

**State-of-the-Science
WHITE PAPER:**

BRACKISH GROUNDWATER CONCENTRATE MANAGEMENT

**Prepared for New Mexico State University (NMSU) and
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(CHIWAWA)**

by

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OVERVIEW

The subject of inland concentrate management has evolved through periods of expanding information, knowledge, and understanding. With this, issues and needs have reached clarity.

Although desalination had its commercial beginnings in the late 1960s, concentrate management (CM) became a subject of more than minor discussion only in the late 1980s. Since then, attention given to CM in conferences, literature, and research had grown slowly and steadily until the last 5-10 years. In this more recent time frame, discussion and research given to CM has increased significantly.

It is helpful to understand the history and evolving periods of CM as they reflect the nature and distinguishing characteristics of CM that frame and define present issues and needs.

Thus, the purpose of this White Paper is to provide a basis for shared understanding and appreciation of the subject; and from this to define meaningful research topics to address present issues and needs.

Of course the thoughts and ideas expressed by the author are limited by the author's experience, perceptions, and biases.

The following contextual aspects frame the present situation in which we address challenges and develop solutions. They are not aspects, however, for discussion with respect to research needs. They are areas that we have very little control over. It is helpful to recognize them.

- Water is not managed according to its true value.
- There is no national policy and plan for water management that includes the role of inland brackish water desalination. (lack of a guiding policy)
- The economics of the municipal community are different from most other industries and do not permit more costly technical solutions

1.0 INTRODUCTION

There are several resources to draw upon in reviewing the history, issues, and needs of CM. These include past reports, past research, and past definitions of research needs. The following sections borrow heavily from these areas. The bulk of the paper focuses on characterizing the issues of inland CM; first through a brief review of a previous report/white paper and then through discussion to update and extend the previous work.

Sections 2.0, 3.0, and 4.0 review background information. Section 2.0 discusses the evolution of concentrate management as a subject, giving an historical picture of milestones and events which shaped the subject. Section 3.0 reviews a 2005 White Paper by the author (Mickley, 2005) entitled 'State of the Science - Concentrate Management' that was prepared for the Joint Water Reuse and Desalination Task Force of consideration in updating the Desalination Roadmap. Section 4.0 briefly discusses broad issues and context that further define and shape our understanding of CM. Together, these three sections provide the basis from which to consider more recent events and issues that frame the present status of inland concentrate management. Section 5.0, by far the largest section, presents relatively new and updated information that reflects present day understanding of inland CM issues and

needs. Section 6.0 addresses the general areas of need for consideration in defining research topics. An appendix lists past funded research projects.

2.0 EVOLUTION OF CONCENTRATE MANAGEMENT

The subject of CM has evolved in scope over the past 20 years. The first major report addressing the subject was funded by AwwaRF and was entitled 'Membrane Concentrate Disposal' (Mickley et al., 1993). Since that time there have been many studies and events reflecting the growing importance of CM as a limiting and determining factor in desalination plant feasibility.

Some of the milestones associated with CM in the U.S. map the growth of the industry in terms of the number of plants. Table 1 lists the rough number of municipal desalination plants operating in the U.S. of size 25,000 gpd and larger, by date.

Table 1. Cumulative Number of U.S. Municipal Desalination Plants Operating by Year

Year	Number
1980	30
1990	100
1995	180
2000	222
2003	234
2010	261

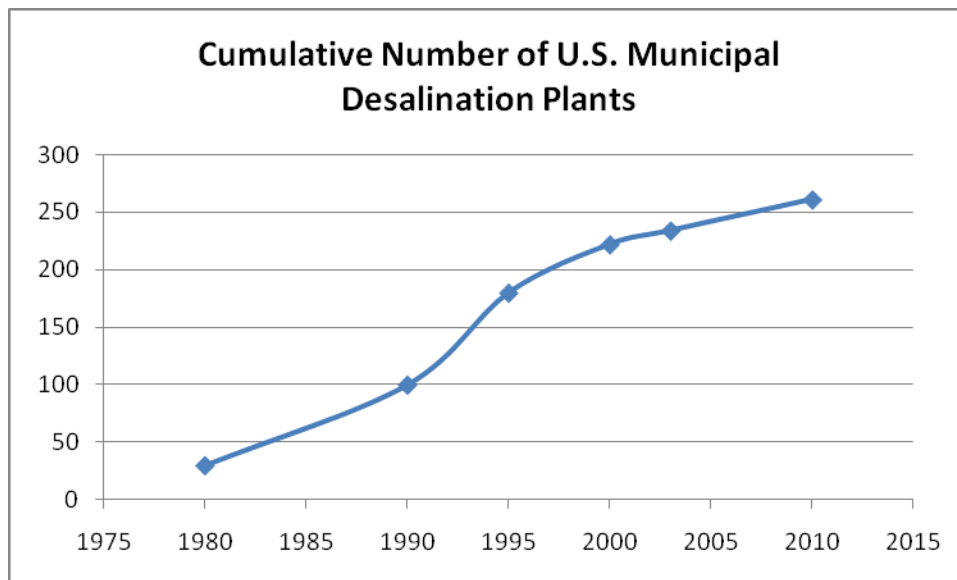


Figure 1. Cumulative Number of U.S. Municipal Desalination Plants by Year

The evolution of terminology and general focus of concentrate disposal/management by decade is reflected in Figures 2 and 3 and discussed in the following section.

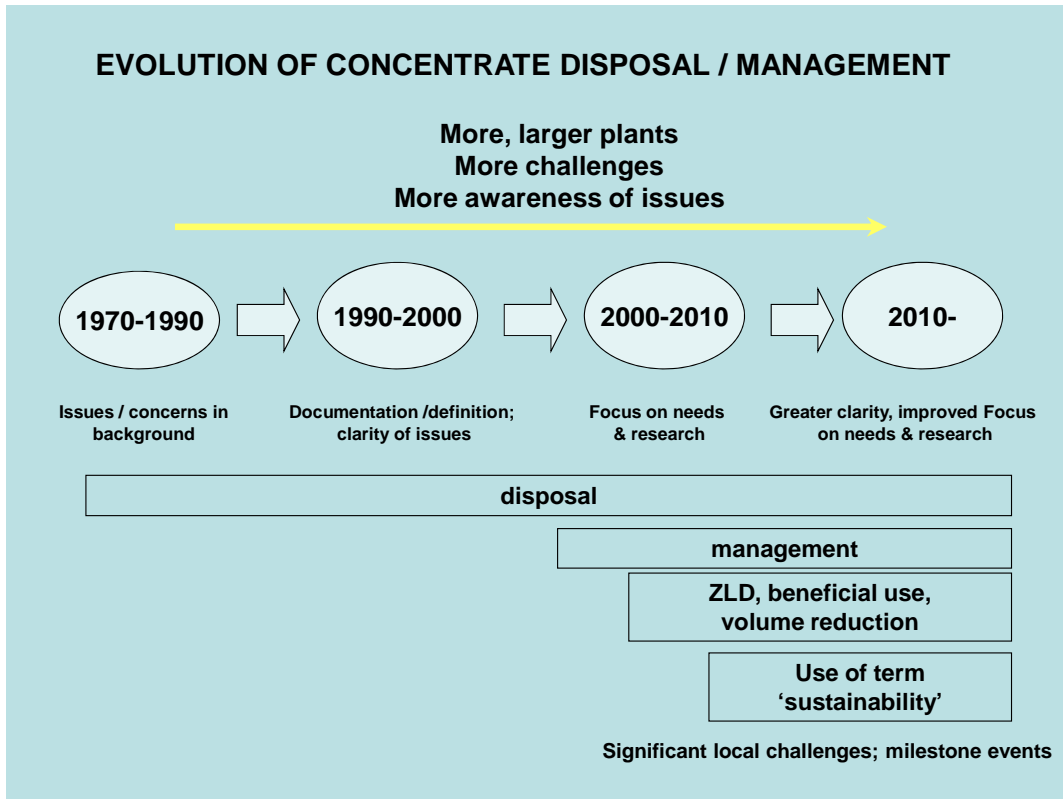


Figure 2. Evolution of Concentrate Disposal

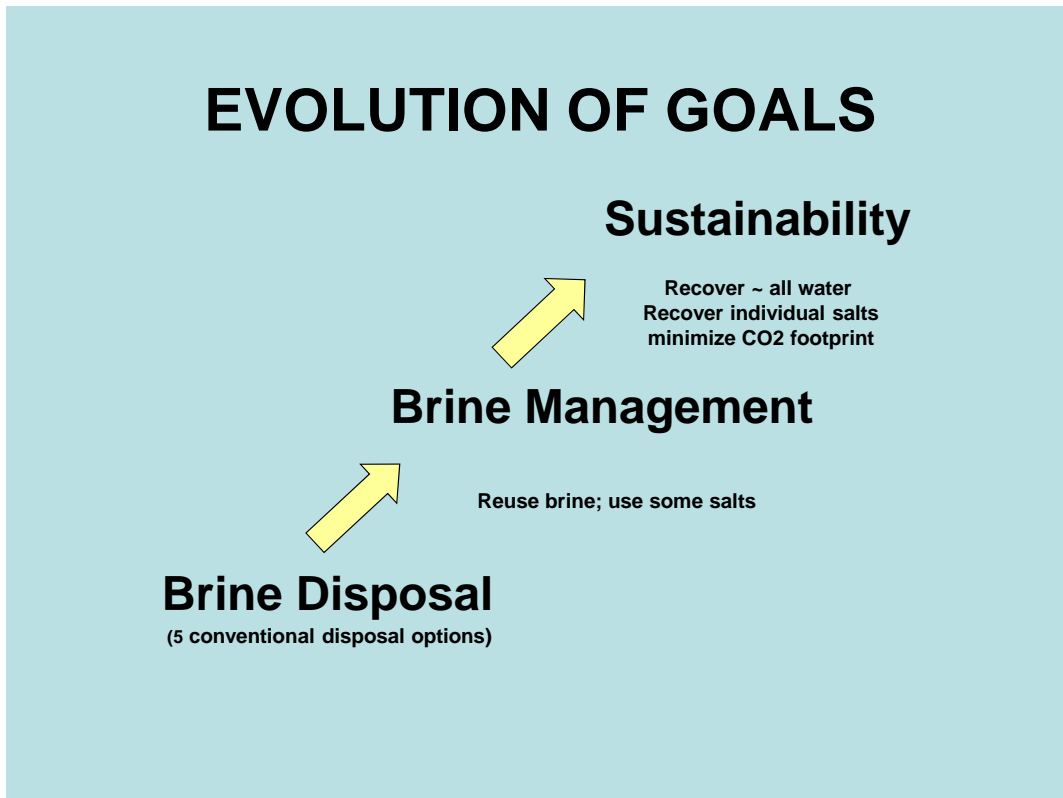


Figure 3. Evolution of Goals

2.1 Selected milestone events

2.1.1 1980 to 1991

Most (perhaps 80%) of the municipal desalination plants at this time were in Florida. Florida Department of Environmental Regulation (now FDEP) had minimal monitoring and reporting requirements but became increasingly concerned about the growing number of plants, and began to look at concentrate composition.

1986

- FDER study that examined concentrate water quality data (over 40 parameters) from 36 Florida plants. Data revealed that:
 - hydrogen sulfide needed to be removed prior to discharge of concentrate originating from groundwater sources
 - chloride (& specific conductance) criteria were not being met
 - radionuclides were elevated above background levels
 - as a result of this study, FDEP became aware of concentrate discharge problems and began to require more data with discharge permit applications; they also began to develop more complete guidelines and strategies for addressing site-specific problems.

1990

- Article by Baker, DeGrove and Pierce presenting data from the 1986 FDER study
- 1990
- AwwaRF study (Mickley et al., 1993) began
 - first comprehensive study of concentrate disposal
 - the author began attending membrane-related conferences and documenting practices and issues; nearly all the conferences were in Florida; there was a general adversarial relationship between membrane facilities and regulating agencies (at least in Florida) and there was little recognition/acceptance of environmental impacts of concentrate by the industry.

2.1.2 1991 to 2001

As seen in Figure 1, this was a period of accelerated growth - when the number of states having municipal desalination facilities increased and Florida began requiring more monitoring data and instituted whole effluent toxicity (WET) test requirements for surface water discharge. The AwwaRF study was published in 1993 and conferences began having sessions devoted to concentrate disposal. Through the decade, the author is not aware of any desalination plants not being built due to concentrate disposal challenges. Several Florida plants encountered challenges meeting more stringent disposal requirements but all received variances/allowances to permit continued operation.

1993

- Published AwwaRF study
 - first major survey of municipal desalination plants and concentrate disposal practices in U.S.
 - identification of concentrate disposal options
 - identification of regulations affecting concentrate disposal
 - discussion of design factors for the disposal options
 - cost models for the disposal options (including zero liquid discharge)
 - identification/recommendations for research areas - including investigation into several failed whole effluent toxicity tests from inland concentrates

1995

- In reaction to several failed WET tests in Florida, FDEP published Protocols for Determining Major-Seawater-Ion Toxicity in Membrane-Technology Water-Treatment concentrate. Tallahassee, Fla.: FDEP.

2000

- AwwaRF study: Major Ion toxicity in Membrane Concentrate (Mickley, 2000)
 - determined toxicity cause in 9 Florida membrane concentrates (through extensive laboratory analysis) to be due to high levels of Ca (7 cases), high levels of F (3 cases), and low level of K (1 case).
 - developed toxicity levels for mysid shrimp exposed to major ions at several salinities
 - developed method to predict occurrence of major ion toxicity in groundwater membrane concentrate (based on concept of percent difference from balance - PDFB)

2.1.3 2001 to 2010

Dramatic growth on several fronts: amount of research funded, visibility of issues at conferences, recognition of the critical role in desalination plant feasibility, etc. Some planned desalination plants were never built due to concentrate disposal challenges. The reports listed are mostly those that address broad issues (several good reports are not listed).

- 2001 *Membrane Concentrate Disposal: Practices and Regulation*. (Mickley, 2001) USBR
- 2003 Desalination and Water Purification Technology Roadmap
- 2004 *Membrane Concentrate Disposal: Practices and Regulation, Second Edition*. (Mickley, 2004a) USBR
- 2004 *Committee Report: Current Perspectives on Residuals Management for Desalting Membranes*. AWWA Membrane Residuals Management Subcommittee. Awwa Journal. (AWWA, 2004)
- 2006 update of National Roadmap
- 2006 *Beneficial and Non-Traditional Uses of Concentrate*. (J. Jordahl, CH2M, 2006)) WaterReuse Foundation Project
- 2006 *Zero Discharge Seawater Desalination: Integrating the Production of Freshwater, Salt, Magnesium, and Bromine* (T. Davis, U. South Carolina) USBR
- 2007 *Zero Liquid Discharge for Inland Desalination*. (R. Bond, Black & Veatch) AwwaRF.
- 2007 Tampa Bay Desalination Plant begins operation
- 2007 Operation at Kay Bailey Hutchison Desalination Plant
- 2007 Brackish Groundwater National Desalination Research Facility opening
- 2008 Desalination - A National Perspective, Study by National Research Council
- 2008 *Regional Solutions to Concentrate Management* (E. Mackey, T. Secord, Carollo) WaterReuse Foundation.
- 2008 *Survey of Volume Reduction and Zero Liquid Discharge Technologies for Water Utilities*, (Mickley, 2008) WaterReuse Foundation
- 2008 Two projects started for development of guidelines for Desalination (Stratus, 2010 - funded by AwwaRF) and Concentrate Management (Mickley, 2010 - funded by WaterReuse Foundation)
- 2009 *Treatment of Concentrate* (Mickley, 2009) USBR
- 2009 CIDS (Center for Inland Desalination Systems) - beginning
- 2009 (NCED) Australian National Centre of Excellence in Desalination - beginning

In addition to the bulleted milestones there were several other items of note:

- while the Bureau of Reclamation started as 'the' major funding source for desalination projects and remained an important source through the decade, the WaterReuse Foundation and the Office of Naval Research became major players in funding of desalination research projects - including concentrate management oriented projects
- various organizations were formed to look at desalination topics, including concentrate management; these organizations included:
 - CHIWAWA (Consortium for Hi-Technology Investigations in Water and Wastewater)
 - MSSC (Multi-State Salinity Coalition)
- AMTA became the major U.S. organization focusing on desalination issues
- Senator Peter Domenici (NM) was a major force in influencing Federal desalination funding
- emergence of salt recovery as an important topic on the path toward sustainability; patent and commercialization (Gerry Groot of Superior Salt, Inc., Aro Arakel of Geo-Processors Pty Limited, Tom Davis of ZDD - and UTEP)
- increased number of sessions devoted to concentrate management at water-related conferences
- increased funding of research projects (see Appendix A). Examination of the dates shows the significant increase in funded studies since 2000.
- increased awareness of and focus on concentrate management from a watershed - regional perspective
- increased awareness of similar salinity management challenges in other industries and in other countries
- absolute awareness that concentrate management is one of the major if not the major limitations to further development of desalination. Desalination plants have experienced this in different ways - largely dependent on location. Unlike in previous decades, in this decade, several desalination plants were not built because a suitable concentrate management solution could not be found.

This last point is reflected in Figure 4 where the primary limitations on the feasibility of membrane desalination plants are cost and concentrate management.

Along with the increased activity in the 2000 to 2010 period have been changes in the terms used to describe the subject area:

- 'Concentrate management' has come to replace concentrate 'disposal' - a much broader, more general term that allows for beneficial use of concentrate in addition to direct disposal.
- 'Beneficial use' has entered the vocabulary as a new category under concentrate management. The term represents the use or reuse of concentrate which, on the surface, is a good thing. The details of beneficial uses, however, need to be understood. Beneficial use is discussed in more detail in a later section of the paper.
- 'Volume reduction,' 'high recovery,' and 'zero liquid discharge' have become familiar words within the concentrate management community. These terms and a general discussion of the technologies and characteristics of the areas are discussed in section 5.
- 'Sustainability' has increasingly been used in papers, presentations, and reports in regards to environmental concerns, issues, and goals associated with concentrate management. Given the widespread use of the term now, it is surprising to the author that the first time he used it in a presentation was in 2004 (Mickley, 2004b).

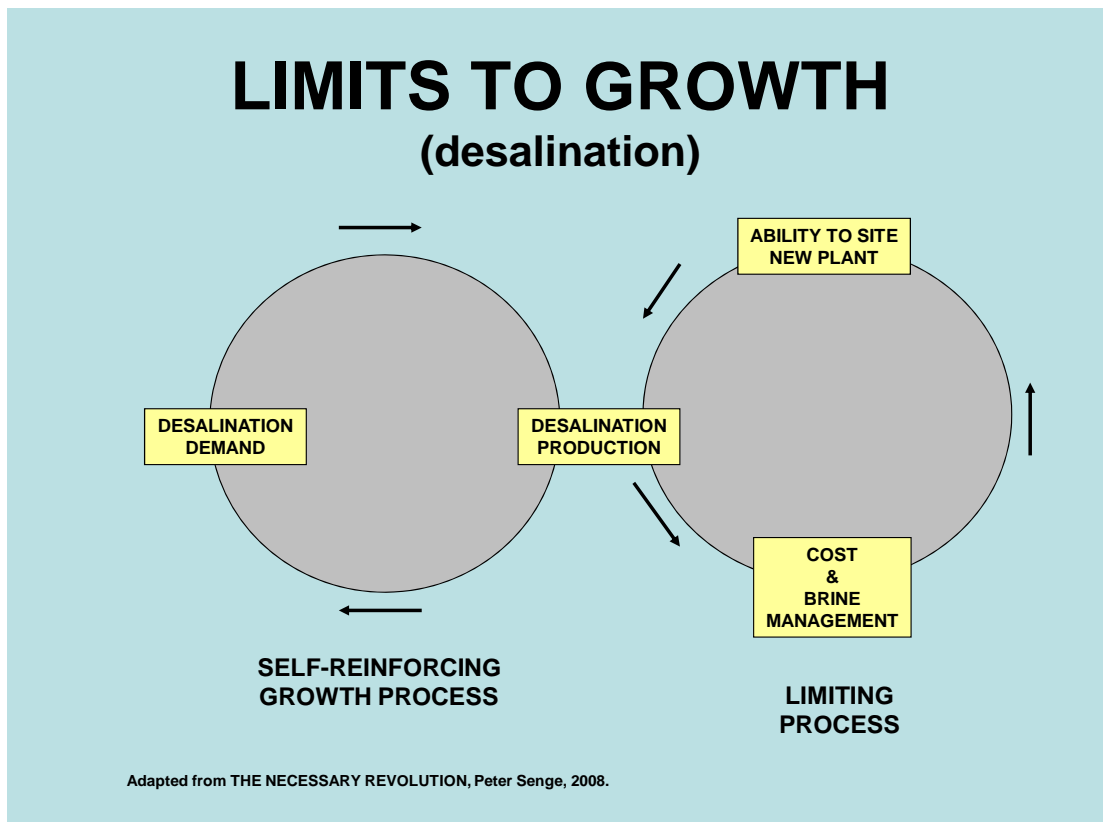


Figure 4. Limits to Growth

- 'Brine' and 'concentrate' are used interchangeably in the literature and by many in the treatment industry. Historically, 'brine' refers to higher salinity water, typically taken to mean waters of seawater salinity and higher - thus waters above about 33,000 mg/L. According to this definition, some concentrates are brine and some are not. The term 'concentrate' is the more general term.

The purpose of this section has been to:

- 1- illustrate the evolving nature of the subject of concentrate management
- 2- provide a basis for considering the more detailed issues of concentrate management

Several of the events representing the expansion of the concentrate management field are shown in Figure 5.

Before highlighting major current topics, it is helpful to review basic background information concerning concentrate management. For this purpose I refer to the 2005 report entitled 'State of the Science- Concentrate Management' (Mickley, 2005), a copy of which was provided to everyone a few weeks ago by email.

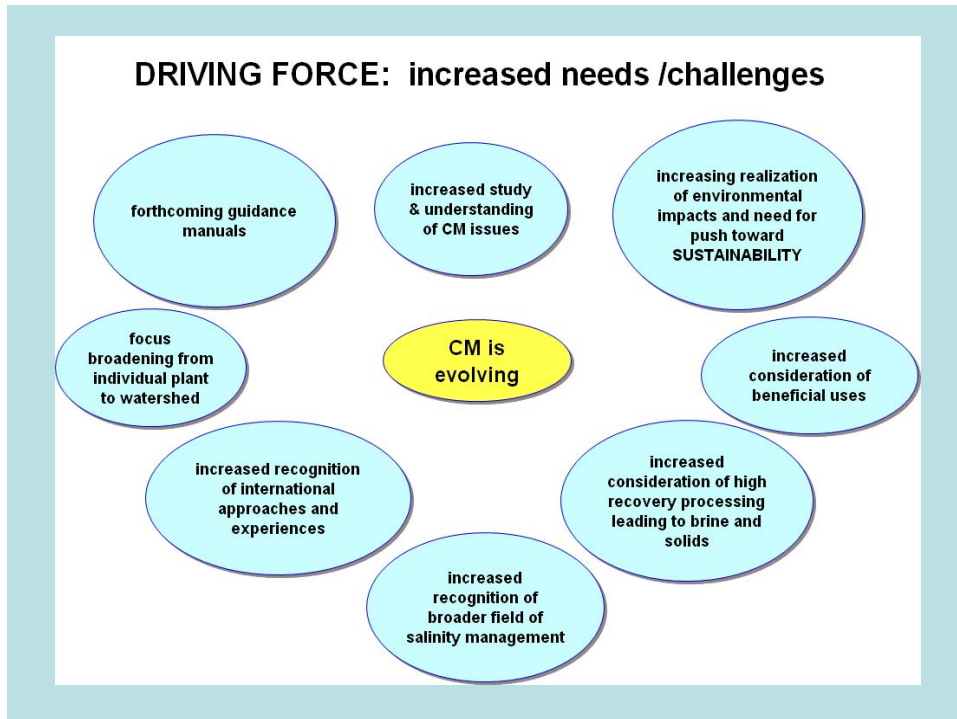


Figure 5. Areas Reflecting Evolution of Concentrate Management

3.0 REVIEW OF 2005 'STATE OF THE SCIENCE - CONCENTRATE MANAGEMENT' REPORT

In 2005, the author prepared a report (Mickley, 2005) for the Joint Water Reuse and Desalination Task Force for use in meetings to update the Desalination Roadmap (Desalination and Water Purification Technology Roadmap). The 2005 report served similar purposes to those of the present White Paper. As such it provides useful background information to the present White Paper. Only highlights of the report will be reviewed here.

A full listing of the summary points made in the 2005 report is provided in the next several sections.

3.1 *Conventional Disposal Options*

- The number and size of desalination plants continue to increase
- Five traditional 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 3 traditional disposal options (deep well injection, land application, and evaporation ponds) have limited widespread application, primarily due to hydro-geological and climate requirements.
- Thus, as a group the five traditional disposal options are not widely available; local availability of options is typically very limited.

3.2 *Concentrate Disposal Challenges*

- The concentrate disposal challenge is framed by two factors: severe limitation in local availability of options (regardless of concentrate volume) and the increasingly larger volumes of concentrate further reduce the feasibility of each of the traditional disposal options.

CONCENTRATE MANAGEMENT OPTIONS

FIVE 'CONVENTIONAL' CM OPTIONS:

- **Surface Water Discharge**
 - Direct ocean outfall (includes brine line when direct to ocean)
 - Shore outfall
 - Co-located outfall
 - Discharge to river, canal, lake
- **Disposal to Sewer**
 - To sewer line
 - Direct line to WWTP
 - Via brine line (where brine line goes to WWTP)
- **Subsurface Injection**
 - Deep well injection
 - Shallow well (beach well)
- **Evaporation Ponds**
 - Conventional Pond
 - Enhanced evaporation ponds/schemes
- **Land Application**
 - Percolation ponds / rapid infiltration basins
 - Irrigation

OTHER OPTIONS:

Landfill (for solids)
 -- industrial landfill
 -- dedicated monofill

Beneficial Uses

-- several potential uses
 -- for concentrate, brine, or solids
 -- (in addition to irrigation)

Non-conventional Options

-- too few to mention
 -- not widely applicable

NOTE:

- 1 – the above holds for concentrate/brine of any salinity
- 2 – it includes low recovery to high recovery (including ZLD processing)
- 3 – the processing may involve salt recovery

Table 2. Concentrate Management Options

- The challenges are further complicated by more stringent regulation, increased public concern, and the growing needs for water in the arid southwest (where traditional disposal options are, in general, not feasible.)
- Other driving forces for developing alternative disposal options include: increased concern for concentrate being a lost water resource and realization of longer-term need to develop sustainable technologies / solutions.
- While traditional disposal options will continue to play an important role in many parts of the U.S., there is a growing number of locations, and particularly in the arid southwest, where use of most traditional disposal options is not possible or cost-effective, and alternative disposal options are needed.

3.3 The Context of Meeting Concentrate Disposal Challenges

- The challenges of concentrate disposal are different than those of lowering production costs
- The limitations on disposal options include factors other than cost, such as regulatory requirements, climate, land availability, hydro-geological conditions, etc.
- In general, there is little or no cost reduction in the simple equipment associated with traditional disposal options
- This explains the fact that while production costs have been decreasing, concentrate disposal costs have not.
- As with most industrial waste disposal situations, few options exist.

- Unlike most industrial waste disposal situations, the economics of the municipal setting make cost-effectiveness more difficult to achieve.

3.4 Consideration of Concentrate Management and Desalination Research Areas

- Concentrate ‘management’ implies more than concentrate disposal; however, the management concepts of beneficial use and volume reduction, in general, do not address the critical challenge of concentrate disposal
- New desalination technologies do not solve concentrate disposal challenges.
- Relative to the critical goal of reducing concentrate disposal costs and developing alternative disposal options, these distinctions are important.

3.5 Consideration of Non-conventional Disposal / Management Options

- While several possible beneficial uses of concentrate can be identified, none are widely applicable, most are unproven, and most do not address the concentrate disposal challenge
- There are very few viable uses of concentrate or brine obtainable from concentrate
- Selective salt recovery (discussed more fully in a later section) and use of concentrate as makeup water for inland power plants having ZLD technology are two promising possibilities
- Volume reduction of concentrate is desirable from the standpoint of recovering more water from the water resource. However, in general, it makes concentrate disposal more difficult
- Unless disposal options of evaporation ponds or deep well injection are available and cost-effective (neither is likely), there is little gained by minimizing the volume of concentrate, unless it is part of a ZLD processing scheme.

3.6 Consideration of ZLD

- ZLD technologies have not been applied in the municipal drinking water field due to excessively high costs
- The uses of mixed salts obtained from concentrates are very limited
- The high operating costs of conventional ZLD technologies are due to one or more of the costs associated with energy, chemicals, and solids disposal.
- ZLD processing (a desalination process) like membrane desalination has the same challenges: while processing (equipment-related) costs can be reduced, final disposal costs (of brine or mixed solids) will likely not be reduced significantly.
- In the future, more efficient desalination technologies may reduce the processing costs associated with ZLD, including the energy and chemical costs. However, solids disposal costs will remain high and be limiting.
- There is an increased realization that an ultimate goal of all technologies must be to minimize environmental impact and to attain a high degree of sustainability.
- These various factors lead to consideration of harvesting individual salts for 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 ZLD costs without waiting on the development of more efficient technologies and avoiding the limiting cost of solids disposal.

3.7 Consideration of Selective Salt Recovery

- There are applications for each of the salts composed of major ions in concentrates.
- Technology appears to exist (as evidenced by Geo-Processors’ claims of success) to obtain such salts, although the level of documentation is limited. Some details of Geo-Processors’

- technologies are proprietary, and various aspects of these and other likely appropriate technologies are patented.
- The feasibility of a given site-specific operation to recover and market salts from a concentrate is dependent on many factors. These include:
 - volume of concentrate
 - water quality (salts obtainable from the concentrate)
 - quality (form and purity) of salts obtained
 - reliability, consistency of salt quality
 - types of applications for the obtainable salts (types of markets)
 - existence of a local market
 - size of the local market
 - reliability of the local market
 - combined income from sale of the different salts
- Economic success depends not only on the technology to bring about selective salt recovery but also on the local salt market and the challenges associated with marketing each salt.
- Long-term there is a need for market development – the development of value-added products to remove feasibility dependence on existing markets.
- (General) The recovery of individual salts from concentrate and the marketing of such salts have potential to offer cost-effective concentrate disposal solutions to many locations, including those for which no such solutions currently exist.
- Associated benefits of salt recovery and sale include increased overall water recovery and decreased environmental impact

4.0 GENERAL CHANGES SINCE 2005

Moving beyond this slightly dated perspective begs the question: what has changed since 2005? Would any statements made in the 2005 report be changed?

In terms of desalination industry changes:

- More plants have been built
- Average size of the plants continues to increase
- There has been more focus on water reuse (this may become the fastest growing application of municipal desalination)
- There is a greater consideration of seawater RO in U.S.
- Treatment costs continue to decrease
- Progress has been made on decreasing RO energy requirements
- New technologies are going commercial or are on the horizon (Forward Osmosis, WAIV Enhanced Evaporation - as examples)

In terms of items directly related to concentrate management:

- There has been more consideration and investigation of Deep Well Injection
- Improvement in enhanced evaporation
- Increased consideration of and understanding of high recovery and ZLD practices
- Increased consideration of and understanding of salt recovery practices

These last items and other items are discussed further in the next section.

5.0 NEW AND UPDATED INFORMATION

5.1 Deep Well Injection

In 2003 only 2 states (FL & CA) used deep well injection (DWI) for disposal of municipal membrane concentrate. Since then, Texas, more than any other state has explored DWI for this purpose with the El Paso plant implementing it. DWI was investigated by the City of San Antonio as a disposal option and remains the preferred option. Membrane concentrate, being classified as an industrial waste, requires a Class I well which means:

- Concrete covered casing all the way to the injection zone
- Tubing and packer arrangement to allow monitoring of tubing leaks
- Injection below the USDW (underground source of drinking water) zone; this is the depth at which aquifer salinity becomes greater than 10,000 mg/L. [The 10,000 mg/L limit was defined before the age of desalination plants.]

In Texas there are now three possibilities for disposal of concentrate by injection:

- Class I well (just described)
- Class II well (for the purpose of enhanced oil recovery)
- Class V well (provided the concentrate salinity is less than 10,000 mg/L and the concentrate meets primary water quality standards)

5.2 Enhanced Evaporation

Besides being climate dependent, evaporation ponds are land intensive and can be very expensive depending on site-specific factors. Historically, they have been used only for small volume concentrates and only in 3 southern states. Per acre costs have ranged from \$60,000/acre to \$600,000/acre.

There have been several approaches to enhance evaporation rates from evaporation ponds. The methods have included:

- Spraying water into the air using a sprinkler system and snow making equipment
- Letting water fall from a height above the pond surface level
- Using various materials suspended vertically to wick and/or absorb water to provide increased surface area from which evaporation can take place
- Evaporation from rocks placed in shallow ponds

While enhanced rates of evaporation (on a per acre basis) have resulted, several problems have been encountered that include:

- Drifting of mist to areas adjacent to the ponds
- Health concerns associated with mists affecting people working with the ponds
- Clogging of spray nozzles by solids left from evaporation
- High energy requirement

The most successful of the systems appears to be the WAIV system from Israel. Per acre evaporation rates can be as high as 5 to 8 times that of standard ponds. The land requirement is reduced by this factor. This reduces the CAPEX significantly but by less of a factor because of the added cost of the WAIV equipment. OPEX costs are increased due to the energy and maintenance required. The net result is a decrease in the annualized cost, generally by a factor of 1.5 to 3. Even with this improvement, the cost of evaporation ponds remains high.

5.3 *Global Perspective*

This subject of Inland Brackish Concentrate Management in the U.S. may be seen as a subset of broader subject areas involving worldwide salinity water management. There are:

- Other industries dealing with similar challenges (Examples: use/disposal of produced waters; mining waters)
- Other countries having urgent similar challenges
- Other municipal desalination processes sharing some similar challenges (EXAMPLES: seawater desalination, desalination used for water reuse)

Consequently, information from other countries, from other industries, and from other types of facilities can be helpful in addressing inland municipal concentrate management challenges in the U.S. Recent studies were undertaken by the author to determine concentrate management issues and practices in other industries and in other countries (Mickley, 2010).

The three general areas where desalination is involved in water treatment are:

- Treatment of water resources (surface water and groundwater) for use (potable, agricultural, industrial).
- Treatment of wastewater for reuse or recycle (residential, industrial, agricultural wastewater) or disposal
- Treatment of byproduct water (produced water, mining water) and wastewater for disposal

While the desalination treatment is undertaken to address salinity challenges, it, of course, produces concentrate, which itself requires management.

The many global salinity management situations include:

agricultural situations

- Dryland salinity: where native deep root native vegetation has been removed and replaced with short root agriculture crops; this results in a rising water table
- Excessive salinity: due to excessive irrigation and resulting rising water table
- Overpumping of groundwater: this lowers the water table and causes farmers to access lower quality water in the aquifer or to drill into a deeper and lower quality aquifer for water; also-seawater intrusion in areas near seas
- Agricultural drainage water: lack of adequate disposal means

produced and mine water

- Produced water without uses or means of disposal
- Mine water which cannot be disposed of

urban practices

- Residential water softeners and other contributions to TDS of WWTP effluent: typically 200 or more ppm higher than drinking water TDS; makes water recycle treatment more difficult

desalination concentrates

- Disposal to surface water and sewer: increases salt load of receiving water which makes downstream use/treatment of the water more difficult; further limits downstream recycle of WWTP effluent more difficult
- Use in irrigation: which can increase salt loads of underlying groundwater and/or result in salt laden drainage water requiring management

naturally occurring waters

- Example: Salt River in Phoenix, groundwater in cities near seas

Some of the observations made from reviewing global inland water salinity management situations and treatment include:

- Many uses of inland desalination address situations such as those described
- Many situations in less developed countries are made more challenging due to mixing of wastewaters (agricultural, domestic, industrial)
- Many non-municipal industries have money to spend on water treatment
- Environmental concerns are becoming important factors globally
- In many non-municipal industries, due to the pressures of meeting environmental regulations, high recovery treatment schemes are common
- There is a wide range of water qualities in non-municipal industries: salinity and composition
- Widespread use of RO and evaporators (few other technologies)
- Consequently in high recovery situations, reverse osmosis plays a smaller role in volume reduction than thermal processes and evaporation ponds
- No new alternative concentrate management options have been identified that haven't been considered in the U.S.
- In non-municipal industries there is a much greater, location dependent, consideration of salt recovery; for example for production waters in the Middle East, where salt needs to be imported
- There are a handful of manufacturers of brine concentrators for the purpose of salt recovery (as opposed to wastewater brine concentrators that are frequently used in the U.S.)

Particularly relevant to inland concentrate management in the U.S are:

- Information about high recovery processing, salt recovery, non-wastewater brine concentrators, and processing sequences
- Confirmation of shared challenges, issues, and concentrate management options

5.4 Water Quality Challenges

Concentrate management challenges are, in general, site-specific. Performance of desalination steps (whether at conventional recovery levels or high recovery levels) are dependent on the site-specific water quality (salinity and composition). The performance of the desalination steps and the initial feedwater volume determine the volume of concentrate to manage. This, as well as the distance (site-specific) of the disposal or management option from the desalination plant, affects the cost of concentrate management options. The point here is that performance and costs are heavily dependent on water quality.

In an later section, the performance and costs of various high recovery (including zero liquid discharge) options are examined as a function of water quality - illustrating this point. This section reviews the general nature of water qualities from water salinity management situations.

The global range of water qualities encountered is large. While geochemistry texts present various ways to categorize and represent varying water qualities, there have been two efforts that the author is aware of to categorize water qualities with concentrate management in mind.

The first is due to Geo-Processors Pty Limited and is included in their patents. Figure 6 categorizes inorganic saline waters according to 7 basic compositional types. These types were determined from analysis of a great number of waters across the globe, and provide insight into both treatment approaches and salts that can be practically obtained from the different waters. The types depend on levels of salinity and the ratios of Cl/SO₄ and Cl/HCO₃. Note that beside each type of water is a short listing of global waters of that type.

The second approach, called Percent Difference from Balance (PDFB), is due to Mickley (Mickley, 2000). While originally developed as a predictive indicator for major ion toxicity in groundwater-based concentrate, the parameter also serves to characterize the composition of waters relative to seawater. *From a physiological perspective, seawater and more specifically the relative major ion composition of seawater at any salinity is considered a 'balanced' water. Freshwater and marine organisms are least challenged by major ion concentrations that are 'balanced' at a salinity appropriate for the particular organism.* The PDFB parameter compares a water composition to that of seawater diluted or concentrated to the same salinity. Thus it eliminates salinity as a variable and reflects the composition of the water relative to seawater. A water having a relatively greater amount of a major ion than seawater at the same salinity has a positive PDFB value for that ion. Similarly, a water having a relatively lesser amount of a major ion than seawater at the same salinity has a negative PDFB for that ion. Seawater by definition has PDFB values of zero percent for each species.

Table 4 shows PDFB values from various Australian waters and Table 5 from US municipal concentrates. Each column of Table 4 (for Australian waters) and Table 5 (for U.S. municipal concentrates) ranks the PDFB value for a given ion from the highest value to the lowest found in the saline waters. In Table 4, the color code identifies the general water source. In both Tables 4 and 5, the dark red cells denote the zero values for seawater. The columns are independent of each other; i.e., columns in a given row do not correspond to the same water.

In Tables 4 and 5, the red bar represents seawater taken as a salinity of 33,000 mg/L and PDFB values of zero. Moving left to right (from Cl to HCO₃) the number of sites having concentrations higher than that of seawater at the same salinity increases. Both data sets were taken from a global data set that contains water qualities from several hundred sites and for different types of waters requiring treatment. The variability in PDFB values for the Australian, U.S. (municipal concentrate portion), and global data sets by ion is given in Table 6.

Table 6. Variability in PDFB values for Different Data Sets

	Na	Cl	Mg	SO ₄	Ca	HCO ₃
Australia	-93 to 22	-92 to 39	-99 to 383	-100 to 908	-100 to 1056	-98 to 17803
U.S.	-81 to 0	-99 to -2	-91 to 130	-100 to 642	-33 to 988	144 to 18070
Global	-93 to 39	-99 to 39	-100 to 383	-100 to 908	-100 to 1223	-99 to 18070

From Tables 4, 5, and 6 it can be seen that the largest variability is in the HCO₃ values, followed by Ca and then SO₄. Points pertinent to the paper include:

- Concentrates vary widely in salinity and composition
- Because of this, care need be taken in generalizing the results from site-specific studies concerning concentrate management.
- To some extent it is possible to categorize concentrate management option performance and costs based on water qualities; this may be important for high recovery studies.

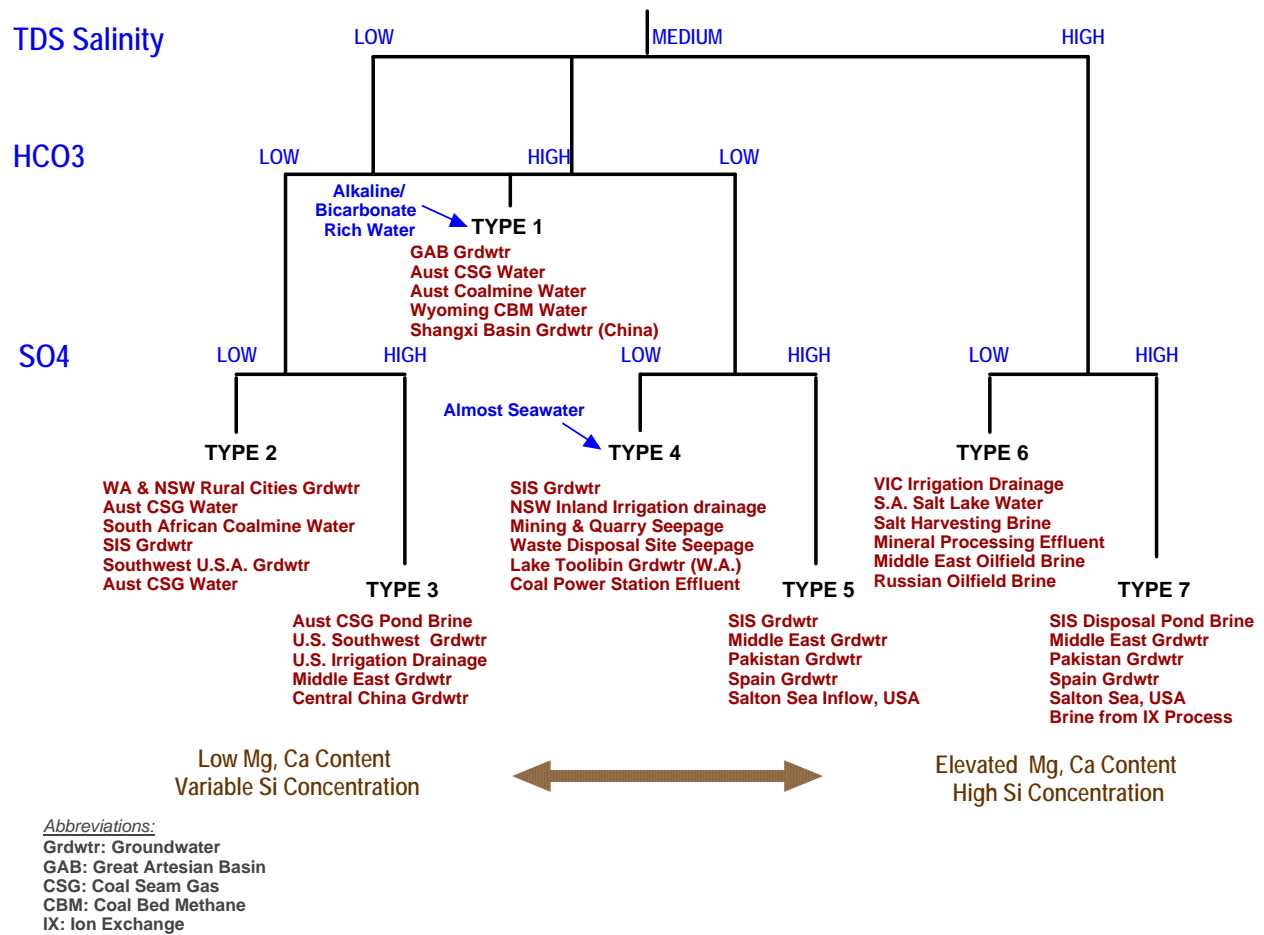


Figure 6. Classification of Saline Waters by Geo-Processors Pty Limited (with permission of Geo-Processors Pty Limited) (from Arakel and Mickley, 2009)

5.5 Definition of ZLD

Largely because of the more extensive use of high recovery processing in other industries and in other countries, ZLD might be considered to be a subset of high recovery. ZLD processing is high recovery processing where the final residuals meet the definition of ZLD. There are multiple uses of and lack of a clear definition of ZLD in municipal concentrate management literature. The original definition means that there is no liquid discharge across the plant boundary. The first ZLD plants were mandated for the power industry so that plants near the Colorado River would not discharge into the Colorado River and further increase its salinity. The early mechanical vapor compression evaporators and what we now call wastewater brine concentrators were developed for this purpose. ZLD systems originally consisted of brine concentrators treating cooling tower blowdown with the resulting brine going to either thermal crystallizers (evaporators or spray dryers depending on the volume) or to evaporation ponds within the plant boundary. Later, in an effort to reduce the volume of water going to the energy- and cost-intensive brine concentrators, the water was typically treated first by reverse osmosis to reduce its volume. Later yet, some ZLD systems eliminated the thermal evaporators (brine concentrators and crystallizers) and went with high recovery membrane-based treatment systems. Thus ZLD does not mean taking feedwater all the way to solids or processing by thermal evaporators. These distinctions are shown in Figure 7.

Table 4. Classification of Australian Saline Waters by PDFB Method

Type of source water represented by color according to:

Groundwater underlying rural towns facing salinity (WA and NSW)

Coal mine and coal seam gas produced water

Groundwater associated with Salt Interception Schemes (NSW, VIC and SA)

Various groundwaters, mine seepage waters and storage lake water

Seawater

TDS (g/L)	Cl	Na	SO4	Mg	Ca	HCO3
48.7	39	22	908	383	1056	17803
44.6	27	19	181	207	564	16847
41.9	9	17	166	196	525	16061
37.9	6	16	125	102	448	15577
36.6	2	13	91	89	397	15056
33.8	2	13	53	69	323	9414
31.9	2	12	41	67	226	7636
27.7	1	6	40	65	215	7581
26.3	1	6	34	50	208	6672
23.6	0	1	33	41	189	6310
16.7	-1	0	27	34	149	5974
15.4	-2	0	17	32	115	4943
14.0	-2	-1	14	23	110	3902
13.2	-2	-2	11	10	89	2548
12.9	-3	-2	-7	6	82	2055
12.5	-4	-4	-7	6	75	1465
12.4	-8	-5	-9	-5	58	1313
12.2	-10	-5	-13	-6	53	1302
8.9	-16	-5	-30	-9	48	1055
7.7	-16	-6	-31	-12	34	808
7.2	-16	-6	-31	-12	34	808
6.9	-21	-9	-33	-17	20	437
6.4	-21	-9	-33	-17	20	437
4.3	-28	-10	-40	-29	18	299
4.2	-28	-10	-40	-29	18	299
4.1	-29	-11	-40	-37	12	234
4.0	-29	-11	-40	-37	12	234
3.9	-32	-13	-41	-42	7	217
3.2	-32	-13	-41	-42	7	217
2.9	-33	-14	-46	-47	7	213
2.8	-33	-17	-61	-71	-10	199
2.8	-33	-17	-61	-71	-10	199
2.3	-38	-18	-64	-74	-16	159
1.8	-38	-18	-64	-74	-16	159
1.6	-60	-32	-82	-76	-25	99
1.2	-60	-32	-82	-76	-25	99
1.2	-62	-33	-86	-83	-26	79
1.2	-62	-33	-86	-83	-26	79
1.2	-73	-40	-96	-85	-35	44
1.2	-73	-40	-96	-85	-35	44
1.2	-83	-43	-98	-95	-60	44
1.2	-83	-43	-98	-95	-60	44
1.2	-84	-49	-99	-97	-67	-22
1.2	-84	-49	-99	-97	-67	-22
1.2	-85	-50	-99	-98	-74	-28
1.2	-85	-50	-99	-98	-74	-28
1.2	-89	-57	-99	-98	-82	-34
1.2	-89	-57	-99	-98	-82	-34
1.2	-91	-58	-100	-99	-83	-44
1.2	-91	-58	-100	-99	-83	-44
1.2	-92	-66	-100	-99	-85	-97
1.2	-92	-66	-100	-99	-85	-97
1.2	-92	-93	-100	-99	-100	-98
1.2	-92	-93	-100	-99	-100	-98

Table 4. Classification of U.S. Municipal Concentrates by PDFB Method

TDS (mg/L)	Cl	Na	SO4	Mg	Ca	HCO3
			642	130	988	18070
26026	-2	0	635	128	944	17920
14014	-6	-3	563	84	943	17769
11637.2	-6	-7	525	62	942	10109
11630	-22	-12	524	58	917	8829
11380	-29	-15	478	48	915	6813
9915.03	-30	-15	477	45	914	6698
9823	-31	-16	437	33	883	6520
9456	-43	-16	437	31	874	5684
8692	-58	-17	413	21	702	5269
8245	-60	-20	412	20	687	4340
6318.1	-62	-24	307	15	686	4053
6308	-63	-24	277	5	594	3408
6261	-64	-27	258	3	518	3111
5260	-69	-37	248	3	426	2801
4965	-69	-39	245		426	2796
4611	-70	-50	231	-22	343	2776
4490	-74	-50	171	-28	284	1361
4301	-75	-53	104	-30	267	1288
3970.8	-75	-53	37	-30	244	949
1993	-79	-56	11	-30	231	939
1930.75	-80	-57	10	-50	180	908
1639	-82	-59	3	-62	177	836
1456	-83	-59		-65	134	476
1369.05	-83	-64	-21	-67	131	476
1318	-87	-65	-97	-82	109	405
1075.5	-98	-74	-98	-82		404
855.9	-98	-80	-100	-88	-15	144
644	-99	-81	-100	-91	-33	

HIGH RECOVERY (HR) & ZLD

- Recovery greater than that typical of a single membrane step where recovery may be 65-85% (brackish RO)
- As of 2003, no HR or ZLD municipal facilities. Many facilities in other industries.
- ZLD is a subset of high recovery



DEFNs of ZLD used
In municipal industry:

1. No liquid discharge across plant boundary
2. Processing using thermal evaporators
3. Processing to solids

Figure 7. Definition of ZLD and Relationship to High Recovery

5.6 Approaches to High Recovery Processing

The treatment challenge of desalination systems is that at certain levels of volume reduction (concentration of feedwater) solubility limits of sparingly soluble salts, silica, silica complexes, and metals (at high pH) will be reached, and precipitation will occur. The precipitation can scale membranes and heat transfer tubes and significantly compromise performance. The salts and metals of most typical concern from groundwater are:

- CaCO₃
- CaSO₄
- BaSO₄
- SrSO₄
- CaF₂
- Ca/PO₄ salts
- Fe
- Mn
- Al

Brackish water RO and EDR systems typically use antiscalants and dispersants to allow greater recovery than otherwise possible by interfering with (slowing) the kinetics of precipitate formation. Frequently, acid is also used to increase recovery for systems otherwise limited by CaCO₃ and Ca/PO₄ precipitates.

Commercial treatment of brackish inland water is done by either brackish reverse osmosis or EDR. Typical recovery limits are from 65 to 85% for BRO and up to 90% for EDR.

Dependent on feedwater quality and pretreatment steps, there are instances where high recovery can be achieved in a single membrane step. More typically, however, for recoveries above, say, 92% (an arbitrary number), the term high recovery means achieving recoveries beyond what can be done with single membrane systems.

For most feedwater considered, this means that the resulting concentrate has a salinity of less than 50,000 mg/L and most times much less than this level. Again, there are exceptions to this. Since seawater RO systems can achieve 50% recovery on feedwater of 35,000 mg/L, producing concentrates of 70,000 mg/L, concentrate from brackish water membrane systems have potential to be further concentrated by seawater RO. Where the RO1 (brackish water RO) concentrate is of lower salinity, the second RO (RO2) may be another brackish RO.

Thus, in most cases the attainment of higher recovery refers to the further treatment of brackish membrane concentrate by additional processing steps. The additional steps may be membrane (additional RO step) or thermal evaporation (brine concentrator and crystallizer). Where possible, and in nearly all instances, the process of choice is a second RO step, whether or not followed by a thermal step.

In discussing approaches to high recovery of brackish water we are usually talking about how to further process RO1 concentrate, where recovery can be limited by the same salts, silica, and metals that may have limited RO1 recovery.

Figure 8 shows the various general approaches to achieve high recovery. They include approaches where:

- Precipitates are allowed to happen within the desalination equipment
 - in these processes volume reduction takes place past the point where precipitation of some species occurs. The precipitates are kept from scaling membranes or heat transfer surfaces by a) precipitation on a circulating slurry such as CaSO_4 solids, or b) high velocities and shear rates. While many precipitating solids adsorb onto the circulating slurry, some do not. Thus seeded slurry brine concentrator performance can be limited by BaSO_4 precipitate, by glauberite, $\text{Na}_2\text{Ca}(\text{SO}_4)_2$, and eventually by Na_2SO_4 , and NaCl .
- Precipitating species are removed before desalination steps
 - this is the most typical approach to high recovery where chemical treatment steps prior to or after desalination steps are used to reduce concentrations of species that might otherwise end up in a precipitate upon concentration of the solution.
 - there are many versions of this, with different groups giving their own names to essentially similar processing schemes (some of the names/labels are shown in Figure 8.)
 - variants of this approach include selective salt removal, where individual salts are removed for use or market
- Unique processing sequences allow high recovery by other means
 - some approaches (ARROW, HEEPM) use unusual sequences of treatment steps to achieve high recovery
 - the Tandem RO approach uses improved antiscalants and pH manipulation to achieve high recovery with 2 membrane steps (without chemical precipitation)
 - ROTEC is an approach to increase recovery by sensing incipient precipitation and reversing the feed flow to the membrane system

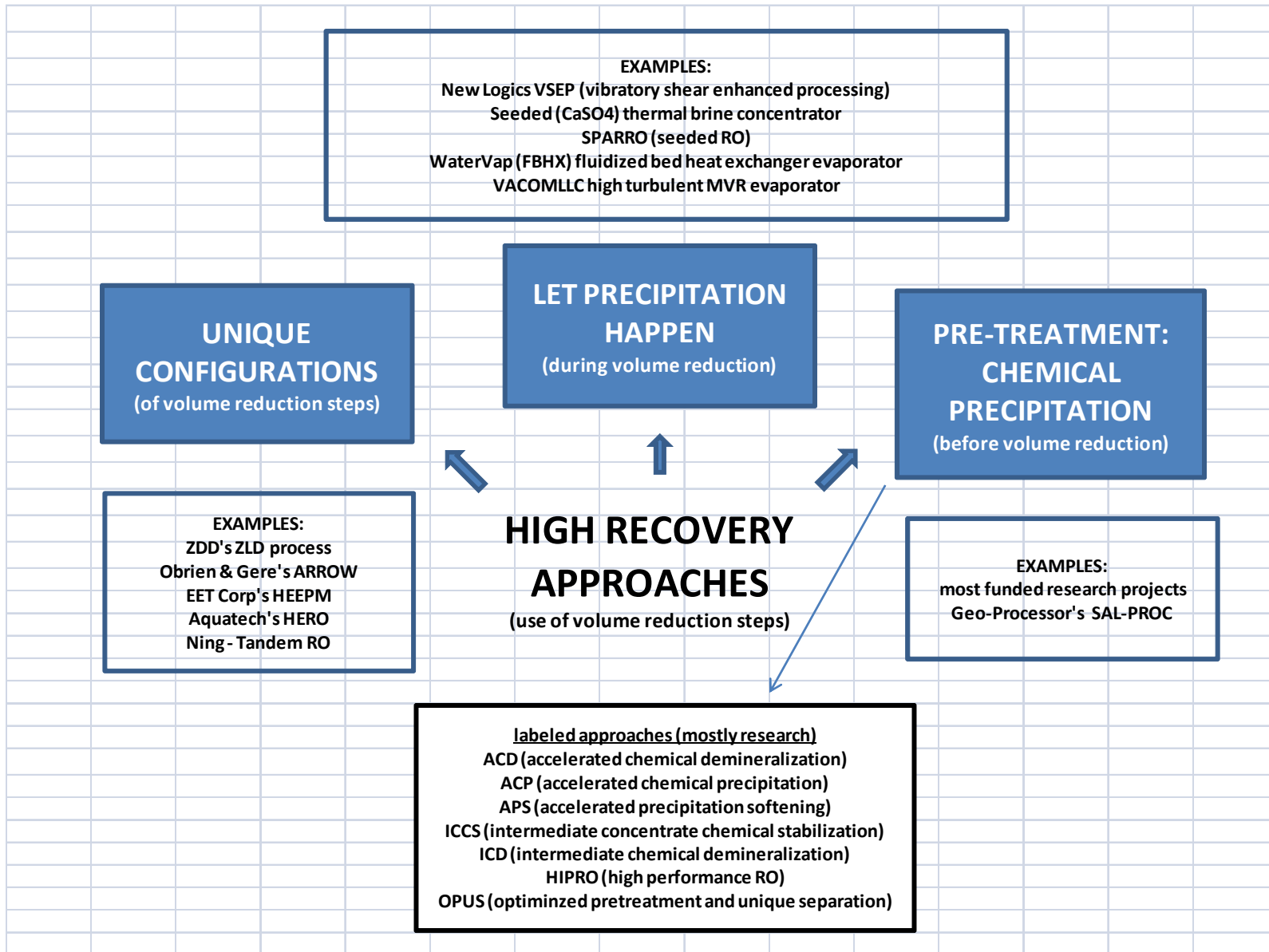


Figure 8. Representation of High Recovery Approaches

- HERO may utilize ion exchange in addition to high pH operation of the RO step

There have been many funded research studies over the past 5 years looking at how to achieve high recovery. These studies confirmed for municipal concentrate what has been known in other industries: that high recovery is not a technical problem but one of cost. More recent funded studies have concentrated on reducing high recovery costs, and perhaps some of the several approaches taken to achieve high recovery will prove to have cost advantages.

It is important to realize that high recovery processing does not necessarily solve the concentrate management problem - there are still final residuals to manage. The advantages of high recovery processing include:

- Minimizing waste volume (and in some sense waste footprint)
- Maximizing utilization of the water resource; minimizing 'lost resource water'
- Providing a feasible (though costly) solution where otherwise none might not be possible
- Minimum dependence on location

As pointed out in the definition of ZLD: high recovery processing schemes can be part of ZLD schemes if: 1) the final brine is sent to an evaporation pond or 2) the final brine is further processed to solids.

5.7 Disposal of Final High Recovery Residuals

The final concentrate from a high recovery process needs to be managed. In general, concentrates from high recovery processes are of higher salinity than concentrates from conventional recovery processes (and certainly so for feedwater of the same salinity). As the salinity of concentrate increases, it becomes more incompatible with the salinity of the most of the potential receiving waters - whether the receiving water is a surface water, sewer water, or groundwater. The incompatibility usually also applies to many constituents of the concentrate. The increased incompatibilities of the concentrate with their receiving water typically eliminates discharge/disposal to any potential receiving water.

5.7.1 Disposal by Deep Well Injection

Of the 5 conventional disposal options, this leaves deep well injection and evaporation ponds. As we have seen from the 2005 report and from the summary of it (above), these two disposal options are not widely used in the U.S. for municipal desalination concentrate. In the case of DWI, it is primarily due to the lack of identified suitable receiving aquifers and to regulatory constraints. While the latest concentrate management survey is several months away from completion (Mickley, 2010), it appears that only 4 or 5 states presently use DWI for this purpose.

Higher salinity concentrate raises some issues with feasibility of DWI. The difference between concentrate salinity and receiving water aquifer salinity is likely more pronounced than for concentrate from conventional recovery processes. This raises questions about the results of blending of the two waters. As in all DWI of desalination concentrate, due to the use of antiscalants and dispersants the concentrate will have some constituents (salt, metals, silica) at or above supersaturation. The kinetic (limited time) effect of these additives means that eventually precipitates will form. The timing is dependent on several factors including:

- Amount of antiscalant and dispersant
- Blending effects (temperature, pH, chemistry)
- Adsorption of antiscalants and dispersants by aquifer media

There is little data on DWI injection of higher salinity desalination concentrates, and care must be taken to anticipate, study, and guard against unwanted results.

5.7.2 Disposal by Evaporation Pond

As with DWI, evaporation ponds have been used in only a few southern states for disposal of municipal desalination concentrate. As discussed in the 2005 report, use of ponds is climate dependent, land-intensive, lacks economy of scale, requires flat land, and thus is rarely available and even more rarely feasible.

Higher salinity concentrate affects evaporation pond feasibility by:

- Reducing evaporation rates, thus requiring more land per volume of concentrate
- More quickly filling up of ponds with solids such that the life of the pond is decreased; this may mean that the pond would need to be a) cleaned out during the life of the desalination plant (with solids being sent to a landfill) or b) covered over and retired (in which case new pond area would need to be provided).

Both of these factors increase the cost of disposal to evaporation ponds.

5.7.3 Disposal of Solids from Additional Treatment of High Recovery Brine

When thermal crystallizers (or spray dryers for smaller volumes) are used to produce solids from brine, the resulting solids are usually of a mixed nature. Given that there are few uses of mixed solids, the solids are typically sent to landfill. As with evaporation ponds, the amount of solids can be high and high enough to require a dedicated monofill to be built for disposal of the solids. Landfill costs are roughly similar to evaporation pond costs and thus are not inexpensive. Costs of a dedicated monofill are frequently similar to the costs of hauling waste to an industrial landfill (provided one is available).

5.7.4 Nature of Final Solids

It is important to undertake an extensive analysis of feedwater quality prior to consideration of high recovery processing. By calculating the solids composition of feedwater taken all the way to solids (without consideration of treatment effects), a worst case chemical composition of the final solids can be estimated (Mickley, 2009). If the solids composition resulting from this calculation is not classified as hazardous (due to metals, NORMS, arsenic, etc. content), then the feedwater is likely a candidate for processing all the way to solids.

If the solids contain constituents that would cause them to be classified as hazardous, then landfill disposal costs would be very high, likely prohibitively high for municipal situations.

5.7.5 Final Residual Brine from Crystallizers

Dependent on the presence of highly soluble salts ($MgCl_2$, $CaCl_2$), thermal crystallizers may have a final bittern that cannot be solidified, in which case there is a blowdown stream from the crystallizer. In most cases this goes to a small evaporation pond.

The primary message from section 5.7 is that disposal of final residuals - whether brine or solids - can be and usually is costly. This underscores the fact that in industries where high recovery processing is widely used, it is used for reasons other than to reduce disposal costs. It is usually done to provide an acceptable solution - from an environmental and thus regulatory standpoint. High recovery processing also can reduce outside water requirements for the industrial facility by providing recycle water.

5.8 Effect of Salinity and Composition on High Recovery Performance and Costs

5.8.1 Preliminary Study of High Recovery Approaches

In 2000 the USBR (USBR, 2000) published a study considering the hypothetical situation of disposing 20 mgd of concentrate from the Phoenix area. Included in the analysis were two options: construction of large areas of evaporation ponds and long distance transport of the concentrate to the Sea of Cortez.

In 2006 (Mickley, 2009) three additional options were considered for this same situation: 1) volume reduction of the concentration by brine concentrator with final brine going to evaporation ponds, 2) volume reduction by RO and then brine concentrator with final brine going to evaporation ponds, and 3) volume reduction by RO only with final brine going to evaporation ponds. The results are summarized in Tables 6 and 7.

As seen in Table 6, the use of high recovery approaches significantly decreased CAPEX values - primarily due to the extremely high costs of evaporation ponds and of transporting concentrate long distance. Both of these original options, however, have modest OPEX values, whereas the high recovery options have significant OPEX values. The high recovery approaches do recover significant volumes of water but the value of the water makes little difference in the relative costs of the approaches. The annual costs of the high recovery approaches in Table 6 are all higher than that of the pipeline option. Thus OPEX has replaced CAPEX. Table 7 takes a closer look at the OPEX values. High recovery approaches 2 and 3 include an RO step in front of the thermal step (approach 2) or in place of the thermal step (approach 3). Evident from the breakdown of OPEX line items, the high energy costs of the thermal process (\$31M/yr) are replaced by high chemical and solids disposal costs. Thus while energy savings are considerable, overall OPEX values remain high.

This study was conducted based on a single water quality. A more detailed study of the effects of salinity and composition on high recovery processing was undertaken in a following project (Mickley, 2008b).

5.7.2 Study of Salinity and Composition Effects on 5 High Recovery Approaches

In this project, 8 concentrates, some actual and some projected from raw water qualities, were used as the basis to compare performance and costs of 5 different commercially used high recovery approaches. In order to uncouple effects of salinity and composition, both of which varied among the concentrates, concentrate salinities (which varied from about 4,000 to 11,000 mg/L) were normalized to 8,000 mg/L. Each constituent was ratioed in the same manner to provide the 8,000 mg/L composition. These cases and their water composition are shown in Table 8 - labeled 1A, 1B, 2A, 2B, and 3. This approach eliminated salinity as a variable, allowing focus on the effect of composition alone. The 5 high recovery commercial approaches considered are shown in Figure 9. The salt recovery process, due to Geo-Processors, was not included in the same analysis but was evaluated and discussed separately. In addition, 5 cases explored the effects of concentrate volume and salinity using a single relative composition (cases 1 - 5). The water composition, salinity and volume of these cases are shown in Table 9.

The project results are extensive in terms of tables and figures and difficult to summarize in only a few example figures and tables. The reader is referred to the project report for details.

Comparison of Disposal Approaches (Hypothetical Phoenix Case)

	Pipeline to Sea of Cortez	Evap. ponds	1 Thermal evap.+ evap. pond	2 High recovery RO + thermal evap.+ evap. pond	3 High recovery RO + Evap. pond
Capital \$	310 MM	410 MM	136 MM	76 MM	92 MM
Operating \$/yr	0.8 MM	1.6 MM	33 MM	29 MM	21 MM
Annual \$/yr	24 MM	33 MM	43 MM	35 MM	27 MM
Water lost	20 mgd	20 mgd	0.8 mgd	0.8 mgd	2.5 mgd

Pipeline and evaporation pond analysis from Bureau of Reclamation study
 Thermal options by Mickley & Associates
 Thermal options assume \$30/ton for solids disposal and \$0.05/kwhr
 Annual costs figured at 40 years and 7.125% interest

Table 6. Cost Comparison of Disposal Approaches

Operating Costs for High Recovery Options

	1 Thermal evap. + evap. pond	2 High recovery RO + thermal evap. + evap. Pond	3 High recovery RO + evap. pond
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
Evap. pond	0.8	0.8	0.8
TOTAL	32.9	28.7	20.8

Table 7. Comparison of Operating Costs for High Recovery Options

CASES 6-12
Same size and salinity
Different composition

CASE #	6	7	8	9	10	11	12
Na	456	1074	2062	1009	2043	1015	1857
Ca	912	967	574	941	75	944	488
Mg	677	212	147	310	36	338	206
K	114	73	97	24	63	81	7
SO4	4577	2206	638	1669	6	3313	3852
Cl	798	1158	4141	1640	95	1323	1376
HCO3	336	2176	161	2212	5682	920	184
Si (as SiO2)	130	134	180	194	0	64	29
approx. TDS	8000	8000	8000	8000	8000	8000	8000
flow (MGD)	10	10	10	10	10	10	10

Table 8. Composition of Cases Studied at Same Salinity and Volume

COMMERCIAL ZLD PROCESSING SCHEMES

- 1A: CONCENTRATE >>> BC >>> EP
 1B: CONCENTRATE >>> BC >>> CRYST >>> solids (to landfill)
- 2A: CONCENTRATE >>> LS >>> RO2 >>> BC >>> EP
 2B: CONCENTRATE >>> LS >>> RO2 >>> BC >>> CRYST >>> solids (to landfill)
- 3: CONCENTRATE >>> LS >>> RO2 >>> EP

Where: BC = thermal brine concentrator (evaporator)
 EP = evaporation pond
 CRYST = thermal crystallizer (evaporator)
 LS = lime softener
 RO2 = second RO stage

NOTE: in schemes 2A, 2B, and 3, lime softening solids go to landfill

[4: selective salt recovery (developed, patented, and licensed outside of the United States)]
 CONCENTRATE >>> sequence of desalination then salt recovery steps
 PROCESSING SCHEME 4 was evaluated separately

Figure 9. Five High Recovery Approaches Studied

CASES 1-5

Same composition
Different size and salinity

CASE #	1	2	3	4	5
	BASE CASE	low salinity - low flow	low salinity - high flow	high salinity - low flow	high salinity - high flow
Na	1226	613	613	1840	1840
Ca	731	365	365	1096	1096
Mg	355	178	178	533	533
K	63	32	32	95	95
SO4	3564	1782	1782	5346	5346
Cl	1111	555	555	1666	1666
HCO3	928	464	464	1393	1393
Si (as SiO2)	22	11	11	32	32
approx. TDS	8000	4000	4000	12000	12000
flow (MGD)	10	1	20	1	20

Table 9. Composition, Salinity, and Volume of Cases Studied at Same Relative Composition

To obtain meaningful costs, it is necessary to accurately estimate the performance of each process step. While this can be done reasonably well for the RO step by using software made available by several sources, it is difficult to do for brine concentrators and crystallizers. For this purpose we interacted with GE-Ionics-RCC, giving them the water composition and having them predict performance. The results of this are shown in Table 10 and 11.

Of note is the widely varying effluent TDS from the brine concentrators that reflect the influence of water composition on performance. The effluent TDS ranges from a low of 145,000 mg/L to a high of 358,000 mg/L. Similar care was taken to predict performance of the other process components (RO, crystallizers, evaporation ponds, landfill).

Costs were developed for each case and high recovery approach. Figure 10 is a rather complicated figure summarizing the 'unit annualized costs.' The term 'unit' refers to the normalization of all costs by the volume of the case. Thus the annualized costs are in units of M\$/mgd. This puts costs on the same volume basis and allows direct comparison to see the effects of salinity and volume (in cases 1 to 5) and of composition (in cases 6 to 12). The unit annualized cost is calculated by amortizing the CAPEX at 8% interest over 20 years to come up with an annual CAPEX value, adding this to the yearly OPEX value, and dividing the sum by the process feed volume.

Performance of BC – Process Schemes 1A and 1B

	feed TDS	feed flow	effluent TDS	effluent flow	limiting
case	(mg/L)	(MGD)	(mg/L)	(gpm)	parameter
1	4,000	1	257,000	210	glauberite
2	4,000	20	257,000	21	glauberite
3	8,000	10	257,000	421	glauberite
4	12,000	1	263,000	30	glauberite
5	12,000	20	263,000	604	glauberite
6	8,000	10	261,000	210	glauberite
7	8,000	10	226,000	231	glauberite
8	8,000	10	358,000	154	NaCl
9	8,000	10	226,000	231	TSS
10	8,000	10	167,000	302	glauberite
11	8,000	10	258,000	210	TSS
12	8,000	10	199,000	278	glauberite

Table 10. Predicted Performance of Brine Concentrator for the 12 Cases - High Recovery Approaches 1A and 1B

Performance of BC – Process Schemes 2A, 2B & 3

	feed TDS	feed flow	effluent TDS	effluent flow	limiting
case	(mg/L)	(MGD)	(mg/L)	(gpm)	parameter
1	60,803	1.21	145,000	352	glauberite
2	61,010	0.06	145,000	18	glauberite
3	61,010	1.2	145,000	350	glauberite
4	58,506	0.19	145,000	53	glauberite
5	58,506	3.74	145,000	1047	glauberite
6	57,623	1.45	145,000	400	glauberite
7	58,953	0.92	145,000	282	glauberite
8	61,156	1.3	263,000	161	NaCl
9	58,578	0.92	143,000	284	glauberite
10	61,851	1.26	247,000	219	NaCl
11	59,153	1.24	145,000	283	glauberite
12	60,766	1.25	145,000	291	glauberite

Table 11. Predicted Performance of Brine Concentrator for the 12 Cases - High Recovery Approaches 2A, 2B, and 3.

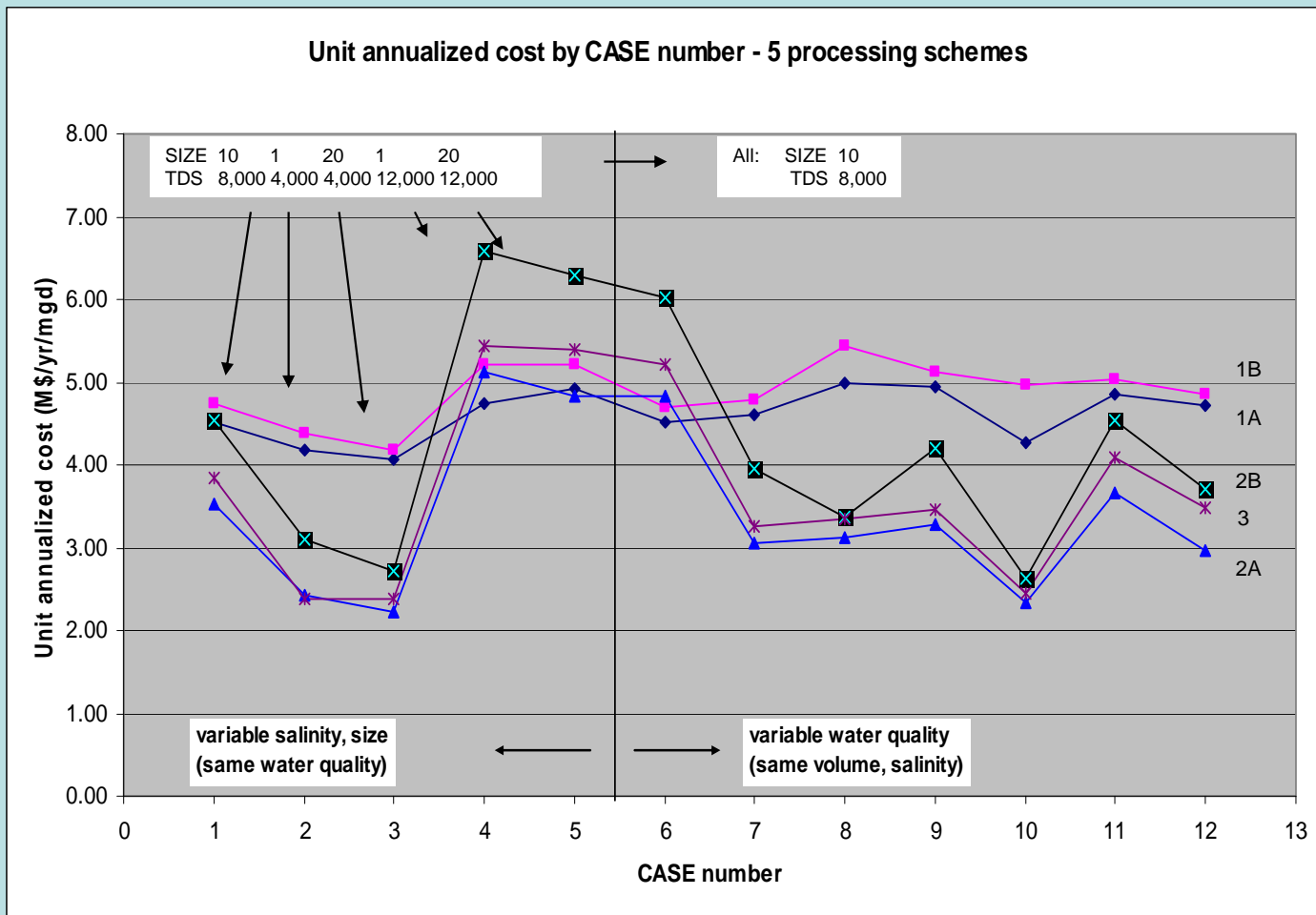


Figure 10. Unit Annualized Cost for the 12 Cases and 5 High Recovery Approaches

In explanation of Figure 10:

- Since the cost is represented as unit annualized cost, the effect of concentrate volume is eliminated
- The 5 lines extending from left to right represent the 5 high recovery approaches
- The first 5 cases represent the effects of salinity and volume
- Cases 6 through 12 represent the effects of composition only

Examples of cost contributions from individual process steps are shown in Figures 11 and 12. Figure 13 shows the energy contributions of the individual processing steps for one case.

Selected results include:

1. Dramatic effects of all three variables (volume, salinity, and composition) on the unit annualized cost
2. This is especially significant for the high recovery approaches involving RO steps (processing schemes 2A, 2B, and 3)
3. These three schemes that include RO are of lower unit annualized cost in all cases except cases 4 and 5, which correspond to the highest feedwater salinity (12,000 mg/L)
4. The lowest cost high recovery approach is usually 2A - but not always (exceptions are cases 2 and 3); this illustrates an important point: the lowest cost (in terms of unit annualized cost) processing scheme is a function of salinity and composition
5. The highest cost processing scheme in nearly every case was scheme 1A (BC >> EP)
6. Significant composition effect is due to lime softening
7. (In general) costs increase with salinity and with hardness but also are dependent on alkalinity
8. ZLD systems are made up of several processing steps; performance and cost of each step are dependent in different ways on salinity and composition
9. Due to this complex interaction between processing steps, simple rule of thumb predictions of performance and cost can be misleading and inaccurate
10. In general, for nearly every case, use of crystallizers resulted in higher costs (note however, use of crystallizers may be necessary to achieve a solution in some situations - such as where evaporation ponds are not possible)
11. Use of second stage RO prior to brine concentrators is nearly always beneficial in terms of cost
12. Costs increase with salinity (for same composition)
13. Costs generally increase with hardness (for same salinity) but costs are dependent on the composition
14. The most location-specific processing steps are evaporation ponds and landfill
15. Note that evaporation ponds are not often available
16. Dedicated landfill costs are CAPEX, whereas hauling wastes to an existing landfill is an OPEX (and typically a greater cost)
17. Highest CAPEX processing steps are typically brine concentrators, evaporator ponds, or landfill
18. Highest OPEX processing steps are typically brine concentrator energy or lime softening chemical costs

Perhaps the most important point from the study is that it is risky to generalize from a single case, as results are highly dependent on salinity, composition, and concentrate volume.

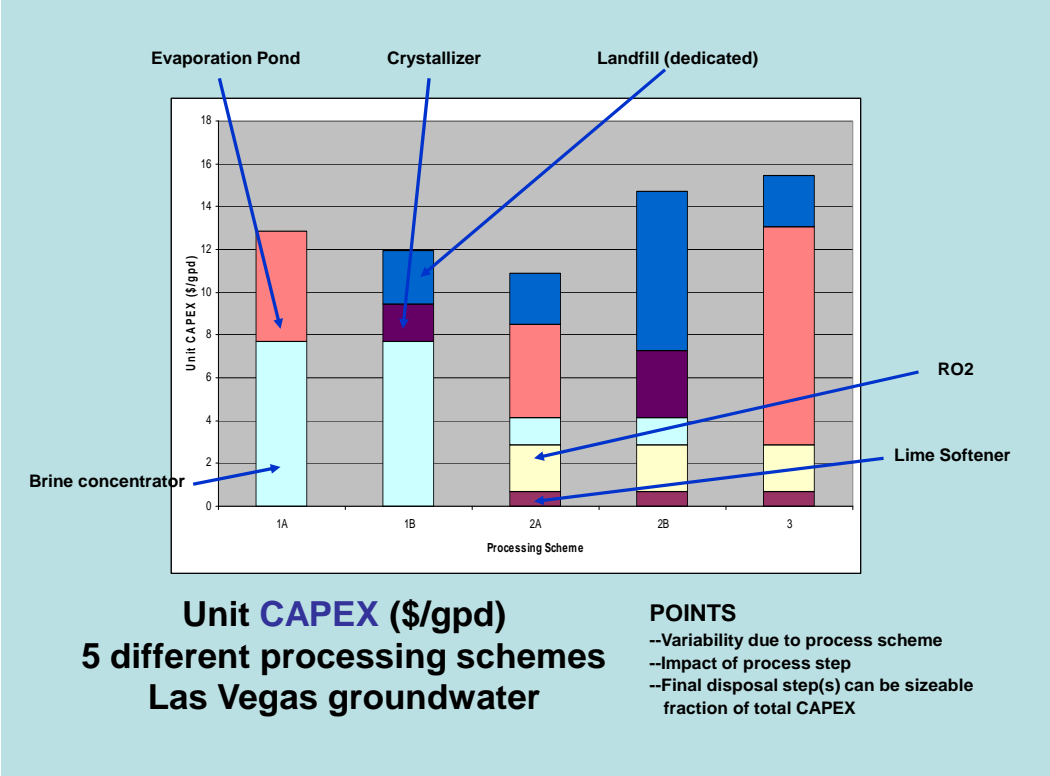


Figure 11. CAPEX Contributions of Individual Processing Steps for One Case

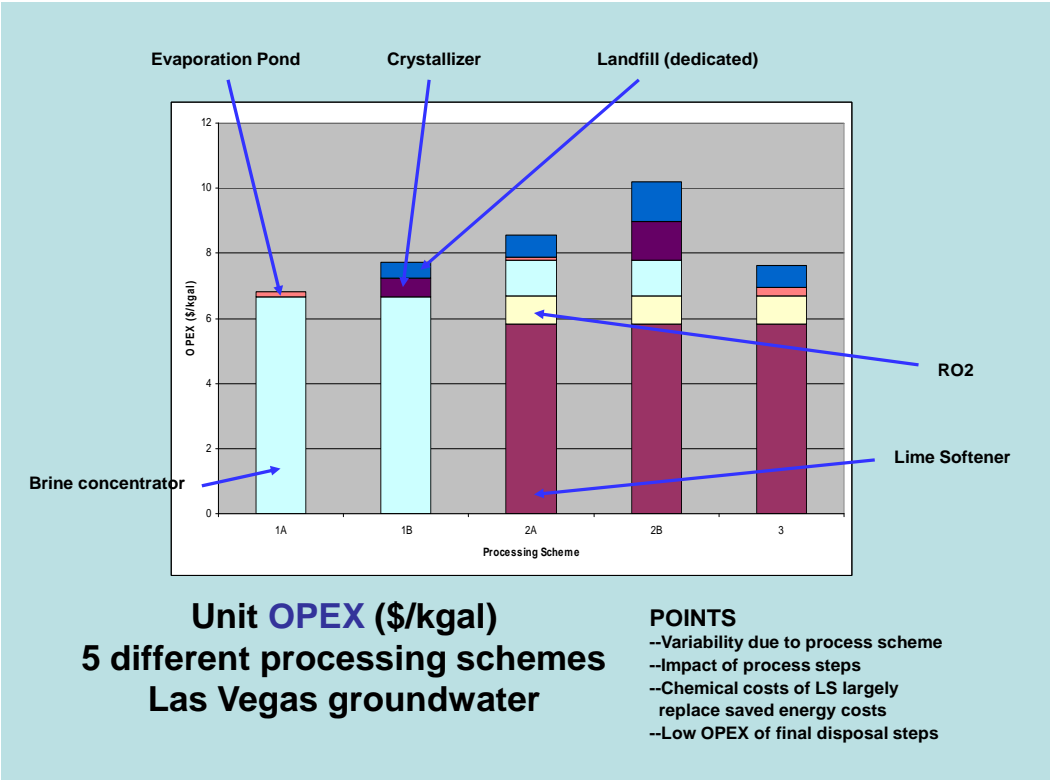


Figure 12. OPEX Contributions of Individual Processing Steps for One Case

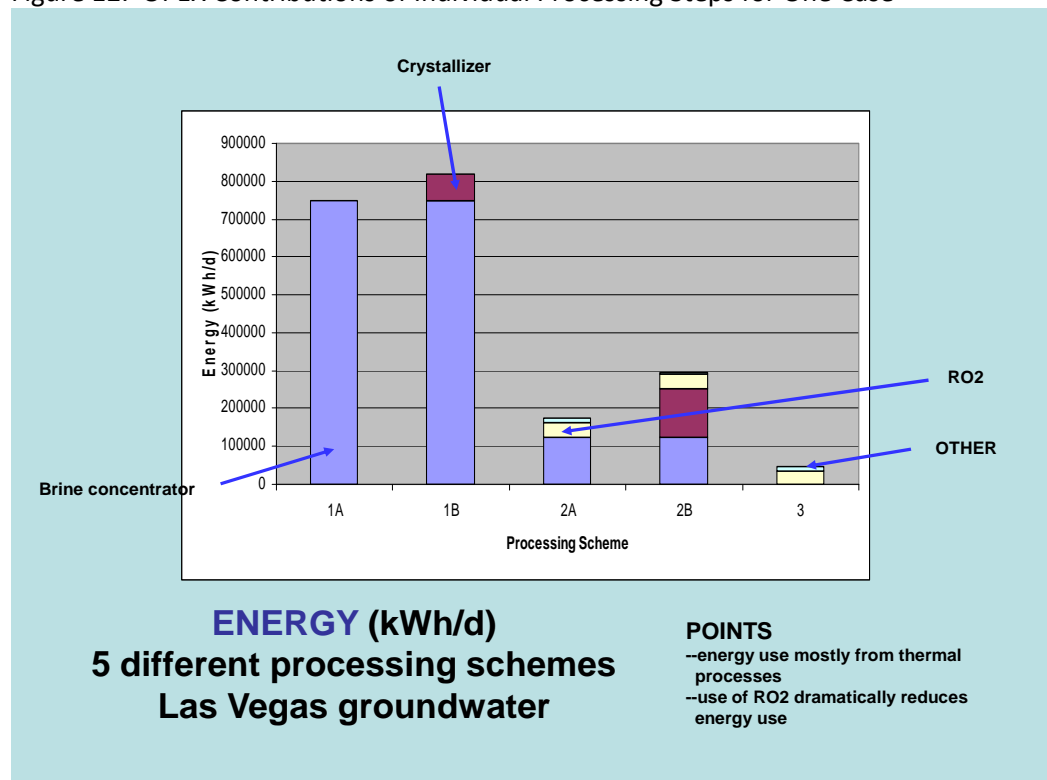


Figure 13. Energy Contributions of Individual Processing Steps for One Case

5.8 Beneficial Uses and Salt Recovery

The promise of beneficial use of concentrate is that the same drop of water can be used more than once. This sounds and is potentially important. My bias, however, shows through when talking about beneficial uses of concentrate, brine, and mixed solids. The 2006 WaterReuse Foundation report (Jordahl, 2006) entitled *Beneficial and Non-Traditional Uses of Concentrate* extensively reviewed beneficial uses. My position on beneficial uses is that:

- Most do not have widespread applicability
- Most are unproven
- Most do not provide for final disposal
- (BUT) due to the challenges in finding CM solutions, it is important to consider local beneficial uses at the planning stage of every new desalination facility.

A partial listing of beneficial uses of concentrate that has appeared in the literature is:

- Oil/gas well field injection to maintain pressures
- Aquaculture
- Transport of mineral resources
- Feedstock for hypochlorite generation
- Dust control and de-icing
- Soil remediation
- Solar ponds
- Wetlands
- Cooling water

- Scrubber water
- Subsurface storage

A few comments:

- Long-term use of concentrate requires that the use be available throughout the life of the desalination plant; this is a problem for the oil/gas well injection use
- While aquaculture use may result in a new economic entity employing people and having other benefits, the concentrate picks up an organic load and must be disposed of or treated and recycled.
- Dust control requires large amounts of dirt road for a relatively small volume of concentrate
- There is a real need for soil remediation, and some concentrates and salts obtained from concentrate could be used for that purpose; land owners, however, are usually not willing to use anything but the least expensive product.
- Solar gradient ponds require significant amount of time (months/years) to reach the point where they are fully operating; unless the concentrate used for this is evaporated or treated to recovery water the pond will need to continually grow in size.
- Several years ago in discussing use of concentrate for deicing with a California County, I was told that more and more products for such uses need to undergo environmental approval and meet standards set up by the overseeing industry. Many mixed salts and brine from desalination plants have a wide range of constituents and thus are not comprised mainly of salts typically used for de-icing.
- A major concern with irrigation of salt tolerant plants is the effect of high salinity concentrate on underlying groundwater. This requires an efficient drainage system to capture the applied irrigation water. The drainage water will need treatment, such as ZLD processing, to produce salts for disposal.

The general comments about beneficial use of concentrate extend to use of higher salinity brine and the mixed solids produced from brine.

5.8.1 *Salt Recovery*

The one area of beneficial use that I have championed is the production of individual salts for use and or market. The author has written chapters in various reports examining selective salt recovery (Jordahl, 2006; Mickley 2008; Mickley 2009).

In the past 2 years, the author has participated in projects in South Africa, Oman, UAE, and Australia, where salt recovery was considered a favored processing approach. These projects were for treatment of produced waters, mining waters, and brine from potable water desalination plants.

One of the findings from examination of desalination practices in other industries and in particular in other countries was that salt recovery is more prevalent than in the U.S. An example is a project in Oman where produced water needs to be managed. In several Middle East countries salts are imported at significant cost and thus high recovery treatment of produced water has been considered as a means of providing useable salt while producing usable water, minimizing waste, and in total providing a viable solution for managing the produced water.

There are companies, mainly from Europe, that make thermal evaporators specifically for the purpose of recovering salts. This is in contrast to the wastewater thermal evaporators used in many U.S. non-municipal high recovery/ZLD situations.

In the U.S. the efforts of ZDD (Dr. Tom Davis), Gerry Groot, and Geo-Processors Pty Limited are noteworthy for considering and addressing salt recovery for several years. Other groups have begun to explore salt recovery, an example of which is the Phoenix study by Carollo Engineers (He et al., 2008).

Selective salt recovery has received increasing attention in the past few years due to:

- The growing need for alternative concentrate management options
- The potential benefits of selective salt recovery in
 - avoiding negative environmental impacts associated with concentrate, brine, and solids disposal
 - decreasing operating costs through sale of recovered salts
 - providing a means of approaching the ideal of sustainability
 - decreasing the CO₂ footprint of the desalination process through removal of carbonate species
 - the feasibility of a site-specific operation to recover and market salts, however, depends on several factors, including:
 - volume of concentrate
 - water quality (salts obtainable from the concentrate)
 - quality (form and purity) of salts obtained
 - reliability, consistency of salt quality
 - types of applications for the obtainable salts (types of markets)
 - existence of a local market
 - size of the local market
 - reliability of the local market
 - combined income from sale of the different salts

Each site-specific consideration of the concept will require a feasibility analysis phase to address these and other issues prior to commitment to the concept. It is also important to note that market value is not directly related to economic feasibility. A sufficient mass of salts must be available to make processing and recovery feasible. There is likely a fundamental conflict that must be resolved between the economic structures suitable for producing water as a utility and producing salt or other by-products as price-variable commodities. There is a need to develop value-added products that utilize salts removed from concentrate to uncouple feasibility from dependence on existing markets. This remains a significant challenge.

In general, salt separation and marketing of salts hold considerable promise to provide concentrate management solutions for some locations – including locations in the arid southwest U.S., where desalination plants are not being built due to the lack of a cost-effective concentrate disposal solution.

Of importance beyond providing cost-effective concentrate disposal solutions, the separation of salts and their marketing are a strong step toward achieving a sustainable, environment supporting solution where water recovery is maximized and salts are recycled.

6.0 NEEDS AND RESEARCH

6.1 *Goals for a Research Program and Projects*

Needs may be considered from the perspective of getting from where we are now (point A) to where we want to go (Point B - the goal).

Point B might be something like:

- cost-effective, environmentally sound/sustainable concentrate management solutions that are well-defined, well-guided, well-communicated, applicable to small and large facilities, are part of an integrated water resource management plan, consistent with national and state water and energy policies, supported by federal and state initiatives, and are supported by science-based policies and regulations.

It continues to be a challenge to define clear, detailed pathways to get to Point B for CM. Reasons for this include:

1. Until recently, CM has received relatively little attention within the water and desalination industries

Desalination plants produce less than 3% of the potable water in the U.S., and the number of desalination plants having significant CM challenges are a small (but growing) subset of this. Critical CM challenges are mostly found in the arid southwest U.S.

For many years the issues of desalination were focused on the technology and not on environmental and by-product (concentrate) areas. Although CM issues were getting recognized in the 1990s they were (correctly) considered areas of future importance. It was not until the 2000s that CM started to be seen with growing significance as a cost and general feasibility factor in implementing desalination plants.

The desalination industry (thermal and membrane) developed and grew due to large amounts (\$1.6 billion in 2006 dollars) of federal funding in the 1950s, 1960s, 1970s and into the 1980s; funding from OSW (Office of Saline Water) and later OWRT (Office of Water Research and Technology). Comparable funding to address more recent challenges, including CM, have not been forthcoming. To a large extent, funding has been left to the industry, which, understandably and typically, addresses challenges only when forced to.

Thus, it has taken time to define the more detailed issues, challenges, and needs of CM. There are relatively few people within the water treatment and desalination industry who have experience in this area. There have, until recently, been few workshops, little funded research, and in general, only minor attention given to CM.

2. CM is quite different from other water treatment and desalination topics/areas

Desalination plants have a high volume of waste (concentrate) relative to other types of drinking water plants. Setting aside the more recent focus on high recovery processing, historically, CM focus has been on the 5 conventional disposal options. The choice of treatment option for desalination water production is dictated by performance goals and cost; while design is site-specific (dependent on water quality among other variables), the basic technology is the same for every location. The choice of CM option, however, is dictated by availability of options, ability to get the option permitted, and then cost. There is much less focus on the equipment and design associated with the CM options - and much less

likelihood of reducing the equipment related costs associated with the relatively simple equipment used in the 5 conventional CM options.

As a result of these two factors, it has taken time to define the issues, challenges, needs, and pathways to meet the needs for the area of CM.

In the past, larger goals have been relatively clear. In recent years, pieces of the path have been defined and explored, but it still remains to define the more detailed step-by-step pathways to meet the needs and goals.

Some research pathways lend themselves to more definition than others. For example, the pathway to determining environmental impacts is something that seemingly could be well defined in terms of research areas and a sequence of parallel and series studies. It involves more information gathering on definable steps than, e.g., research to reducing costs - an area that has more unknowns in terms of how to proceed. Both areas, of course require creativity and are important but there is a difference in the likelihood of defining appropriate projects and in their success of meeting Point B goals.

6.2 Areas of Need

There are several areas of needs relative to CM. These have been categorized in different ways by different groups. Several areas of need can be identified from consideration of efforts from several past planning and workshop groups, and from comparing the present status of the industry with the above-mentioned goals. These areas are:

- Technology
- Environment
- Regulation
- Implementation / Direction
- Information

6.3 General Discussion of Areas

By means of bullets, a layer of detail is added to the needs of the various areas:

- Technology
 - reduce footprints of CM equipment (including high recovery process equipment)
 - cost
 - physical
 - energy
 - CO₂
 - waste
 - reduce capital costs of CM equipment (including high recovery process equipment)
 - reduce operating costs of CM equipment (including high recovery process equipment)
 - energy
 - chemicals
 - final waste volume
 - improve information base and tools
 - cost models
 - mapping of brackish water qualities

- mapping of DWI opportunities
- Environment
 - understand impacts
 - develop protocols
 - develop technology and approaches to minimize impacts
 - avoid hazardous and toxic wastes
- regulation
 - define based on concentrate
 - define based on science
 - reclassify municipal concentrate (to counter perceptions of the industrial waste classification)
- implementation / direction / information
 - policy
 - federal and state leadership and investment
 - national water policy
 - real value of water
 - develop guidelines
 - develop standards
 - improve communication
 - make information more readily available
 - communicate information more effectively
 - gather and document information more efficiently

While these areas are important they may not be all-inclusive.

6.4 Breakthrough Areas

The most challenging areas on the path from A to B will require creative 'breakthroughs.' Some breakthrough areas are:

- significantly reducing high recovery processing costs
- developing widespread uses of concentrate, brine, and solids that do not transfer the 'waste' to another entity or site
- creating value-added products made from sodium and calcium salts
- developing widespread uses for NaCl brine

The above discussion is offered as a framework from which to define paths, and specific research projects to support moving toward Point B goals.

7.0 WHITE PAPER - AFTERWORD

The purpose of this White Paper is to provide a basis for shared understanding and appreciation of the subject; and from this to support definition of meaningful research topics to address present issues and needs for concentrate management. The thoughts and ideas expressed by the author are limited by the author's experience, perceptions, and biases - but hopefully not too limited. The author acknowledges funding from several sources for various projects mentioned in the paper. The sources include:

- Bureau of Reclamation
- WateReuse Foundation
- Water Research Foundation (formerly AwwaRF)

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APPENDIX A: PARTIAL LIST - FUNDED RESEARCH - Concentrate Management

revision 3/9/10

Mickley & Associates

USBR - United States Bureau of Reclamation

	date	research group
16 - Eastern Municipal Water District RO Treatment/Saline Vegetated Wetlands Pilot Study	published 1996	USBR
32 - Brackish Groundwater Treatment and Concentrate Disposal for the Homestead Colonia El Paso	published 1999	UTEP
35 - Halophyte Crops and a Sand-Bed Solar Concentrator to Reduce and Recycle Industrial, Desalination and Agricultural Brines	published 1998	U. of Az; Texas A&M
54 - Evaluation of Two Concentrate Disposal Alternatives for the Phoenix Metropolitan Area: Evaporation Ponds and Discharge to the Gulf of California	published 2000	USBR
69 - Membrane Concentrate Disposal: Practices and Regulation 2nd edition - available 2005	published 2001	Mickley & Associates
89 - Zero Waste Brine Management for Desalination Plant	published 2002	UTEP
98 - Systems Development for Environmental Impact Assessment of Concentrate Disposal	published 2003	Oregon Health and Science Univ.
36 - Reverse Osmosis Treatment of Central Arizona Project Water for the City of Tucson	published 2004	Tucson Waster Dept; USBR
46 - Salinity and TOC Removal Using Nanofiltration	published 2002	UTEP
72 - Desalting Handbook for Engineers	published 2002	Rostek Assoc, DSS Consulting, Aqua Resources International
95 - Desalination and Water Purification Technology Roadmap	published 2003	USBR, Sandia National Lab.
108 - Volume Reduction of High Silica RO Concentrate Using Membranes and Lime Treatment	published 2004	UTEP
Use of Depleted Oil and Gas Well Fields for Disposal of Desalination Concentrate	completed 2005	TWDB and Bureau of Economic Geology
111 - Zero Discharge Seawater Desalination: Integrating the Production of Fresh Water, Salt, Magnesium, and Bromine	published 2006	University of South Carolina
112 - Using Oil Fields for the Disposal of Concentrate from Desalination Plants: Please Pass the Salt	published 2006	Texas Water Development Board
119 - Reverse Osmosis Recovery Maximization	published 2008	Carollo Engineers
123 - Membrane Concentrate Disposal: Practices and Regulation	published 2006	Mickley & Associates
125 - Cost-Effective Volume Reduction of Silica-Saturated RO Concentrate	published 2008	University of Texas at El Paso
132 - Systems Development for Environmental Impact Assessment of Concentrate Disposal - Development of Density Current Simulation Models, Rule Base, and Graphic User Interface	published 2007	Portland State University
135 - P/Pilot Testing of Zero Discharge Seawater Desalination - Application to Selenium Removal from Irrigation Drainage	published 2008	University of South Carolina
149 - Evaluation and Selection of Available Processes for a Zero-Liquid Discharge System for the Perris, California Ground Water Basin	published 2008	Eastern Municipal Water District
155 - Treatment of Concentrate	published 2009	Mickley & Associates

AwwaRF - America Water Works Association Research Foundation

3151 - Report on Concentrate Management Working Group	issued 2005	several participating groups
3096 - Inland Brine Treatment Strategies for Water Reclamation Systems	issued 2004	Arizona State University
3030 - Desalination Product Water Recovery and Concentrate Volume Minimization	issued 2005	Carollo Engineers
3010 - Zero Liquid Discharge and Volume Minimization for Inland Desalination	issued 2003	Black & Veatch
498 - Current Management of Membrane Plant Concentrate	published 2000	Clarkson University
290 - Major Ion Toxicity in Membrane Concentrate	published 2000	Mickley & Associates
Membrane Concentrate Disposal	published 1993	Mickley & Associates
4148 - Evaluation of VSEP to Enhance Water Recovery During Treatment of Brackish Water and RO Concentrate	published 2007	University of Washington / HDR

WRF - Water Reuse Foundation

WRF-02-006a - Survey of Volume Reduction and Zero Liquid Discharge Technologies for Water Utilities	published 2008	Mickley & Associates
WRF-02-006b - Beneficial and Non-traditional Uses of concentrate	published 2006	CH2M-Hill
WRF-02-006c - Impacts of Membrane Process Residuals on Wastewater Treatment	published 2006	Black & Veatch
WRF-02-006d - Investigation of Regional Solutions for Disposing of Concentrate	published 2008	Carollo Engineers
WRF-05-009-01 - Dewatering Reverse Osmosis Concentrate form Water Reuse Applications Using Forward Osmosis		
WRF-05-010 - Oxidative Destruction of Organics in Membrane Concentrates	in progress	Arizona State University
WRF-07-02 - Development of Information Clearinghouse on Concentrate and Salt Management	in progress	Mickley & Associates

California Proposition 50

005 - Under Ocean Floor Seawater Intake and Discharge Demonstration Project	issued 2005	City of Long Beach
012 - Coachella Valley Groundwater Desalination Project	issued 2005	Coachella Valley Water District
022 - Desalination Recovery Enhancement and Concentrate Management Study	issued 2005	Eastern Municipal Water District
008 - Study of Low Concentration Metals Removal from Brine	issued 2005	Calleguas Municipal Water District
016 - Feasibility Study of Brackish Water Desalination	issued 2005	Montara Water and Sanitary District
041 - Pajaro Watershed Groundwater Desalination Feasibility Study	issued 2005	San Benito County Water District
F2006-05 - Feasibility of Regional Concentrate Conveyance Facility in San Diego County	issued 2006	San Diego County Water Authority
F2006-08 - Zero Discharge Novel Hybrid Membrane Desalination Process with Minimal Pretreatment and Concentrate	issued 2006	Colorado of School of Mines

TWDB - Texas Water Development Board

Feasibility Study on Product Water Desalination		A&M Texas Engineering Extension Service
Guidance Manual for Brackish Groundwater Desalination in Texas	completed 2008	North Cameron Regional Water Supply Corporation
Self-Sealing Evaporation Ponds for Desalination Facilities in Texas	revised 2009	Bureau of Economic Geology
Desalination Brine Discharge Model	completed 2006	University of Texas at Austin
Evaluation of Economic and Reliable Methods of Brine Management	completed 1996	Stonewall County

Trinity Aquifer, VSEP, Concentrate Management	in progress	San Antonio Water System
Concentrate Management, Laboratory Study	in progress	University of Texas at Austin
Concentrate Management, VSEP, El Paso County	in progress	El Paso Water Utilities - PSB
WERF - Water Environment Research Foundation		
NONE - several membrane related projects; none directly related to concentrate disposal; some joint funding of research overseen by other groups		
NWRI-USA - National Water Research Institute		
NONE - several membrane related projects; none directly related to concentrate disposal		
MEDRC - Middle Eastern Desalination Research Center		
97-AS-007 Investigation of the use of evaporation ponds for brine disposal in inland desalination plants	completed	
00-AS-020 Enhanced evaporation for treatment of desalination brines	completed	
98-AS-020 Assessment of Composition of Desalination Disposal Brines	ongoing	
00-AS-010 Spirulina Culture Using Reject Brine from Desalination Plants	ongoing	
IO-3 Literature Survey of Intake / Outfall Systems for Desalination of Brackish and Seawater - Including Structures, Materials of Construction	RFP topic	
IO-4 Survey of Existing Models and Development of Improved Simulation for Discharge Brine Dispersion	RFP topic	
SJRWMD - St Johns River Water Management District, FL		
Investigation of Demineralization Concentrate Management Project	completed 2001	Reiss Environmental, Inc.
Seawater Demineralization Feasibility Investigation	completed 2002	R.W. Beck, Inc.
Demineralization Concentrate Management Project	completed ~ 2007	CH2M Hill
DRIP - Desalination Research and Innovation Partnership		
Research into volume reduction of concentrate	completed in 2005?	