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Intakes and Outfalls for Seawater Reverse-Osmosis Desalination Facilities

Innovations and Environmental Impacts

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Foreword

The *Greening* of Seawater Reverse Osmosis (SWRO) Systems: Focus on Intakes and Outfalls

Seawater reverse osmosis (SWRO) has emerged as the conventional seawater desalination technology, globally. While SWRO is less energy intensive than thermal processes' such as multi-stage flash (MSF) and multi-effect distillation (MED), it is still an energy intensive process (3–4 kWh/m^3). Moreover, with increasing emphasis on green technologies, the present practice of SWRO is characterized by a number of significant environmental impacts, including energy consumption, greenhouse gas (GHG) emissions, entrainment and impingement of marine organisms through intakes, and marine pollution during concentrate discharge via outfalls. SWRO is also a chemical-intensive and material-intensive process with a sizable footprint. Besides salts, SWRO brines can also contain chemicals used in pretreatment (e.g., coagulants and antiscalants) and RO cleaning agents. Periodic replacement of RO modules results in a significant solid waste problem. Thus, a challenge is realization of the *greening* of SWRO systems.

It has been estimated that further optimization of the SWRO process and its various components could potentially provide a 20 % reduction in specific energy consumption, with a concomitant reduction in GHG emissions. However, beyond this perceived limit, only emerging technologies such as forward osmosis (FO) offer the possibility of further energy reduction. SWRO pretreatment by ultrafiltration (UF), as an alternative to granular media filtration (GMF), provides an opportunity for reduced amounts of chemical coagulant (e.g., UF with in-line coagulation). New fouling resistant RO membranes can provide an opportunity for reduced use of chemical cleaning agents. Improvements in membrane fabrication have resulted in extended material life and less frequent replacement of RO modules. However, beyond these improvements, potentially major contributions to the greening of SWRO can be realized through advancements in the design and operation of SWRO intakes and outfalls, the focus of this book.

While intake choice is generally perceived as being between surface (open) and subsurface intakes, there are many subcategory options. Surface intakes can be single purpose or colocated with a power plant as well as offshore submerged, nearshore submerged, or nearshore surface intakes. Subsurface intakes can be onshore (vertical wells), including vertical beach wells or deep aquifer wells, horizontal wells, radial or collector wells, and beach infiltration galleries; or offshore wells, including horizontal drains (wells), and seabed infiltration galleries.

The use of surface, colocated, nearshore intakes is typical for water and power cogeneration plants (e.g., many in the GCC region), but these are also used by some SWRO plants (e.g., Tampa Bay USA). The use of surface, single purpose intakes is common for many larger SWRO systems. Subsurface, onshore intakes are used by small to medium capacity SWRO plants; however, subsurface, offshore intakes are under consideration for larger SWRO systems. An under-recognized attribute of subsurface intakes is that they also function as an SWRO pretreatment process, simulating a slow sand filter as a physical and biological process, without chemicals. Of particular importance is the ability of subsurface intakes to remove bacteria, algae, and biopolymers (e.g., proteins and polysaccharides), reducing both organic and biofouling of RO membranes; moreover, subsurface intakes inherently eliminate impingement and entrainment. A notable example is the Fukuoka (Japan) seabed infiltration gallery which operates before a UF pretreatment step, alone reducing the silt density index (SDI) to below three and allowing the subsequent UF to operate for long periods without backwashing. Improvements in open intake design and operation have largely focused on minimizing impingement and entrainment.

In summary, open surface intakes are generally characterized by high intake volumes (i.e., larger SWRO systems), offer a potential for colocation, are unaffected by (but also do not beneficially affect) feed water quality, and are vulnerable to impingement and entrainment. Subsurface intakes are generally used for smaller capacity SWRO systems (but seabed galleries are increasingly being considered for larger systems), are unaffected by (but can beneficially affect) water quality, and can mitigate impingement and entrainment. To drive home the importance of intakes and outfalls, it has been estimated that they account for up to 35 % of the costs of SWRO systems.

The two general categories of SWRO outfalls are surface and subsurface outfalls. The former can take the form of nearshore and offshore, with further delineation into an outfall channel, a single pipe, or a multiport diffuser. Less common are offshore and inland subsurface outfalls, taking the form of a percolation gallery, deep well injection, evaporation ponds, sewer discharge, and zero liquid discharge (ZLD), most of the latter (except for percolation galleries) being the domain of inland brackish water RO (BWRO) systems. Nearshore outfall channels are more typical for cogeneration (distillation and power) plants or colocation (SWRO plant next to power) plants. Single offshore pipes are more common for smaller SWRO plants. Multiport diffusers are more common for larger SWRO plants and are increasingly becoming the norm for such new plants. There are several types of multiport diffusers, including pipeline diffusers (nozzles arranged along a pipe) and rosette-style diffusers (several outlet risers above the seafloor with a small number of nozzles). Advancements in modeling of multi-diffuser systems allow prediction of a regulatory mixing zone. In subsurface offshore outfalls, the concentrate is slowly dissipated into the surf zone (e.g., perforated laterals placed under the ocean floor).

The *greening* of SWRO can be promoted by the use of subsurface intakes (no impingement/entrainment of organisms, pretreatment without chemicals and associated residuals); the minimization of chemical use (e.g., UF with lower or no coagulant addition); no antiscalants (scaling control by acid addition and/or limiting recovery); brine disposal through a multiport-diffuser outfall (i.e., minimize extent of mixing zone); and integration of renewable energy (e.g., solar, wind, and/or or geothermal) in design and operation (direct use or (indirect) energy compensation, reduced GHG emissions (95 % of which are associate with direct energy use)). This book will highlight the important role of two of these SWRO system components, *intakes and outfalls*.

Gary Amy
Sabine Lattemann

Preface

Freshwater supplies are dwindling as global population growth, industrialization, and agricultural expansion occur worldwide. Desalination of seawater is rapidly becoming a key aspect of global water management to balance the needs of numerous coastal countries, particularly in arid lands and industrialized counties. Seawater desalination is an energy-intensive process that has some real and perceived environmental impacts. Therefore, it is important to reduce the energy consumption of desalination, the carbon footprint, the environmental impacts, and the overall cost. Currently, the most energy efficient desalination large-scale commercial process is seawater reverse osmosis (SWRO).

It is the purpose of this book to address two important aspects of the SWRO process, design of intakes and outfalls and assessment and reduction of environmental impacts. Most of the book content is based on technical presentations made at an international workshop on desalination system intakes and outfalls sponsored and held during October 7–8, 2013 at the King Abdullah University of Science and Technology (KAUST) in Thuwal, Saudi Arabia. Additional chapters were solicited by the editors to cover various aspects of intakes and outfalls not occurring during the workshop.

The Water Desalination and Reuse Center and the Red Sea Research Center at KAUST jointly organized the workshop with generous support from KAUST's Office of Research Support. The presence of KAUST on the Red Sea, where increasing urbanization and industrialization along the coast demands additional freshwater supply, provided much of the impetus for the workshop. Saudi Arabia currently produces about 18 % of the global production of desalinated water with an expected capacity of nearly 6 million cubic meters per day in 2015. Over the long term the dependence on desalinated water in the region and much of the world will only increase. A long-term goal of this workshop and similar efforts is to reduce the energy intensity and increase water-use efficiency throughout the life cycle of desalination plants, minimizing environmental impacts to the greatest extent possible. In other words, the goal is to develop desalination plant design that promotes sustainable interaction of the human environment within our natural environment.

This book covers a considerable number of subjects that have not been published extensively in the peer-reviewed literature. The book is divided into two major sections; intakes and outfalls with some overlapping subject matter involving environmental impact assessment and reduction. The intakes section is further subdivided into surface or “open-ocean” intakes and subsurface intakes.

The overall design philosophy of intakes for SWRO plants is covered in Chap. 1. Design concepts for velocity-cap, and tunnel intake systems are covered in Chaps. 2–3. The very important issue of impingement and entrainment is covered in Chap. 4, which includes a summary of the latest U.S. environmental regulations and a summary of research. Design and impacts of passive screen intake systems are discussed in detail in Chap. 5. In recent years it has been suggested that deep intake systems could be used to obtain higher quality feed water for SWRO systems. In Chap. 6, the use of deep intakes along the Red Sea coastline of Saudi Arabia is assessed. This comprehensive study shows the variation in algae, bacteria, and various types of natural organic matter with depth in the Red Sea and how the bathymetric features of the Red Sea impact deep intake system feasibility.

Discussion of subsurface intake systems begins with Chap. 7, which provides a comprehensive planning methodology that is used to analyze the Red Sea coastal areas of Saudi Arabia and the coasts of Florida to assess technical feasibility of using various subsurface intake systems. Use of wells as intakes, the most mature subsurface intake technology, is covered in Chap. 8 with an assessment of the improvement in raw water quality that occurs between the raw seawater and after traveling through an aquifer to a production well occurring in Chap. 9. Beach and seabed gallery intake system design and innovations in their use are covered in Chaps. 10–12. Applications of seabed gallery feasibility for the Red Sea and Arabian Gulf coasts and nearshore areas of Saudi Arabia are discussed in detail in Chaps. 11 and 12. The generally new concept of using slant wells as intakes is discussed in Chap. 13. The application of coastal modeling to assess the technical feasibility of developing gallery intake systems, with an emphasis on southern California, is covered in Chap. 14. The innovations in design and operation of SWRO intake system are summarized in Chap. 15.

The second part of the book covers assessment and mitigation of environmental impacts associated with discharge of concentrate from SWRO plants and subsequent wastewater discharge. Overall, this group of papers progresses from modeling approaches for coastal discharges.

Chapter 16 provides an overall of coastal discharges and how they are managed. Chapter 17 discusses the results of laboratory modeling of various configurations of concentrate diffusers, their performance and design criteria, and applications. Chapter 18 builds from the nearfield modeling toward a tiered approach of nearfield and farfield modeling, observation, and analysis for design, placement, and implementation of new facilities. Additional evaluations and design criteria for dense brine discharges are provided in Chap. 19. Chapter 20 presents a modeling evaluation of the dispersion of heat and salt from a discharge in the Gulf of Arabia and the response of the dispersion to variations in the coastal currents. Because the

Red Sea is an enclosed basin, discharges within that basin may have impacts that can spread either along the coast or even across the axis of the basin. The model results described in Chap. 21 demonstrates the potential for that very farfield dispersion. Chapter 22 discusses the use of AUV's for farfield mapping and long-term deployments building a statistical database that can be used for comparison against numerical models where the resolution is now approaching the scale of the near-field. Chapter 23 discusses the innovations in management of coastal discharges and evaluation of environmental impacts.

The purpose of this book is to provide the latest summary of pertinent research on intake and outfall design concepts for SWRO facilities. It should be used by design engineers, geologists, project owners, and facility operators for use as a reference and to obtain new ideas that could produce innovative designs that will reduce the energy consumption and operational costs of SWRO facilities. Also, we have provided summaries of where additional scientific and engineering research should be conducted to make improvements to intake and outfall performance.

Fort Myers, Florida, January 2015 Thomas M. Missimer
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Part I
Intakes

Chapter 1
Overview of Intake Systems for Seawater Reverse Osmosis Facilities

Thomas Pankratz

Abstract The intake is a critical component of every seawater reverse osmosis facility and controls to a great degree the design and operational cost of downstream treatment processes. Two general classes of intake types occur; surface or open-ocean intakes and subsurface intakes. Globally, most large-capacity SWRO plants use open-ocean intake systems with the actual intake located either onshore (commonly shared with a power plant) or offshore. The most common offshore intake type uses a velocity cap at the top of the invert pipe. Inshore or offshore passive screen intakes are used to reduce the impacts of impingement and entrainment. Subsurface intake systems, either wells or galleries, are being used in hundreds of small to medium capacity SWRO facilities. Because of the greater attention being given to the environmental impacts of impingement and entrainment of marine organisms, subsurface intake systems are being specified for a greater number of facilities with higher capacity.

1.1 Introduction

Seawater desalination facilities require an intake that is capable of providing a reliable quantity and relatively consistent quality of seawater to ensure that the plant production targets can be met. While this fundamental objective may appear obvious, it is complicated by the fact that the ocean is a dynamic entity with constantly changing conditions.

Powerful waves and changing currents can damage structures, affect water depths, and dramatically alter water quality and temperature. And, as one moves

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closer to shore, these changes often become more dramatic and occur with increasing frequency. Operational problems are compounded by the corrosiveness of seawater and the marine organisms that can attack and foul equipment and systems.

To meet the design objectives, it is essential that a thorough assessment of the intake site conditions be conducted. Physical characteristics, meteorological and oceanographic data, marine biology and the potential effects of fouling, pollution and navigation must be evaluated. Only then can an appropriate intake design be selected.

As reverse osmosis (RO) has grown to become the predominant seawater desalination process, so have the number and production capacities of the resulting facilities. More and larger capacity plants are being built in locations where none had previously existed, raising concerns over the possible environmental impacts of withdrawing large volumes of seawater. For many seawater desalination projects, the potential for intake-related marine life mortality may represent the most significant direct adverse environmental impact of a project.

Because intake designs are highly site specific—perhaps more so then any other aspect of the desalination plant—the design, modeling, monitoring and permitting activities that surround them may represent a significant portion of a project capital costs. Whereas, seawater intakes formerly represented 4–12 % of an entire facility capital cost, some intake arrangements may now cost 35 % or more of a project capital cost, and it is possible that intake-related issues may ultimately determine the feasibility of the desalination plant itself.

This chapter will consider the seawater intake technology options available for seawater RO plants, including intakes shared with electric power plants, and will review the technologies employed to minimize environmental impacts, while meeting the intake objective of providing a reliable quantity of seawater at the best quality available. A comparison of the intake types is given in Table 1.1. Greater descriptive detail on intakes and diagrams and photographs of various types are contained in Missimer (2009) and in various chapters in this book.

1.2 Water Quality and Quantity

Historically, most large seawater desalination plants have employed the multistage flash evaporation (MSF) or multiple effect distillation (MED) desalination processes and have been co-located at an electric power generating plant with which they share a common shoreline, or nearshore seawater intake. Because a power plant condenser and a MSF or MED facility utilize similar size condenser tubes, both require only a nominal level of treatment, and usually that can be provided by a traveling water screen or rotating drum screen with 6–9.5 mm wire mesh openings.

Table 1.1 Assessment of intake options for SWRO plants

	Intake options summary				
	Vertical wells	Infiltration gallery	Open ocean, with offshore passive screens	Open ocean with velocity cap, onshore mechanical screens	Conventional shoreline, with mechanical screens
Feasibility	Limited by local geology	Limited by local hydrogeology, offshore sea conditions	Moderate-high	High	High
Feedwater quality produced	High	High	Moderate-high	Moderate	Low
Environmental implications	No impingement, entrainment	No impingement, entrainment, but construction impacts	No impingement, low entrainment	Low impingement, moderate entrainment	Impingement and entrainment
Flexibility	Low, space limitations may limit well addition	Low	Production limitations can be overcome by adding screens	Moderate	Moderate
Reliability	Wells can be rehabilitated and/or new ones added	Difficult to predict, cleaning may be marginally effective	Plugging can be monitored and cleaning is effective	Plugging can be monitored and cleaning is effective	Plugging can be monitored and cleaning is effective
Susceptibility to operational anomalies	Low	Low	Moderately vulnerable to jellyfish runs, algal blooms	Moderately vulnerable to algal blooms	Moderate to highly vulnerable to jellyfish runs, algal blooms
Maintenance	Low	When/if required, could be substantial	Pig pipeline 2X per year, clean/inspect screens quarterly	Pig pipeline 2X per year, maintain screens as required	Maintain screens as required
Construction risk	Moderate	High	Low-moderate	Low-moderate	Low
Relative capital cost, typical	Low-moderate	High	Moderate-high	Moderate-high	Moderate

Conversely, the performance of a seawater reverse osmosis (SWRO) plant may benefit greatly from a more consistent quality of water and a finer level of screening. Since most seawater RO plants are standalone facilities with a purpose-built intake, there is a much greater focus on selecting a design/location that will provide a consistent seawater quality possible and the lowest practical suspended solids. As the first step in the SWRO pretreatment process, the intake effectiveness can have far-reaching effects on overall plant operation and performance.

Like most process systems, desalination plants operate most efficiently and predictably when feedwater characteristics remain relatively constant and are not subject to rapid or dramatic water quality fluctuations. Therefore, the water quality review should consider both seasonal and diurnal fluctuations. The assessment should consider all constituents that may impact plant operation and process performance including a thorough review of historical water quality data including seawater temperature, total dissolved solids (TDS), total suspended solids (TSS), and total organic carbon (TOC) is crucial.

Most seawater RO facilities convert 40 to 50 % of the intake water to product water, while the remaining water, which includes the salt removed by the RO system, is pumped back to the sea for controlled discharge. It is therefore beneficial to locate the desalination plant as close to the seashore as possible to minimize intake/discharge pumping requirements.

1.3 Environmental Considerations

Potential environmental impacts associated with concentrate discharge are often considered the greatest single ecological impediment when siting a seawater desalination facility. However, it has now been widely demonstrated that a properly modeled, designed and strategically located outfall can effectively mitigate discharge impacts, while marine life impingement and entrainment resulting from intake operation is often a greater, harder-to-quantify concern.

Impingement occurs when marine organisms are trapped against intake screens by the velocity and force of water flowing through them (Chap. 4). The fate of impinged organisms differs between intake designs and among marine life species, age, and water conditions. Some 'hardy' species may be able to survive impingement and be returned to the sea, but the 24-h survival rate of less robust species and/or juvenile fish may be less than 15 %.

Entrainment occurs when smaller organisms pass through an intake screen and into the process equipment (Chap. 4). Entrained organisms are generally considered to have a mortality rate of 100 %.

The number of affected organisms will, of course, vary considerably with the volume and velocity of feedwater and the use of mitigation measures employed to minimize their impact. If intake velocities are sufficiently low, usually less than 0.15 m/s, fish may be able swim away to avoid impingement or entrainment. The swimming performance for different species of fish can predict the types and ages that are most vulnerable, however, even large fish are frequently caught on intake screens, indicating that swimming ability is not the only factor in impingement. Cold temperatures or seasonal variations in age-selective migrations or growth are also factors.

Since the early 1970s, seawater intakes for electric power plant cooling water intakes have been required to employ the best technology available to minimize adverse environmental impact under §316(b) of the US. Environmental Protection Agency (USEPA) Clean Water Act (CWA). The section of the CWA has been updated three times and applies to all intakes that withdraw greater than 7570 m^3/d of seawater and use 25 % or more of the water for cooling purposes. Some state regulatory agencies have indicated that the siting of a new or existing seawater intake for a desalination facility will require a §316(b)-type assessment of impingement and entrainment impacts as part of the environmental review and permitting process.

1.4 Intake Categories

Seawater intakes can be broadly categorized as *surface intakes* where water is collected from the open ocean above the seabed, and *subsurface intakes* where water is collected via vertical wells, infiltration galleries or other locations beneath the seabed. The most appropriate type of seawater intake can only be determined after a thorough site assessment and careful environmental evaluation.

1.5 Surface Water Intakes

Large seawater desalination plants have traditionally employed open-ocean, surface water intakes that are equipped with mechanically cleaned screens and virtually identical to those installed electric power generating plants use to obtain condenser cooling water.

In most arrangements, a pump station and screening chamber is located onshore and directly connected to the open ocean by means of a concrete channel or jetty, or an intake pipe that may extend out hundreds of meters into the sea.

1.5.1 Traveling Water Screens

Traveling water screens, also referred to as band screens, have been employed on seawater intakes since the 1890s (Fig. 1.1). The screens are equipped with revolving panels fitted with wire mesh panels that usually have 6–9.5 mm openings.

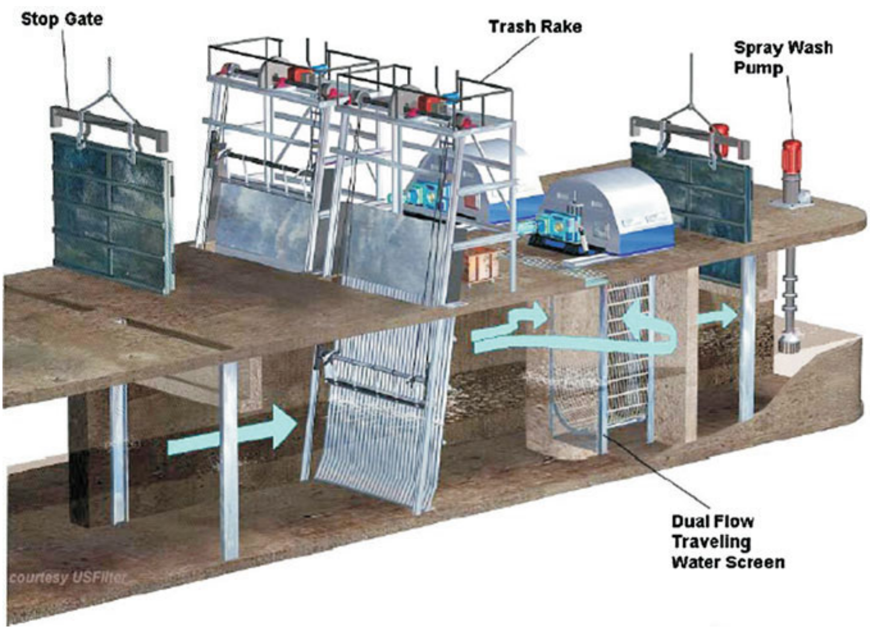

Fig. 1.1 Dual-flow traveling water screen (From Pankratz 2007)

As the wire mesh panels revolve out of the flow, a high-pressure water spray is used to remove accumulated debris, washing it into a trough where it is sluiced away for further disposal.

The screens are almost always located onshore in concrete channels, either at the far end of a forebay or a longer channel that extends out beyond the surf zone. The screens may also be installed in a wet well or pump station that is connected to the sea by a pipe that extends out into the sea and terminates in a coarse-screened inlet or a velocity cap.

The screens are usually designed so that the maximum water velocity through the screen is less than 0.15 m/s.

1.5.1.1 Rotating Drum Screens

Rotating drum screens are an alternative to traveling water screens, and consist of wire mesh panels mounted on the periphery of a large cylinder that slowly rotates on a horizontal axis (Fig. 1.2). They are cleaned with a spray wash system similar to traveling water screens. Drum screens may range up to 15 m in width and 4 m in diameter.

Fig. 1.2 Drum screen (From Pankratz 2007)

1.5.1.2 Fine Mesh Traveling Screens

Fine mesh traveling screens have been used to successfully reduce entrainment of eggs, larvae and juvenile fish at some intake locations where traveling water screens have been outfitted with wire mesh panels having openings ranging from 0.5 to 5 mm, and which may reduce entrainment by up to 80 %.

However, fine mesh screens may result in operational problems due to the increased amount of debris removed along with the marine life, and in some locations, the fine mesh is only utilized seasonally, during periods of egg and larval abundance.

1.5.1.3 Ristroph Screens

Ristroph screens are a modification of a conventional traveling water screen in which screen panels are fitted with watertight fish buckets that collect fish and lift them out of the water where they are gently washed from the screen with a low-pressure spray, prior to debris removal with a high-pressure spray wash (Fig. 1.3).

Studies at a New York power plant seawater intake, showed the 24-h survival of marine life impinged on conventional screens averaged 15 % compared with 80–90 % survival rates for Ristroph-type traveling water screens. A review of 10

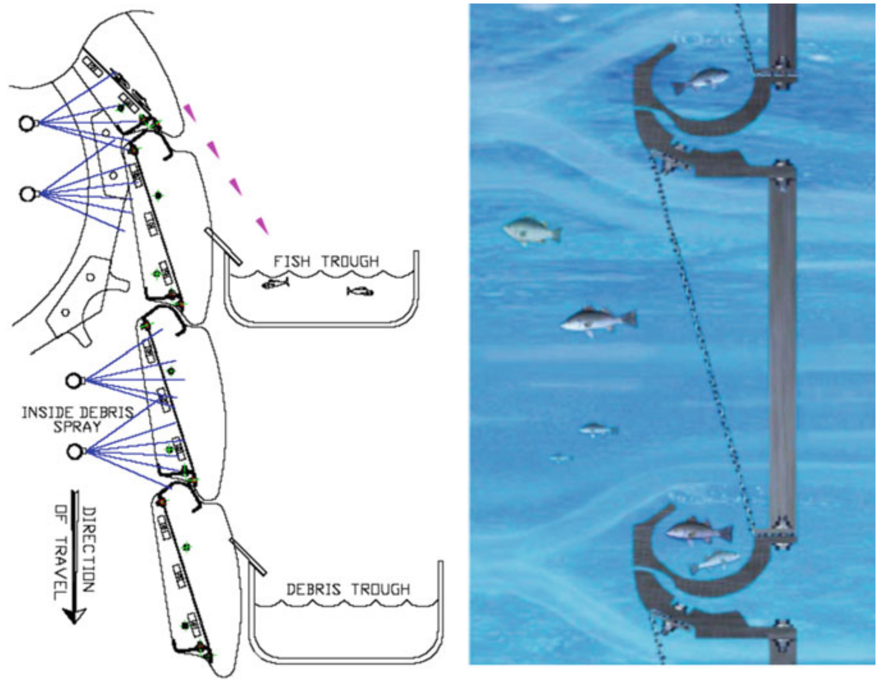

Fig. 1.3 Ristroph screen apparatus

similar sites reported that Ristroph modifications improved impingement survival 70–80 % among various species.

Although Ristroph screens may be effective at improving the survival of impinged marine life, they do not affect entrained organisms.

1.6 Offshore Intakes

Submerged, offshore intakes have long been a preferred seawater intake arrangement, particularly for shallow coastlines. Power plants and desalination plants often employ them in a desire to obtain a ‘better’, more consistent quality of water that is less susceptible to operational upsets from storm events, algal blooms and jellyfish. An offshore intake may also mitigate environmental impacts if it is designed and located in an area so as to reduce marine life impingement and entrainment.

In most offshore intake arrangements, the intake structure is usually located well beyond the surf zone, so it is less vulnerable to wave action. In some locations, this may be as little as 200 m offshore, but for larger plants, or locations with gently sloping sea bottoms, the intake could be located more than 1000 m offshore.

The offshore intake terminal is usually equipped with a coarse screen having 50–225 mm openings, or a velocity cap (see Sect. 1.7). Water enters the intake structure and is conveyed to an onshore pump station through a connecting pipe or tunnel (see Chaps. 2 and 3).

For most SWRO applications, especially those locations with a sandy seabed, a high-density polyethylene (HDPE) pipe can be fitted with concrete collars/anchors and laid directly on the seabed, although the portion of the pipeline that extends through the surf zone and onshore to the pump station is usually laid in a dredged trench and backfilled (Chap. 5).

Where intake lines must pass through environmentally sensitive areas or extend far offshore to reach deeper water, trenchless installation methods including tunneling, pipe jacking (microtunnelling) or horizontal directional drilling (HDD) may be used for all, or a portion of the line (Chaps. 2 and 3).

Unless the intake terminal of an offshore intake is fitted with a passive screen system, the onshore pump station must be equipped with traveling water screens or rotating drum screens to protect downstream pumps and pretreatment equipment.

1.7 Velocity Caps

The vertical riser of an offshore intake pipe may be fitted with a velocity cap that acts as a behavioral barrier to guide aquatic organisms away from the intake structure. The velocity cap is a horizontal, flat cover located slightly above the terminus of the vertical riser to convert a vertical flow into a horizontal flow at the intake's entrance (Fig. 1.4).

The cover converts vertical flow into horizontal flow at the intake entrance, and works on the premise that fish will avoid rapid changes in horizontal flow. Fish do not exhibit this same avoidance behavior to the vertical flow that occurs without the use of such a device. Velocity caps have been implemented at many offshore intakes and have been successful in decreasing the marine life impingement.

The design is based on the premise that a change in flow pattern created by a velocity cap, and operating at an entrance velocity of about 0.30 m/s, and as high as 0.9 m/s, triggers an avoidance response mechanism in fish, which aids in escaping impingement. This avoidance behavior was not exhibited in response to a vertical flow that would occur with an uncapped riser. It was also found that extending the cap and riser lip by 1.5 times the height of the opening would result in a more uniform entrance velocity, increasing the reaction time of a fish.

In recent years, the definition of a velocity cap has strayed well beyond its original definition, and many now incorrectly refer to any offshore covered intake head—regardless of its entrance velocity and the height of its opening—as a velocity cap.

This was noted in a 2012 USEPA review of proposed rule changes for the Section 316(b) of the Clean Water Act:

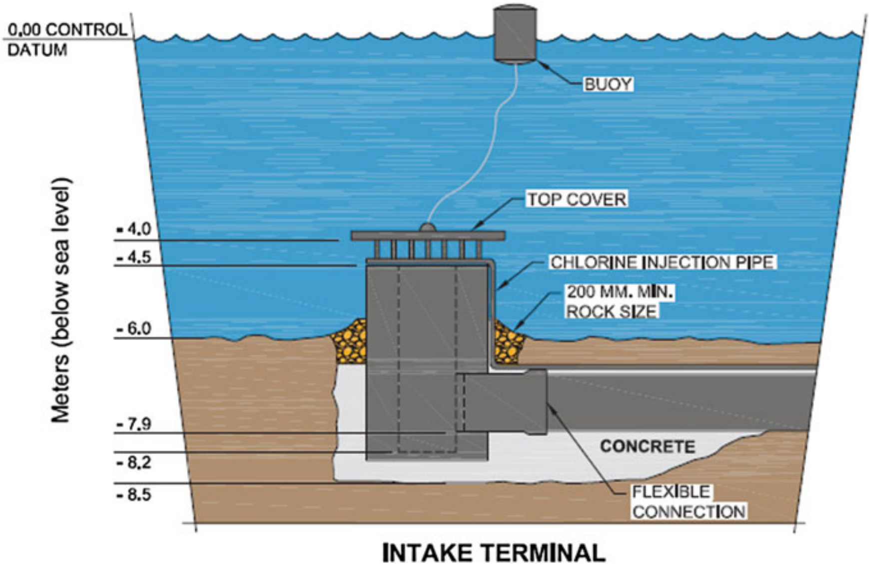

Fig. 1.4 Velocity cap intake structure (From Missimer 2009)

> "EPA is aware that low intake velocity is sometimes confused with velocity cap technologies, and EPA would like to clarify that these concepts are not the same. Most velocity caps do not operate as a fish diversion technology at low velocities, and in fact are often designed for an intake velocity exceeding one foot per second."

In its final rule on cooling water intake structures issued on 15 August 2014, the USEPA noted that it had reviewed studies documenting performance from 11 offshore intakes equipped with a velocity cap. The data shows that by solely locating an intake over 240 m offshore, even without a velocity cap, it is possible to achieve a 60–73 % impingement reduction. Similarly, it also shows that the use of an EPA-defined velocity cap alone can achieve a 50–97 % reduction in impingement.

Based on this record of performance, the final rule designated offshore intakes fitted with a properly designed velocity cap as one of the "pre-approved" best technologies available for impingement.

To qualify as a pathway for impingement compliance, a velocity cap must usually be located more than 240 m offshore.

Virtually all velocity cap intakes require some on-shore screening system, usually a traveling water screen or rotating drum screen to protect downstream pumps and pretreatment equipment. The screens may be equipped with a Ristroph-type marine life handling system to further reduce impingement mortality and/or fine screens to reduce entrainment of entrapped organisms.

1.8 Passive Screens

Another intake arrangement utilizes fixed cylindrical screens constructed of trapezoidal- or triangular-shaped “wedgewire” bars arranged to provide 0.5–3.0 mm wide slotted openings (Chap. 5). The screens are usually oriented on a horizontal axis with the total screening area sized to maintain a velocity of less than 0.15 m/s to minimize debris and marine life impingement.

Passive screens are best suited for areas with an ambient cross-flow current that acts to ‘self-clean’ the screen face. Systems may also be equipped with an air backwash system to clear screens if debris accumulations do occur. As with all submerged equipment, material selections should reflect the corrosion and biofouling potential of seawater.

Passive screens have a proven ability to reduce impingement—due to their low through-flow velocities—and entrainment—through exclusion resulting from the narrow slot openings. Tests have shown that 1 mm openings are highly effective for larval exclusion and may reduce entrainment by 80 % or more.

1.9 Subsurface Intakes

Subsurface intakes are those in which seawater is withdrawn below the surface of the seabed and may consist of horizontal or vertical beach wells, infiltration galleries, or seabed filtration systems. In each of these designs, the open seawater is separated from the point of intake by a geologic unit (Missimer 2009; Missimer et al. 2013). A subsurface intake can be used where geologic conditions beneath the seabed can support water extraction while providing some level of natural filtration.

The use of subsurface intakes offers a distinct environmental advantage because the ecological impact associated with impingement and entrainment of marine life is virtually eliminated. However, subsurface designs must consider their potential impact on nearby fresh groundwater aquifers.

1.9.1 Vertical Wells

Vertical onshore wells that are hydraulically connected to the sea, or draw water from saline aquifers or deep regional aquifer systems that contain seawater may be used to feed seawater desalination plants (see Chap. 8). The site geology must be adequate to allow individual well yields to be high enough so that the number of production wells needed to meet an RO plants raw water supply is reasonable or cost-competitive with other supply options.

Often, the term 'beach well' is used to describe any vertical well, but this is incorrect if it applies to wells that are not directly recharged by seawater and located on or very near to the beach.

Many vertical wells make use of beach sand, coral or other geologic structures as a filter medium, and are often economical alternative to open sea intakes for desalination plants, especially those with production capacities less than 20,000 m^3/d, although one 80,200 m^3/d seawater RO plant has successfully employed vertical wells.

A vertical beach well usually consists a non-metallic well casing, well screen, and a vertical turbine or submersible pump. Site suitability is determined by drilling test wells and conducting a detailed hydrogeologic investigation to determine the formation transmissivity and substrate characteristics. It is preferred to locate beach wells as close to the coastline as possible, and the maximum yield from individual wells may range up to 4000 m^3/day or more.

1.9.2 Horizontal Directional Drilling

Horizontal directional drilling (HDD) techniques can be used to position a horizontal well within porous strata 2–4 m under the seabed. Drilling can be accomplished by sonic, rotary, percussion, or jetting techniques. The advantages offered by HDD technology versus conventional trench installation techniques include minimized surface disturbance/impacts, reduction in the quantity of excavated material, accuracy of conduit placement, and backfill and compaction of open trenches is eliminated.

One HDD wellfield system uses a relatively new type of porous polyethylene well pipe that acts as both a well screen and packing in one, and does not require additional external media packing for long-term operation. Pre-packed well screens and filter mesh well screens that can be pulled over a slotted pipe are other options offered by several manufacturers.

When designing a seabed filtration system the well screen and packing system should be sized so that the entrance velocity through the packing and screen does not exceed the prescribed maximum flow velocity for the adjacent formation materials.

Multiple horizontal wells can be installed from the same origin within a caisson in a similar manner to collector wells to supply higher production requirements.

1.9.3 Slant (Angled) Well

A slant well or angled well is similar to both vertical and horizontal directionally drilled (HDD) wells. This is because a slant well is nearly horizontal, yet constructed like a vertical well. The shallow-entry drill rig is angled approximately

15–25° from the horizontal, and then drilled straight, unlike a HDD drill rig that gradually turns as it drills to achieve a horizontal well (see Chap. 13).

1.9.4 Radial Collector Wells

Radial collector wells are a variation of the beach well in which multiple horizontal collector wells are connected to a central caisson that acts a wet well or pumping station from which water is pumped to the desalination plant. The use of multiple horizontal wells means that the production of each radial well can be significantly greater than a single vertical well.

Individual horizontal wells can be drilled or well screens can be hydraulically jacked out from the bottom of the caisson using a direct-jack or pull-back process. Caissons may be 2.75–6 m in diameter and 9–45 m deep, with 200–300 mm diameter radial arms. The caisson can be completed with a flush-grade top slab or in a buried concrete vault and backfilled with beach sand to reduce visual impact. The laterals can extend up to 150 m away from the central caisson.

1.9.5 Infiltration Galleries

An infiltration gallery type intake is a variation of the slow sand granular media filter that has been used in the water treatment industry for two centuries. The systems rely on the slow movement of seawater through the sand to remove particulate matter and biologically degrade bacteria and other organic compounds.

Galleries are designed similarly, whether located close to shore and beneath a beach, or hundreds of meters offshore (see Chaps. 10–12). A typical system consists of a header/lateral underdrain system buried in trenches 2–4 m below the seabed and backfilled with graded sand and/or gravel. The underdrain is used to collect seawater that filters through the seabed at a rate that usually ranges from 2–8 m/day, and conveys it to shore via a pipeline.

Large-scale galleries can be difficult to construct and may require expensive and time-consuming construction methods for their installation. However, they generally produce higher quality water than surface intakes, and their use may reduce the cost and chemical requirements of RO pretreatment systems.

1.9.6 Onshore Karst Pit

In some locations the onshore geology may be hydraulically connected to the sea by underground fissures typical of karst topography formed by the dissolution of soluble limestone or dolomite rocks. These underground networks may serve to

Fig. 1.5 Onshore karst pit intake in Curaçao

feed a below grade basin constructed onshore, and from which seawater may be pumped to a desalination plant.

One such intake was employed for a 26,000 m^3/d SWRO plant in Curaçao, in which a 6 m deep intake basin was located 100 m inland from the shoreline (Fig. 1.5). The basin walls were constructed of prefabricated, perforated concrete slabs and large, limestone rocks were installed around the basin's periphery to ensure a continuous infiltration of seawater.

1.10 Conclusions

The intake system is a critical component of all SWRO plants. The production of feed water to a SWRO plant must be reliable and consistently meet the operational capacity of the plant and should be of a consistent quality.

The intake water quality is critical to the downstream process operations within a SWRO plant. Pretreatment processes must be used to remove debris, suspended solids and organic compounds that adversely impact the primary membrane process. Therefore, the design and location of the intake play an important role in the full plant design and in the overall operational cost of a facility.

A key issue impacting the choice of which intake type to use is the operational reliability of the intake under all operating conditions that could occur at a site. While lower environmental impacts and reduced cost of operation are very important issues, reliability of a facility allows it to be financed and built. Therefore, there is a general bias toward the use of existing and proven intake types, particularly for large capacity SWRO facilities.

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Chapter 2
Design Considerations for Tunnelled Seawater Intakes

Peter Baudish

Abstract As a result of prolonged drought conditions and declining raw water storages, six large capacity seawater reverse osmosis (SWRO) desalination plants were constructed to secure the water supplies of the five major Australian state capital cities. For a variety of reasons including capacity, local geology, site topography, environmental concerns as well as the construction programme and construction risk mitigation considerations associated with hostile marine conditions, tunnels were adopted for five of the SWRO plants, connecting the desalination plants with their open intakes and brine concentrate outfall systems. The tunnel system is a relatively new concept for SWRO intake and outfall design. The design of marine intake and outfall works is very complex because of the wide range of constraints that must be accommodated as well as the hydraulic interactions among the intake system, pre-treatment facilities, desalination plant, and outfall system over a wide range of possible climatic, physical, and operational conditions. The challenges posed in the design and construction of tunnel and marine structures in high-energy open ocean environments are presented. These challenges include those associated with waves and currents, short- and long-term hydraulic considerations, durability and corrosion, biofouling control, and ongoing operation and maintenance. Different intake design approaches at two of the Australian SWRO plants are discussed.

2.1 Introduction

Between 2004 and 2012 six major seawater reverse osmosis (SWRO) desalination plants were constructed to serve Australia's largest coastal cities—two for Perth and one each for Brisbane-Gold Coast, Sydney, Melbourne and Adelaide (Fig. 2.1). The plants range in production capacity from 45 to 150 GL/a, with their intakes and brine return outfalls designed for flows as high as 18.5 m^3/s. Five of the plants have

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Fig. 2.1 Location of major Australian SWRO desalination plants

had tunnelled intakes and outfalls. The marine works are located in relatively hostile wave climate environments in the South Pacific, Southern and Indian Oceans.

The intake and outfall tunnels are up to 65 m below sea level, 2500 m in length, 4 m in internal diameter and of both incline and decline configurations. As well as the tunnels, there are marine intake structures, brine return diffusers, connective risers through the seabed floor, shore based seawater pump stations and fine screens. The tunnel and associated marine works are major engineering undertakings in their own right, forming a significant proportion of the project capital cost, and may also be the area of greatest project risk.

This chapter presents technical challenges associated with the design and construction of seawater tunnels and marine works in hostile marine climates with a focus on intakes. As many of these issues and challenges also apply to brine concentrate return systems only a few considerations specifically related to brine concentrate return tunnel and marine works are discussed. This chapter covers:

- Site-specific onshore and offshore topographic, geotechnical and geological conditions
- Marine wave climate and oceanography

- Risk, environmental and cost drivers for tunnelled intake and brine concentrate return conduits
- General hydraulic and environmental performance requirements
- Hydraulic considerations
- Operability, fouling, sedimentation, maintenance, and durability considerations
- Tunnel profile issues
- Intake pumping station and screen configurations.

2.2 Background

Australia is a highly urbanized country and though equal to mainland USA in land area, it is relatively sparsely populated. Over 80 % of the 22 million people live near the coast, with some 65 % in the major state capital cities. Increasing population accompanied by the longest recorded drought and limited alternative water resources led to the construction of major desalination plants around Australia to provide strategic diversification of water sources and drought security (Alspach et al. 2009). Most of the desalination plants were delivered through fast-track design-build contracts combined with an operational and maintenance contract (DBOM).

One of the disadvantages of a high coastal population density is the lack of available sites for large desalination plants with sufficient land area and/or suitable zoning classification. In the Australian context of rapid implementation of these desalination projects (as a drought response measure), this was a significant issue.

Consequently, the sites chosen may not have been ideal due to some or all of the following reasons:

1. Sites not located immediately adjacent to the ocean
2. Intakes and outfall in oceans with hostile wave climates with marine construction potentially at risk from large swells, rogue waves, or seasonally unfavourable climatic conditions
3. Unfavourable geotechnical conditions
4. Not close to the center of demand and thus having high connective product water infrastructure costs
5. Potential impacts on coastal and marine environments

The first three factors in conjunction with the large plant capacities, specific environmental constraints, cost effectiveness as well as the assessment of construction risk and delivery time frame, led to the use of tunnelled intakes and outfalls as the selected solution in Australia for the seawater intakes and brine concentrate returns for all but the first major desalination plant (Table 2.1).

Table 2.1 Seawater intake and outfall configuration

SWRO plant location (city served)	Conduit details[a]	Marine conditions	Launch[b] depth	Seabed depth
Kwinana (Perth)	1 × 2.4 m, 1 × 1.6 m dia. GRP ~350 m	Quiescent—Cockburn Sound	NA	8 m
Tugun (Brisbane—Gold Coast)	2 × 2.8 m dia. Tunnels ~2200 m long	Hostile (8 m Hsig[c]) and cyclone risk	70 m	22 m
Kurnell (Sydney)	2 × 2500 m long 3.4 m dia. tunnels	Hostile (7 m Hsig) and wave reflection	18 m	25 m
Binningup (Perth)	3 × ~960 m, 2.4/2.0 m dia. tunnel and bored	Moderate (4 m Hsig), protected reef	NA	10 m
Port Stanvac (Adelaide)	2 × ~1250 m long 2.8 m dia. tunnels	Moderate (4 m Hsig)	50 m	30 m
Wonthaggi, Melbourne	2 × 1200 m, 4.0 m dia. tunnels	Hostile (8 m) + Bass Strait	18 m	20 m

For descriptions of site geotechnical, environmental and oceanographic at each location refer Baudish et al. (2011)

[a]Lengths of intakes and brine outfalls are indicative

[b]Tunnel depth below ground level at launch shaft

[c]*Hsig* significant wave height

2.3 Intake Design and Construction Considerations

Open sea water inlet conduits are prone to marine organism ingress and colonization as well as sediment accumulation from sand and shell matter. Long, large diameter conduits, such as tunnels, amplify these issues as they cannot be readily taken out of service. They are difficult to inspect because of their depth and length. They are also likely to have internal conduits for maintenance purposes or biofouling control and therefore, are not suitable for pigging. They have a number of specific design considerations and issues that are not common with open shore based intakes.

2.3.1 Marine and Geomorphological Information Requirements

General marine issues and information requirements for the design of seabed structures and conduits include:

- Seabed geomorphology and bathymetric profile information is required for construction and siting seabed assets ideally being on relatively flat terrain clear of reefs and large boulders so as to minimise underwater preparation works

Fig. 2.2 Surge and wave conditions—Sydney desalination plant inlet

- Seabed surface sediment particle size distribution data is required for the consideration of scour as well as height of sediment suspended by currents, particularly by storm-wave induced orbital currents in the water column
- Extreme sea levels driven by tide and climatic conditions are of particular importance for pump stations, outlet shafts and gravity brine drains and overflow systems. These conditions include potential long-term sea level rise and drive hydraulic performance criteria as well as onshore ground and structure levels
- Currents induce loading on both permanent seabed structures and temporary marine construction equipment, such as jack-up barges and associated construction plant and equipment. Prevailing currents may be used to advantage in the design of brine diffusers to maximize dispersion and dilution as well as to optimize the relative positioning of intake and brine return systems to each other
- Long term wave climate data is unlikely to be available specific to the selected site. Regional data may have to be calibrated, modelled and interpreted taking into account the specific bathymetry, shore features and wave reflectance issues (Fig. 2.2)
- Site-specific wave climate data is necessary to derive wave-induced currents and loads on seabed structures—this data can be used to optimize positioning of structures in water deep enough to minimize loading on marine structures, but at the same time shallow enough to minimize length of tunnels for economic (cost) and construction timing reasons

- Environmental conditions need to be well understood. These include salinity and temperature, the range of marine flora, fauna and biofouling organisms. Their considerations may impact the design of intake screens, antifouling measures and operation as well as maintenance of offshore works.

2.3.2 Marine and Tunnel Construction and Operation

The detailed design of the tunnel and marine structures must take into account the construction methodology and type of equipment likely to be employed. Tunnel boring machines (TBMs) and jack-up barges for marine works and drilling risers are highly specialized equipment and both are likely to be long lead items. Jack-up barges in particular must be selected and potentially modified to suit the site-specific marine works, depths and oceanographic conditions.

Construction and operational issues to be addressed during the design include the following:

- In a fast track environment, TBM and jack-up barges will be on the critical path for construction, requiring early decisions on intake riser style and diameter, tunnel diameter and profile.
- Seabed structures should be deep enough to avoid being a navigation hazard, to avoid the effects of extreme waves and at a depth where good seawater quality is expected. They also need to be shallow enough to be constructed from jack-up barges. Intakes also should be positioned high enough off the seabed to minimize sediment entrainment.
- Jack-up barges must be able to be raised during storms to provide clearance for maximum swells caused by inclement weather. Weather causes wave intensity variations and storm surges which can limit marine construction activities. The occurrence of intense storms dictates the need for accurate forecasts and early warning systems.
- Stable and accurate positioning requirements for drilling, for the installation of riser liners, riser caps and screen and diffuser structures as well as accurate intersection with tunnels.
- Timing of marine (riser construction) and tunnelling construction operations also impacts the marine structures design. Tunnel risers may be constructed before or after the tunnelling and this needs to be considered, as risers may be connected to the tunnel through the crown or offset and connected via a lateral.
- Pressure differential limits for segmented liner construction impact on bolting and grouting design.

For large remote intakes that use HDPE pipelines on the seabed, a duplicate intake line may be installed to allow one intake to be taken out of service, while the other is pigged or its screen maintained. This “luxury” does not apply to large tunnel intakes. It is only a marginal cost difference to construct tunnels and marine works to suit an ultimate capacity. Due to the size and cost of tunnels, and in particular their construction risk, a single intake tunnel (and outfall) is typical. Thus future operation and maintenance requirements associated with a single intake in deep water needs to be addressed in the design development. Consideration needs to be made for the:

- inspection (and maintenance) provisions for the tunnels which are typically 20 m below sea bed and 40 m below sea level
- potential dewatering and safely carrying out inspection and maintenance
- limitations on diver access and ROV technology.

Of note is that since the long seawater intake tunnels in Australia have entered into service (i.e. from 2008 onwards) there have been advances in monitoring technology. ROV video cameras are now employed for regular monitoring of tunnel condition, in particular, for signs of sediment ingress and marine growth.

2.3.3 Intake Design

Intakes need to operate in a way that minimizes marine impacts, particularly impingement and entrainment of marine life. Key environmental performance criteria for intakes include limitations on maximum intake screen aperture and associated screen velocities. Similarly, outfall systems are now required to achieve stringent environmental performance objectives even when running at reduced capacity.

The upper limit to velocity through the intake screen bars is typically specified as an average of 0.10 or 0.15 m/s. While this limit on velocity may have the objective of protecting marine life or to avoid the intake of sediment, it is a major factor impacting on the size and weight of the seabed intake structure.

Typical screen bar/aperture spacings are in the range of 50–300 mm and, in combination with an allowance for marine growth on the bars, can have a significant impact on the overall size of the intake structure. Thus design needs to balance the size, constructability (in hostile marine environments) and cost factors versus long-term operation and maintenance. Considerations include:

- providing an allowance for marine growth, and interpreting any flow-on effects in the context of meeting project performance specifications, ambient ocean currents, the specified bar spacing and determining resultant impacts on the structure size
- use of anti-fouling copper-nickel alloys to suppress marine growth
- planning in situ maintenance regimes and/or design of removable screens
- the prevention or control of marine growth inside the riser and tunnels.

2.3.4 Hydraulic Design

Typically the tunnelled intakes and outfalls in Australia have been designed and constructed as segmented precast concrete lined tunnels. Minimum practical diameters for tunneling by TBM are about 2.8 m internal diameter. Diameters larger than 2.8 m are only constructed if required to suit the hydraulic requirements of an intake.

Large diameter HDPE pipeline style intakes are typically installed by floating, sinking and anchoring on the ocean floor. These HDPE pipelines are often designed to be cleaned by pigging, so that their internal condition can be restored. Piping provided for biofouling control or for other types of maintenance can be located external to the pipe. For tunnels small diameter piping is usually installed internal to the tunnel. Thus, the tunnel is not suited to mechanical cleaning or pigging. Due to their length and depth and internal fixings, tunnels are likely to be difficult to clean once in service.

Whilst there is published information on friction co-efficients for segmented tunnels, these co-efficients are not reflective of long-term friction over the 50 or 100 year tunnel design life of a seawater intake. Even if seawater tunnels have been designed to enable their dewatering and cleaning, the intention is not to do so. Thus, the designer must take a view as to the potential long-term changes in hydraulic characteristics due to marine growth and related performance alteration including:

- potential long term loss of diameter in some or all of the intake conduit components
- long term roughness factors to be adopted.

These are significant issues as they affect the choice of tunnel diameter, long term pumping heads, intake pump selection and screen design. Long-term data on marine growth in long conduits where biocide control is practiced is lacking, but it is clear that some growth will still occur. The highest rates of growth will occur at the intake screen, riser and tunnel entry, and then decreasing along the tunnel length where there is less light.

Intake screens require particular attention for the design of cleaning provisions. Ideally screens should be removable so that they can be mechanically cleaned above water. Biocides cannot be used for biofouling control on the screen proper due to risk of escape into the marine environment. They should be applied at the entry to the intake riser, with particular attention given to achieving effective mixing.

Other factors that need to be considered in design include:

- effect of tidal variations, swells and storm surges, as well as the potential long term impacts of climate change
- hydraulic limitations caused by fixed brine nozzles which are quite sensitive to flow rate and with some flow combinations potentially resulting in overflows of seawater within the site proper. This may require design mitigation measures such as spill provision from the brine outlet to the seawater intake
- temperature and salinity.

Dynamic surge impacts associated with sudden stoppage of the seawater pumps must also be considered, as this can lead to significant surges of over 5 m at intakes and potentially overflow onto the site. These effects can be mitigated by reducing momentum by increasing tunnel diameter or providing a large volume in the intake wet well to absorb the surge. Surge is a factor to be taken into account in deciding on the internal diameter of the tunnel.

2.3.5 Durability Aspects

Durability issues for tunnelled infrastructure and associated connective works should not be underestimated. Tunnel and marine works may be specified to have design lives of 50 or even 100 years. Achieving such design lives needs careful control through design, fabrication, construction and operational stages. The use of fibre reinforced concrete for tunnel segments has greatly extended the expected design life of the tunnel lining compared to conventional reinforcement.

When estimating expected design life of tunnel segments, it is also important to consider the accelerated ingress and corrosion rates expected to result from the occasional exposure of the concrete segments to air during tunnel dewatering. This requires chloride ingress modelling.

Coarse intake bar screens and metal fittings are typically composed of a super-duplex or copper nickel alloy. The latter is preferred due to its natural inhibition properties against marine growth. Coated steel with anodic protection may be appropriate for accessible shore-based equipment, such as screens.

Within intake tunnels there are additional considerations, such as when chlorine is used for control of marine growth, injected at the mouth of the intake risers. While this requires transport of diluted chlorine solution in piping within the tunnel, consideration of the impact of chlorine needs to be taken into account in materials selection of tunnel fixings and chlorine piping. Metals may not be appropriate, while plastics must also be selected for permanent installation to meet the 100-year design life of each component. Chlorine is typically delivered to the injection point as diluted sodium hypochlorite or gaseous chlorine in solution. Scaling risk needs to be addressed with the former, and the more aggressive nature of chlorine in the latter.

2.4 Integration of Design

The intake tunnel is inextricably linked to the design of the intake pump station and intake screens. Almost invariably site-specific solutions are required. Traditionally, fine 3 mm screens are placed upstream of the pumps. These screens capture any material that may pass through the coarse ocean intake screens, including filamentous algae and non-motile marine life such as jellyfish, and also protect the pumps from damage. This following section outlines alternative design solutions developed for the Sydney and Gold Coast desalination intakes (and outfalls), largely due to geotechnical conditions, tunnel drive method, and specific site limitations.

2.4.1 Gold Coast SWRO Desalination Plant

The GCD site is located about 700 m inland on a former municipal waste landfill site adjacent to the north west corner of the Gold Coast airport at Tugun (Fig. 2.3).

The on-site geotechnical conditions show deep consolidated sand both onshore and offshore overlaying sedimentary bedrock. Sound rock is found at depths around −55 to −60 m AHD. The plant site is approximately RL +7 m AHD grading gently seawards down to developed coastal dunes at about RL +5 to 6 m.

Marine climate issues include a summer cyclone season with ocean maximum currents up to 0.5 m/s. During high wave storm events (8 m height at ARI 1000 years) seabed orbital currents can reach 3 m/s or greater. The 6-month summer cyclone season precluded marine construction in this period. There is littoral sediment drift of some 500,000 m^3 per annum northward. The required siting of the intake to achieve stability required seabed depths below 18 m of depth to minimize sand and sediment entry into the intake. This also allows it to be located clear of the

Fig. 2.3 Gold Coast desalination plant—tunnel and marine structures locations

Fig. 2.4 Tunnel access shaft and TBM components/TBM segment being lowered for assembly below ground

more active near-coastal zone which could have otherwise resulted in undermining or covering the intake or outfall structures.

As outlined in Chap. 3, although there is little marine vegetation on the sandy seabed, the area is regarded as having a high environmental value. Tunnels were selected on the basis of program, environmental factors and visual impact during construction, as well as to minimize marine construction risk. Tunnelling also eliminated the need for an intake pump station remote from the plant site. This simplified the design and greatly reduced local impacts, as a suitable site for such a pump station was not readily available.

Specific features of the Gold Coast intake and outfall tunnel, and the seawater intake pumping arrangement were:

- Deep intake and outfall shafts. Tunnel boring machines (TBMs) work most effectively in rock or hard ground conditions. At the Gold Coast site, this meant that 70 m deep launch shafts were required to locate the TBM's in suitable rock (Fig. 2.4). This necessitated that the shafts be used for all construction activities including lowering and raising of TBM components, shift personnel, tunnel segments and also for removal of tunnel spoil.
- The depth at which sound rock was located was very consistent and did not favour an incline or decline arrangement. Both the intake and brine concentrate return tunnels were therefore graded upwards from land to sea in a slight incline (Fig. 2.5). This ensured any water entering the tunnels during construction drained back to the shaft by gravity, where it was easy to manage. This also resulted in the tunnel being slightly higher and closer to the seabed at the distal end, reducing the time to construct the riser connecting the tunnel to the sea floor.
- The single intake screen is approximately 4.4 m high, 5.8 m in diameter and with 2 m high copper nickel screens with a bar spacing of 140 mm (Fig. 2.6).
- The four 1.33 m^3/s vertical turbine seawater intake pumps were located within the 9.6 m dia. tunnel intake shaft (Fig. 2.7). This simplified the intake arrangement and reduced both costs and construction time for this element of the project, which was on the critical path for the overall project. However, this also

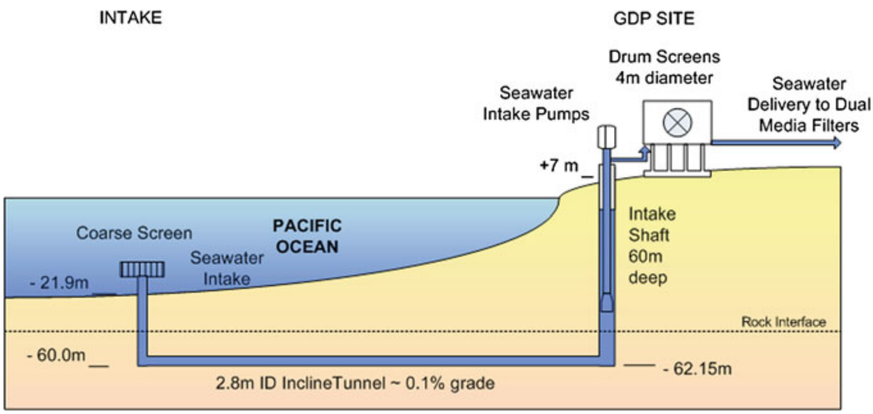

Fig. 2.5 Schematic of the GCD seawater intake arrangement

Fig. 2.6 Intake coarse screen being installed from the jack-up barge

meant that it was not feasible to locate fine screens upstream of the pumps, introducing a potential risk of pump fouling under very poor water quality conditions. Given the good intake conditions afforded by locating the intake far enough offshore in deeper water, and through the use of high clearance pumps, this risk was considered acceptable. Both numerical and physical modelling of the intake/pump suction were carried out to optimize pump inlet design to avoid the development of unfavourable pumping conditions (unbalanced flows/vortexes) for these large capacity pumps (Mould and Sprengel 2010).

- Seawater is delivered from the intake pumps to the two (duty/standby) 4 m diameter, 3 mm mesh dual entry drum screens (Fig. 2.8). The screens are housed in an above ground structure enabling gravity flow to the pre-treatment filters. During operation of the plant to date, there has been very little trash collected by the fine screens, demonstrating the advantages of careful location of the intake structure to ensure good intake water quality.

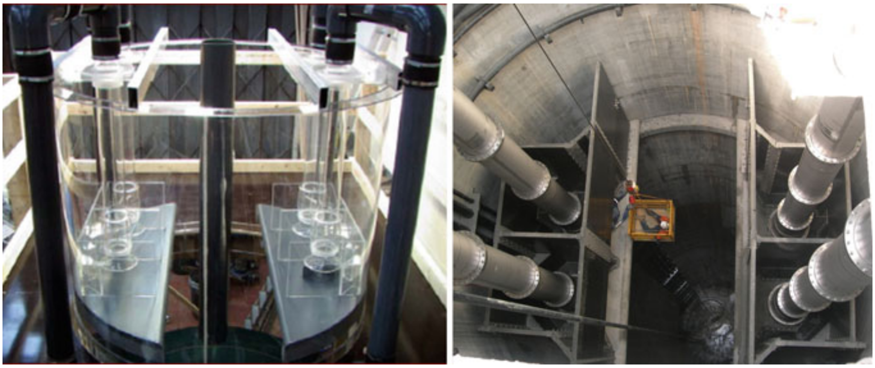

Fig. 2.7 Intake physical model and as-installed seawater pumps

Fig. 2.8 Intake pumps and elevated screen structure 4 m diameter drum screen

2.4.2 Sydney SWRO Desalination Plant

The Sydney desalination plant (SDP) is located at Kurnell, to the south of the Sydney airport (Fig. 2.9). Site constraints included a conservation area to the north and a freshwater ecosystem that leads to the Towra Point wetlands adjoining Botany Bay. The plant site geotechnical conditions included shallow loose sands with a high water table interspersed with peaty lenses, underlain by firm sandstone that ranges from −6 to −30 m AHD and undulates underground across the site. This relief is caused by the buried remnants of former drowned river valleys.

Though closer to the sheltered waters of Botany Bay, the intake and brine outfall are located eastwards to the Tasman Sea (Pacific Ocean).

The desalination plant site itself is located at a relatively low elevation (5–6 m ASL finished level), but the ground and rock profile rises seawards to nearly 35 m before sloping down to the 20–25 m high sandstone cliffs at the edge of the Tasman Sea. The sea floor below the cliffs is rocky, and descends to 25 m below sea level

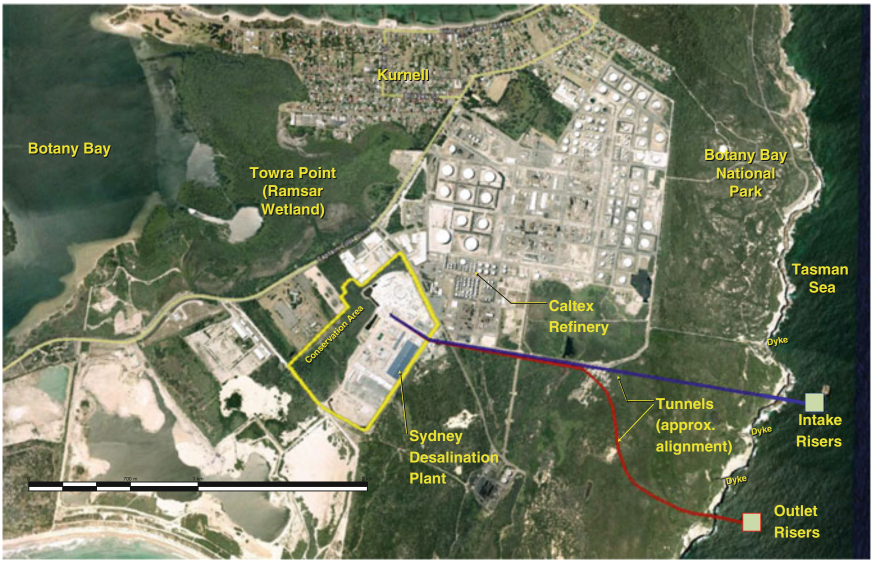

Fig. 2.9 Tunnel and marine structures location—Sydney desalination plant

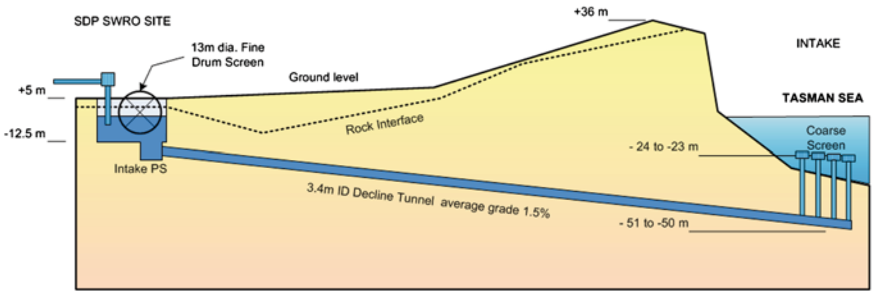

Fig. 2.10 Schematic of the SDP seawater intake arrangement

within a few hundred metres of the cliffs, a depth at which both the intake and concentrate return structures are located (Fig. 2.10).

The coastline bordering the Tasman Ocean is within Botany Bay National Park. There is a wide range of marine flora and fauna associated with reefs and rocky seabed. Migrating whales are frequently observed in the area between April and December. Restrictions to riser construction activity were required when whales were in close proximity.

Specific marine conditions at the intake and outlet site included continuous high energy incident and reflected waves with 1:10 year Hsig of 7.3 m and estimated extreme waves heights of approximately 12 m. Currents typically range between 0.1 and 0.4 m/s. Modelling of the specific local wave climate (as distinct from regional data) was required to assess the influences of the steeply rising floor and

Table 2.2 Key design issues for incline and decline tunnels

Issue	Incline tunnel	Decline tunnel
Tunnel dewatering	At the landside shaft	Sea side (or landside by progressive movement of pump)
Sediments	May be transported towards seawater pump station	Likely to accumulate at intake end of tunnel
Floating matter	Likely to remain near the intake marine riser	Likely to be transported towards the seawater pump station
Air entrainment (brine return)	Air will flow along the tunnel crown to the brine outlet	Air must be released before entering the tunnel

cliff face on extreme wave heights as well as frequencies and influences of reflected waves.

Trenched pipelines were never considered for the intake and outlet because of the cliff profile, marine conditions and sandstone geology (both onshore and sea-bed). Tunnels were adopted. Though primarily in hard sandstone, the tunnel routes crossed near vertical fault lines (weathered dykes). Due to location within the national park, extensive exploratory drilling was not possible. Thus, geotechnical information related to dyke strike and dip and expected condition at the dyke-tunnel route intersections was limited. Igneous dykes had measured widths of 1.3–2.7 m. A limited joint swarm was present at mid length of the route for both tunnels.

The shallow sound rock available at one end of the desalination plant site opened up the possibility of a decline tunnel. This approach was adopted after careful consideration of the technical and operational advantages and disadvantages of a decline arrangement (Table 2.2).

In terms of construction, the decline tunnel offered significant advantages in construction efficiency, including ease of assembly/disassembly of the TBM within a “box-cut”, and transport of tunnel segments and removal of tunnel spoil which did not have to be lowered or raised via a shaft (Fig. 2.11).

A decline tunnel was adopted for both the intake and brine return tunnels, connected directly to an intake pump station. Compared to the Gold Coast plant this resulted in a more conventional arrangement of the fine screens upstream of the sea water inlet pumps (Fig. 2.12).

There are two 12.7 m diameter (2 × 100 %) capacity drum screens for the 250 ML/d Sydney plant (Fig. 2.13). When the plant is augmented to 500 ML/d, two additional screens will be added, resulting in four 33 % capacity screens. The large screen diameter was required to accommodate the tidal range as well as ultimate friction effects through the long intake tunnel. There are five 2 m^3/s seawater intake pumps, two for each 125 ML/d SWRO module and a common standby. An additional five pumps will be installed when the plant is augmented. As for the Gold Coast plant, modelling of the inlets to the pump suction was required to ensure optimum flow and performance of the pumps.

Marine construction was extremely difficult due the prevalent swells and the reflected wave waves from the nearby cliff face. Originally, the risers to tunnel were

Fig. 2.11 TBM assembly within the "box-cut" leading to the tunnel portals/haulage railway and spoil conveyors leading out of the "box-cut"

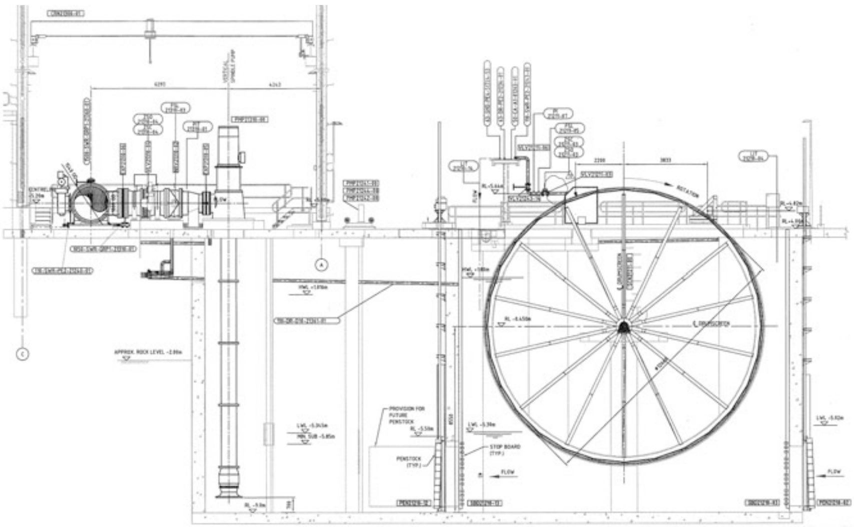

Fig. 2.12 SDP Intake pumps and fine screen general arrangement

planned to be connected through the tunnel crown. A change of design to a lateral connection arrangement was adopted early during the construction phase to enable more independent construction of the tunnel and riser/marine works. The risers are connected to the tunnel via stub laterals. Some further details of the construction methodology for the marine works are provided in Chap. 3.

The risers were of ribbed GRP construction, and grouted into bored holes. The lateral also has a GRP liner. The main elements of the seabed marine intake and brine return structures were precast concrete sections to which copper-nickel alloy screens/super duplex nozzles were attached respectively.

Fig. 2.13 SDP intake pump/fine screen during installation

2.4.3 Construction Scale

A few details from the Sydney desalination project give some idea of the magnitude of the tunnel and marine works. The intake and outlet structures were positioned within a contract prescribed area. The areas are located approximately 300–350 m offshore from the headland at Cape Solander and approximately 700 m apart as shown in Fig. 2.9.

The intake system comprises:

- Four cylindrical, precast concrete intake structures 8.5 m in diameter and 5.2 m high (Fig. 2.14)
- 32 screens (8 per intake structure) 1.9 m high × 3.0 m long with copper-nickel alloy bars at 340 mm spacing
- Four fibreglass lined 'risers' each with a 1.5 m ID, located approximately 20 m apart and extending from the seabed down to tunnel level; fibreglass lined connective stub cross tunnels with a 1.4 m ID approximately 6.0 m in length, connecting the risers to the tunnel

Fig. 2.14 Pre-cast intake coarse screen structure/screen base being lowered

- A 3.4 m ID tunnel approximately 2.5 km in length, sloping downwards at up to a 2.5 % decline from on-shore and lined with fibre reinforced precast concrete segments
- Eight chlorine solution pipes mounted within the tunnel (one duty and one standby pipe per intake riser)
- A reinforced concrete pumping station structure approximately 35 m^2 and 20 m deep with a distribution channel and bays for four drum screens
- Two drum screens 12.7 m in diameter
- Five 2 m^3/s vertical pumps.

The brine concentrate return outlet system comprises:

- Two cylindrical, precast concrete outlet structures 6.8 m in diameter and 3.7 m high located on the seabed in more than 20 m of water
- Eight tapered super duplex UNS32750 brine nozzles, (four per outlet structure) with an exit ID of 370 mm for a plant capacity of 250 ML/d. The nozzles will be changed when the plant is expanded to 500 ML/d
- Two fibreglass lined risers each with a 1.4 m ID extending up from tunnel level to the seabed
- Two 1.8 m diameter stub cross tunnels approximately 6.0 m long connecting the risers to the main tunnel
- A 3.4 m ID decline tunnel approximately 2.5 km long
- A reinforced concrete deaeration—air release structure approximately 40 m × 5 m wide and 12 m deep
- A 900 mm diameter raw seawater pump discharge cross-connection and control valve to supplement flows and achieve specified brine dispersion requirements over the full operating range of SWRO plant flows.

Major construction equipment included:

- A jack-up barge (self elevating marine construction platform) from which the riser shafts were drilled and constructed. When elevated the barge was 10 m above the mean sea surface level. The barge had a displacement of 2820 t and had 66 m long legs

- Two double shielded hard rock tunnelling machines, one each for the inlet tunnel and one for the outlet tunnel. The cutting face was 4165 mm in diameter and the TBM body 4100 mm in diameter. The TBM cutting face weighed 33 t, and there were 16 trailers with a total length 123 m
- The tunnel lining erected behind the TBM was a six segment configuration. A total of 22,800 segments were required for the 5.0 km combined length of tunnels. Each segment is 225 mm thick and weighs 1.5 t.

2.5 Conclusions

Where desalination plants are constructed on coastlines exposed to hostile open ocean conditions, and tunnels are adopted as intake and brine concentrate return conduits, the tunnel and marine infrastructure become a significant proportion of the overall capital cost of the project. The marine works are an area of the project where a large part of the overall project risk lies, usually being on the critical path and potentially subject to extremes of weather and ocean conditions.

The design of the marine intake and outfall works is very complex because of the wide range of constraints that must be accommodated as well as the hydraulic interactions between the intake system, pre-treatment, desalination plant and outfall system over a wide range of possible climatic, physical and operational conditions.

As each desalination site has a unique combination of physical, environmental and social constraints, the solutions developed for the seawater intake and brine return systems may well be quite different even if they have similar performance requirements.

Acknowledgments The information presented in this chapter has largely been derived from experiences gained by Jacobs staff during siting and environmental studies and tender and detail designs related to the six major Australian SWRO plants, in particular the Gold Coast and Sydney SWRO plants. I would like to acknowledge the valuable contributions and insights of Daryll Pain, Phil Banks, Ralph Burch and Doug Franklin.

The Gold Coast Desalination Plant was designed and constructed by the Gold Coast Desalination Alliance comprising alliance partners SureSmart Water, John Holland, Veolia Water; Jacobs (SKM), Halcrow and Cardno.

The plant is operated by Veolia Water for SureSmart Water. The Sydney Desalination Plant was designed and constructed by John Holland and Veolia Water (the Bluewater construction JV) and the Jacobs (SKM)–Mansell design JV. The plant is operated by Veolia Water.

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Chapter 3
Sydney and Gold Coast Desalination Plant Intake Design, Construction and Operating Experience

Keith Craig

Abstract Australia has embarked on the development of several large capacity seawater reverse osmosis (SWRO) facilities to meet future water demands and to provide water security during severe drought conditions. Two of these SWRO facilities, Sydney and Gold Coast, have installed permeate capacities of 266,000 and 133,000 m^3/day respectively. The coastal areas of Sydney and Gold Coast contain sensitive marine environments that necessitated the development of intake systems that connect tunnels from the SWRO plant to offshore capacity cap intake structures. The design of these tunnel intake systems is quite unique and has been successfully designed and constructed. The design of the tunnels and intake structures are herein documented with an initial operational assessment.

3.1 Introduction

The Sydney and Gold Coast seawater reverse osmosis (SWRO) desalination plants are among the largest desalination plants in Australia and provide water to major urban centres of Sydney, Gold Coast and Brisbane. The plants were designed and are operated by Veolia.

A key aspect of the design was the selection of the intake type and design for these large plants to provide suitable seawater quality and quantity to the plants and minimise any environmental impacts from the intake (Craig 2013).

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3.2 Sydney Plant Overview

The Sydney Desalination plant has a capacity of 266,000 m^3/day and is located in the southern part of Sydney at Kurnell (Figs. 3.1 and 3.2). The plant can supply up to 15 % of Sydney's water supply and was built following a prolonged drought period.

The Sydney plant is a seawater reverse osmosis process and is divided into two 133,000 m^3/day modules. The treatment includes:

- Open intake with screening
- Sulphuric acid
- Ferric chloride and polydadmaac coagulants
- Dual media filtration pre-treatment
- Cartridge filtration
- Two pass RO
- Remineralisation with lime, carbon dioxide and
- Chlorination, fluoridation then chloramination

The plant was placed into full operation in June 2010. The plant is owned by the Sydney Desalination Company and operated by Veolia.

Fig. 3.1 Sydney SWRO plant