncontrolled intake conditions (US EPA, 2008). Technologies that can meet these impingement and entrainment performance standards are defined by US EPA as Best Technologies Available (BTA).

Subsurface Intakes. Subsurface intakes (e.g., wells and infiltration galleries) are considered a low-impact technology in terms of impingement and entrainment. However, to date there are no studies that document the actual level of entrainment reduction that can be achieved by these types of intakes.

Wedgewire Screen Intakes. Wedgewire screens are cylindrical metal screens with trapezoidal-shaped "wedgewire" slots with openings of 0.5 to 10 mm (see Figure 3). They combine very low flow-through velocities, small slot size, and naturally occurring high screen surface sweeping velocities to minimize impingement and entrainment.

Wedgewire screening technology is the only technology approved by US EPA as Best Technology Available, provided that sufficient ambient conditions exist to promote cleaning of the screen face; the through screen design intake velocity is 0.15 m/s (0.5 fps) or less; and the slot size is appropriate for the size of eggs, larvae, and juveniles of any fish and shellfish to be protected at the plant intake site.

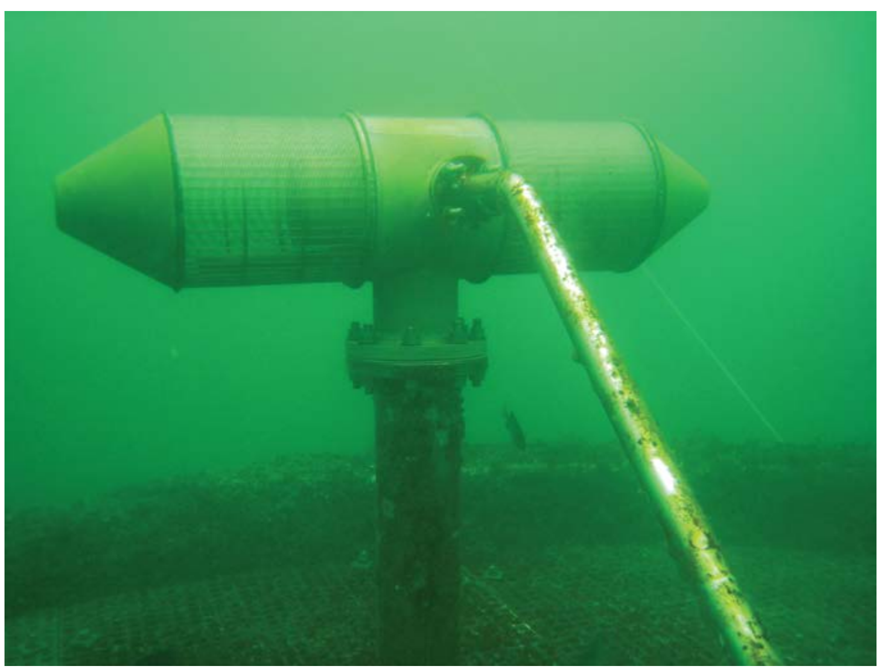

Figure 3 – Wedgewire Screen

Wedgewire screens are suitable for source water collection from locations in the ocean or sea where significant prevailing ambient cross-flow current velocities of 0.3 m/s (1 fps) or more exist. This high cross-flow velocity allows organisms that would otherwise be impinged on the wedge-wire intake, to be carried away with the flow.

An integral part of typical intake with wedge-wire screens is an air-burst back-flush system, which directs a charge of compressed air to each screen unit to blow-off debris back into the water body, where they are carried away from the screen unit by the ambient cross-flow currents.
Figure 4 depicts a schematic of the wedge-wire screen intake used at the 150,000 m^3/day (40 MGD) Beckton desalination plant in London, England.

This plant is one of the largest desalination facilities in Europe, and is equipped with seven 3-mm wedgewire screens installed on the suction pipe of each of the plant intake pumps. The total screen length is 3500 mm (11.5 ft) and the screen diameter is 1100 mm (3.6 ft). The plant intake is under significant influence of tidal exchange of river water and seawater.

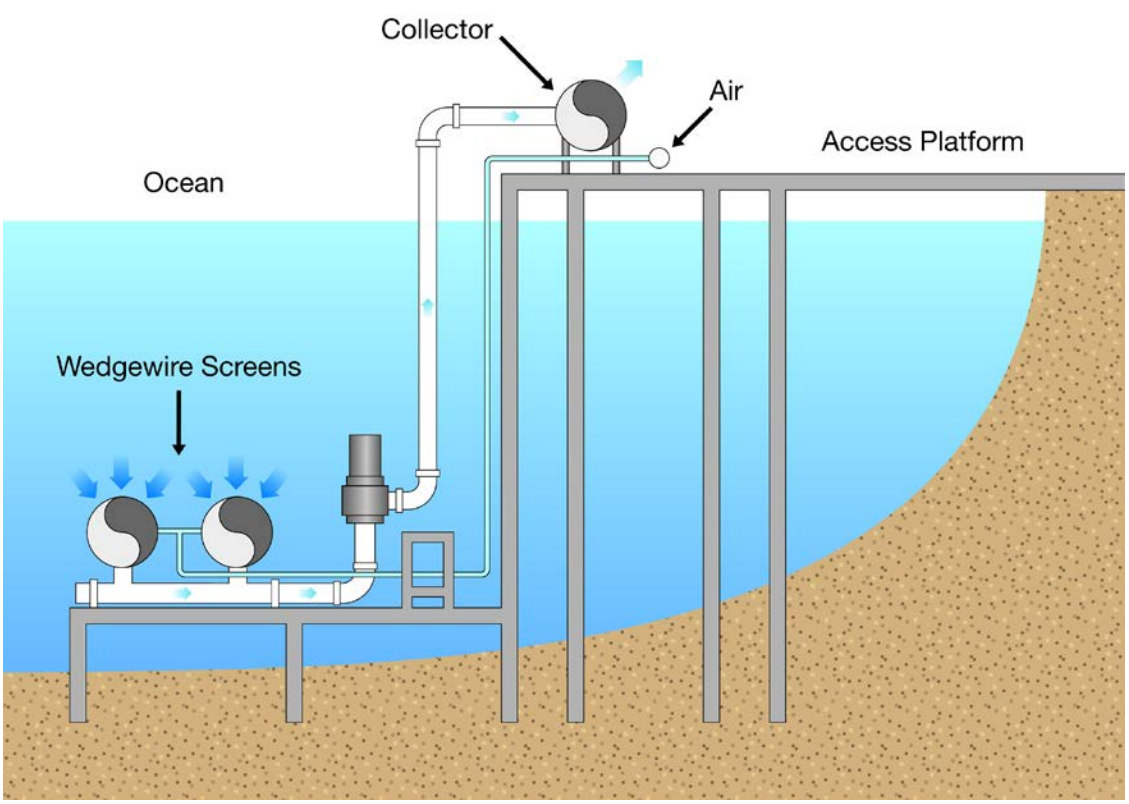

Figure 4 – Wedgewire Screen Intake of Beckton Desalination Plant

Offshore Intake Velocity Cap. A velocity cap is a configuration of the open intake structure that is designed to change the main direction of water withdrawal from vertical to horizontal (see Figure 5). This configuration is beneficial for two main reasons: (1) it eliminates vertical vortices and avoids withdrawal from the more productive aquatic habitat which usually is located closer to the surface of the water body; and (2) it creates a horizontal velocity pattern which gives juvenile and adult fish an indication for danger – most fish have receptors along the length of their bodies that sense horizontal movement because in nature such movement is associated with unusual conditions. This natural indication provides fish in the area of the intake ample warning and opportunity to swim away from the intake.

The velocity cap intake configuration has a long track record and is widely used worldwide. This is the original configuration of many power plant intakes in Southern California and of all new large seawater desalination plants in Australia, Spain and Israel constructed over the last five years. Based on a US EPA technology efficacy assessment, velocity caps could provide over 50% impingement reduction of marine species between the inlet structure and the fine plant screens (US EPA, 2011).

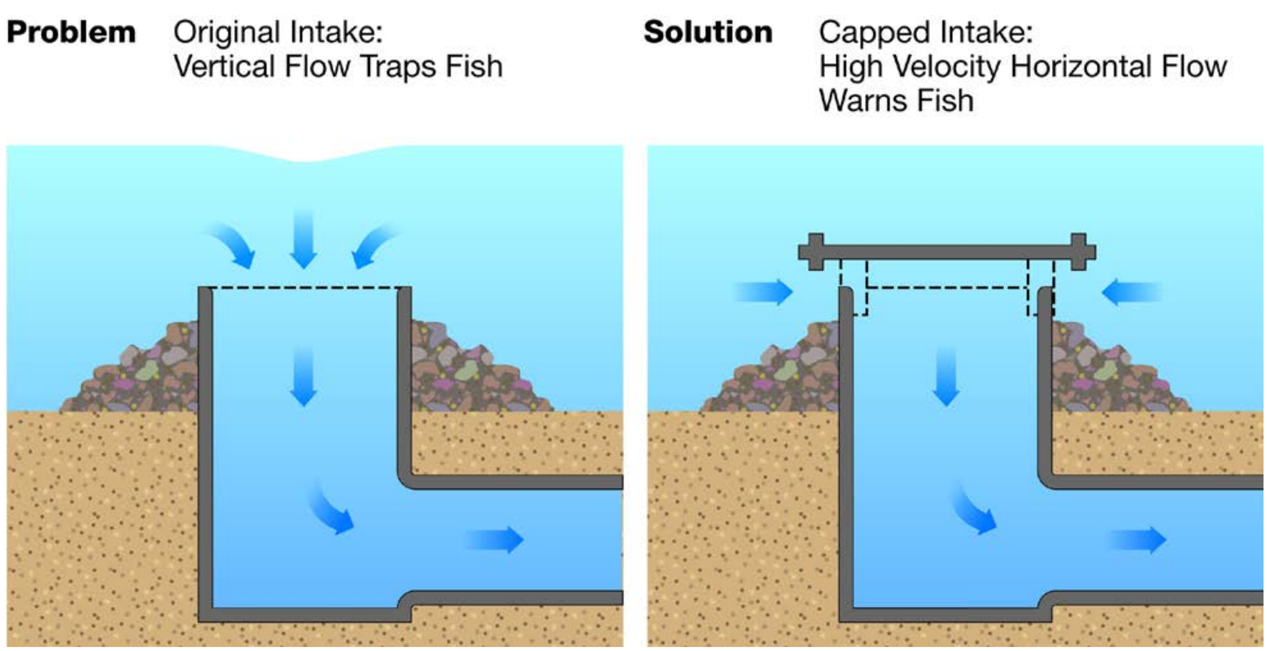

Figure 5 – Velocity Cap for Entrainment Reduction

Other Impingement and Entrainment Reduction Technologies. In addition to the intake technologies described above, there are a number of other technologies which have been demonstrated to reduce the impingement and entrainment of open intake operations, mainly based on testing at existing power plant intakes.

Table 1 provides a summary of such technologies. Not all of the technologies listed in the table can meet the US EPA performance targets under all conditions and circumstances or deliver both impingement and entrainment benefits. However, if needed, these technologies could be used in synergistic combination to achieve project-specific environmental impact reduction targets.

Table 1
Potential Impingement and Entrainment Reduction Technologies

Type of I&E Reduction Measures	**How Do They Work?**	**Technologies**	**Impact Reduction Potential**	
			Impingement	**Entrainment**
Physical Barriers	By Blocking Fish Passage and Reducing Intake Velocity	• Wedgewire Screens • Fine Mesh Screens • Microscreening Systems • Barrier Nets • Aquatic Filter Barriers	Yes	Yes
Collection & Return Systems	Equipment is Installed on Fine Screens for Fish Collection and Return	• Ristroph Travelling Screens • Fine Mesh Travelling Screens	Yes	Yes
Diversion Systems	Devices Which Divert Fish from the Screens and Return	• Angled Screens with Louvers • Inclined Screens	Yes	Yes
Behavioral Deterrent Devices	Repulsing Organisms from the Intake by	• Velocity Caps • Acoustic Barriers	Yes	No

	Introducing Changes that Alert Them	• Strobe Lights • Air Bubble Curtains		

Fine mesh screens are one of the technologies equally popular for both desalination and power plant intakes. One type of fine mesh screen associated with the operations of the 95,000 m^3/day (25 MGD) Tampa Bay seawater desalination plant is shown on Figure 6.

This desalination plant is collocated with the 1200 MW Big Bend Power Plant and uses cooling water from this plant as source seawater for desalination. The Tampa Bay desalination plant does not have a separate seawater intake. However, the intake of the power plant is equipped with 0.5-mm Ristroph fine-mesh screens, which have been proven to reduce impingement and entrainment of fish eggs and larvae through the downstream conventional bar and fine screens of the power plant intake by over 80% at this site (US EPA, 2011).

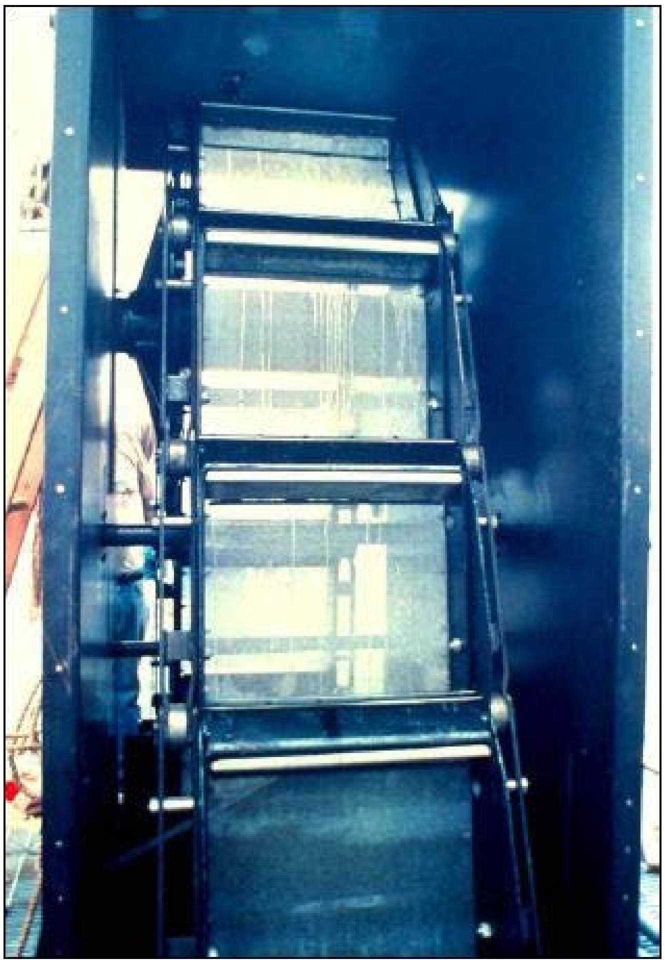

Figure 6 – 0.5 mm Fine-mesh Screens of the Tampa Bay Power Plant Intake

Unfortunately for the desalination plant, these screens are periodically bypassed (as allowed by permit) and/or screenings are conveyed to the power plant discharge outfall from where the desalination plant collects source seawater. As a result, the screenings can find their way to the desalination plant intake and impact desalination plant pretreatment system performance. This challenge necessitated the need for the remediated desalination plant to be equipped in 2005 with another set of fine screens located just upstream of the pretreatment facilities.

I&E Mitigation Measures

Environmental impact mitigation is typically applied if the site, design and technology measures described above do not provide adequate impingement and entrainment reduction to sustain the biological balance of the marine habitat in the area of the intake. Examples of types of activities that may be implemented by desalination facilities to provide environmental impact mitigation include:

- Wetland restoration;
- Coastal lagoon restoration;
- Restoration of historic sediment elevations to promote reestablishment of eelgrass beds;
- Marine fish hatchery enhancement;
- Contribution to a marine fish hatchery stocking program;
- Artificial reef development; and
- Kelp bed enhancement.

The type and size of the mitigation alternative or combination of alternatives most suitable for a given project are typically selected to create a new habitat capable of sustaining types of species and levels of biological productivity comparable to those lost as a result of the intake operations. Since coastal wetlands are often the nursery areas for many of the species impacted by desalination intakes, wetland restoration is frequently the mitigation measure of choice. For example, development of new coastal wetlands is the preferred impingement and entrainment mitigation alternative for the 190,000 m^3/day (50 MGD) Carlsbad seawater desalination project in California.

The time and cost expenditures involved in the permitting, implementation, maintenance, and monitoring of such mitigation measures are significant, and such habitat restorative measures are typically used when the impingement and entrainment reduction measures described in the previous sections are not readily available or viable for a given project.

Some environmental groups do not consider mitigation as an acceptable I&E management alternative and have challenged the legality of the use of I&E mitigation measures for both power plant and desalination plant intakes. Court resolutions to recent legal challenges associated with the permitting of the Carlsbad and Huntington Beach SWRO projects in California, however, indicate that mitigation by environmental restoration is an acceptable I&E management solution as long as it is applied along with Best Technology Available and suitable for the site specific project conditions.

2.2. Subsurface Intakes

Because subsurface intakes naturally filter the collected saline water through the granular formations of the coastal aquifer in which they operate, their use minimizes entrainment of aquatic organisms into the desalination plant. The source saline water collected by this type of intake typically does not require mechanical screening and therefore, subsurface intakes do not cause impingement impacts on the aquatic organisms in the area of the intake.

Subsurface intakes could have a number of environmental impacts, such as loss of coastal habitat during construction, visual and aesthetic impacts, and could affect nearby coastal wetlands depending upon their method of construction and their design for well completion. The magnitude of these impacts and potential mitigation measures are discussed below.

Loss of Local Habitat during Construction

Small desalination plants (i.e., facilities with fresh water production capacity of 20,000 m^3/day/ 5 MGD or less) typically require a limited number of vertical intake wells and their impact on the natural habitat near the wells during construction is generally minimal. The individual vertical intake wells for such installations are usually of capacity between 400 to 4,000 m^3/day (0.1 to 1.1 MGD) can often be constructed as low-profile structures or completely buried structures to minimize visual impacts. Because of the higher number of wells needed to supply adequate amounts of water for a large desalination plant, construction of these facilities may result in impacts over a larger area of local habitat, and since large wells are often constructed as above-grade structures, they have visual and aesthetic impacts – Figure 7.

If the site-specific geological conditions allow, SWRO plants collecting source water from coastal aquifers or BWRO plants using brackish aquifers could use high-production HDD and/or radial/collector wells to reduce the number of the needed individual wells and thereby, to minimize environmental impacts associated with their installation. This type of high-productivity wells would typically yield 7,500 to 20,000 m^3/day (2 to 5 MGD) or more of source water per individual well.

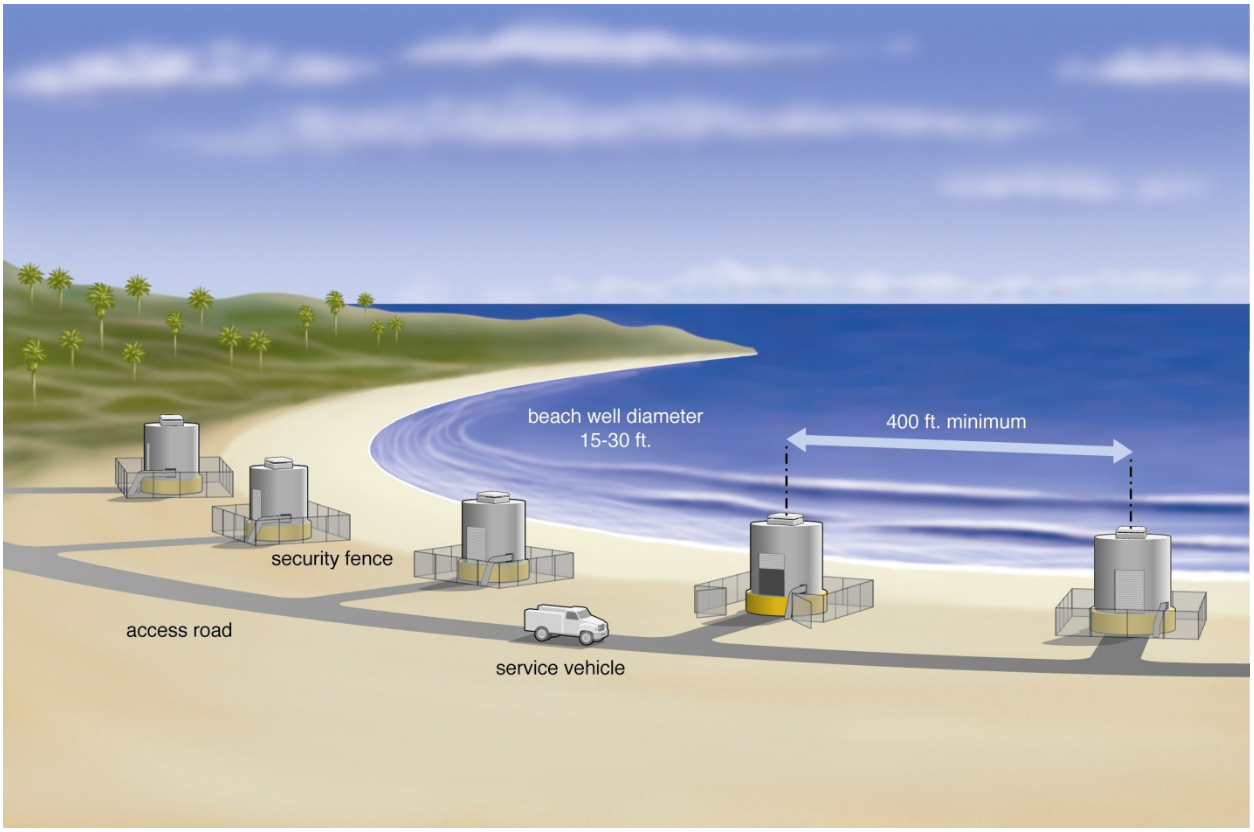

Figure 7 – Beach Well Intakes – Visual Impact

For example, a hypothetical 40,000 m^3/day (11 MGD) seawater desalination plant (which requires 100,000 m^3/day (26 MGD of intake flow) would need the construction of up to five operational and one standby beach wells of unit capacity of 20,000 m^3/day (5 MGD) each to provide an adequate amount of source water.

If radial or HDD wells are used, the minimum distance between the individual wells would be 120 meters (400 ft) and the impacts would be spread over up to 600 meters (2,000 ft) of the shoreline. Therefore, the minimum terrestrial area (i.e., seashore) impacted during the construction of beach wells for a 40,000 m^3/day (11 MGD) desalination plant could be up to 30 m x 600 m = 18,000 m^2 = 1.8 ha (4.5 acres).

Visual and Aesthetic Impacts

The visual and aesthetic impacts of well intakes will be dependent upon the location of the wellhead and the style of well completion used. If the well intake must be constructed above-grade, the pumps, electrical controls, motors, and auxiliary equipment typically are installed above the wet well of the caisson and/or above known or anticipated high water (e.g. tidal or flood) elevations. In these cases, the height of the structure may be 3 meters (10 ft) or more above ground as seen in Figure 8.

The above-grade pump house facility could be designed in virtually any architectural style, however, this facility and its access provisions would change the visual landscape of the area in the vicinity of the intake. Taking under consideration that the desalination plant source water has to be protected from acts of vandalism and terrorism, if built above ground, the individual wells may need to be fenced-off or otherwise protected from unauthorized access. The access to large above-grade intake well structures would need to be secured and/or to be fenced off (see Figure 7).

If the intake wells are located in visually sensitive areas (i.e., public beaches), the installation of above-grade wells may degrade the recreational and tourism uses and value of the intake area (i.e., seashore), and may change area's appearance and character.

A potential solution to this environmental challenge is to construct the intake wells below-grade, at grade or near-grade to minimize impacts. The electrical controls and auxiliary equipment of the well intake system could be installed within the water-tight structure or located in a remote area near the intake for protection, if needed.

In these cases, there might be little or no visual and aesthetic impacts for this kind of intake completion. However, the costs associated with such well intakes and their support structures (pump control facilities, electrical substation, power supply conduits, etc.) would increase measurably.

Another alternative solution is to use open intakes, which similar to near- and below-grade well intakes are typically lower-profile structures that may blend better with the surrounding environment. The open intake piping can be directionally drilled under the seashore and/or ocean bottom to minimize both visual impact and impact on other coastal uses (recreation, water sports, fishing, etc.).

Figure 8 – Radial Intake Well of Large Seawater Desalination Plant

If the desalination plant is collocated with an existing power plant, construction of new on-shore structures or facilities is typically not required and therefore, it is more favorable in terms of additional negative visual and aesthetic impact on the coastal environment and landscape.

Potential Impact on Wetlands and Groundwater Supplies

Operation of intake wells may have a negative impact on other local groundwater resources (i.e., fresh drinking water aquifers) or water bodies (i.e., perched water, wetlands or salt water-fresh water interfaces), which are hydraulically connected to the well extraction aquifer and such groundwater resources are within the radius of influence of the intake wells.

Special attention should be given to intake well sites in the vicinity of existing fresh water supply well fields. Beach wells which area of influence/source water collection extends to a nearby fresh/brackish groundwater aquifer may have a negative impact on the aquifer capacity and water quality, and in some cases their operation may result in enhanced seawater intrusion (see Figure 9).

The operation of large intake wells located adjacent to wetlands may result in a drawdown of the groundwater table that could affect (i.e., dry-up) the wetlands, degrade local groundwater quality (e.g. increase its salinity) and cause other environmental impacts. Year-around study of the interaction between the aquifer/s from which water is extracted and nearby wetlands and underlying groundwater resources is warranted under such circumstances.

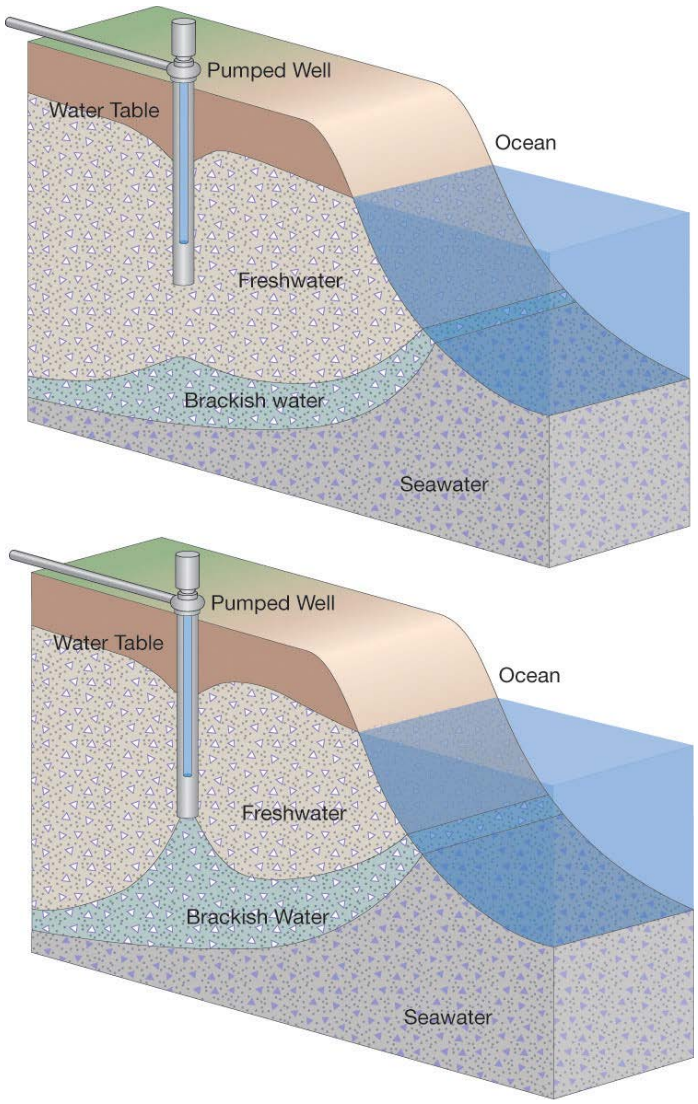

Figure 9 – Seawater Intrusion Caused by Beach Well Operation

3. Discharge – Environmental Challenges and Solutions

One of the key limiting factors for the construction of new desalination plants is the availability of suitable conditions and locations for disposal of the high-salinity side-stream commonly referred to as concentrate or brine. 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. If chemical pretreatment is used, such as coagulants, antiscalants, polymers or disinfectants, some or all of these chemicals may reach or may be disposed along with the plant discharge concentrate.

The quantity of the concentrate is largely a function of the plant recovery, which in turn is highly dependent on the TDS concentration of the source water. Concentrate quality is determined by the content of minerals and other contaminants in the saline source water.

Because the most prevalent method of concentrate disposal for both seawater and brackish water desalination plant is surface water discharge, this course focuses mainly on environmental impacts desalination plant discharges to surface waters.

Key environmental issues and considerations associated with concentrate disposal to surface waters include: (1) salinity increase beyond the tolerance thresholds of the aquatic species in the area of the discharge; (2) concentration of source water constituents (i.e., metals, nutrients, radioactive ions, etc.) to harmful levels; (3) discharge discoloration and low oxygen content.

3.1. Salinity Tolerance of Aquatic Species

The main environmental impact of concentrate on aquatic life in the vicinity of desalination plant discharge is typically associated with the salinity of this discharge and the ability of the native habitat to tolerate this salinity.

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 during which these organisms are exposed to elevated salinity (Mickley, 2006). 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 salinity fluctuations in the surface waters receiving concentrate from a given desalination plant 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 surface water quality monitoring. In open ocean waters, the typical range of natural salinity fluctuation is at least ± 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 (Voutchkov, 2013). Please note that 1 ppt (parts per thousand = 1,000 mg/L. Typical Pacific Ocean water salinity is 33.5 ppt (e.g., contains 33,500 mg/L of dissolved solids)

Salinity in brackish surface waters and bays and estuaries, could vary in a significantly wider range and therefore, most species inhabiting such water are more easily adoptive to high salinity discharges. Seawater desalination plants usually produce concentrate salinity, which is approximately 1.5 to 2 times higher than the salinity of the ambient seawater. Since ocean water salinity in US open-ocean coastal waters typically varies between 33 ppt to 35 ppt, concentrate salinity is usually in a range of 52 ppt to 70 ppt.

While many marine organisms can adapt to this salinity range, some aquatic species are less tolerant to elevated salinity concentrations than others. For example, gobies, which are one of the most common species inhabiting California coastal waters, are tolerant to relatively high salinity concentrations and are well-known to inhabit the Salton Sea of California, which currently has an ambient salinity of 45 ppt. However, other common organisms such as the abalone and sea urchins have lower salinity tolerance.

The nature, magnitude and significance of elevated concentrate salinity impacts mainly depend upon the type of marine organisms inhabiting the discharge area and the length of time of their exposure. A salinity tolerance study implemented in 2005 as part of the environmental impact review of the 50 MGD Carlsbad seawater desalination project, and completed based on testing of over two dozen marine species frequently encountered along the California coast, indicates that based on whole effluent toxicity (WET) tests these marine species can safely tolerate salinity of 40 ppt (19.4 % above ambient salinity) – (Poseidon Resources, 2007).

For this case in point, it is important to note that subsequent acute toxicity bioassay testing using standard top smelt test organisms (*Atherinops affinis*) completed in conformance with the National Pollutant Discharge Elimination System (NPDES) permit requirements for the Carlsbad desalination project identified the following:

- The No Observed Effect Concentration (NOEC) of the test occurred at 42 ppt of concentrate salinity;
- The Lowest Observed Effect Concentration (LOEC) was found to be 44 ppt;
- The plant was well below the applicable toxicity limit for salinity of 46 ppt or lower;
- The No Observed Effect Time (NOET) for 60 ppt concentration was 2 hours,
- The Lowest Observed Effect Time (LOET) for the 60 ppt concentration was 4 hours. This means that for a short period of time the species may be exposed to salinity as high as 60 ppt without any observed effect (Poseidon Resources, 2007).

A site investigation of a number of existing full-scale seawater desalination plants operating in the Caribbean completed by scientists from the University of South Florida and the South Florida Water Management District (Hammond et al., 1998) has concluded that the salinity levels of 45 ppt to 57 ppt have not caused statistically significant changes in the aquatic environment in the area of the discharge.

3.2. Concentration of Source Water Constituents to Harmful Levels

As indicated previously, salinity-related toxicity to aquatic life is the prime source of environmental impacts associated with surface water discharges. However, besides salinity, RO membrane separation process also removes over 90% of most of the other constituents in the source water and concentrates these constituents in the discharge between 1.5 and 10 times depending on the desalination plant recovery. Therefore, some contaminants in the saline source water (i.e., heavy metals, arsenic, cyanide, nitrates, toxins) that are regulated due to their potentially harmful impacts on the environment may be concentrated to levels that exceed acceptable regulatory thresholds.

In order to assess the potential environmental impacts of regulated water constituents, concentrate water quality should be tested for such constituents and their actual levels should be compared to pertinent numeric regulatory standards. Practical experience shows that in most cases, BWRO and SWRO concentrate water quality meets regulatory standards associated with most surface waters. However, depending on the site-specific conditions and discharge configuration and location, some source water constituents, other than TDS, could potentially reach harmful levels.

For example, 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 surface source 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 SWRO plant concentrate is likely to contain elevated gross alpha radioactivity. This condition is not unusual for both Pacific and Atlantic Ocean waters and must be well documented with adequate water quality sampling in order to avoid potential regulatory challenges.

Toxins such as domoic acid and saxitoxin, which are released by decaying algae during red tides and other algal bloom events could potentially be harmful to human health and/or the marine environment, and are known to cause shellfish poisoning. However, practical experience shows that even under severe algal bloom conditions, such toxins typically occur at levels that do not present threat for human health through direct injection of the desalinated water or concentrate.

These toxins could cause shellfish poisoning because they concentrate in shellfish tissue several hundred times at which level they exceed human health toxicity levels. For comparison, SWRO plants concentrate algal toxins only 1.5 to 2 times and at such concentrations these toxins are below the human toxicity threshold. A practical solution to such challenge is to either use desalination plants with deep open intakes or subsurface intakes in order to minimize the collection of algae and therefore the toxins in their cells.

3.3. Discharge Discoloration and Low Oxygen Content

Concentrate from Plants with Open Intakes. Typically, concentrate from desalination plants with open surface water (ocean, river) intakes has the same color, odor, dissolved oxygen (DO) content and transparency as the source water from which it was produced, and increase or decrease in salinity will not change its physical characteristics or aesthetic impact on the environment. Usually, there is no relation between the level of salinity and biological or chemical oxygen demand of the desalination plant concentrate from open intakes.

Therefore, concentrate generated by desalination plants with open intakes typically does not pose significant environmental challenges in terms of color and oxygen content. In fact, in some cases, such plant discharge may have higher content of oxygen than the surface waters to which it is discharged and actually may improve the quality on the receiving water body in terms of dissolved oxygen content.

Acids and scale inhibitors are often added to the desalination plant source water to facilitate the salt separation process. Typically, these additives are rejected by the reverse osmosis membranes and are collected in the concentrate. However, such source water conditioning compounds are applied at very low concentrations and their content does not alter significantly the water quality and quantity of the concentrate. The environmental implications of the use of such additives are typically well tested before their use, and only additives that are proven harmless for the environment and approved by pertinent regulatory agencies are actually applied for seawater treatment. All chemical additives used at desalination plants are typically of high-grade purity and are approved for human consumption.

One condition which may cause a reduction and ultimately a depletion of the naturally high level of oxygen in the concentrate from desalination plants with open intakes is the overdosing of reducing chemical (i.e., sodium bisulfite of sulfur dioxide) which is added to remove chlorine in the saline water fed to the desalination plant RO membrane system.

Typically, reducing chemical is applied at dosage proportional to the chlorine content in the source water such that total chlorine residual in this water is reduced to less than 0.05 mg/L in order to protect the RO membranes from oxidation. However, sometimes due to operator error or monitoring instrument malfunction, the concentration of sodium bisulfite may exceed the dosage needed for removal of chlorine in the RO system feed water. In such cases, the excessive content of reducing chemical left after de-chlorination will react with the oxygen in the source water and reduce its content. As a result, both the desalination plant concentrate and the product water will have DO levels lower than these of the saline source water.

This potential environmental challenge is typically addressed by the installation of multiple instruments for monitoring of chlorine content and oxidation-reduction potential (ORP) of the water treated with reducing chemical and concentrate – typically two ORP meters and one chlorine residual analyzer are installed in series on the pipeline feeding the RO system with source water. The ORP of the source water is an indirect indication of its oxygen content. In addition, ORP is measured in the desalination plant source water and concentrate. If the ORP of the water treated with reducing chemical decreases below 10% of the ORP of the source water, than the dosage of the reducing chemical is decreased.

On condition when the concentrate from surface water source could be discolored is when it is blended with untreated spent filter backwash water from the desalination plant pretreatment facilities especially if such backwash water contains iron-based coagulant (ferric hydroxide). Since ferric hydroxide (which also is commonly known as rust) has a red color when it is blended with the colorless concentrate it will discolor the desalination plant discharge and may degrade the quality of the receiving surface waters.

If such discharge is directed to a groundwater aquifer via deep well injection, it will degrade aquifer water quality and over time will decrease well discharge capacity. If discharged to the ocean, it will cause reddish discoloration of the ocean water, which is not acceptable by US EPA regulatory requirements (see Figure 10).

Figure 10 – Desalination Plant Discharge with Elevated Iron Content

A commonly applied solution to such environmental challenges is treatment of spent filter backwash water in solids handling facilities including lamella sedimentation with subsequent dewatering of the sludge collected in the sedimentation tanks by mechanical dewatering equipment (centrifuges or belt filter presses).

The dewatered sludge, which typically contains over 95% of the coagulant is usually disposed to a landfill in solid form. For smaller desalination plants, the desalination plant spent filter backwash water and other pretreatment conditioning chemicals are discharged to the nearby sanitary sewer for further treatment in a wastewater treatment plant. Most membrane pretreatment-based systems do not use a coagulant and therefore, are not challenged with the discharge discoloration issue.

Concentrate from Plants with Subsurface Intakes. The dissolved oxygen concentration of source water collected by intake wells is usually less than 2 mg/l, and it often varies between 0.2 and 1.5 mg/L. Desalination plant processes do not add appreciable amount of DO to the intake water. Therefore, desalination plant product water and concentrate typically have DO concentration similar to that of the source water. Low DO concentration of the product water will require either re-aeration or will result in significant use of chlorine.

If the low DO concentrate from desalination plant is to be discharged to an open water body – an ocean or a river, this discharge typically would not be in compliance with the United States Environmental Protection Agency's daily average and minimum DO concentration discharge requirements of 5 mg/L and 4 mg/L, respectively. Because large desalination plants using intake wells would discharge a significant volume of low-DO concentrate, this discharge could cause oxygen depletion and stress to aquatic life. Therefore, this beach well desalination plant concentrate has to be re-aerated before surface water discharge.

For a large desalination plant, the amount of air and energy to increase the DO concentration of the discharge from near zero to 4 mg/L is significant and would have effect on the fresh water production costs. Discharge of this low DO concentrate to a wastewater treatment plant outfall would also result in a significant additional power use to aerate this concentrate prior to discharge. For comparison the concentrate from desalination plants with open intakes would typically have DO concentration of 5 to 8 mg/L, which is adequate for disposal to a surface water body, without re-aeration.

An alternative solution to this low discharge DO concentration challenge is to direct the concentrate for discharge to an aquifer of lower oxygen content, if such aquifer is available in the vicinity of the desalination plant and discharge water quality will not degrade the aquifer in terms of other water quality parameters, such as salinity, solids, silt, etc.

4. Greenhouse Gas Emissions Associated with Plant Operations

4.1. Introduction

Gases that trap heat in the atmosphere are referred to greenhouse gases (US EPA, 2006). Some greenhouse gases such as carbon dioxide occur naturally and are emitted to the atmosphere through natural processes and human activities. Other greenhouse gases (e.g., fluorinated gases) are created and emitted solely through human activities. The principal greenhouse gases that enter the atmosphere because of human activities are carbon dioxide, methane, nitrous oxide, and fluorinated gases.

Carbon dioxide enters the atmosphere through the burning of fossil fuels (oil, natural gas, and coal), solid waste, trees and wood products, and also as a result of other chemical reactions (e.g., manufacture of cement). Carbon dioxide is also removed from the atmosphere (or "sequestered") by plants as a part of their biological carbon cycle.

Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock and other agricultural practices and by the decay of organic waste in municipal solid waste landfills. Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.

Hydrofluorocarbons, per fluorocarbons, and sulfur hexafluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes. These gases are typically emitted in smaller quantities, but because they are potent greenhouse gases, they are sometimes referred to as High Global Warming Potential gases ("High GWP gases").

Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans and ultimately result in global and local climate variability and permanent changes (NRC, 2001). Many elements of human society and the environment are sensitive to climate variability and change. Human health, agriculture, natural ecosystems, coastal areas, and heating and cooling requirements are examples of climate-sensitive systems. The extent of climate change effects, and whether these effects prove harmful or beneficial, will vary by region, over time, and with the ability of different societal and environmental systems to adapt to or cope with the change.

Rising average temperatures are already affecting the environment. Some observed changes include shrinking of glaciers, thawing of permafrost, later freezing and earlier break-up of ice on rivers and lakes, lengthening of growing seasons, shifts in plant and animal ranges and earlier flowering of trees (IPCC, 2007).

Global temperatures are expected to continue to rise as human activities continue to add carbon dioxide, methane, nitrous oxide, and other greenhouse (or heat-trapping) gases to the atmosphere. Most of the United States is expected to experience an increase in average temperature as a result of increase in greenhouse gas emissions (IPCC, 2007).

According to a recent US EPA GHG emission inventory the primary greenhouse gas emitted by human activities in the United States in 2006 was CO2, representing approximately 84.8% of total greenhouse gas emissions (US EPA, 2008). The largest source of CO_2, and of overall greenhouse gas emissions is fossil fuel based production of electricity. Second largest source is transportation. Despite the disproportional attention of some environmental groups to greenhouse emissions associated with water production, both conventional and membrane water treatment plants are actually not major sources of GHGs.

4.2. Greenhouse Gas Emission Management

GHG management of seawater desalination plant is relatively new in the USA. The key steps in such management is the development of a Climate Action Plan (CAP), which defines the carbon footprint of desalination plant operations as well as identifies a portfolio of alternative technologies and measures to achieve carbon footprint project neutrality: from the use of state-of-the-art energy reduction technologies to the implementation of renewable energy projects, and of carbon dioxide sequestration initiatives including onsite carbon dioxide use, reforestation and coastal wetland restoration.

An example of the key steps and approaches for the development of CAP is presented in a case study for the 190,000 m^3/day (50 MGD) Carlsbad seawater desalination plant. This plant is collocated with the Encina coastal power generation station, which currently uses seawater for once-through cooling (Figure 11). The desalination plant has been in operation since December 2015.

To address the raising global greenhouse emissions challenge, in 2006 California legislation introduced the AB 32 Global Warming Solutions Act which aims to reduce the greenhouse gas (GHG) emissions of the state to 1990 levels by year 2020. In response to this legislation, the Carlsbad project proponent and desalination plant owner, Poseidon Water has developed a CAP to completely offset the carbon footprint associated with desalination plant operations. The key components of the Climate Action Plan are described below.

Assessing Project Gross Carbon Footprint

The carbon footprint of the seawater desalination plant is the amount of greenhouse gases that would be released into the air from the power generation sources that will supply electricity for the plant. Usually, carbon footprint is measured in pounds (lbs) or metric tons of carbon dioxide (CO_2) emitted per year. The total plant carbon footprint is dependent on two key factors: (1) how much electricity is used by the desalination plant; and (2) what sources (fossil fuels, wind, sunlight, etc.) are used to generate the electricity supplied to the plant. Both of these factors could be variable over time and therefore, the Climate Action Plan has to have the flexibility to incorporate such changes.

Figure 11 – Configuration of Intake and Discharge of Carlsbad Desalination Plant

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The Carlsbad seawater desalination plant is operated continuously, 24 hours a day and 365 days per year, and to produce an average annual drinking water flow of 189,000 m^3/day (50 MGD). When the plant was originally conceived, the total baseline power use for this plant was projected at 31.3 megawatts (MW) or 3.96 KWh/m^3 (103 KWh/1,000 gallons) of drinking water. This power use incorporates both production of fresh drinking water and conveyance, and delivery of this water to the distribution systems of the individual utilities and municipalities served by the plant.

However, over the lengthy period of project environmental review, the seawater desalination technology has evolved. By taking advantage of the most recently available state-of-the art technology for energy recovery and by advancing the design to accommodate latest high efficiency reverse osmosis system feed pumps and membranes, the actual project power use was reduced down to 3.56 kWh/m^3 (13.48 KWh/1,000 gallons) of drinking water. As a result, the total annual energy consumption for the Carlsbad seawater desalination project used to determine the plant carbon footprint is 246,000 MWh/yr. This energy use is determined for an annual average plant production capacity of 189,000 m^3/day (50 MGD). As actual production capacity may vary from year to year, so it would the total energy use.

Next, in order to convert the desalination plant annual energy use into carbon footprint (CF), this use is multiplied by the electric grid emission factor (Emission Factor), which is the amount of greenhouse gasses emitted during the production of unit electricity consumed from the power transmission and distribution system:

$$\text{CF (lbsCO}_2\text{/yr)} = \text{Annual Plant Electricity Use (MWh/yr)} \times \text{Emission Factor (lbs of CO}_2\text{/MWh)}$$

The actual value of the Emission Factor is specific to the actual supplier of electricity for the project. In the Case of the Carlsbad seawater desalination project this is San Diego Gas and Electric (SDG&E). Similar to other power suppliers in California, SDG&E determines their Emission Factor based on a standard protocol developed by the California Climate Action Registry

(CCAR). CCAR was created by California Legislature (SB 1771) in 2001 as a non-profit voluntary registry for GHG emissions and is the authority in California that sets forth the rules by which GHG emissions are determined and accounted for.

Based on information provided in their year 2008 emissions report (CCAR, 2008) the SDG&E emission factor is 546.46 lbs of CO_2 per MWh of delivered electricity. At 246,000 MWh/yr of energy use and 546.46 lbs CO_2/MWh, the total carbon footprint for the Carlsbad seawater desalination project is calculated at 134.4 million lbs of CO_2 per year (61,100 metric tons CO_2/yr). This carbon footprint is reflective of the latest energy efficient design of the desalination plant. A more conventional desalination plant design (274,000 MWh/hr) would have a carbon footprint of 68,100 tons CO_2/yr.

It is important to note that the value of the emission factor is reduced with the increase of the portion of renewable power sources in power supplier's energy resource portfolio. Because of the statewide initiatives and legislation to expand the use of renewable sources of electricity, the emission factors of all California power suppliers are expected to decrease measurably in the future. For example, currently approximately 10% of SGD&E's retail electricity is generated from renewable sources (solar radiation, wind, geothermal heat, etc.). In their most-recent Long-term Energy Resource Plan, SDG&E has committed to increase energy from renewable sources by 1% each year, reaching 20% by the end of year 2017.

Table 2 presents the total annual amount of carbon dioxide emissions associated with the operation of the Carlsbad desalination plant expressed in tons of CO_2 per year of 61,100 tons CO_2/yr – which is also referred to as the total desalination plant "carbon footprint".

Table 2
Desalination Project Net GHG Emission Zero Balance

Carbon Dioxide Emission Generation		
Source	**Total Annual Power Use (MWh/ year)**	**Total Annual Emissions (tons CO_2/ year)**
1. Seawater Desalination and Product Water Delivery – High Energy Efficiency Design	246,000	61,100
2. Carbon Emission Reduction Due to	190,700	47,400

Reduced Water Imports		
3. Total Net Power Use & Carbon Emissions (Item 1 – Item 2)	**55,300**	**13,700**
On-site Carbon Dioxide Emission Reductions		
4. Energy Efficient Plant Design	Accounted for In Item 1	Accounted for In Item 1
5. Use of Warm Cooling Water	(12,300)	(3,100)
6. Green Building Design	(500)	(124)
7. On-site Solar Power Generation	(777)	(193)
8. Use of CO_2 for Water Production	NA	2,100
9. Reduced Energy for Water Reclamation	1,950	(484)
10. Subtotal On-site Power/GHG Emission Reduction (Sum of Items 4 through 9)	**(15,527)**	**(6,001)**
Off-site Carbon Dioxide Emission Mitigation		
11. CO_2 Sequestration by Re-vegetation of Wildfire Zones	(NA)	(166)
12. CO_2 Sequestration in Coastal Wetlands	(NA)	(526)
13. Investing in Renewable Energy Projects	(2,260)	(561)
14. Other Carbon Offset Projects and Purchase of Renewable Energy Credits	(37,513)	(6,446)
15. Subtotal Off-site Power/GHG Mitigation Reduction (Sum of Items 11 through 14)	**(39,773)**	**(7,699)**
Total Net CHG Emission Balance (Item 3 – Item 9 – Item 14)		**0**

Taking under consideration that the plant supplies water for 416,000 people, the average carbon footprint per person is 0.15 tons/person per year. Taking under consideration that the carbon footprint of the average American is 20 tons/year, desalinated water constitutes 0.75% the total annual carbon footprint of a single person.

Table 2 summarizes the measures incorporated into the plant design and operations to mitigate the desalination plant carbon footprint and to ultimately reduce it down to zero. These measures are summarized in a formal environmental impact mitigation document referred to as "Climate Action Plan for Carbon Footprint Reduction".

Climate Action Plan For Net Carbon Footprint Reduction

The main purpose of the activities included in the Climate Action Plan for a given desalination project is to eliminate plant's net carbon footprint by implementing a combination of as many of the following measures as practically viable: energy efficient facility design and operations; green building design; use of carbon dioxide for water production; on-site solar power generation; carbon dioxide sequestration by creation of coastal wetlands and reforestation; funding renewable power generation projects, and acquisition of renewable energy credits. Project carbon neutrality typically is achieved by a balanced combination of these measures.

The size and priority of the individual projects included in the Climate Action Plan should be determined based on a life-cycle cost-benefit analysis and overall benefit for the local community. Implementation of energy efficiency measures for water production, green building design, and carbon dioxide sequestration projects in the vicinity of the project site will be given the highest priority.

This table also summarizes the measures incorporated into the plant design and operations to mitigate the desalination plant carbon footprint and to ultimately reduce it down to zero. These measures are summarized in a formal environmental impact mitigation document referred to as "Climate Action Plan for Carbon Footprint Reduction".

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The main purpose of the Climate Action Plan for a given desalination project is to eliminate plant's net carbon footprint by implementing a combination of as many of the following measures as practically viable: energy efficient facility design and operations; green building design; use of carbon dioxide for water production; on-site solar power generation; carbon dioxide sequestration by creation of coastal wetlands and reforestation; funding renewable power generation projects, and acquisition of renewable energy credits. Project carbon neutrality typically is achieved by a balanced combination of these measures.

The size and priority of the individual projects included in the Climate Action Plan should be determined based on a life-cycle cost-benefit analysis and overall benefit for the local community. Implementation of energy efficiency measures for water production, green building design, and carbon dioxide sequestration projects in the vicinity of the project site will be given the highest priority.

The project Climate Action Plan is a living document that has to be updated periodically in order to reflect the dynamics of development of desalination and green energy generation technologies; and the efficiency and cost-effectiveness of various carbon footprint reduction and offset alternatives.

For example, once the Carlsbad seawater desalination plant is operational, the actual carbon footprint will be verified at the time of plant startup and will be updated periodically to account for changes in power supplier's Emission Factor, and for the actual performance of the already implemented carbon footprint reduction initiatives. Periodic assessment and re-prioritization of activities that keep the desalination plant operations "green" is a very essential component of the Climate Action Plan because both desalination technology and green power generation (i.e., solar, wind and bio-fuel-based power) are expected to undergo accelerated development over the next decade as they evolve from marginal to mainstream sources of water supply and power supply, respectively.

The specific carbon footprint reduction measures incorporated in the Carlsbad Climate Action Plan, and their key benefits and constraints are discussed below.

Offsetting Carbon Footprint By Reduced Water Imports

In many parts of the World such as Spain, Israel, Singapore, and Australia and for example in California, most seawater desalination plants are built to replace in or out of state water transfers. Long-distance water transfers are often very energy intensive and the carbon footprint of such water supply alternatives may be comparable to that of desalination plant of similar capacity. Offsetting the carbon footprint of such long-distance water transfers by building desalination plant can be counted as a carbon-footprint reduction measure for the desalination plant.

For example, San Diego County imports approximately 90% of its water from two sources – the Sacramento Bay – San Joaquin River Delta, traditionally known as the "Bay-Delta", and the Colorado River. This imported water is captured, released and conveyed via a complex system of intakes, dams, reservoirs, aqueducts and pump stations (State Water Project), and treated in conventional water treatment plants prior to its introduction to the water distribution system. The total amount of electricity needed to deliver this water to San Diego County via the State Water Project facilities is 2.76 KWh/m^3 (10.45 KWh/1,000 gallons), which includes 2.62 KWh/m^3 (9.93 KWh/1,000 gallons) for delivery, 0.06 kWh/m^3 (0.21 KWh/1,000 gallons) for evaporation losses, and 0.08 KWh/m^3 (0.31 KWh/1000 gallons) for treatment.

Over the past decade the availability of imported water from the State Water Project has been in steady decline due to prolonged drought, climate change patterns and environmental, and population growth pressures. One of the key reasons for the development of the Carlsbad seawater desalination project is to replace 189,000 m^3/day (50 MGD) of the water imported via the State Water Project with fresh drinking water produced locally by tapping the ocean as an alternative drought-proof source of water supply.

Since the desalination project will offset the import of 189,000 m^3/day (50 MGD) of water via the State Water Project, once in operation, this project will also offset the electricity consumption of 2.76 KWh/m^3 (10.45 KWh/1,000 gallons), and the GHG emissions associated with pumping, treatment and distribution of this imported water.

The annual energy use for importing 189,000 m^3/day (50 MGD) of State Water Project water is therefore, 190,700 MWh/yr. At 546.46 lbs CO_2 /MWh, the total carbon footprint of the water imports that will be offset by desalinated water is therefore, 104.2 million lbs of CO_2 per year (47,400 metric tons CO_2/yr).

Taking under consideration that the gross carbon footprint of the desalination plant is 61,100 metric tons CO_2/yr, and that 47,400 metric tons CO_2/yr (77.4 %) of these GHG emissions would be offset by reduction of 189,000 m^3/day (50 MGD) of water imports to San Diego County, the Carlsbad desalination plant's net carbon footprint is estimated at 13,700 metric tons CO_2/yr.

Lines 1-3 of Table 2 summarize the total annual power use and emissions, the power and emission reduction attributable to reduced water imports, and the net power use and net annual emissions.

Energy Efficient Design and Operations

Over 50% of the energy used at seawater desalination plants is applied for salt-fresh water separation by reverse osmosis. The seawater desalination project design should incorporate technologies and equipment minimizing plant energy consumption. One of them is the use of state-of-the art pressure exchanger-based energy recovery system that typically allows recovering and reusing over 30% of the total initial energy applied for salt separation. After membrane separation, most of the energy applied for desalination is retained in the concentrated stream ("brine") that also contains the salts removed from the seawater.

This energy-bearing stream is applied to the backside of the pistons of cylindrical isobaric chambers, also known as "pressure exchangers". These pistons pump approximately 45 to 50 %

of the seawater fed into the reverse osmosis membranes for desalination. Since a small amount of energy (4 to 6 %) is lost during the energy transfer from the concentrate to the feed water, this energy is added back to feed flow by small booster pumps. The remaining (45 to 50%) of the feed flow is pumped by high-pressure centrifugal pumps, which are equipped with high-efficiency motors (see Figure 12).

For example, the pressure exchanger energy recovery system for the Carlsbad seawater desalination plant is projected to recover 10,200 hp (7.6 MW) of power and yield 2,650 hp (1.98 MW) of additional power savings as compared to the energy that could be recovered using an older generation pelton wheel energy recovery equipment which is common is the US and worldwide.

In addition to the state-of-the-art pressure exchanger energy recovery technology, the Carlsbad desalination plant design incorporates variable frequency drives on seawater intake pumps, filter effluent transfer pumps, and product water pumps as well as premium efficiency motors for all pumps in continuous operation that use electricity of 500 hp-hr or more. Installation of premium-efficiency motors and variable frequency drives on large pumps would result in additional 1.26 MW (4%) power savings.

Harnessing, transferring and reusing the energy applied for salt separation at very high efficiency by the pressure exchangers for the Carlsbad project allows reducing the overall amount of electric power used for seawater desalination with over 11.5% (3.24 MW) as compared to standard designs of similar facilities. These savings correspond to a total annual electricity use reduction of 28,380 MWh/yr and a carbon footprint reduction of 7,000 tons of CO_2/yr and, as shown in Line 4 of Table 2, are already accounted for by the High Energy Efficiency Design figures used in Line 1 of Table 2.

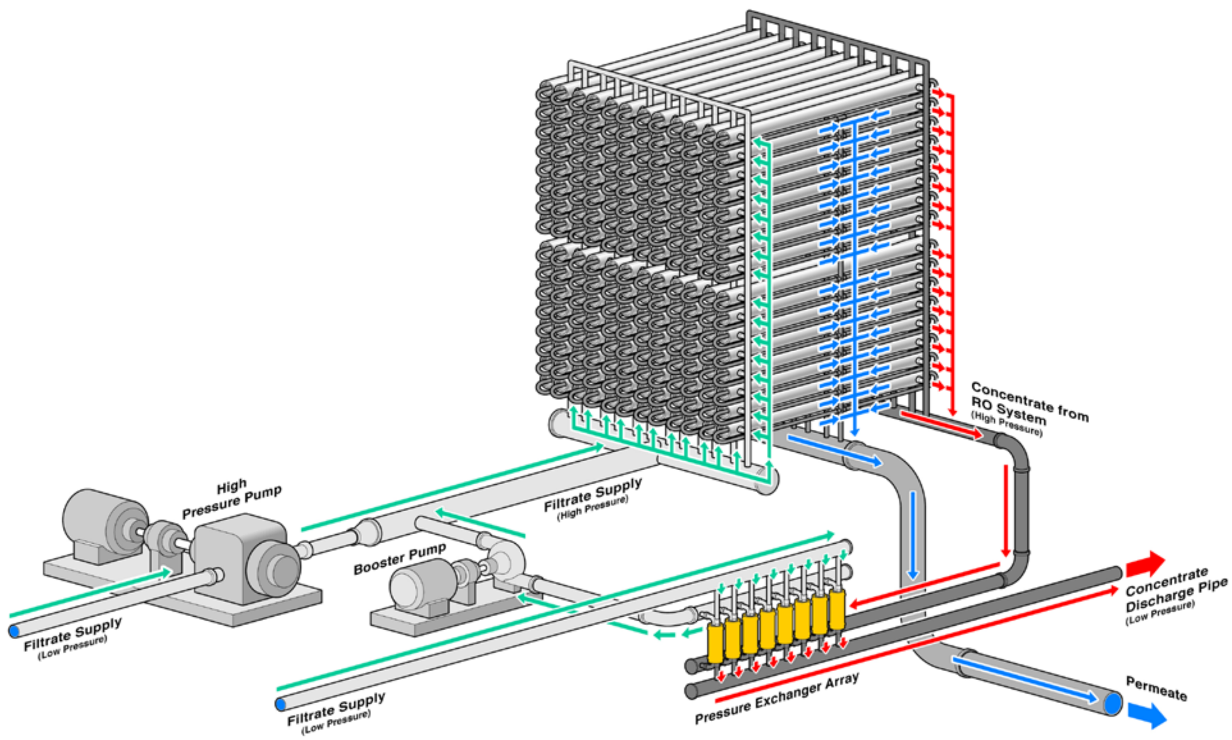

Figure 12 – SWRO Train with "Pressure Exchangers" for Energy Recovery

Over 80% of the desalination plant piping would be made of low-friction fiberglass reinforced plastic (FRP) and high-density polyethylene (HDPE) materials, which in turns would yield additional energy savings for seawater conveyance. The desalination plant operations will be fully automated, which would allow reducing plant staff requirements and associated GHG emissions for staff transportation and services.

Use of Warm Cooling Water

Viscosity of seawater decreases with the increase of seawater temperature – as a result desalination of warmer seawater requires less energy. The Carlsbad seawater desalination plant is collocated with the Encina power plant and its intake is connected to the cooling water canal to take advantage of the warmer seawater discharged by the desalination plant. The difference between the average annual temperatures of the ambient ocean seawater and the warm seawater, which will be used as source water for the desalination plant, is 5^0C.

Based on pilot testing results, this temperature increment is projected to result in 5% of additional energy savings and carbon footprint reduction, as compared to desalinating cold seawater of ambient temperature. Because of this, 5% of additional energy savings and respective carbon footprint reduction (12,300 MWh/yr and 3,100 tons/CO_2 per year) are achieved by using warm cooling water from the Encina Power Generation Station as source seawater for the desalination plant. These savings in power and emissions are shown in Line 5 of Table 2.

There are no additional capital and operations costs to use warm water from the power plant once-trough cooling system. Therefore, when the power plant is operational the desalination plant will use only warm cooling water. When the power plant is down the desalination plant intake is designed to collect cold seawater from the same intake.

Green Building Design

Whenever practical and viable, the desalination plant should be located on a site of little current value or public use. Reclaiming low-value land will reduce project imprint on the environment as compared to using new undisturbed site for the desalination plant. For example, the Carlsbad seawater desalination plant will be located on a site occupied by dilapidated fuel oil tank. This tank and its content will be removed and the site will be reclaimed and reused to construct the desalination plant.

Another approach to reduce desalination plant physical imprint on the environment is to minimize desalination plant site footprint. For example, a key "green" feature of the Carlsbad seawater desalination plant design is its compactness. The desalination plant facilities are configured as series of structures sharing common walls, roofs and equipment, which allows significant reduction of its physical footprint. The total area occupied by the desalination plant facilities is approximately 2 ha (5 acres) - see Figure 13).

Figure 13 – Areal View of the 50 MGD Carlsbad Seawater Desalination Plant, California

It should be pointed out that the Carlsbad seawater desalination plants holds the record for being the smallest site footprint desalination plant in the world per unit production capacity - 2 ha per 189,000 m^3/day (5 acres per 50 MGD). For comparison, the 95,000 m^3/day (25 MGD) Tampa Bay seawater desalination plant (see Figure 14) occupies 8.5 acres; and the 325,000 m^3/day (86 MGD) Ashkelon, Israel seawater desalination plant (Figure 15), which currently is one of the largest seawater reverse osmosis facility in the world, occupies 9.7 ha (24 acres).

Figure 14 – Areal View of the 25 MGD Tampa Bay Desalination Plant, Florida

Figure 15 – Arial View of the 86 MGD Ashkelon Desalination Plant, Israel

A plant with a smaller physical footprint would also yield a smaller construction-related carbon footprint: lower construction material expenditures and GHG emissions from construction equipment due to the smaller volume of excavation and concrete works. Reduced construction site footprint also generates less dust emissions and requires less water for dust control.

Whatever economically viable and practical, building design should follow the principles of the Leadership in Energy and Environmental Design (LEED) program. This is a program of the United States Green Building Council and is developed to promote construction of sustainable buildings that reduce the overall impact of building construction and functions on the environment by: (1) sustainable site selection and development; (2) energy efficiency; (3) materials selection; (4) indoor environmental quality, and (5) water savings.

Consistent with the principles of the LEED program, the desalination plant buildings should include features and materials that allow minimizing energy use for lighting, air conditioning and ventilation. For example, a portion of the walls of the main desalination plant building of the Carlsbad seawater desalination plant will be equipped with translucent panels to maximize daylight use and views to the outside. Non-emergency interior lighting will be automatically controlled to turn-off in unoccupied rooms and facilities. A monitoring system will ensure that the ventilation in the individual working areas in the building is maintained at its design minimum requirements. In addition, building design will incorporate water-conserving fixtures (lavatory faucets, showers, water closets, urinals, etc.) for plant staff service facilities and for landscape irrigation.

The green desalination plant buildings should incorporate low-emitting materials and thus pose less risk to the natural environment and building's occupants. Low emitting paints, coatings, adhesives, sealants and carpet systems should be used on the interior of the buildings whenever possible. Building design team should include professional engineers that have achieved the LEED Accredited Professional designation and are well experienced with the design and construction of green buildings.

For the Carlsbad seawater desalination project for example, the additional costs associated with the implementation of the green building design as compared to the costs for a standard building are estimated at US$5 million and the potential energy savings are approximately 500 MWh/yr. The potential carbon footprint reduction associated with this design is 124 tons of CO_2 per year (0.9 % of the net power plant footprint). This figure is presented in Line 6 of Table 2.

The unit cost of carbon footprint reduction associated with green building design was estimated for project life of 30 years and annual debt service of 6.5% (capital recovery factor of 0.07657). At capital costs of US$5 million, the annualized cost of this capital investment is US$382,850/yr. Because of the higher level of complexity and automation of the "green building" design, as compared to conventional design, the additional O&M costs associated with the "green" systems of the building for the Carlsbad project are US$34,650/yr. Therefore, the total annual costs associated with this design are estimated at US$417,500/yr. At 124 tons of CO_2 reduction per year, this annualized cost corresponds to unit carbon footprint reduction cost of US$3,400/ton CO_2.

The total actual energy reduction that would result from green building design should be verified during plant commissioning, which will incorporate a LEED-compliance review process. The LEED-review process has to be completed by independent consultant certified for such reviews.

On-site Solar Power Generation

One enhancement of the green building design is the installation of rooftop photovoltaic (PV) system for solar power generation. For example, the main desalination plant building is planned to have a roof surface of approximately 50,000 square feet, which would be adequate to house a solar panel system that could generate approximately 777 MWh/yr of electricity and reduce the net carbon footprint of the desalination plant by 193 metric tons of CO_2 per year, which is approximately 1.4% of the net desalination plant carbon footprint of 13,700 tons of CO_2 per year.

The construction cost of the rooftop solar power system for the Carlsbad project is estimated at US$4.1 million. The annual cost of power generation using this alternative is US$313,937/yr (at 30 years and 6.5%). In addition, the annual operation and maintenance costs for this system are estimated at US$52,763/yr.

Therefore, the total annual costs for operation of this system are estimated at US$366,700/yr, which corresponds to unit cost of generated electricity of 47.2 cents/kWh (US$366,700/yr /(777,000 KWh/yr = US$47.19/KWh). This unit cost is approximately five times higher than the cost of power supply from the electric grid. The unit cost of carbon footprint reduction for this alternative is US$1,900/ton of CO_2. Because of its very high cost, installing a rooftop solar power generation system was deferred to a later date when solar power generation technology becomes more affordable. Meanwhile, the associated offset of the plant's carbon footprint (124 tons of CO_2 per year) is provided by purchasing of renewable energy credits (RECs).

Use of Carbon Dioxide for Water Production

Approximately 2,100 tons of CO_2 per year are used at the desalination plant for post-treatment of the fresh water (permeate) produced by the reverse osmosis system. Carbon dioxide in a gaseous form will be added to the RO permeate in combination with calcium hydroxide or calcium carbonate in order to form soluble calcium bicarbonate which adds hardness and alkalinity to the drinking water for distribution system corrosion protection.

In this post-treatment process of RO permeate stabilization a large quantity of gaseous carbon dioxide is sequestered into soluble form of calcium bicarbonate. Because the pH of the drinking water distributed for potable use is in a range of 8.3 to 8.5 at which CO_2 in a soluble bicarbonate form, the carbon dioxide introduced in the RO permeate would remain permanently sequestered in this form and ultimately would be consumed with the drinking water.

A small quantity of carbon dioxide used in the desalination plant post-treatment process is sequestered directly from the air when the pH of the source seawater is adjusted by addition of sulfuric acid in order to prevent RO membrane scaling. Most of the carbon dioxide, which is used for post-treatment of desalinated water is delivered to the plant site by a commercial supplier.

Depending on the supplier, carbon dioxide is of one of two origins: (1) a CO_2 Generating Plant or (2) a CO_2 Recovery Plant. CO_2 Generating Plants use various fossil fuels (natural gas, kerosene, diesel oil, etc.) to produce this gas by fuel combustion. CO_2 Recovery Plants produce carbon dioxide by recovering it from the waste streams of other industrial production facilities which emit CO_2-rich gasses: breweries, commercial alcohol (i.e., ethanol) plants; hydrogen and ammonia plants, etc. Typically, if these gases are not collected via CO_2 Recovery Plant and used in other facilities, such as the desalination plant, they are emitted to the atmosphere and therefore, constitute a GHG release.

The Carlsbad desalination plant uses only carbon dioxide produced in a CO_2 Recovery Plant. This requirement will be enforced by requiring the commercial supplier of carbon dioxide for the desalination plant operations to provide a certificate of origin of each load of this water treatment chemical delivered to the plant site.

Sequestration of CO_2 at the desalination plant by its conversion from gaseous to chemically bounded soluble form is therefore, considered a desalination plant carbon footprint reduction alternative. By sequestering 2,100 tons of CO_2 per year in the desalination plant post-treatment process (see line 8 of Table 2), the net carbon footprint of the plant (13,700 tons of CO_2 /yr would be reduced by 13%). At annual expenditure for carbon dioxide supply of approximately US$147,000/yr, this carbon footprint reduction alternative is very cost-competitive (US$70/ton CO_2).

Emissions Offset by Reducing Energy Needs for Water Reclamation

Often water reclamation plants are equipped with brackish water reverse osmosis systems in order to reduce the salinity of the reused water. If the seawater desalination plant is designed to significantly reduce the salinity of the drinking water and therefore of the reclaimed water, then the operation of the brackish desalination system at the water reclamation plant could be discontinued thereby saving energy and reducing GHG emissions.

For example, the Carlsbad Municipal Water District owns and operates a 15,000 m^3/day (4 MGD) water reclamation plant which consists of advanced tertiary treatment facilities for the entire flow and of 3,785 m^3/day (1 MGD) brackish reverse osmosis water desalination system, which at present uses 1,950 MWh of electricity per year. The purpose of the brackish water desalination plant is to reduce the salinity of the treated effluent from 1,400 mg/L to below 1,000 mg/l in order to make the effluent suitable for irrigation. The current high level of salinity of the reclaimed water is mainly due to the relatively high salinity of the City's drinking water, which could reach 1,000 mg/l at times.

Since December 2015, when the Carlsbad seawater desalination plant began operation the salinity of the City's reclaimed water is projected to be reduced in a half. Therefore, the replacement of the existing City high-salinity imported water supply with desalinated water eliminated the need for operation of the brackish water desalination plant at the Carlsbad Water Reclamation Facility.

This in turns reduced the carbon footprint of the Carlsbad Water Reclamation Facility by 1,950 MWh x 546.46 lbs of CO_2 /MWh = 1,065,957 lbs of CO_2/yr (484 tons of CO_2/yr). Since this GHG reduction is directly credited to the seawater desalination plant operations, the Carlsbad desalination plant's carbon footprint is reduced by 3.5%. Carbon footprint credit associated with reduced energy for water reclamation is presented in line 9 of Table 2.

Carbon Dioxide Sequestration by Re-vegetation in Wildfire Zones

Almost every year in many dry parts of the world, such as California, are exposed to measurable loss of forest, urban and suburban trees due to large wildfires. A desalination project could participate in a locally administered carbon offset program, which aims at the re-vegetation of areas impacted by the wildfires or planting of new trees and other vegetation to combat GHG emissions.

For example, in response to reforestation program administered by the California Coastal Commission the Carlsbad project proponent had committed to investing US$1.0 million in reforestation activities. More specifically, when project developer updates Carlsbad desalination plant's net carbon footprint for the preceding year, they will calculate the cost of offsetting that year's net carbon emissions at a rate equal to the purchase of such carbon offsets. The project owner then pays the amount resulting from this calculation to either the San Diego County Air Pollution Control District or another entity identified by the California Coastal Commission as responsible for administering a San Diego area wildfire re-vegetation program.

The plant owner, Poseidon Water will continue making its annual offset payments to the re-vegetation program until the cumulative total of such payments reaches US$1 million, at which time the project developer may elect to direct annual offset payments to other projects, so long as those projects satisfy accepted standards for offsetting carbon emissions.

According to the Tree Guidelines for Coastal Southern California Communities issued by the USDA Forest Service (McPherson, et. all, 2000) the average annual costs for tree planting and care increase with mature tree size and for medium-size trees range between US$16 and US$23 per tree (avg. US$19.5/tree). Average annual maintenance costs for trees are estimated at US$3 to US$5 per tree (avg. US$4/tree). Updated for inflation, the year 2008 average tree planting cost is US$26.7/tree and the average annual maintenance cost is US$5/tree.

Assuming tree maintenance costs for the entire useful life of the desalination Plant of 25 years, at US$5/tree, the total lifecycle expenditure per tree is US$137. When added to the three planting cost of US$26.7, the total cost for planting and maintaining of the trees included in the reforestation project is US$164.2/tree. At commitment of US$1.0 MM and total costs of US$164.2/tree, the total amount of trees to be planted is 6,090.

At a typical annual tree sequestration rate of 27 kg (60 lbs)/tree over 25-year period of the desalination plant operations, the total annual carbon footprint reduction associated with the tree sequestration project is estimated at 365,400 lbs (166 metric tons) of CO_2 per year as shown in Line 11 of Table 2. This is approximately 1.2% reduction of the net desalination plant footprint. At annual expenditure for tree reforestation of approximately US$33,500/yr, the unit carbon footprint reduction cost for this alternative is US$200/ton of CO_2.

Carbon Dioxide Sequestration in Coastal Wetlands

In addition to the benefit of marine habitat restoration and enhancement, coastal wetlands also act as a "sink" of carbon dioxide. Tidal wetlands are very productive habitats that remove significant amounts of carbon from the atmosphere, a large portion of which is stored in the wetland soils. While freshwater wetlands also sequester CO_2, they are often a measurable source of methane emissions. For comparison, coastal wetlands and salt marshes release negligible amounts of greenhouse gases and therefore, their carbon sequestration capacity is not measurably reduced by methane production.

Based on a detailed study completed in a coastal lagoon in Southern California (Brevik & Homburg, 2004) the average annual rate of sequestration of carbon in coastal wetland soils is estimated at 0.0556 kg of C/m^2.yr.

For example, a part of the Carlsbad seawater desalination project, the project developer is planning to develop 64 acres of new coastal wetlands in San Diego County. These wetlands will be designed to create habitat for marine species similar to these found in the Agua Hedionda Lagoon from which source seawater is collected for the power plant and for desalination plant operations. Once the wetlands are fully developed, they will be maintained and monitored over the life of the desalination plant operations. The cost of the wetland restoration project is estimated at US$28.0 million.

Taking under consideration that the total area of the proposed wetland project is 64 acres (259,000 square meters) and the maximum sequestration capacity of the coastal wetlands could be 0.0556 kg of C/m^2.yr, than the wetland carbon sequestration capacity would be up to 144 tons of C/yr. With a conversion factor from carbon to carbon dioxide of 3.664 the estimated offset of the desalination plant carbon footprint by the wetland project is estimated at 526 tons of CO_2/year as shown in Line 12 of Table 2 (3.8% reduction of the net carbon footprint). At total annual cost for wetland development and maintenance of approximately US$210,500/yr, the unit carbon footprint reduction cost for this alternative would be US$1,400/ton of CO_2).

Carbon Emission Offsets by Investing in Renewable Energy Projects
An alternative approach to offset GHG emissions of a given desalination project is to invest into renewable energy projects located in the service area of the desalination plant. For example, the project developer plans to invest in a number of green power projects (roof-top photovoltaic systems, diesel bus conversion to clean-natural gas vehicles, etc.) with its public partners who will be receiving desalinated water from the Carlsbad seawater desalination Plant. The total carbon footprint offset for the desalination plant is projected at 2,260 MWh/yr or 561 tons of CO_2/year (4.1% of net carbon footprint). This credit is shown in Line 13 of Table 2.

Other Carbon Offset Projects and Renewable Credits
The remainder of the project's carbon emissions could be offset by the purchase of a combination of carbon offset projects and Renewable Energy Credits (RECs). Contracts for offset projects provide more price stability and are typically established for longer terms (10-20 years) then RECs (1-3 years).

For example, in about one-and-half-to-two years before operations begin, the project owner will develop and issue a request for proposal (RFP) for carbon offset projects and renewable energy credits. The project owner then selects the best mix from the responses and contracts for their acquisition or development. The offset amount of RECs is at value of 6,446 tons CO_2/year as shown in Line 14 of Table 2. Purchase of RECs is used as the swing mitigation option to "true-up" annual changes to the project's net carbon footprint.

Project Annual Net-Zero Carbon Emission Balance

As indicated previously, Table 2 summarizes the total and net carbon footprint of the Carlsbad seawater desalination project and quantifies GHG emission reduction and mitigation options, which are implemented in order to reduce the plant net carbon emission footprint to zero. Analysis of data presented in Table 2 reveals that for this example case study up to 40% of the GHG emissions associated with seawater desalination and drinking water delivery will be reduced by on-site reduction measures and the remainder will be mitigated by off-site mitigation projects and purchase of renewable energy credits.

It should be noted that the contribution of on-site GHG reduction activities is expected to increase over the useful life (i.e., in the next 30 years) of the project because of the following key reasons: (1) in the near future, most power suppliers countrywide are planning to increase significantly the percentage of green power sources in its electricity supply portfolio, which in turn will reduce its Emission Factor and the net desalination plant carbon footprint; (2) advances in desalination technology are expected to yield further energy savings and carbon footprint reductions. The mitigation costs of the various GHG reduction alternatives are summarized in Table 3.

Table 3
Unit Costs of Carbon Footprint Reduction Alternatives

Alternative	**Unit Cost (US$/ton CO_2 reduced)**
Green Building Design	3,400
On-site Solar Power Generation	1,900
CO_2 Sequestration in Coastal Wetlands	1,400
CO_2 Sequestration by Re-vegetation of Wildfire Zones	200
Use of CO_2 for Water Production	70

The lowest unit cost of carbon footprint reduction can be achieved by using carbon dioxide for post-treatment of the desalinated water (US$70/ton CO_2). The most costly carbon footprint reduction options are green building design (US$3,400/ton CO_2) and installation of rooftop solar power generation system (US$1,900/ton CO_2). Development of new coastal wetlands is a very promising but fairly costly carbon footprint reduction option (US$1,400/ton CO_2).

Reforestation could be a cost-competitive GHG reduction alternative (US$200/ton CO_2). As compared to green power generation alternatives (solar and wind power) reforestation and wetland mitigation have added environmental benefits.

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