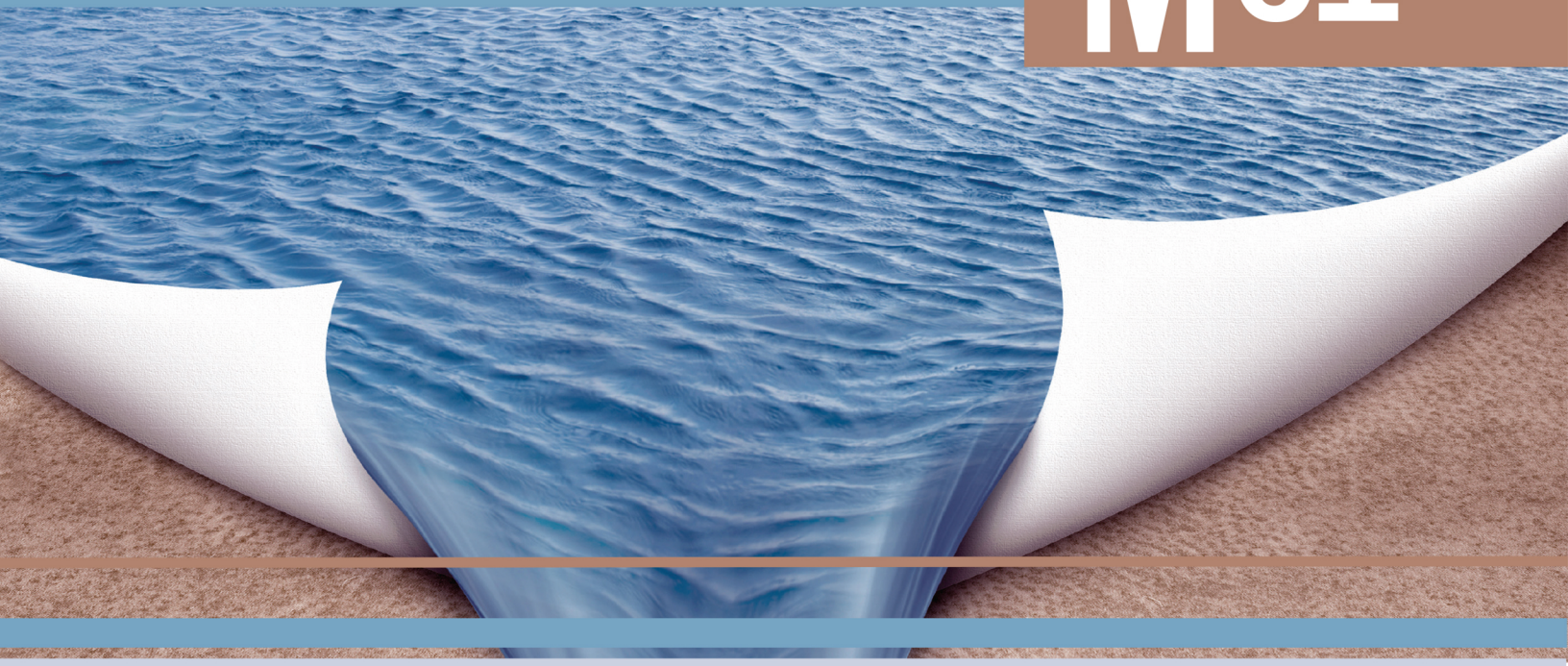
Desalination of Seawater

MANUAL OF WATER SUPPLY PRACTICES M61



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Desalination of Seawater

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Contents

Chapter 1 Seawater Desalination Overview **1**

Introduction, 1
Desalination Technologies Overview, 3
Membrane Separation, 3
Thermal Evaporation, 6
Novel Desalination Processes in Development, 9
References, 13

Chapter 2 Water Quality **15**

Source Water Quality, 15
Product Water Quality, 17
Health Concerns, 17
Product Water Stability, 21
Irrigation and Industrial Use Concerns, 21
General Aesthetic Concerns, 23
References, 24

Chapter 3 Treatment Approaches **27**

Pretreatment, 27
SWRO Design Parameters, 33
Disinfection, 36
Posttreatment, 37
Energy Recovery, 38
Corrosion and Materials of Construction, 43
References, 47

Chapter 4 Environmental Impacts and Mitigation Measures **49**

Introduction, 49
Source Water Intakes, 50
Concentrate Discharge, 57
Management of Desalination Plant Residuals, 69
Greenhouse Gas Emissions—Impacts and Management, 72
Noise, Air Pollution, and Traffic, 79
References, 80

Chapter 5 Cost of Treatment **83**

Introduction, 83
Summarizing Project Costs, 83
Construction Costs, 85
Estimating Capital Costs, 85
Estimating Operation and Maintenance Costs, 89
Financing Cost, 93
Cost of Water, 94
Summary, 94
References, 98

Documents
Document Sharing Hub

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Full document details: AWWA Manual M61 2011

Chapter 6 Safety and Security.....**99**

Safety, 99
Security, 102

Documents
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Figures

Figure 1-1 Global growth of desalination facilities 2
Figure 1-2 Basic concept of osmosis and reverse osmosis. 4
Figure 1-3 Multistage flash distillation 8
Figure 1-4 Multiple effect distillation 8
Figure 1-5 Vapor compression 9
Figure 1-6 Schematic of forward osmosis desalination process. 10

Figure 2-1 Sea-surface salinities 16
Figure 2-2 Boston Ivy with tip burn from chloride 20
Figure 2-3 Boron toxicity on camphor. 20

Figure 3-1 Projected impact of recovery on power consumption for SWRO. 34
Figure 3-2 Projected SWRO feed pressure requirements as a function of influent water temperature for different flux rate and element type. 35
Figure 3-3 Projected impact of temperature on SWRO permeate boron 35
Figure 3-4 Pelton wheel generators at Tampa Bay SWRO facility. 39
Figure 3-5 Hydraulic turbocharger in an RO system. 39
Figure 3-6 ERI™ TurboCharger device (low pressure turbine) 39
Figure 3-7 ERI™ PX energy recovery device flow diagram 40
Figure 3-8 PX™ Pressure exchanger device installation in Sand City, Calif. 40
Figure 3-9 Dual Work Pressure Exchanger flow diagram 41
Figure 3-10 Installation of Flowserve DWEER energy recovery device 41
Figure 3-11 Three center design layout 42
Figure 3-12 Resistance to crevice corrosion 44

Figure 4-1 3.8 MGD intake beach well of a large seawater desalination plant 52
Figure 4-2 Beach well intake system (above-grade completion) 52
Figure 4-3 Beach well intake system (at grade completion). 53
Figure 4-4 Beach well intake system (dual completion) 53
Figure 4-5 Tidal zone (onshore) discharge of the Ashkelon SWRO Plant, Israel 60
Figure 4-6 Perth SWRO Plant discharge configuration. 61
Figure 4-7 Perth desalination plant mixing zone. 62
Figure 4-8 Perth desalination plant discharge diffuser – rhodamine dye test 63
Figure 4-9 5.5 MGD Santa Barbara seawater desalination plant, California. 64
Figure 4-10 Colocation concept for the Carlsbad Seawater Desalination Plant. 66
Figure 4-11 Colocation of Tampa Bay Seawater Desalination Plant 66
Figure 4-12 32 MGD Carboneras SWRO plant in Spain. 67
Figure 4-13 Carlsbad seawater desalination project. 73

Figure 5-1 Seawater RO construction cost. 86
Figure 5-2 Seawater RO cost of water 93

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Tables

Table 1-1 Operational seawater desalination facilities in the United States 2

Table 2-1 Seawater mineral quality compared to national source waters. 16
Table 2-2 Pathogen reduction requirements for surface waters 19

Table 3-1 Seawater RO pretreatment components for surface seawater sources 30
Table 3-2 Seawater RO treatment advancements for surface seawater sources 31
Table 3-3 Partial list of pretreatment installations in SWRO plants since 1995 32
Table 3-4 Log removal credits for potential treatment processes. 37
Table 3-5 Energy recovery devices (ERD): pros and cons 43
Table 3-6 Galvanic series for alloys in flowing seawater at 4 m/s and 24°C 44
Table 3-7 PREN values for common materials. 46

Table 4-1 Potential impingement/entrainment reduction technologies 56
Table 4-2 Concentrate disposal methods for existing desalination in the U.S. (including brackish RO, NF, and SWRO) 60
Table 4-3 Residuals from seawater desalination processes 70
Table 4-4 Comparison of waste streams from granular media and membrane pretreatment. 71
Table 4-5 Desalination project net GHG emission zero balance 78
Table 4-6 Unit costs of carbon footprint reduction alternatives. 78

Table 5-1 Seawater intake alternatives cost example. 95
Table 5-2 Seawater RO plant capital cost example 96
Table 5-3 Annual Operation and Maintenance Cost Example Treatment Technology: SWRO 97
Table 5-4 Annual Cost of Water Example Treatment Technology: SWRO (with a power plant) 97

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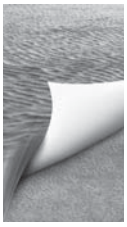
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Chapter 1

Seawater Desalination Overview

Sandeep Sethi
Greg Wetterau

INTRODUCTION

As worldwide fresh water supplies become increasingly stressed and world populations continue to grow, seawater desalination has become an increasingly sought-after alternative for new water supply in coastal areas. While three-quarters of the globe is covered with water, less than 0.3 percent is considered a renewable freshwater supply. More than half of the population in the United States lives within 50 miles (80 kilometers) of a coast, so the use of seawater as a source for potable water production is of great interest, especially in areas with stressed and overdrawn freshwater resources. Historically, the high cost of desalination has made it less attractive than freshwater supplies, even where those freshwater supplies were hundreds of miles away (i.e., Southern California).

As desalination becomes more economical, its use for municipal water supply has increased dramatically. Figure 1-1 shows that the worldwide desalination capacity more than doubled between 2002 and 2010. In the United States, most desalination facilities treat brackish water or are membrane softening plants; however, seawater desalination plants currently outnumber brackish water plants by 60 percent worldwide (GWI 2009).

Table 1 lists some of the more than two dozen seawater desalination plants built and operated in the United States. The majority of these facilities are industrial with a capacity of less than 1 million gallons per day (mgd) or 3.8 megaliters per day (MLD). In addition, a number of these plants are used intermittently because of the high cost of operation or problems experienced during operation. As coastal municipalities in the United States

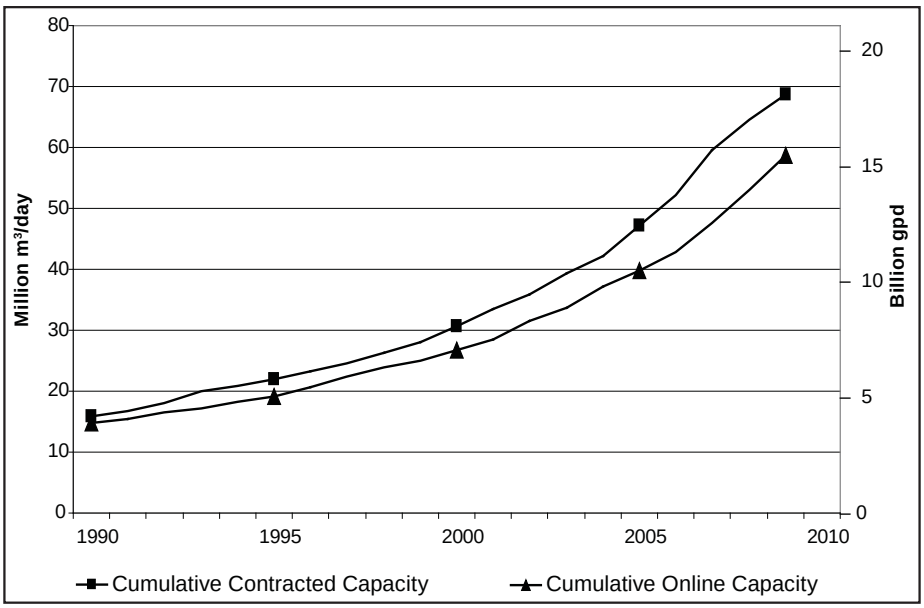
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begin to consider implementing larger seawater facilities, it is essential to ensure that these are constructed and operated in an efficient and reliable fashion without adversely impacting fragile coastal environments. Large capacity, highly efficient seawater desalination facilities have been successfully implemented within the last five years in Australia, Singapore, Spain, and several countries in the Middle East. In the United States, there are currently more than two dozen new seawater projects in various stages of development, primarily in California, Texas, and Florida.

The purpose of this manual of practice is to identify lessons learned from recent studies and seawater desalination projects around the world, and to use these to provide guidance for seawater desalination facilities that are reliable, economical, and environmentally sound.



Source: Global Water Intelligence 2010, data reproduced from DeSalData.com/Desalination Markets

Figure 1-1 Global growth of desalination facilities

Table 1-1 Operational seawater desalination facilities in the United States

Diablo Canyon, CA (0.6 mgd or 2.3 MLD)	Tampa, FL (25 mgd or 95 MLD)
Gaviota, CA (0.4 mgd or 1.5 MLD)	Stock Island, FL (2 mgd or 8 MLD)
Morro Bay, CA (0.6 mgd or 2.3 MLD)	Marathon, FL (1 mgd or 4 MLD)
Moss Landing, CA (0.5 mgd or 1.9 MLD)	Kauai, HI (0.2 mgd or 0.8 MLD)
Monterey Bay Aquarium, CA (0.04 mgd or 0.15 MLD)	Swansea, MA (2 mgd or 8 MLD)
Sand City, CA (0.3 mgd or 1 MLD)	Brockton, MA (5 mgd or 19 MLD)
Avalon, CA (0.1 mgd or 0.4 MLD)	

Courtesy of Greg Wetterau

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DESALINATION TECHNOLOGIES OVERVIEW

Desalination processes can be divided into two broad categories: membrane separation and thermal evaporation. Membrane-based desalination processes typically employ mechanical pressure, electrical potential, or a concentration gradient as the driving force across a semi-permeable membrane barrier to achieve physical separation. Thermal desalination processes employ heat to evaporate the water from a salt solution, and the water vapor is then condensed and recovered.

Thermal technologies were the only options available for seawater desalination until reverse osmosis (RO) membranes were developed in the early 1960s. Since then, RO membrane processes have steadily been improved, and the efficiency has increased to the point that they are now the technology of choice for most seawater desalination applications. An exception to this is the Middle East, where low energy costs allow for thermal desalination to remain relatively competitive.

Besides the established desalination technologies, there are several newer technologies that are nearing commercialization or undergoing active research and development. A discussion of the established membrane and thermal technologies is presented first in this manual, followed by a brief discussion of developing technologies. The remaining chapters in this manual focus on pressure-driven membrane applications, as this presently has the most applicability to seawater desalination in the United States.

MEMBRANE SEPARATION

Membrane desalination technologies have been designed around the ability of semi-permeable membranes to selectively permit or minimize the passage of certain ions. Three fundamental driving forces can be used in membrane desalination systems including pressure, electric potential, and concentration gradient. RO and nanofiltration (NF) are pressure driven processes. Electrodialysis (ED) and electrodialysis reversal (EDR) are electric potential driven processes. Forward osmosis (FO) is a concentration-driven process.

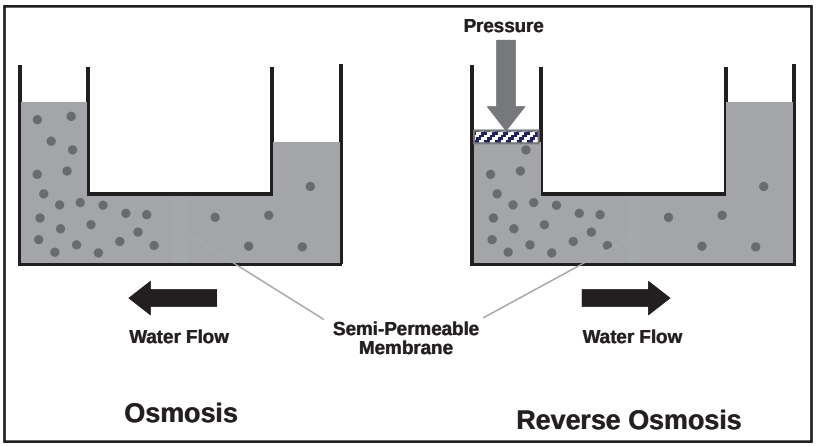
Membrane-based seawater desalination processes have typically applied only RO. Although NF and ED/EDR are also mature technologies and can be used for desalination, ED/EDR are typically not cost competitive for desalination of seawater (Amjad 1993), and NF is not ordinarily considered for seawater desalination for potable water production. However, a novel approach employing two-pass (NF) configuration has been developed and tested for seawater desalination by the Long Beach Water Department in California. Similarly, FO is a developing technology and has not yet been commercialized for large-scale applications.

Reverse Osmosis (RO)

Desalination through RO is a well-established and nonproprietary unit process that currently represents the state-of-the-art of desalination technology for a number of reasons. In addition to the ability to reject a variety of contaminants, RO treatment generally has lower energy consumption, lower feed water flows, and no thermal impacts in the concentrate discharge in comparison to thermal desalination processes. Improvements in membranes and energy recovery devices used for seawater RO (SWRO) have improved the overall process efficiency thereby lowering the costs associated with treatment.

Reverse osmosis is based on overcoming the natural phenomenon of osmotic pressure, which occurs when a semi-permeable membrane separates two solutions with different concentrations of ions. The osmotic pressure created by the concentration gradient drives the flow of water from the dilute solution to the concentrated solution, until chemical equilibrium is established. The flow of water can be reversed with the application of an external hydraulic force (pressure) if this force is greater than the osmotic pressure. Figure 1-2 illustrates the basic concepts of osmosis and reverse osmosis.

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Courtesy of Sandeep Sethi

Figure 1-2 Basic concept of osmosis and reverse osmosis

RO membranes are designed to retain salts and low-molecular weight solutes while allowing water to pass through. The original asymmetric cellulose acetate (CA) membranes, developed in the 1960s, were less permeable than modern thin-film composite (TFC) membranes and required a higher driving pressure, in excess of 1200 pounds per square inch (psi) or 8.3 megapascals (MPa) for seawater at typical operating fluxes. Additionally, the ability of CA membranes to reject salts was originally less than current materials.

Cellulose acetate membranes utilized an asymmetric structure while the TFC contained multiple layers made from different materials. In the asymmetric configuration, the membrane consists of the same material throughout with a dense layer at the top and porous layer beneath. In contrast, the TFC membrane consists of a thin but dense layer of one material over a porous support consisting of a different material.

Currently, there are a variety of modified and improved blends of CA membranes available to the desalination industry, but these membranes are rarely used in large-scale desalination applications. CA membranes can tolerate continuous exposure to low concentrations of chlorine (0.1 to 0.5 mg/L at 25°C), which is an advantage for biofouling control in seawater applications. They are, however, susceptible to hydrolysis, which compromises the membrane's salt rejection performance. Hydrolysis of CA membranes is accelerated if the operating pH is less than approximately 4 or greater than approximately 7 and temperatures are greater than 30°C (Mallevialle et al. 1996). Therefore, pH depression into this range is needed for seawater desalination with CA membranes.

The development of TFC membranes provided greater salt rejection and higher water production per unit membrane area. TFC membranes are made by combining a thin, dense membrane film with a porous underlying material that provides structural support. The thin film typically consists of aromatic polyamide (PA) and the bottom support layer is typically polysulfone. Most of the solute rejection occurs at the thin nonporous film, and its small thickness can significantly reduce the pressure required to drive water through it in comparison to CA membranes. TFC membranes are stable over a broad pH range (2-11) and can withstand temperatures as high as 45°C. However, unlike the CA membranes, they are susceptible to degradation by strong oxidants such as free chlorine. Although the degradation rate caused by free chlorine is a function of pH, membrane materials generally deteriorate upon exposure to chlorine (sometimes catastrophically).

High pressures are required to overcome the osmotic pressure of the salts and minerals, and the resistance from the membrane material, and other associated system losses.

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SWRO membranes are typically operated at feed pressures of approximately 800 to 1,000 psi (5.5 to 6.9 MPa). RO membranes are capable of rejecting contaminants as small as 0.1 nm; however, the process of water transfer is mostly diffusion controlled rather than convection controlled as with microfiltration and ultrafiltration. In addition to the effects of the major ion matrices, mass transfer of ions through RO membranes is also impacted by broader water quality characteristics, such as temperature and pH.

The amount of water recovered using SWRO membranes ranges from 35 to 60 percent, and commercially available SWRO membranes typically reject 99.5 to 99.8 percent of the total dissolved solids (TDS) in the feed water. However, removal of a few constituents, such as boron, is sometimes not as great as might be required (see Chapter 2). If product water goals are not met, additional treatment may consist of two-pass RO, in which a portion or all of the permeate produced in the first pass is treated again in a second pass. New membranes with improved boron rejection are currently being developed by SWRO manufacturers to avoid the need for two-pass treatment; however, other water quality goals besides boron may also impact the need for a two-pass system. An optimized SWRO design will therefore depend on the feed water quality, system operating conditions, and specific finished water quality requirements.

Because membrane processes are based on physical separation, they do not require thermal energy to vaporize the water (with the exception being membrane distillation, discussed later in this chapter). As a result, the energy consumption for treatment components of an SWRO plant typically falls in a range of 10 to 20 kilowatt-hours (kWh)/1,000 gallons (2.6 to 5.3 kWh/m^3). In comparison, total energy used for thermal desalination treatment processes can range from 10 to 40 kWh/1,000 gallons (2.6 to 10.6 kWh/m^3), depending on the unit processes.

Energy recovery devices are increasingly used in SWRO applications. These devices can recover from 25 to over 45 percent of input energy for SWRO. Examples of such devices as presented in Chapter 3, include Pelton wheels, work exchangers, pressure exchangers, and hydraulic turbo-exchangers.

One of the greatest challenges for membrane desalination processes is fouling and scaling of the membranes. Fouling can occur as a result of inadequate pretreatment or measures for reduction of particulate, colloidal, or organic matter to tolerable levels, or biological growth in the membrane pressure vessels. Scaling results from precipitation of sparingly soluble salts in the system and tends to be less of a concern in seawater desalination than in brackish water systems, which run at higher recoveries. Compounds such as calcium carbonate, calcium sulfate, silicate, barium sulfate, and strontium sulfate in the feed water may, however, contribute to limiting the recovery of the RO process. Acid or scale inhibitors (also known as *antiscalants*) may be added to reduce alkalinity and prevent formation of scale, allowing for higher recovery than otherwise possible. As a result of high levels of particulates and the generally aerobic state of seawater, SWRO plants require comprehensive pretreatment and chemical conditioning of the feedwater for successful operation.

Nanofiltration (NF)

Nanofiltration is typically used to soften water and remove disinfection by-products (DBP) precursors such as dissolved organic matter. NF is typically not used for seawater desalination, although unique configurations of two-pass NF have been successfully used to desalinate seawater.

Nanofiltration uses semi-permeable membranes and a driving force of hydraulic pressure; however, in comparisons to RO, NF membranes typically have a higher molecular weight cut-off (MWCO). NF membranes remove a high percentage (90 to 98 percent) of divalent ions (i.e., those associated with hardness) but removal of monovalent ions is somewhat limited (typically 60 to 85 percent) .

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Because a higher concentration of monovalent ions can pass through the NF membrane, the osmotic pressure is lower compared to RO. This, combined with a more permeable membrane skin layer, reduces the hydraulic pressure requirements to 500 to 700 psi (3.4 to 4.8 MPa) for seawater applications. Recognizing these advantages, the Long Beach Water Department (California, United States) has developed and patented an innovative two-pass nanofiltration method for the desalination of seawater. This will be discussed further in Chapter 3.

Electrodialysis (ED) / Electrodialysis Reversal (EDR)

ED and EDR processes use ion-selective membranes and an electrical potential as a driving force to separate charged species from water. Pressure driven systems (RO and NF) selectively pass water through a membrane and retain dissolved salts in the concentrate. In contrast, ED and EDR use an electrical potential to draw dissolved ions through a set of membranes (cations to one side, anions to the other), while the deionized water passes between the membranes and is ultimately recovered.

An electrodialysis stack consisting of alternating layers of cationic and anionic ion-selective flat-sheet membranes creates channels of desalted product water and concentrated reject water. Cations migrate to the cathode and anions migrate to the anode while cation-selective membranes allow only cations to pass and anion-selective membranes allow only anions to pass. The net effect is to remove the salt from every other cell.

A modification of the ED process, EDR, periodically reverses the polarity of the applied electrical potential on the stack to minimize the effects of inorganic scaling and fouling by switching product channels into concentrate channels and vice versa. This allows the EDR system to operate at higher recoveries compared to ED.

ED/EDR processes are typically not used for seawater desalination because with higher salinities, the ED/EDR process generally becomes less efficient than other membrane-based desalination technologies. Additionally, bacteria, nonionic constituents, and residual turbidity are not affected by this process and therefore remain in the product water, requiring additional treatment before drinking water standards are met. Because ED/EDR are not typically used for seawater desalination, these processes will not be discussed further in this manual.

THERMAL EVAPORATION

Thermal desalination technologies work by evaporating water from a saline solution and then condensing the vapor (steam) to produce distilled water. All large-scale thermal processes involve heating water to its boiling temperature to produce the maximum amount of water vapor. The pressure of the system is typically decreased so that the temperature required for boiling is reduced. Commercially available distillation systems are designed to allow for "multiple boiling" in a series of vessels that operate at successively lower temperatures and pressures.

Thermal technologies that are used for desalination include multistage flash (MSF), multiple effect distillation (MED), and vapor compression (VC). MSF and MED systems typically use direct heat exchange from steam as the energy source for evaporation, while VC systems use the heat from the compression of the vapor as the energy source for evaporation. Thermal processes can produce water with very low salt concentrations (TDS levels of 10 mg/L or less) from TDS levels as high as 60,000-70,000 mg/L TDS; however, there are limitations associated with distillation processes for seawater desalination.

One of the most significant limitations of thermal technologies is the energy requirement of the vaporization step. High levels of salts result in boiling point elevation, and the energy required to vaporize seawater ranges from around 25 to 100 kWh/1000 gal of fresh water produced (Wade 2001). It should be noted that these thermal energy requirements are

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in addition to the electrical energy required for the other aspects of the process. Often, large distillation plants are coupled with steam or gas turbine power plants, making use of low grade heat to reduce power input requirements. Thermal technologies are more commonly used in the Middle East, where energy costs are relatively low, the large land requirements are not cost prohibitive, and ecological permitting requirements are less stringent. There has long been interest in using solar energy as a source of heat for accomplishing the evaporation in distillation, but suitable technologies for a large-scale project are not yet available.

Operational issues for thermal desalination include corrosion and scaling. Because seawater is highly corrosive in nature, special alloys, such as cupronickel alloys, aluminum, and titanium, are used most commonly in desalination with distillation processes. These special alloys contribute significantly to the capital cost of a distillation plant, particularly with the large surface area required for efficient distillation. The scaling of sparingly soluble salts at elevated temperatures on the inner walls of pipes and equipment is another operational issue that reduces the heat transfer efficiency of the heat exchangers, increasing the overall energy required for distillation. Also, additional permitting concerns may arise because concentrate discharged from a thermal distillation process has a higher temperature than the ambient water in the discharge location. While the cost of thermal desalination is often considerably higher than RO, very little pretreatment is required ahead of thermal processes, and the product water quality is extremely high (less than 10 mg/L TDS), avoiding the need for additional treatment to address boron, chloride, or bromide concerns.

Multistage Flash Distillation (MSF)

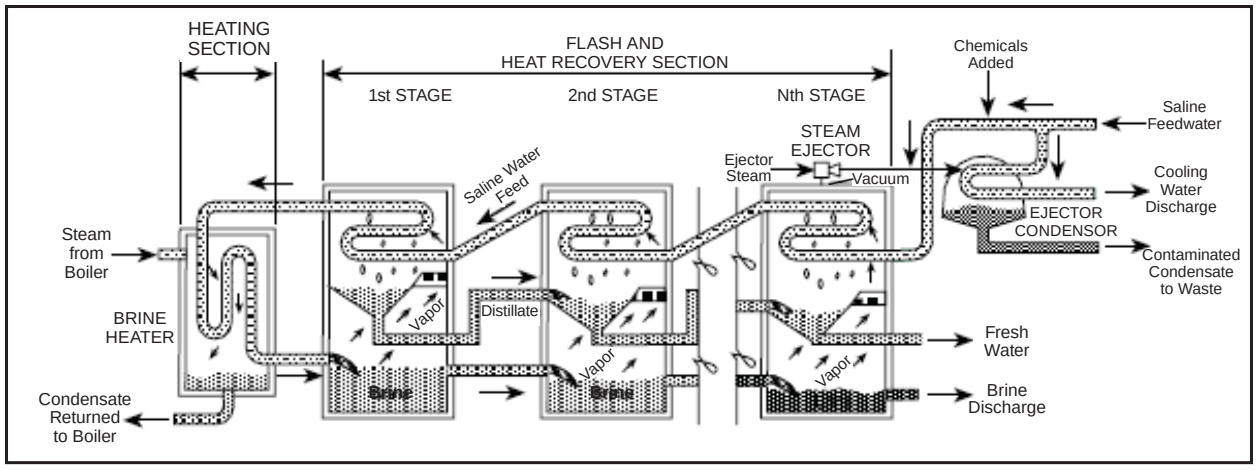
MSF accounts for the greatest installed thermal distillation capacity worldwide. In the MSF process, water is heated in a series of stages, each with successively lower pressures and temperatures. Typically, MSF plants can contain from 15 to 25 stages. Vapor generation or boiling caused by reduction in pressure is known as *flashing* (illustrated in Figure 1-3). As the water enters each stage through a pressure-reducing nozzle, a portion of the water is flashed to form vapor. In turn, the flashed water condenses on the outside of the condenser tubes and is collected in trays. As the vapor condenses, the latent heat is used to preheat the seawater that is being returned to the main heater, where it will receive additional heat before being introduced to the first flashing stage. The condensate collected in each stage forms the product, and the whole process is driven by a subatmospheric pressure gradient through the stages.

Evaporation or flashing of a small portion of the feed continues in each successive stage at a lower pressure. The MSF process generates and condenses vapor in the same stage or effect. The range of recoveries for conventional MSF desalination processes is limited to about 10 to 30 percent for seawater desalination.

Multiple Effect Distillation (MED)

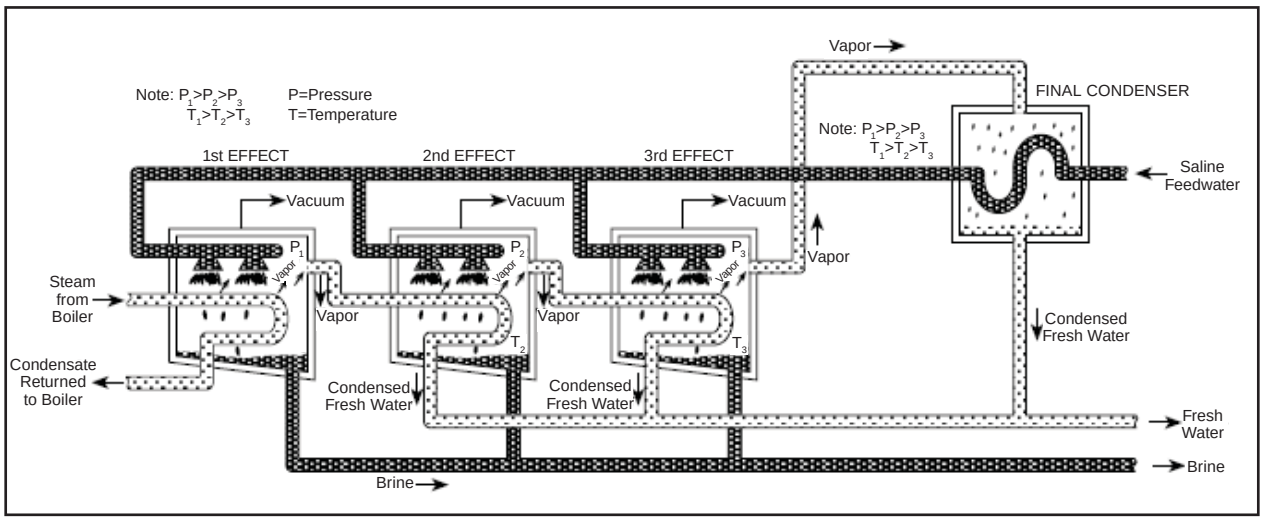
The MED process, like the MSF process, uses multiple vessels (or effects) arranged in series with reduced ambient pressure in each subsequent effect. Typically, 8 to 16 effects are used in MED to minimize the energy consumption. The feed water is distributed on the outside of the evaporator tubes in a thin film (see illustration in Figure 1-4) to promote rapid boiling and evaporation. Steam is condensed on the colder inside surface. Vapor produced by evaporation is condensed in a way that uses the heat of vaporization to heat the remaining saline solution at a lower temperature and pressure in each succeeding effect, allowing water to undergo multiple boiling without supplying any additional heat after the first effect. Thus, the vapor produced in each effect is used to heat the feed water in the next effect. This not only reduces the energy required for distillation but also the overall electrical power consumption. As a result, energy costs for operating an MED plant are lower than that of an MSF plant.

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Figure 1-3 Multistage flash distillation



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Figure 1-4 Multiple effect distillation

The steam generated in the final effect is typically at a pressure and temperature too low to be of further use. MED systems normally condense this steam using an external cooling source to remove the heat of condensation.

Energy is required in an MED system as follows: (1) to create steam of sufficient pressure to drive evaporation in the first stage; (2) to power vacuum systems to reduce the boiling pressure in the downstream effects (if operated at low temperatures); (3) to pump influent water through the heat exchangers to the evaporator(s), to recirculate the concentrate within each evaporator stage, and to pump the condensate and concentrate through the heat recovery prior to exiting the system; (4) cooling water to condense the steam from the final stage. Energy efficiencies may be gained via the combination of the evaporator systems with available low-pressure or waste steam/heat sources or by the

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addition of efficiency enhancement devices to the conventional MED system. The range of recoveries for conventional MED is limited to approximately 20 to 35 percent for seawater desalination.

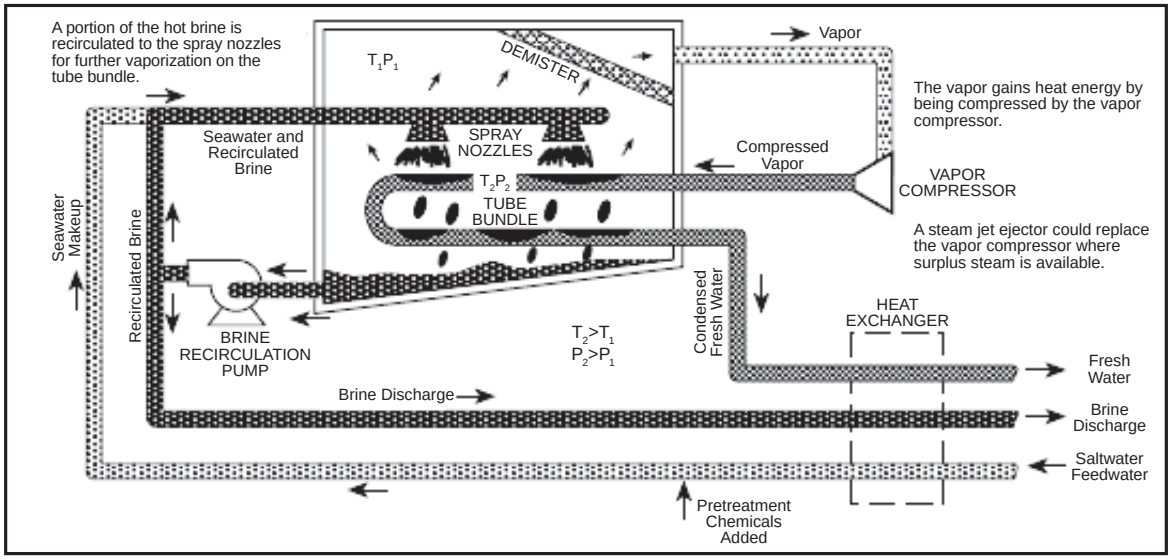
Vapor Compression (VC)

Heat for evaporation in VC systems is provided by one of two approaches: mechanical vapor compression (MVC) or thermo vapor compression (TVC); an illustration of the former is provided in Figure 1-5. MVC systems use electricity while TVC systems use high-pressure steam to compress the water vapor created from distillation to higher pressure and temperature, so that it can be returned to the evaporator and used as a heat source. The vapor compression process is well established and is used for seawater desalination as well as treating RO concentrate for residuals management. Vapor compression systems typically have recoveries in the range of 40 to 50 percent for seawater desalination.

NOVEL DESALINATION PROCESSES IN DEVELOPMENT

Forward Osmosis

As in the case of RO and NF, FO employs a semi-permeable membrane to separate water from a saline solution; however, instead of using external hydraulic pressure to create the driving force for water transport through the membrane, the FO process employs a natural pressure gradient provided by a higher salinity "draw" solution (such as ammonium carbonate or specially prepared magnetic nanoparticles). The higher osmotic pressure of the draw solution causes water to move toward it through a membrane. Freshwater is then separated from the draw solution using an additional separation process, which can vary depending on the nature of the draw solute. The separated draw solutes are either recovered and reused in the FO process or discharged.



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Figure 1-5 Vapor compression

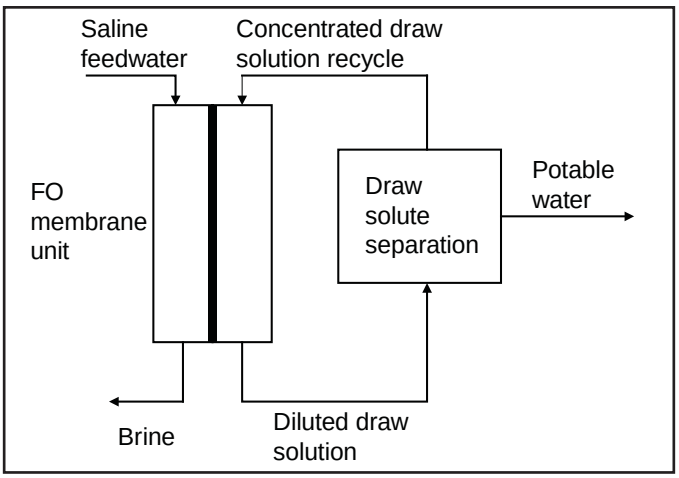
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Osmotic driving forces in FO can be significantly greater than hydraulic driving forces used in RO. The use of a suitable draw solution with very high osmotic pressure driving forces can be used in principle to generate high water fluxes and recoveries. The FO process, once fully developed and commercialized, is expected to have potential advantages in terms of relatively low fouling potential, low energy consumption, and simplicity. Identification of appropriate draw solutions and development of efficient membranes are two of the most pressing challenges for FO. An effective draw solute should have the following characteristics:

- High osmotic efficiency, meaning that it has to be highly soluble in water and have a low molecular weight in order to generate a high osmotic pressure.
- Nontoxic as trace amounts may be present in the product water.
- Chemical compatibility of the membrane.
- Easy and economical separation from recovered water.

Commercial RO membranes are not suited for the FO process because of relatively low product water fluxes. This low water flux is due mainly to internal concentration polarization within the porous support layer of the membrane, which alters the effective driving force across the active layer of the membrane, thereby limiting water flux. One of the important tasks for future research is the development of a semi-permeable FO membrane having high salt rejection and minimal internal concentration polarization to realize higher product water fluxes. Figure 1-6 illustrates the general process used in forward osmosis.

FO technology is still in development. Bench-scale FO units have been built and operated at Yale University laboratory (McCutcheon and Elimelech 2006) supported by Office of Naval Research (Award No. N000140311004). The draw solution employed in this study consists of highly concentrated ammonium carbonate, prepared by mixing ammonia and carbon dioxide gases. Upon heating (to approximately 60°C), ammonium carbonate decomposes back into ammonia and carbon dioxide gases, leaving behind the desalinated water. This separation needs to be essentially complete because of limits on ammonia in drinking water. Thermal recovery of ammonia and carbon dioxide from the draw solution requires energy, so the process may be suited for applications where low-grade heat is available.



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Figure 1-6 Schematic of forward osmosis desalination process

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FO has also been studied for use as pretreatment for RO in several novel applications including water reclamation and nutrient recovery (Cath et al. 2005, Holloway et al. 2007). Several hybrid processes have also been developed including osmotic dilution prior to desalination, which reportedly can significantly reduce the energy demand of desalination in some applications (Lundin 2009). Finally, FO has been proposed as a method of energy generation in blending highly concentrated desalination brine with fresh wastewater flows prior to discharging into the ocean. Such an approach would employ two waste products to produce electrical power and reduce the overall energy footprint of the desalination facility.

Membrane Distillation

Membrane distillation (MD) is a hybrid process using principles of both membrane separation and thermal distillation. MD involves evaporation of water from a saline solution and transport of the water vapor through the pores of a hydrophobic membrane. The membrane allows water vapor to pass through but prevents the solution from passing through. Water vapor is transported across the membrane in response to a change in partial pressure across the membrane because of a thermal gradient. The clean vapor is subsequently carried away from the membrane and condensed as pure water either within the membrane package or in a separate condenser system.

MD differs from pressure-driven membrane technologies in that, rather than applying pressure to force liquid through a membrane, the driving force for desalination is the difference in vapor pressure of the liquid across the membrane. Increasing the temperature of the liquid increases the vapor pressure and results in increased membrane penetration rate. The efficiency of an MD process largely depends on the feed water quality, system design, and heat recovery from the permeate stream. MD has been reported to run at relatively low temperature (approximately 70°C) and thus can utilize waste heat or low-grade heat sources. The energy source for feedwater heating and/or for a vacuum system to sweep away the vapor may be low-grade thermal energy such as supplied by low-pressure steam, waste heat, solar energy, or geothermal energy.

Potential advantages of MD are the ability to use low-grade heat, minimal pretreatment needs, and negligible scaling or precipitation concerns. Challenges include need of waste heat for economic feasibility, membrane fouling, and membrane degradation due to loss of hydrophobicity. MD technology is currently in the development and demonstration phase.

A variety of arrangements and configurations can be used to induce the vapor through the membrane, collecting and condensing it as product water. Common to all concepts is that the feedwater directly contacts the membrane. Condensation can be achieved using one of four process configurations:

1. Air-Gap Membrane Distillation. This configuration, which is the most common and most versatile arrangement, provides an air gap after the membrane, followed by a cool surface for condensation to occur.
2. Direct-Contact Membrane Distillation. The cool condensing solution (pure water) directly contacts the membrane and condenses the vapor as it passes through the membrane, where the coolant liquid typically flows countercurrent to the feed water.
3. Sweep-Gas Membrane Distillation. A sweep gas pulls the water vapor out of the membrane gap for subsequent condensation outside of the membrane package.
4. Vacuum Membrane Distillation. Vacuum is applied to the membrane space to pull the water vapor out of the system.

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Freeze/Thaw

The freeze/thaw approach to desalination is similar to thermal desalination in the fundamental concept of relying on a phase change to achieve separation. In the case of freeze/thaw, the phase change is from liquid to solid. Ice crystals exclude salt from their structure and the salt is then able to be separated as a brine from the ice. A key aspect of the process is that the energy required for the phase change from water to ice is less than one-seventh the energy that is required for the phase change from water to vapor (however, practical thermal desalination processes such as MSF and MED use much less energy than the heat of evaporation due to the use of multiple effects or stages as previously discussed). Challenges with freeze desalination include implementing the proper washing and separation of the crystals without premature melting and/or recontamination with the excluded salt. Different configurations of freeze/thaw desalination systems that have been developed include direct freezing, indirect freezing, and absorption (AWWA 2004).

Capacitive Deionization (CDI)

Carbon aerogel is an ideal electrode material because of its high electrical conductivity, high specific surface area, and controllable pore size distribution (Yang et al. 2001, Ying et al. 2002). The Lawrence Livermore National Laboratory (LLNL) began its research into carbon aerogels and capacitive deionization technology (CDT) in the late 1980s. LLNL developed and optimized carbon aerogel materials, which multiplied the effective surface area of the deionization electrodes by a factor of 60,000, dramatically improving their capacity to attract and hold charged water constituents.

In the process of capacitive deionization (CDI), the high salinity solution flows between the electrode pairs and ions are adsorbed onto the surface of the porous electrodes by applying a low voltage electric field thereby producing deionized water. The major mechanisms related to the removal of charged constituents during CDI are physisorption, chemisorption, electrodeposition, and/or electrophoresis. Unlike ion exchange, no additional chemicals are required for regeneration of the electrosorbent in this system. Adsorbed ions are desorbed from the surface of the electrodes by eliminating the electric field, resulting in the regeneration of the electrodes. The efficiency of CDI strongly depends on the surface property of electrodes, such as their surface area and adsorption properties.

CDI systems exhibit several advantages: a simple, modular, plate-and-frame construction, and low energy requirement. However, current challenges include the limited adsorption capacity of carbon aerogel electrodes, slow kinetics of transport of ions into and out of the highly porous electrodes, relatively high costs of the CDI modules, and the fouling potential of the aerogel surface caused by natural organic matter. CDI is still in the development stage with on-going bench and pilot tests.

Supercritical Desalination (SCD)

Recent research by the Wetsus, Centre of Excellence for Sustainable Water Technology in the Netherlands (Ingo et al. 2009) has looked at the use of supercritical conditions in water to promote desalination. Supercritical conditions are achieved at elevated temperatures and pressures, where the liquid and gas form of water both exist and are indistinguishable from each other. Supercritical water is an extremely poor solvent of inorganic salts, allowing dissolved salts to be removed through precipitation, producing a solid or near solid waste stream and a purified product. The purity of the product depends on the temperature and pressure of the supercritical fluid; however, SCD has been proposed as a pretreatment step for RO in seawater desalination, where SCD is used to produce a water with TDS levels close to 3,500 mg/L using a pressure of 22 MPa (3,200 psi) and temperature of

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approximately 350°C. Brackish water reverse osmosis (BWRO) membranes could then be used for further desalination, with the theoretical energy requirements being comparable with conventional SWRO, but with higher recoveries on the order of 70 to 80 percent. SCD technologies are still in development and have not been tested outside of the laboratory; however, these technologies may play a role in future desalination applications as they offer unique opportunities not currently available with either membrane- or evaporation-based technologies.

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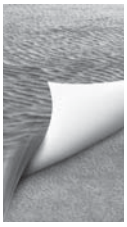
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Chapter 2

Water Quality

Greg Wetterau
Shane Trussell

SOURCE WATER QUALITY

While seawater quality in the open ocean does not vary more than 10 percent over time and location, large variability can be seen in partially isolated seawater bodies, such as bays, estuaries, and seas, where influences from freshwater flows and evaporation have considerable impact on the water quality patterns. Figure 2-1 shows the worldwide surface salinity of oceans, as modeled by the Ocean Climate Laboratory of the National Oceanographic Data Center (World Ocean Atlas 2005). The figure presents salinity in Practical Salinity Units (psu), with one psu equal to 1,000 milligrams per liter (mg/L). While higher than average salinities are common in areas receiving little rainfall, such as the Red Sea, the Mediterranean, and the Arabian Gulf, seawater bodies surrounding the United States are typically average or below average in salinity. Considerably lower salinities are also seen in the U.S. in partially closed water bodies receiving high contributions from freshwater flows, such as the San Francisco Bay, Tampa Bay, and Chesapeake Bay, where seawater desalination facilities are either currently operational or are being actively evaluated. Extensive monitoring of seawater quality was first documented by William Dittmar in 1884, after four years of water quality sampling over nearly 70,000 nautical miles. The extremely high concentrations of dissolved minerals, many of which are orders of magnitude higher than typical fresh water supplies (see Table 2-1), demonstrate the challenge of treating seawater to a quality acceptable for potable water use.

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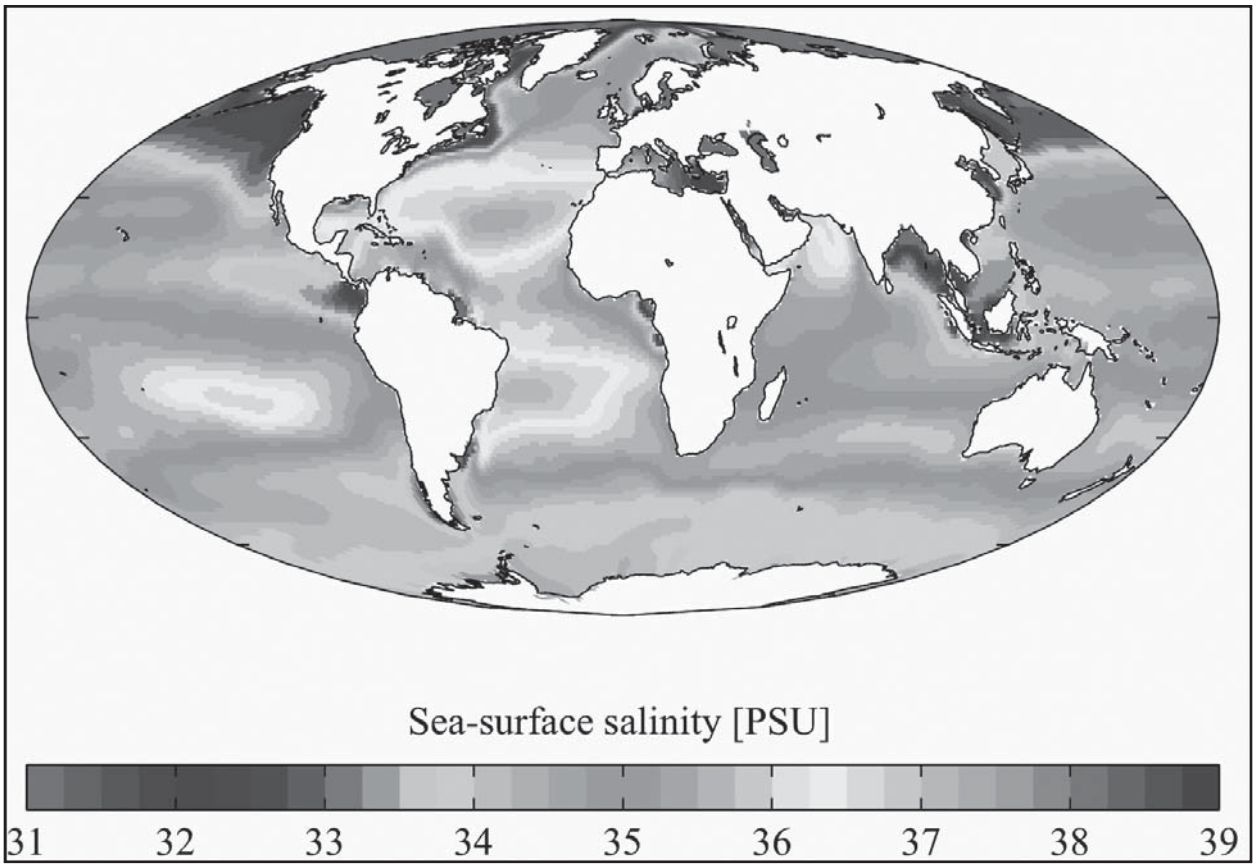


Figure 2-1 Sea-surface salinities (World Ocean Atlas 2001)

Table 2-1 Seawater mineral quality compared to national source waters

Constituent	Seawater	U.S. Freshwater Supplies	
	Average	Median	Upper Quartile
	mg/L	mg/L	mg/L
Chloride	19,350	10	20
Sodium	10,710	30	80
Sulfate	2,690	30	75
Magnesium	1,304	10	20
Calcium	419	40	60
Potassium	390	2	4
Alkalinity	146	190	250
Bromide	70	0.02	0.06
Boron	4.4	0.08	0.2
Fluoride	1	0.2	0.4
TDS	35,079	330	480

Adapted from Dittmar 1884 and James M. Montgomery 1985

Courtesy of Greg Wetterau and Shane Trussell

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While the concentrations of dissolved inorganic constituents are relatively consistent throughout the open ocean, concentrations of suspended materials and colloids will vary drastically between locations and over time. As an example, the turbidity of seawater measured over one year of pilot testing at the Santa Cruz, California desalination pilot varied from 2 to 30 nephelometric turbidity units (ntu) with no significant storm events or red tide blooms experienced (Desormeaux et al. 2009). In contrast, a longer pilot study conducted by West Basin Municipal Water District near Los Angeles, California never saw turbidity exceed 10 ntu, even during a severe red tide event (Lauri et al. 2010).

Seawater turbidity can consist of suspended sediment from surface water runoff or the ocean floor, or from phytoplankton, marine larvae, and other organic matter. Similar to the variability in turbidity, the concentration of total organic carbon (TOC) varies with storm events, ocean currents, and periodic algal blooms. Turbidity, TOC, and various biological parameters can present significant challenges to seawater desalination, requiring optimized pretreatment processes or the use of subsurface intakes to provide acceptable quality water to the reverse osmosis (RO) membranes. In addition, the entrainment of marine larvae in seawater intakes has raised environmental concerns, in some cases requiring that mitigation measures be taken to address the problem. Pretreatment alternatives are discussed in detail in Chapter 3. Environmental concerns are discussed in Chapter 4.

PRODUCT WATER QUALITY

The treatment processes used in seawater desalination result in a product water that has been stripped of nearly all the mineral content, with the exception of a few constituents that are either insufficiently removed by RO membranes (such as boron and bromide) or are exceptionally high in the source water (such as sodium and chloride). These water quality characteristics result in unique water that must be further conditioned, treated, and possibly blended to produce a finished water that is acceptable for potable water systems. The key issues that must be addressed include:

1. Health concerns
2. Product water stability
3. Irrigation and industrial use concerns
4. General aesthetic concerns

Each of these issues is discussed briefly in the following section.

HEALTH CONCERNS

Issues related with public health in drinking water are regulated under the United States Environmental Protection Agency (USEPA) as administered through state health and environmental protection departments. While the requirements for seawater desalination facilities are the same for all public drinking water systems, the key health concerns with desalinated product water differ somewhat because of the unique nature of the source water and the processes used in desalination. The key health issues can be divided into (1) issues related to potentially high levels of specific minerals in the RO product, (2) issues related to pathogen removal, and (3) issues related to distribution system water quality.

Mineral Content of Product Water

Seawater RO membranes used in desalination produce high quality water that meets water quality requirements for most regulated compounds. It is generally only boron that has a significant risk of exceeding current federal or state guidelines, and these guidelines are

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based primarily on issues other than public health, as will be discussed later. Similar to boron, the chloride concentrations produced by seawater RO membranes may also be a concern for nonhealth related issues; however, these concentrations are unlikely to exceed state and federal guidelines for chloride. The presence of some unregulated organic compounds, such as algal toxins, has also caused some concern among State and Federal regulatory agencies, with numerous studies being done to document the removal effectiveness and prevalence of these compounds.

Boron. Because of its low molecular weight and weak ionic charge, boron is difficult to remove with most RO membranes. Typical removals vary from 40 to 90 percent at near neutral pH. Higher removals can be achieved at elevated pH, with greater than 99 percent removal reported at pH greater than 9.5 (Oo and Song 2009). With levels of boron in seawater typically at 4.4 mg/L, RO product from a single-pass treatment approach is typically on the order of 1 to 2 mg/L, depending on the temperature, flux, and specific membranes employed.

Animal tests with boron have shown adverse effects on the reproductive systems of rats and male dogs; however, the USEPA recently decided not to regulate boron with a maximum contaminant level (MCL), due to its low prevalence at levels of concern in U.S. drinking water supplies (USEPA 2007). The USEPA has established a long-term health advisory level for children of 2 mg/L and for adults at 5 mg/L, based on health effects observed during animal testing. In addition, several states (California, Florida, Maine, Minnesota, New Hampshire, and Wisconsin) have adopted standards, guidelines, or notification levels for boron ranging from 0.6 to 1 mg/L (USEPA 2008). Beyond U.S. guidelines, the World Health Organization has set a health guideline for boron since 1993. This was set initially at 0.3 mg/L, was increased to 0.5 mg/L in 1998, and is expected to increase to 2.4 mg/L in 2011.

Chloride. Chloride is generally not raised as a health issue for drinking water but is established as a secondary MCL (set at 250 mg/L), primarily for aesthetic concerns related to the taste of high chloride water. Because of the high concentration of chloride in seawater, RO product from a single-pass system can range from 100 to 200 mg/L, depending on the temperature, flux, and specific membranes employed. Lower levels may be sought by some utilities based on aesthetic concerns.

Nonregulated parameters. A large number of emerging contaminants or contaminants of emerging concern are being studied in terms of their health effects and prevalence in U.S. water supplies. While some of these contaminants can be found in seawater sources at concentration approaching those in freshwater supplies, most are considerably lower in seawater and are less of a concern to seawater desalination than they are to conventional water treatment facilities. However, compounds that are of unique concern to seawater desalination are currently unregulated toxins related to periodic algal blooms or red tide events. Two common algal toxins detected in U.S. waters are found off the Pacific Coast and include domoic acid, the cause of amnesic shellfish poisoning, and saxitoxin, the cause of paralytic shellfish poisoning. The toxins are typically not found in the water column at concentrations that are considered toxic but have been found to accumulate in shellfish to levels that are toxic to both humans and other mammals. The algae that produce the toxins are readily removed by the pretreatment filters within a desalination plant and by the RO membranes; however, there is a concern that cells will break during the pretreatment filtration process and release more dissolved toxins into the water. Pilot studies in Southern California (Carlsbad and West Basin) have demonstrated excellent removal of the toxins during large harmful algal blooms; also, a spiking of dissolved toxins at 1,000 times typical concentrations during pilot testing in Santa Cruz demonstrated greater than 3 log (>99.9%) rejection using kainic acid, a common surrogate for domoic acid.

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Pathogen Removal

The USEPA Surface Water Treatment Rule (SWTR) requires removal and inactivation of viruses and *Giardia* cysts, as well as turbidity reduction, for surface waters and ground waters under the direct influence of surface water (GWUDI). The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) sets removal and inactivation requirements for *Cryptosporidium*. Seawater is currently regulated as a surface water supply in the U.S.; however, the biological activity in seawater and the survival rate of common pathogens is considerably different in seawater than in natural freshwater bodies. The survival rates of *E.Coli*, *Giardia* cysts, and *Cryptosporidium* oocysts have been shown to be low in seawater when compared with freshwater systems. These pathogens have, nonetheless, been found to be present in seawater bodies directly impacted by wastewater and stormwater outfalls (Fayer et al. 1998).

Pathogen removal requirements established by the USEPA require a multiple barrier approach to provide both removal and inactivation of pathogens. The SWTR requires a minimum of 99.99 percent (4-log) reduction in viruses and 99.9 percent (3-log) reduction in *Giardia* through filtration and disinfection. The LT2ESWTR requires between 2-log and 5.5-log reduction in *Cryptosporidium*, depending on the prevalence of *Cryptospordium* found in two years of source water monitoring, and on the type of treatment employed. In addition to the federal requirements, some states include multiple barrier requirements for specific pathogens (*Giardia* and viruses) and may require higher removal for impaired water bodies where high concentrations of total coliforms have been measured in Watershed Sanitary Survey (WSS) monitoring. Table 2-2 summarizes the minimum and maximum reduction requirements for *Giardia*, *Cryptosporidium*, and viruses.

Distribution System Water Quality

Distribution system water quality concerns relate both to corrosion within the distribution system and to the formation of disinfection by-products (DBPs). Corrosion issues, while relating to health concerns about lead and copper leaching from residential plumbing, also have aesthetic components and are discussed in the section on Product Water Stability. This section will focus primarily on the impact of desalinated water on DBP formation. The formation of DBPs, such as trihalomethanes (THMs), is impacted primarily by the presence of natural organic matter (NOM) when free chlorination is used for disinfection. Levels of NOM in desalinated product water are considerably lower than in most conventional treatment products. The formation of DBPs is therefore a concern primarily when desalinated seawater is blended in a distribution system with treated surface waters containing significant levels of NOM.

Table 2-2 Pathogen reduction requirements for surface waters

Pathogen	Log Reduction Requirement		Criteria for Determination
	Minimum	Maximum	
Virus	4	6	Total coliforms(1)
Giardia	3	5	Total coliforms(1)
Cryptosporidium	2	5.5	*Cryptosporidium*(2), total coliforms(1)

1. California Department of Public Health requires up to 2-log additional removal based on high levels of total coliforms.
2. LT2ESWTR requires up to 5.5 log *Cryptosporidium* removal, based on bin classification from *Cryptosporidium* monitoring

Courtesy of Greg Wetterau

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Source: HortScience Inc.

Figure 2-2 Boston Ivy with tip burn from chloride



Source: HortScience Inc.

Figure 2-3 Boron toxicity on camphor (cinnamomumcamphora)

As noted previously in Table 2-1, seawater contains unusually high levels of bromide, when compared with most freshwater sources in the U.S., with the concentration of bromide roughly three orders of magnitude larger in seawater than in the highest quartile of freshwater supplies. Bromide removal with seawater RO membranes is comparable to the removal of chlorides; however, the level of bromide that results from seawater treatment in a single-pass system is still an order of magnitude larger than in most freshwater supplies (ranging from 0.5 to 0.8 mg/L under typical operating conditions). High bromide

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levels have been associated with the formation of brominated DBPs. Chlorine added for disinfection can oxidize bromide to bromine; the bromine may then react with NOM to form brominated DBPs. Brominated DBPs are a concern because of an increased health risk compared with chlorinated DBPs, and because brominated compounds increase the mass-based concentration more than chlorinated DBPs due to the molecular weight of bromide, which is approximately double that of chloride.

Brominated DBPs can be expected to form in zones where desalted water blends with other supplies when free chlorine is used for disinfection residual maintenance. DBP formation tests are commonly recommended with blends of the desalinated water and local treated surface water to assess if this is a potential issue. Previous studies of desalinated water disinfection have also shown that high levels of bromide can have adverse impacts on the stability of chloramine residual in distribution systems (USEPA 2001).

PRODUCT WATER STABILITY

Seawater desalination results in a product water quality that is characterized by low hardness (calcium and magnesium), low alkalinity, and relatively high chloride. The hardness and alkalinity are so low that desalination facilities typically condition the product water to achieve a slightly positive Langelier Saturation Index (LSI) to control corrosion in the distribution system and consumer plumbing. Soft water supplies are well known to have a higher potential to create corrosion-related apparent color (red water) problems when conveyed in iron pipe and to cause leaching of lead and copper in home plumbing, which can increase health risks and violate requirements of the Lead and Copper Rule. High chloride content may also exacerbate these problems, increasing the corrosivity of the water. Cast-iron or ductile-iron pipes, either unlined or lined with older epoxy coatings, are susceptible to iron release and red water complaints if the softened water is not appropriately conditioned for corrosion protection.

The LSI, an index first defined by Wilfred Langelier in 1936 (Langelier 1936), has become the most widely used measure of product water aggressivity, and a positive LSI is used as a target for many desalination post-treatment facilities. Other measures of product water aggressivity include the calcium carbonate precipitation potential (CCPP), which is often kept between 4 and 10 mg/L, and the aggressiveness index (AI), which is often kept above 12. The adjustment of $CaCO_3$ saturation, however, is not uniformly practiced nor is it always successful in meeting corrosion control objectives. Other common approaches for mitigation of corrosive effects from soft water can include pH adjustment and addition of orthophosphate. It is generally most important, however, to avoid significant variations in either pH or calcium carbonate saturation to prevent problems with pipeline corrosion or customer complaints from cloudy or red water.

IRRIGATION AND INDUSTRIAL USE CONCERNS

While desalinated product water from seawater supplies has a low risk of exceeding health related water quality goals, the levels of boron, chloride, and sodium in the product of single pass RO system could create significant problems for irrigation and industrial users. The primary issues related to these types of users are discussed in the following sections.

Irrigation and Agricultural Use

High levels of chloride, sodium, and boron are known to impact numerous different ornamental plants, citrus trees, and other common agricultural crops. Although the total dissolved solids (TDS) concentration is low in desalinated ocean water, the concentrations of chloride and sodium comprise a majority of the TDS. Chloride and sodium toxicity have

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been more commonly observed than boron toxicity to date because of the increased use of reclaimed water for irrigation purposes, particularly in the arid Southwest. Some of the better-known cases of chloride toxicity have occurred where irrigation of redwood and avocado trees was converted from local water supplies to recycled water, resulting in significant impacts on the health of these species. The most common symptom of chloride, sodium, and boron toxicity is tip burn, but chloride or sodium toxicity can also result in tattered leaves, reduced leaf size, reduced growth rate, yellowing of leaves in conifers, and in extreme cases, plant death. Similar to boron, chloride and sodium accumulate in the older leaves, and these leaves typically exhibit the symptoms first. Figure 2-2 shows an example of chloride toxicity observed in Southern California and caused by irrigation using reclaimed water with high chloride content.

Concerns with boron may arise if there is a significant difference between the boron content of the traditional water supply source or sources and the desalinated water, and if chloride and boron-sensitive plants and crops are present in the service area. Figure 2-3 shows mild and advanced stages of boron toxicity.

Boron concentrations greater than 2 mg/L are unhealthy for most plants, while a boron concentration greater than 1 mg/L may still have an impact on sensitive plant species. If the boron concentration of water used for irrigation is maintained below 0.5 mg/L, boron toxicity should not result in significant impacts on plant appearance. Water with boron concentration between 0.75 and 1.0 mg/L may still impact some trees, plants, and ornamentals that are commonly used for landscapes and residences in southern coastal areas of the U.S. where seawater desalination is being considered. Some of these plants include gardenia, crape myrtle, camellia, giant birds of paradise, heavenly bamboo, hydrangea, lemons, lily of the Nile, oranges, philodendron, photinia, pink trumpet vine, southern magnolia, violet trumpet vine, dwarf pittosporum, xylosma, and various roses (Yermiyahu et al. 2005).

Yermiyahu et al. (2007) reported that the seawater desalination plant (73 mgd) in Ashkelon, Israel is producing desalinated water with a boron level of 0.2 to 0.3 mg/L to meet Israeli recommendations for domestic and agricultural usage. It should be noted that a large portion of the water produced by the Ashkelon plant is used for irrigation of citrus crops, which are sensitive to boron levels in the water of more than 0.75 mg/L. The main rationale for producing a water with half of this boron level was to reduce the overall boron level of existing surface water supplies of naturally high boron content with which this desalinated water is blended. For similar reasons, Tampa Bay Water has targeted the chloride level in their desalinated water to be less than 100 mg/L. This high-quality water is blended with other surface water and groundwater sources, which have significantly higher chloride and TDS levels, improving overall water quality in the distribution system in terms of chloride, boron, and TDS.

Industrial Use

The level of chloride in the treated water may also be an important consideration for industries located within the service area of the desalination plant. As previously mentioned, the maximum chloride concentration in desalinated seawater treated using only a single-pass RO system is significantly higher than the concentrations observed in conventional water supplies (typically 150 to 220 mg/L v. less than 100 mg/L). It is known that some industries (i.e., petrochemical, power generation, pharmaceutical, breweries, and semi-conductor wafer manufacturing) use high purity water, which has chloride levels significantly lower than 100 mg/L. If these types of industries are large water users in the desalination plant service area, product water quality targets in terms of chloride, TDS, and other compounds may need to be adjusted to accommodate their requirements. An example is Contra Costa Water District in Northern California which has set a water

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quality objective of 100 mg/L chloride based on the requirements of the industries served in the desalination plant service area. The Water and Sewarage Authority of Trinidad and Tobago has set a chloride objective of 80 mg/L for their 36 mgd Point Lisas seawater desalination project based on the requirements of the industries served there. The Point Lisas plant is located in an industrial park where over 80 percent of its water is used by local industries.

It should be noted that many of the industrial plants that have stringent requirements in terms of TDS, chloride, or other compounds are often equipped with water purification facilities, and it is often much more cost effective for these installations to be upgraded or modified than to impose a significant incremental cost increase for a more elaborate desalination system to the general population. This is especially true when industries with very stringent product water quality requirements constitute a relatively small portion of the water demand in the plant service area.

Addressing Irrigation and Industrial Use Concerns

To address the issues with boron, sodium, and chloride as previously discussed, several seawater desalination plants worldwide have been designed with RO systems that have a partial or full second pass, where a portion of the permeate produced by the first-pass RO system undergoes additional RO treatment. By using a partial or full second pass, boron and chloride levels in the finished product water can be targeted to specific needs of irrigation and industrial users in the area served by the desalination facility.

Examples of facilities that have a partial or full RO second pass include Tampa, Florida (25 million gallons per day (mgd) or 95 megaliters per day (MLD)–50 percent second RO pass); Trinidad and Tobago (36 mgd or 136 MLD–100 percent second RO pass); Fukuoka, Japan (13 mgd or 49 MLD–100 percent second RO pass); and Tuas, Singapore (36 mgd or 136 MLD – 100 percent second RO pass). In contrast, most of the seawater desalination plants in Spain, Cyprus, and Malta, providing water for both human consumption and agricultural irrigation for grain crops and vegetables, have single-pass SWRO systems only. Most municipal SWRO treatment plants in the Caribbean are also built with a single-pass SWRO system.

GENERAL AESTHETIC CONCERNS

Although aesthetics are typically considered better for desalinated product water than most conventional water supplies, some concern should be considered when variability is possible in the temperature or taste and odor of the water delivered to residential customers. These two issues are discussed briefly in the following sections.

Temperature

Ambient ocean water temperature is typically lower than or equal to that of most conventional surface water sources. Membrane desalination processes do not result in significant increases in product water temperature, and therefore, desalinated seawater is typically of temperature comparable to that of other water sources. However, in the case of seawater desalination plants that are collocated with power plants, where cooling water from a power plant is used as a source for desalination, the product water may be 2 to 5°C higher than the ambient ocean water temperature. Therefore, in this case, the temperature of the desalinated water may be higher than that of the existing water sources, which may have an impact on water quality aesthetics. The temperature aspect of desalinated seawater should be evaluated on a case-by-case basis. For example, experience at the Tampa Bay Water seawater desalinated plant and environmental impact reports of the collocated Carlsbad and Huntington Beach seawater desalination plants indicate that the

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desalinated water temperature is well within the temperature of all other water sources in the desalination plants service area.

Taste and Odor

Depending on how the desalinated water is introduced to the distribution system, water supply to some consumers may be converted entirely from the conventional water source to the new desalinated water. If these consumers remain on the new supply 100 percent of the time, following a transition period, the number of taste and odor complaints would not be expected to be significant as a result of the conversion to desalinated water. It is common, however, that on days of peak water demand or days when portions of a desalination plant are down for maintenance, a water utility may need to supplement their desalinated water supply with conventional water supplies, creating a risk of taste and odor complaints. It is important to develop an appropriately designed connection point and distribution system infrastructure that prevents consumers from transitioning between the two supplies on a routine basis. The number of taste and odor complaints would be expected to increase proportionally with the frequency of that transition. This means that each time conventional water supplies are required to supplement the desalinated water, there would be two sensitive periods where taste and odor complaints would be likely to occur. Any significant transition in water supply will be noted by consumers, and taste and odor complaints will become a significant issue if the delivered water source is frequently changed. This issue can be addressed by ensuring adequate blending and mixing with a local supply prior to distribution, which may allow for providing a consistent water supply. Such an approach was taken for the Sand City coastal desalination facility near Monterey, Calif., where up to 50 percent distribution system water is blended with the desalination product to provide a consistent water quality within the system.

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