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Treatment of Concentrate



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14. ABSTRACT (<i>Maximum 200 words</i>) Approaches and technologies to treat membrane concentrate are identified and evaluated as a potential means of providing solutions to growing challenges of concentrate management. While most treatment schemes are yet too costly to implement for many municipal facilities, the report serves to identify needs, issues, promising technologies, economics, and practical considerations of concentrate treatment. The report reviews concentrate management options in general and in particular covers commercially available high recovery treatments including zero liquid discharge. Three commercial technologies are highlighted as having promise to impact concentrate management: selective salt recovery, electrocoagulation, and high shear membrane processing.					
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Treatment of Concentrate

by

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Technical Service Center
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Abbreviations and Acronyms

Al	aluminum
Ag	silver
As	arsenic
AZ	Arizona
Ba	barium
BC	brine concentrator
BDAT	best demonstrated available technology
Br₂	bromine
BOD	biological oxygen demand
BRO	brackish reverse osmosis
Ca	calcium
CaCl₂	calcium chloride
CA	California
CAPEX	capital expenditure
Cc	concentrate concentration
Cd	cadmium
CF	concentration factor
Cfo	feed concentration
CFR	code of Federal regulation
Cl	chloride
CO	Colorado
CO₂	carbon dioxide
Cr	chromium
Cs	cesium
d	day
DDT	dichlorodiphenyltrichloroethane
DWI	deep well injection
EC	electrocoagulation
ED	electrodialysis
EDR	electrodialysis reversal
EP	evaporation pond
F	fluoride
Fe	iron
FL	Florida
FO	forward osmosis

GA	Georgia
gpd	gallons per day
gpm	gallons per minute
I	iodine
HCO₃	bicarbonate
hr	hour
HRRO	high recovery reverse osmosis
H₂S	hydrogen sulfide
K	potassium
KCl	potassium chloride
kgal	thousand gallons
kWh	kilowatthour
KS	Kansas
L	liter
m	meter
MA	Massachusetts
MCL	maximum contaminant level
MD	Maryland
MF	microfiltration
mg	milligram
Mg	magnesium
MG	million gallons
MgCl₂	magnesium chloride
MGD	million gallons per day
Mg(OH)₂	magnesium hydroxide
mg/L	milligram per liter
MgSO₄	Magnesium sulfate
M	million
MO	Missouri
MTBE	methyl tert-butyl ether
MVR	mechanical vapor recompression
Na	sodium
NaCl	sodium chloride
Na₂CO₃	sodium carbonate
NaHCO₃	Sodium bicarbonate
Na₂SO₄	sodium sulfate
NC	North Carolina

NE	Nebraska
NF	nanofiltration
NH₃	ammonia
NORM	naturally occurring radioactive material
NPDES	National Pollutant Discharge Elimination System
NTU	nephelometric turbidity unit
O	
	oxygen
OK	Oklahoma
OPEX	operating expenditure
PA	
	Pennsylvania
pH	measure of acidity or alkalinity of a solution
PM	particulate matter
ppm	parts per million
r	
	rejection (membrane)
R	water recovery
RCRA	Resource Conservation and Recovery Act
RO	reverse osmosis
S	
	sulfur
SAR	sodium adsorption ratio
SC	South Carolina
Si	silicon
SO₄	sulfate
Sr	strontium
SRO	seawater reverse osmosis
S/S	solidification/stabilization
SSR	selective salt recovery
STLC	soluble threshold limit concentration
SWRO	seawater reverse osmosis
TCLP	
	toxic characteristic leaching procedure
TDS	total dissolved solids
TENORM	technologically enhanced naturally occurring radioactive material
TS	total solid
TTLC	total threshold limit concentration
TX	Texas
UF	
	ultrafiltration
U.S.	United States
USDW	underground source of drinking water

USEPA	United States Environmental Protection Agency
V	volt
VA	Virginia
WET	whole effluent toxicity
WWTP	waste water treatment plant
ZLD	zero liquid discharge
Zn	Zinc
~	approximately
>	greater than
<	less than
%	percent

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1. Executive Summary

The purpose of the project was to identify promising avenues for addressing the growing challenges of municipal concentrate disposal through examination of issues and options for further treatment of desalination concentrate.

Much of the work effort took place in 2003 and 2004. Results of the effort subsequently provided the framework, background, and impetus for other more recent work. Most of the project results have been previously discussed and presented (1, 2, 3, 4, 5, 6, 7, 8)¹ in some form. Further, results from the project have been used to influence/determine research needs (9). Some such projects have even been completed. The material, however, is still relevant in terms of framing the present and on-going challenges of concentrate management, and it is in this light that the report is offered.

1.1 Background and Reason for the Research

The conventional methods and challenges of disposing of municipal membrane concentrate are well documented (1, 2, 3, 6, 10). Of the approximately 234 municipal desalination plants operating in 2003 within the United States, the frequency (in percent [%]) of use of conventional disposal options was (2):

45%	disposal to surface water
27%	disposal to sewer
13%	disposal via deep well injection
8%	disposal via land application (spray irrigation, percolation pond)
4%	disposal to evaporation pond

These five conventional disposal options account for over 98% of the disposal cases. Among the conventional options, however, some are significantly limited in their geographic application; deep injection wells, evaporation ponds, and land applications have each occurred in only two or three States—due primarily to hydrogeological and climate requirements.

Increasingly, particularly in the arid Southwest United States, desalination plants are not constructed because cost-effective concentrate disposal options are not available. The research reported herein was performed to address the concentrate disposal challenges that are currently limiting the feasibility of siting and operating municipal membrane drinking water facilities.

¹ Numbers within parenthesis refer to respective number in the “Reference” section.

1.2 Project Objective

The project objective is to identify and preliminarily evaluate approaches and technologies available to treat membrane concentrate or pretreat membrane system feedwater, such that the treatment might increase the options available for concentrate disposal. Emphasis is placed on identifying technical and implementation issues and raising their visibility for future more detailed consideration.

1.3 Project Studies

Project studies included:

- Review and detailed characterization of conventional concentrate disposal options
- Review and characterization of other concentrate management options
- Identification of disposal options for brine and solids resulting from high recovery processing
- Characterization of issues associated with the selective recovery of salts
- Identification of technologies that might be used as part of treatment processing schemes
- Preliminary testing of electrocoagulation as a possible treatment technology
- Characterization of time-effectiveness of antiscalants

With the exception of laboratory tests addressing the time effectiveness of antiscalants and the treatment effects of electrocoagulation, the project research was nonlaboratory in nature.

1.4 Summary of Results

The project work revealed that there are promising options for further treatment of concentrate that may yield future solutions to meet the increasing challenges of concentrate disposal. Cost reduction is a major need before most of these options can be incorporated into municipal membrane desalination facilities. Categories of concentrate management options include:

- Conventional disposal options
- Nonconventional disposal options

- Beneficial use of concentrate
- High recovery (including zero liquid discharge [ZLD]) processing of concentrate
- Selective salt recovery from concentrate (most often a high recovery process)

1.4.1 Conventional Disposal Options

There are only a limited number of conventional concentrate disposal options. As mentioned, over 98% of the municipal membrane desalination plants in the United States dispose of concentrate by five conventional disposal options. Some of the options are very geographically dependent, with deep injection wells, evaporation ponds, and land applications each being used in only two or three States for municipal concentrate disposal. With growing challenges to concentrate disposal (regulatory, environmental, larger plant size, public perceptions, etc.), alternative disposal options will be increasingly needed to assure widespread application of municipal desalination technologies. There are no high recovery or selective salt recovery operations at municipal water treatment sites.

1.4.2 Beneficial Use of Concentrate

Options for beneficial use of concentrate (and of brine and solids derived from concentrate) are very limited (4). The conventional disposal option of land application includes some instances of using concentrate for irrigation. Aside from this, several other beneficial uses can be listed, but they are not widely available, are mostly unproven, many times do not represent a means of disposal but transfer the disposal task to another entity, and may compete with less expensive means of meeting the applications. Concentrate use (or brine or mixed solids from concentrate) is complicated by the fact that each concentrate is site-specific. Many potential applications are approved only for products having passed environmental tests and/or meeting industry standards. Unless some treatment is done to produce a concentrate, brine, individual, or mixed solids to meet product or application standards and do so in a manner yielding cost-competitive products, the uses may be unavailable.

While beneficial use options are not promising, they should be considered in every site-specific review of options as overall management options are limited. One promising direction that is discussed in a stand-alone chapter is selective recovery of commercial grade salts from concentrate.

1.4.3 High Recovery (including ZLD) Processing of Concentrate

Various definitions of ZLD have been used in recent desalination literature. The recommended definition is the original one and the one used in the ZLD industry: ZLD means that no liquid leaves the plant boundary. The term ZLD does not

imply what technologies are used or whether the final waste is solid or liquid. When the final waste is liquid, it typically is sent to an evaporation pond within the plant boundaries.

The term 'high recovery' processing is commonly used within the desalination industry to refer to a second membrane stage operating on first stage concentrate. High recovery, however, is attainable by other technologies. ZLD processes are high recovery processes with the restriction that no liquid leaves the plant boundaries. ZLD processing is, thus, a subcategory of high recovery processing.

It is important to note that, as of 2007, there are no high recovery (including ZLD) facilities at municipal sites due to the high costs involved. There are approximately 120 ZLD systems operating in nonmunicipal industries. Early systems were thermal-based and included using evaporators (brine concentrators and possibly crystallizers or spray dryers). More recent ZLD systems include mixed membrane/thermal systems and membrane (only) systems. All ZLD systems are high recovery systems where no liquids are discharged across the plant boundary. ZLD processing includes final steps of taking brine to solids or disposal of brine in onsite evaporation ponds.

At the start of the project, the hypothesis was that further treatment of concentrate by high recovery processing may result in defining alternative concentrate disposal options.

Early project considerations showed that increased concentrate salinity associated with increased recovery generally makes concentrate more incompatible (in terms of TDS and constituents species) with receiving waters and reduces the feasibility of surface water discharge, disposal to sewer, and land application of concentrate. Thus, disposal of high recovery brine by three of the five conventional disposal options (and ones that historically account for about 85% of the disposal situations occurring with municipal desalination concentrate) are likely no longer possible. While this leaves the conventional disposal options of deep well injection and evaporation ponds, these options are not widely available.

With some exceptions, the general options available for disposal of brine and mixed solids from high recovery processing include:

For brine:

- Deep well injection
- Evaporation ponds
- Solidification and disposal of solids to landfill

For mixed solids:

- Disposal to landfill

Thus, the only ‘new’ disposal option resulting from the project review is the typically costly option of disposal of solids to landfill. Selective salt recovery is a means of reducing the amount of solids, in brine or as solids, requiring disposal (as well as reducing the environmental footprint and reducing disposal costs). Disposal of any remaining wastes, however, is generally restricted to those listed for brine and mixed solids.

Analysis revealed that, besides the more typical ZLD processing technologies (thermal brine concentrators, thermal crystallizers, spray dryers, RO, and evaporation ponds), there are emerging commercially available patented technologies for high recovery processing of concentrate. Thus, technical feasibility of high recovery processing is not an issue.

Additional processing of concentrate is costly, and the various technologies used in other industries are, in general, too costly for municipal application. The elevated costs of high recovery processing result from both high capital cost and high operating costs. Some processing approaches with lower capital costs have higher operating costs such that annualized costs remain high. Operating costs are typically high from either high energy requirements or high chemical usage and high solids disposal costs. Cost reductions will be necessary before using high recovery technologies in most municipal settings.

Review of pathways to cost reduction suggested that recovery of individual salts in commercial grades for market (selective salt recovery) is worth considering. Preliminary exploration of this possibility and its promise is one of the primary findings of the report.

The challenges thus associated with high recovery processing plants include:

- Reducing the capital and operating costs associated with processing
- As with concentrate, finding available and cost-effective disposal options for the final wastes

1.4.3.1 Regulatory Issues

There is a regulatory issue associated with high recovery processing that is usually not a concern with conventional desalination processing. The high recovery processing may produce concentrate, brine, or mixed solids that can contain contaminants at a level rendering the waste to be hazardous or of sufficient radioactivity to be of concern. Because of this possibility, it is important to conduct a detailed water quality analysis of concentrate (as opposed to feed water) to pick up contaminants that might be present in low levels in feed but upon significant concentration may be present at problematic levels.

1.4.4 Selective Salt Recovery

As mentioned, one potential approach to reducing costs is selective salt recovery (SSR), where individual salts are harvested in commercial grade qualities and marketed. Income from the sale of one or more salts can offset other operating costs and reduce the environmental impact. Removal of salts reduces the amount of salts left for disposal. Removing carbonate species can also help reduce the process carbon dioxide (CO₂) footprint.

Examination of the issues involved with selective salt recovery suggests that the approach is quite feasible. This position is further supported by identifying a company that has patented, developed, and licensed technology, outside of the United States, to selectively recover salts from a wide range of waste waters (11). Ultimately, widespread success will require the local manufacture of value-added products from recovered salts.

1.4.5 Review of Nonconventional/Emerging Technologies

Various technologies were reviewed for their potential application in municipal concentrate treatments. Promising technologies include Geo-Processors' SAL-PROCTM (selective salt recovery processing), New Logic Research's VSEPTM (high recovery membrane processing), and Powell Water System's version of electrocoagulation (for pretreatment to remove contaminants and suspended solids). A look at the sequencing (order) of desalination process steps revealed some surprising, nonintuitive benefits. Most of these approaches have been incorporated in high recovery processing patents.

1.4.5.1 Bench-scale Testing of Electrocoagulation

Laboratory testing of electrocoagulation demonstrated significant potential for removing contaminants and suspended solids from feed water (or concentrate). Energy requirements for electrocoagulation decrease with increasing salinity (solution conductivity); and, thus, the technology is likely most cost-effective treating concentrate (or brine) as opposed to feedwater.

1.4.6 Antiscalants

Preliminary studies aimed at devising a simple method for utilities to use to indicate remaining time-effectiveness of antiscalant in concentrate were unsuccessful. This was due to lack of reproducibility within the framework of using simple equipment.

2. Introduction

As stated in the executive summary, the purpose of the project was to identify promising avenues for addressing the growing challenges of municipal concentrate disposal through examination of issues and options for further treatment of desalination concentrate.

The project objective is to identify and preliminarily evaluate approaches and technologies available to treat membrane concentrate or pretreat membrane system feedwater, such that the treatment will increase the options available for concentrate disposal.

The need for such a study was based on the clear realization that new approaches and new alternatives to concentrate disposal will be needed to address a growing number of challenges. To further define the particular needs and to better frame the project evaluation tasks, a more detailed analysis of conventional disposal options (than had previously been done) was undertaken. Insights from this evaluation helped to focus other general project tasks. In this manner earlier tasks influenced later tasks; and as a result, the project ‘evolved’ along directions suggested by findings. As a consequence of this, findings occurred throughout the project and were communicated via several presentations (1, 2, 3, 4, 5, 6, 7, 8) during the course of the project.

Much of the research effort took place in 2003 and 2004. Results of the effort subsequently provided the framework, background, and impetus for other more recent work. Most of the project results have been discussed previously and presented in some form. Further, results from the project have been used to influence/determine research needs and projects (9), some of which have been completed. The material, however, is still relevant in terms of framing the present and ongoing challenges of concentrate management; and it is in this light that the report is offered. The report is aimed at clarity rather than detail, as it is the clear identification and distinction of issues and directions that are needed to support more detailed future research to develop new management alternatives.

2.1 Project Tasks

In the course of the investigation, several categories of treatments were defined to bring clarity to the landscape of possible treatments. These categories include:

- Reuse of concentrate
- High recovery (including zero liquid discharge [ZLD]) processing of concentrate
- Selective salt removal from concentrate
- Contaminants removal from concentrate

Each of these categories was reviewed and evaluated as to the impact on ultimate concentrate disposal.

Specific studies undertaken included:

- Review and detailed characterization of conventional and other concentrate disposal options
- Identification of technologies that might be used as part of treatment processing schemes
- Characterization of issues associated with the selective recovery of salts
- Preliminary testing of electrocoagulation as a possible treatment technology
- Characterization of time effectiveness of antiscalants

With the exception of laboratory tests addressing the time effectiveness of antiscalants and the treatment effects of electrocoagulation, the project research was nonlaboratory in nature.

2.2 Report Content

Chapter 3 contains a review of the five conventional concentrate disposal options. Chapter 4 discusses the broader topic of concentrate management options in order to bring clarity to this relatively new subject area. Chapter 5 looks at one of the newer management options, selective salt recovery. Chapter 6 reviews some technologies that may have potential to be part of high recovery (including ZLD) processing. Results for bench-scale testing of one of the promising pretreatment technologies, electrocoagulation, are discussed in chapter 7. Regulatory issues associated with further treatment of concentrate are addressed in chapter 8. Chapter 9 discusses the results of a laboratory study to better define remaining antiscalant longevity in concentrates. Finally, chapter 10 presents project conclusions, and chapter 11 presents project recommendations.

3. Review of Conventional Disposal Options

3.1 Background – Municipal Desalination

The disposal of concentrate from advanced water treatment processes has been well documented (1, 2, 3, 10, 12). At the start of 2003, 431 municipal membrane plants of size 25,000 gallons per day (gpd) or greater had been built in the United States. This included 234 desalination plants using reverse osmosis (RO), nanofiltration (NF), and electrodialysis/electrodialysis reversal (ED/EDR) technologies and 197 low-pressure plants utilizing ultrafiltration (UF) and microfiltration (MF) technologies(2). Figure 3.1 illustrates the growing number of plants with time, and figure 3.2 shows the number of different types of desalination plants that had been built. Only 4 percent (%) of the desalination plants are seawater reverse osmosis plants, with only the Tampa Bay plant being larger than 2 million gallons per day (MGD) in size.

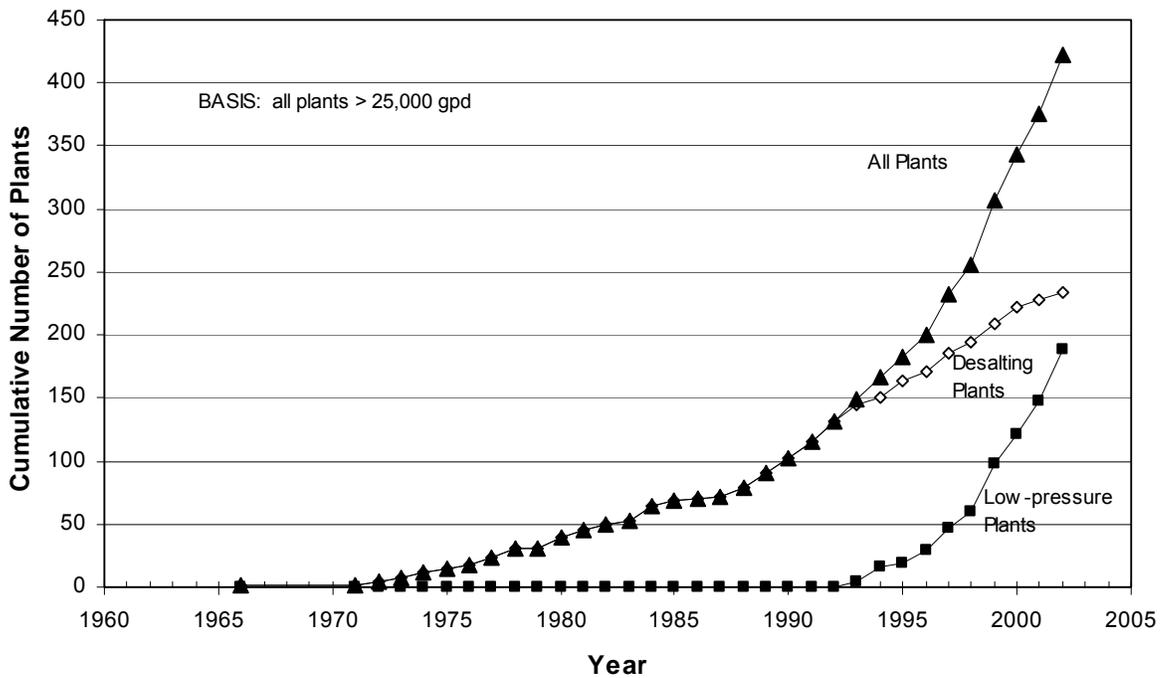


Figure 3.1 Cumulative number of municipal membrane plants by year with capacity greater than 25,000 gpd.

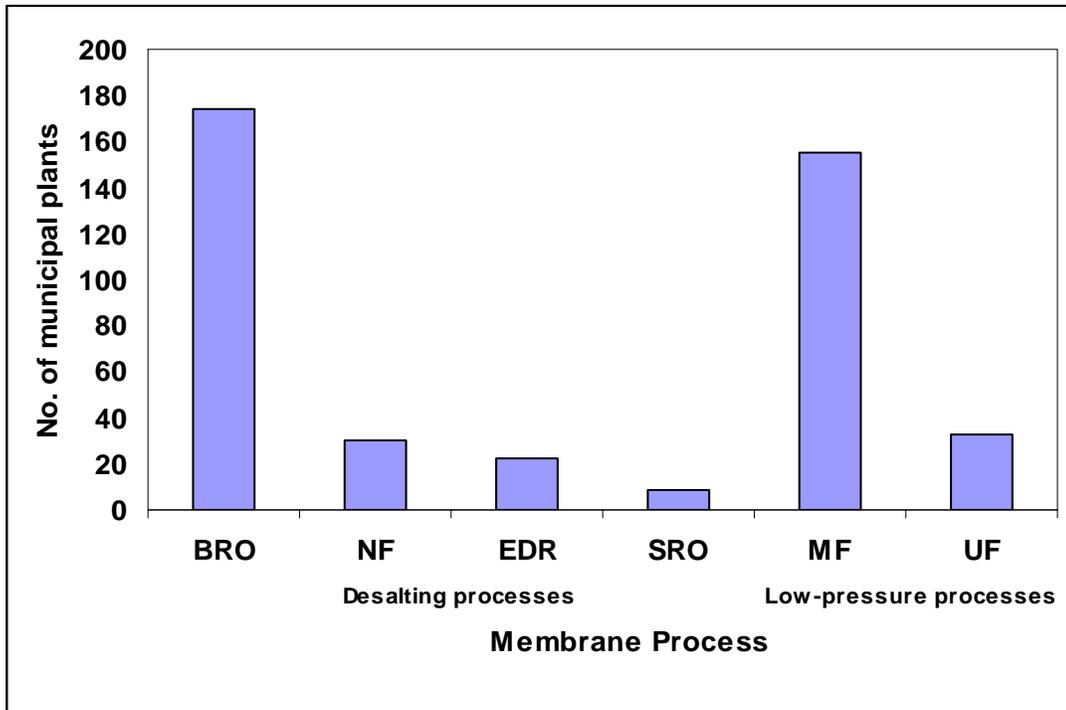


Figure 3.2 Numbers and types of municipal membrane plants built through 2002.

Figure 3.3 shows the number of operating desalination plants (total of 234) by State. Florida has the most plants with 114, followed by California with 33, and Texas with 20. The number and location of desalination plants have changed dramatically between 1993 and 2003. In 1993, municipal desalination plants existed in only 13 States, with Florida having 61% of these plants. As of 2003, 25 States have desalination plants. Of the plants built from 1993 to 2003, only 28% of the plants were in Florida. The growing size of plants (and, thus, of concentrate volume) with time may be seen in figure 3.4. Of the desalination plants built prior to 1993, many were smaller than 0.1 MGD and few greater than (>) 6 MGD. This situation is reversed for plants built between 1993 and 2003.

An unpublished estimate (13) added another 36 desalination plants under construction since the last survey and through the end of 2004. Of these plants, 10 were in Florida, 8 in California, and 5 in Texas—as these States continued to be the centers of desalination activity. No other States added more than two new desalination plants during this time period (PA-2, OK-2, MO-1, GA-1, NC-1, KS-1, MD-1, CO-1, SC-1, NE-1, and VA-1).

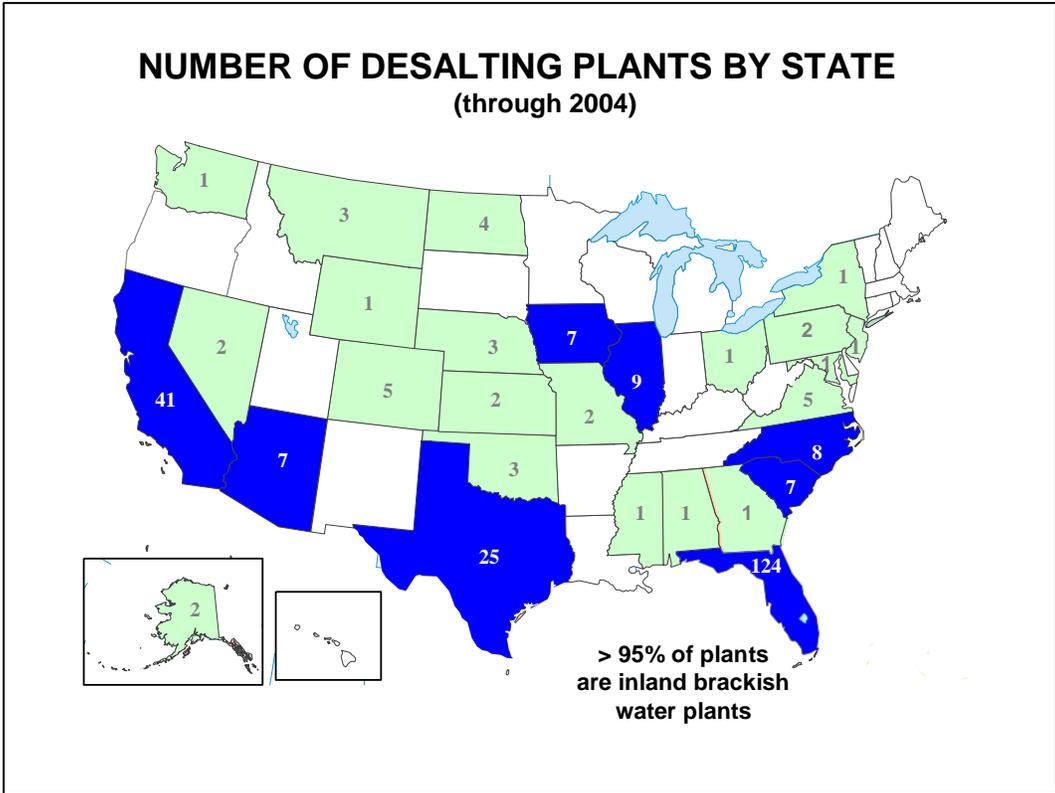


Figure 3.3 Number of municipal desalination plants by State.

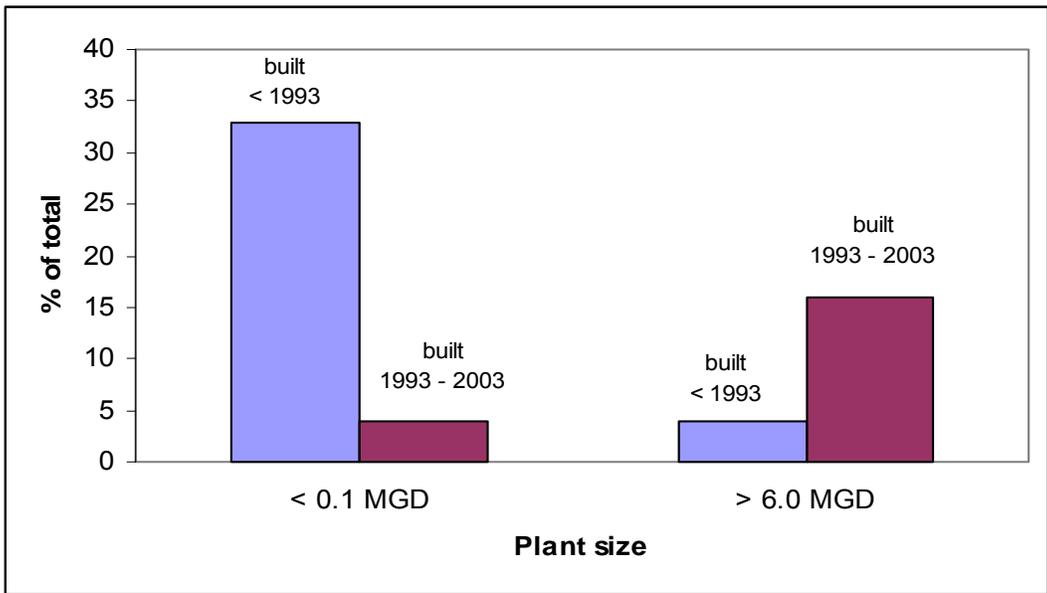


Figure 3.4 Changes in desalination plant size before and after 1993.

3.2 Nature of Concentrate

In general, membrane desalination processes produce a product water of total dissolved solids (TDS) lower than the feedwater and a waste stream of higher TDS than the feedwater. For pressure-driven systems, such as RO and NF, the waste stream is referred to as concentrate. For electrodialysis systems, combined nonproduct streams typically are referred to as waste. For the purposes of the present discussion, EDR waste is considered to be similar to concentrate. Some common characteristics of desalination concentrates are:

- They are of higher salinity than the feed water.
- They contain higher concentrations of most feedwater constituents.
- Concentrate water quality is site specific because raw water and feedwater are site specific.
- Concentrate is composed mainly of raw water constituents with some process-added chemicals. Process-added chemicals may include:
 - Acid (sulfuric or hydrochloric)
 - Antiscalant (synthetic chemicals)
 - Residual chemicals from other pretreatment steps
 - Chlorine
 - Dechlorinating species (such as sodium bisulfite)

Due to the relatively low levels of these chemicals in concentrate, concentrate reflects the composition of the raw water and has been described as ‘raw water concentrated.’ Environmental concerns, however, usually are associated with the increased salinity of concentrate, the increased concentrations of species present in the raw water, and the concentrations of process-added chemicals.

The concentration factor, CF, relates the concentration of a given constituent in the concentrate to the feed concentration by the relationship (10):

$$CF = C_c/C_{f0} = (1 - R)^{-r} \quad (1)$$

Where CF is the concentration factor:

- C_c is the concentration of the constituent in the concentrate stream
- C_{f0} is the concentration of the constituent in the feedwater stream
- R is the fraction of water recovery
- r is the average fraction of the constituent rejected by the membrane

For seawater RO (SWRO) membranes where ion rejections are close to unity ($r = 1$), the concentration factor relationship simplifies to the more familiar form:

$$CF = C_c/C_{f0} = 1/(1 - R) \quad (2)$$

This expression can be used to estimate concentrate levels for ions and TDS for SWRO processes. Due to the slightly lower but still very high ion rejections of brackish RO (BRO) membranes, the expression is also useful for BRO processes.

For NF membranes where rejection of monovalent ions is considerably less than unity, individual ion and TDS concentration factors cannot be estimated in this way without the risk of considerable error. Readily available membrane system software should be used to predict NF concentrate characteristics, which can also be used to predict SWRO and BRO concentrate characteristics.

Table 3.1 defines the typical feed TDS range and recoveries for NF, BRO, and SWRO systems.

Table 3.1 Typical operating ranges for NF and RO processes¹

Membrane system	Feed TDS range (mg/L)	Recovery (%)	Minimum concentrate TDS (mg/L)	Maximum concentrate TDS (mg/L)
NF	<1,000	90+	<1,000	² ~12,000
BRO	1,000–20,000	60–85	2,500	³ ~70,000
SWRO	20,000 and above	30–60	~28,000	⁴ ~70,000

¹ Milligrams per liter = mg/L; less than = <; approximately =~.

² Assuming 97% recovery and TDS rejection of 70%.

³ Typically limited by solubility of sparingly soluble salts and silica—even when acid and antiscalants are used. Higher membrane system recoveries and higher concentrate TDS levels are possible only with treatment to remove the limitation of scaling by sparingly soluble salts and silica or by processing with membrane systems that allow precipitation to occur (see chapter 6).

⁴ Limited by osmotic force considerations.

From this table the differences between NF, BRO, and SWRO concentrates become more apparent. Specifically:

- The volume of concentrate relative to feed volume is much greater for SWRO than for BRO and NF.
- The concentrate salinity is typically much greater for SWRO than for BRO, with NF concentrate typically of low salinity relative to BRO concentrate.

Concentrate management possibilities and practices differ according to concentrate characteristics. These characteristics are somewhat different for SWRO, BRO, and NF concentrates. With 96% of the municipal desalination plants inland, the following sections focus on BRO concentrate. Seawater and NF concentrate are mentioned periodically when it is important to make distinctions.

3.3 Five Conventional Concentrate Disposal Options

3.3.1 Size-related Limitations

These five traditional disposal options account for over 98% of the disposal situations. Figure 3.5 shows the frequency of use of these disposal options based on plants built by 2003. Surface water disposal (106 plants or 45%), disposal to sewer (63 plants, 27%), and disposal via deep well (31 plants, 13%) together account for 85% of the disposal situations. Figure 3.6 shows this same information broken out by size of plant with the size ranges of less than 1 MGD, between 1 and 6 MGD, and greater than 6 MGD. Characteristics of the disposal options reflected in figure 3.6 include:

- Surface water disposal is used widely regardless of plant size.
- Sewer disposal is used less frequently as the desalination plant size increases due to impacts of the higher volume and higher salinity concentrate on the waste water treatment plant (WWTP) operation. These include effects on biological components and on the effluent salinity from the WWTP.
- Deep well injection (comprising nearly all of the subsurface injection cases) is used infrequently with small plants and more frequently with larger plants due to a relatively high cost for a small-sized well and a strong economy of scale resulting in lower unit costs for larger wells.
- Land application (irrigation, percolation pond, rapid infiltration basin) is used only with small plants due to the lack of economy of scale and high land requirements and associated costs.
- Evaporation ponds are similar to land application in lacking economy of scale and having high land requirements and unit capital cost.

Plant sizes in figures 3.5 and 3.6 are presented in terms of product water with small, medium, and large plants assigned sizes of less than 1 MGD, between 1 and 6 MGD, and greater than 6 MGD, respectively. Inland brackish water plants typically have recoveries between 60 and 85 percent. For the purpose of this paper, we assume that the concentrate flow in small plants is smaller than 0.43 MGD (300 gallons per minute [gpm]), which corresponds to a recovery of 70% in a 1-MGD plant.

Table 3.2 shows the percentage of plants using each disposal option for the two periods, prior to 1993 and from 1993 to 2003. Note that the number of plants disposing concentrate to land and to evaporation pond decreased from 18 to 4% from the first to the second period. The primary reason likely is related to the significant increase in plant size, as reflected in figure 3.4., and the low frequency use of these two disposal options with larger size plants, as reflected in figure 3.6.

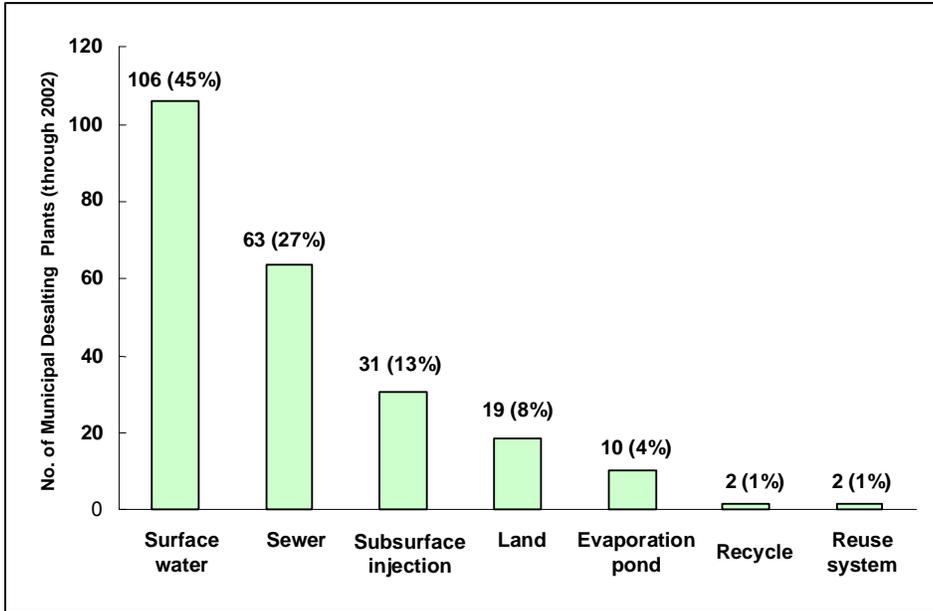


Figure 3.5 Prevalence of concentrate disposal options.

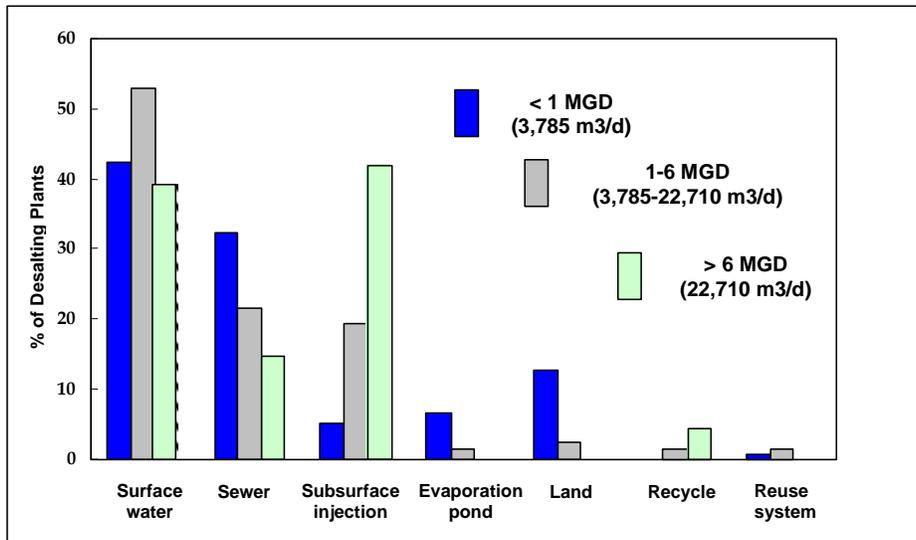


Figure 3.6 Prevalence of concentrate disposal options by size of desalination plant.

Table 3.2 Prevalence of concentrate disposal options for two time periods

	Less than 1993 (%)	1993–2003 (%)
Surface discharge	48	42
Sewer	23	34
Injection	12	15
Land application	12	2
Evaporation pond	6	2
Other	0	4
Total	101	99

3.3.2 Geographic Limitations

Frequency-of-use statistics presented in is figure 3.6 and table 3.2 are somewhat misleading in that the availability of these conventional disposal options is site specific, with rarely more than one or two options possible at a given location. Further, the availability of many of the options is regional, reflecting the following facts:

- Surface water disposal is not readily available in the arid Southwest.
- Deep well injection is not possible everywhere due to the lack of adequate hydrogeological conditions necessary for such wells, and some States do not permit deep well injection of industrial waste.
- Land applications require relatively level ground and warmer climates to allow year-around operation and are not permitted in many locations that have underlying aquifers regulated by nondegradation requirements.
- Evaporation ponds similarly require relatively level ground and warmer climates.

For the 203 (of the 234) desalting plants built by 2003 that are inland BRO, NF, or EDR plants located at drinking water facilities (thus, eliminating water reuse WWTPs), the number of States using the different disposal options is as shown in table 3.3.

Of the disposal cases *not* using surface water or sewer, 84% are in Florida, 9% are in Texas, 2% in California, and 2% in Arizona. Only three States have used evaporation ponds, and only two States have used deep well injection and land application. As these statistics reflect, using specific disposal options is highly regional.

Table 3.3 Disposal options used by plants built by 2003 and number of States using the option

	Number of Plants	Number of States¹
Surface discharge	97	17
Sewer	51	15
Deep well injection (DWI)	26	2 (FL-25, CA-1) ²
Land application	20	2 (FL-18, TX-2)
Evaporation pond	9	3 (TX-5, FL-3, AZ-1)

¹ Abbreviations for individual States are listed in the Abbreviation and Acronym list at the front of this document.

² Texas recently became the third State with DWI being used at the Kay Bailey Hutchinson Desalination Plant (Ft. Bliss).

3.3.3 Interim Summary of Conventional Disposal Parameters

- The number and size of desalination plants continue to increase.
- Five conventional disposal options account for over 98% of the disposal situations.
- Discharge to a surface water or the sewer account for 72% of the cases nationwide but 100% of the cases for 21 of the 25 States having desalination plants.
- The other three conventional disposal options (deep well injection, land application, and evaporation ponds) have limited widespread application, primarily due to hydrogeological and climate requirements.
- Site-specific availability of multiple options is typically very limited.
- The challenge for conventional concentrate disposal is thus framed by two factors:
 1. Size: The increasingly larger volumes of concentrate further reduce the feasibility of each of the conventional disposal options. This point is reflected in figure 3.6 for four of the options with the exception being deep well injection. Sections 3.3.4.1 and 3.4 discuss size-related limitations in greater detail, including those related to deep well injection.
 2. Geography: Significant limitations in local availability of disposal options (regardless of concentrate volume).

3.3.4 Other Characteristics of Conventional Disposal Options

Distance from a desalination plant to the disposal site is a site-specific variable that is typically different for each available disposal option. Conveyance costs (pumping, pipeline, and right-of-way costs) can be an important cost factor in

determining cost-effectiveness of any disposal option. Since conveyance issues and costs are independent of specific disposal options, they are not included in the following discussion. In the following sections, major characteristics are discussed. The following sections review characteristics of the five conventional disposal options. A later section (3.11) summarizes disposal option characteristics in tabular form.

3.3.4.1. *Surface Water Discharge*

Discharge to surface waters is typically the simplest and least expensive disposal option—when it is available. Potential costs include minor pretreatment, such as pH adjustment, and an outfall structure.

Surface water discharge feasibility generally increases as the ratio of concentrate flow to receiving water flow decreases and as the salinity of concentrate decreases. Concentrate compatibility with the receiving water is the major issue for determining whether surface water discharge is a feasible option. This situation is regulated by the permitting process, National Pollutant Discharge Elimination System (NPDES), which includes receiving water standards and mixing zone policies.

In most situations, it is desired to discharge concentrate to a receiving water having a lower TDS or lower concentration in one or more constituents. In waters where strict nondegradation regulations apply, discharge may not be allowed. In other waters, the river segment considered for receiving the discharge may have receiving water standards for TDS and individual constituents greater than the actual ambient levels. In this case, the receiving water has some capacity to take on increases in TDS or individual constituents and, thus, discharge may be allowed. The exact calculation method used in making these decisions can vary from State to State. Frequently, mixing zones are allowed where local instream levels of TDS or individual constituent levels are permitted to exceed instream standards, as long as adequate mixing and dilution within the receiving water zone result in a blended water that meets instream standards. In these situations, the receiving water salt load, in terms of TDS concentration or some individual constituents, increases. The receiving water then has less capacity to take on additional increases in TDS or the same individual constituents from other discharges. Future additional discharges from other entities are, thus, more restricted.

3.3.4.2 *Disposal to Sewer*

Discharge permits under the NPDES program are not required for discharges to sewers. However, permission is necessary from the receiving WWTP. A fee may be charged based on the perceived impact of the concentrate on the WWTP operation. General feasibility of disposal to sewer increases as the ratio of concentrate flow to WWTP influent flow decreases and as the salinity of the

concentrate decreases. Since most WWTP effluents discharge to surface waters, salt loading or compatibility with other constituents becomes an issue here, as with direct discharge to surface water.

3.3.4.3 Deep Well Injection

In the United States, membrane concentrate is classified as an industrial waste. The industrial waste classification is used within the United States Environmental Protection Agency (USEPA) as part of the industrial classification codes. One category of industrial waste is municipal drinking water plant waste. While the historical origin of this classification is unclear, even to several USEPA officials the author has talked to, the classification itself is quite clear and is used throughout USEPA and, consequently, by the States.

As an industrial waste, concentrate requires a Class I well for disposal. Class I wells utilize aquifers that are structurally isolated from overlying drinking water aquifers (defined as any aquifer having TDS less than 10,000 mg/L). Monitoring requirements stipulate a tubing and packer arrangement that prevents direct leakage of concentrate from the well. The injection tubing is surrounded by an annular space between it and the casing string. This space is filled with a monitoring fluid that is tested for changes in salinity to monitor leaks. Total cement casing is also required. These requirements (wells below the drinking water aquifers, tubing/packer arrangement, total cement casing) add considerable cost to the injection wells. Shallow monitoring wells are also required. The general requirements for a Class I disposal well include:

- Depth – The injection zone must be below the depth of potential drinking water sources (known as the underground source of drinking water [USDW] depth).
- Layering – The receiving aquifer needs to be hydraulically confined and isolated from overlying drinking water aquifers.
- Salinity – The receiving water aquifer must have a TDS greater than 10,000 mg/L.
- Receiving aquifer capacity – The capacity must be large enough to accommodate the projected volume of concentrate over the life of the desalination plant. Aquifer capacity is determined by the porosity and permeability of the receiving formation; these two characteristics determine the maximum injection rate for an individual well.
- No seismic activity – While there are historical incidents of earthquakes associated with deep well disposal, they generally are correlated with high injection pressures used to obtain higher injection rates—pressures typically greater than fracture pressure. Injection pressures for Class I wells are generally much less than fracture pressures; therefore, seismic activity is usually unlikely unless wells are located in a fault zone.

Extensive front-end costs may be involved in conducting hydrogeological studies, drilling test holes, performing an environmental review, doing geophysical studies, drilling a pilot well, etc.—all before the option is determined to be feasible. While costs associated with deep well injection can be considerable, there is a good economy of scale, and deep well injection is generally an increasingly favored disposal option for larger concentrate flows in a single well. As discussed below, however, single well injection rates may be limited by aquifer characteristics.

Although DWI of concentrate is only allowed in Class I wells, many utilities and researchers have suggested that concentrate could or should be re-classified by regulators to permit disposal in other types of wells (38). Other potential well classifications that have been considered for injection of concentrate include:

- Class II well injection – for enhanced oil recovery
Class II wells are for oil and gas operations only. However, if the concentrate is nonhazardous, it may be possible to inject it along with produced water to maintain reservoir pressures. A factor in making this option not generally feasible is the need for the injection site (sites) to be available over the entire life of the desalination plant.
- Class II well injection – for disposal only
Using Class II wells for disposal of industrial wastes is currently not legal. However, in some States, there is movement towards defining a Class I/II situation.
- Class V well injection
This option may become possible in some States if concentrate TDS (and other constituents of concern) is less than the receiving aquifer TDS and if the concentrate is nonhazardous. This approach was used at the Kay Bailey Hutchinson Desalination Plant (Ft. Bliss) in El Paso, where Class V wells were built to the more restrictive Class I standards.

Although DWI is widely discussed, its application for municipal desalination concentrate is quite limited. Nearly all of the existing deep wells are located in Florida where parts of the State have near-ideal hydrogeological conditions, more ideal than in any other part of the United States. Well descriptions in a national deep well data base (14) provide the injection capacities of all existing Class I deep wells—not just the few used for municipal concentrate disposal. Table 3.4 shows the largest capacity Class I well in each of several States.

Table 3.4 Largest Class I wells in various States

State	Size of Largest Class I Well (MGD)
Florida	22
Texas	3
North Dakota	0.9
Oklahoma	0.7
Illinois	0.6
Wyoming	0.5
Louisiana	0.43
Michigan	0.36
Kansas	0.3

It can be seen that the Florida well of 23 MGD is much larger than the 3-MGD Texas well and the largest wells in other States. In many States, the largest well is less than 0.3 MGD. Injection rate of a single well is limited by the permeability and porosity of the subsurface formation. Aquifers with lower permeability and porosity—and, thus, lower injection rates per well—may require multiple wells. As permeability and porosity decreases, the spacing of the wells increases.

The deep well aquifer must be able to receive concentrate over the life of the desalination plant. Reservoir capacity can, thus, further limit total injection rate (concentrate flow).

Costs aside, because of the well size limitations, it is more feasible to dispose of smaller concentrate flows than larger flows in many States. There are several States, however, where suitable hydrogeological conditions do not exist and/or deep well injection of industrial waste is prohibited.

Deep disposal wells are required to undergo periodic mechanical integrity testing. In Florida, where most injection sites consist of a single well and when desalination plant operation is not to be interrupted, an alternative permitted disposal option is required when the well is taken out of service. Where multiple injection wells exist, the need for an alternative permitted disposal option may not exist.

3.3.4.4 Evaporation Ponds

Where climate (high net evaporation rates) and land requirements (inexpensive, level land) can be met, evaporation ponds are a potential concentrate disposal option. Evaporation pond acreage and costs, however, are usually high, even for small concentrate flows. Table 3.5 lists the existing municipal desalination plant sites (as of 2004) utilizing evaporation ponds. The plant sizes are all very small.

Table 3.5 Municipal membrane plants as of 2002 using evaporation ponds

Location	Plant Type	Size (MGD)
Buckeye, AZ	EDR	1.5
Terlingua, TX	BRO	0.05
Experanza, TX	BRO	0.058
El Paso, TX	BRO	0.08
Lucien, OK	MF	0.12
Sarasota, FL	BRO	0.2
Los Ybanex, TX	BRO	0.022
Austin, TX	BRO	0.144

The reason for this can be seen by looking at land requirements and pond costs. A high net evaporation rate (such as possible near Las Vegas) for the life of an evaporation pond might be 2 gpm per acre. If the volume of concentrate were 0.3 MGD (200 gpm), the nominal land requirement would be over 100 acres. With evaporation pond costs ranging from \$100,000 to over \$400,000 per acre, the capital cost could range from \$10–40 million.

In colder climates, evaporation ponds may be operable only during part of the year. In this situation, winter cold season storage or an alternative disposal method is needed during those months when the pond is not operating.

There are several types of enhanced evaporation systems that take advantage of the increased evaporation possible through increasing the exposure of the impounded concentrate to air. Some approaches used include spraying or misting the water into the air, letting the water fall through the air, or saturating a cloth material and exposing it to the air flow. These methods have not achieved commercial success for municipal concentrate but have the potential to reduce required land area and capital costs. Operational concerns include drift onto adjacent property, wind sensitivity of the enhanced evaporation effect, safety concern with frozen mist in winter, and higher energy costs. In the best of conditions, the various enhanced evaporation systems increase the net evaporation rate (reduce the evaporative surface area required) by a factor of 5 to 7. The savings in required land area are offset somewhat by an increased capital cost per acre for the enhanced evaporation equipment.

In a recent Ft. Bliss, Texas, evaluation (Kay Bailey Hutchinson Desalination Plant) conducted for 3.2 MGD of concentrate, using enhanced evaporation (using a Turbo-mist evaporator) was projected to decrease capital costs of evaporation ponds by 46% and increase operating costs by 330% (15). The evaporation area was reduced by a factor of 5.2. In this case, the capital cost per acre of the enhanced evaporation system is significantly greater, but this is more than compensated for by the reduced acreage required.

3.3.4.5 Land Application

Like evaporation ponds, land application is best suited where climate is favorable (allowing year-round operation) and where level and suitable land is available. The primary difficulty with land applications is that the concentrate discharge needs to meet State and local ground water protection regulations based on the salinity and use classification of the underlying ground water. Direct discharge of concentrate is rarely possible. Typically, concentrate must be diluted prior to discharge in order to meet the regulations, and the volume of dilution water required can be several times that of the concentrate. The diluted concentrate, now larger in volume, can require substantial land for discharge. In a similar manner as described with surface water discharge, land application of concentrate may increase TDS and other constituent levels of the underlying ground water up to regulatory limits. Future additional discharges will be more limited as the capacity of the underlying ground water to take on additional TDS or individual constituent loads is decreased. In colder climates, cold season storage of concentrate or an alternative disposal option may be required for several months.

3.4 Influence of Size on Disposal Option Availability

In this section, the effects of concentrate flow are considered. Salinity effects are addressed in section 3.5.

Figure 3.6 showed the prevalence of the five conventional disposal options as a function of plant size, and section 3.3.1 briefly discussed the general reasons for this. Following the more detailed discussion of concentrate disposal issues just provided, this section discusses size-related limitations of the disposal options in more detail. Table 3.6 reflects how the general feasibility of the five conventional disposal options changes with desalination plant size (and, thus, concentrate size). [Although not discussed until chapter 4, the final column of table 3.6 applies to high recovery processing.] Plant size and concentrate size (flow) increase from left to right. The divisions between the general plant size groups are somewhat arbitrary but are reasonable and useful in illustrating the size issues. Evaporation pond and land application options are feasible only for very small-sized municipal desalination plants; and, as plant size (concentrate flow) increases, these options become costly and are generally no longer feasible. Furthermore, at some point, discharge to sewer is no longer feasible due to impacts on the WWTP. Eventually, only deep well injection and surface discharge remain as possible options; and as we have seen, deep well injection is not widely available. In the arid Southwestern United States, surface discharge is not a viable option, except for small plants.

There are two aspects to how concentrate size affects disposal feasibility. The first has to do with the concentrate flow size relative to a given disposal option size (i.e., the capacity of the disposal option). As the size of concentrate flow decreases, there is a greater chance of each of the disposal options being

Table 3.6 General feasibility of disposal option relative to concentrate flow (assumes options are otherwise available)

General Plant Size	Feasibility of Conventional Processing*					High Recovery Processing
	Very Small	Small	Medium	Large	Very Large	All Sizes
Plant size (MGD)	< 0.15	0.15 to 1	1 to 6	6 to 15	>15	all sizes
Concentrate size (MGD)	< 0.06	0.06 to 0.4	0.4 to 2.6	2.6 to 6.4	> 6.4	all sizes
Concentrate size (gpm)	< 45	45 to 300	300 to 1,785	1,785 to 14,870	> 14,870	all sizes
Surface discharge	yes	yes	yes	depends ⁶	depends ⁶	no ⁷
Sewer discharge	yes	yes	yes	no ⁴	no ⁴	no ⁷
Deep well injection	yes	yes	yes	depends ⁵	in FL (?) ⁵	depends ⁸
Evaporation pond	yes	depends ¹	no ³	no ³	no ³	depends ⁹
Land application	yes	depends ²	no ³	no ³	no ³	no ¹⁰

*Arbitrarily based on 70% recovery.

¹ Land and capital cost can be significant.

² Land, dilution water, distribution system, and associated costs can be significant.

³ Land cost can become prohibitive.

⁴ Dependent on salt load but at some level impact to WWTP becomes significant and unacceptable.

⁵ In States other than Florida, multiple wells would be needed. As individual well size becomes more limited, typically, the wells need to be further apart. If many wells are required, a distribution system is needed, and costs escalate due to complexity of the system.

⁶ As concentrate flow increases, the impact on receiving water increases and at some level discharge is no longer feasible.

⁷ High salinity in high recovery system brine will be limiting in most situations.

⁸ Reduced volume (flow) of the brine may make deep well injection more feasible; saturated salts and high salinity are concerns in terms of reservoir plugging and unwanted blending effects.

⁹ High salinity can reduce the evaporation rate up to 50% and result in evaporation ponds filling up more rapidly with solids; in turn, this may result in the need for solids removal or new, additional ponds.

¹⁰ High salinity requires significant quantity of dilution water.

feasible—assuming hydrogeological, climate, and other technical factors do not preclude the disposal options. The second aspect has to do with the number of potential disposal sites as a function of flow quantity. In general, more disposal sites are available for a given option as the size of the concentrate flow decreases.

Not reflected in table 3.6, but equally important, is the salinity of the concentrate—particularly for the options of surface water discharge, discharge to sewer, and land application. Feasibility increases greatly with decreasing concentrate salinity, as there is less impact on the receiving media.

3.5 Salinity-Related Limitations

Desalination of brackish and seawater resources has increased as freshwater resources have become utilized to capacity. At any given site being considered for a desalination plant, generally the lowest salinity alternative available water source is targeted for use, providing other quality parameters are reasonable. For brackish water/inland plants, the range of salinity of ground water used as source water has varied significantly from situations employing NF desalination with feedwaters of 500 to 1,000 mg/L salinity to RO desalination with feedwaters of up to 14,000 mg/L. Most of the higher salinities occur on islands where ground waters are ultimately in contact with surrounding seawater and are, thus, of higher salinity. Disposal of concentrate is, in nearly all such cases, directly to the sea. Inland plants on the mainland have had feed salinities up to 3,000 mg/L (2). It is likely that the upper range of salinities considered for inland desalination will increase with time due to 1) consideration of desalination plants in areas not previously considered and 2) exhaustion of higher quality source waters.

Salinity of concentrate is related to the salinity of feedwater. The salinity constituents concentrations in the feedwater determine the recovery possible in a single stage membrane unit and thus the concentrate salinity. Feedwater composition aside, concentrate salinity generally follows feedwater salinity. Increased concentrate salinity usually has the following influences on conventional disposal options:

- **Surface Discharge:** Decreased compatibility with receiving water (certainly in terms of TDS but also frequently in terms of individual constituents). Increasing salinity limits the allowable concentrate flow (assuming some level of discharge is possible) and reduces the likelihood of finding suitable receiving water.
- **Sewer Disposal:** Decreased compatibility with receiving water (other influent flows); greater potential impact on WWTP microorganisms and greater impact on WWTP effluent salinity. Increasing salinity further limits the allowable concentrate flow (assuming some level of discharge is possible) and also reduces the likelihood of finding a WWTP with sufficient capacity.
- **Deep Well Injection:** Increased concern with corrosion; increased concern with possible aquifer plugging issues. As concentrate salinity increases, constituent concentrations also increase. Upon blending/mixing with aquifer water, the higher constituent concentrations may push the blend closer to saturation/precipitation limits for various salts, increasing the probability of precipitation and possible plugging of the reservoir.
- **Land Application:** Decreased compatibility with ultimate receiving water (ground water); greater amount of dilution water required if land application is possible. Increasing salinity reduces the allowable

concentrate flow quantity (assuming some level of discharge and blending is possible) and the likelihood of finding a suitable application site.

- **Evaporation Pond:** Decreased net evaporation rate; shorter time to filling the pond with solids. Net evaporation rates for high salinity brines can be as much as 50% lower than freshwater rates. Lower net evaporation rate increases the amount of evaporative area required for a given concentrate flow quantity. An even greater effect, however, is that higher salinity concentrates will more quickly fill the pond with solids. If ponds fill during the life of the desalination plant, this will lead to additional costs associated with removing solids from ponds and land filling them OR of covering the ponds over and replacing them with new ponds.

The availability, permitability, and costs of conventional disposal options are generally favored by lower salinity concentrate.

3.6 Other Concentrate Disposal Challenges

While disposal options are site specific, until the late 1990s, one or more of the five conventional options (surface water discharge, disposal to sewer, deep well injection, land application, evaporation ponds) were available to nearly every site/location considered.

More recently, there have been trends toward larger plants and consideration of plants in locations where disposal options are not as available (namely the arid Southwest and the Denver Basin). These trends have increased the challenges of finding a suitable disposal option. The challenge also is complicated by increasingly more stringent regulation and increased public concern, both of which may result in increased costs associated with the permitting phase and less likelihood of obtaining a permit. Greater volumes of concentrate due to increased number of plants in a given region complicates disposal in a manner similar to increased volume of concentrate due to increased plant size.

As stated in section 3.3.2, there are limitations in local availability of options regardless of concentrate volume. The increasingly larger volumes of concentrate, in general, further reduce the feasibility of the traditional disposal options (refer to figure 3.6).

Conventional disposal options will continue to play an important role in many locations and be cost effective. However, there are a growing number of locations where the time, effort, and cost of implementing conventional disposal options is increasing due to the above factors.

In recent years, there has been increased concern over concentrate representing a lost water resource for the desalination utility. In some evaluations of concentrate disposal options at large water utilities having considerable infrastructure, a cost

has been assigned to the concentrate equal to the cost of obtaining water rights to replace the same volume of this ‘lost resource.’ The concern has also increased attention on volume reduction of concentrate (discussed in the next chapter).

Disposal of concentrate to surface waters, to the sewer, and to land applications may result in salt loading of the receiving water—as described in section 3.3.4.1. Although discharge may be acceptable from the perspective of not violating regulatory standards for the receiving water and being able to secure disposal permits, various constituent concentrations and salinity of these waters may increase. Future additional discharges by other entities become more limited, as there is less capacity of the receiving water to uptake TDS or individual constituents while remaining within receiving water standards. At some point, future additional discharges may not be possible. Increased use of these options for disposal is ultimately not sustainable.

3.7 Conventional Disposal Options’ Capital Costs

Cost reduction of traditional disposal options is unlikely because their economic feasibility is less dependent on technology and equipment than on the nontechnical factors and limitations discussed above. Further, the equipment-related costs are unlikely to decrease due to their simple nature. Equipment, in addition to conveyance equipment of pumps and pipe, may include:

Surface discharge:	Possible pretreatment, outfall structure, diffuser
Sewer:	Possible pretreatment
Deep well injection:	Possible pretreatment, injection wells (casing, tubing, cement, etc.), monitoring wells
Land application:	Possible pretreatment, land preparation, possible blending equipment, sprinkler/distribution system, storage for rainy days
Evaporation pond:	Possible pretreatment, land preparation, liners, monitor wells

While the cost of desalting water using membrane technologies has decreased, the cost of disposal has not—giving rise to the disposal costs becoming an increasing percentage of total plant cost.

Desalination literature has been slow in recognizing the distinction between treatment costs and disposal costs. Most current literature still uses the term ‘desalination costs’ to mean treatment costs and discusses the reduction in ‘desalination costs’ over the past several years, neglecting the increasingly limiting issues and costs of concentrate disposal.

3.7.1 Cost of Options

Capital and operating costs for disposal increase with size of concentrate flow. Smaller flows, however, will lose any economy of scale that might be available for larger flows; and, thus, unit capital costs are either similar or higher for smaller flows.

DWI is costly for small flows but has a large economy of scale, making it more attractive for larger flows (reflected in figure 3.6). On the other extreme, evaporation ponds and land applications (such as vegetation irrigation) have low economies of scale and are used only for small flow situations—becoming cost-prohibitive for large flows. Conveyance (piping and associated pumping) have a large economy of scale, resulting in lower per volume costs for larger flows.

Figure 3.7 depicts the relative cost of the different disposal options for most situations (7). The highly variable and site-specific costs of conveyance of concentrate to the site of disposal are not included. There are many exceptions to this representation because concentrate has site-specific characteristics; available disposal options are site specific, and the above limitations, while not eliminating feasibility, may play a role in determining the cost of that disposal option for any particular location.

Design parameters and preliminary cost models for the conventional disposal options are provided in a Bureau of Reclamation publication (2).

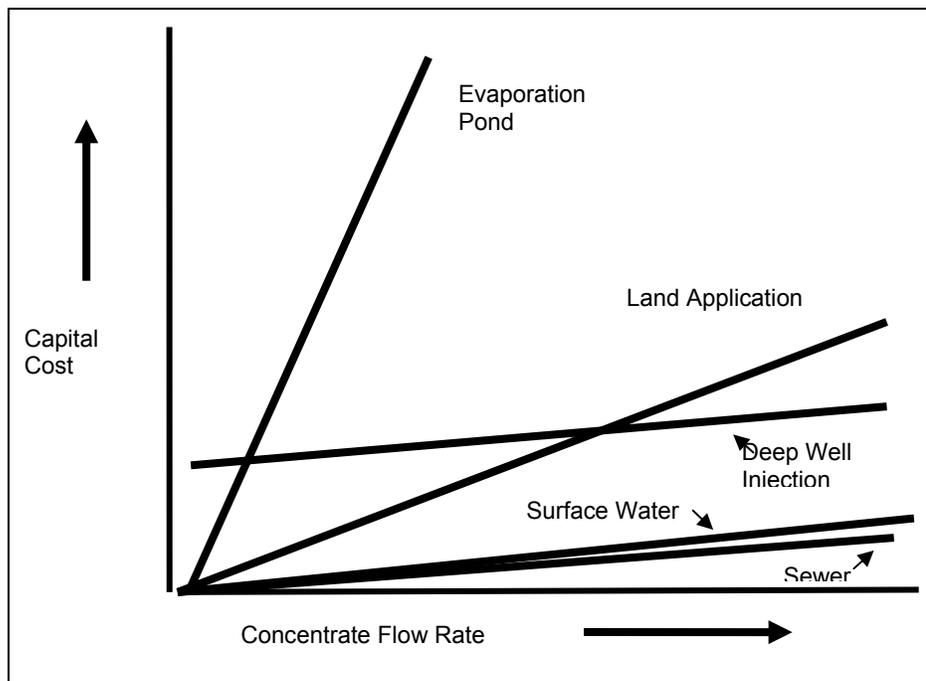


Figure 3.7 Relative capital costs of conventional disposal options.

3.8 Interim Summary of Challenges to Conventional Disposal Options

- Availability of conventional disposal options is limited by several factors, including:
 - Site-specific hydrogeology, geographics, and climate
 - Quantity of concentrate
 - Concentrate salinity
- Challenges to finding feasible conventional concentrate disposal options include:
 - Increasingly more stringent regulations
 - Increased public concern
 - Increased size of desalination plants (i.e., greater quantity of concentrate)
 - Increased number of desalination plants in a given region
- While conventional disposal options will continue to play an important role in many parts of the United States, there are a growing number of locations, particularly in the arid Southwest and the Denver Basin, where these disposal options are not possible or cost effective for which alternative disposal options are needed.
- Other issues impacting the need for development of alternative disposal options include:
 - Increased concern for concentrate being a lost water resource
 - Realization of longer-term need to develop sustainable technologies/solutions
- The cost-related challenges of concentrate disposal are much different from those of desalination processing as limitations on disposal options include factors other than cost, such as regulatory requirements, climate, land availability, hydrogeological conditions, etc.
- Costs reductions in equipment associated with concentrate disposal will be minimal due to the low-tech nature of the equipment involved.
- As a result, while membrane treatment costs have been decreasing, concentrate disposal costs have not.

3.9 Seawater Desalination Concentrate Disposal

Seawater concentrate is considerably different from brackish RO concentrate in terms of salinity and volume. Due to the coastal location, the obvious and conventional disposal option for seawater concentrate is to return it to the sea (i.e., surface water discharge). The high salinity and large volume of the concentrate generally preclude using the other conventional disposal options.

Critical factors involved in potential environmental impacts from brine discharges to the sea include (16, 17):

- The nature of the local eco-systems
- The extent of mitigation measures taken
- The volume of the discharge
- The local currents—or more broadly, the mixing and flushing conditions of the receiving water

The environmental concerns include those due to both salinity of the concentrate and the constituents present in the concentrate. Potential impacts from undiluted concentrate may be from:

- Constituents present in the feed water; some raw water components are modified or removed as a result of pre-treatment.
- Higher concentration of these components than the receiving water; thus higher salinity.
- Residual chemicals from the pretreatment process; most pretreatment chemicals are removed as a result of sedimentation and filtering, but residuals remain.
- Heavy metals from intermittently used cleaning solutions and from equipment, pipe, and pump materials.
- Other components from cleaning solutions, such as acid, base, detergents, complexing agents, enzymes, etc.
- Chlorine from disinfection.
- Dechlorination chemicals, such as sodium bisulfite from dechlorination.
- Lower dissolved oxygen, as a result of dechlorination chemical use.
- Organohalogen compounds formed from interaction of chlorine with naturally occurring organic material.

- pH difference from receiving seawater.
- Antiscalant.
- Temperature difference from receiving seawater.
- Time variations in the above.

Some receiving seawaters are high energy, providing much mixing and dispersion; others are low energy such as in more confined bays that have long time periods for flushing. To minimize the compatibility issues, many new seawater desalination plants are using cooling water from powerplants or effluent from waste water treatment plants for dilution of the concentrate prior to discharge. Other advantages of this co-siting arrangement include shared use of intake and outfall structures and consequent easier permitting path.

While most organisms can adapt to minor changes in salinity (and other conditions) or temporarily manage higher deviations, the continuous discharge of higher saline effluent to seawater, may be harmful to marine life. The individual concentrate properties also have potential effects on the marine environment, and their effects may be additive or synergistic.

Most components of concentrate have a limited dispersal range so that the environmental effects are restricted to the discharge site (near-field) and its more immediate vicinity (far-field). The environmental fates include chemical changes (e.g., chlorine), transport into sediments (e.g., heavy metals), ingestion/uptake (by flora and fauna), and dispersion/dilution. Most residual chemical concentrations in the concentrate are relatively low but may eventually amount to heavy loads due to the large concentrate volumes produced (17).

A major factor in determining the level of impact is the receiving water condition. From both simulation of and measurements in receiving waters for discharges in waters of limited mixing, the concentrate discharge forms a distinct mass characterized as a plume that originates at the discharge outlet and grows and disperses away from the outlet in the direction of net receiving water movement. The concentrate is of higher salinity and higher density and, thus, negatively buoyant. The plume sinks and spreads along the sea floor, affecting the less mobile benthic organisms. The extent to which this will occur is dependent on the depth of the sea floor relative to the sea surface and the mixing/dispersion conditions of the receiving water. In a high energy receiving water of greater depth, impacts will be minimized. In a low energy receiving water of shallow depth, impacts will be heightened. Using diffusers at the end of the discharge pipe can increase mixing and dispersion and can help to mitigate impacts.

3.10 Nanofiltration Concentrate Disposal

Typically at the other salinity extreme, NF concentrate is of low enough salinity and low enough volume for several traditional disposal options to be feasible. In particular, surface water disposal, disposal to sewer, and land applications usually have fewer compatibility issues than are associated with discharge of BRO concentrate.

3.11 Other Topics Related to Concentrate Disposal

3.11.1 Presence of Contaminants

Care must be taken in early feasibility studies to address the presence of contaminants in concentrate. A particular challenge that may increasingly occur is where concentrate contains a level of contaminant (arsenic, selenium, radionuclides, pesticides, etc.), such that treatment and removal may be necessary prior to concentrate disposal. This may result from treatment of lower quality source waters and could significantly increase disposal cost.

Examples where contaminants have occurred naturally include:

- Radionuclides in ground water in southwest Florida, which occur at levels that would prevent discharge of the concentrate to surface water. The availability of deep well injection has mitigated this problem.
- Hydrogen sulfide in ground water that must be removed prior to surface water discharge of the resulting concentrate. Degasification of concentrate is now routinely used when this situation occurs.

Contaminants present at acceptable levels in ground water and concentrate may result in a hazardous waste when they are processed to high salinity brine or solids. Naturally occurring radionuclides are of concern in this regard (6). These issues are discussed more fully in chapter 8.

3.11.2 Major Ion Toxicity

Major ion toxicity is possible in concentrates originating from ground water. As with other toxicities, it is determined in whole effluent toxicity (WET) tests that are sometimes required for surface water discharge permits. Occurrence of major ion toxicity is dependent both on the test organism used (some organisms are more sensitive than others) and the concentrate water quality. Major ion toxicity (18) of the concentrate may occur when common ions are present in very high (or very low) concentrations relative to those in a receiving water having the same overall salinity. Seawater may be considered to be ‘balanced’ in terms of major ion composition with respect to most biological systems, and major ion toxicity appears to occur when a water has a composition ‘imbalanced,’ in terms of major ions, relative to seawater. The toxicity has occurred most frequently in Florida

with the very sensitive mysid shrimp test organism and high calcium and/or high fluoride levels. A case of very low potassium amount was also identified. Fortunately, the toxicity has sharp thresholds, and dilution of the concentrate by a factor of 4 or 5 typically negates the toxicity.

3.11.3 Economics of Water Utilities Versus That of Other Industries

Water is an undervalued commodity, and water utilities that produce it have substantially different purposes, goals, and financial where-with-all than most other industries. Consequently, the cost of treatment and disposal that can be afforded by most nonmunicipal industries is significantly greater than what water utilities can afford. A direct reflection of this is using costly, high recovery (including ZLD) processes in other industries while there are no municipal applications of these technologies. More generally, disposal situations affordable to many other industries are cost prohibitive to water utilities.

3.11.4 Desalination Concentrate, Brine, and Solids as Industrial Wastes

The current industrial classification of municipal concentrate is misleading and detrimental. The classification combines concentrate with a variety of other industrial wastes, many of which are toxic, hazardous, and of significantly greater environmental concern. Concentrate has relatively few process-added chemicals and, thus, still retains the general nature of the starting raw water—only more concentrated. Many industrial wastes, however, are characterized by their process-added chemicals. The classification has had two major negative effects on concentrate disposal. First, public perception of concentrate is that of a generic industrial waste, which is commonly equated to a toxic, hazardous waste. Public concerns at the time of permit application review can influence the permitting process and outcome. Second, in most States, regulations governing the disposal options are not specific to municipal desalination concentrate but instead apply to a broader category such as industrial wastes. As discussed in section 3.2, concentrate is different from most industrial wastes. The specific nature of concentrate usually is taken into consideration in the regulatory process in some ways, but the framework for regulation may result in concentrate being evaluated from the perspective of regulations developed for other wastes. There is movement in some States to develop regulations specific to municipal desalination concentrate. The result may simplify the regulatory process, reduce associated costs, and allow some disposal situations to occur that otherwise may not be possible.

3.11.5 Concentrate Management Versus Concentrate Disposal

There are good reasons for using the broader and more general term ‘concentrate management.’ Public perceptions are influenced by names and terms, and the term ‘concentrate disposal’ implies that concentrate is indeed a waste. Public perceptions of industrial wastes, as just discussed, are negative. The term

‘concentrate management’ supports distinguishing concentrate from industrial waste by implying that it is or can be a resource. Thus, the term ‘concentrate management’ is helpful from a public relations perspective. Use of the term has also fostered increased consideration and research of beneficial uses of concentrate in an attempt to find alternatives to disposal. Indeed, this project is an exploration of concentration management options with a focus on further treatment of concentrate.

From another perspective, however, use of the term ‘concentrate management’ has clouded the reality of the situation and has led individuals/groups to think new and cost-effective alternatives to disposal are simply a matter of searching and researching.

Beneficial use of concentrate is discussed in section 4.2, where it will be seen that there are very few uses of concentrate or of brine and mixed solids produced from concentrate. Section 4.3 considers high recovery (including ZLD) processing of concentrate, another major concentrate management tool. High recovery processing has not been used at any municipal site due to high costs. It will be seen that high recovery processing leads to only one new disposal option—that of landfill of solids. This option may result in siting desalination plants where otherwise none can exist due to the lack of other disposal options—but it is an expensive option; and, in general, the costs of high recovery processing will need to be substantially reduced before high recovery processing can be more routinely used in municipal settings.

While these statements are getting ahead of the report chapter sequence, they point out that in reality: 1) presently nearly 100% of the municipal desalination plants dispose of their concentrate without beneficial reuse and 2) in the future, this percentage will remain very high. Consequently, the term ‘concentrate management’ may imply more than can be delivered.

When concentrate is considered from the perspective of a waste to be disposed, some useful insights are forthcoming. All wastes are disposed of unless they can be beneficially used (not a widely available opportunity with concentrate) or can be transformed into useful products. It is from this last possibility that a new alternative to concentrate disposal emerges. Selective recovery of commercial grade salts from concentrate is a technically viable option that has been researched, developed, and licensed outside of the United States. Selective salt recovery is the subject of chapter 5.

3.11.6 Limited Availability of Information

There is a growing wealth of information available concerning concentrate disposal and related topics. These include research reports from studies funded by various agencies, both governmental and private. They also include papers and presentations associated with various conferences. While useful, this information is not as visible or available as it could be.

3.12 Summary of Characteristics and General Feasibility of Conventional Disposal Options

Table 3.7 lists attributes of the five conventional disposal options under the headings of:

- Characteristics
- Major cost factors
- Environmental concerns
- Regulation basis

This table incorporates points previously mentioned in the text and adds additional points where appropriate.

Table 3.7 Characteristics, cost factors, environmental concerns, and regulatory basis of conventional disposal options

Surface Water Discharge
CHARACTERISTICS
Includes disposal to river, creek, lagoon, ocean (via outfall, shared outfall, beach wells, etc.), interceptor
Includes after combination and/or dilution with WWTP effluent, other available water
Need relatively nearby moving water of sufficient volume year round
Not usually available in arid regions
Historically used with all sized plants
Requires a discharge permit
MAJOR COST FACTORS
Some post-treatment such as aeration, degasification, pH adjustment may be required for ground water based concentrates
> Aeration to increase dissolved oxygen
> Degasification for hydrogen sulfide (H ₂ S), CO ₂
> pH adjustment to meet receiving water standards
Piping and pumping
Outfall structure
Monitoring
Frequently a lower cost disposal option
ENVIRONMENTAL CONCERNS
Regulation based on compatibility of concentrate with receiving water (salinity and individual constituents)
Low dissolved oxygen levels and possible high dissolved gas (H ₂ S, ammonia [NH ₃]) levels in concentrate from ground water sources
Concerns of salt and mineral loading

Table 3.7 Characteristics, cost factors, environmental concerns, and regulatory basis of conventional disposal options—continued

Surface Water Discharge (continued)
ENVIRONMENTAL CONCERNS (continued)
<p>Potential detrimental impacts on environmentally sensitive areas</p> <p>Risk of CO₂ emission from discharged alkaline waters</p> <p>Increasingly globally disregarded as a sustainable inland saline effluent management option</p> <p>Mitigation: enhanced mixing and dispersion through discharge site choice, use of diffuser, outfall design; pre-dilution</p>
REGULATION BASIS
<p>Based on comparison of concentrate flow and water quality with receiving water flow and water quality</p> <p>Typically, tied to a worst case scenario: a low receiving water flow condition (based on historical records) and maximum concentrate flow</p> <p>Receiving water standards based on its use classification</p> <p>May include WET testing requirements</p> <ul style="list-style-type: none"> > Mixing zones may be granted for establishing compatibility conditions <p>Monitoring requirements</p> <p>Typically need to periodically monitor TDS, designated specific constituents, dissolved oxygen, pH, others</p>
Sewer Disposal
CHARACTERISTICS
<p>Offers advantage of lowering the biological oxygen demand (BOD) of domestic sewage effluent</p> <p>Used less frequently with increasing concentrate volume</p> <p>Utilizes existing waste water infrastructure</p>
MAJOR COST FACTORS
<p>Piping and pumping</p> <p>Fee charged by waste water treatment plant</p>
ENVIRONMENTAL CONCERNS
<p>Compatibility issues</p> <ul style="list-style-type: none"> > TDS > Specific constituents > Other <p>Effect of concentrate salinity (and constituents) on biologicals, effect of concentrate salinity on effluent salinity</p>
REGULATION BASIS
<p>Generally, no permit is required but need permission of waste water treatment plant, which may enforce treatment requirements</p>

Table 3.7 Characteristics, cost factors, environmental concerns, and regulatory basis of conventional disposal options—continued

Sewer Disposal (continued)
REGULATION BASIS (continued)
Based on comparison of concentrate volume and water quality with waste water treatment plant influent volume and water quality
Comes down to a decision on the part of the waste water treatment plant; they do not have to grant permission
Deep Well Injection
CHARACTERISTICS
Wastes the resource
Need adequate aquifer characteristics
<ul style="list-style-type: none"> > Structurally isolated from and below drinking water aquifers > Receiving aquifer must have poor water quality > Sufficient permeability, porosity for adequate individual well injection rate
High cost for small volume but good economy of scale
Used primarily with larger volumes
Adequate aquifer characteristics are not often found
Expensive feasibility determination
Future applications may include use of existing or abandoned oil wells
MAJOR COST FACTORS
Piping and pumping
Possible pretreatment
Land preparation
Mobilization
Testing
Well construction
Backup disposal system for during system integrity tests (periodic)
Monitoring wells
ENVIRONMENTAL CONCERNS
Potential for contaminant migration to potable water aquifers
Long-term sustainability under question due to doubts with the results from fate and compatibility studies
Concern with earthquakes
Concern with overpressure causing fracture and earthquakes
REGULATORY BASIS
Typically a multistep process involving test wells
Construction requirements based on well type (Class I well in the United States)
Periodic well integrity tests are required
May require a permitted second disposal option for use during periodic integrity tests

Table 3.7 Characteristics, cost factors, environmental concerns, and regulatory basis of conventional disposal options—continued

Land Application
CHARACTERISTICS
Includes spray irrigation of lawns, parks, golf courses, crop lands
Also includes percolation ponds, rapid infiltration basins
Land intensive
May require dilution water
Relatively level land required
Climate dependent
Low economy of scale
Used with smaller concentrate volumes
MAJOR COST FACTORS
Piping and pumping
Land preparation
Storage for use during rain days
Distribution system with associated valves and control
Costs associated with possible dilution requirements
Costs associated with drainage system (if required)
Costs associated with possible surface runoff control system
ENVIRONMENTAL CONCERNS
Possible surface runoff and downstream impacts
Compatibility concerns
> With underlying ground water
> With vegetation (sodium adsorption ratio [SAR] is important)
> With soil
Concern with salt loading
REGULATORY BASIS
Based on concentrate characteristics and land use classification and resulting ground water standards
Possible drainage system requirements
Evaporation Pond
CHARACTERISTICS
Land-intensive
Requires level land
Low economy of scale
Climate dependent
Most suitable for areas with high evaporation rates and low precipitation

Table 3.7 Characteristics, cost factors, environmental concerns, and regulatory basis of conventional disposal options—continued

Evaporation Pond (continued)
CHARACTERISTICS (continued)
Used for smaller concentrate volumes
Evaporation rate decreases as solids level/salinity increases
COST FACTORS
Piping and pumping
Land
Land preparation
Possible distribution system with associated valving and control
Synthetic or clay liner
Monitoring
Solids disposal
ENVIRONMENTAL CONCERNS
Exposure to wildlife can produce adverse impacts
Contamination of underlying aquifer due to leakage risk
Produces a concentrated brine or solid which by itself requires safe disposal means
Risk of CO ₂ emission from high alkaline waters
Source of salt spray to the surrounding environment
REGULATORY BASIS
Usually requires natural or synthetic liners
Usually requires monitoring of ground water for potential contamination

3.13 Chapter Summary

- The U.S. municipal desalination industry continues to grow with more plants of increasing size being located in an increasing number of States. Between 1969 and 2003, at least 234 municipal desalination plants have been built in the United States.
- Five conventional concentrate disposal options account for over 98% of the disposal methods used.
- Several conventional disposal options have both size and geographic limitations so that in 20 of 25 States having municipal membrane desalination plants, only two conventional disposal options are used—disposal to surface water and disposal to sewer.

- Land application options are used in only two States, and deep well injection evaporation ponds are used in only three States for municipal membrane concentrate disposal.
- The size, location, and salinity limitations present increasing challenges as desalination plants are considered at more locations.
- Additional disposal challenges result from more stringent regulation and increased public concern and involvement in the regulatory process.
- Cost reduction for conventional disposal options is not likely due to the nature of the simple equipment used in the options. Thus, while membrane production costs have decreased in the past several years, concentrate disposal costs have not.
- Detailed characteristics of the conventional disposal options are provided (table 3.3) along with an analysis of the feasibility of the options with plant size (table 3.4).

The increasing challenges of concentrate disposal are the primary reason for considering other concentrate management options.

4. Concentrate Management Options

From chapter 3, the limitations of the five conventional disposal options are readily apparent. In this chapter, other possibilities for treating or using concentrate are considered.

The term ‘concentrate management’ has come to replace the more limiting term ‘concentrate disposal.’ Management includes disposal but also allows consideration of concentrate as a resource for beneficial use. Beneficial use includes extraction and reuse of salts and reuse of the concentrate, which may increase the availability of higher quality water resources for other uses. The term ‘management’ is also more palatable to public perceptions than ‘disposal.’

Concentrate management options include:

- Five conventional disposal options—see chapter 3
- Nonconventional disposal options
- Beneficial use options
- High recovery (volume reduction) treatment of concentrate (including ZLD processing)
- Selective salt recovery (a special case of high recovery processing)—see chapter 5
- Combinations of the above

Due to the relatively recent use of these terms within the desalination community, clear and concise description of these areas is lacking. Each of these areas will be reviewed to characterize and distinguish the nature of the options and their impact on final disposal of concentrate, or brine and solids derived from concentrate. Clarity in the use of terms and scope of general options is a goal of this chapter.

4.1 Nonconventional Disposal Options

Section 3.3.1 provided statistics on the five conventional disposal options that account for over 98% of the options used at the 234 municipal membrane desalination plants in the United States as of 2003. The other approximately 2% includes such situations as:

- A very small evaporation shed where a metal roof is used to heat an otherwise open air enclosure holding water (10).

- WWTPs using low-pressure membrane processing with RO as a final polishing step. The low TDS feed produces a relatively low TDS concentrate which is recycled to the front of the WWTP (2).

These and a few other nonconventional options are not widely applicable to desalination plants treating ground water.

4.2 Beneficial Use of Concentrate

This section addresses beneficial uses of concentrate, except that section 4.4 addresses uses of brine and mixed salts obtained from further treatment of concentrate and section 5.4 addresses uses of individual salts obtained from concentrate.

One of the conventional disposal options, land application—in terms of irrigation—is a beneficial use of concentrate. While this and other beneficial uses exist, most if not all have considerable limitations (4). Many beneficial uses do not provide for disposal of the concentrate—they use the concentrate and leave a residual stream to be disposed. An example is an aquafarm where concentrate can support a fish industry but results in an effluent, now with an increased organic component, to be disposed. While this type of a situation may create a new economic entity that has the financial means to attend to ultimate disposal and may be beneficial to the local community, concentrate disposal is simply passed on to another group. Most beneficial uses do not have widespread applicability, and most have not achieved commercial success. However, given the growing challenges of concentrate disposal, beneficial use options should be evaluated at an early screening stage of considering management options.

Possible beneficial uses (4) include:

- Oil well field injection
- Solar ponds
- Aquaculture
- Wetlands
- Extraction of mineral resources
- Subsurface storage
- Feedstock for hypochlorite generation
- Cooling water
- Dust control and deicing
- Scrubber water
- Soil remediation

Dust control, deicing, and soil remediation are examined in more detail in chapter 5, where recovery and use of individual salts are addressed.

Some of the challenges of finding beneficial uses for concentrate include:

- Concentrates vary in composition. Each concentrate is site-specific as the raw water from which it was derived is site-specific. Thus, a beneficial use for one concentrate might not be available for another concentrate.
- Control of dust emissions from unpaved roads is of increasing interest, particularly related to attainment of the ambient particulate matter (PM) standard. USEPA issued a new ambient standard for PM in 1997 (19). Dust from roads and agriculture has not been regulated explicitly by the USEPA. But in January 2006, the USEPA issued a proposed rule to revise the National Ambient Air Quality Standards of the Clean Air Act that would address coarse particulate matter, such as dust, from roads in urban (but not rural) areas. In midyear, the USEPA was receiving comments on this proposed change.
- More generally, environmental testing is frequently and increasingly being required when new products are being considered for various applications. In such situations, with each concentrate being different, testing would be required for each concentrate. As an example: San Bernardino County Transportation suggested that any product considered for dust suppression and roadbed stabilization would have to have a Material Safety Data Sheet approved by their environmental group (20).
- In some cases, an application of concentrate may not be permitted because application requirements cannot be monitored or enforced. An example: Colorado Department of Public Health and Environment told the author that use of brine for dust suppression is no longer allowed, as previous permissions resulted in dumping brine in limited areas (21).
- Practical issues restrict some applications to small volumes. For example, 1 million gallons (MG) of concentrate might provide enough volume for dust suppression for 50 linear miles of road for 1 year. For a 1-MGD plant, the volume of concentrate is much larger than the local need.
- If local needs cannot be found, then issues and costs of transport come into play.
- Ideally, any beneficial use of concentrate would be available for the life of the desalination plant. For example, it is unlikely that a dust suppression option, or an oilfield injection pressure maintenance option, would be available for 20 years.

- Other beneficial applications might have to meet product specifications. Concentrate use may require treatment/transformation of the concentrate to meet such specifications.

Nevertheless, beneficial uses should be sought as they may serve for a partial or temporary solution for concentrate management.

4.3 High Recovery and ZLD Processing

4.3.1 Distinction Between High Recovery Processing and ZLD Processing

Meaning of the term ‘ZLD’ varies considerably in desalination literature. It is important to have clear definitions in place as the use of the term increases. Towards the aim of consistent and meaningful use of terms, we offer the following:

ZLD means that no water leaves the plant boundary.

This was the original meaning first applied to power plants along the Colorado River which were mandated in the early 1970s to not discharge process waste water into the River. To meet this no-discharge requirement, cooling tower blowdown was further concentrated by a thermal brine concentrator (evaporator) with the resultant brine going to either an onsite crystallizer to evaporate the brine to solids or to an onsite evaporation pond. The important term here is ‘onsite,’ meaning within the plant boundary. A more recent and cost-effective processing alternative is to treat the blowdown by an RO stage to reduce its volume before being treated by the energy intensive brine concentrator and even more energy intensive thermal crystallizer. Where a crystallizer is not used, the brine from the brine concentrator goes to an onsite evaporation pond and the overall recovery is typically greater than 90%. When a crystallizer is used, nearly all water is recovered.

In some desalination literature, ZLD is taken to mean processing by brine concentrators and crystallizers to produce solids for disposal. While this has some historical relevance, the definition is no longer accurate. Many new industrial ZLD processing schemes involve mixed membrane/thermal systems and some are membrane (only) systems.

High recovery means that concentrate (or the effluent in question) is further treated to reduce its volume and recover more water. In desalination circles, high recovery processing has come to imply additional membrane system processing; however, in concept it is not restricted to membrane processing. When the brine from a high recovery process is further processed to solids or sent to an evaporation pond AND this is done within the plant boundary, the high recovery process is also a ZLD process. When the brine from the high recovery process is

further processed or disposed outside of the plant boundary, it is not, by definition, a ZLD process. The same overall processing sequence may be used in both cases; the difference is where the final processing is done—inside or outside the plant boundary.

All ZLD schemes incorporate high recovery processing; however, not all high recovery processes achieve ZLD. ZLD processing is a special case of high recovery processing where no liquid effluent leaves the plant boundary.

4.3.2 High Recovery Processing

As of 2007, due to the high costs, high recovery processing (and, thus, including ZLD processing) has not been used in a municipal setting. Volume reduction of concentrate is desirable from the standpoint of recovering more water from the water resource. However, additional processing is expensive—more expensive than conventional processing. In the context of concentrate disposal, high recovery processing is considered only when the conventional disposal options of chapter 3 are not feasible. This situation is increasingly occurring, and high recovery processing has been considered in several recent cases where conventional disposal options are not available or are not cost effective.

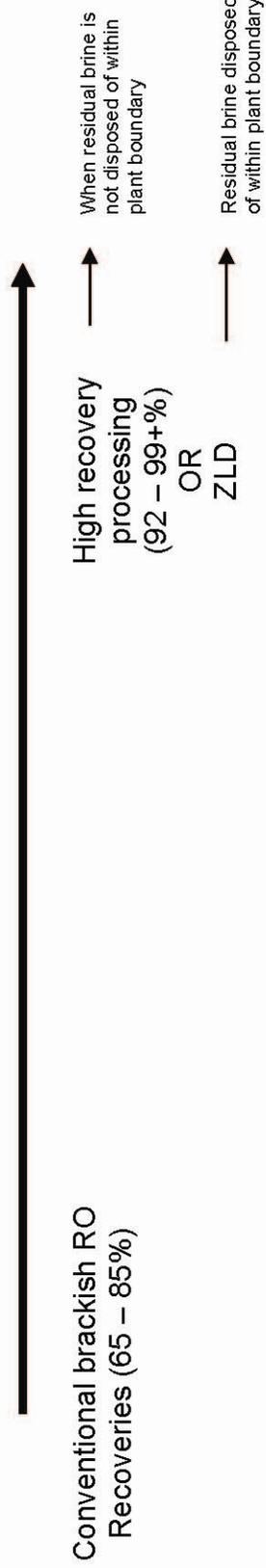
High recovery processing does not guarantee a disposal option. The reduced volume results in higher salinity, which affects conventional disposal options as follows:

- Effectively eliminates surface disposal
- Effectively eliminates discharge to sewer
- Effectively eliminates land application
- May permit deep well injection
- May permit use of evaporation ponds

Figure 4.1 depicts a continuum of recoveries starting at more conventional RO recoveries at the left and increasing in recovery to the right. At the extreme right are the high recovery cases.

Conventional BRO processing recoveries typically are limited to the range up to 85%. They produce a concentrate of at least 15% of the feed volume. Volume minimization in the municipal desalination context has come to mean reducing the concentrate volume relative to that produced by this ‘conventional’ processing. If recovery is increased from, i.e., 70% to 85%, it is arguable that little is gained—from the perspective of concentrate disposal. While the volume of concentrate is reduced by a factor of 2 (from 30% of the feed volume to 15%), the concentrate salinity has increased by a factor of 2. This increase in salinity usually results in a greater incompatibility between the concentrate and any potential receiving water (surface water, sewer water, ground water), making it more difficult to dispose of the concentrate by these options. Disposal by the

RECOVERY



Conventional brackish RO Recoveries (65 – 85%)

High recovery processing (92 – 99+%)

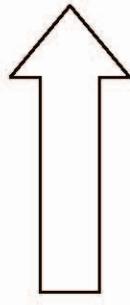
OR
ZLD

When residual brine is not disposed of within plant boundary

Residual brine disposed of within plant boundary

Conventional disposal options:

- -- surface water discharge
- -- discharge to sewer
- -- deep well injection
- -- evaporation pond
- -- land application



Conventional disposal options Available for high recovery?

- NO (possible ocean exception)
- NO
- ?? increased concerns with well plugging
- ?? concerns with lower net evaporation rates
- NO

Possible high recovery disposal options for final brine:

- Lower salinity brine to a surface water (ocean)
- Crystallization to solids for landfill
- Evaporation pond
- Deep well injection
- Solidification of high solids brine for landfill
- Combination of the above

Figure 4.1 Range of recoveries and possible high recovery disposal options.

other two conventional disposal options, deep well injection and evaporation ponds, is frequently not possible at the location of interest. Unless the reduced volume of brine is further concentrated so as to produce solids (or a sludge) or a smaller volume brine, disposal options may not be available.

4.3.3 Conventional ZLD Processing

This section deals with true ZLD processing as it is used in other industries—high recovery processing where no liquid leaves the plant boundaries. While ZLD has not been used in municipal drinking water plants in the United States, it is a widely used commercial technology applied in many industries, including the power industry with over 120 installations (6). Most conventional ZLD plants utilize thermal/mechanical vapor recompression (MVR) technology for the primary desalination step. The MVR equipment commonly is referred to as a brine concentrator. In most instances, the brine concentrator is operated in a seeded slurry mode, where calcium sulfate is circulated to provide a co-precipitation/adsorption site for salts coming out of solution during the evaporation process. This technology can take low salinity effluents/waters up to approximately 160,000 to 360,000 mg/L total solids depending on the specific initial water quality involved (6). The degree to which a feed water may be concentrated may be limited by a) the onset of precipitation of salts such as glauberite (sodium-calcium sulfate), sodium sulfate, or sodium chloride or b) the production of an unacceptably high level of suspended solids. The theoretical range of concentration factors possible varies widely, such as from about 1.67 for a feed salinity of 60,000 mg/L with an effluent salinity limitation of 160,000 mg/L, to 90 for a feed salinity of 4,000 mg/L with an effluent salinity limitation of 360,000 mg/L.

ZLD processing schemes may include the following components:

- Thermal brine concentrator
- Thermal crystallizer
- Spray dryer (for very small final brines of less than 10 gpm)
- Evaporation ponds
- Second RO system (with pretreatment)
- Land fill

There have been three general ZLD processing sequences used in the United States, which are shown in table 4.1. The first processing scheme involves reducing the volume of waste water by a thermal brine concentrator. High quality water (< 10 mg/L) is recovered as product, and the resultant brine is either sent to evaporation ponds or further processed by a crystallizer. Crystallizer solids are taken to a landfill. Both thermal process steps are energy intensive with the brine concentrator requiring from 65 to 95 kilowatthours per thousand gallons

Table 4.1 Frequently used ZLD processing schemes

The traditional ZLD plants almost exclusively involve the use of thermal brine concentrators in one of the following schemes:

GENERAL ZLD PROCESSING SCHEME 1:

A - concentrate → pretreatment (minimal) → thermal brine concentrator → evaporation pond (standard/enhanced)
 B - concentrate → pretreatment (minimal) → thermal brine concentrator → crystallizer → solids (with possible very small blowdown stream)

GENERAL ZLD PROCESSING SCHEME 2:

More recently, high recovery RO systems have been used to reduce the volume of solution going to the thermal brine concentrators. The processing schemes include:

A - concentrate → treatment → 2nd stage RO → thermal brine concentrator → evaporation pond
 B - concentrate → treatment → 2nd stage RO → thermal brine concentrator → crystallizer → solids

In general, the treatment used in this high recovery RO scheme is significantly more intensive than in processing scheme 1

GENERAL ZLD PROCESSING SCHEME 3:

In some cases the two stage membrane system is used alone without any thermal processing:

concentrate → treatment → 2nd stage RO → evaporation pond

GENERAL ZLD PROCESSING SCHEME 4:

Another more recent processing scheme (Geo-Processors, 2007), not yet used in the United States, is to selectively/sequentially recover individual salts from the effluent. The processing scheme used depends on the particular effluent being treated. An example of a treatment scheme is:

concentrate → salt removal → 2nd stage RO → salt removal → brine concentrator → mixed salts recovery

(kWh/kgal) and the crystallizer from 200 to 250 kWh/kgal. This type of processing defined the first generation of ZLD facilities. In an effort to reduce energy use, the second processing scheme gained consideration. In this scheme, the waste water to be treated was first reduced in volume by a RO system. (In the case of concentrate, this would be a second-stage RO system.) The reduced volume brine from the RO system is then treated by a brine concentrator. The final processing steps are the same as in the first processing scheme—brine going either to evaporation ponds or to a crystallizer. The third general ZLD processing scheme eliminates the brine concentrator. Brine from the RO system is sent to evaporation ponds but may be further treated by a crystallizer.

A fourth general ZLD processing scheme that has been applied outside of the United States involves selective salt recovery and is discussed in chapter 5.

4.3.4 Consideration of High Recovery (Volume Reduction) in Municipal Desalination

Within some sectors of the municipal desalination industry, there has been a growing concern for concentrate representing a lost water resource; and given the growing general challenge of disposing concentrate, there has been interest in volume reduction of concentrate. The usual means considered to accomplish this is a second RO system. This is represented in processing schemes 2 and 3 of table 4.1. In order to avoid the recovery limitation in the second stage RO due to sparingly soluble salts and silica, either treatment of the first stage RO concentrate to remove these species or combination of treatment and high pH operation of the second stage are employed (29). In chapter 6, some of the technologies described offer newer alternative membrane-based processes for high recovery processing.

Membrane processing cannot presently concentrate feedwater to the same degree as evaporative processes. Thus, the processing schemes not employing thermal process steps usually result in a less concentrated and larger final brine flow to be dealt with. For smaller applications, this may still be a small flow. For larger applications, final brine flow can be significant. There are, thus, tradeoffs in cost associated with utilizing RO processing prior to or in place of a brine concentrator. The next section considers these tradeoffs through an example.

4.3.5 Analysis of a Hypothetical Concentrate Management Challenge

ZLD has been prohibitively expensive for the municipal setting. Equipment descriptions, design practices, and costs have been developed in a previous Bureau of Reclamation (Reclamation) report (2).

Analysis of ZLD processing options shows that while volume reduction prior to the brine concentrator can reduce energy requirements significantly, these costs

are in large part replaced by chemical costs for treatment and increased solids disposal costs. This is particularly true for high hardness waters. The following analysis demonstrates this point.

The basis for the calculations was a year 2000 study done by Reclamation (22) looking at two concentrate disposal options for a hypothetical 20 MGD of concentrate generated in the Phoenix area. The report considered two disposal options: a 320-mile pipeline from the Phoenix area to the Sea of Cortez and a large area of evaporation ponds.

For these two options, the author developed preliminary level costs for three ZLD processing options. These processing schemes are:

Concentrate	→		Brine concentrator	→	Evaporation pond	
Concentrate	→	High Recovery RO	→	Brine concentrator	→	Evaporation pond
Concentrate	→	High Recovery RO	→		Evaporation pond	

Assumptions made in this analysis include:

- Concentrate TDS is 6,520 mg/L
- The brine concentrator produces a brine of 220,000 mg/L
- The high recovery RO produces a brine of 65,000 mg/L

In the following tables, BC = brine concentrator, EP = evaporation pond, and HRRO = high recovery RO.

The costs in table 4.2 are based upon the following assumptions: \$0.05/kWh energy cost; sludge disposal at \$30 per ton; annualized cost at 40 years and 7.125% interest (the basis for the year 2000 Reclamation study). The capital cost savings of the ZLD technology schemes (options 3, 4, and 5) are evident in the capital cost row. The much higher operating costs are evident in the operating cost row.

Options 4 and 5 offer considerable cost advantages over option 3; however, both of these ZLD options have significant annual operating costs.

There are some advantages of options 3, 4, and 5. They offer a much smaller environmental footprint and reduced liability risk. They also recover a significant amount of the original 20 MGD of concentrate (shown in the bottom row of the table).

Table 4.3 shows a breakdown of the operating costs for options 3, 4, and 5. Utilizing a second RO system prior to the brine concentrator results in considerable energy savings. The saved energy cost is, however, replaced with a high chemical (lime/soda ash) cost and with a very high solids disposal cost. The solids disposal cost represents over 50% of the operating cost.

Table 4.2 Costs associated with disposal options in example study

	1 Pipeline	2 EP	3 BC + EP	4 HRRO + BC + EP	5 HRRO + EP
Capital, M\$ ¹	310	410	136	76	92
Operating M\$/yr ²	0.8	1.6	33	29	21
Annual M\$/yr	24	33	43	35	27
Water lost, MGD	20	20	0.8	0.8	2.5

¹ M\$ = million dollars.

² M\$/yr = million dollars per year.

Table 4.3 Operating cost detail for disposal options in example study

	3 BC + EP	4 HRRO + BC + EP	5 HRRO + EP
Labor	1.1	3.1	2.0
Energy	31.0	3.9	1.0
Chemical	----	6.2	5.0
Sludge disposal	----	14.7	12.0
Evaporation pond	0.8	0.8	0.8
Total	32.9	28.7	20.8

Option 5, eliminating the brine concentrator, further reduces the energy requirement but still has significant chemical and solids disposal costs.

In summary, inclusion of high recovery RO dramatically reduces the size of the thermal brine concentrator that follows it and, in so doing, reduces the capital cost (from \$136 to \$76 million, respectively) and the energy costs (from \$31 to \$3.9 million per year, respectively). The decreased energy costs, however, are partly offset by the increased costs of chemicals and sludge disposal.

This preliminary analysis suggests that the reduction of ZLD costs is not simply a matter of reducing energy consumption. It also reflects the challenges of further cost reduction necessary for high recovery/ZLD processing to be applied in the municipal setting. Cost reductions will need to come primarily from capital costs as well as from energy, chemical, and solids disposal costs.

A recent report by the author (6) confirms this analysis and develops indepth cost analyses for different processing schemes.

4.4 Beneficial Uses of Brine and Mixed Salts

4.4.1 Composition of the Final Residual Brine

In section 4.2, the limited beneficial use of concentrate was discussed. Here, beneficial use of brine or mixed salts derived from concentrate is addressed.

Composition of brine and solids depends not only on the original water source but on the processing sequence as well. The salt composition of the brine is the salt composition of the original concentrate (or raw water) minus the salts removed from the concentrate (or raw water) in the course of high recovery and ZLD processing. Less soluble salts are removed first.

As explained in chapter 5, the following list provides a general categorization of salt solubilities.

General solubility level	Salt examples
Sparingly soluble salts	Calcium carbonate, calcium sulfate
Moderately soluble salts	Sodium carbonate, sodium sulfate
Soluble salts	Sodium chloride
Highly soluble salts	Calcium chloride, magnesium chloride

When a salt precipitates, it will do so down to the solubility limit for that salt corresponding to the conditions at hand. With multiple salts involving the same ion (such as sodium carbonate, sodium sulfate, and sodium chloride), precipitation pathways may include competition for the common ion. The closer the solubility limits of the salts, the greater the competition. Typically for a given salt, one of the ions is in excess; and after precipitation to the solubility limit, more of that ion will remain in solution. The salt with the lowest solubility will preferentially be precipitated; however, the final solution concentrations can be difficult to predict. This is especially true as the number of salts in solution increases and when the solution is not dominated by one or two salts. With these complications noted, however, some generalizations can be made.

Brine containing 400,000 mg/L total solids (TS) will consist of highly soluble salts. The TDS of brine containing between 100,000 and 160,000 mg/L TS can be dominated by sodium salts because the sparingly soluble salts and silica would have already precipitated. A brine containing less than roughly 100,000 mg/L TS may still have some level of sparingly soluble salts and silica present.

All of these salinity levels are possible in high recovery processing. For example, if the feed concentration of TDS is only 1,000 mg/L, processing to 100,000 mg/L represents a recovery of 99%. A feed TDS concentration of 10,000 mg/L, processed to 300,000 mg/L represents a lower recovery of 96.7%.

For most high recovery systems where final brine is not taken to solids, the brine will be sodium dominated. This assumes that sparingly soluble salts and silica have been removed from solution due to having minimal solubility at the final

salinity. One of the major challenges associated with high recovery processing is how to dispose of sodium-dominated brine.

There are few uses for such brines, particularly on a scale suitable for a large desalination plant. For instance, sodium brine may be used to regenerate some ion exchange resins, but the amount of brine needed likely would be much less than the amount of brine available. Further, as with most beneficial use situations, the regeneration process does not dispose of the brine; disposal is simply delayed or passed on to another entity.

4.4.2 Composition of Mixed Salts from Brine

In conventional high recovery processing, solids derived from concentrate may occur at two different processing steps. Treatment of concentrate to allow volume reduction in a second spiral wound RO system will remove some level of sparingly soluble salts and silica. Most frequently, this treatment has been a high pH precipitation step, such as lime softening. Solids removed at this step are usually magnesium hydroxide and calcium carbonate, which are usually dewatered and sent to a landfill.

A crystallizer will precipitate solids containing salts still present in the brine after the previous processing steps (brine concentrator or RO)—with the exception of highly soluble magnesium chloride and calcium chloride salts. Their presence may necessitate a purge (blowdown) stream from the crystallizer.

In some cases, the mixed solids obtained may be dominated by only one or two salts in high enough degree to find some use; however, there are no general uses for mixed salts.

As with concentrate (section 4.2) and brine from concentrate (section 4.4.1), there are few uses of solids produced from ZLD operations (from evaporation ponds or crystallizers, or spray dryers). The primary reason for this is the mixed salt nature of the solids.

Most beneficial applications for brine or precipitated salts (e.g., soil remediation, deicing salts, and dust suppression) need to meet environmental or application-specific standards. Meeting such requirements is less likely for a concentrate, brine, or solids containing mixed salts.

4.5 Disposal Options for High Recovery Final Waste

4.5.1 Volume Flow of Brine

As with concentrate from conventional membrane processing, the disposal options for high recovery brine depend on the size or volume of the brine flow. The volume of high recovery final brine depends on the size of the desalination system. A 40-MGD system can produce a 4.44-MGD brine at a system recovery

of 90%—thus, the brine flow is not necessarily small. Figures 4.2a and 4.2b illustrate brine flows resulting from different sized desalination plants and overall plant recoveries.

Of importance here is how high recovery processing affects disposal volumes. Figure 4.2a shows brine flows in (MGD) as a function of recovery for plants from 5 to 60 MGD. With recoveries of 90% and higher, brine flows are less than 1 MGD for plant sizes of about 10 MGD and smaller. Figure 4.2b shows that, for small plants of size 1 MGD and smaller and with recoveries of 90% or greater, brine flows (in gpm) are 77 gpm or less.

While it is generally easier to find a disposal option for small volumes of brine as opposed to large volumes, the disposal options are limited.

4.5.2 Disposal Options for High Recovery Brine and Solids

The disposal options for the brine include:

- Disposal of lower salinity brine to saline surface water
- Taking the brine to solids via thermal evaporative crystallizers (or spray dryers), followed by landfill of solids
- Disposal of brine to evaporation ponds
- Disposal of brine by deep well injection
- Solidification of brine by chemical addition, followed by landfill of nonleachable solids/paste
- A combination of the above

In high recovery processing, disposal to surface water would be considered only in the treatment of low salinity waters where high recovery would yield relatively low salinity brine. For instance, 96% recovery (assuming 100% rejection) of a feedwater of 800 mg/L produces a brine of 20,000 mg/L. Such brine might be disposed to a high salinity surface water, such as the ocean or a naturally high salinity inland water.

Using thermal crystallizers is expensive and energy intensive (2, 6). Taking brine to solids, however, should be evaluated with other options, as the number of options is quite limited and, despite the high cost, crystallization is a technology that can be applied at most any location having adequate power supply. For small volume brines, such as less than 10 gpm, spray dryers may be considered for processing brine to solids. Solids would be disposed at a suitably classified landfill. Concerns with levels of contaminants in solids need be addressed (see chapter 8).

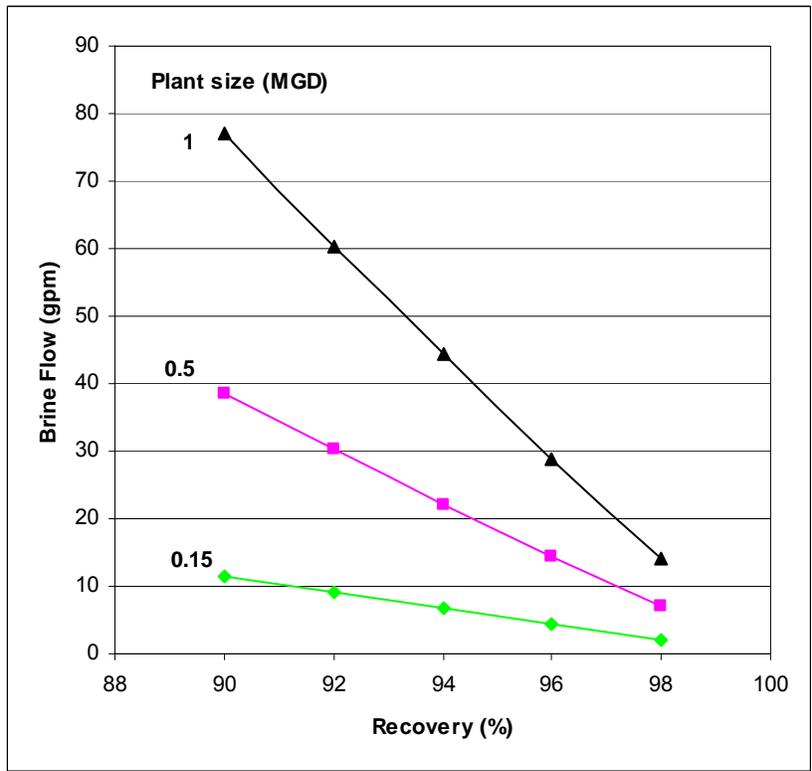
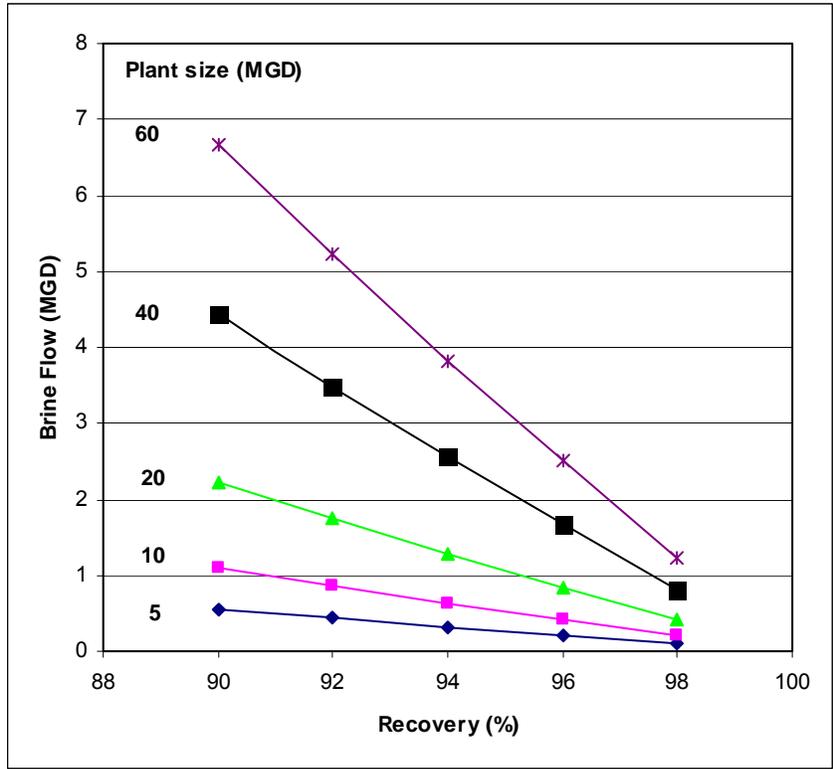


Figure 4.2 a and b Brine flow as a function of desalination plant size and total recovery.

Disposal of high recovery brines to evaporation ponds has the same concerns that were discussed in chapter 3 with regard to disposal of concentrate. This option is very expensive and usually cost effective for only relatively small volumes, and siting of evaporation ponds is limited by climate and land availability. An additional complicating factor for disposal of high salinity brines is that evaporation rates decrease with increasing salinity. Evaporation rates can decrease to 50% of dilute water evaporation rates at very high salinities (2, 6). The high solids content of such brines means that ponds more rapidly will fill with solids. This may necessitate either removal of solids from ponds and disposing them in a landfill, or covering the ponds over and building additional ponds during the life of the desalination plant. Both choices are expensive factors added on to an already expensive option.

Deep well injection may be possible with brines. Relative to injection of concentrate, injection of brine has some additional concerns. One is associated with the presence of high levels of suspended solids that have potential to plug reservoirs. Suspended solids may precipitate from high recovery processes that use antiscalant inhibitors since antiscalants have time-limited effects on precipitation kinetics, may deteriorate over time, and may be absorbed by aquifer media. Gross amounts of suspended solids may need to be filtered from the brine prior to injection. Also of concern is the unknown chemistry associated with blending of brine with aquifer water; as waters become more concentrated, the potential for precipitation reactions increases.

Small volumes of brine may be solidified by chemical addition to pass the paint filter test required for disposal in landfills. Costs for large volumes, including hauling costs to the landfill, can become prohibitive. Disposal of mixed solids currently is limited to landfilling.

The next chapter explores the concept of selective salt recovery in which concentrate or brines are processed in such a manner to yield commercial grade salts for market. Such processes represent another beneficial option, which incorporates high recovery and ZLD processing schemes.

The disposal options just discussed are represented in table 3.4 in the right-hand column.

4.6 Costs and Directions Associated with High Recovery Processing

The high costs of conventional ZLD technologies are due to high capital cost and one or more of the costs associated with energy, chemicals, and solids disposal. In the future, more efficient desalination technologies may reduce capital and processing costs, including energy and chemical costs. However, solids disposal costs will remain high and limit the application of these technologies.

Historically, concentrate management has consisted of conventional concentrate disposal; and in the vast majority of cases, it will be so in the future. This is not surprising when concentrate is viewed as a ‘waste product.’ Concentrate shares some characteristics with other ‘wastes’ in that disposal options are limited and, in large part, have been well defined for years. More recent trends have been to treat wastes to develop marketable products through ‘recycle’ programs.

An ultimate goal of all technologies is to minimize environmental impacts and to attain a high degree of sustainability. These and other factors lead to consideration of harvesting individual commercial grade salts for commercial use. Sale of salts could not only reduce the costs associated with solid waste disposal but also offset costs associated with energy and chemical use—thus, reducing high recovery costs without waiting on the development of more efficient technologies. Beneficial use makes most sense in this context—transforming concentrate into useful products that offer a solution to the disposal challenge rather than transferring it to another entity.

A former Australian company (now a U.S. company) provides a commercial service that treats waters and waste waters to selectively and sequentially removing individual salts for market. Their technology has been researched, developed, patented, and licensed outside of the United States. This company, Geo-Processors USA, Inc. more recently has established itself in the United States to market their technologies. Selective salt recovery is the subject of chapter 5.

4.7 Chapter Summary

- Due to growing challenges of conventional concentrate disposal and planned location of desalination plants in sites having few if any conventional disposal options (such as the Southwestern United States), it is increasingly important to consider alternatives to these conventional options.
- Concentrate management options beyond conventional concentrate disposal include beneficial use of concentrate and further (high recovery) processing of concentrate
- Beneficial uses of concentrate are limited in number and commercial success. Most do not provide for a final disposal of concentrate. Further, few can assure that they will exist for the life of the desalination plant.
- Consideration of high recovery processing has been driven by the thought that reducing the volume of concentrate to be disposed may yield a solution to concentrate disposal challenges. It also is driven by the goal of making better use of the water resource as concentrate disposal may be viewed as water that is lost or wasted by the water utility.

- ZLD processing is a special case of high recovery processing where any liquid produced is disposed of within the plant boundary.
- Due to high capital and operating costs associated with high recovery processing, there are no municipal desalination plants (as of 2007) using high recovery technologies.
- ZLD and various high recovery technologies, however, are well established and have been used in other industries.
- Technical feasibility of high recovery processing is not an issue; however, cost is.
- High recovery processing of concentrate produces brine or mixed solids.
- With few exceptions, the only disposal options for brine include:
 - Deep well injection
 - Evaporation ponds
 - Solidification and landfill of solids
- With few exceptions, the only disposal option for mixed solids is landfill.
- Landfill costs can be significant; and consequently, high recovery processing does not provide a cost-effective disposal option.
- High recovery processing, however, may provide a disposal option where otherwise none exist.
- High costs of conventional ZLD technologies (and other high recovery technologies) are due to high capital cost and one or more of the costs associated with energy, chemicals, and solids disposal.
- In the future, more efficient desalination technologies may reduce capital and processing costs, including energy and chemical costs. However, solids disposal costs will remain high and be limiting.
- A promising direction of consideration is that of selective salt removal where commercial grade salts are harvested as part of a high recovery process. Sale of salts can reduce the amount of brine/solids needing disposal, and income from sale of salts can help offset disposal costs.

5. Selective Salt Recovery

5.1 The Case for Selective Salt Recovery (SSR)

The consideration of selective and sequential salt removal from concentrate and marketing of the salts resulted from the logical consideration of and elimination of other concentrate disposal options for locations where conventional disposal options are not available. Selective salt recovery is also an approach with benefits of maximizing water recovery, reducing environmental impacts including the desalination plants' CO₂ footprint, ultimately with the important goal of a sustainable solution.

Improvements in desalination technologies are the subject of research and development, and some of these technologies likely can be incorporated into high recovery processing schemes. In the long term, high recovery processing costs will be lowered by such technology improvements. Costs associated with disposal of solids, however, are unlikely to decrease. In the short term, recovery and sale of individual salts may be one of the few options to significantly reduce operating costs and, thus, impact the total cost associated with disposal. Longer-term, selective salt recovery can continue to provide benefits.

More specifically, the previous analysis of disposal options, including the hypothetical Phoenix situation (chapter 4), resulted in the following observations:

- Conventional disposal options may not be available or cost effective. This includes surface water disposal, disposal to the sewer, deep well injection, land application, and evaporation ponds.
- Concentrate, in general, does not have any beneficial use that also serves as a means of final disposal.
- If concentrate is processed in a conventional ZLD scheme to obtain solids, the mixed salts obtained from concentrate, in general, do not have any use and ,thus, must be land-filled at considerable cost.
- Thermal brine concentrators (which presently are not used for treating municipal concentrate) are very energy intensive, have high operating costs, and are, thus, also not cost effective.
- Using commercial volume reduction technologies (such as high recovery RO systems) prior to brine concentrators can lower capital costs significantly but still results in high operating costs, where high chemical usage and high solids disposal costs in large part replace reduced energy costs.

- In general, high recovery (including ZLD) processing presently does not lead to cost-effective processing or to a cost-effective disposal solution. It may, however, lead to an available concentrate disposal solution where otherwise none exist.

These various factors lead to consideration of harvesting individual salts for beneficial use and sale. Sale of salts could not only reduce the costs associated with solid waste disposal but also offset costs associated with energy and chemical use—thus reducing high recovery/ZLD costs without waiting on the development of more efficient technologies and avoiding the limiting cost of solids disposal. More generally, SSR has the following potential benefits:

- Creating an income stream from the sale of one or more commercial grade salts
- Decreasing concentrate disposal costs
- Recovery of additional water—as the processing involves separating salts from water
- Decreasing environmental impacts

There is also a larger need being served by consideration of SSR. Landfills, even if they were a cost-effective means of disposing of salts, may at some point become point sources of pollution. The counter argument in terms of sustainability is that if lined cells are used, landfilling is a sustainable practice for at least the near future. The only truly sustainable solution to concentrate disposal over the long term is recovery and reuse of most of the water and salts. The recovery of most of the water is highly desirable in regions of limited water resources.

5.2 Precipitation Pathways

Two fundamental questions in considering SSR are:

- (1) What salts are available?
- (2) What is the basis for recovering the salts?

As water is evaporated from a mixed salt solution, salts will precipitate (or be removed from solution) in a sequence, according to their solubility and propensity for co-precipitation and adsorption. This precipitation is dependent on the particular salt solution, temperature, pH, residence time, agitation, presence of other species such as antiscalants, and other variables. Control of salt form in terms of crystal size, morphology, and purity, for example, is a complex function of such variables and an important consideration in defining a technical approach to produce the salts.

A general sequence of common salt precipitations is obvious from experience with reverse osmosis, thermal brine concentrators, and crystallizers. Reverse osmosis is limited by the precipitation of sparingly soluble salts that include calcium carbonate, silica, and calcium sulfate. Use of antiscalants (and historically acid) has allowed operation past the saturation level of such sparingly soluble salts; however, recovery is still limited by these salts and silica. Extensive pretreatment can reduce the concentrations of sparingly soluble salts and silica and allow higher recovery. In theory, if sufficient pretreatment is done to remove these salts and silica, osmotic force becomes the limiting factor for second stage RO recovery. With brackish sources, however, a limitation due to sparingly soluble salts usually exists with practical pretreatment levels. Thermal brine concentrators that process concentrate and other waste water are sometimes limited by the formation of sodium sulfate and sodium carbonate precipitates. In this situation, they typically produce brine in the range of 160,000 to 360,000 mg/L. Thermal crystallizers operating on the brine from thermal brine concentrators will precipitate Na_2CO_3 , Na_2SO_4 , and NaCl , but may require a blowdown stream for the highly soluble CaCl_2 and MgCl_2 salts.²

From this general consideration, one can see the promise of sequential and, thus, selective removal of salts from solution, with a likely sequence being:

General solubility level	Salt examples
Sparingly soluble salts	calcium carbonate, calcium sulfate
Moderately soluble salts	sodium carbonate, sodium sulfate
Soluble salts	sodium chloride
Highly soluble salts	calcium chloride, magnesium chloride

Prediction of the salt precipitation sequence in terms of amounts corresponding to physical and chemical conditions is challenging. Most software programs are limited in one or more ways, in part due to the fact that they were not designed to perform these calculations and that many double salts are poorly characterized and seldom encountered. Software used for estimating membrane system recovery with antiscalant use are limited in terms of the different salts included, the salinity range, accuracy (due to the inclusion of safety factors), and difficulty of incorporation into an iterative calculation necessary for defining the precipitation path.

Better suited for precipitation path calculations are various geochemical speciation programs that are used to determine how a given water chemistry will separate into liquid and solid phases. These programs, however, are generally difficult to use, limited in predicting pH changes that occur during precipitation

² See “Abbreviations and Acronyms” for definitions of chemicals.

involving carbonate species, limited in the range of salinity that can be analyzed, and not suited for predicting the path of sequential precipitation as the solution becomes more concentrated.

It appears that the useful codes in the speciation programs are mass transfer codes that keep track of water mass. They can speciate an aqueous solution and simulate changes in solution chemistry caused by mass transfer processes, such as dissolution/precipitation, ingassing/outgassing, ion exchange/adsorption, evaporation, boiling temperature and pressure changes, and mixing of two waters. Available software programs include:

- PHREEQC
- EQ3/6
- SOLMINEQ.88
- MINTEQ(4.00)
- MINEQL
- Geochemist's Workbench
- OLI

The primary concern with using software packages is that they predict equilibrium conditions. The many chemical reactions that can take place in mixed salt solutions are subject to a wide range of kinetics; the resulting predictions based on equilibrium can be in error.

The OLI software appears to be the only software capable of making the precipitation path iterative calculations. It also appears to be the most sophisticated and capable software package, as well as the most expensive. It appears not to have the other limitations, except possibly not having a few salts that might be useful in certain situations. OLI, however, can develop and implement these salts in their database (23).

5.3 Salt Recovery in the Literature

A review of the literature has shown that the terms most frequently used to describe SSR processing are 'fractional crystallization' and 'fractional precipitation.' Fractional crystallization refers to where one or more ions in a mixture are precipitated by changing salt concentrations in solution through evaporation or temperature control. Fractional precipitation involves adding a precipitating agent to selectively remove an ion from solution.

The literature contains various discussions of processes where a multicomponent solution is separated into different species using fractional crystallization. Similar species may be separated by crystallization, dissolution, and recrystallization in repeated cycles to yield successively purer substances.

A few examples of research applications include:

- A 1999 final report entitled *Salt Utilization* from the San Joaquin Valley Drainage Implementation Program and the University of California Salinity/Drainage Program looked at removing the major component of salt in the San Joaquin Valley—sodium sulfate and recovering selenium from agricultural drainage waters. Processing technologies, salt markets, and research needs were defined (24). The conclusion was that the opportunity exists to utilize salt and selenium as commercially viable resources; however, this was not one of the approaches taken forward in the full-scale implementation of the program.
- A 2005 article in *Desalination* entitled “Salt Production from Coal-Mine Brine in ED-Evaporation-Crystallization System” by Turek et al. considered recovering CaSO_4 and $\text{Mg}(\text{OH})_2$ from brine utilizing ED/EDR technology as pretreatment to a conventional ZLD system of brine concentrator followed by a crystallizer (25). The study focused on the role of the ED/EDR pretreatment/preconcentration system on reducing energy requirements and increasing the purity of separated salts.
- A 2005 article in *Desalination* entitled “Extraction of Strategic Materials from the Concentrate Brine Rejected by Integrated Nuclear Desalination Systems” by Dirach et al. focused on recovering valuable elements from seawater desalination concentrate (26). Elements of interest were identified, processing approaches were evaluated, and future experiments were planned.

Other more general commercial and industrial examples include:

- Salt production by solar evaporation where seawater flows into shallow ponds where the sun evaporates the water, causing salt precipitation. As the specific gravity of the evaporating brine increases, it is possible, by moving it from basin to basin, to effect fractional crystallization and, thus, remove most of the impurities. When practically all impurities have been removed, the brine is allowed to evaporate completely. These can be mechanized operations consisting of several interconnected evaporation ponds and crystallizers. Ponds can have sizes of a few to several hundred acres, each with depths of 0.5 meters (m) up to 1.5 m. Seawater is pumped into the first pond and flows by gravity through sequential evaporation ponds. While passing through the ponds, system salinity levels gradually build up as a result of evaporation. As the salinity increases, salts with low solubility precipitate primarily as carbonates and sulfates. Once the seawater has evaporated to about one-tenth of its original volume (to a brine of about 260 grams per liter), brine is pumped into the crystallizer ponds where sodium chloride precipitates. Before all sodium chloride has crystallized, the remaining brine slurry, now called bittern, has to be drained off. Otherwise, the sodium chloride deposits will be contaminated

with highly soluble MgCl_2 , MgSO_4 and KCl salts that start precipitating at this elevated salinity. The technique of salt production thus involves fractional crystallization of the salts within different ponds. To assure that the different salts precipitate in the correct pond, salinity in each pond is strictly controlled and kept at a constant level during most of the year.

- Soluble radionuclides have been separated from salts where sodium and potassium salts are removed by addition of nitric acid to convert hydroxyl and carbonate, and nitrite to nitrate. The acidified solution is next fed to a continuous thermal crystallizer unit coupled to a filtering/separation device to separate the crystals from the mother liquor. The soluble radionuclides stay in the mother liquor, except for the fraction that remains occluded within the crystals or adheres to the surfaces. The crystals are decontaminated by washing and are then dissolved and sent to a facility to produce a Class A waste. The radionuclide in question was cesium.
- Several salt separation steps are carried out in raw sugar refining, and many such steps are carried out in the separation of rare earth materials. Alternatively, a train of crystallization processes can operate continually to produce a number of pure salts. Thus salt lake brines can be processed to produce NaCl ; and depending on local variations in composition, NaHCO_3 , Na_2SO_4 and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, KCl and CaSO_4 . The same principal applies to mineral ores that can be processed to yield different substances. Thus, potash (KCl) ores exist in three principal forms: KCl (sylvite), KCl/NaCl mixture (sylvinit), and $\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ (carnallite). A succession of crystallizers can be operated such that each produces only one of the pure salts KCl , NaCl , and MgCl_2 (27).

Three efforts of note go beyond a site-specific focus or a single application of selective salt recovery concepts.

5.3.1 Gerald Grott, Superior Salt, Inc.

For many years, Gerald Grott has been an advocate for using salts obtained from concentrates, drainage water, produced waters, and other waste waters in a variety of applications. Much of his focus has been on using waters that have a salt composition directly applicable to addressing soil remediation problems.

One of the more recent and continuing efforts involves developing an ion exchange “hardener” (as opposed to a softener) that replaces sodium with calcium. Such technology could be used to produce brines to remediate sodic soils (28).

Other efforts have been directed towards:

- Tailoring the irrigation/remediation water to meet the needs of the local soil
- Using salts to remediate sodic (high SAR) soils

- Increasing the rate of infiltration of soils to limit loss of rainfall through evaporation
- Using higher salinity water where possible—for soils with good SAR and hydraulic conductivity
- Using salts derived from concentrate and other waste waters for dust suppression, soil sealing, soil stabilization, and deicing

5.3.2 Prof. Tom Davis, University of South Carolina

Tom Davis has been studying a modification of electro dialysis that uses monovalent ion selective membranes as the heart of various process schemes to recover salts and slurries of value. Original focus was on recovering NaCl, Mg(OH)₂, and Br₂ from seawater. Patents are pending, and a pilot test has been conducted on irrigation drainage water. The processing concept is owned by ZDD, Inc. which has recently licensed the concept to Dow Chemical for their possible development of the technology (29).

5.3.3 Dr. Aharon Arakel, Geo-Processors USA, Inc. (GEO)

After initial evaluation of SSR in this project, an Australian company was identified that has developed, patented, and licensed SSR technology in several locations outside of the United States. They have used their technology to recover a wide variety of salts from a broad range of natural waters and waste waters.

It appears that GEO is the only group that has systematically developed an approach and the necessary technology to treat virtually any water/waste water to obtain salts for market (11). As part of this, GEO has developed nonsolar technologies that could be applied without regard to climate and location. Such nonsolar technology is also necessary for fine control of salt product form and purity. They have developed a water classification system, and typically examine several alternative processing schemes to tailor processing and salt production to local salt market needs. GEO has successful projects in Australia and other countries, but rigorous documentation is lacking, and criteria for commercial success have not been defined. Recently, GEO moved operation to the United States and is preparing to demonstrate and apply the technologies to the treatment of concentrate, produced waters, drainage, and other waters. Their technologies need to be optimized for the municipal concentrate types found in the United States and for the U.S. salt markets.

Where multiple salts are recovered and where they have a wide range of solubility, the processing may involve a series of alternating concentration and treatment steps. The initial steps recover the salts of lowest solubility; the final steps recover the salts of highest solubility. The concentration (desalination) steps have included RO, NF, ED/EDR, thermal evaporation, thermal crystallization, evaporation ponds (including enhanced evaporation ponds), and shallow solar

ponds. The treatment steps have included such operations as pH adjustment, chemical addition, temperature control, thickening, washing, etc.

Some salts whose market values are low (some forms of NaCl, CaSO₄, etc.) cannot be cost effectively processed by equipment-intensive processing schemes. These salts more typically are recovered by solar pond treatment of specialized water/waste water having high concentration of the salt(s) of interest. This becomes a climate-dependent and land-intensive process not suitable for most locations.

While there are some applications of crude salts of lower quality, many applications require salts to meet quality specifications that may include form, size, and purity. Salts obtained from the initial precipitation may need to be washed to remove surface impurities and even re-dissolved and then re-crystallized or reformed to remove “bubbles” of impurities of highly soluble salts. This processing also allows control over crystal size. Reformed NaCl is produced from crushing, grinding, and dissolving NaCl crystals and then crystallizing under climate-controlled conditions. This “refinement” of salt quality adds value to the salt at the expense of additional production cost.

In general, there is a need for cost-effective equipment/processing not dependent on climatic changes (temperature, rainfall) to allow accurate control of salt characteristics to meet product specifications. This is typically not possible with solar ponds.

GEO has such technology and has applied it to a variety of situations. Some details and insights into GEO’s technology are available in their patents. While the exact processing conditions and treatment sequence for a given salt recovery operation are not evident from the patents, it is apparent that the key to their success is a detailed and indepth understanding of the many possible chemical reactions that can take place, including how the reactions are affected by temperature, pressure, pH, other salts, and chemicals present. This understanding allows for precise control and tailoring of processing conditions for a wide range of water qualities and salts. Surface waters often have varying water chemistry, and it is uncertain whether or to what extent these variations affect the process.

5.3.4 General Processing Scheme

An example of a general processing scheme for selective salt recovery is given in figure 5.1. This figure is taken from GEO’s literature and pertains to treatment of a concentrate containing significant hardness and bicarbonate. Processing schemes for other waters may differ in specific steps but would follow this general scheme of alternating salt recovery steps (SAL-PROCTM) and desalination steps (RO and brine concentrator). Subsystem C represents the maximum energy need and minimum footprint option. Subsystem E represents the lowest energy

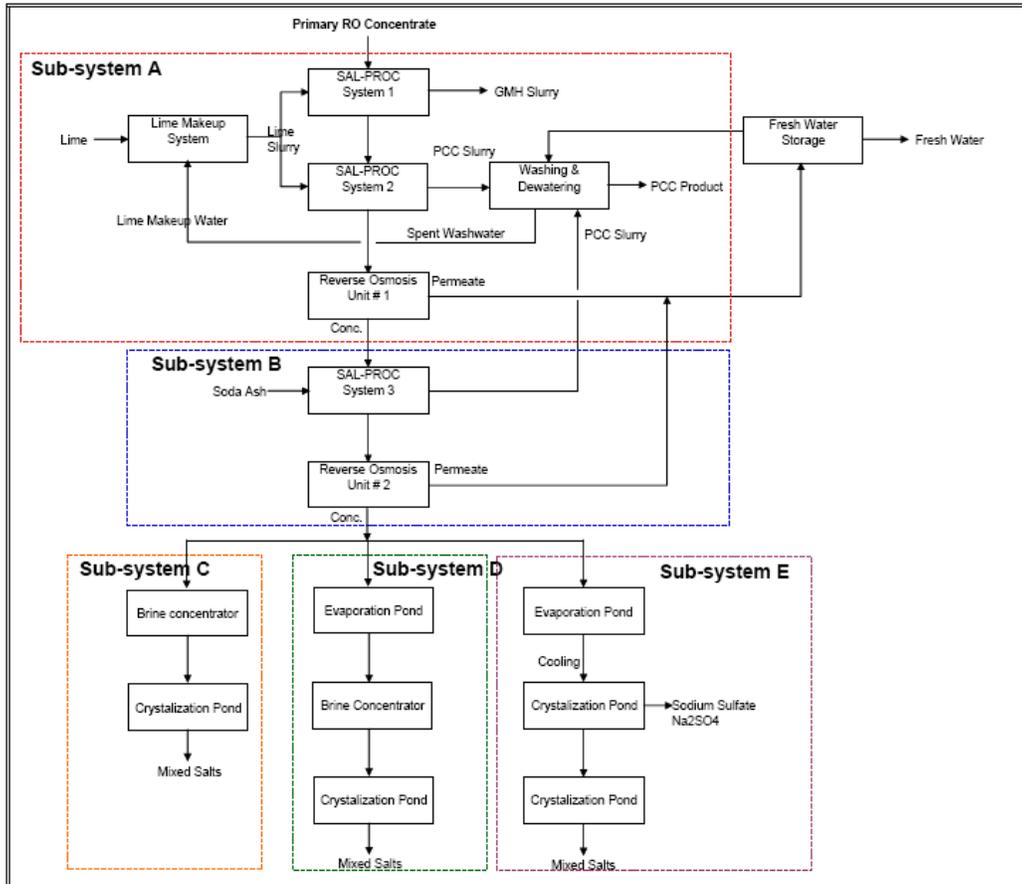


Figure 5.1 Generic block diagram for SSR options.

need and maximum land requirement. Subsystem D is an intermediate case. Processing steps need to be optimized for different feedwaters (concentrates).

Here, GMH stands for gypsum and magnesium hydroxide and PCC stands for precipitated calcium carbonate.

The processing sequence reveals several characteristic aspects of the recovery process:

- Processing is by a series of desalination and salt recovery (SAL-PROC™) steps.
- Multiple salts may be recovered
- Low cost salts (lime) may be added to enable formation and recovery of more expensive salts (such as precipitated calcium carbonate)

Additional information may be found at the GEO's Web site (11).

5.4 Salt Applications and Market Values

5.4.1 Applications

Table 5.1 lists various salts that could potentially be extracted from concentrates using SSR technology and some of their applications.

Table 5.1 Major salts and application areas¹

Chemical Formula	Name	Some Application Areas
CaCO ₃	Calcium carbonate	Paper coating pigment // Filler for plastics and rubbers, special inks, paints, and sealants
CaSO ₄ ·2H ₂ O	Gypsum	Remediation of sodic soils // Manufacture of building products
CaSO ₄ *2H ₂ O+Mg(OH) ₂ Slurry	Gypsum magnesium hydroxide	Waste water treatment // pH buffering // Soil conditioner for sodic soil
CaCl ₂ (liquor)	Calcium chloride	Dust suppression // Road base stabilization // Sodic soil remediation // Cement/concrete stabilizer // Construction industry
KNaSO ₄	Glacerite	Potassium fertilizer
Mg(OH) ₂ slurry	Magnesium hydroxide	Water/waste water treatment // Environmental // Animal stock feed // Feedstock for magnesium metal production // Fire retardant & refractories // Acid neutralization
xMgCO ₃ *yMg(OH) ₂ *zH ₂ O	Magnesium carbonate light	Fire retardant // Feedstock for magnesium metal production // Filler for paper manufacturing, rubber, and paint
NaOH	Caustic soda	Many applications industrially // Basic feedstock for chemical processes // pH adjustment, etc.
NaCl	Halite	Food and industrial processes // Chlor-alkali production // Many industries require bulk salt supply
Na ₂ CO ₃	Soda ash	Water treatment, chemical industry, etc.
Na ₂ SO ₄	Thenardite	Surfactants manufacture // Detergents manufacture // Glass manufacture // Remediation of calcareous soil
NaOCl	Sodium hypochlorite	Disinfection // Chemical industries // Pool chlorine
NaClO ₄	Sodium chlorate	Paper bleaching // Chemical industries

¹ Table is based on information from www.geo-processors.com.

Applications such as using precipitated calcium carbonate in high quality paper appear to be more readily accessible (30). Other salt applications, while representing real needs, are frequently beset with challenges that may limit their use. The following examples discuss this situation.

5.4.2 Example 1: Soil Remediation

A soil remediation example is using CaCl_2 for sodic (high SAR) soils in place of gypsum, which is cheaper and well accepted. Rainfall on sodic soils does not soak into the soil and is lost by evaporation. The soil does not support agriculture, and the water is lost to the local area, as the water does not enter local ground water pathways. Through the addition of calcium salts, it is possible to change the hydraulic conductivity of soils to obtain increased rates of infiltration and reduce the amount of “lost” rainfall and significantly increase the supply of usable water (28).

Current practices for soil remediation include applying gypsum to sodic soils. Research has shown that more effective soil remediation techniques include using calcium and magnesium chloride for sodic soils (30). These products, however, are more costly than gypsum, and farmers are reluctant to pay more money for remediation, even though the more expensive chemicals may be more efficient.

In this example, a large-scale need (soil remediation) could reap large, long-term benefits that include increased agricultural yields and reduced water loss due to evaporation of rainfall. The more beneficial salts available from concentrate processing, however, are often more costly to produce than the salts that are currently used. A formidable challenge to developing this market is to bring about a shift from the short-term focus on chemical cost to a comprehension and appreciation of longer-term benefits and resulting lower “total cost” associated with the other salts.

Increasingly, salts made for this use will need to meet product specifications for or undergo environmental testing for the application.

5.4.3 Example 2 – Dust Suppression

Dust suppression is an existing market for calcium chloride, along with magnesium chloride. Moisture is the key to keeping fine particles in unpaved roads together as it coats all particles and binds them. Calcium chloride absorbs large amounts of water, holds the water tightly, and has a high surface tension that reduces evaporation, coats soil particles with a strong thin film of moisture that reduces friction between particles so they compact readily. Once compacted, the surface tension creates a cohesive force, holds the consolidated base together, and performs a soil sealing, soil stabilization function.

In this example, the market for calcium chloride exists but the product will, in most cases, need to meet established product specifications. The challenges in this case are those mentioned in section 4.2 under beneficial uses of concentrate. Ideally, a beneficial use of the concentrate would be implemented for the life of the desalination plant. In the case of dust suppression, the amount of concentrate or salts recovered through SSR likely would be much greater than for a local dust suppression application.

5.4.4 Market Values

Market values of salt depend upon form and purity and vary over time and location. An example from an issue of the *Chemical Marketing Reporter* of 2006 illustrating the value of salt as a function of grade and form is given in table 5.2.

These chemical listings are based on pricing information obtained from suppliers. Posted prices do not necessarily represent levels at which transactions have actually occurred, nor do they represent bid or asked prices. Price ranges may represent quotations from different suppliers, as well as differences in quantity, quality, and location. Although prices are reported as accurately as possible, they do not carry any guarantees. The prices are intended as a benchmark reference for *Chemical Market Reporter* readers and are not to be used as a basis for negotiations between producers and customers.

Sodium chloride and calcium sulfate (gypsum) (not listed in table 5-2) are among the lower value salts and typically under \$20 per ton. In terms of evaluating the overall economic potential of marketing salts obtained from SSR processes, it is important to note that NaCl is the dominant salt in seawater concentrate, and gypsum is typically the first or second most predominant salt in brackish ground water concentrate. The treatment of calcium sulfate-dominated brackish ground water concentrate, however, does not imply that calcium sulfate will be a product salt. Other calcium salts can be recovered through adding inexpensive reagents to produce salts desired for commercial sale.

5.5 General Feasibility and Potential of SSR

The feasibility of a given site-specific operation to recover and market salts from a concentrate is dependent on many factors. These factors include:

- Volume of concentrate
- Water quality (salts obtainable from the concentrate)
- Quality of recovered salts (i.e., form and purity)
- Reliability, consistency of salt quality
- Types of applications for the obtainable salts (types of markets)
- Existence, size, and reliability of a local market
- Combined income from sale of the different salts

The first of these factors generally limits the application of SSR to larger volume concentrates where adequate amounts of salts are produced to assure market penetration. Thus, SSR is not generally applicable to small-sized desalination plants.

Table 5.2 Salts and market prices

Name	Description	Weight	Price Range, \$
Calcium carbonate	(ground) dry, coarse (9–17 microns) bgs., bulk, t.l.	ton	60–66
	(ground) medium (4–9 microns) bgs., t.l.	ton	95–100
	(ground) fine (0.5 microns) 50-lb. bgs., t.l., f.o.b. works	ton	230–280
	Precipitated, tech. (0.5 microns) 50-lb. bgs., t.l., f.o.b., Adams, MA	ton	264–350
	Ultrafine (0.05–0.5 microns) 50-lb. bgs., f.o.b., works	lb.	0.43– 6.2
	Surface-treated, tech. 50-lb. bgs., f.o.b., Adams, MA	lb.	0.205
Calcium chloride	Conc. Reg. 77–80%, flake, bulk, c.l., works	ton	200
	Conc. Reg. 77–80%, flake, 50-lb. bgs., paper, plastic, works	ton	250–280
	Anhyd. 94–97%, flake or pellet, bulk, c.l., works	ton	275
	Anhyd, 94–97%, flake or pellet, 50-lb. bgs., c.l., works	ton	346–354
	Anhyd. 94–97%, flake or pellet, 50-lb. bgs., works	lb.	0.35
	Liq. 35% basis t.c., t.t.	ton	132–153
	Liq. 45% basis, t.c., t.t.	ton	160–175
Magnesium hydroxide	Slurry, technical, dms, t.l., l.t.l., f.o.b.	dry ton	238–250
	Powder, technical dms., bags, t.l., f.o.b.	lb.	0.45
Sodium carbonate	Dense, 58% Na ₂ O 100-lb. paper bgs., c.l., works, f.o.b.	ton	152–159
	Dense 58% Na ₂ O, bulk works, f.o.b.	ton	127–135
	Light, 58% Na ₂ O 100-lb. paper bgs., c.l., works, f.o.b.	ton	188–215
	Light, 58% Na ₂ O bulk, works, f.o.b.	ton	176
Sodium sulfate	East bulk, c.l., works, frt. Equald.	metric ton	115–130
	Gulf bulk, c.l., works, frt. Equald.	metric ton	110–135
anhyd.	anhydrous		
bgs.	bags		
c.l.	carload		
conc.	concentrate		
equald.	equalized		
f.o.b.	free on board		
frt.	freight		
lb.	pound		
liq.	liquid		
tech.	technical		
t.c.	tank car		
t.l.	truck load		
t.t.	tank truck		
l.t.l.	less than truck load		

Typical costs of landfilling solids range from \$30 to \$60 per ton. To illustrate the swing in potential operating costs possible due to recovery and sale of salts, consider the case where (1) the total income from sale of salts averages \$60 per ton based on all the salts produced, (2) the local landfill cost is \$60 per ton, and (3) the concentrate is 1 mgd in volume with a salinity of 4,000 mg/L. The total amount of salts obtainable from the concentrate in 1 year is 12.2 million pounds. To landfill this amount of solids (neglecting additional solids produced due to chemical treatment of the concentrate to produce the solids) at \$60 per ton would cost more than \$365,000 per year. If instead, the solids could be sold at an average price of \$60 per ton, they would bring an income stream of \$365,000 per year. If the average salt price were \$180 per ton, the income stream would be over \$1.3 million per year.

Assuming these salts were derived from concentrate produced from a BRO plant operating at 5-MGD product flow, this income (\$1.3 million per year) would be equivalent to \$0.60 per kgal of product flow, which represents a substantial offset of typical operation and maintenance costs. Unfortunately, data is not available for the additional capital and operation and maintenance expenses required to concentrate, precipitate, and produce a saleable salt for comparison with this hypothetical income stream.

Each site-specific consideration of the concept will require analysis to determine technical and economic feasibility of the proposed SSR project. The mass of salts available through SSR must be matched with the potential salt market. The feasibility analysis would have to address the issue of a water utility entering into a commercial salt production venture. The situation might be addressed by the formation of a private entity taking the brine or solids from the utility in similar manner to a garbage/recycle company that receives, processes, and reuses waste materials from clients.

Development of value-added products of local need that utilize salts removed from concentrate would avoid SSR dependence on markets for individual salts.

5.6 Chapter Summary

- SSR offers some promise to reduce operating and annualized costs of municipal membrane desalination plants.
- Efforts to implement SSR have appeared in the literature, mostly focused on a limited application or a single-site application.
- Analysis of precipitation pathways provides the basis and approach for developing the SSR site-specific SSR process.

- One company, Geo-Processors USA, Inc., has developed, patented, and licensed technology outside of the United States and are looking to optimize the technology for U.S. applications.
- Potential applications exist for the wide variety of salts obtainable from desalination concentrates.
- Marketing will play an integral role in determining the feasibility of any site-specific application of salt recovery technology.
- In general, salt separation and marketing of salts hold considerable promise to provide a concentrate disposal solution for many locations by significantly reducing operating costs of high recovery processing and reducing the challenges and limitations of disposal of final brine or salts from high recovery processing.
- Of importance beyond providing a cost-effective concentrate disposal solution, the separation of salts and their marketing is a strong step toward achieving an environmentally sustainable solution where water recovery is maximized and salts are recycled.

6. Review of Technologies for High Recovery Processing

6.1 Task Objective

High recovery (including ZLD) processing schemes are a combination of different technologies or process steps. One project task was to consider different technologies that might have potential to be part of a high recovery processing scheme.

6.2 Categories of Technologies

Technologies were evaluated with regard to their different roles in a high recovery process. The following categories/designations were helpful in this regard:

- Evaporative technologies (for final brine volume reduction)
- Solids-liquid separation systems (for final solids separation and concentration)
- Desalination systems
- Contaminant removal systems

The various technologies that were reviewed are discussed in general terms, however, most promising technologies are discussed in further detail.

6.2.1 Evaporative Technologies for Brine Volume Reduction

Within the context of high recovery processing, evaporative technologies may be used to further reduce the volume of final brine prior to hauling and disposing in an industrial landfill. The reduced volume of waste results in reduced hauling costs. The reduced water content brings the waste closer to passing the paint filter test required for noncontainerized disposal at industrial landfills. Solidification of final brine still may be required.

There are many different small-volume evaporative systems used in various industries for final waste water minimization. In many applications, the wastes are hazardous, with per gallon disposal costs of several dollars. Volume minimization can significantly reduce these disposal costs. The evaporated water typically is not recovered. The systems are generally small, with units under

30 gpm in size. Systems include submerged combustion (31, 32) and low-waste-heat evaporation (33), among others. Such technologies may be appropriate for small volume applications.

6.2.2 Solids-Liquid Separation Systems

Brine from high recovery processing may have substantial suspended solids content. Another approach to reducing the volume of the brine is to separate the solids for disposal and to find application for the filtrate. Many approaches are used for such separations, depending on solids amounts, sizes, flow rates, etc. Solid-liquid separation systems include centrifuges, hydrocyclones, and settling tanks. A newer option is Voraxial Separator (34). The technology generates a strong vortex, allowing separation based on specific gravities of fluids and solids. The energy requirement is substantially lower than for centrifuges and also hydrocyclones.

The limitation of such processing is that, while concentrating the solids for disposal, it produces a brine that may be without use. This is particularly true of higher salinity brines, which are usually sodium-dominated. This technology, however, may also be of use in concentrating or thickening product streams as part of a SSR processing scheme.

6.2.3 Contaminant Removal Systems

Regulatory issues surrounding the possibility of contaminants in concentrate or brine and solids derived from concentrate are discussed in chapter 8. If contaminants are projected to be present, they may, within the context of municipal desalination economics, make the desalination plant not feasible, due to higher disposal costs.

If the contaminants are organic in nature, they might, in theory, be removed by a number of different technologies that include cavitation (35), wet oxidation (36), and high energy pulsed plasma (37). The latter technology also has potential to precipitate some metals, including some sparingly soluble salts. These technologies are usually small in capacity and are targeted for industrial waste water markets.

Electrocoagulation is a technology that has significant potential in removing contaminants. It is the subject of chapter 7.

6.2.4 Innovative Desalination Systems

By far the largest category of technologies for increasing product recovery is “innovative desalination technologies.” Although innovative desalination technologies will produce concentrate, brine, or solids for disposal similar to existing desalination technologies, they may do so with better performance and reduced costs. As such, they might be incorporated into a high recovery processing scheme. Some of these systems were recently reviewed (38).

Fluidized Heat Exchanger (FBHX™)

Watervap LLC (39) has developed a heat exchanger that utilizes solids to scour heat transfer surfaces, thus keeping them clean. The system can, thus, exceed precipitation limits in other types of evaporators. Presently, the system is energy intensive, but the concept might be extended to more efficient evaporators, such as in vapor compression systems.

Seeded RO (SPARRO™)

This is a seeded RO system similar in concept to seeded slurry brine concentrators. Calcium sulfate seed crystals are added to the feed and recirculated to provide co-precipitation and adsorption sites for various salts when their solubility limits are sufficiently exceeded. The preferential deposition of sparingly soluble salts on the seed slurry limits scale formation on the membrane. The system uses tubular membranes of sufficient diameter to prevent plugging. The technology has been piloted in South Africa (40) and more recently at the Eastern Municipal Water District in California. Concerns have been raised about membrane degradation due to abrasion by the circulating slurry.

Dewvaporation

This technology is a humidification-dehumidification process that uses air as a carrier-gas within a series of towers to sequentially evaporate water from saline feeds and dew to form a relatively pure condensate at atmospheric pressure. Saline water is evaporated by heated air and deposits on hydrophobic heat transfer surfaces cooled by heat transfer across the surface to the evaporation side. The energy needed for evaporation mostly is supplied by the energy released upon dew formation.

The goal of this technology is to provide a less expensive desalination method for small-scale applications. Pilot tests have provided some encouraging data, but the technology is still in the development stage.

Forward Osmosis (FO)

The technology is not new but has received considerable recent attention with at least four different groups presently conducting research (42, 43). As in RO, water is transported across a high rejection, semipermeable membrane. In RO, high feed side pressure is required to overcome the osmotic force created by the large salinity difference between the higher salinity feed and the low salinity permeate. In FO, a draw solution of high concentration of a nonpermeable substance is used on the permeate side. The relatively less concentrated water on the feed side develops substantial osmotic force causing forward osmotic flow of clean water through the membrane into the draw solution. The nonpermeable substance used in the draw solution is then separated from the low salinity permeate and recycled.

The FO technology is still in the developmental stage. Fluxes using conventional RO type membranes have been relatively low due to concentration polarization occurring in the relatively thick layers of the support structure upon which the membrane is deposited. The different research groups are investigating a variety of draw solutions and different membranes. The key to flux improvement appears to be development of a much thinner membrane while maintaining structural support and high salt rejection.

High Efficiency Electrodialysis Reversal

Although EDR has been a widely accepted and successful desalination technology since the late 1960s, advances in the technology over the last 10 years have not been widely recognized. The classical attributes of EDR relative to RO are still present (lower chemical needs, less restricted feedwater requirements, and higher recoveries); and improved membrane spacers, system design, and operating efficiency have improved EDR performance and cost effectiveness. Of importance to concentrate disposal, EDR frequently can achieve recoveries of 92–94%, thus qualifying as a high recovery system. Combinations of RO/EDR have achieved recoveries of 97% and greater. EDR is most cost competitive on feed waters of less than 2,000 mg/l (44, 45).

Energy-efficient MVR

Aqua Dyne JetWater technology (Aqua Dyne Australia Pty LTD) may offer some energy savings over more conventional brine concentrator technologies—all utilizing mechanical vapor recompression evaporator systems. Energy requirements are touted as being 50% lower than conventional evaporator systems. The systems are in commercial operation and appear to be available in sizes up to 2 or 3 MGD (46).

Capacitive Deionization

A low voltage is impressed across specialized electrode pairs to enable adsorption of ions onto the electrode surfaces. Carbon aerogel has been the favored electrode material due to its unique porous properties that provide very high specific surface area, low hydrologic resistance, and exceptional electrical conductivity. The adsorption capacity is finite and, upon elimination of the electric field, ions are desorbed from the electrodes, allowing capture of the ions and regeneration of the electrode surfaces. The technology is in the developmental stage and appears best suited for low salinity feedwater applications.

HEEPMTM (High Efficiency Electro-pressure Membrane) by EET Corporation

There are two keys to the HEEPMTM technology. The first and primary key is a proprietary and patented ED stack design that significantly reduces the energy requirement and allows processing to high salinities—up to 150,000 and 200,000 mg/L. The second key is a unique processing arrangement where the ED and RO technologies are both used, independent of one another, taking feed from the same working tank. ED product is returned to the tank, and the

RO concentrate is returned to the tank. Thus, the system waste is the ED waste, and the system product is the RO product. This processing arrangement minimizes ED membrane area relative to ED-only systems, while maximizing recovery relative to RO-only systems. The HEEPTM system is applicable to batch, semibatch, or continuous flow arrangements. The advantages are most obvious for batch processing, where the arrangement allows for maintaining a lower feed concentration to the RO system, while the batch volume is being reduced by treatment. Here, the purpose of the ED is to keep the RO feed TDS at a relatively constant level over the high recovery processing time. The arrangement allows for both the ED and RO subsystems to work synergistically, each operating in their respective optimal range.

While processing to high recovery could be done by the ED system alone, the combination of ED and RO is frequently more cost effective. Product quality is also improved with the dual system. Pretreatment to reduce the potential scaling of sparingly soluble salts and silica is the same as used with other RO systems (44).

ARROWTM by O'Brian & Gere

The ARROWTM technology is a high recovery membrane-based treatment system that employs a unique placement of the treatment step that reduces sparingly soluble salts and silica to allow high recovery. Instead of the typical front-end or interstage treatment, the ARROW technology places the treatment step at the back-end after the second membrane unit. The back-end treated water is then recycled, most typically, to the interstage site. The feasibility of this processing scheme is not obvious; however, modeling of the situation reveals that this arrangement can allow very high recovery operation. The primary benefits of this processing configuration are that the size of the stream to be treated is smaller in volume and the process has a smaller footprint. The result is a savings in capital cost. There are variations of the processing scheme that can be used where appropriate. Recoveries are frequently greater than 95% and have been greater than 99% in some applications. Various piloting operations are underway (47).

6.3 Technologies Selected for Further Discussion

Three technologies were selected for more indepth analysis. These technologies are all patented and commercial and have been applied in nonpotable situations. Each could play a role in improving high recovery and ZLD performance and cost effectiveness and do so in the immediate future. The technologies are:

Geo-Processor USA, Inc.'s SAL-PROCTM Selective Salt Removal Technology

SSR and the GEO's technology were discussed in chapter 5. Geo-Processors USA, Inc (11) appears to be the only company that has approached selective salt recovery from a broad perspective in considering how to treat a wide variety of waters and waste waters. Beginning in the early 1990s, their technology was

developed and licensed outside of the United States. It is presently being optimized for U.S. municipal applications. There are plans for piloting and demonstrating this technology in the United States in 2008. Selective salt recovery and the SAL-PROC™ technology were discussed in chapter 5 as it is an approach to concentrate management in addition to being a treatment technology.

Powell Water Systems' Electrocoagulation (EC) Technology

EC is not a new technology but has suffered from high energy costs and availability in only small system sizes. Powell Water Systems appears to have patented designs that significantly reduce the energy requirements and allow individual modules to treat 500 gpm of system feed. During the past couple years, the author conducted bench-scale tests of the EC technology under a separate contract (48). The study and general results are described in chapter 7. The EC technology would be used as a pretreatment step to remove suspended solids and a wide range of metals, organics, and other contaminants. The technology also could be used as a final polishing step to remove a spike in concentration of a contaminant. A description of EC technology and the results of an EC study, conducted under a separate contract, are discussed in chapter 7.

VSEP™ by New Logic Research, Inc.

VSEP™ stands for vibratory shear enhanced process (49). The process membrane module is simple, consisting only of a flat sheet membrane module mounted in a mechanism that vibrates the module. The high shear at the membrane-solution interface impedes adhesion of sparingly soluble salts, silica, and foulants on the membrane surface and, thus, allows greater recoveries than the conventional stationary membrane configurations, which are limited by scaling of the membrane surface. Sparingly soluble salts and silica are allowed to precipitate; and therefore, high recoveries are attained without pretreatment or adding chemicals. Due to mechanical considerations, the individual module size is limited to flows of 60 gpm; however, many individual modules are easily combined in parallel into a multiple MGD processing scheme. VSEP™ technology is briefly discussed in the following section.

6.4 New Logic Research's VSEP™

A cost analysis of the VSEP™ system was recently developed, and the technology description here borrows heavily from that report (6). New Logic Research developed the technology in the 1980s, and marketing focus and applications have been for difficult to separate solutions such as food waste streams and oil/water mixtures. More recently, a successful potable water pilot test was completed at Big Bear Ski Resort in California (50), and one is being planned for the San Antonio Water System (51). The VSEP™ technology is not cost-competitive for a first stage (low recovery) desalination step; thus, it is used more often to treat concentrate/waste from a first stage RO or EDR system—

without the need for chemical treatment or processing of the concentrate/waste prior to processing.

As solutions and TDS become more concentrated within the VSEP system, the osmotic forces increase until precipitation of a salt occurs. Precipitation reduces the TDS level and, thus, the osmotic force. Processing using conventional high pressure RO pumps can proceed to recoveries beyond what spiral wound RO units would achieve with the same pressures. Recovery in an individual VSEP™ unit may become hydrodynamically limited at very high recoveries because so much water is removed that the velocity of concentrate in the flow path is reduced to a very low level. In this case, the concentrate from the VSEP™ unit may be fed to a smaller, second VSEP™ stage for additional recovery.

The flat sheet membrane/module packaging arrangement involving stainless steel pressure vessels allows for higher pressure/higher osmotic force operation. Current commercial equipment can process waters up to the limit of sodium sulfate precipitation (typically around 150,000 mg/L). Higher pressure units under development will likely push beyond this limit.

The VSEP™ system has a small footprint relative to other membrane systems with an individual module skid (about 60 gpm) measuring 4 by 5 feet.

Most VSEP™ applications in the past have been in industries with difficult to treat waste waters frequently containing substantial organic fractions. The application to ‘cleaner’ waters with low organic levels is a more recent one. A potable water pilot system utilizing a VSEP™ unit after a standard brackish RO unit has recently achieved recoveries up to 92% operating directly on the first stage concentrate (representing an overall recovery based on original feed of 98%).

6.4.1 Osmotic Forces

When seawater is concentrated to between 65,000 and 75,000 mg/L (depending on the seawater) using standard high pressure pumps, increased osmotic forces cause the net pressure driving force for water permeation to decrease to an unacceptable level. Osmotic force is based on the number of ions (i.e., molar concentrations) rather than the mass. The relatively low recovery limit for seawater desalination reflects seawater chemistry being dominated by sodium chloride salts. For waters containing salts of higher molecular weight than NaCl (most are), higher mass concentrations can be reached before the osmotic limit occurs. In most brackish waters then, due to the different makeup of water constituents relative to seawater, these same osmotic forces are not generated until mass concentrations are much higher. This is shown in table 6.1 where the salinity resulting in an osmotic force of 54 atmospheres is given for different salts.

Table 6.1 Salinity at which osmotic force reaches 54 atmospheres

Salt	Salinity, (mg/L)
NaCl	65,000
NaHCO ₃	71,869
CaCl ₂	83,300
Na ₂ SO ₄	105,800
Ca(HCO ₃) ₂	106,307

It is apparent that ground waters dominated by salts other than NaCl can be concentrated to higher levels before the commonly accepted osmotic force limitation for membrane desalination is reached.

One implication of this is that, in systems such as the VSEPTM, feed solutions can be concentrated to levels higher than 65,000 mg/L before osmotic forces become limiting. When a solubility limit is reached and a precipitate forms, the TDS and osmotic force decrease. As the solution is further concentrated, the TDS level and osmotic force will increase until another salt begins precipitating, and then decrease as precipitation takes place. Further concentration will increase the TDS and osmotic force again until another salt is precipitated.

The VSEPTM system with standard RO pumps has reached salinities of 100,000 mg/L and beyond on some waters. With higher pressure pumps, even higher salinities can be reached.

6.5 Approaches to High Recovery Processing

From analysis of different technologies that might impact high recovery processing, it is apparent that several different approaches to attain high recovery have been taken. These are represented in figure 6.1.

Some processes allow precipitation of sparingly soluble salts and silica. The precipitates are kept from scaling the membrane surface by either circulating a slurry of calcium sulfate to provide a site for precipitates to adsorb onto (seeded slurry brine concentrators and the SPARROTM technology) or by vibrating the membrane module to create a high shear force at the membrane-solution interface that will keep precipitated solids in bulk solution away from the membrane surface (VSEPTM technology).

The most common approach is to treat the concentrate prior to a second membrane stage to remove the possible precipitants and/or, in the case of silica, to operate a second stage at high pH to avoid silica scaling. This approach has been taken by Aquatech's HEROTM technology (52). Most of the more recently funded research projects consider front-end of interstage treatment.

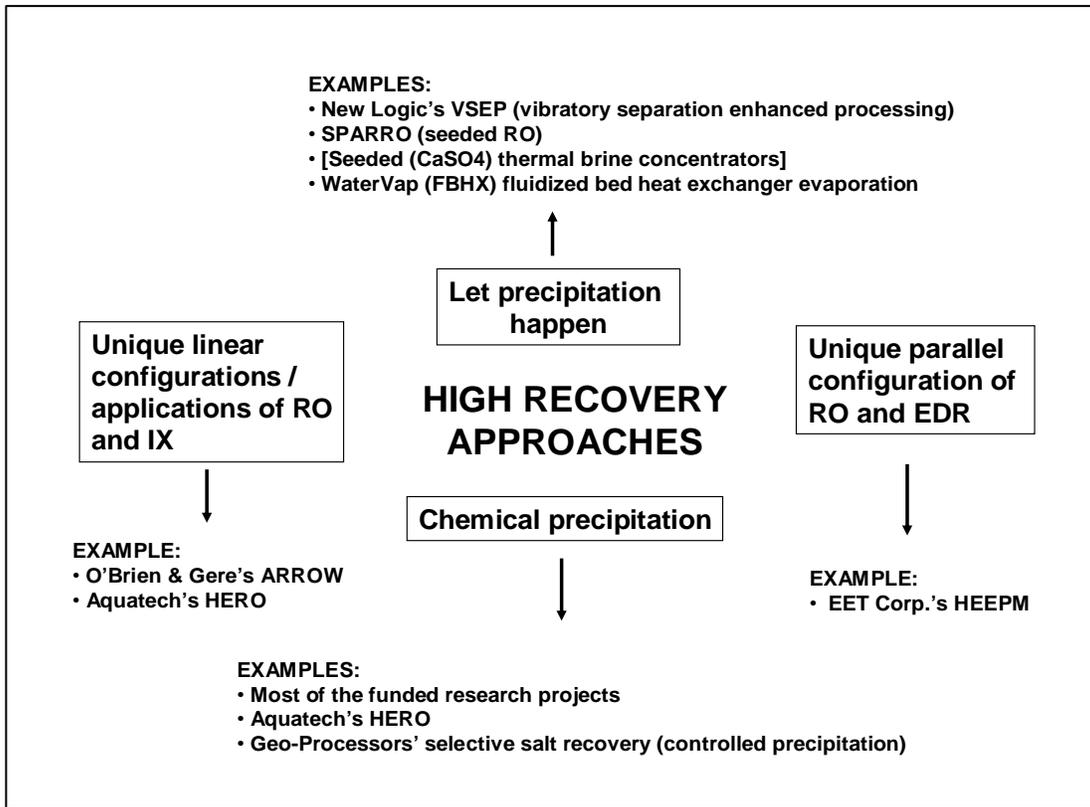


Figure 6.1 High recovery technical approaches.

The other two general approaches are patented processes developed for other industries that have unique, non-intuitive flow configurations, along with treatment, to permit high recovery (the ARROWTM and HEEPMTM processes).

6.6 Chapter Summary

Various technologies were considered for their impact on high recovery processing. Many are still in the development stage, dealing with a variety of technical challenges. Development of such new technologies may lead to cost reductions that will have future impacts on high recovery processing. The technologies considered to have potential impact in the immediate future include:

- Geo-Processors' SAL-PROCTM selective salt removal technology
- Powell Water Systems' electrocoagulation technology
- VSEPTM by New Logic Research, Inc.

Each of these technologies is discussed in more detail in this report. Common characteristics of these technologies include that they are patented, commercial, and have been or will soon be piloted in potable applications.

A general conclusion from evaluating technologies is that there are technologies that have been used in other industries or are being developed for other applications that should be considered in meeting the goal of reducing high recovery processing costs.

7. Electrocoagulation Study

7.1 Introduction

Electrocoagulation was selected for further analysis as one of the promising innovative technologies that might become part of a high recovery processing scheme (chapter 6). During the project, the author conducted laboratory studies of EC under a separate contract (48). Some of those results are relevant to the discussion of high recovery technologies.

The study objectives were to determine the non-optimal removal capabilities of EC on a wide range of chemicals and to determine what role EC might play in a membrane-based processing system. The ‘non-optimal’ qualifier denotes that with the many system variables and chemicals tested, neither time nor budget allowed for optimal contaminant removal conditions to be determined.

7.2 Background – Electrocoagulation Technology

7.2.1 Description of Technology

EC is the application of electrical potential across electrodes placed in a moving solution to be treated. Above a characteristic voltage, dependent on the electrode material, some of the electrode will dissolve (become ionized) in solution. In this way, and only this way, EC resembles chemical coagulation—in that iron or aluminum ions, for instance, may be introduced into the solution to be treated. The EC process goes beyond chemical coagulation since electrical current moves through the solution and promotes several other mechanisms that influence removal of species from solution. This includes the destabilization of colloids and oxidation-reduction reactions, to name just two.

More generally, the removal capabilities of EC are thought to be a result of several different treatment effects that include:

1. Seeding, resulting from the anode reduction of metal ions to metal that become new centers for larger, stable, insoluble complexes that precipitate as complex metal oxides.
2. Emulsion breaking that results from the oxygen and hydrogen ions that bond into the water receptor sites of oil molecules, creating a water insoluble separation of oil, drillers mud, dye inks, etc.
3. Halogen complexing as the metal ions bind themselves to the chlorine atom in a chlorinated hydrocarbon, resulting in a large insoluble complex; this permits separation of pesticides, herbicides, chlorinated hydrocarbons, etc., from water.

4. Bleaching by the oxygen ions produced in the reaction chamber, leading to oxidation of dyes, cyanides, bacteria, viruses, biohazards, etc.
5. Electron flooding of the water eliminates the polar/bipolar effect of the water complex, allowing colloidal materials to precipitate; plus the increase of electrons creates an osmotic pressure that ruptures bacteria, cysts, and viruses.
6. Oxidation/reduction reactions are forced to their natural endpoint within the reaction chamber, which speeds up the natural process that occurs in wet chemistry.

The EC process is an electrochemical means of introducing coagulants and removing suspended solids, colloidal material, and metals and semimetals, as well as other dissolved solids from waters and waste waters. EC has been successful in removing pesticides and radionuclides, and is effective in removing bacteria, viruses, and biohazards, etc. Most systems use direct current where electrode plates are sacrificed (dissolved into solution), causing increased high metal concentrations that end up as oxide precipitates. Due to improved process design and equipment materials, this electrical technology now offers advantages over chemical processes.

Although EC equipment has been available for several years and significant removal capabilities have been reported, only recently have design improvements made cost effective and larger volume treatment possible (53). The application of EC as pretreatment to membrane processes has not been reported in the literature, and only one example (EC in front of RO at a car wash) has been identified. The research undertaken was of an applied nature, using bench-scale equipment of a commercially available technology.

7.2.2 Applications

EC has been successfully used for (53, 54, 55, 56, 57):

- Removing metals and oils from waste water
- Recycling industrial waste water
- Reconditioning antifreeze by removing oils, metals, and dirt
- Treating effluent prior to discharge for removal of silica, hardness, suspended solids, and dissolved solids
- Removing bacteria and chlorine
- Treating drinking water
- Removing heavy metals

Specific applications include:

Textile and dye industry	Cooling towers
Ground water remediation	Water reuse
Process rinse and waste water	Metal recovery
Potable water	Influent/effluent water control
Industrial waste water	Pretreatment for drinking water
Oil emulsion breaking	Medical waste remediation
Antifreeze recycling	Removal of non-ionic colloids
Landfill runoff	

7.2.3 Comparison with Chemical Coagulation

Chemical coagulation chemicals end up in the sludge, increase its volume, and make the sludge more difficult to dewater. They also may increase the TDS content of the recovered liquid. EC potentially can reduce concentrations below that possible with chemical precipitation while eliminating the use of expensive chemical agents. EC produces a cleaner water than either chemical precipitation or sedimentation (58). Table 7.1 provides a comparison of removal percentages:

Table 7.1 Comparison of removal percentages from different treatments (58)

	Electrocoagulation (%)	Chemical coagulation (%)	Sedimentation (%)
Many metals	95–99	80–90	50–70
Biological oxygen demand (BOD)	50–98	50–80	25–40
Bacteria	95–99.999	80–90	25–75

The EC floc tends to contain less bound water, is more shear resistant, and is readily filterable. Perhaps most important, EC can precipitate out large quantities of different contaminants in one operation.

Table 7.2 lists specific removal capabilities for EC found in other literature (53, 54, 55, 56, 57).

EC produces an environmentally friendly sludge ranging from 6 to 7 pH. Metals in the sludge at this pH range are stabilized in a nonhazardous form as oxides, and they pass the USEPA toxic characteristic leaching procedure (TCLP) and California Title 22 soluble threshold limit concentration (STLC) and total

threshold limit concentration (TTL) leach tests. Chemically produced sludge, on the other hand, is usually in the caustic pH range, with metals in the form of hydroxides. In this form, the metals can become soluble again at the neutral pH range of around 7. In addition, the volume of chemical sludge is much greater due to the presence of most of the added chemicals.

Table 7.2 EC percent removal capabilities

Removal focus	% Removal
BOD	90%+
Total suspended solids (clay, silt, coal dust, etc.)	99%+
Fats, oils and grease in water	93 to 99%+
Water in sludge	50 to 80%+
Heavy metal	95 to 99%+
Phosphate	93%+
Bacteria, viruses, cysts	99.99%+
TDS	15 to 30%+

7.2.4. Summary of EC Benefits Relative to Chemical Coagulation

- EC requires no chemicals or associated safety requirements.
- EC kills virus and cysts as well as coliform bacteria.
- EC provides better removal capabilities for the same species.
- EC removes a greater variety of contaminants.
- EC produces a cleaner water.
- EC produces less sludge.
- EC sludge is more readily filterable.
- EC sludge contains metal oxides that pass the leachability tests.
- EC sludge may be utilized as a soil additive.
- EC sludge disposal costs are lower (lower volume and nonhazardous nature of the sludge).
- EC has minimal setup time; turn on the switch.
- EC has no temperature effect; will operate over a wide range of temperature.
- EC has no moving parts.
- EC has small space requirement; a 1-MGD (3,785-cubic-meters-per-day) system would occupy less than 500 square feet (46.5 square meters).

On the disadvantage side relative to chemical coagulation, EC is an empirical water treatment technology whose performance basis is not well understood and whose performance is not easily predicted. There are no standard reactor designs and relative little discussion of underlying principles. Historically, energy costs have been considered high for many applications, and individual units have been restricted to small applications on the order of 50 gpm or less. More recent designs, however, have significantly lowered energy costs and have permitted individual units to be designed for applications of over 2,000 gpm (53).

7.2.5 Other Comments

EC will not remove low molecular weight organics, sodium, potassium, chloride, and other monovalent ions. It will remove pesticides and radionuclides (such as from the use of warheads using depleted uranium).

7.2.6 Costs

Over a wide range of applications, capital costs for EC typically range from \$1 to \$3 gpd while operating costs are from \$0.10 to \$1.50 per 1,000 gallons (53, 54, 55, 56). These costs do not reflect several of the cost benefits mentioned above. Costs of chemical coagulation are also very application dependent and are increasing due to higher costs of chemicals and higher solids disposal costs. As discussed, the amount of chemicals and the amount of solids produced are significantly less for EC. Only a few cost comparisons have appeared in the literature (53) reflecting the higher chemical coagulation costs for specific applications considered.

7.3 Study Methods

7.3.1 Powell Water Systems EC Technology

While there are several companies making EC equipment, it appears that some designs are more energy efficient and scalable to larger applications. Conventional EC technologies are limited to the size of a single stand-alone processing unit. Most systems are limited to approximately 20 gpm by design constraints. The Powell Water Systems' units (53), however, can be designed up to close to 1 MGD per unit. These systems contain simple plate electrodes and blades that are inexpensive and easy to install and remove. This is unlike most other designs that feature machined electrodes with laser-drilled holes for mounting. The energy use has been decreased significantly relative to that of many conventional EC designs using separate, simple, flat, multiple blades with power attached to only a few of the blades. Powell Water Systems has several patents on their unique designs.

7.3.2 Bench-scale Test Unit

Due to the many varying parameters and number of tests that were conducted, it was both convenient and necessary to use a small bench-scale EC system. The tests used a 1.0-liter-per-minute EC unit manufactured by Powell Water Systems. The test unit is pictured in figure 7.1

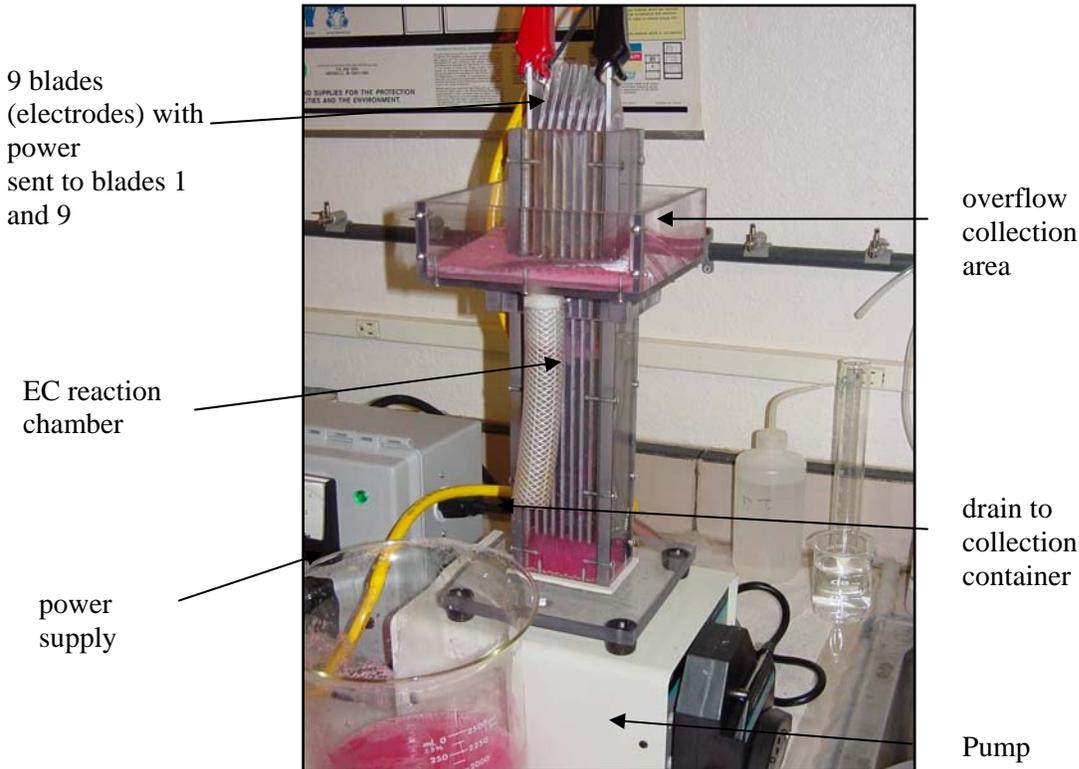


Figure 7.1 Electrocoagulation bench-scale test system.

The Power Water Systems' 110-volt bench-scale demonstration EC unit consists of power supply, peristaltic pump, reaction chamber, metal blade sets (iron and aluminum), and supplies.

Power was transmitted from the power supply to the EC electrodes (blades) by cable. Power typically was connected to the two outer blades as shown in the picture. Alternatives to this are possible to generate greater amperage at a given voltage level. At the start of a test run, test solution is pumped into the bottom of the reaction chamber prior to sending power to the blades. Pump and power then are turned on to initiate the run. Because the initial chamber solution volume does not see power during its entire residence time, it is collected separately and discarded as being unrepresentative of the more steady-state treated solution. The test solution flows through the reaction chamber, moving up between the blades before spilling over the top into a holding area, then draining to a collection

container. Most tests involve small volumes of feed solution (less than 1 gallon), run for less than 5 minutes in a once-through mode.

EC treated solution contains floc generated during treatment. These solids were removed from the solution by gravity filtering using Whatman 11 filter paper. Figure 7.2 shows (on the right) a feed solution of high turbidity (494-nephelometric-turbidity-unit [NTU]) latex paint, and (on the left) the floc collected on filter paper and the clear resultant filtrate. Removal in terms of turbidity was 99.61%. Figure 7.3 shows a similar test where the feed solution contained 10 parts per million (ppm) of tannic acid and 10 ppm of humic acid. Removal, in terms of turbidity, was approximately 90%.



Figure 7.2 Treated filtered solution (on left) and EC feed solution (on right) for latex paint test run.



Figure 7.3 Tannic/humic acid feed solution (on left) and treated, filtered solution (on right).

7.3.3 Studies Conducted

Over the course of the research, removal of several different contaminants/chemical species was evaluated. Removal was studied for:

- Suspended solids
 - Oil/water emulsions
 - Humic acid/tannic acid mixtures
 - Latex paint
 - Hydrocarbon condensate from a coal-cleaning operation
- Metals and semimetals
 - Al, Ag, As, Ba, Ca, Cd, Cr, Cs, Fe, I, Mg, Na, Si, Sr, and Zn.
- Pesticides
 - Dichlorodiphenyltrichloroethane (DDT)
 - Chlorpyrifos
 - Lindane
 - Malathion
- Other compounds:
 - Nitrate
 - Phosphate
 - Perchlorate
 - Surrogates for radionuclides
 - Cesium
 - Strontium
 - Iodine

Study variables included:

- Feed pH
- Feed salinity
- Feed flow rate
- Feed temperature
- Electrode blade material (iron, aluminum)
- Power to the electrodes (voltage and amperage)
- Background solution matrix
- Contaminant and dosage
- Number of contaminants present in a given test

While treatment of the feed solution by the EC system lasted only a few minutes, monitoring of conditions, filtering of solutions, cleanup of the system, etc. extended the run time to over 30 minutes.

Removal of suspended solids was indicated by turbidometer readings. Removal of inorganics was determined by specific analysis for the individual species. Removal of pesticides was determined by spectrographic methods.

7.4 Study Results

A summary of the EC study results is provided below. Details of the results are included in a separate report (48).

7.4.1 Suspended Solids Removal

In general, very high turbidity removal was achieved in all tests. Individual contaminant removal levels included:

- Latex Paint – Mock Solution: Obtained 99.6% removal for feed turbidity of 494 NTU.
- Oil-Water Emulsions – Mock Solutions: Achieved > 99.5% turbidity removal with one exception (98.3%); oil content ranged from 100 to 200 ppm. The background chemical matrix, where the six different solutions were used, did not appear to have any effect on removal.
- Tannic and Humic Acid Mixture – Mock Solutions: Test runs were made with 10 ppm of each acid. Removal levels were from 88 to 98%; not as high as compared to test runs using different contaminants; likely due to a broader range or smaller size of the tannic acid solids.
- Silt – Mock Solutions: The silt was obtained from a local creek bed. The mixture contained some visible solids that settled with time. The solution was filtered (11 micron) to provide a feed solution having turbidity of 612 NTU for the test runs. Two test runs were conducted at different initial pH levels and slightly different solution makeup. Both runs gave high removal levels (99.9 and 99.6%).
- Hydrocarbon Condensate – Real Water: Water was obtained from a coal cleaning operation. The solution was of low conductivity, as reflected in the low amperage level at 100 volts during testing. The feed was jet black and had a very odorous and visually obvious organic nature. The solution left a brownish film adhering to glass container walls of the test apparatus. Good removal levels (>99.5%) were obtained at higher amperage and lower pH.

Test solutions containing suspended solids consistently yielded the highest removal levels at low power among all the contaminants studied. There was no minimum power threshold evident before high removal levels were attained.

7.4.2 Metals and Semimetals Removal

The level of removal of the test ions and compounds varied considerably. Table 7.3 gives the ranges in removals found over the range of conditions studied (background matrix and pH).

Table 7.3 Percent removal ranges for various elements

Element	% Removal Range
As	24–99.5%
Si	0–99.6%
Ca	0–89%
Fe	65–93%
I	8–92%
Sr	3–99.1%

Some ions were removed at high levels regardless of the background solution chemical matrix and operating conditions (Ag, Cd, Cr, and Zn, for example), while others were dependent on background matrix, operating conditions, or both. Examination of the literature showed instances of high removal of most of the ions and compounds studied. Clearly, the removal of many contaminants depends on the water composition as well as the operating conditions—again noting that no attempt was made to optimize removal levels in the study.

Table 7.4 gives removal results from a set of runs made at pH 7, using 8 amperes of current. The current is at an electric potential of 50 volts.

The test runs contained contaminant concentrations from 2 to 10 mg/L, with a background matrix of 1,200 mg/l of mixed salt ions (Na, K, Ca, Mg, Cl, SO₄, HCO₃).

Amperage appears to be the key electrical characteristic necessary for contaminant removal. In some systems, a threshold of amperage was necessary before any significant removal was attained. The salinity concentration had a minor effect on removal levels but major effect on the power required to accomplish removal. The higher conductivity (lower resistance) of higher salinity solutions allowed a given amperage level to be reached at much lower voltage and, thus, lower power.

Table 7.4 Representative removal percentages

Species	% Removal
Cadmium	99.6%
Chromium 6	99.5%
Zinc	97.7%
Arsenic 3 and 5	97.6%
Iron 3	92.5%
Copper 2	92.1%
Silicon	87.2%
Aluminum	56.9%
Barium	30.0%
Strontium	16.7%
Cesium	9.1%

7.4.3 Radionuclide Removal

Nonradioactive isotopes of radioactive species were tested as surrogates for cesium, iodine, and strontium. Strontium was removed at relatively high levels (>73%) in all test runs. Cesium had a low (13.3%) removal in all tests, and the removal of iodine was low except for the higher pH and higher amperage test, where it rose significantly to >91.7%.

7.4.4 Perchlorate, Phosphate, and Nitrate Removal

Perchlorate, phosphate, and nitrate were combined in one solution, and two test runs were made at amperages of 8 and 15. Phosphate was removed at a high level (>96.16% in both tests). Perchlorate removal was 17.3 and 11.0% for the two tests; and nitrate removal was even less at 6.8 and 1.5%.

7.4.5 Pesticide Removal

Feed levels for pesticides varied from 16 to 81 parts per billion in deionized water. Percent removal levels are given in table 7.5.

Either the 95.9% removal of malathion at 0.5 amp or the 37% removal at 1.0 amp is likely incorrect. Except for this one anomaly, contaminant removals increase with increasing amperage.

Table 7.5 Percent removal levels for various pesticides

Pesticide	Amperage Level		
	0.5 amps	1.0 amps	2.5 amps
DDT	83.8	86.9	98.1
Chlorpyrifos	30.0	32.5	90.5
Lindane	46.8	49.4	99.0
Malathion	95.9	37.0	>99.0

7.5 Energy Cost Calculations

Energy cost calculations for the EC tests assumed an energy cost of \$0.08 per kWh and based on the quantity of energy consumed per unit volume of feed water treated by EC. Energy costs ranged from a low of less than \$0.01 to a high of \$10.64 per kgal. Most of the test runs of interest were in the range of < \$2 per kgal, some being substantially lower. The test runs having high energy consumption and costs do not, in general, correspond to the best removal rates obtained. It is further noted that the testing protocols made no attempt to optimize removal results. Consequently, the costs should be viewed as conservative estimates. It also is noted that the energy consumption in the Powell Water Systems' commercial EC units is about 25% less than the energy consumption of the bench-scale test unit due to design differences.

7.6 Chapter Summary

The goals of the research project were 1) to demonstrate the removal capabilities of the EC technology and 2) to define the best application of the technology within the context of providing pretreatment to RO systems.

The most efficient and lowest cost removal was for suspended solids. It was hypothesized that, for removal of dissolved salt ions, energy is required to change valence, form compounds, nucleate, and increase size to obtain floc (suspended solids). However, for species that were already present as suspended solids, energy was needed only to destabilize the floc.

Due to the excellent EC removal of suspended solids and the simplicity of the EC operation, the most promising application of EC in a membrane system was found to be as pretreatment to a multimembrane system of UF/RO or MF/RO. In this function, the EC provides protection of the low-pressure membrane that is more general than that provided by chemical coagulation and more effective. EC is more effective at removing species that chemical coagulation and other technologies can remove, and it removes many species that chemical coagulation cannot remove.

The high removal levels for several potential contaminants suggest that EC might be used in a high recovery processing stream to remove contaminants that might otherwise hinder disposal or use of the brine (or solids) produced. Since power consumption decreases with increasing solution conductivity (salinity), the EC process might be considered as a means of removing contaminants at smaller volume and higher salinity conditions.

8. Review of Regulatory Issues

8.1 Introduction

Membrane desalination concentrate from conventional processing has rarely been toxic, hazardous, or radioactive. When concentrate is further processed to produce a brine or a solid, the increased concentrations of constituents may render the waste toxic, hazardous, or otherwise of concern, even when they are of no concern at the initial concentrate level. It is this situation that is addressed in this chapter. Since high recovery processes have not been used in municipal desalination plants, the probability of this situation occurring is unknown.

The disposal of concentrate, brine, and solids resulting from high recovery processing is regulated based on the composition of the concentrate/brine/solids and the particular disposal method being used.

This chapter discusses the regulatory framework for characterizing and categorizing brine and solid wastes. It does not address specific numerical standards, as they vary from State to State, with many States presently in the process of addressing these issues with regards to radionuclides.

8.2 Specific Disposal Options for Brine

As mentioned in section 4.5.3, disposal options for the brine include:

- Disposal of brine to saline surface water (e.g., ocean).
- Taking the brine to solids via thermal evaporative crystallizers; followed by landfill of solids
- Disposal of brine to evaporation ponds.
- Disposal of brine by deep well injection.
- Solidification of brine by chemical addition; followed by landfill of nonleachable solids/paste.
- Selective salt recovery of one or more salts from the brine in commercial grade quality.
- A combination of the above.

The regulatory issues associated with these options include:

- Surface water discharge: compatibility with receiving water.

- Landfill of solids: both the source and nature of solids dictates the classification of landfill suitable for the solids. Hazardous nature of solids is determined from leaching tests.
- Landfill of brines: brines are not directly disposable in landfills but may be solidified to pass the paint filter tests (59). The solidification process may dilute and immobilize contaminants such that a brine may be hazardous but the solids nonhazardous.
- Evaporation pond disposal of brines: the concern is the effect on wildlife and in particular onshore nesting birds.
- Selective salt recovery processes: contaminants may be removed at an initial processing step prior to isolation of individual salts. In this case, the contaminants may be present in a solid form which would go to a landfill.

8.3 Regulation of Contaminants in Brine

8.3.1 Toxicity

Toxicity is a concern primarily associated with disposal of concentrate or brine to surface waters. Toxicity is determined through whole effluent toxicity (WET) tests (bioassays). In high recovery processing, this disposal option would be considered only in treating low salinity waters, where high recovery would yield relatively low salinity brine; otherwise concentrate generally would be of too high a salinity for surface discharge.

Membrane concentrate usually has very low levels of process-added chemicals. The small amounts of chemical additives and the nontoxic choices available are such that, if toxicity is found, it is most likely due to raw water constituents, including salinity.

The fact that membrane concentrate can be toxic to specific indicator organisms is well established. A handful of historical occurrences of toxicity, as determined in WET tests, have been noted (10). These include concentrates low in dissolved oxygen and high in dissolved H₂S or NH₃ (typical of ground water sources), concentrates with high heavy metal levels due to processing material incompatibilities, and concentrates (such as in southwest Florida) with high levels of naturally occurring radionuclide material (NORM). As a result of these historical occurrences, concentrates from ground water sources intended for surface discharge are routinely aerated to increase dissolved oxygen, degassed to remove H₂S and NH₃ (when present), and processed using materials carefully chosen to avoid metal contamination. In the case of NORM processing in Florida, the concentrates have been disposed of by deep well injection rather than by surface water discharge. In more recent times, some concentrates from ground water sources have had major ion toxicity, a toxicity due to high or low levels of

various common ions such as calcium, fluoride, and potassium (18). This type of toxicity has occurred most often where mysid shrimp, a highly sensitive test organism, has been used in the bioassay, such as in Florida. This type of toxicity is considered differently from other types, as it is due to common ions and is quickly diluted away in the mixing zone close to the point(s) of discharge. Toxicity is also possible when test organisms are exposed to salinity outside their normal range of adaptability.

Toxicity due to high levels of contaminants such as arsenic, perchlorate, methyl tert-butyl ether (MTBE), pesticides, etc. has not, to date, been a major problem in the United States, although the occurrence of situations involving high levels of such contaminants will likely increase due to the treatment of lower quality, impaired source waters.

8.3.2 Hazardous Waste

The Resource Conservation and Recovery Act (RCRA) provides definitions of hazardous wastes. The definitions include both specific lists of hazardous wastes and clear and specific characteristics of such wastes. Membrane concentrate, brine, or solids from concentrate are not among the listed wastes. Concentrate, brine, and solids from concentrate, however, may contain amounts of listed hazardous wastes such that the concentrate, brine, or solids from concentrate may be hazardous wastes. Membrane concentrate, brine, and solids from concentrate are generally not ignitable, toxic, reactive, or corrosive by RCRA definitions. Therefore, hazardous waste concerns are associated with constituents in the original raw water or constituents added during processing that get concentrated enough to render the concentrate, brine, or solids from concentrate to be hazardous. A helpful resource is the August 2006 USEPA document EPA 816-F-06-001, entitled *A System's Guide to the Identification and Disposal of Hazardous and Non-Hazardous Water Treatment Plant Residuals*.

8.3.3 Naturally Occurring Radionuclides

The concern for radionuclides is mostly from waters containing NORMs and their subsequent treatment and concentration to produce technologically enhanced NORMS (TENORMs). Some locations may also have radionuclides from processing or detonating nuclear materials, but this would be the general exception. Treatment processes such as dewatering, ion exchange, reverse osmosis, and other volume reduction and ZLD processes may concentrate radionuclides to a level of concern.

TENORM may be hazardous or not. If a waste has radionuclides present AND is also hazardous by RCRA standards, the waste is considered a 'mixed waste.' In the absence of hazardous materials, a waste containing radionuclides typically is regulated by the same State agency that regulates effluents not containing radionuclides. These wastes may be considered separately from other wastes and regulated as such.

Whereas the guidelines and regulations for wastes other than those containing radionuclides are well defined and relatively straight-forward to understand and document, the same is not true with radionuclide wastes. The radionuclide rule (pertaining to drinking water facilities) went into effect in December 7, 2000, with a schedule through December 31, 2007, for drinking water systems and States to meet requirements. It provided maximum contaminant levels (MCLs) for radionuclides in drinking water and mandated compliance for both drinking water and residuals produced in drinking water treatment facilities. It did not, however, provide guidelines on how to get rid of the residuals. A July 2005 EPA document entitled *A Regulator's Guide to the Management of Radioactive Residuals from Drinking Water Treatment Technologies* provides general guidelines but no numerical standards. In the previous draft version of the document, numbers were provided. USEPA, however, subsequently decided to leave the numbers and details up to the States. States are at various levels of progress in developing policies and standards for disposal of these residuals. The general situation is not easily documented and represented. Many States are dealing with situations of radioactive residuals on a case-by-case basis. Other States have no residual issues at all, due to low levels of NORMs.

8.4 Regulation of Contaminants in Solids

Solids handling and disposal are not typical areas of consideration in conventional municipal membrane concentrate disposal. High recovery systems may produce solids in pretreatment processes such as lime softening, and ZLD systems produce solids as a byproduct of the processing. These solids may come from disposal of brine into evaporation ponds (with precipitating solids building up over time), from treatment processes to remove sparingly soluble salts (such as lime softening), or from final processing of brine into solids by crystallizers or spray dryers.

Solids not containing hazardous materials and not containing naturally occurring radionuclide material (NORMs and TENORMs) may be disposed in a landfill suitable for industrial waste. Disposal costs include hauling (trucking) and tipping fee. The hauling cost depends on the distance between the solids generation site and the landfill. Hauling fees of \$10 to \$40 per ton are not uncommon. Tipping fees are typically in the range of \$15 to \$30 per ton, resulting in a total solids disposal cost frequently in the range of \$25 to \$70 per ton.

Disposal of solids typically requires passing the Paint Filter Liquids Test (59), a method used to determine the presence of free liquids in a representative sample of waste. Wastes not passing the test may be 'solidified' by adding other salts/chemicals, such that they will pass the test.

8.4.1 General Regulation of Solids Content (not Containing Radionuclides)

The regulatory levels for nonradionuclide solid constituents are based on leachable levels. The TCLP is an USEPA SW-846 analytical method (Method 1311) that simulates sanitary landfill contaminant leaching in waste samples. Based upon concentrations of the TCLP constituents and guidelines set forth in 40 Code of Federal Regulations (CFR) 261.4, the solid waste samples can be deemed hazardous or nonhazardous. Different types of leaching tests have been developed in recent years to address a variety of leaching situations. The concentration of constituents leached from the solid are compared to established limits for various constituents. If the leached concentration is greater than the limit, the solid is considered a 'toxicity characteristic' hazardous waste.

8.4.2 Solidification of Solids

Mixing of the solids with cement can prevent contaminants from moving into the environment from treated wastes. This approach may be used to treat solids failing the TCLP tests to render them nonhazardous and likely disposable in standard landfills. The cement used is the same as used in concrete. This solidification/stabilization (S/S) process immobilizes contaminants within the cement/waste material. The immobilization occurs through physical and chemical bonding with the contaminants and, in some cases, via chemical changes within the contaminants themselves (60). The cement-based S/S has been used to treat a variety of contaminants, including both inorganic and organics. The USEPA considers S/S as an established treatment technology and has identified S/S as the best demonstrated available technology (BDAT) for over 57 commonly produced industrial wastes (RCRA listed hazardous wastes).

Brine and slurries can also be solidified by adding other chemicals. Some industrial landfills charge a fee for this service (61).

8.5 Predicting Occurrence of Hazardous Concentrate or Byproducts

The primary regulatory and hazardous waste regarding concentrate is that further concentration to a brine or solid may result in the brine or solid becoming hazardous or radioactive in nature. The potential for this to occur may be predicted to a good extent by analyzing the starting concentrate (or even the starting raw water). In the case of raw water, the concentrate may be simulated using software programs such as those available from membrane manufacturers. It is important to obtain a broad characterization of the concentrate (or raw water) in terms of the constituents present to allow consideration of minor constituents. The level of a constituent present in the final brine or solid may be estimated by assuming that all of that constituent would still be present in the brine or solid.

This calculated level of a constituent can then be compared with available standards to determine if, in this worst case, the resulting brine or solid would be considered hazardous or radioactive.

This task is complicated somewhat in the case of radionuclides, as standards are left up to the individual States and many States are still in the process of defining policies and standards.

8.6 Chapter Summary

A major unknown in treating concentrate streams is whether the additional treatment will produce a brine or solid that is a toxic, hazardous, or TENORM-regulated waste. When this occurs, there will be fewer and more costly disposal options available. Within the municipal economic framework, such options would be cost-prohibitive unless for very small volumes. In this chapter the regulatory issues associated with further processing are discussed in brief. Whether or not treatment of a concentrate would result in a more highly regulated waste is dependent on the concentrate makeup, specific treatment involved, the degree of further concentration, the particular disposal option in question, and the regulations applying to that option—often State-specific. It is beyond the scope of the present report to investigate and document this situation in greater detail. However, the most important step towards answering questions concerning a given concentrate is to obtain a full analytical characterization of concentrate. Analysis of concentrate—as opposed to that of raw water—is important, as levels of contaminants of concern may be found that are below detection limits in the raw water. With such information in hand, early interaction with State regulatory agencies is advised to define the situation-specific concerns that apply.

9. Preliminary Antiscalant Study

9.1 Study Objectives

The purpose of antiscalants is to delay the onset of scaling of sparingly soluble salts and silica in situations where solubility limits have been exceeded. Specifically in RO processing, the purpose is to prevent this onset from occurring within the membrane processing system. The effect of most antiscalants is to slow the kinetics of nuclei growth and crystal growth, such that precipitation will not take place within the membrane equipment and associated downstream plumbing. The residence time in the RO equipment is usually on the order of several to many seconds. Safety factors resulting in somewhat higher antiscalant dosages are necessary to assure confidence, given occasional process fluctuations. As a result, the antiscalant may be functional from hours to even days, depending on the specific concentrate, antiscalant, dose, and post-RO concentrate environment.

Unless concentrate is diluted, eventually precipitation will occur. This can be in holding tanks, in pipelines, in sample containers, and other situations where concentrate might be held or processed. The impact of precipitation in concentrates has not been addressed other than to raise questions about the possible problems that might result. The author is not aware of any documented problematic situations, although surely there are some.

The fate of concentrate is unique in each desalination system after concentrate leaves the membrane system in terms of times, temperatures, agitation, and other variables which can affect the residual time-effectiveness of the antiscalant. Sampling concentrate directly after exit from the membrane system would eliminate variables in the fate path and give an indication of the safety factor afforded by the particular antiscalant and dose used.

Thus the intent of project effort was to better define the residual time effectiveness of antiscalants after the concentrate leaves the membrane system. The objective was the development of a simple test that could be used by desalination plant personnel to determine time effectiveness of the antiscalant in their concentrate. The time effectiveness would be measured as the length of time required until the onset precipitation of sparingly soluble salts is observed.

The steps envisioned in the study included:

- Develop a reliable and simple test to determine the time effectiveness of the antiscalant in a given concentrate for use by water utilities
- Provide several utilities with the test system for study of their concentrate

- Compare the results of lab and field determinations, including the effect of shipping the concentrates

The study was envisioned to be preliminary, semiquantitative, and supportive of future, more detailed studies.

The antiscalant study was unable to achieve the research objective, and the laboratory work was eventually stopped. This chapter discusses the intent of the study, the methodology used, and the results.

9.2 Literature and Antiscalant Manufacturer Information

There are several literature studies looking at the inhibitory effects of antiscalants on sparingly soluble salt and silica precipitation from solution (62, 63, 64). In retrospect, the considerable challenge of obtaining meaningful data was reflected in this literature. Discussions with various antiscalant manufacturers suggested several challenging factors in studying antiscalants: the sensitivity of precipitation onset times, the degree of mixing of the antiscalant solution, and the potential influence of cleanliness and age of glassware (presence of scratches), temperature, and other variables.

From the literature and discussions, the many variables considered in the antiscalant study were:

- Temperature
- Dose
- Humidity
- Flow versus no-flow
- Degree of stirring and agitation in no-flow situations
- Container and circuitry characteristics—ratio of surface area to bulk volume, cleanliness of surfaces, glass surface imperfections (scratches), etc.

The literature also described various indicators of precipitation or the onset of precipitation, which include:

- Turbidity measurement
- Particle counter measurement
- Calcium measurement (for calcium salts)
- pH measurement (for carbonate precipitates)
- Visibility of solids

The study used two synthetic concentrates corresponding to typical concentrates: one with calcium carbonate above its solubility limit and the other with calcium sulfate above its solubility limit.

Solutions were made in two parts to assure all salts were dissolved and to avoid any precipitation prior to mixing of the parts. The two solutions were made in quantities large enough for several runs over several days to eliminate solution preparation as a variable. A run was initiated by pouring the two solutions together in a glass beaker. Various degrees of stirring and agitation upon sampling were used during the course of the run.

9.3 Study Results

Several (127) individual runs were undertaken to develop a consistent protocol for obtaining reproducible results. The dependency of the time required for the onset of precipitation on different variables was significant, and adequate reproducibility was never attained. Using simple, manually operated instruments and the long timeframes (days) necessary for precipitation of solids using synthetic concentrates also added a large uncertainty in the accuracy time measurements. Together, these and other factors compromised the usefulness of the results.

It was determined that a simple testing protocol suitable for utility use was not attainable; and, consequently, the goal of providing this to utilities and having several utilities generate 'field' data was not achievable.

9.3.1 General Description of Test Runs

Experiments began with careful attention to and direct study of the above mentioned variables. The solution agitation emerged as the most significant variable affecting onset of precipitation; therefore, subsequent experiments were conducted at a single stirring speed. Reproducibility was poor, despite taking great care to minimize variability between runs. It was then decided to focus on the two extremes of 'nonmovement' and 'maximum movement.' In the case of 'nonmovement,' the only motion seen by the solution after the initial mixing protocol was a periodic pipetting of sample for turbidity determination. On the other extreme, the solution was stirred at 'maximum' rate limited by the magnetic stirrer. Between these two extremes, the time required for onset of precipitation for a given solution varied significantly—from a few minutes to several days. Reproduction of either extreme was poor other than in terms of order of magnitude.

To get solid formation during an 8-hour day, the effort to achieve reproducibility of results and define protocol for later studies shifted to study of solutions of high (but unrealistic) supersaturation levels of calcium carbonate or calcium sulfate. This enabled precipitation to occur in a relatively short timeframe of less than

6 hours. At these high levels of supersaturation, the eventual precipitation amounts were significant and readily visible. Turbidity changes were measured well before this visible change occurred. When lower (more realistic) levels of supersaturation were studied, the elapsed times for onset of precipitation for concentrate solutions with antiscalant were frequently many days—especially in the case of ‘nonmovement’ test conditions. The amount of precipitation that occurs in these low level supersaturation cases can be minimal, such that detection by turbidity or visible signs was difficult. Frequently, very small amounts of precipitation occurred while the onset was not observed.

Another challenge with antiscalant tests was to determine which ‘degree’ of movement is most meaningful (reproducibility aside). Examination of literature shows a variety of conditions used for antiscalant effectiveness tests. (The literature also described the lack of reproducibility of the data—similar to this study.) When the focus of antiscalant studies is on its behavior within the RO system, perhaps the most sensible testing condition (and related movement of the solution) involves running a solution through a membrane system (62). However, when the focus is on the behavior of the antiscalant after the concentrate exits the RO system, the test conditions (and related amount of movement) are more arbitrary.

It was judged that, with sufficient care, more sophisticated equipment, and suitable protocols it would be possible to achieve better reproducibility. However, data from the literature using much more sophisticated equipment still showed considerable time scatter in precipitation onset data.

Considering the arbitrariness of the test conditions, the lack of data reproducibility regardless of the test conditions, and the difficulty of detecting precipitation onset under realistic supersaturation levels, it was decided that definition of a suitable protocol that would give reproducible results was not possible within the confines (time and budget) of the project.

9.3.2 Specific Test Runs

Results from a limited number of the over 100 test runs are described in this section to better illustrate the challenges with reproducibility and the influence of agitation. Figure 9.1 shows a series of runs with the same starting composition and conducted in the same manner, with the exception of one run labeled ‘no stir.’ The ‘no stir’ run was conducted with minimum agitation of the solution, and it has one of the longest delayed precipitation onsets. Scatter in the results reflects the lack of reproducibility. Figure 9.2 provides the same data minus the high and low runs and the single ‘no stir’ run. Figure 9.2 shows fair reproducibility. The solutions used in these runs correspond to very high supersaturation levels that are unrealistic relative to field situations.

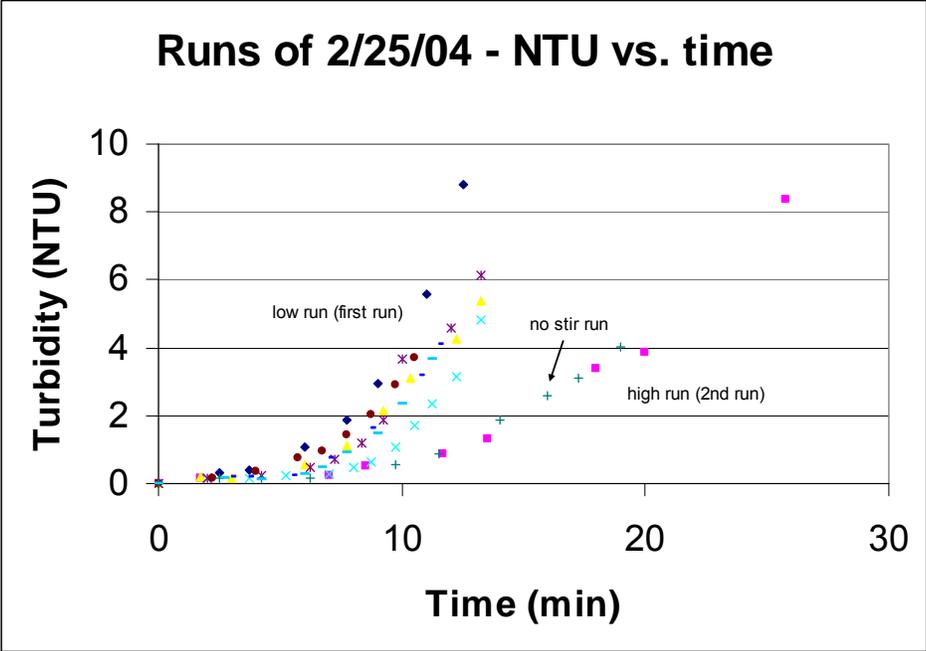


Figure 9.1 Test runs 54 to 66.

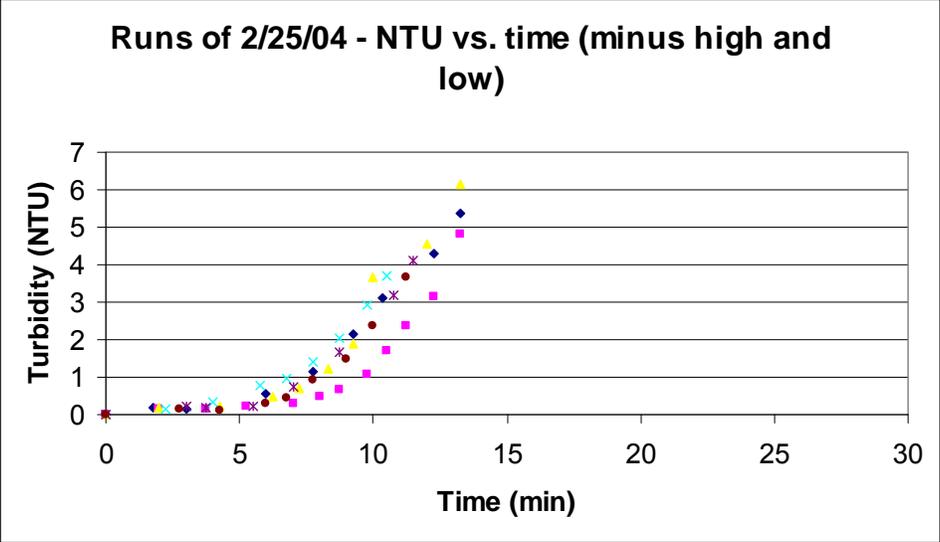


Figure 9.2 Test runs 54 to 66 with high, low, and 'no stir' runs removed.

A series of test runs starting with a slightly different highly supersaturated composition was made to compare maximum agitation (stirring) results with 'no stir' results. Turbidity levels were measured periodically. In the 'no stir' cases, turbidity was less than 1.0 NTU after 2 hours. In the maximum agitation runs, turbidity increased to greater than 1.0 NTU in less than 10 minutes. The three maximum agitation runs are depicted in figure 9.3, again reflecting the lack of reproducibility.

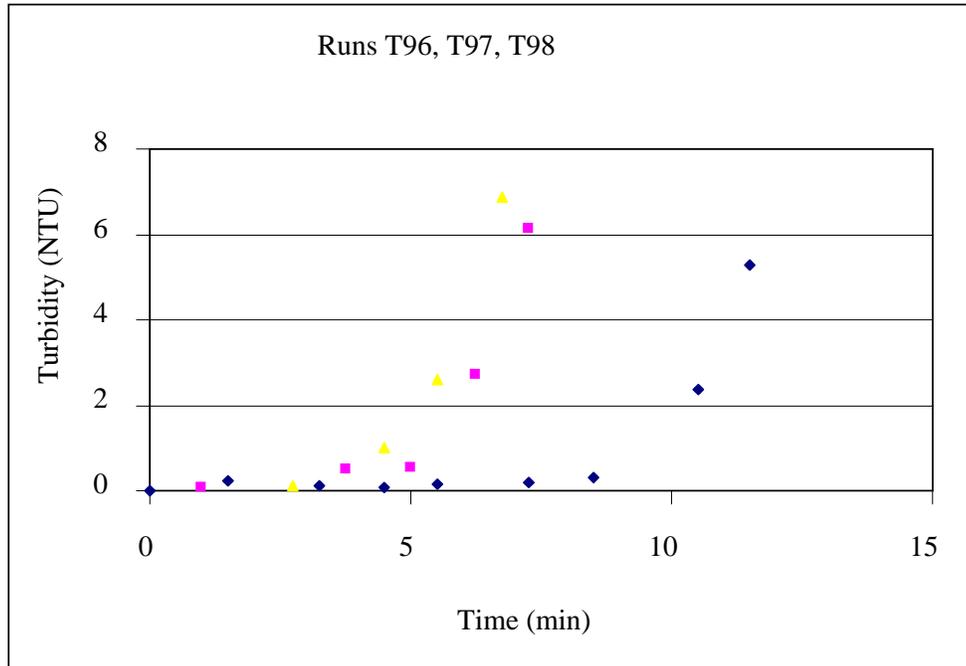


Figure 9.3 Three maximum agitation runs.

9.3.3 Experimental Observations

Some of the observations noted during the many test runs included:

- Turbidity values prior to any increasing trend were consistently less than 0.5 and frequently less than 0.3 NTU.
- Visible indications of solids typically occurred at about turbidities of 5 NTU.
- Mixing of two solutions at the beginning of each run proved to be helpful in standardizing the protocol and reducing a source of variability. For calcium carbonate and calcium sulfate systems, one solution contained all ions except for calcium. The second solution, which was added to the first at the initiation of a run, was a CaCl_2 solution. Makeup of both solutions was predetermined to provide the desired mock concentrate.

- Where open beakers were used along with minor stirring (and, thus, long times prior to solid formation), evaporation from surface lead to formation of a scum assumed to be precipitation at the solution-air interface. Thus, take care to guard against unwanted evaporation effects.

9.4 Chapter Summary

The goal of the antiscalant study was to develop a simple approach for utilities to use to determine residual antiscalant effectiveness in their concentrates as measured by the time delay until onset of precipitation. Although the fate of concentrate in each desalination system is unique in terms of transit time, temperature, agitation, and other variables which can affect the residual time effectiveness of the antiscalant, the idea was to sample concentrate directly after exit from the membrane system. The approach taken was to develop the test protocol and simple equipment in a lab setting using mock concentrates and then to use the testing system at various desalination sites.

Due to the challenges of obtaining reproducible data using simple approaches and simple equipment at the lab setting, this goal was not met. Only qualitative results were obtained for unrealistic concentrations that would not be found in the field.

10. Conclusions

The purpose of the project was to examine issues and options dealing with further treatment of membrane desalination concentrate and to identify promising avenues for resolving the growing challenges of municipal concentrate disposal.

Several tasks were undertaken to address this purpose. The conclusions reached below are the results of task work. The conclusions are only applicable to municipal desalination plants in the 50 United States.

10.1 Conventional Concentrate Disposal Options

Use of conventional disposal options is geographically dependent, such that only a few options are generally available for a given plant site.

Although over 98% of all municipal desalination sites utilize one of the five conventional disposal options (surface water discharge, discharge to sewer, subsurface injection, evaporation ponds, land application), using the options is very location-dependent. Florida is the only State in which all five conventional disposal options have been used. Using the options is very regionally dependent. Over 96% of the deep well injection sites are in Florida. Only three States utilize evaporation ponds (Texas, Arizona, and Florida). Only two States utilize land application (Florida, Texas), and 20 of the 25 States that have desalination plants utilize only surface water discharge and discharge to sewer. Availability of conventional disposal options is also very site-specific, as regionally available options may be at different distances from the desalination plant, making some of the options not feasible.

The use and feasibility of deep injection wells for municipal concentrate disposal has been very limited, except in a few locations.

Class I wells for industrial wastes are used in several States for disposal of wastes from nonmunicipal industries. Only three States at present utilize such wells for municipal concentrate disposal. In general, hydrogeological parameters of aquifers required by regulation limit using deep injection wells. Florida, the site of most of the deep injection wells used for concentrate, has the highest concentrate injection rate for Class I wells, which is an indication of favorable aquifer characteristics—one individual well has an injection rate of 22 MGD. Texas, the State with the second largest injection rate, is where most new consideration of deep well injection for concentrate is taking place. Texas has one well with an injection rate of 3 MGD. The next largest injection rate for Class I deep wells in other States is 0.9 MGD (North Dakota). In most other States having Class I wells, the largest injection rate is below 0.3 MGD. Thus, the availability of deep injection wells is not widespread.

Federal regulatory and general technical requirements for deep well injection are not often found in most other States; these regulatory requirements include:

- An injection aquifer that is structurally isolated from overlying drinking water aquifers
- An injection aquifer of sufficient capacity to receive concentrate over the life of the desalination plant
- An injection aquifer with sufficient injection rate to minimize the number of individual wells necessary to inject the concentrate
- An injection aquifer essentially free from seismic activity

Additionally, some States do not permit Class I deep injection wells.

The use and feasibility of evaporation ponds are very limited

The use of evaporation ponds has been restricted to very small desalination plants in States where climate conditions allow year-round operation. A relatively high net evaporation rate of 2.0 gpm per acre results in the need for 347 acres of evaporation surface for 1 MGD of concentrate. With the capital cost of evaporation ponds generally ranging from \$100,000 per acre to over \$400,000 per acre, a 1 MGD concentrate could cost from \$35 to \$140 million—a prohibitively large cost for many plants. Consequently evaporation ponds are severely limited, not only by climate restrictions but also by land availability and cost.

Significant (65) advancements have been made in enhanced evaporation technologies (such as the WAIV technology) that can reduce area requirements by a factor of 5 or more. Per acre capital and operating costs for enhanced evaporation ponds are higher than for standard pond design, but land acquisition costs are significantly lower because enhanced evaporation reduces the land area required to achieve evaporation. The net result is lower capital costs and higher operating costs than that for a standard pond design resulting in a lower annualized cost for enhanced evaporation.

The use and feasibility of land applications are very limited.

The land application of concentrate (by spray irrigation, percolation ponds, and rapid infiltration basins) has been restricted to very small plants in States where climate permits year-round operation. Land applications are restricted by ground water protection laws that typically require the dilution of concentrate to meet either TDS standards or individual constituent standards. The resultant larger volume (flow) concentrate requires significant land area and a distribution system which limits the application to small desalination plants.

A growing concern surrounds the issue of salt loading for surface water discharge, discharge to sewer, and for land application, which will increasingly limit disposal via these options.

Many waters have discharge standards for various parameters which are higher than ambient levels. This provides capacity in the receiving water to accept discharges of waters having higher levels of such parameters. Discharges may increase the ambient level of constituents or TDS; and, with more and more dischargers doing this, eventually the ambient levels will approach the receiving water standards. In many cases, mixing zones are allowed where the discharge concentration of one or more constituents (or of TDS) is greater than that receiving water standard. Upon dilution by the receiving water, the receiving water standard is met at some distance away from the discharge location. In some cases, TDS is not directly regulated by a receiving water standard but is indirectly controlled by chloride and sulfate standards. In this situation, the TDS of the receiving water can increase until the chloride and sulfate limits are reached. In all these situations, the receiving water is becoming more loaded with one or more salts. This practice of ‘salt loading’ is not allowed where receiving water standards are violated. At some point, additional dischargers will not be allowed, or the existing discharges will be subject to more stringent regulation. Such a situation has already occurred in the Denver basin for the South Platte River.

Growing challenges have made and will continue to make finding a feasible concentrate disposal solution more difficult.

Growing challenges in finding a feasible concentrate disposal solution include:

- *Public perception* plays a role during permit application review when the public can comment on applications. Perceptions colored by misinformation and/or nonscientific agendas have been obstacles to securing permits.
- *Larger plants*: it is more difficult to dispose of a larger concentrate flow than a smaller flow; the trend has been towards building larger desalination plants.
- *More plants in a region*: it is more difficult to dispose of a greater total volume of concentrate flow in a region than a smaller volume.
- *More stringent regulation*: Disposal regulations are becoming more stringent, making the permitting process more time consuming, more costly, and less successful.
- *Concentrates with contaminants*: Although this has not been a major issue, plants with concentrates containing a regulated contaminant (such as nitrate) are increasing. In some cases, removing the contaminant spike may be required before using conventional disposal options.
- *Some regulation is not specific to concentrates*: this is not a new issue, but it is one having a greater effect as more and more desalination plants are being proposed, piloted, and built. Ideally, the exact nature of the concentrate would be considered in the permitting process—as opposed to

concentrate being evaluated based on regulations developed for other wastes.

- *Limited availability of information:* while the amount of research and study of concentrate issues grows, the information is not always readily available.
- *Valuing 'lost water':* the water contained within concentrate may be considered to be a lost resource to the utility. With increasing costs of developing/securing new resources, more thought is given to treating and more efficiently utilizing concentrate as a water resource.

Costs associated with conventional concentrate disposal options are increasing and are becoming a larger fraction of total plant costs.

Technologies and equipment utilized in the conventional disposal options are simple and not amenable to cost reductions through improvement. To the contrary, costs for conventional disposal likely will increase due to the growing challenges. Given that desalination water production costs may continue to decrease while concentrate disposal costs will likely increase, the portion of total plant cost assigned to concentrate disposal will grow.

The present situation is such that, in most parts of the United States, conventional disposal options will continue to be used, albeit with increasing challenges and costs. However, new solutions are needed for the arid Southwest.

Most States rely on conventional surface water discharge and discharge to sewer for concentrate disposal. Outside of the arid Southwest United States, these solutions generally will continue to be available. In the arid Southwest, however, desalination plants are not being built due to conventional disposal options not being available or not being cost effective.

10.2 Alternative Concentrate Management Options

The term 'concentrate management' has appropriately come into use to recognize that there are alternatives to direct concentrate disposal. The term, however, can be misleading in suggesting that other alternatives are readily and widely available.

Use of the term 'concentrate management' is more politically correct, broader, and less negative than the term 'concentrate disposal.' It is a better term than 'disposal' for affecting general perceptions. Historically, however, disposal of concentrate is what has been done with well over 98% of the existing municipal membrane desalination plant concentrates, and disposal will continue to be the primary management option for some time to come.

Concentrate management options include various general categories.

All subcategories of management options can fit under the following general categories:

- Conventional concentrate disposal options
- Beneficial use of concentrate or brine and mixed solids from concentrate through:
 - Treatment of concentrate
 - High recovery processing
 - Zero liquid discharge processing

Beneficial use of concentrate is very restricted and currently does not represent a widely applicable option.

Beneficial options are possible, and there are a few instances where such options have been used (such as irrigation). However, most options are not readily available, not commercially viable or demonstrated, and may not represent a final disposal solution to the concentrate. Due to the challenges associated with concentrate disposal, however, the possibility of a local beneficial use needs to be addressed in each site-specific case.

More broadly, there are very few uses of concentrate and brine or mixed solids derived from concentrate.

In theory, concentrate and brine could find application in dust suppression, road deicing, and soil remediation. However, these applications are limited by increasing requirements for environmental testing/approval, by the need for meeting product and application specifications, by practical factors such as being available for the duration of the project life of the desalination plant, and by the mismatch between amount of concentrate or brine and the local capacity of the application. In addition, the chemistry of each concentrate is site-specific, further complicating supply of a ‘standard’ product.

Mixed solids produced from processing concentrate generally have no beneficial applications and require landfill disposal. Concentrate composition is site-specific and, although there are concentrates that are substantially dominated by one particular salt, they rarely meet existing product/use specifications.

These factors tend to eliminate most potential beneficial applications for concentrate, brine, or mixed solids derived from concentrate.

Further processing of concentrate does not necessarily eliminate the need to dispose of some form of waste such as brine or mixed solids.

10.3 High Recovery (Including ZLD) Processing

Higher recovery processing of concentrate eliminates some conventional disposal options from consideration and in itself does not solve the concentrate disposal challenge.

Conventional membrane (reverse osmosis) processing typically achieves a recovery from 60 to 85%. Incremental improvements of recovery, such as from 65 to 75%, may represent more efficient use of the water resource but can complicate disposal by conventional options. The volume reduction associated with higher product water recovery caused increased salinity and concentration of most constituents in the concentrate. In most cases (where discharge is to lower salinity receiving water), the higher salinity makes the concentrate more incompatible with the receiving water and less likely to be permitted. This situation is true for concentrate disposal to surface water, sewer, and land application (where the receiving water is ground water). The reduced volume of concentrate can make the use of evaporation ponds more feasible—as long as the volume is small. The higher salinity will decrease the net evaporation rate and require more evaporation area. The higher salinity will also result in the ponds filling up more rapidly with solids—as the increased rate of pond filling is greater than the decreased rate of evaporation. For deep well injection, the reduced volume of concentrate will require a lesser injection rate or well capacity but may increase the potential for corrosion and down-hole well plugging. If conventional disposal options are not feasible, the brine produced from high recovery processing would need to be dewatered, solidified, or treated in some other way to reduce the costs of disposal to landfill.

High recovery processing of concentrate can also be attained using nonmembrane process steps such as thermal brine concentrators; however, the same final disposal challenges exist.

High recovery is best suited for concentrate disposal when recoveries are greater than 90% and preferably in the higher 90s.

Very high recoveries represent the most efficient use of the water resource and may allow disposal of brine (to evaporation ponds, deep injection well, landfill) with minimal additional treatment.

The term ‘zero liquid discharge’ has been loosely used, and the difference between high recovery processing and ZLD processing can be minimal.

The term ZLD evolved out of the power industry and means that no water leaves the plant boundary. Several ZLD sites involve using evaporation ponds as the final disposal step—where the ponds are within the plant boundary. In this case, the processing is effectively a high recovery process with final disposal to evaporation ponds. Thus, ZLD does not mean ‘all water is recovered.’ In other ZLD cases, highly concentrated brine from a thermal brine concentrator is taken to solids through using a thermal crystallizer or spray dryer (for small flows). Although the terms ‘high recovery process’ and ‘ZLD process’ have different meanings, they may both apply in some applications. For example, if the high recovery process final waste is disposed within the plant boundary, it is a ZLD process.

Unit costs for high recovery (including ZLD) processing are higher than for conventional processing.

The unit processing costs, \$ per gpd for capital costs and \$ per kgal for operating costs, for high recovery systems (and ZLD systems) are higher than for conventional processing systems. The additional processing generally has higher energy requirements and requires different and more expensive materials of construction. Thus higher recovery processing is, in general, subject to diminishing returns on the investment. However, high recovery (including ZLD) processing may provide a concentrate disposal solution where otherwise none exist.

There are no existing municipal desalination plants utilizing high recovery (including ZLD) processing.

Existing municipal desalination plants do not utilize high recovery technologies due to the higher unit cost and historic availability of lower cost conventional disposal technologies. High recovery technologies have been successfully applied in several other industries. Municipal industry economics are such that municipalities cannot afford higher cost technologies that are used in other industries. Cost reduction of these technologies is, thus, a major goal and challenge.

Consideration of high recovery (including ZLD) processing should take place only when conventional disposal options are not available or are not cost effective.

There are several successful approaches to achieve high recovery from membrane-based systems.

High recovery technologies have been developed, patented, and piloted for other industries. The limitation to initial stage membrane processing (reverse osmosis systems) is scaling of membrane by sparingly soluble salts and/or silica. The approaches taken to avoid or surpass this limitation include:

- Allowing precipitation to occur while keeping the solids away from the membrane surface
- Removing the limiting scalants through treatment
- Arranging two membrane steps (in addition to treatment) in an innovation manner that allows higher recovery

While there are no high recovery (including ZLD) systems at municipal sites, there are approximately 120 commercial ZLD systems in the United States for treating waste water.

Most ZLD systems use mechanical vapor compression evaporators (brine concentrators) with a circulating calcium sulfate seeded slurry to provide an adsorption media for precipitating sparingly soluble salts and silica. This keeps

most precipitants from scaling heat transfer surfaces. The technologies are very energy intensive with most applications below 2 MGD.

Costs of conventional ZLD processing schemes are high and substantially higher than can be supported by municipal desalination operations.

To avoid the high energy costs associated with brine concentrators, one increasingly used option is to further concentrate the feed stream (the feed being RO concentrate) using a second stage membrane unit. Operation of the second stage membrane unit makes the two-stage membrane portion of the process a high recovery system in itself. Particularly for high hardness feedwater, there are cost tradeoffs when using this approach. The energy costs are dramatically reduced because of the smaller size of the brine concentrator. However, operation of the second stage membrane unit, in the typical case where concentrate from the first stage is treated to reduce the occurrence of scaling in the second membrane stage, greatly increases chemical costs and solids production. Consequently, high energy costs are substantially replaced by high chemical and solids disposal costs. The net result can be a significant savings in capital cost but only slightly reduced operating cost. While the annualized total cost is somewhat reduced, it is still higher than generally can be supported by municipal desalination plants. A recent report evaluates the costs of commercial ZLD processing sequences (6), substantiates the high costs, and evaluates the effects of application size, salinity, and water chemistry on costs.

Cost reductions are necessary to implement high recovery (including ZLD) applications in municipal desalination plants.

Cost reduction paths may include reducing capital cost, energy usage, chemical use, and solids disposal costs through use of alternative technologies—either in place or in tandem with the conventional technologies. Solids disposal costs may also be reduced by sale of solids, and in particular, individual commercial grade salts.

Final disposal options for high recovery (including ZLD) processing are different than for conventional processing.

The final waste from the various high recovery processing schemes is either concentrate, brine (from further volume reduction of concentrate), or solids (from evaporating concentrate to solids.)

In the case of high recovery and ZLD processing, surface water discharge (with the possible exception of ocean discharge), discharge to sewer, and land applications are not readily available due to the high salinity of the brine. Evaporation ponds may be feasible if the brine flow is small, and deep well injection may also be possible. Evaporation ponds and deep injection wells, however, are both geographically limited.

Other options for highly concentrated brine include solidifying the brine through chemical addition and landfill of the resulting solids. Landfill costs, however, can be high.

A recent study of high recovery and ZLD processing (6) has noted that the removal of sparingly soluble salts and silica that limit first stage membrane recovery produces sodium-dominated water containing sodium chloride and possibly sodium carbonate. The brine disposal challenge from high recovery processing may, in general, be characterized as disposing of sodium-dominated brine. The only general disposal option for mixed salts (solids) is landfill.

10.4 Selective Salt Recovery

Selective recovery of salts from concentrate brine or mixed solids in commercial grade quality and quantity could provide several benefits to high recovery (including ZLD) processing.

The sequence of recovering individual salts depends on their individual solubility. A general sequence is predictable, at a general level, from literature, software programs, and field experience with various technologies. Recovery of salts in commercial quality and quantity requires a deeper understanding of the many possible chemical reactions, the dependence of these reactions on temperature, pH, pressure, and other constituents present. The recovery is also complicated by the existence of double salts, by the metastable nature of various salts, and by kinetics that are dependent on many variables.

Potential benefits of selective salt recovery include:

- Reducing disposal costs
- Reducing environmental impact (including the CO₂ footprint)
- Providing an income stream from salt sales
- Making subsequent processing steps more efficient

Consideration of selective salt recovery is an important step towards the goal of developing sustainable technologies.

There is a growing and important trend toward treating or modifying wastes produced by society so they can be recycled or reused. In the case of concentrate, an ideal outcome would be more efficient use of the resource water (higher recovery processing) and utilization of the byproducts from the water treatment process (such as through selective salt recovery), which would produce environmental and economic benefits.

Markets exist for each of the salts that can be recovered, although market challenges exist.

Examination of literature reveals markets for the salts obtainable from concentrate as well as the market value of commercial grade qualities of each of the salts. There are several marketing challenges that need be addressed which include:

- Finding local markets to avoid transportation costs
- Penetrating existing local markets

- Saturating local markets
- Developing a marketing system that addresses and/or avoids the municipality becoming a chemical producer/marketer

Additionally, long-term, value-added products could be developed from salts, which could increase the market for salts obtained through SSR technologies.

The technology for SSR has been developed, patented, and licensed outside of the United States to produce and market commercial grade salts.

A company, Geo-Processors USA, Inc. (11) has developed and patented SSR processing schemes suitable for a wide variety of feed waters. They have piloted, demonstrated, and applied the technologies outside of the United States with a focus on Australia, where the company started. Geo-Processors is presently setting up piloting operations in the United States. Their extensive experience and know-how should facilitate study and evaluation of SSR in the United States.

10.5 Possible Technologies for High Recovery (Including ZLD) Processing Steps

Examination of some innovative technologies that might be used in high recovery (including ZLD) processing reveals some promising candidates:

Innovative technologies of most interest are desalting and contaminant removal technologies that could efficiently remove one or more contaminants from either feedwater, concentrate, or brine. Various technologies were reviewed with this potential in mind. Particular note was given to commercially patented technologies. Technologies of promise include:

- SAL-PROC™ by Geo-Processors, USA, Inc.: This is a SSR processing technology that has been successfully piloted and demonstrated outside of the United States. It is not specific to any particular feedwater type or quality. It can be used to reduce disposal costs, provide an income stream from salt sale, and reduce environmental footprints.
- VSEP™ by New Logic Research, Inc.: VSEP™ stands for vibratory shear enhanced processing. It is a membrane process that can be used to directly treat first stage RO concentrate without additional chemicals—thus reducing chemical costs
- Electrocoagulation, such as by Powell Water Systems, Inc.: This is a contaminant removal process that can remove multiple contaminants in a single treatment and produce a nonleaching and, thus, nonhazardous solid for disposal.

Other technologies of some promise are still in the development stage.

10.6 Regulatory Issues of High Recovery (Including ZLD) Processing

A regulatory concern stems from further treatment of concentrate to produce brine or solids more concentrated than the original concentrate.

There is environmental concern that constituents in the feed might produce a brine or solids that are hazardous or of low-level radioactivity. TENORMS are of growing concern in the water industry, largely from having been a somewhat neglected area of regulation that is now receiving considerable attention. TENORM regulation is in flux, with policies being defined by State agencies. The primary finding from the study is that there is need for detailed water quality analysis of concentrate to monitor constituents of concern because these constituents may be below detection limits in the RO feedwater.

10.7 Testing of Electrocoagulation

More detailed study of EC technology shows it to have considerable potential in removing multiple contaminants from concentrate.

Improvements in design of EC systems have reduced energy requirements and allowed individual modules to treat up to 500 gpm. Designs are being prepared for a multiple MGD EC system. This nonchemical process can remove multiple contaminants (inorganic and organic) while disinfecting and removing suspended solids. Characteristics of EC equipment and operation have been described along with laboratory data describing EC removal performance.

10.8 Preliminary Antiscalant Study

The development of a simple test to determine remaining time effectiveness of antiscalant in concentrate was not possible under the constraints of the project.

Laboratory tests conducted to determine the residual effectiveness of antiscalants over time had poor reproducibility, consistent with published literature. In hindsight, the goal was difficult to achieve given that the fate of concentrate in the field varies considerably and directly influences the remaining time effectiveness of antiscalants.

11. Recommendations

The following recommendations are for addressing concentrate disposal challenges associated with municipal desalination membrane concentrate. They are influenced by the fact that there are no existing municipal high recovery (including ZLD) desalination plants.

Surveys of municipal desalination plants should be updated to reflect more recent practices and trends in concentrate management.

Survey information (2, 10, 12) provided the basis and reason for the present project and have been used by many groups to present a picture of the membrane desalination industry. The most recent survey provides information from plants operating at the end of 2002. Data on subsequent plants as well as an update on prior-built plants will provide valuable information to the membrane community.

Several patented and developed technologies that have been used in other industries should be tested and evaluated for their application to municipal desalination concentrate management.

High recovery processes recommended for further evaluation include SAL-PROCTM selective salt recovery technology (Geo-Processors USA, Inc.), VSEPTM membrane technology (New Logic Research, Inc.), and electrocoagulation (such as by Powell Water Systems, Inc.). Combinations of these and other technologies should also be considered.

Detailed analysis of commercial high recovery (including ZLD) processing systems should be conducted to provide more indepth information about performance and cost of these treatment systems.

Analysis of a commercial high recovery system has just been completed by the author (6), building on some of the findings of this report. The final disposal options for high recovery (including ZLD) systems should be evaluated in greater detail. The influence of flow quantity, salinity, and brine chemistry on high recovery technologies will provide a better understanding of final disposal issues and costs.

Detailed water quality analyses of pilot stage concentrates are needed to ensure concentrate, brine, and solids are not hazardous and/or do not contain problematic levels of TENORMS.

Concentrate and particularly brine or solids derived from concentrate may contain contaminants that are nondetectable or not of concern in the feed water. Of particular interest are TENORMS, which are the subject of increasing consideration in the water treatment industry.

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