

Inland Desalination and Concentrate Management



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Inland Desalination and Concentrate Management



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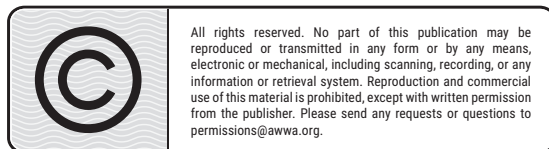
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Preface

With population and economic growth stressing global freshwater supplies, desalination of brackish water and the appropriate management and disposal of concentrate are increasingly attractive options. In the past few decades, the number and capacity of US municipal desalination plants increased rapidly. More than one-third of these facilities are in inland areas. Many concentrate management and disposal options were proven at these facilities, including surface water discharge, discharge to sewer, deep-well injection, land application, discharge to evaporation ponds, near-zero liquid discharge, and zero liquid discharge.

Because of rapid growth, the need for a manual is urgent. The industry has accumulated enough knowledge and experience to provide guidance. After several years of diligent coordination, the AWWA Water Desalting Committee proudly presents AWWA Manual M69, *Inland Desalination and Concentrate Management*.

This manual provides technical and planning guidance for inland water utilities (public and private) that are operating, developing, or considering brackish water desalination. It presents practical information on inland desalination, concentrate treatment technologies and management strategies, permitting procedures, environmental impacts, costs, safety, and more.

The concentrate management topic of this manual is also relevant to direct and indirect potable reuse practices where nanofiltration and reverse osmosis might be utilized. It can also apply to produced water treatment, industrial ultrapure water system brine management, and cooling water blowdown management.

Charlie (Qun) He
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*M69 Inland Desalination and
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Chapter **1**

Overview of Inland Desalination

Greg Wetterau and Mike Mickley

According to the United Nations' first edition of the World Water Development Report, 50 percent of the world will face water stress or water shortage by 2025, and 75 percent of the world's population could face water scarcity by 2050 (United Nations 2003). With the world's population increasing and reliable freshwater supplies becoming more limited, desalination has become a growing water supply alternative in many locations. Desalination offers a means of providing freshwater from abundant saline water sources. Its use has historically been most prevalent in coastal areas, treating either seawater directly or seawater-influenced groundwaters. However, as desalination technologies have advanced and the availability of conventional freshwater sources becomes more limited, inland water users have increasingly turned to desalination.

The increased use of inland desalination has created a need for advancements in reliable, cost-effective, and environmentally sensitive means of concentrate management. Coastal desalination facilities often discharge residual concentrate to the ocean; however, with inland facilities, concentrate conveyance lines to coastal areas are often cost prohibitive, requiring alternative concentrate disposal options or the use of costly zero liquid discharge (ZLD) technologies to eliminate concentrate discharge.

This manual presents the key issues and challenges of developing inland desalination facilities, including concentrate management and disposal methods. The manual aims to aid water utilities, industrial facilities, and other water users in evaluating and adapting inland desalination for their water supply needs.

BRACKISH WATER SOURCES

Brackish water can be defined as any water containing between 1,000 and 15,000 mg/L of total dissolved solids (TDS); however, waters with salinity in excess of 15,000 mg/L are sometimes referred to as brackish. Brackish water is present in tidally influenced estuaries, seawater intrusion-impacted groundwaters, inland seas/lakes, and many deep aquifers or shallow aquifers in arid locations. This water was once considered unusable as a drinking water source. However, with the invention and development of reverse osmosis (RO) and other desalination technologies such as electrodialysis, multistage flash distillation, and multiple-effect distillation, brackish waters have become a source for production of drinking water in many arid or water-stressed locations. As this manual is focused on inland desalination, the brackish water sources discussed herein are primarily saline aquifers and inland water bodies rather than tidal or seawater intrusion-influenced waters. While water characteristics of coastal and inland supplies are often similar, the challenges associated with residual and concentrate disposal create unique considerations for an inland brackish water desalination process.

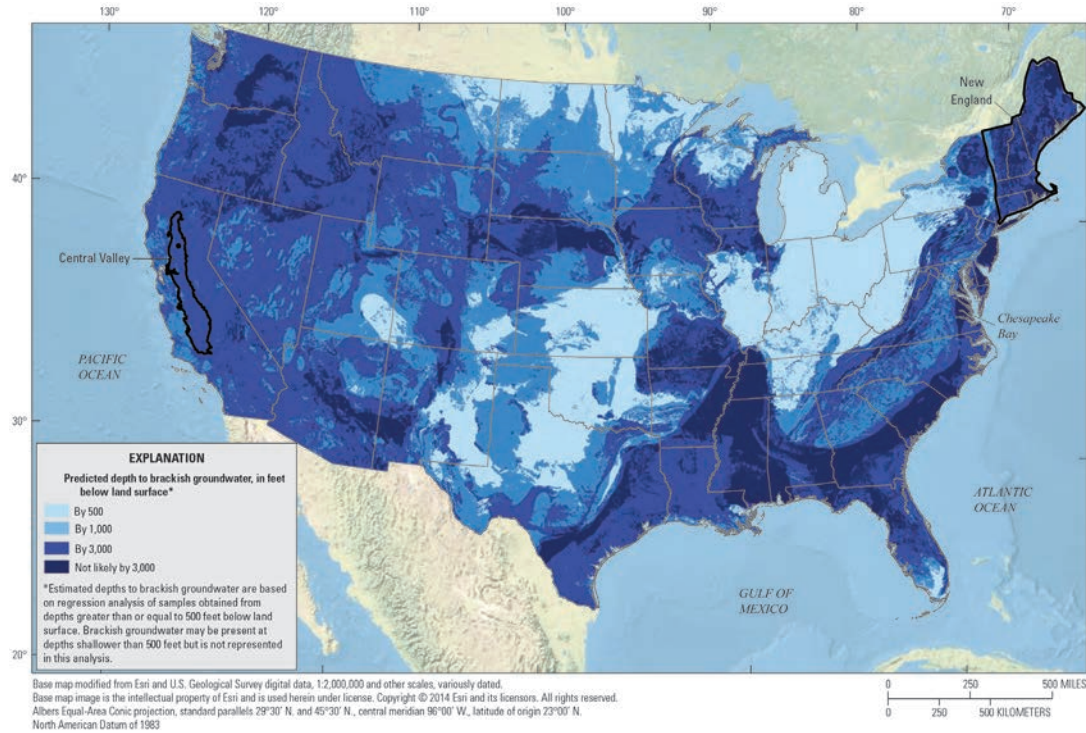
In 2003, the US Geological Survey (USGS) reported that little was known about the hydrogeology of aquifers containing saline water, as groundwater resource evaluations had focused primarily on the prevalence and quality of freshwater aquifers and the freshwater portions of mixed aquifers (USGS 2003). Available evidence indicated that a significant quantity of brackish groundwater exists throughout the United States, although much of this information came from surveys conducted in the 1950s, 1960s, and 1970s. A 2003 study conducted for the Texas Water Development Board found that there is approximately 880 trillion gallons (2.7 billion ac-ft) of brackish groundwater in the aquifers of Texas (LBG-Guyton Associates 2003). In New Mexico, it has been estimated that 75 percent of groundwater is too saline for most uses without treatment.

While it is clear that large quantities of saline groundwater exist throughout the country and that these quantities outnumber freshwater supplies in many water-stressed locations, more study has been needed to better characterize the availability and quality of brackish water in the United States. To work toward that aim, USGS has completed a comprehensive National Brackish Groundwater Assessment (USGS 2017), providing information on brackish groundwater quality and prevalence throughout the mainland United States. Figure 1-1 presents information from this assessment on the depth to brackish groundwater across the country. As part of the assessment, USGS has created a publicly available database containing chemical data and aquifer information for known quantities of brackish groundwater. More recently, the US Bureau of Reclamation and USGS have collaborated on an interactive map tool to increase the ease of use of the National Brackish Groundwater Assessment for water resource planning.

STATUS OF DESALINATION

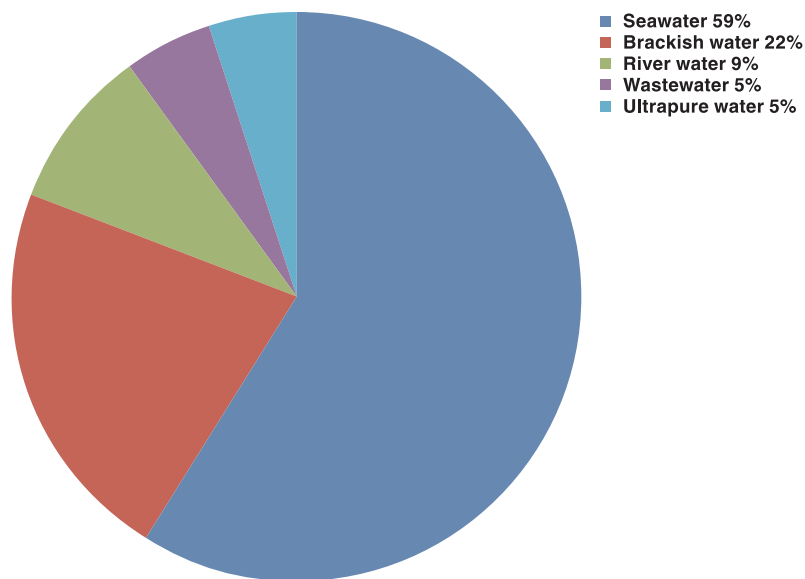
Global and Domestic Overview

The global use of desalination today exceeds 24 billion gallons per day (bgd) (IDA 2018), employing core technologies developed primarily in the United States with more than \$2.0 billion (2018 dollars) of federal research funds between 1959 and 1974 (NRC 2008). With a few exceptions, new desalination plants have predominantly used seawater as their source of supply. Today, 59 percent of the global desalinated water production is from seawater, while only 22 percent is from brackish water, predominantly from groundwater sources. Figure 1-2 shows a breakdown of the source waters for existing desalination facilities. The “ultrapure water” category incorporates various low-salinity sources, including municipal drinking water and local groundwater, to produce high-purity water for industrial use.



Source: USGS 2017

Figure 1-1 Depth to brackish groundwater in the United States



Adapted from International Desalination Association 2018

Figure 1-2 Total worldwide installed desalination capacity by feedwater category

An exception to the global trend is the United States, where the vast majority of installed desalination facilities use brackish water sources. The locations of these brackish water plants remain predominantly in coastal areas; however, nearly 23 percent of the installed desalination facilities in the United States are located in states that do not border any oceans (Mickley 2018).

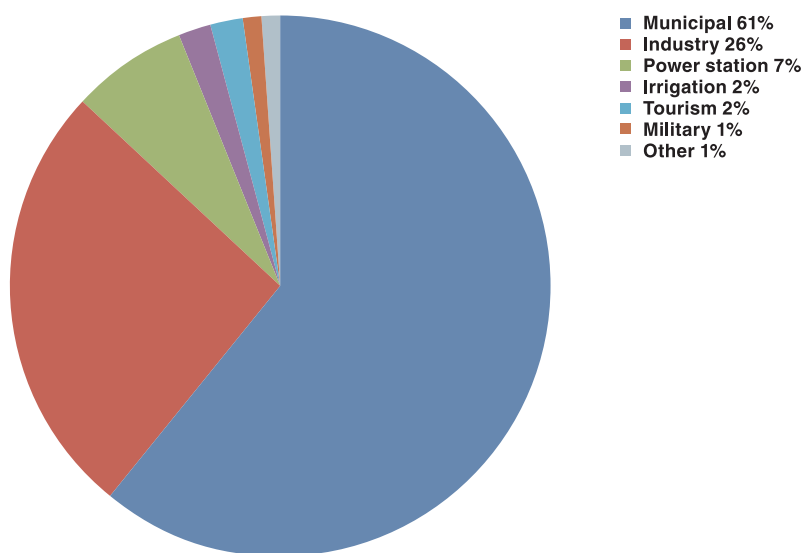
Most inland desalination is currently used for municipal applications producing potable water, water for disposal or recycle, and facilities producing water for aquifer recharge or aquifer storage and recovery. Nonmunicipal applications of desalination mainly include supply, discharge, and reuse for industry. Industrial water supply applications include those where high-purity water is required, such as for boiler feed, biopharmaceutical manufacturing, food and beverage preparation, and ultrapure water (for semiconductor and pharmaceutical industries). These applications typically are smaller in volume than municipal water production. Discharge applications treat effluent to meet discharge standards, including discharge to surface waters or to sanitary sewers. Many discharge applications are of relatively small volumes; however, applications in the oil and gas industry, including those associated with more recent unconventional oil and gas mining, can be of larger volumes, particularly where regional treatment is used.

Figure 1-3 compares global uses for desalination, including both seawater and brackish water facilities.

US Desalination Facilities

As of 2011, 2.2 bgd (8.5 million m³/d) of desalination capacity had been installed in the United States. Data on desalination use in the United States are currently limited to municipal facilities, which make up the majority of installed capacity. The municipal facilities use membrane technologies and are overwhelmingly brackish water plants.

A series of detailed surveys of US municipal desalination facilities has been conducted over a 20-year period. The approach of each survey was to identify and contact each plant of size 25,000 gpd (95 m³/d) or greater built in the 50 US states. The surveys were funded by the Water Research Foundation (WRF), the US Bureau of Reclamation (USBR), St. Johns

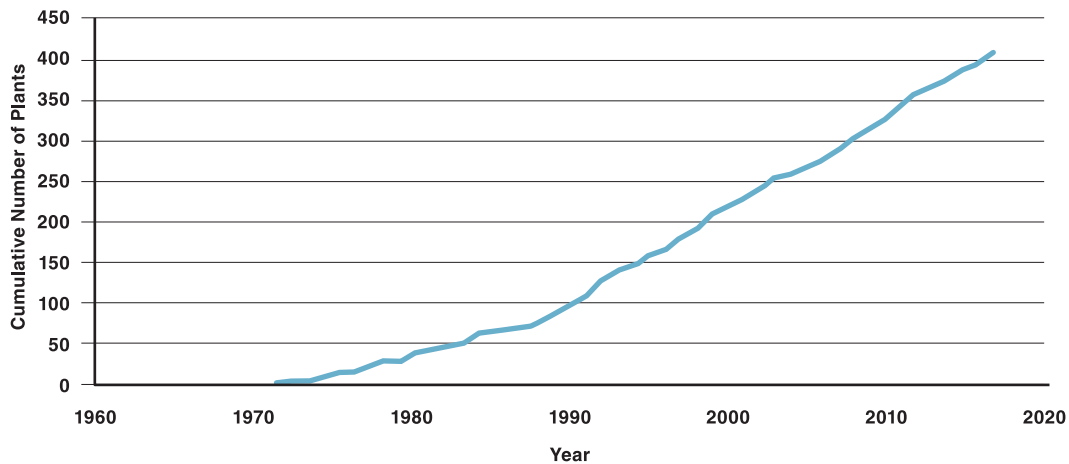


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Figure 1-3 Total worldwide installed desalination capacity by user type

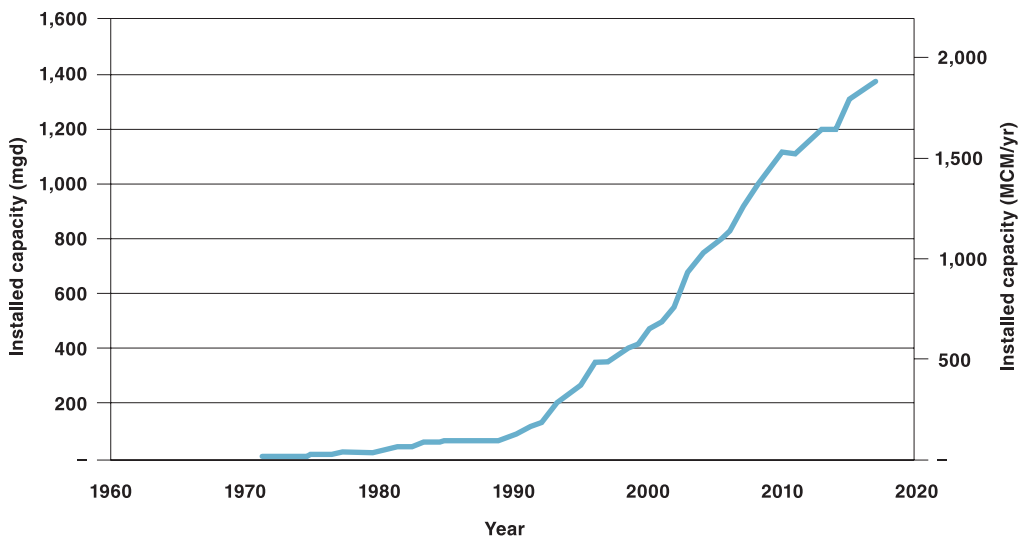
River Water Management District (SJRWMD), and the WaterReuse Research Foundation (now the Water Research Foundation). *Development of a Knowledge Base on Desalination Concentrate and Salt Management*, a project published in 2013, provided data for municipal desalination facilities built through 2010. This information was supplemented in 2018 with the publication of the *Updated and Extended Survey of U.S. Municipal Desalination Plants* (Mickley 2018).

Number and types of plants. Data in Figures 1-4 and 1-5 are based on this detailed survey of municipal desalination facilities that provides data for 414 municipal desalination facilities identified from 1971 through 2017 with capacities of 0.025 mgd or greater (Mickley 2018). The number of US municipal desalination plants built with time, and the cumulative capacity of these plants with time, are shown in Figures 1-4 and 1-5,



Adapted with permission from Mickley 2019

Figure 1-4 Cumulative number of US municipal desalination plants



Adapted with permission from Mickley 2019

Figure 1-5 Cumulative installed capacity of US municipal desalination plants

respectively. Capacity is taken as built capacity at the time the plants were surveyed and is presented in both mgd and million cubic meters per year (MCM/yr). The total capacity is an estimate, as many plants have been expanded since they were surveyed and many small, older plants are no longer operating.

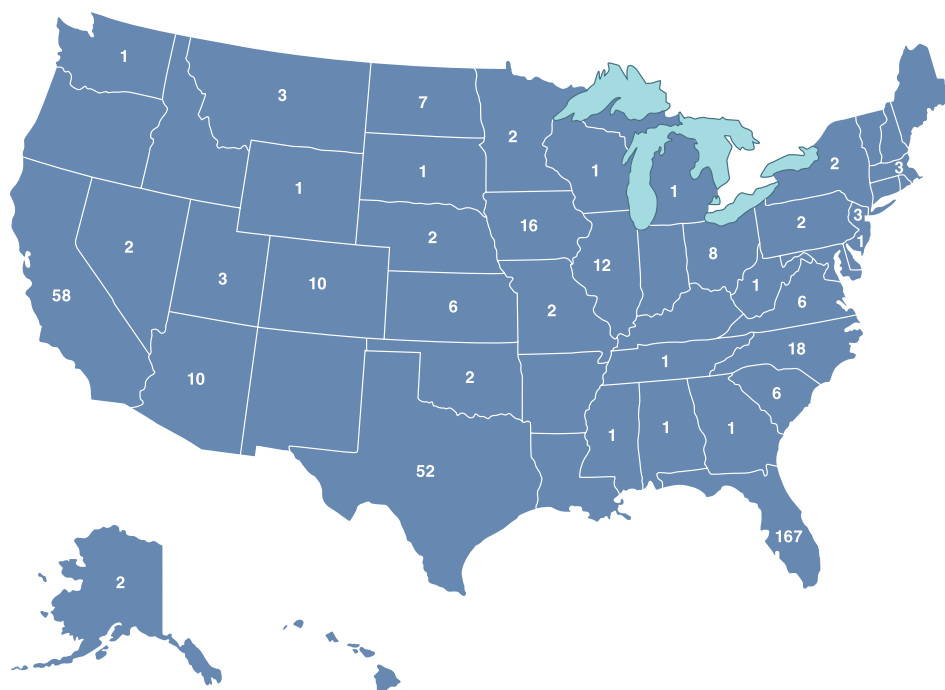
Table 1-1 presents the number of plants using various membrane processes at US desalination facilities. It should be noted that these numbers differ slightly from those included in the referenced source (Mickley 2019), as the category “Wastewater RO” used here is different from the integrated membrane system categories used in the source document.

Plant locations. Figure 1-6 shows the existing municipal desalination plants located in 35 states and their distribution. Sixty-seven percent of the facilities (as of 2017) are located in the coastal states of Florida (40 percent), California (14 percent), and Texas (13 percent). The remaining 33 percent are spread over 32 other states, 22 of which have no ocean border.

Table 1-1 Number of different US municipal desalination membrane processes as of 2017

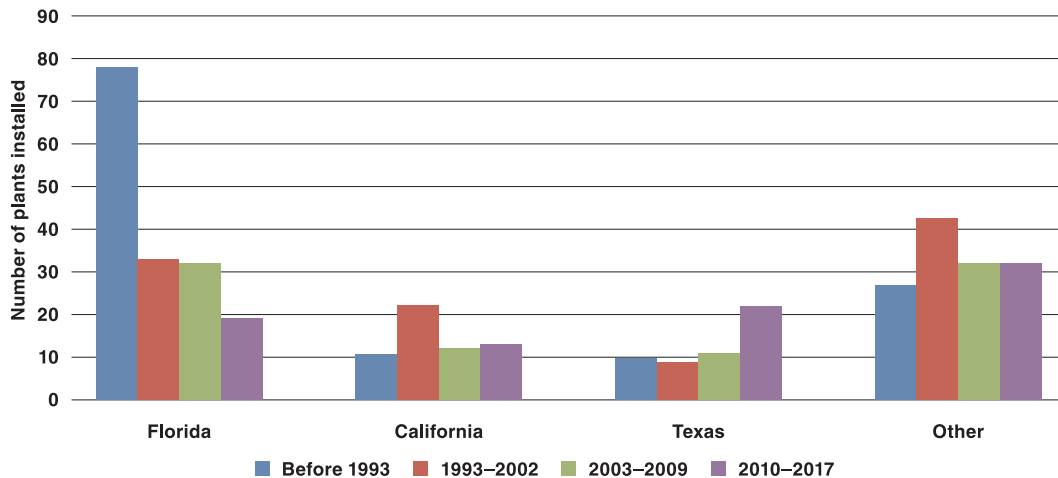
	Number	Percent
Brackish water reverse osmosis (RO)	302	74%
Nanofiltration	61	15%
Electrodialysis reversal	22	5%
Seawater RO	13	3%
Wastewater RO	12	3%

Source: Mickley 2019



Adapted with permission from Mickley 2019

Figure 1-6 Number of US municipal desalination plants by state as of 2017



Adapted with permission from Mickley 2019

Figure 1-7 Number of US municipal desalination plants installed by state in different time periods

Figure 1-7 shows the number of plants built in the three major states and the remaining states over four different time periods. Florida was the most active state in all time periods before 2010. During the most recent time period (i.e., after 2010), Texas has become the most active state for new desalination facilities. Since 1993, the percentage of plants being built in Florida has declined from a high of 62 percent in 1993 to the present level of 22 percent. Over this period, the operating capacity of desalination plants has increased from an average of 1.6 mgd per plant built before 1993 to 5.5 mgd per plant built in 2009. During the most recent period, between 2010 and 2017, the average capacity decreased to 3.7 mgd; however, 25 percent of the plants built in this period were in states with no ocean border. With the size of plants increasing, and with more plants being built farther away from coastal areas, the need for reliable concentrate disposal and management alternatives has become more critical.

CONCENTRATE MANAGEMENT OPTIONS

Five conventional concentrate disposal options are currently used by more than 98 percent of the municipal desalination plants built in the United States: surface water discharge, discharge to sewer, deep-well injection, land application, and discharge to evaporation ponds (Mickley et al. 2013). The application of these options has been a function of plant size, water quality, location, regulatory policy, and cost.

Landfill should also be considered as a concentrate disposal alternative for solids produced by high-recovery (HR) processing, where solids result from either accumulation in evaporation ponds or from a final evaporation step to produce mixed solids.

While several possible beneficial uses of concentrate (besides irrigation) have been identified, none are widely applied, most are unproven, and most do not result in the disposal of concentrate. Few viable uses of concentrate have been demonstrated thus far—although some, such as constructed wetlands, may contribute to improved water quality through removal of specific problematic constituents such as selenium or nitrate, making blending and discharge more viable. Given the challenges of concentrate management, it is prudent to explore all beneficial use options early in project planning, as the options are site-specific. A combination of methods linking more conventional options with beneficial uses may provide redundancy, reliability, and potentially some ancillary benefits.

Table 1-2 Concentrate management options

-
1. Conventional disposal options
 - Surface water discharge
 - Offshore ocean outfall (includes brine line when direct to ocean)
 - Onshore ocean outfall
 - Collocated outfall with coastal power plant or WWTP outfall
 - Discharge to river, canal or lake
 - Discharge to sewer
 - Sewer line
 - Direct line to WWTP
 - Concentrate codisposal with WWTP effluent
 - Hauling of concentrate to a WWTP
 - Subsurface injection
 - Deep-well injection
 - Shallow well (beach well) infiltration
 - Evaporation in ponds
 - Conventional ponds
 - Enhanced evaporation ponds/schemes
 - Land application
 - Percolation ponds/rapid infiltration basins
 - Irrigation
 2. Landfills (for solids)
 - Dedicated monofills
 - Industrial landfills
 3. Beneficial use (other than irrigation, which was addressed previously under “land application”)
-

Source: Mickley 2019

The use of the term *concentrate management* (rather than *concentrate disposal*) and the use of higher-recovery processing are relatively new to municipal desalination. As a result, some publications list ZLD and near-zero liquid discharge (NZLD) as concentrate management options. This view is correct from the perspective of having an existing concentrate and considering options for how to manage it. However, in most other industries, ZLD and NZLD are processing options that are considered and possibly implemented with the initial design of the treatment system. Table 1-2 presents concentrate management options from this perspective, including all options for the final fate of concentrate, or solids, whether from a low- or high-recovery process.

Table 1-3 presents the percentage use of the five conventional disposal options and the number of states having municipal desalination plants using the option. Thirty-five states were identified as having desalination plants practicing the concentrate management options listed in Table 1-2. Few of these states use deep-well injection, land application, or evaporation ponds. The states using disposal alternatives other than surface discharge or discharge to sewers or wastewater treatment plants (WWTPs) are presented in Table 1-4. In summary:

- Seventy percent of the plants discharge concentrate to surface water, to the sewer, or to a WWTP.
- Deep-well injection and land application are used in only five of the 35 states.
- Evaporation ponds are used in only four of the 35 states.

- In 28 states, 100 percent of the plants discharge concentrate either to a surface water body or to the sewer.
- In 2017, all but six of the 70 deep-well injection sites were in Florida.
- Twenty of the 27 land application sites are in Florida.
- Florida, California, and Texas are the only states using all five conventional disposal options.

The pattern of use of concentrate disposal options varies greatly in the three states with the largest number of desalination plants (Florida, California, and Texas). These are three of the four most populous states and have experienced the greatest growth in residents since 2000 (Mickley et al. 2013). They have thus experienced the greatest increase in potable water demand. These three coastal states are also the centers of interest and activity for large-scale seawater RO plants. Florida, California, and Texas may be considered as distinct regions because of the number of plants, the resulting awareness of the regulatory agencies and the public to desalination and concentrate management issues, and the different patterns of use of the five conventional disposal options. In particular, the following conclusions can be drawn about the plants in each region:

- California plants primarily discharge to surface water (ocean) and dispose to sewer.
- Texas plants primarily discharge to surface waters and evaporation ponds.
- Florida plants use a mix of methods with the highest percentage of use of deep-well injection.

The other 32 states that have municipal desalination plants rely almost exclusively on discharge to surface water and disposal to sewer.

While those conclusions represent the trends of facilities built to date, the trend toward larger desalination facilities in more inland locations should be expected to have an impact on the types of concentrate disposal options used. As plants grow larger, the impacts of concentrate disposal on the surface water body or watershed become more significant and will push more facilities toward alternative concentrate disposal options.

Table 1-3 Number of states using the disposal options for municipal desalination concentrate

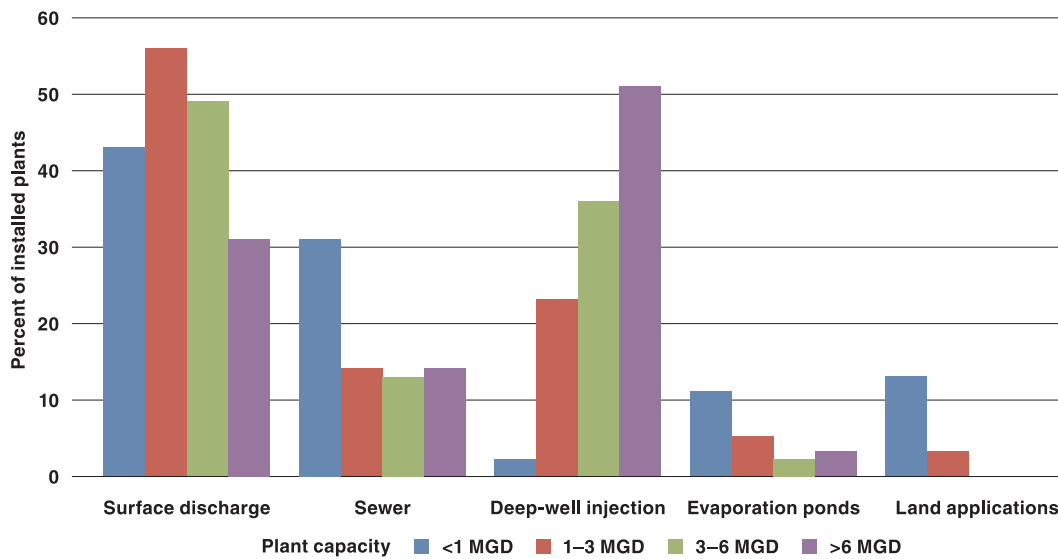
	Percentage use	Number of states
Surface water discharge	46	27
Discharge to sewer or wastewater treatment plant	24	24
Deep-well injection	17	4
Land application	7	4
Evaporation in ponds	5	3

Source: Mickley 2019

Table 1-4 States using various disposal options and number of plants in each state

	FL	CA	TX	KS	AZ	PA	CO
Deep-well injection	64	1	2	1	0	0	2
Land application	20	1	5	0	1	0	0
Evaporation ponds	3	2	13	0	3	0	0
Recycle	0	4	4	0	1	1	0

Source: Mickley 2018



Adapted with permission from Mickley 2019

Figure 1-8 Concentrate disposal options for US municipal desalination plants

Figure 1-8 shows a breakdown of concentrate disposal alternatives by plant capacity. Based on the trends present in these numbers, and on a comparison of plants built before 1993 with those built after 2002, the following conclusions can be drawn:

- Relative to plants built before 2002, there has been greater use of deep-well injection and a declining use of evaporation ponds or greater application.
- In the past several years, there has been increased consideration and investigation of deep-well injection in states other than Florida as well as enhanced evaporation. However, neither has had much impact on practices.
- An increasing number of plants are treating source water to remove specific contaminants as well as to reduce salinity.
- An increasing number of plants have concentrate containing contaminants that restrict application of concentrate management options or require treatment to remove the contaminants before disposal.
- Increasing concentrate management challenges have led to planning-phase consideration of plants of HR processing of concentrate. To date, a few ZLD plants have been built (Mickley 2018), and a few HR nanofiltration plants are now being built.

Trends in US Concentrate Management

Although “management” is the broader and more inclusive term for addressing handling of concentrate flows, nearly all concentrate from desalination plants is currently discharged to surface water bodies or subsurface formations. The primary challenge of inland concentrate management continues to be finding a cost-effective and environmentally sustainable option (NRC 2008).

The time and effort required to find a solution, in large part defined by the regulatory framework and permitting process, are increasing in most locations. An emerging issue is that more stringent regulations for protecting source water will pose additional impediments to discharge options that can affect source water. These include surface water

discharge and disposal to sewer, which together currently are used by 80 percent of the municipal desalination facilities. An increasing number of water reclamation plants are treating source water to remove contaminants and reduce salinity. As a result, as was found in the most recent municipal desalination concentrate management survey, a handful of desalination plants have concentrate containing contaminants that restrict discharge of concentrate or require treatment to remove the contaminants before disposal (Mickley et al. 2013).

This trend is likely to continue as regulations become more stringent because of nutrients, emerging contaminants, and other contaminants being considered for regulation. Because of these and other challenges, there has been increased interest in HR processing, usually under the label of volume reduction or concentrate minimization. This has been reflected in funded research projects and more frequent consideration of HR processing at the planning phase of plants. Several plants now incorporate HR processing, and a few ZLD plants are operational, treating drinking water desalination concentrate in the United States (Mickley et al. 2018).

MANUAL OVERVIEW

This manual contains the following chapters:

Chapter 2, *Water Quality and Planning Strategies*, defines the water quality challenges and goals associated with inland desalination and the general planning strategies involved in developing a brackish water supply and managing concentrate.

Chapter 3, *Brackish Water Desalination*, describes the most commonly used technologies involved with brackish water desalination, detailing the key issues associated with facility design and the primary treatment components of a brackish water desalination facility.

Chapter 4, *Discharge Options for Concentrate Disposal*, describes concentrate management options that do not involve treatment of concentrate to recover part or all of it as product water.

Chapter 5, *Enhanced Recovery and Zero Liquid Discharge*, discusses technologies used to support zero liquid discharge or near-zero liquid discharge desalination facilities, including benefits and challenges of various process trains currently in use or in development.

Chapter 6, *Cost of Desalination and Concentrate Management*, provides a general discussion of the cost of inland desalination, including concentrate disposal, and the primary factors impacting the associated costs.

Chapter 7, *Regulatory, Safety, Operational, and Environmental Issues*, discusses key regulatory challenges with implementing inland desalination as well as safety, operational, and environmental concerns that must be addressed when planning for and developing a new facility.

Chapter 8, *Case Studies*, includes detailed information on a wide variety of inland desalination projects, including lessons learned from facilities already using brackish supplies to address their water needs.

Chapter 9, *Technological Trends, Salt Recovery, and Beneficial Uses*, discusses technology advancements on emerging concentrate treatment alternatives, including salt recovery, nutrient recovery, and beneficial use of concentrate.

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Chapter 2

Water Quality and Planning Strategies

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This chapter provides an overview of planning strategies for implementing inland desalination and concentrate management. The need for desalination and concentrate management may be driven by different factors. For example, concentrate may be generated by the desalination process when an additional water supply is developed to meet increasing demands from new sources of impaired water quality. Moreover, a source water with better water quality [e.g., lower concentrations of total dissolved solids (TDS) and target ions] is desired for special agricultural or industrial needs. This chapter focuses on planning driven by water scarcity challenges.

Desalination and water reuse are potential solutions to global water scarcity issues; however, concentrate management is an unavoidable result of these solutions. This is because water reuse often relies on desalination technologies such as reverse osmosis (RO) to achieve its removal goals for dissolved solids, emerging contaminants, and pathogens. However, after water is used for many cycles, dissolved salt will accumulate and interfere with the reuse efficiency to an extent that the water has to be desalinated for any further use. In both cases, once desalination technologies are employed, a concentrate waste stream is generated, requiring proper management and disposal.

Concentrate disposal options vary from one system to another, and several concentrate disposal options should be considered before employing complex concentrate treatment and management technologies. Sewer discharge may be the simplest and cheapest option, but it is often not sustainable as the salt content in the reclaimed water increases. For most inland communities, surface water discharge to an ocean or a salt lake nearby is not feasible. Deep-well injection could be a solution, but viable hydrogeological

conditions may not exist for every inland application and the injection could negatively impact seismic conditions. Even when they are available, the capacity of confined aquifers suitable for deep-well injection may be limited, requiring minimizing the volume of the concentrate.

For most areas with little precipitation, evaporation ponds remain a reliable resource. Evaporation ponds are relatively easy to construct, require little maintenance, and can be expanded as needed to avoid significant investment all at once. However, for a brackish water RO system at municipal scale with a typical recovery of 70–85 percent, evaporation ponds without concentrate volume reduction could occupy square miles of land and potentially result in other environmental issues. Some enhancement options (e.g., mechanical mixing and wind aided) could be applied to reduce evaporation pond size.

If concentrate disposal options are limited by available land for evaporation ponds, treating concentrate to reduce its volume and removing limiting constituents that prevent high recovery may become necessary. Concentrate treatment is often more difficult than conventional water treatment and handling of solid phase residuals. Concentrate management is complex; it is affected by many factors and involves multiple steps. Generally, the optimal approach to concentrate management involves a combination of several technologies and strategies.

The quality of natural water sources can vary significantly from one location to another. In addition, water quality variations are amplified in the brine streams after being concentrated. Currently, there is no single technology or methodology that can resolve all salinity management challenges for all situations. The best approach often lies in developing site-specific solutions. The process of developing site-specific solutions to salinity management challenges often involves the following steps:

- Evaluate brackish source water quality and quantity as well as the characteristics of the contaminants limiting concentrate management options.
- Establish water quality goals for the site-specific conditions of a given project.
- Identify treatment strategies based on water quality goals and limiting factors, and provide a basis for planning strategies.
- Combine strategies and solutions into a cost-effective project design.
- Demonstrate efficiencies of critical components through bench-scale and pilot testing.
- Optimize and enhance customized strategies and solutions.

These steps are important in ensuring that water quality and recovery goals are met while minimizing life-cycle costs.

SOURCE WATER QUALITY AFFECTING DESALINATION

This section discusses how brackish source water quality affects desalination and treatment goals; water quality monitoring recommendations; guidance on desalination technology performance projection models; an overview of various treatment levels and desalination and concentrate management technologies; and key planning strategies that apply to inland water utilities developing a water supply from brackish sources.

Brackish Groundwaters

Brackish groundwaters vary considerably by region and often by depth in similar locations. Table 2-1 presents an overview of the water quality of five characteristic brackish water sources currently used for desalination supplies.

Table 2-1 Example of brackish water quality variations

Parameter	South Florida ¹	West Texas ²	Central Colorado ³	Southern California ⁴	Central Arizona ⁵
TDS (mg/L)	3,680	1,125	847	1,700	2,283
pH	7.6	8.2	7.2	7.4	7.5
Calcium (mg/L)	117	67	145	129	188
Magnesium (mg/L)	143	16	40	53	77
Sodium (mg/L)	1,070	295	122	405	606
Potassium (mg/L)	64	12	3.7	7	6
Barium (mg/L)	0.01	0.2	0.05	0.08	0.09
Strontium (mg/L)	11.2	1.5	ND	0.9	ND
Bicarbonate (mg/L)	145	124	308	239	362
Sulfate (mg/L)	440	71	192	181	436
Chloride (mg/L)	2,240	504	136	760	914
Fluoride (mg/L)	ND	0.7	1.5	0.13	1.1
Nitrate-N (mg/L)	ND	3.1	2.6	0.07	18
Silica (mg/L)	8.6	31	8.0	17	27
Iron (mg/L)	ND	ND	0.06	0.09	ND
Manganese (mg/L)	ND	ND	0.07	0.6	ND
Sulfide (mg/L)	2.4	ND	ND	ND	ND
Aluminum (mg/L)	ND	ND	0.008	0.05	ND

ND—No data, TDS—total dissolved solids

¹ South Florida aquifer, Deerfield Beach, Fla.

² Surficial aquifer, El Paso, Tex.

³ Surficial aquifer, East Cherry Creek, Colo.

⁴ San Diego Formation, Chula Vista, Calif.

⁵ Buckeye and Goodyear, Ariz.

The South Florida and West Texas waters are examples of sodium- and chloride-dominated sources in which sodium and chloride make up most of the TDS concentration. In the case of the South Florida water, which has low concentrations of both calcium and sulfate, 90 percent of the source water is sodium and chloride. The Central Colorado water is an example of a source that contains almost equal concentrations of sodium, chloride, calcium, and sulfate. The Southern California water source is also mostly sodium and chloride but has moderate calcium, sulfate, and bicarbonate. West Texas and Central Arizona water has a significantly higher concentration of silica compared to the other sources, which would be a factor in selecting an appropriate desalting technology and recovery rate.

Brackish water quality parameters affecting desalination. The desalination process is directly affected by source water quality constituents such as TDS—organic and inorganic—and origin (e.g., groundwater, surface water, wastewater effluent). The cost of treating brackish water highly depends on the water quality of the source. Waters with higher salinity, higher sparingly soluble salts, or higher oxidizable metals will typically be more costly to treat than water supplies with lower concentrations of these dissolved constituents. The presence of hydrocarbons can also create challenges to using brackish groundwaters.

The following sections discuss the impact that suspended solids, inorganic compounds, minerals, and oxidizable metals have on the desalination process. The treatment processes most commonly used to remove contaminants from brackish water, including RO, nanofiltration (NF), electrodialysis (ED), and electrodialysis reversal (EDR),

are discussed in Chapter 3 of this manual. [AWWA M46](#), *Reverse Osmosis and Nanofiltration* (AWWA 2007), and [AWWA M38](#), *Electrodialysis and Electrodialysis Reversal* (AWWA 1995), also offer more detailed discussions of the treatment technologies used to remove these constituents.

Suspended solids. RO and NF membranes effectively remove not only dissolved constituents but also particulate and colloidal materials. However, the latter is a misapplication of the technology. Suspended solids can accumulate on the RO membrane surface and clog feed channels, resulting in poor performance and sometimes irreversible damage to the membranes in a relatively short time. Even in small concentrations, suspended solids in the source water that accumulate on the membrane surface deposit a foulant layer that reduces permeability and production. The foulant deposits may also increase the thickness of the concentration polarization layer at the membrane surface, resulting in increased salt passage and higher energy consumption. Hence, if solid or colloidal materials are present in the water to be treated, the RO or NF process should be preceded by pretreatment. Essentially all facilities include at least a cartridge filtration step before RO or NF to protect the membrane elements.

One of the most widely used indicators for determining the suspended solids and colloidal fouling potential of desalination feedwater is the measurement of silt density index (SDI). Typically, the target SDI_{15-min} for RO and NF feedwater is less than 3–5. Unlike pressurized membrane processes, ED and EDR do not remove suspended solids and can tolerate a higher concentration of feedwater suspended solids. Manufacturers recommend a target feedwater SDI_{5-min} of less than 10–15 for EDR.

Inorganic compounds. Both RO and EDR can effectively remove a wide range of inorganic contaminants (Antony et al. 2011). As a result, they could both be affected by scaling of inorganic compounds. With the exception of silica, the extent of such impacts is very similar for RO and EDR. The following discusses impacts of oxidizable metals and minerals, sparingly soluble salts, and silica on desalination processes.

Oxidizable metals and minerals. The presence of iron, manganese, or hydrogen sulfide in a brackish water supply can be problematic for desalination facilities, as these ions are easily oxidized by ambient oxygen and can cause excessive particulate fouling when oxidized. Iron and manganese do not present a fouling risk when present in their reduced state, and desalination facilities have successfully operated with iron and manganese levels exceeding 2–3 mg/L, provided anoxic conditions are maintained within the wells, transmission piping, and treatment facility. Reduced and oxidized forms of iron and manganese are removed by RO, NF, and EDR membranes and therefore do not create the risk of red or black water in desalinated product water. However, if iron and manganese are already in oxidized forms, $Fe(OH)_3$ and $Mn(OH)_3$ may precipitate out and foul the membrane.

If iron and manganese cannot be conveyed to the desalination process without exposure to oxygen in the air or other oxidizing agents, pretreatment is necessary. Typically, if iron and manganese concentrations are greater than 0.05 mg/L in the feedwater and anoxic conditions cannot be maintained to prevent them from being oxidized, pretreatment using oxidation and filtration is recommended to remove iron and manganese before desalination. Numerous facilities have experienced rapid and repeated plugging of membrane elements when oxidized iron and manganese have not been adequately removed. The presence of iron exacerbates silica fouling, which is discussed later in this chapter.

Similar to iron and manganese, an insoluble form of aluminum can form $Al(OH)_3$ in the desalination system. Aluminum can be introduced to the feedwater through the use of coagulants in pretreatment processes and its carryover to the desalination process. Aluminum solubility is lowest around pH 6.5, and the pH suppression commonly used to

control fouling from other sparingly soluble salts can therefore make aluminum fouling worse. When aluminum fouling is present, alternative coagulants can be considered.

Hydrogen sulfide, similar to iron and manganese, does not present a fouling risk when anoxic conditions are maintained. However, hydrogen sulfide is not well rejected by RO or NF membranes and often must be removed from the desalination product water through degasification. Where anoxic conditions cannot be maintained, hydrogen sulfide may be oxidized to elemental sulfur, causing excessive fouling on desalination membranes.

Sparingly soluble salts. Sparingly soluble salts are those minerals that have a lower solubility, such as calcium sulfate, and can create complications in the desalination of brackish water. As the membrane recovers permeate from the feedwater, the concentrations of some of the sparingly soluble salts and silica can exceed solubility thresholds and form a precipitate (scale) on the membranes. Scale formation leads to a decrease in permeability, deteriorating the quality of water produced and requiring an increase in operating pressure and frequent chemical cleanings. The common precipitates that limit desalination recovery are calcium carbonate, calcium sulfate, calcium fluoride, calcium phosphate, barium sulfate, strontium sulfate, and silica. Usually only one or two of these constituents are limiting in each situation. Identifying and addressing the limiting factor are critical for planning and designing desalination facilities.

Acid addition and polymeric antiscalants are used to reduce the risk of scaling on the membranes, with different antiscalants tailored for different types of scaling agents. Commonly used RO design software will calculate the solubility of many sparingly soluble salts, such as calcium carbonate, calcium sulfate, strontium sulfate, barium sulfate, and silica. However, some desalination facilities have reported challenges with other salts, such as calcium phosphate, calcium fluoride, and aluminum silicate, which are less commonly modeled in most vendor software. Desalination facilities struggling with scale from sparingly soluble salts will often perform membrane “autopsies” to identify specific scaling agents and adjust operating conditions or cleaning approaches to reduce the risk of scaling. Scale can be removed through acid cleaning of the membranes; however, excessively scaled membranes can become damaged or permanently fouled, requiring membrane replacement.

Silica. Silica is generally found in three forms in natural waters—namely, reactive silica (dissolved silica), colloidal silica, and particulate silica. Reactive silica in water can be found in many forms, e.g., monosilicic acid, disilicic acid, and polysilicic acid with molecules smaller than the colloidal range (Ning et al. 2006). Reactive silica, $\text{Si}(\text{OH})_4$, is monomeric and contains a single silicon atom. The dissolution rate depends mainly on pH and temperature.

Colloidal silica is widely thought to be both silica that has polymerized into silicon dioxide and silica that has formed complex compounds with organic and/or inorganic substances in the source water. Particulate silica is larger in size and mostly consists of sand or suspended solids. Silica polymerization on the membrane leads to increased chemical cleaning frequency and may eventually lead to replacement of membrane elements. The presence of silica can be problematic for pressure-driven desalination processes (NF and RO), but is less of a concern for electrochemical-driven processes (ED and EDR), which do not concentrate or remove silica.

For reducing silica polymerization on the membrane surface, operation at either low pH (<5.0) or high pH (>10.0) is desirable. The use of antiscalant specific to silica is also beneficial for restricting silica fouling on the membrane surface. Chemicals used for silica fouling control can be divided into three categories:

- chemicals for inhibition of silica scale formation (silica inhibitors),
- chemicals for silica dispersion, and
- chemicals for silica scale removal from membrane surfaces.

Silica inhibitors can retard the polymerization of silica at supersaturated concentrations. Dispersants place a surface charge on the polymerized silica and cause repulsion and dispersion of these polymerized structures to prevent formation of colloidal silica (Sheikholeslami and Tan 1999). Besides using antiscalant, removing silica through a process such as lime softening is effective and is discussed in Chapters 5 and 8.

In the western states, the recovery rates of RO systems often may be limited by the solubility of silica. When silica is present at high concentrations, precipitation and deposition of amorphous silica and silicates could result in consequential RO membrane fouling and loss of efficiency. Particulate and colloidal silica cause severe, irreversible fouling that is difficult to remove.

Organics and Hydrocarbons

Desalination membranes can be fouled by organic constituents, depending on the interactions between the natural organic matter in the feedwater and the RO membrane. This is typically an issue in surface water sources such as river water, seawater, and wastewater. Less commonly, brackish groundwater sources contain high concentrations of organic material, except in regions such as Florida. If present, organic material can foul the RO membrane, interfere with the functioning of the antiscalant, and potentially aggravate biofouling. Typically, organic fouling is reduced by optimizing pretreatment, adjusting the operating pH, and using compatible antiscalants.

Biofouling is one of the most challenging fouling phenomena that is prevalent in surface water and wastewater sources. Biofouling commonly occurs when the feedwater has a high concentration of organic material and nutrients. The large area of membranes provides surface areas for microbial growth. Typically, colonization of the microorganisms results in the formation of biofilm on the surface of the membrane because of the production of extracellular polymers that attach to the membranes. Other foulants typically get imbedded within this biofilm, increasing the severity of the fouling. Biofouling is controlled by adequate pretreatment of feedwater, reduction of stagnant feedwater in the membranes when not in service, use of oxidants that do not damage the membranes, and periodic chemical cleaning of membranes. In reuse applications treating wastewater containing ammonia, chlorine is added in pretreatment to form chloramines, which continue through the desalination system to help minimize biofouling.

Hydrocarbons can cause severe and sometimes permanent fouling of desalination membranes, adsorbing to the membrane surface and restricting water flow. RO vendors typically limit oil and grease in membrane feedwater to 0.1 mg/L or lower to prevent such fouling. RO facilities treating water high in hydrocarbons have been successful at reducing fouling by operating under high pH conditions or by implementing significant levels of pretreatment to reduce residual oils and greases.

PRODUCT WATER QUALITY GOALS

Product water quality goals vary depending on the intended use of the water. This section provides a brief overview of water quality requirements for various uses. Some utilities may have goals that differ from those listed in this section.

Potable Water Quality Goals

In the United States, the quality of potable or drinking water is regulated by the Safe Drinking Water Act (SDWA), including the National Primary Drinking Water Regulations (NPDWR) and the National Secondary Drinking Water Regulations (NSDWR). A detailed list of these standards can be found on the US Environmental Protection Agency (USEPA)

website. Other regions of the world have similar drinking water standards (Guidelines for Canadian Drinking Water Quality, European Commission Standards, etc.). Most developing countries follow the World Health Organization guidelines for drinking water.

Table 2-2 provides a list of typical water quality goals for various inorganic contaminants; this list can be used as a reference when developing water sources. Some of these goals are based on drinking water quality standards, noted with their maximum contaminant level (MCL) or secondary MCL (SMCL). Many utilities or local regulatory agencies may choose to use a percentage of the MCL and SMCL levels (e.g., 80 percent) as their targets to provide additional operational buffer. Many factors such as TDS and temperature affect consumer taste preferences (Gallagher and Dietrich 2010). Some utilities successfully conducted outreach campaigns such as Decision H₂O by the City of Tucson, Ariz., to involve the public in determining an acceptable and affordable mineral content in the drinking water (Gallagher and Dietrich 2010).

Water that is high in calcium and magnesium is often referred to as “hard water.” While hardness is not a health risk and is not regulated, it causes unpleasant aesthetic

Table 2-2 Examples of drinking water quality goals

Contaminant	Primary MCL or TT* (mg/L)	Secondary MCL (mg/L)
Antimony	0.006	
Arsenic	0.010 as of 01/23/06	
Barium	2	
Beryllium	0.004	
Cadmium	0.005	
Chromium (total)	0.1	
Copper	TT [†] ; Action level=1.3	1.0
Cyanide (as free cyanide)	0.2	
Fluoride	4.0	2.0
Lead	TT [†] ; Action level=0.015	
Mercury (inorganic)	0.002	
Nitrate (measured as nitrogen)	10	
Nitrite (measured as nitrogen)	1	
Selenium	0.05	
Thallium	0.002	
Aluminum		0.05–0.2
Chloride		250
Iron		0.3
Manganese		0.05
Silver		0.1
Sulfate		250
Total dissolved solids (TDS)		500
Zinc		5

* TT – treatment technique; a required process intended to reduce the level of a contaminant in drinking water.

[†] Copper and lead are regulated by a treatment technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps. For copper, the action level is 1.3 mg/L; for lead, 0.015 mg/L.

Table 2-3 Examples of short-term salinity goals

Constituent, Units	Maximum Contaminant Level Ranges		
	Recommended	Upper	Short Term
Total dissolved solids (TDS), mg/L*	500	1,000	1,500
Specific conductance, $\mu\text{S}/\text{cm}^*$	900	1,600	2,200
Chloride, mg/L	250	500	600
Sulfate, mg/L	250	500	600

Source: Barclays Official California Code of Regulations, Title 22. Social Security, Division 4. Environmental Health, Chapter 15.

Domestic Water Quality and Monitoring Regulations, Article 16. Secondary Drinking Water Standards. §64449 Secondary Maximum Contaminant Levels and Compliance.

* Meet TDS or specific conductance goals.

impact on laundry, bathing, and water heaters. Water fixtures and pipes can become clogged with calcium and magnesium scale that reduces flow and requires their replacement. Softeners are often used to remove hardness, but they do not remove TDS.

Desalination technologies such as RO and ED are effective for removal of chloride, hardness, TDS, and other inorganic substances. However, these technologies, especially when considering the associated concentrate management, are fairly expensive and may be impractical. Some inland utilities and regulatory agencies may choose to establish a target range or temporary goals similar to the values presented in Table 2-3.

Nonpotable Reuse

When reclaimed water is reused for nonpotable reuse (e.g., for irrigation), several issues could result from high concentrations of salt and certain ions individually or in combination. The degrees of impact depend on time, concentration, crop sensitivity, and crop water use.

High-TDS water limits the ability of certain crops and grasses to grow and flourish. Salt buildup in the root zone is a prevalent problem. Flushing these salts involves applying more water than normal, dissolving the existing salts in the plant's root zone, and "flushing" those salts further into the ground. This increases the water usage and reduces the irrigation efficiency.

A critical constituent of TDS that requires specific attention is sodium ion (Na^+). High sodium concentrations in soil result in poor infiltration. Sodium adsorption ratio (SAR) is a measure of the suitability of water for use in agricultural irrigation. The formula for calculating sodium adsorption ratio is as follows:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{\frac{1}{2}(\text{Ca}^{2+} + \text{Mg}^{2+})}} \quad (\text{Eq 2-1})$$

where

Na^+ = sodium ion concentration

Ca^{2+} = calcium ion concentration

Mg^{2+} = magnesium ion concentration

All concentrations are expressed in milliequivalents/liter (meq/L).

According to the US Bureau of Reclamation (USBR), water with SAR less than 3 is safe for irrigating turf and ornamental landscape plants (USBR 2003a, 2003b). SAR greater than 9 can cause severe damage to the soil condition. However, SAR is only one of the factors that determine the suitability of water for irrigation (Clark et al. 2000, Maas 1984). For example, if irrigation water contains relatively high amounts of bicarbonate ion, the bicarbonate can affect the calcium and magnesium concentrations in the soil to which the

water is applied. For this reason, the water's bicarbonate and total salinity are often taken into account (in addition to its calcium, sodium, and magnesium concentrations) and reported as adjusted SAR. In general, the higher the SAR, the less suitable the water is for irrigation. Some utilities have adopted treatment goals for sodium (e.g., sodium < 125 mg/L; Chesters et al. 2007) and SAR goals (e.g., SAR < 5) for their reclaimed water reuse facilities.

Ayers and Westcot (1985) gave the known tolerances of several crops to sodium, chloride, and boron. These values may be used as a reference when establishing water quality goals, supplemented by local experience and comprehensive environmental impact assessments.

Potable Reuse

For potable reuse, reclaimed water must be treated to meet drinking water regulations similar to those being developed by the California State Water Resource Control Board Division of Drinking Water (DDW) and the Texas Commission on Environmental Quality (TCEQ). The World Health Organization (WHO 2017) provided information on specific aspects of potable reuse, including the water quality, types of treatment processes, additional monitoring considerations, potential use of environmental buffers and engineered storages, and public acceptance. WaterReuse Research Foundation (WRRF), AWWA, Water Environmental Federation, and National Water Research Institute (NWRI) provided a detailed framework for the implementation of direct potable reuse (DPR), covering not only water quality-related public health standards or quality measures but also means to ensure that such standards can be reliably met (WRRF 2015). The USEPA has also developed guidance on potable reuse through the 2017 Potable Reuse Compendium (USEPA 2017). Examples of water quality criteria for potable reuse are provided in Tables 2-4 and 2-5.

To meet a 500 mg/L TDS regulatory limit, a desalination process such as RO or NF is often required. However, as part of a potable reuse train, RO may be used for more than just desalination to remove other chemical, microbial, or radiological contaminants. When RO is used, a concentrate stream will be generated and must be handled appropriately. In areas where concentrate disposal options are limited, consider whether a non-RO-based potable reuse scheme could be sufficient to avoid concentrate management.

WATER QUALITY ANALYSIS AND MONITORING

Accurate and representative water quality data provide a sound basis for planning desalination and concentrate management facilities. Furthermore, for a facility in operation, water quality monitoring continues to provide critical information for process control and operational optimization.

Table 2-4 Regulations in California for groundwater recharge into potable aquifers

Minimum Criteria
>12-log virus inactivation
>10-log <i>Giardia</i> and <i>Cryptosporidium</i> inactivation
<2.2. total coliform/100 mL
<0.5 mg/L TOC for 100% recycled water contribution
<5 mg/L total nitrogen
Drinking water MCLs

MCLs—maximum contaminant levels; TOC—total organic carbon

Table 2-5 Example of product water quality criteria for direct potable reuse applications

Microbial Group	Criterion
Enteric virus	12 log removal
<i>Cryptosporidium spp.</i>	10 log removal
Total coliform bacteria	9 log removal
Chemicals	Criterion
Trihalomethanes	80 µg/L
Halogenated acetic acids	60 µg/L
N-Nitrosodimethylamine	10 ng/L
Bromate	10 µg/L
Chlorate	800 µg/L
Perfluorooctanoic acid	0.4 µg/L
Perfluorooctane sulfonate	0.2 µg/L
Perchlorate	15 µg/L
1,4-Dioxane	1 µg/L
Steroid Hormones	Criterion
Ethinyl Estradiol	None. Will be in ng/L level if established.
17-b-Estradiol	None. Will be in ng/L level if established.
Pharmaceuticals	Criterion
Cotinine/Primidone/Phenytoin	1/10/2 µg/L
Meprobamate/Atenolol	200/4 µg/L
Carbamazepine	10 µg/L
Estrone	320 ng/L
Other Chemicals	Criterion
Sucralose	150 mg/L
Tris [2-chloroethyl]phosphate	5 µg/L
N,N-diethyl-meta-toluamide	200 µg/L
Triclosan	2,100 µg/L

Source: NWRI 2013

Collecting and analyzing source water quality data is one of the most critical steps when developing brackish water sources and selecting the appropriate concentrate management technology. To provide a reliable basis for planning while controlling the analytical efforts and costs, it is important to understand what to measure, how to measure, at what frequency to measure, and how to analyze the data.

Relevant water quality constituents of concern should include a fully balanced set of cations and anions, including calcium, magnesium, sodium, potassium, strontium, barium, ammonia, alkalinity, sulfate, chloride, fluoride, nitrate, orthophosphate, silica, iron, manganese, and boron, as well as TDS, conductivity, pH, and temperature. Additional water quality data are required to assess the organic and biological fouling potential as well as removal of organics and pathogens, including total or dissolved organic carbon (TOC or DOC), total hydrocarbons, and microbial constituents (total and fecal coliform, heterotrophic plate count, etc.). To assess the propensity of particulate fouling, SDI and turbidity are often used. In wastewater applications, emerging contaminants such as endocrine disruptors and carcinogens (e.g., NMDA) will also have to be measured if the water is intended to be used for indirect potable reuse or DPR. Furthermore, for facilities

in operation, chemical usage and operational parameters are also critical for assessing the baseline scenario and characterizing the concentrate quantity and quality.

Assessment of the source water quality is essential for developing a future desalination facility. The characterization of the prospective concentrate stream can be estimated using membrane performance projection software, which is also used to project membrane performance. Supplemented by antiscalant manufacturers' projection models, these tools can be used to quantify the scaling and fouling potential and characterize the concentrate quality. If an existing desalination facility is in operation, water quality monitoring should cover the water quality for not only the feedwater but also the final product and the concentrate. To capture changes in the water quality that will affect planning, design, or operation, historical water quality data over a relatively long period of time should be analyzed instead of relying on limited data sets or a few grab samples. Do not simply assume water quality remains relatively constant without sufficient data to support such an assumption. Ideally, monthly or quarterly data for a full set of pertinent parameters should be analyzed for at least a year. Additionally, for operating facilities, efforts should be made to gather and analyze data from continuous monitoring of feed, product, concentrate conductivity, pH, flow, temperature, etc.

RO AND EDR PERFORMANCE MODELING

Several RO/NF membrane and EDR manufacturers have created and made available membrane system performance projection computer models. These models are available either through download from the manufacturers' websites or through contact with the manufacturers or their representatives (DeMichele et al. 2014). A sample list of available computer models is provided in Table 2-6. The computer models are periodically updated. The latest version of any modeling software should be obtained before developing planning and design criteria for a new desalination process.

Each of these models has a graphical user interface that allows the user to visualize the physical configuration of the system. They are instrumental in

- assessing the feed, product, and concentrate water quality;
- identifying limiting scalant and foulant;
- determining the anticipated recovery of the desalination process; and
- estimating energy consumption for the desalination process.

Supplemented by antiscalant manufacturers' projection models, these tools can be used to quantify the scaling and fouling potential and characterize the concentrate quality. Water quality inputs required for these models typically include TDS, conductivity, pH, calcium, magnesium, sodium, potassium, strontium, barium, ammonia, alkalinity, sulfate, chloride, fluoride, nitrate, orthophosphate, silica, iron, manganese, boron, and SDI.

TREATMENT LEVELS

Comparing raw water quality to the product water quality goals will determine whether desalination technologies are required. Assuming other means (e.g., water conservation, source salinity control, alternative sources, alternative treatment using lime softening or ion exchange) alone cannot meet the product water quality goals, desalination is determined to be inevitable. Concentrate management components must be included to properly handle the residuals generated from the desalination process.

Inland desalination and concentrate management typically involve multiple treatment and disposal steps to treat the various types of source water to meet the product

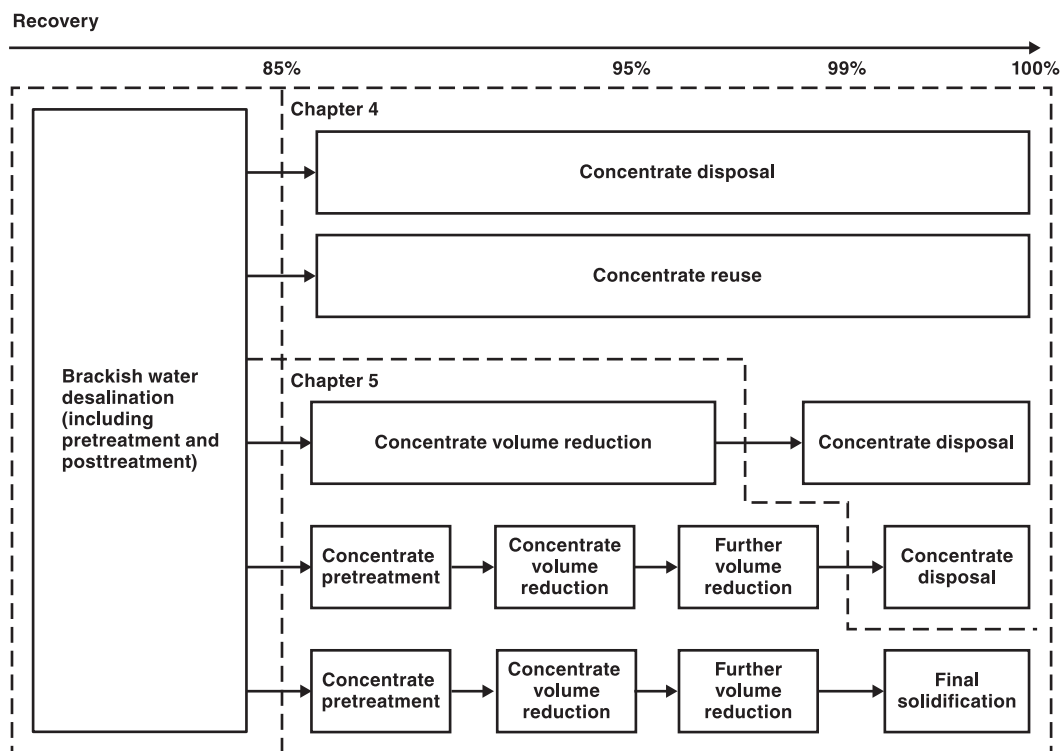


Figure 2-1 Treatment and disposal levels for inland desalination and concentrate management

Table 2-6 Reverse osmosis and nanofiltration design computer models

	Manufacturer	Model Name	Website
RO Projection	CSM	CSMPro V.5.0	www.csmfilter.com
	Dow Water & Process Solutions	ROSA V.8.0.3	www.dowwaterandprocess.com
	Hydranautics	IMSDesign V.2012.8	www.membranes.com
	Koch Membrane Systems	KMSROPRO V.8.06	www.kochmembrane.com
	LGChem (NanoH ₂ O)	Q+ V.2.0	www.lgwatersolutions.com
	Toray	TorayDS2 V.2.0.1.58	www.toraywater.com
	Trisep	TROI	www.trisep.com
EDR Projection	Suez Water Technologies	Winflows 3.1.2	www.suezwatertechnologies.com/resources/winflows
	Suez Water Technologies	Watsys 3.0.30	www.suezwatertechnologies.com

water quality goals. Figure 2-1 illustrates the levels of treatment using a general block diagram. Definitions of these treatment and disposal levels are as follows:

- Brackish water: Water having a mineral content in the range between freshwater and seawater. In water-desalting practice, brackish water is generally considered to be water containing 1,000–15,000 mg/L of TDS.
- Desalination or desalting: A water treatment process, such as distillation, RO, or ED, that removes dissolved mineral salts and other dissolved solids from water.
- Pretreatment: One or more actions or processes occurring immediately before water enters the downstream desalination treatment unit process.

- **Post-treatment:** The additional treatment of product water (i.e., distillate, permeate, or filtrate) from a desalination system to produce finished water that meets quality requirements, such as permeate post-treatment for corrosion control or disinfection following membrane desalting.
- **Concentrate disposal:** The process of ultimately discharging a reject stream, most often associated with desalination or membrane processes, to the environment. Concentrate disposal often involves ocean discharge, deep-well injection, or discharge to another receiving medium with a mineral concentration at least as high as the concentrate's concentration.
- **Concentrate reuse:** The reuse of concentrate for one or more purposes (e.g., dust control, cooling water makeup, wetland or habitat creation), generally only as part of a planned reuse scheme.
- **Concentrate pretreatment:** One or more actions or processes occurring immediately before concentrate from a desalination treatment process enters the downstream concentrate treatment process.
- **Concentrate volume reduction:** A concentrate treatment process that aims at reducing the volume of the concentrate by maximizing recovery of product water.
- **Further volume reduction:** A concentrate treatment process that aims at further reducing the volume of the concentrate by maximizing recovery of product water. This term is often used when multiple concentrate volume reduction technologies are involved in series to achieve high recovery goals.
- **Zero liquid discharge (ZLD):** Term used to describe the operation of a facility that results in no liquid discharge to a body of water. In desalting, this commonly refers to all liquid streams.
- **Final solidification:** A concentrate treatment process, such as crystallization, achieving ZLD by converting all dissolved solids in the concentrate into dry solids or crystal form.

TYPES OF BRACKISH WATER DESALINATION TECHNOLOGIES

Understanding the tools in the desalination and concentrate management toolbox helps planners to leverage the strength of each tool when developing site-specific solutions.

Processes used for brackish water desalination can be categorized as follows:

- pressure-driven membranes,
- electric potential driven membranes,
- thermal evaporation,
- ion exchange, and
- other emerging technologies.

Pressure-driven membrane separations include technologies such as RO and NF. These processes use hydraulic pressure to produce purified water from saline feedwater through a semipermeable membrane. Both NF and RO effectively remove inorganic and organic compounds and produce product water of superior quality. NF typically has lower operating pressure requirements than RO. NF is effective in removing TDS, hardness, and constituents with large-size molecules such as arsenic and bromide. But the overall salt rejection and the removal of nitrate, iron, manganese, volatile organic compounds, and emerging contaminants using NF are less than the rejection experienced with RO technologies. These technologies are further discussed in depth in Chapter 3, mainly as primary tools for inland desalination. Coupled with pretreatment addressing the limiting factors, they can also be used for secondary desalination (e.g., concentrate volume reduction,

as discussed in Chapter 5). Innovative pressure-driven membrane technologies also include vibratory shear-enhanced processing (VSEP), tubular RO membrane separation, and slurry precipitation and recirculation RO (SPARRO). Various improvements to conventional NF/RO membranes, configurations, and control strategies are also available, such as the closed circuit desalination (CCD) technology or reversible RO.

Electrically driven membrane separation technologies include ED and EDR. This category can be extended to include technologies such as electrodeionization and even nonmembrane processes such as capacitive deionization (CDI). In ED and EDR processes, an electric current migrates dissolved ions through an ED stack consisting of alternating layers of cationic and anionic membranes. Because it does not separate nonpolar substances, it is not as constrained by silica concentration in the feedwater. Because of the open-channel design of ED and EDR membranes, a significant level of suspended materials can be tolerated in the feedwater. However, this process is not a barrier to organics and is less suitable for primary treatment of water containing organics, pathogens, and other nonionic contaminants. A newly developed ED technology, electrodialysis metathesis (EDM), uses four solution compartments and four membranes—rather than two of each in the repeating units for ED or EDR. The employed membranes include both ordinary anion and cation exchange membranes and monovalent selective cation and anion exchange membranes. Chapter 3 discusses these technologies as primary desalination options. Chapter 5 further explores the benefits of using ED and EDR as viable concentrate treatment options for achieving near ZLD concentrate management.

Thermal evaporation-based processes include membrane distillation (MD), multi-effect distillation (MED), vapor compression distillation (VCD), and multistage flash (MSF) distillation. These technologies generally have higher capital and operating and maintenance costs than other desalination processes such as RO. If used for primary desalination, these technologies are generally used for industrial processes, especially when waste heat is available, and could be cost prohibitive for brackish groundwater applications at the municipal scale. However, they remain viable and often crucial for achieving ZLD concentrate treatment.

Emerging technologies include cutting-edge innovations that are currently in the research and development phase, such as membrane desalination cells, aquaporin membrane separation, adsorption desalination (AD), etc. These technologies are not a main focus of this manual but are briefly discussed in Chapter 9, *Technological Trends, Salt Recovery, and Beneficial Uses*.

Table 2-7 presents an estimated range of recoveries, treatment costs, and energy consumptions for treating a given source water using these categories of desalination technologies.

TYPES OF CONCENTRATE MANAGEMENT TECHNOLOGIES

Typical concentrate management technologies are presented in Chapters 4 and 5 of this manual. In Chapter 4, concentrate disposal options and reuse opportunities are discussed, including evaporation ponds, deep-well injection, sewer discharge, and surface water discharge.

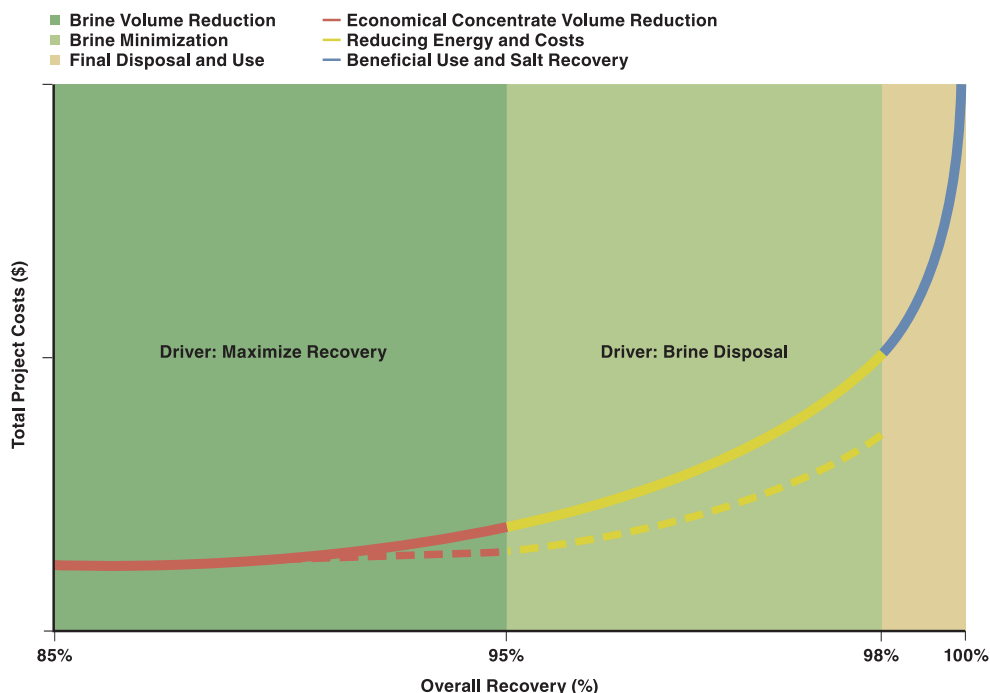
In Chapter 5, two main components of concentrate treatment are discussed. First, the concentrate from a brackish desalination process discussed in Chapter 3 may be conditioned, stabilized, or pretreated to address the limiting fouling and scaling issues and to be reduced in volume through secondary desalination technologies such as RO or EDR. This can typically enhance the overall brackish water desalination system recovery from 75–90 percent to 93–95 percent. The second component of concentrate management, referred to as “further volume reduction” in Figure 2-2, aims to increase

Table 2-7 Types of desalination technologies

	Pressure-driven Membrane Separations	Electrically Driven Membrane Separations	Thermal Evaporation Processes	Emerging Technologies
Examples	NF/RO, CCD, SPARRO, VSEP	ED/EDR, EDM, CDI, EDI	MSF, MD, MED, VCD, crystallizer	AD
Major Benefits	• Relatively high energy efficiency • Superior product water quality	• Less susceptible to fouling • Require lesser degree of pretreatment • More flexible operational control of product water TDS	• Ability to use waste heat • Excellent product water quality • Energy consumption relatively insensitive to TDS	• Potential higher recovery and lower energy consumption
Major Limitations	• Energy consumption increases with feed TDS • High scaling and fouling propensity • Require high level of pretreatment	• Energy consumption increases with feed TDS • Poor removal of nonionic contaminants	• Relatively higher energy consumption	• Still in research and development stage

AD—adsorption desalination, CCD—closed circuit desalination, CDI—capacitive deionization, ED—electrodialysis, EDI—electrodeionization, EDM—electrodialysis metathesis, EDR—electrodialysis reversal, MD—membrane distillation, MED—multi-effect distillation, MSF—multistage flash, NF—nanofiltration, RO—reverse osmosis, SPARRO—slurry precipitation and recirculation reverse osmosis, TDS—total dissolved solids, VCD—vapor compression distillation, VSEP—vibratory shear-enhanced processing

Brine Management

**Figure 2-2 Three strategic focuses for inland desalination and concentrate management**

overall freshwater recovery to 97–99 percent by using thermal brine concentrators or other innovative technologies such as osmotic brine concentrators incorporating forward osmosis technology. The most advanced brine volume reduction technologies allow achievement of concentrations approaching saturation of sodium chloride at around 200,000–300,000 mg/L TDS. Such brine concentration is typically followed by a final disposal step using small evaporation ponds or a final thermal solidification process using crystallizers and mechanical dewatering of the high-salinity waste stream.

PLANNING STRATEGIES

As mentioned previously, concentrate management is complex, affected by many factors, and involves multiple steps. There is no single technology or solution that can address challenges for all inland communities. Generally, the optimal solution is a combination of several technologies and strategies, customized in a way that site-specific restrictions and resources are considered.

Several key planning strategies for concentrate disposal, treatment, and management are briefly discussed subsequently to provide guidance for utilities to develop customized solutions. These strategies include but are not limited to the following:

- managing salinity proactively, leveraging regional resources, and forming partnerships;
- strengthening water quality databases and establishing an integrated water and salt balance model;
- combining technologies to form customized solutions;
- keeping track of new technologies; and
- tailoring product water quality.

Proactive Salinity Management

As easy as it is for salt to dissolve into water, it is difficult to remove salt from water. Most desalination technologies separate salt from water, which does not eliminate salt and results in a concentrate waste stream. For many inland communities, the concentrate is difficult to treat and manage. Water reuse, desalination, and concentrate disposal, if not well planned, could result in salinity buildup in the recycled stream and contamination of freshwater sources such as the aquifer. If not managed properly, salinity buildup will impact future water resources, resulting in costly treatment before water can be used for human, agricultural, or industrial consumption. Water utilities should proactively manage salinity before the situation worsens and expensive treatment remedies become inevitable.

Many utility companies have water conservation programs that educate customers not only on water use efficiencies but also on salinity issues (e.g., City of Fresno 2007). Such programs promote conservation of salt—using less and putting less down the drain—and may provide tips on how the public can personally contribute to salinity management by using liquid instead of powder laundry soap, using dryer sheets instead of liquid softeners, using mopping pads instead of a traditional mop and bucket of water, and sweeping instead of hosing down an outside area. Many programs promote the use of compost instead of chemicals and fertilizers and recommend more efficient alternatives to salt-based residential water softener units.

At the utility level, proactive salinity management could start with establishing a salinity management plan as part of the system-wide integrated water resource management plan. Early development and adoption of a salinity management plan will allow inland communities to minimize adverse impacts of salinity on economic growth. This effort

will help raise awareness of the significance of salinity management, bolster the utilities' long-term efforts, and identify critical gaps and “low-hanging fruit” opportunities. This plan will delineate a roadmap for utilities to manage water portfolios faced with salinity impacts, supporting development and protection of alternative water sources to reduce salinity impacts. Contents of the salinity management plan could vary among communities but typically include adding TDS in the industrial pretreatment program; establishing local limits on sensitivity ions such as sodium, chloride, boron, and selenium; continuing funding; embarking on data collection; planning and protecting new water sources; and considering alternatives to desalination such as water conservation, nonpotable reuse, and indirect and direct potable reuses. Prioritizing industrial development and agricultural activities will help prevent severe environmental issues.

Developing solutions to salinity problems can be challenging and expensive. Utilities should leverage national, regional, and local resources, and consider forming partnerships to combat salinity. Consider joining collaboration efforts such as those led by the Multistate Salinity Coalition, the Texas Water Development Board, the Central Arizona Salinity Study, the Central Valley Salinity Coalition, the Southern California Salinity Coalition, and others. Leverage funding opportunities and federal grants to support salinity management research. Stay connected and form partnerships to develop regional solutions on a larger scale.

Integrated Water Balance Model

Establishing an integrated water and salt mass balance model could provide many benefits for the planning and design of desalination and concentrate management facilities. Unlike the RO and EDR projection models, which are a more detailed analysis of one single process, such a model is designed to help utilities evaluate the system-wide impact and cost implications of salinity. Many planners typically utilize Excel to perform such mass balance calculations. For complex systems, more advanced water system models could offer better platforms to help utilities capture significant savings (Carollo Engineers 2017). This type of model integrates brine treatability evaluation, concentrate management optimization, water resources management, engineering cost estimates, financial analysis, etc., for better decision support. In the big data age, more and more utilities find themselves with a large volume of historical data (e.g., flows, TDS, conductivity, hardness, chlorides, etc.) but do not know how to leverage such information to optimize planning and concentrate management. These advanced decision-support tools fill in the gap. They leverage advanced computing techniques such as Monte Carlo simulation, scenario management (USBR 2012), full factorial analysis, and multi-objective optimization to help utilities develop customized desalination and concentrate treatment solutions that capture million-dollar cost savings (He 2018).

Whether a water and salt balance is established using an Excel spreadsheet or more advanced planning and design software, the ability to manage flow and water quality data—and compare that with demands and product water quality goals—is the first and most critical step toward identifying the concentrate treatment and management requirements, assessing alternative technologies, and developing and optimizing customized solutions. By tracking various flow streams in the whole water cycle as well as TDS and individual ions through the system, the planners and engineers can evaluate multiple desalination and concentrate alternatives side by side, optimize the configurations of the desalination and concentrate management systems, and tailor the product water quality to meet the needs in the most efficient way.

Combining Technologies to Form Customized Solutions

Because the source water qualities and the tolerance of the local environment to salinity and individual ions are different for each inland community, no single technology or any fixed combination of technologies can fit all brackish water desalination needs. As presented in Figure 2-1, many levels of treatment technologies and strategies must be involved to form a site-specific solution. Understanding the mechanism, strength, and limitations of each technology helps to leverage and combine them to achieve an overall solution. While the later chapters of this manual will provide more in-depth discussion on individual technologies, this section presents several strategies and principles on combining them into customized solutions.

As illustrated in Figure 2-2, the total project costs and efforts associated with inland desalination and concentrate management increase exponentially as the overall recovery increases. On this curve, three critical areas of concentrate management—brine volume reduction, brine minimization, and final disposal and use—should be given strategic emphasis when combining technologies to develop customized brine management solutions.

First, with the improvements in desalination technologies and the pretreatment, enhanced recovery (typically 85–95 percent) could be achieved relatively economically. Concentrate from the primary desalination steps could be reduced by half or up to two-thirds when applying technologies such as lime softening (Gabelich 2007), ion exchange softening, or organic pretreatment (Carollo Engineers 2013) before the secondary desalination using RO, NF, ED, or EDR.

One example to illustrate the value of this strategy is given subsequently. The recovery of brackish water RO is often limited by sparingly soluble constituents, such as silica, barium, strontium, and calcium. To maximize RO recovery, the limiting scale-forming constituents must be identified, removed, and/or controlled. This can be accomplished by maximizing scaling control using an optimized scale inhibitor dosing strategy (i.e., high doses of innovative scale inhibitor products with optimized pH control). However, the effectiveness of scale inhibitors could still be limited. For example, the RO recovery for a brackish groundwater desalination application in Phoenix, Ariz., was limited to 85 percent. When operating at 90 percent recovery with a dendrimer-type scale inhibitor at the maximum dose, the same RO plant performed better initially but showed scaling/fouling in the RO membranes after less than 30 days. Periodic membrane cleaning was not able to sustain permeate production (Carollo Engineers 2006).

Alternatively, removing the scale-forming constituents through a chemical precipitation (i.e., lime softening) step allowed higher recovery through a subsequent secondary RO system. For the same Phoenix application discussed previously, when calcium carbonate, magnesium hydroxide, and silica are removed using a solids-contact clarifier, an overall system recovery of 94–95.5 percent was achieved using a subsequent secondary RO system to recover more water from the softened concentrate (Carollo Engineers 2009, He 2010). Additional information about such technologies is provided in Chapter 5.

Second, achieving higher recovery (>95 percent) would require additional efforts to address several limiting factors. As the cost for producing water using these technologies are too high compared to conventional water production or desalination technologies, the main goal becomes brine minimization in lieu of enhancing recovery. The focus is to find technologies that can reduce the brine volume more economically than ZLD technologies such as thermal brine concentrators and crystallizers.

To achieve this goal, the power of multiple processes may have to be combined to address the limitations of a single technology. Using this principle, many commercialized concentrate treatment packages are basically combining various pretreatment and

desalination processes. For example, the High Efficiency Reverse Osmosis (HERO™) process uses lime softening and ion exchange to pretreat the feed for primary and secondary RO to maximize recovery. GE's AquaSel™ system combines EDR and chemical precipitation to recover approximately 95 percent or more product water. In this system, the EDR concentrate recirculation stream is diverted to a chemical precipitation reactor, where the limiting scale-forming ions (e.g., barium, calcium) are removed through chemical softening using chemicals such as lime, caustic soda, and/or soda ash. The softened concentrate is then returned to the EDR feed. By addressing the limiting constituents in the chemical precipitation step, higher recovery can be achieved without scaling the membranes.

Third, costs required to further reduce the concentrate volume and achieve ZLD become even higher. To offset such costs, attention is often given to turning the waste into a resource and recovering salt products from the last one or two percent of the concentrate. Technically, this is achievable but the feasibility highly depends on the marketability of the recovered products. Relevant technologies are discussed in Chapter 9 of this manual.

Keeping Track of New Technologies

Continuing innovations in desalination and concentrate management technologies provide opportunities for improved performance with reduced cost and energy consumption. In the past several decades, better antiscalant and antifoulant agents, more efficient pretreatment systems, and better membranes have been lowering the barrier for implementation of concentrate management facilities. Newly developed nanomodified membranes improved the energy efficiency of RO membranes while reducing the fouling potential. Mechanical improvements were implemented for conventional systems to improve the ability to handle higher concentrations and more aggressive applications. More advanced control strategies and system optimization, such as RO and CCD, provide opportunities to reduce desalination costs and concentrate volume for certain applications. New operation strategies such as predictive cleaning methodology reduce overall operation costs (Chesters et al. 2013). Refer to Chapter 9 for more details on such trends and developments.

Desalination and concentrate management often involve complex and expensive treatment and require long-term planning. Inland utilities combating salinity challenges should act proactively, act early, and keep track of the latest developments in desalination and concentrate management technologies. Although not all of these innovations are applicable for all communities, keeping apprised of industry trends and current best practices helps in formulating the right customized solution to local salinity challenges. Utilities should participate in local or regional salinity research and accumulate firsthand experience and data to prepare them for solving the complex challenge of salinity management. Given that the planning phase for a desalination plant often extends beyond five to ten years, technologies that are currently in the research and development stage could be mature and ready to implement as the planning and implementation phase proceeds.

Tailored Water Quality Using Technologies with Better Selectivity

Waters of differing quality are needed for different end uses, including drinking and cooking, irrigation of yards and public parks, urban lake replenishment, toilet flushing, groundwater recharge to replenish local groundwater, and water recycling for cooling towers and various industrial uses. Desalination technologies such as RO are effective in removing TDS and most contaminants but often cannot remove the target contaminants selectively. By tailoring water quality to meet different needs, utilities may capture cost-saving opportunities to reduce the use of RO and the generation of concentrate, conserve

energy, facilitate local water reuse, promote nutrient recovery, and have an overall lower carbon footprint.

When groundwater contains inorganic contaminants but the TDS is not high, RO or other desalination technologies may not be the best solution. This could also apply to developing non-RO-based treatment trains capable of producing water suitable for DPR. When applicable, utilities should consider employing alternative water treatment technologies (e.g., ion exchange, adsorption, EDR, softening, coagulation, granular media filtration, biological filtration, granular activated carbon, advanced oxidation) that can be used to replace, minimize, or supplement concentrate-generating technologies such as RO.

For reclaimed water recycling, tailored water quality makes sense when certain nonpotable reuse demands can be met without treating the product water to drinking water quality—at least not 100 percent of the stream. For example, if the product water is for irrigation, removing all ions and nutrients using RO and then applying more chemicals and fertilizers could be more sustainable. Also, water with lowered sodium concentrations is more suitable for irrigation, and water with lowered hardness is more ideal for cooling towers. To accomplish this, selected treatment technologies must be flexible enough to selectively remove target ions. In the planning and development of desalination and concentrate management facilities, technologies with the ability to selectively remove target contaminants deserve priority consideration, as they could help utilities meet the ultimate water supply goals more economically. Finding ways to tailor water quality to meet all needs requires sound engineering judgment and tools such as the advanced integrated water and salt balance model mentioned previously.

CONCLUSIONS

The following summarizes the key points discussed in this chapter:

- Evaluate the brackish source water quality and quantity as well as the characteristics of the contaminants limiting concentrate management options.
- Establish the most suitable treatment goals for the site-specific conditions of a given project.
- By comparing the water quality with the treatment goals, identify treatment requirements and limiting factors and provide a basis for the development of planning strategies.
- Several key planning strategies for concentrate disposal, treatment, and management can help utilities to develop customized solutions to salinity issues, including establishing a salinity management plan; collecting relevant water quality data; developing integrated water and salt balance models; and combining multiple technologies to overcome concentrate management challenges.
- Utilities should leverage national, regional, and local resources and form partnerships to combat salinity.

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